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Introduction

The International Association of Geodesy (IAG) is publishing its reports regularly since 1923 (Tome 1). They were called "*Travaux de la Section de Géodésie de l'Union Géodésique et Géophysique Internationale*" in the first years. According to the renaming of the IUGG Sections as Associations, the name was changed in 1938 to "*Travaux de l'Association de Géodésie*". They are published on the occasion of the IUGG General Assemblies, which were held every three years until 1963, and since then every four years. These volumes serve as comprehensive documentation of the work carried out during the past period of three or four years, respectively. The reports were published until 1995 (Volume 30) as printed volumes only, and since 1999 (Volume 31) in digital form as CD and/or in the Internet.

Since 2001, there are also midterm reports published on the occasion of the IAG Scientific Assemblies in between the General Assemblies. Usually, they are presented before the Assembly to the IAG Executive Committee (EC) and are discussed in the EC meetings to receive and give advice for future work. The present Volume 43 contains the reports of all IAG components for the period 2019 to 2023 and is presented at the IUGG General Assembly in Berlin, Germany, July 11 – 20, 2023.

The editors thank all the authors for their work. Feedback from the readers is welcome. The digital versions of this volume as well as the previous ones since 1995 may be found on the IAG website (http://www.iag-aig.org).

Markku Poutanen
IAG Secretary General

Commission 1 – Reference Frames

https://com1.iag-aig.org

President: Christopher Kotsakis (Greece)
Vice President: Jean-Paul Boy (France)

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Overview

Terms of Reference

Reference systems and frames are of primary importance for Earth science research and applications, satellite navigation and orbit determination as well as for practical applications in positioning, mapping and geo-information related fields. A precisely defined reference frame is needed for an improved understanding of the Earth system, including its rotation and gravity field, sea level change with time, tectonic plate motion and deformation, glacial isostatic adjustment, geocentre motion, deformation due to earthquakes, local subsidence, and other crustal displacements. Commission 1 activities and objectives deal with the theoretical and operational aspects of how best to define reference systems and how reference systems can be used for practical and scientific applications at different spatio-temporal scales on the deformable Earth. Commission 1 closely interacts with other IAG Commissions and Services, the ICCT, the newly established ICCC, and the GGOS components where reference system aspects are of concern, to address related problems for the realization of celestial and terrestrial reference systems in conformity with present and future accuracy needs. Commission 1 is also linked with the IUGG/COSPAR joint Sub-Commission B2 (International Coordination of Space Techniques for Geodesy) under the aim to develop links and coordinate the work between various groups engaged in the field of space geodesy and geodynamics.

Objectives

As stated in the IAG by-laws, the main objectives of Commission 1 are:

- Definition, establishment, maintenance and improvement of the geodetic reference frames;
- Advanced terrestrial and space observation technique development for the above purposes;
- International collaboration for the definition and deployment of networks of terrestrially-based space geodetic observatories;
- Theory and coordination of astrometric observation for reference frame purposes;
- Collaboration with space geodesy/reference frame related international services, agencies and organizations;
- Promote the definition and establishment of vertical reference systems at global level, considering the advances in the regional sub-commissions;
- Work to maintain a reference frame that is valuable for global change studies.

Steering Committee 2019-2023

President:	*Christopher Kotsakis (Greece)*
Vice President:	*Jean-Paul Boy (France)*
Chair SC 1.1:	*Urs Hugentobler (Germany)*
Chair SC 1.2:	*Xavier Collilieux (France)*
Chair SC 1.3:	*Carine Bruyninx (Belgium)*
Chair SC 1.4:	*Zinovy Malkin (Russia)*
Representative of IGS:	*Paul Rebischung (France)*
Representative of IERS:	*Detlef Angermann (Germany)*
Member-at-Large:	*Guangli Wang (China)*

During the 2019-2023 period, the Steering Committee of Commission 1 did not have the chance to meet physically, mainly due to travel restrictions imposed by the COVID-19 pandemic. Commission-related business was discussed at several on-line meetings of the IAG's Executive Committee, and they were also conducted through email discussions and electronic exchange of information among the members of the Steering Committee (i.e. planning of Commission 1 symposia and related sessions in IAG and IUGG scientific meetings, organizing the REFAG2022 scientific program, etc.).

Activities during the reporting period 2019-2023

This report presents the activities of the entities of Commission 1 for the period 2019-2023. As shown above, Commission 1 consists of four sub-commissions (SCs), whereby SC 1.3 is composed of six regional SCs, and several Working Groups, Joint Working Groups and Study Groups. Many of these entities were very productive and made significant progress in their specifically stated objectives according to their programmes of activities despite the severe impacts of Covid-19. The detailed activity reports of these entities can be found in following chapters and their main achievements are summarized at the end of this section.

During the period 2019-2023 Commission 1 was represented in the Steering Committees of various IAG components, including the Inter-Commission Committee on Theory (ICCT), the Inter-Commission Committee on Climate Change (ICCC), the Inter-Commission Committee on Marine Geodesy (ICCM) and the IAG Project "Novel Sensors and Quantum Technology for Geodesy". Commission 1 was also represented in the ILRS Governing Board and the GGOS Executive Committee, as well as in all the IAG Executive Committee Meetings at which brief progress reports of its activities were presented. In addition, Commission 1 was represented and participated in the work of the IAG Cassinis Committee for the updating of the current IAG Statutes and By-Laws. The results of this work and the proposed changes shall be presented to the IAG Council Meeting during the IUGG2023 General Assembly in Berlin.

Commission 1 was involved in the organization of several IAG scientific conferences, symposia and workshops, as well as in numerous thematic sessions at the EGU, AGU and COSPAR meetings. Commission 1 also actively contributed to GGOS-related activities, including the organization of the Unified Analysis Workshop (UAW) 2022 that was held in Thessaloniki, Greece, in conjunction with the REFAG2022 international symposium. These activities are presented in detail in the following sections of this report. However, it should be noted that many theme-specific events and other research activities of Commission 1 were severely affected (either cancelled, delayed or postponed) due to the Covid-19 pandemic situation.

Commission 1 is linked with COSPAR and its Sub-Commission B2 "International Coordination of Space Techniques for Geodesy". Under the dual role as chair of Sub-Commission B2 and IUGG representative to COSPAR, the President of Commission 1 participated in several COSPAR-related events including the COSPAR Council Meetings that were held during the 43rd and 44th COSPAR Scientific Assemblies.

Meetings and conferences

REFAG 2022

One of the regular highlights of Commission 1 activities within the four-year period between two consecutive IUGG General Assemblies is the organization of the *REFAG International Symposium* ("Reference Frames for Applications in Geosciences"), which is the main scientific event of the Commission and its sub-components. For the reporting period, the REFAG symposium was held in Thessaloniki, Greece, from 17 to 20 October 2022. The venue of the symposium was located at the Electra Palace Hotel in the heart of downtown Thessaloniki, overlooking the city's magnificent seafront. A total number of 96 participants from 22 countries attended the symposium which took place in traditional form with on-site only participation. The event was organized by the Department of Geodesy and Surveying of the Aristotle University of Thessaloniki, under the scientific coordination of IAG Commission 1 and its four sub-commissions.

The REFAG2022 symposium carried on the well-established tradition of IAG dedicated symposia on Reference Frames that were previously held in Munich (2006), Marne-la-Vallee (2010), Luxemburg (2014) and Pasadena (2018). The primary scope of the symposium was to address current theoretical concepts, advancements and open problems related to reference systems and their practical implementation by space geodetic techniques and their combinations, underlying also limiting factors, systematic errors, infrastructure-related aspects and novel approaches for future improvements. The scientific program of REFAG2022 covered all main topics in relation to the activities of Commission 1 and its subgroups, including also other initiatives and ongoing projects which endorse the role of geodetic reference frames in Earth science applications. The symposium's program was organized into five thematic sessions as follows:

Session 1: Global Reference Frame Theory, Concepts and Computations
Session 2: Space Geodetic Measurement Techniques
Session 3: Regional Reference Frames and their Applications
Session 4: Celestial Reference Frames and Earth Orientation Parameters
Session 5: Usage and Challenges of Reference Frames for Earth Science Applications

A total of eighty eight papers were presented during the four days of the symposium by leading experts and young scientists from academia, research institutions and public authorities. The presentations are freely accessible through the symposium's website at www.regaf2022.org, while the symposium proceedings will soon be published, after a peer-review process, in Springer's IAG Symposia Series (IAGS) with open access to the entire community.

Participants of the REFAG 2022 Symposium, 17-20 October 2022, Thessaloniki, Greece

IAG Scientific Assembly 2021 (Beijing, China)

Commission 1 was strongly involved in the preparation of the scientific program of the virtual IAG Scientific Assembly 2021. The organization of Symposium 1 *"Reference Frames"* was coordinated by the Commission President and the SC chairs, and it included six sessions that were dedicated on various themes of Reference Systems and Frames and their related applications:

Session 1.1: International Terrestrial Reference Frames: strengths, weaknesses, and strategies for future improvements

Session 1.2: Advancements and open problems in global reference frame theory and methodology

Session 1.3: Terrestrial and space geodetic ties for multi-technique combinations

Session 1.4: Regional reference frames and networks

Session 1.5: Comparison and combination of space geodetic techniques for improving consistency between TRF, CRF and EOPs

Session 1.6: Vertical Reference Systems: methodologies, realization and new technologies

Session 1.2 was organized jointly with the IAG Inter-Commission Committee on Theory (ICCT) while Session 1.6 was co-sponsored by ICCT, Commission 2 and the QuGe IAG Project. There were a total of 80 papers presented in Symposium 1, many of which have been published in the open-access peer-reviewed proceedings of Springer's IAG Symposia Series (vol. 154).

IUGG General Assembly 2023 (Berlin, Germany)

Commission 1 is well represented in the scientific program of the 28th IUGG General Assembly with a dedicated symposium on Reference Frames. The particular symposium (G01) will consist of eight oral sessions and one poster session, with a total of ~70 papers to be presented within a three-day period. The scientific program has been planned and coordinated by *Christopher Kotsakis* (Commission 1 President), *Xavier Collilieux* (Chair of Sub-commission 1.2), *Geoff Blewitt*, *Johannes Bohm* and *Susanne Glaser*, who will serve as conveners of the G01 symposium.

Activities of Sub-commissions

SC 1.1 Coordination of space techniques

The main activities of SC 1.1 include the promotion of research related to space geodetic techniques and their combination for realizing highly accurate and long-term stable terrestrial and celestial reference frames. The emphasis is placed on co-location aspects at fundamental geodetic observatories as well as on co-location approaches in space, considering common parameters such as coordinates, tropospheric parameters, clock parameters. The SC 1.1 is being represented in the Governing Board of the International Laser Ranging Service (ILRS) and contributes to the discussions and planning concerning Galileo tracking for the "Galileo for Science" and the "GASTON" campaigns. During the reporting period there have been significant investigations by SC 1.1 members on the impact of tropospheric ties for microwave and laser observation techniques in support of single- and multi-technique frame estimation. A breakthrough regarding atmospheric tie studies came with the implementation of a VLBI and SLR module in the GFZ version of the PANDA software, as well as the implementation of the capability to perform consistent combination of GNSS, VLBI and SLR data at the observation level. In addition, a lot of research work has been carried out on several new topics, including (but not limited to): the distribution of precise timing signals among geodetic observatories, high precision metrology of reference points using various measurement technologies (i.e. Geometre project), the contribution of SAR reflectors at geodetic observatories in view of mm-level tie vector determination, thermal deformation modelling of VLBI telescopes and its impact on the estimated frame parameters, precise orbit determination for multi-GNSS/LEO combinations, and the inclusion of VLBI transmitters onboard GNSS satellites. A major highlight concerning the scientific objectives of SC 1.1 was the approval of the *Genesis mission* by the ESA Council at Ministerial level in November

2022 which was preceded by a big preparation effort of the geodetic and Earth science community. The particular satellite mission aims at providing precisely calibrated local ties in space between instruments of all four space geodetic techniques, which will trigger a multitude of simulation studies and experiments that should be the focus of SC 1.1 in the following period.

SC 1.2 Global Reference Frames

During the reporting period, the main activities of SC 1.2 were primarily focused on the new realizations of the International Terrestrial Reference System (ITRS) by the three ITRS Combination Centers (IGN, JPL, DGFI-TUM) of the International Earth Rotation and Reference Systems Service (IERS). The new ITRF2020 solution by IGN was provided in April 2022 and it offers an augmented reference frame for the nonlinear part of systematic station motions that allows to model the annual and semi-annual periodic deformations of the Earth's surface. In contrast to the previous ITRF2014 solution, the new solution was created in a single process by stacking the data time series of all space geodetic techniques (DORIS, VLBI, SLR, GNSS) with a total span of more than forty years. In addition to estimating (i) station positions/velocities, (ii) Earth Orientation Parameters (EOPs) and (iii) post-seismic displacements (PSDs), seasonal signal parameters were also estimated for all stations of the four techniques with sufficient data span. The new JTRF2020 solution by JPL was provided in February 2023 in the form of optimally estimated daily station positions together with consistently estimated EOPs. JTRF2020 has been computed using a square-root filter and smoother algorithm implemented in a newly developed software named SREF (Square-root Reference frame Estimation Filter) with a station-dependent process noise model. A preliminary version of DTRF2020 by DGFI-TUM was presented in the REFAG 2020 symposium. The solution is based on a stepwise approach which initially provides individual technique-specific multi-year solutions for station positions/velocities and EOPs (in the form of normal equations), which are then optimally combined to the final solution. The new components in the DTRF2020 solution is the reduction of post-seismic displacements for stations affected by earthquakes and non-tidal loading displacements derived from geophysical models by the IERS Global Geophysical Fluids Center (GGFC) from the input data at the normal equations level. The release of the final DTRF2020 solution is expected by the end of 2023.

Though COVID-19 had slowed down significantly geodetic field activities for almost two years (2020-2022), new local tie surveys at several ITRF co-location sites have been performed during the reporting period by various groups around the world (NGS, IGN, Geoscience Australia, NLS, BKG, Frankfurt Univ. of Applied Sciences) using enhanced terrestrial instrumentation and improved protocols to provide accurate tie measurements. A growing interest seems to be emerging on accurate positioning of InSAR targets and including them into tie surveys when co-located with instruments of space geodetic techniques, which will likely be intensified in the coming years. Overall, the progress on local ties for space geodetic techniques (which is a major topic of interest for SC 1.2) is highly commendable and resulted in the increase of tie vectors from ITRF2014 to ITRF2020, and also a decrease in the number of tie vectors showing discrepancies greater than 5 mm with respect to the space geodetic analysis results.

Finally, special mention should be given to the Genesis project which has been approved as a component of the FutureNAV program of the European Space Agency (ESA). This innovative project will supplement the current co-located site network with a new orbiting "co-located site" on a fully-calibrated platform in space, which will help to evaluate the instrumental biases inherent to the different geodetic techniques that currently limit the accuracy of the Terrestrial Reference Frame. The scientific breakthroughs for space geodetic techniques that are anticipated through the Genesis mission should be at the forefront of future activities of SC 1.2 during the next term (2023-2027).

SC 1.3 Regional Reference Frames

SC 1.3 has a coordinating role for the activities of the six regional sub-commissions related to the definition and realization of regional reference frames and their connection to the global International Terrestrial Reference Frame (ITRF). For the reporting period there were significant efforts towards: (a) the augmentation of regional GNSS networks around the world by new additional stations (many of which have been also included in the global IGS network), (b) the development of automated tools for selecting reference stations to facilitate reliable regional and national frame realizations (a EUREF initiative), (c) the release of new densification products for the EUREF/EPN network (including velocity estimates for almost 8000 stations around Europe), (d) the major re-processing efforts in several large regional GNSS networks around the globe to comply with the most recent IGS standards and the latest ITRF releases, (e) the significant updating of the SIRGAS technical guidelines in conformity with the IGS/IERS guidelines and the release of the latest SIRGAS2022 cumulative solution, and (f) the on-going work towards the North American Reference Frame Densification and the establishment of a plate-fixed North American Terrestrial Reference Frame. Significant actions have been also reported by the SIRGAS, APREF and NAREF sub-commissions in relation to the United Nations Initiative on Global Geospatial Information Management (UN-GGIM) and the enhancement of the geodetic infrastructure at national and regional levels to ensure the development, sustainability and promotion of the Global Geodetic Reference Frame (GGRF).

A most significant highlight in the activities of SC 1.3 is the joint work of WG 1.3.1 (“Time-dependent transformations between reference frames in deforming regions”) together with the Coordinate Reference System Domain Working Group (CRS DWG) of the Open Geospatial Consortium (OGC) to develop an approach (functional model) and supporting grid format to enable transformations between reference frames within plate boundary zones and regions affected by glacial isostatic adjustment. These transformations are necessarily time-dependent to account for interseismic strain and also episodic seismic deformation, and special approaches are required to enable transformation results of high precision at different epochs between the source and target reference frames. The outcomes of this joint work are essential to support development and consistency within spatial and positioning software for use in crustal deformation zones. The related products are currently in the final review stage and finalization is expected by the end of 2023. After the review stage is completed, the outcomes of this joint work will be supported by international registries of geodetic parameters such as those hosted by ISO/TC 211 and IOGP/EPSG.

SC 1.4 Interaction of Celestial and Terrestrial Reference Frames

The consistent realization of the International Terrestrial and Celestial Reference Frames, along with the fundamental tie between them as expressed by a series of Earth Orientation Parameters (EOPs), at the mm/μas level of accuracy is a major goal for the geodetic and astronomic scientific community, and it has been the focus of SC 1.4 and its components. During the reporting period (2019-2023) various research groups from several institutions around the world pursued important research activities to achieve this goal. Specifically, the German DGFI-TUM research team has been continuously working on the realization of ITRS and CTRS with the aim of estimating EOP series and a CRF that will be consistent with the latest DTRF2020 solution. Their work is based on the determination of a combined EOP+TRF solution computed with the source coordinates fixed to ICRF3, and also on the determination of a fully combined EOP+TRF+CRF solution - the details of the analysis strategy for these solutions are currently under investigation. Another research team from ETH (Switzerland) and JPL (US) has also been working on the consistent estimation of EOP, TRF and CRF by using the SREF software which was employed in the development of the latest JTRF2020 solution and it is capable of jointly estimating EOP, TRF and CRF. The research group of the Institute for Geodesy at the Leibniz University Hannover (Germany) has been working on the implementation of lunar laser ranging (LLR) to the joint EOP+TRF+CRF solution, whereas another group from the Federal Office of Metrology and Surveying (Austria) is investigating the analysis options for the TRF/EOP/CRF estimation with particular emphasis on new models included in the ITRF2020 and ray-tracing troposphere modeling. The IVS Combination Center at Federal Agency for Cartography and Geodesy (BKG) is also working on the consistent realization of CRF, TRF and EOP as an IVS combined product. Many other related studies have appeared throughout the last four-year period (2019-2023) which are briefly summarized in the activity report of SC 1.4 and its working groups (see following chapters).

During the reporting period the research activities of SC 1.4 were also focused on the modeling of geophysical, atmospheric and astronomical effects and their impact on the determination of celestial reference frames. Members of SC 1.4 and its three working groups have extensively worked on the modeling of source structure variations in the analysis of VLBI observation campaigns (CONT14, CONT17), the modeling of troposphere noise in VLBI data analysis, the investigation of gravitational deformation models of VLBI antennas, and the performance analysis of the VGOS sessions and their comparison with simultaneous S/X sessions. Ongoing efforts are made by several research teams to improve the accuracy of the current CRFs based on various VLBI observing programs, and the ability to accurately link them with the official ICRF3 solution and other Gaia-based CRF realizations. It is anticipated that such efforts will be intensified in the coming years, and they will result in significant improvements for the consistent realization of the TRF and CRF at the mm/μas level of accuracy.

Activities of Study Groups and Working Groups

One Study Group (SG 1.2.1) and four Working Groups (WG 1.2.1, WG 1.3.1, WG 1.4.1, WG 1.4.2) are directly reporting to Commission 1 via SC 1.2, SC 1.3 and SC 1.4. Also, four Joint Working Groups in cooperation with other entities, namely JWG 1.1.1 (jointly with GGOS and IAG SC 4.3), JWG 1.2.2 and JWG 1.2.3 (jointly with IERS) and JWG 1.4.3 (jointly with IERS and IAU Commission A2) are reporting to Commission 1 via SC 1.1, SC 1.2 and SC 1.4. Their activity reports specify main research areas under investigation, achieved results and scientific outputs (namely publications and presentations), and they can be found in the corresponding chapters of the present report. Based on the content of the submitted activity reports, it can be concluded that many Working Groups have been active, although the level of co-operation and/or interaction between their members is not necessarily the same for all groups.

Commission 1 is also actively involved in eight Joint Study Groups and one Joint Working Group as a partner, but none of these groups report directly to Commission 1. Their activity reports for the period 2019-2023 can be found under the respective sections of the reports provided by the leading IAG entities (namely ICCT, ICCC, GGOS, Commissions 2 and 3).

Sub-commission 1.1: Coordination of space techniques

Chair: Urs Hugentobler (Germany)

Overview

Space techniques play a fundamental role for the realization and dissemination of highly accurate and long term stable terrestrial and celestial reference frames as well as for accurate monitoring of the Earth orientation parameters linking the two fundamental frames. Sub-commission 1.1 focuses on the coordination of research related to the geodetic space techniques with emphasis on co-location aspects at fundamental geodetic observatories as well as on co-location targets in space, considering common parameters such as coordinates, troposphere parameters, clock parameters.

Activities during the period 2019-2023

Conferences and meetings

Relevant conferences addressing topics related to Sub-commission 1.1 were the IAG Symposium 2021 in Beijing, China, and the REFAG Symposium 2022 in Thessaloniki, Greece, which was co-located with the GGOS Unified Analysis Workshop.

IAG 2021

At the IAG Symposium, held on 28.6.-02.07.2021 in Beijing, China, and online, session 1.3 "Terrestrial and space geodetic ties for multi-technique combinations" chaired by K. Sośnica, U. Hugentobler, and W. Jiang had a strong focus on Sub-commission 1.1 topics, but also session 1.5 "Comparison and combination of space geodesy techniques" chaired by R. Heinkelmann, Z. Malkin, M. Seitz, and C. Huang covered topics in the focus of the Sub-commission.

Session 1.3 hosted 7 oral presentations and 10 posters. The peak number of participation for the oral session was 114 online participants plus 18 panelists, showing the interest in the topic of the session. There were several highlights: Several presentations demonstrated the distribution of precise timing signals between geodetic instruments, high precision metrology of reference points using various measurement technologies in the context of the Geomètre project and of a kilometer tie vector at McDonald observatory, as well as the contribution of SAR reflectors at geodetic observatories. The determination of sub-millimeter tie vectors using double-differenced SLR observations was demonstrated using measurements from two co-located SLR telescopes. Based on simulations optimum future orbit configurations for low Earth satellites equipped with SLR and DORIS were presented. Two presentations showed promising results on the contribution of tropospheric ties for microwave techniques GNSS, VLBI, and DORIS based on different experiments.

REFAG 2022

The IAG Symposium on Reference Frames for Applications in Geosciences (REFAG) took place in 17.10.-20.10.2022 in Thessaloniki, Greece. Session 2 "Space Geodetic Measurement Techniques" chaired by K. Sośnica and U. Hugentobler had its focus on topics of Sub-commission 1.1. It included 19 presentations.

Papers discussed upgrades of geodetic observatories, thermal deformation modelling of geodetic VLBI telescopes, scale issues and GNSS phase center offset calibrations, multi-GNSS and LEO combinations, multi-technique combination in space, potential of VLBI transmitters on GNSS satellites. Very innovative was the presented method to measure quasars as well as GNSS satellites using an interferometer consisting of a VLBI telescope and a GNSS antenna that was successfully tested and offers a novel method for tying phase centers of the two microwave techniques.

Other meetings
Many topics related to the work of IAG Sub-commission 1.1 were discussed at several other conferences, including the AGU and EGU Annual meetings, and the COSPAR Scientific Assemblies, in sessions related to geodetic infrastructure, consistent geodetic products, reference frames, and precise orbit determination. Several articles published in the period 2019-2023 address the combined use of the different space geodetic techniques (see a selected list below).

Space Co-locations
A highlight was the approval of the Genesis mission by the ESA Council at Ministerial level in November 2022 which was preceded by a big effort in preparation by the scientific community, preparing a white paper and organizing a user workshop. The satellite mission aims at providing precisely calibrated local ties in space between instruments of all four space geodetic techniques. The mission will trigger a multitude of simulation studies and experiments and should be a focus of Sub-commission 1.1 in the following period.

ILRS Representation
The Sub-commission 1.1 is represented in the ILRS Governing Board and contributes among others to discussions concerning Galileo tracking for the "Galileo for Science" and the "GASTON" campaigns.

Selected publications

Bury, G., Sośnica, K., Zajdel, R., Strugarek, D., Hugentobler, U. (2021): Geodetic datum realization using SLR/GNSS co-location onboard Galileo and GLONASS. J. Geophys. Res.: Solid Earth, 10.1029/2021JB022211.

Collilieux, X., Courde, C., Fruneau, B., Aimar, M., Schmidt, G., Delprat, I., Defresne, M.-A., Pesce, D., Bergerault, F., Wöppelmann, G. (2022): Validation of a corner reflector installation at Côte d'Azur multi-technique geodetic observatory. Adv. Space Res., 30(2), 360-370, 10.1016/j.asr.2022.04.050.

Delva, P., Altamimi, Z., Blazquez, A., Blossfeld, M., Böhm, J., Bonnefond, P., Boy, J.-P., Bruinsma, S., Bury, G., Chatzinikos, M., Couhert, A., Courde, C., Dach, R., Dehant, V., Dell'Agnello, S., Elgered, G., Enderle, W., Exertier, P., Glaser, S., Haas, R., Huang, W., Hugentobler, U., Jäggi, A., Karatekin, O., Lemoine, F.G., Le Poncin-Lafitte, Ch., Lunz, S., Männel, B., Mercier, F., Métivier, L., Meyssignac, B., Müller, J., Nothnagel, A., Perosanz, F., Rietbroek, R., Rothacher, M., Schuh, H., Sert, H., Sosnica, K., Testani, P., Ventura-Traveset, J., Wautelet, G., Zajdel, R., (2023): GENESIS: co-location of geodetic techniques in space. Earth, Planets and Space 75, 5, 10.1186/s40623-022-01752-w.

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Working Groups of Sub-commission 1.1:

JWG 1.1.1: Intra- and Inter-Technique Atmospheric Ties

Chair: Kyriakos Balidakis (Germany)
Vice-chair : Daniella Thaller (Germany)

Overview

The Joint Working Group (JWG) 1.1.1 is associated with the IAG Sub-commision 1.1 (Coordination of Space Techniques), GGOS (Global Geodetic Observing System) and the IAG Sub-commission 4.3 (Atmosphere Remote Sensing). It is chaired by Kyriakos Balidakis (GFZ) and co-chaired by Daniela Thaller (BGK).

The purpose of the JWG 1.1.1 is the distinction between real signals and undesired technique-specific artifacts in tropospheric delay estimates and the enhancement of multi-technique combination by the exploitation of atmospheric ties. It focuses on the following questions: (i) How can one relate atmospheric parameter estimates and the time derivatives thereof that refer to different place, time, and observing system? What are the limits in distance, time lag, and observing system? (ii) What is the optimal way to combine atmospheric parameters? (iii) What is the benefit from including atmospheric ties in a multi-technique terrestrial reference frame combination? This is performed through the following activities: (i) Comparison of atmospheric (electrically neutral) delay estimates from single-technique geodetic analysis ; (ii) Comparison of atmospheric delays from state-of-the-art meso-scale weather models, and high-resolution runs utilizing the Weather Research and Forecasting Model; (iii) Assessment of spatial and temporal correlation between atmospheric parameters; (iv) Assessment of multi-technique combination employing atmospheric ties on the single site and global TRF level.

Members

- *David Coulot (France)*
- *Mateusz Drożdżewski (Poland)*
- *Claudia Flohrer (Germany)*
- *Changyong He (France)*
- *Robert Heinkelmann (Germany)*
- *Chaiyaporn Kitpracha (Germany)*
- *Frank Lemoine (USA)*
- *Lisa Lengert (Germany)*
- *Tobias Nilsson (Sweden)*
- *Arnaud Pollet (France)*
- *Víctor Puente (Spain)*
- *Marcelo Santos (Canada)*
- *Benedikt Soja (Switzerland)*
- *Krzysztof Sośnica (Poland)*
- *Jungang Wang (Germany)*
- *Xiaoya Wang (China)*
- *Dudy Wijaya (Indonesia)*
- *Karina Wilgan (Germany)*
- *Florian Zus (Germany)*

Activities during the period 2019-2023

The activities of JWG 1.1.1 (hereinafter JWG) have been inspired by IAG JWG 1.1.3 of the previous term (2015-2019). Building on the experience garnered during the previous term, and the advances in the volume of geodetic data, the quality of space geodetic data analysis, as well as numerical weather prediction, JWG ventures further with its overarching goal being the enhancement of multi-sensor fusion employing atmospheric ties in addition to already established ties such as the global (Earth rotation) and local (station coordinates) ties. Some of the main obstacles in achieving that are the fact that there are very few software packages capable of performing consistent state-of-the-art analysis of space geodetic data from VLBI, GNSS, SLR, and DORIS, and that poorly understood – hence sub-optimally handled – effects manifest into spurious signals in the parameters of interest, that is, station coordinates, polar motion, length of day, and atmospheric delay coefficients. The next paragraphs provide an outline of our activities towards that goal.

A website describing the activities of this working group has been set up:

https://www.gfz-potsdam.de/en/section/space-geodetic-techniques/projects/iag-jwg-atmospheric-ties/

as well as an area for sharing data and group meeting minutes:

ftp://ftp.gfz-potsdam.de/pub/home/kg/kyriakos/iag_jwg_atmospheric_ties/

and a mailing list: *atmtie@gfz-potsdam.de.*

The comparison of atmospheric delay coefficients (usually zenith delays and gradient vector components) estimated from the analysis of observations collected from co-located stations employing microwave signals has a scatter of 1cm or better. This figure varies as a function of time, instrumentation, site, analysis software, and sometimes analyst. To better understand these discrepancies, two studies were undertaken. First, to assess the performance of atmospheric tie determination employing different data sources (in situ observations, high-resolution numerical weather data, empirical meteorological models) and to understand the atmospheric delay coefficients' discrepancy stemming from instrumentation, we have organized an experiment. We have set up four GNSS stations with identical receivers and antennas on the rooftop of building A20 at GFZ Potsdam, varying the absolute height and whether a radome is installed. The results prove that all schemes tested to calculate atmospheric ties have similar performance, no instrumental effects were to be found in the atmospheric delay residuals, and employing or not a radome and near-field multipath effects introduce small but significant biases to the zenith delays at gradients. These investigations have been published in Kitpracha et al. (2021a). Second, since the observation geometry in space geodetic data analysis forces the estimates for station coordinates to be highly correlated with the atmospheric delay coefficient and clock estimates, we investigated the VLBI clock estimates. We have identified that a large number of jumps in the station clock time series have little to do with the performance of the local frequency standard (active hydrogen maser) and are associated with erroneous auxiliary data, namely spurious in situ meteorological observations, measurements of cable and phase calibration, as well as poor ambiguity resolution. Mis-handling these effects often manifests into erroneous signals in the estimated atmospheric delays, what impedes the rigorous intra- and inter-system combination employing atmospheric ties. Details may be found in Balidakis et al. (2021).

We have performed an intra-technique VLBI combination at the normal equation level during the VLBI CONT17 campaign, which offers the unique opportunity of having three networks overlapping in time. Kitpracha et al. (2021b) have performed the combination employing all available local and global ties, as well as atmospheric ties derived from the sigma-pressure levels of hourly ERA5 fields for the co-location sites at Wettzell (Germany) and Kokee Park (Hawai). An improvement was identified when atmospheric ties were imposed in addition to the other inter-system constraints (local and global ties).

A breakthrough regarding atmospheric tie investigations at the GFZ came with the implementation of a VLBI and SLR module in the GFZ version of the PANDA software, as well as the implementation of the capability to perform consistent combination of GNSS, VLBI, and SLR data at the observation level (Wang, 2021). While the combination at later stages (normal equation level or parameter level) is theoretically identical provided certain conditions are met, there are some practical implications which no longer pose a problem at the observation equation level. Early results involving all VLBI CONT campaigns suggest a large improvement in station coordinates, Earth orientation parameters, and atmospheric delay coefficients following a combination employing stochastic equality constraints to tie these three groups of unknown parameters. The weighting of these constraints has been thoroughly investigated and an optimal approach has been proposed. Since the number of GNSS observations employed in a global network solution is orders of magnitude larger than the number of VLBI observations in a typical IVS-R4 or even modern CONT session, of the two VLBI benefits the most. Further details may be found in Wang et al. (2021a; 2021b).

Calibration and instrumental issues aside, atmospheric ties between co-located stations observing in the same frequency domain are mainly driven by the height difference. While a first-degree ansatz is accurate enough to predict zenith delays between stations that differ tens of metres in terms of height, they are not reliable for differences of hundreds of metres or more. To this end, we have investigated how hydrostatic and non-hydrostatic atmospheric delays decay as a function of height, and we have proposed a parsimonious approach to reproduce profiles up to 15 km (Wang et al., 2021c).

Intra-technique comparisons are crucial to achieve the goals of the JWG. Within a research DFG project Advanced MUlti-GNSS Array for Monitoring Severe Weather Events (AMUSE) performed at GFZ and TUB, different tropospheric parameters, i.e. zenith total delays (ZTDs), tropospheric gradients and slant total delays (STDs) from multi-GNSS solutions were calculated and compared. Three solutions: GPS-only, GPS/GLONASS and GPS/GLONASS/Galileo based on a dense German network SAPOS and a global network (GFZ/IGS) were taken into consideration. For the ZTDs and gradients all three solutions obtained very similar level of agreement against global numerical weather models (NWM): ERA5 and ICON (forecast model provided by DWD). For STDs, the GRE and especially the Galileo-only solution had a slightly better agreement with the NWM data, probably due to the use of the post-fit residuals, which contain more tropospheric information and less noise for Galileo than for the other systems. Some information about the project can be found in Wickert et al. (2020).

Since not all co-location sites are equipped with meteorological sensors and in most cases the relative position between the meteorological sensor and the reference point of the geodetic stations is not known accurately enough, numerical weather models are an invaluable resource in the derivation of atmospheric tie vectors. Prior to adopting these constraints in the combination procedure, the relative compatibility in the high- and low-frequency domain needs to be checked. The GNSS-derived precipitable water vapour (PWV) as one of the main products of GRUAN (Global Climate Observing System Reference Upper-air Network) of the World Meteorological Organization (WMO) has been developed during the last years at GFZ, the Central GNSS Data Processing Centre for GRUAN (Dick et al., 2021). In order to provide a timely quality check of the PWV estimates a monitoring system was installed at the GFZ.

As a part of this system the timeseries of GNSS and ERA5 PWV for the GRUAN stations are accessible under

ftp://ftp.gfz-potsdam.de/pub/GNSS/products/nrttrop/MONITORING_IFS/.

A comprehensive study of employing ERA5-derived atmospheric delay models (mapping functions, zenith delays, higher order gradient components) has been undertaken as well. Different schemes of introducing these models into the VLBI data adjustment have been examined by Nilsson and Balidakis (2021).

A service for atmospheric delay models for geodetic systems employing microwave and optical waves has been developed at the GFZ and has been made publicly available. We employ ECMWF's ERA5 data at the native spatio-temporal resolution at hybrid sigma-pressure levels. For example, gridded zenith delays and mapping function coefficients are accessible through: ftp://ftp.gfz-potsdam.de/pub/GNSS/products/gfz-vmf1/.

IGN-France has considered the ties of both tropospheric delays and gradients as potential constraints in the TRF computation, since the tropospheric effects of the microwave techniques (GPS, VLBI and DORIS) are frequency-independent and follow the same theory. A brief summary is given as follows.

1. Different external sources of tropospheric delay and gradients to calculate the ZTD ties are examined. These sources include the model and reanalysis data: GPT3, VMF1-grid & VMF3-grid, ERA-Interim and ERA5.
2. Tropospheric ties from GRAD data provided by TU Wien are examined. No other gradient products are accessible. But 0 of gradient ties are reasonable if collocation sites are within a specific distance.
3. Different uncertainties of tropospheric ties are investigated (std = 0 mm, ~1 mm and ~10 mm) during the CONT14 campaign.
4. The influence of delay and gradient ties on the ZTD differences (GPS-DORIS and GPS-VLBI) is investigated separately during the CONT14 campaign.
5. The influence of tropospheric ties on the estimation of station positions is evaluated during the CONT14 campaign.

Further results from IGN-France were presented at the IAG Scientific Assembly 2021.

SHAO has focused on the following during the first term: (i) nonlinear terrestrial reference frame and EOP determination based on the Singular Spectrum Analysis Method (Zhang et al.,2019); Update software for GNSS/SLR data processing and perform an SLR and GNSS repro following the resolutions of IGS and ILRS (Xi et al,2020,2021; Shao et al.,2019,2021; Zhang et al.,2019); (iii) preparation for the future STRF2020 nonlinear TRF and EOP, which will be provide new models and longer data; and (iv) preparation for atmospheric parameter combination via atmospheric ties. In particular, this nonlinear TRF is a little different from ITRF2014. Firstly, SHAO added the unlabelled jumps detection based on the sequential t-test analysis of regime shifts (STARS) algorithm which is an effective method for detecting jumps in GPS stations time series (Rodionov, 2004; Bruni, 2014). SHAO used the STARS algorithm combined with the generalized extreme studentized deviate (GESD) algorithm (Rosner, 1983) and manual inspection to detect unlabelled jumps contained in the time series. After that SHAO introduced them into the jump information file and recalculated the TRF. SHAO found that the station discontinuities have been repaired very well. Secondly, SHAO found there are some time-varying amplitude periodic signals in the GPS coordinate residual data which caused the station coordinates and velocity determination to be estimated incorrectly. And the accuracy and stability of the TRF are adversely affected. Therefore, SHAO used the Singular Spectrum Analysis (SSA) method to model non-linear time-varying amplitude periodic signals and fit all periodic signals (including annual, semi-annual and seasonal signals) not only annual and semi-annual signals, and also not the same periods for all sites. Thirdly, based on SSA variable-amplitude periodic signals extraction including annual and semi-annual, 34 weeks, 20.8 weeks, 17.3 weeks and so on periodic signals SHAO corrected the non-linear periodic signals and reprocessed the terrestrial reference frame to obtain a nonlinear terrestrial reference frame by CERS TRF and EOP established by SHAO. The two solutions of linear-STRF and nonlinear-STRF are named SOL-A and SOL-B respectively. SHAO compared and analysed its accuracy change from the aspects of the TRF datum definition parameters, station coordinates/velocity, and EOP results. After introducing periodic information and recalculating, the stability of the translation and scale is improved, but it is not particularly obvious, especially the translation parameters. It is maybe because that the periodic signal are mainly focused on GPS, and GPS does not participate in the determination of datum definition. Therefore, after introducing and eliminating the nonlinear time-varying amplitude periodic signals of GPS, the changes of the translation and scale factor are not big. For GPS sites, 10.8% of the station coordinate accuracy is better than 1mm and 4.4% of the station velocity accuracy result is better than 0.1mm/yr. The accuracy of the non-linear STRF (SOL-B) is significantly higher than that of the linear STRF (SOL-A), i.e. more stations are distributed in the high-precision level and less stations are distributed in the lower-precision level. For GPS, 44.5% of the station coordinate accuracy is better than 3mm, and 47.5% of the station velocity accuracy is better than 0.5mm/yr. For VLBI, 3.1% the accuracy of station coordinate comparison is better than 1mm and 3.1% the accuracy of station velocity is better than 0.1mm/yr. But for the SLR and DORIS, there are currently no station with coordinates and velocities better than 1mm and 0.1mm/yr. But there are 7.2% and 3.9% of the total stations with coordinates accuracy better than 3mm respectively and 11.3% and 4.5% of the total stations with velocity accuracy better than 0.5mm/yr for non-linear STRF (SOL-B) and the linear STRF (SOL-A) respectively. In comparison, DORIS results in lower precision. SHAO can conclude that the accuracy of the nonlinear TRF has been further improved after considering the influence of the time-varying amplitude periodic signals.

Unfortunately, state-of-the-art (past the ITRF2020 repro) SLR data analysis does not involve the modelling of atmospheric delay asymmetries, an effect usually treated by setting up gradient vector components as unknowns in the VLBI and GNSS adjustments. Since consistent modelling is a prerequisite for the inter-technique combination, Drożdżewski et al. (2019a; 2019b; 2020) and Sośnica et al. (2019a; 2019b) has investigated the improvement of applying gradients in the SLR data adjustment as well as refined mapping functions. An overall improvement was achieved by reducing the low-elevation angle residuals, and reducing the bias between SLR-derived polar motion with respect to polar motion from GNSS, VLBI, and the IERS C04 product, as well as mitigating a geocenter motion bias. The models used for this work are provided under:
ftp://ftp.gfz-potsdam.de/home/kg/kyriakos/PMF/SLR/.

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Sub-commission 1.2: Global Reference Frames

Chair: Xavier Collilieux (France)

Overview

Sub-commission 1.2 focuses its activity on the definition and realization of the terrestrial reference system (TRS). It studies fundamental questions and more practical aspects that can improve current terrestrial reference frame (TRF) determinations. The terms of reference of the sub-commission can be found in pages 94-95 of the Geodesist's Handbook 2020 (Poutanen and Rózsa, 2020) and won't be repeated here. Numerous activities related to the topics of SC 1.2 are realized in other IAG-related structures and services, namely:

• International Earth Rotation and Reference Systems Service (IERS)

• Other relevant IAG services (IGS, ILRS, IVS, IDS)

• WG Q.3: Relativistic geodesy with clocks

• IAG Global Geodetic Observing System (GGOS):

• GGOS Focus Area "Unified Height System"

• BNO C1: GGOS Committee on Performance Simulations and Architectural Trade-Offs (PLATO)

and, therefore, the reader is encouraged to refer to their individual reports.

Activities during the period 2019-2023

ITRF2020 and new ITRS realizations

A call for participation for providing ITRF2020 input data was realised by the IERS in January 2019 (IERS, 2019). The IAG technique services - namely the international DORIS Service (IDS), the international GNSS service (IGS), the International Laser Ranging Service (ILRS) and International VLBI Service for geodesy and astrometry (IVS) - provided geodetic station time series and Earth Orientation Parameters (EOPs) with their full variance/covariance matrices (or normal equations) in SINEX format (IERS, 2006). Compared to ITRF2014 (Altamimi et al., 2014), six years of additional observations have become available, including new sites and new local tie vectors.

The submitted solutions have been analysed by the ITRS combination centres of the International Earth Rotation and Reference Systems Service (IERS): DGFI, IGN and JPL. The analysis strategy of the three combination centres has been discussed during the meeting "Reference Frames for Applications in Geosciences REFAG 2022" of the IAG commission 1 organized in October 2022 in Thessaloniki, Greece (Altamimi et al., 2022; Gross et al., 2022; Seitz et al., 2022).

The ITRF2020 was provided in April 2022 and made available at https://itrf.ign.fr/en/solutions/itrf2020. Compared to ITRF2014, the coordinate variation model for all stations has been enhanced by adding constant seasonal functions (annual and semi-annual periods). As for ITRF2014, post-seismic displacements are modeled by exponential and logarithmic functions for the stations significantly affected by earthquakes. The newly estimated periodic coefficients are provided in the center of mass (CM) or in the Center of Figure (CF) frame. Although the ITRF coordinates should be theoretically provided in the CM frame, some of the users may want to remove the geocenter motion displacements which affect all the points of the Earth's surface identically. A full description of ITRF2020 analysis and products is provided by Altamimi et al. (2023).

JTRF2020 was published in February 2023 (Abbondanza et al., 2023). As for the previous release JTRF2014, coordinates are supplied as position time series together with the consistently estimated EOPs. 16839 daily SINEX files that include variance/covariance information are made available. JTRF2020 has been computed using a square-root filter and smoother algorithm implemented in a newly developed software named SREF (Square-root Reference frame Estimation Filter). A station-dependent process noise model was chosen using an autoregressive model of order 1 to model time dependency.

A preliminary version of DTRF2020 has been described by Seitz et al. (2022). Post-seismic deformation was approximated by a combination of exponential and logarithmic functions and reduced from input data series for stations affected by earthquakes. Non-tidal loading displacements derived from geophysical models and provided by the IERS Global Geophysical Fluids Center (Boy, 2021) have been reduced, likewise the post-seismic deformation, at the NEQ level. Both data sets will be provided back to the users. The DTRF2020 scale is realized from VLBI and GNSS scale. DTRF2020 will be made available at the DTRF webpage Seitz et al. (2023).

Global height reference frame

The GGOS Focus Area "Unified Height System" works on the implementation of the International Height Reference System (IHRS) and its realization, the International Height Reference Frame (IHRF). During the last four years, a strategy for the establishment of the IHRF was defined. This strategy comprises the appropriate handling of permanent tide effects in the determination of IHRF coordinates in the mean-tide system, the determination and evaluation of IHRF coordinates depending on the data availability (specially surface gravity data and topography models), the improvement of the input data required for the determination of IHRF coordinates, the station selection in regional and national densifications of the IHRF, and the organizational infrastructure required to ensure the usability and long-term sustainability of the IHRF (see Sánchez et al. 2021). The IHRF is based on the combination of a geometric component given by ITRF station coordinates and a physical component given by the determination of potential values at the positions defined by the ITRF coordinates. Consequently, the link between IHRF and ITRF is unavoidable. Currently, the GGOS Focus Area "Unified Height System" is focused on the determination of a first static solution for the IHRF. More details can be found in the GGOS Focus Area "Unified Height System" report.

Genesis

A few missions of co-located satellite in space have been proposed in the past as GRASP (Bar-Sever et al. 2009) or E-GRASP/Eratosthenes (Rotacher and Biancale et al. 2017) projects. Genesis is a new project which has been proposed as a component of the FutureNAV program of the European Space Agency (ESA). The payload of the satellite and the scientific objectives of the mission have been widely described by Delva et al. (2023). Genesis would supplement the current co-located site network with a new site in space. As it is made of a fully calibrated platform, it will help to evaluate the instrumental biases inherent to the different geodetic techniques that currently limit the accuracy of the Terrestrial Reference Frame. Indeed, as shown by Altamimi et al. (2023), less than 50% of the currently available local tie vectors agree with space geodesy at a better level than 5 mm. Thus, the IAG sub-commission 1.2 fully supports Genesis project.

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Working Groups of Sub-commission 1.2:

WG 1.2.1: Assessing impacts of loading on Reference Frame realizations

Chair: Anthony Mémin (France)
Vice-chair: Anna Klos (Poland)

Members
• *Jean-Paul Boy (ITES, France)*
• *Kristel Chanard (IPGP/IGN/ENSG, France)*
• *Anna Klos (Military University of Technology, Poland)*
• *Benjamin Maennel (GFZ, Germany)*
• *Anthony Mémin (Université Côte d'Azur, France)*
• *Laurent Métivier (IPGP/IGN/ENSG,France)*
• *Joëlle Nicolas (ESGT/CNAM, France)*
• *Manuela Seitz (TUM, Germany)*
• *Giorgio Spada (Università di Bologna, Italy)*
• *Daniela Thaller (BKG, Germany)*
• *Wouter van der Wal (The Netherlands)*

Activities during the period 2019-2023
The principal objectives of the scientific work was to assess the effects of load and Earth models and their applications for Terrestrial Reference Frame utilization and to assemble specific recommendations for users and future IERS conventions. During the period 2019-2023, the working group has maintained a bibliography and published numerous scientific papers.

Research activities of the WG 1.2.1 result in publications listed below.

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JWG 1.2.2 : Methodology for surveying geodetic instrument reference points

Chair: Ryan Hippenstiel (USA)
Vice-chair: Sten Bergstrand (Sweden)

Overview

Areas of work of the Working Group on Site Survey and Co-location are standards and documentation (guidelines, survey reports, etc.), coordination (share know-how and join efforts between survey teams), research (investigate discrepancies between space geodesy and tie vectors, alignment of tie vectors into a global frame), and cooperation. Our group has a new set of terms and has received confirmation of new participants in the group. We would continue to encourage participation from any agency or community that is conducting research, improving protocols, or completing field surveys of local ties as sites with various space geodesy techniques present. Our group has continued to share improved protocols, technologies, and instrumentation to provide the most accurate tie measurements possible for all sites around the world. We reminded participants to share their contributions of local tie data for inclusion into ITRF2020 and many were submitted.

Members

- *Zuheir Altamimi (IGN, France)*
- *Sten Bergstrand (BIPM, France)*
- *Steven Breidenbach (NOAA/NGS, USA)*
- *Benjamin Erickson (NOAA/NGS, USA)*
- *Cornelia Eschelbach (Frankfurt Univ. of Applied Sciences, Germany)*
- *Kendall Fancher (NOAA/NGS, USA)*
- *Charles Geoghegan (NOAA/NGS, USA)*
- *Dionne Hansen (LINZ, New Zealand)*
- *Ryan Hippenstiel (NOAA/NGS, USA)*
- *Christopher Holst (Technische Universität München, Germany)*
- *Michael Lösler (Frankfurt Univ. of Applied Sciences, Germany)*
- *Kevin Jordan (NOAA/NGS, USA)*
- *Saho Matsumoto (GSI, Japan)*
- *Jack McCubbine (GA, Australia)*
- *Damien Pesce (IGN, France)*
- *Anna Riddell (GA, Australia)*
- *Owen Smallfield (LINZ, New Zealand)*
- *Jerome Saunier (IGN, France)*
- *Elena Martínez Sánchez, (Observatorio de Yebes, Spain)*
- *Daniela Thaller, (BKG, Germany)*
- *Bart Thomas (GA, Australia)*
- *Agnes Weinhuber (Technische Universität München, Germany)*

Corresponding Members

- *Xavier Collilieux (IGN, France)*
- *Mike Pearlman (Harvard/GGOS, USA)*
- *Robert Heinkelmannm, (GFZ, Germany)*

Activities and publications during the period 2019–2023

Improvements have been made to standardize report and data submissions of local tie surveys to provide consistency across all agencies. Survey data has recently been reported with new standards in place.

The group is continuing to explore methodologies to measure and quantify antenna deformation. Research and continued field tests using laser scanning and terrestrial inSAR have been discussed. In addition, a comparison of two approaches to quantifying deformation effects at Onsala will be undertaken. Members completed and documented work researching site-dependent GNSS antenna calibrations to account for systematic errors and biases. Personnel at Yebes are studying data collected from both a laser scanner and UAV, detailing differences in solutions at various temperatures and times of day.

Measurements were collected at the Zeppelin Observatory (Svalbard, Norway) and Hartebeesthoeck has been reprocessed (Muller et al., 2020). The latter was assisted by updating of local software to allow estimating VLBI and SLR references points from raw survey data into one single processing.

A tie survey at Yarragadee was completed in June of 2021, the results of which were developed into a presentation shared with working group members and participants of the Unified Analysis Workshop in 2022. In addition, Geoscience Australia (GA) recently completed a tie survey at Hobart with survey results and reporting forthcoming. GA continues to look at cooperation with universities to improve resources available and the efficiency of surveys.

Colleagues from Frankfurt Univ. of Applied Sciences, BKG and NLS submitted the results and further processing of tie surveys at Wettzell and Metsähovi for publication in the IAG 2021 conference proceedings.

IGN contributed local tie surveys at Malé, Crozet, Futuna, and Grasse, including new SAR reflectors and additional work processing with fully automated determination of the SLR telescope reference point at Côte d'Azur. This work (Barneoud, et al., 2023) was presented at REFAG2022. IGN also completed an updated of the COMP3D software which now includes full integration of axis determination and increased ability to input data. This software was used to process a 2021 survey of Ny-Ålesund (Brandal).

The US National Geodetic Survey conducted an IERS local site survey at the National Radio Astronomy Observatory in Maui (GNSS and SLR), the Table Mountain Geophysical Observatory in Colorado (new GNSS, gravity), Midway Naval Research Laboratory's OTF in Virginia (GNSS and SLR), and the International Earth Rotation and Reference Systems Service (IERS) Mauna Kea site (VLBA). Surveys were paused in the spring of 2020 due to the COVID pandemic and partially resumed in the fall of 2021. In addition, surveys investigating lines of sight and detailing the calibration piers for the SLR were performed at Goddard Geophysical and Astronomical Observatory (GGAO) in 2021 and 2022. A survey at KPGO - Kōke'e Park Geophysical Observatory was completed in May of 2023 and the final results and report will be released soon.

NGS fully implemented the use of an absolute laser tracking system (Leica AT402) into all completed tie surveys, enhancing precision of terrestrial observations. Progress was made on technical memorandum documenting current NGS procedures which will be released when developments are complete.

NGS has developed deflection of vertical (DoV) measurement capabilities utilizing a robotic total station and camera, and will continue testing equipment for deployment on upcoming local tie surveys. It is being called the TSACS (Total Station Astrogeodetic Control System), and the procedures and specifications were shared with researchers from Frankfurt who built and tested a similar system.

Collaboration among the group members has increased with information sharing leading to software, hardware, processing, and field protocols improvements. As an example, GSI Japan and Land Information New Zealand held a recent workshop with positioning staff. Saho presented about a local tie survey at Ishioka. In addition, GSI also released a video detailing the Ishioka site which highlighting co-location work.

Within the joint project GeoMetre, members determined the reference point of an SLR telescope at Wettzell, the Satellite Observing System Wettzell (SOS-W), using applied close-range photogrammetry instead of a polar measurement system.

Close range photogrammetry was also used to investigate on the deformation behaviour of the receiving unit of the Onsala Twin Telescope (OTT-N), as well as the 20 m Radio Telescope Wettzell (RTW) and the Twin Telescope Wettzell (TTW-2) in joint measurement campaigns of Frankfurt Univ. of Applied Sciences and Bochum Univ. of Applied Sciences. The signal path variations of these radio telescopes were derived using the common approach as well as spatial ray tracing. The results were reported to the IVS. Since VGOS-antennas are designed for broadband reception, the impact of frequency-dependent illumination functions onto the obtained signal path variations was studied in detail.

There is also a general interest from all members about moving towards locating InSAR targets and including them in tie surveys when co-located with other techniques. Some field results were captured in Collilieux et. al. 2022 as listed below.

Overall, the group has been active in this period, increasing the vectors used from ITRF2014 to ITRF2020, and decreasing the number of vectors with a discrepancy of greater than 5 mm (Altamimi, 2023).

Selected publications

Altamimi Z, P Rebischung, X Collilieux, L Métivier and K Chanard (2023) ITRF2020: An augmented reference frame refining the modeling of nonlinear station motions, Journal of Geodesy, doi:10.1007/s00190-023-01738-w

Barneoud J, C Courde, J Beilin, M Germerie-Guizouarn, D Pesce, M Vidal, X Collilieux and N Maurice (2023) Automatic determination of the SLR reference point at Côte d'Azur multi-technique geodetic Observatory , REFAG 2022 proceedings, in review

Bergstrand S, Jarlemark P, Herbertsson M (2020) Quantifying errors in GNSS antenna calibrations: Towards in situ phase center corrections, Journal of Geodesy. 94. 10.1007/s00190-020-01433-0.

Collilieux X, Courde C, Fruneau B, Aimar M, Schmidt G, Delprat I, Defresne M-A, Pesce D, Bergerault F, Wöppelmann G (2022) Validation of a Corner Reflector installation at Côte d'Azur multi-technique geodetic Observatory. Advances in Space Research. 70. 10.1016/j.asr.2022.04.050.

Eschelbach C, Lösler M (2022) A Feasibility Study for Accelerated Reference Point Determination Using Close Range Photogrammetry. 5th Joint International Symposium on Deformation Monitoring (JISDM), 20-22 June 2022, Polytechnic University of Valencia (UPV), Valencia, Spain, 2022. 10.4995/JISDM2022.2022.13417

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Eschelbach C, Lösler M, Haas R, Fath H (2019) Extension and Optimization of the Local Geodetic Network at the Onsala Space Observatory. In: Proceedings of the 10th IVS General Meeting, Svalbard, pp. 27-31, NASA/CP-2019-219039.

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Pollinger et al. (2023) 18SIB01 Geometre, Large-scale dimensional measurements for geodesy, final publishable report, available online at https://www.ptb.de/empir2018/fileadmin/documents/empir/GeoMetre/18SIB01_GeoMetre_Publishable_Summary_M30_v1_ACCEPTED.pdf

Varenius E, Haas R, Nilsson T (2021) Short-baseline interferometry local-tie experiments at the Onsala Space Observatory. J Geod 95, 54, https://doi.org/10.1007/s00190-021-01509-5
Co-location survey online reports http://itrf.ign.fr/local_surveys.php and https://www.ngs.noaa.gov/corbin/iss/:

- Erickson, B., Breidenbach, S., Jordan, K. Maui co-location survey, June 2019
- Jordan, K., Hippenstiel, R., Erickson, B., Fancher, K. Stafford co-location survey, October 2019
- Jordan, K., Hippenstiel, R., Fancher, K. Table Mountain co-location survey, October 2019
- Jordan, K., Hippenstiel, R., May, J. Mauna Kea co-location survey, May 2020
- Muller J.-M., Pesce D., Collilieux X., 2014 Hartebeesthoek co-location survey reprocessing report, dec 2020
- IGN: Malé, Sep 2021
- IGN: Crozet
- IGN: Futuna, Summer 2022
- IGN: Grasse, yearly, most recently Mar 2023

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JWG 1.2.3 : Toward reconciling Geocenter Motion estimates

Chair: Kristel Chanard (France)
Vice-chair: Alexandre Couhert (France)

Overview

The objective of this working group is:

- To review all methods to estimate geocenter motion, both from geodetic data and forward geophysical modelling, and systematically compare results.
- To focus on discrepancies in geocenter motion estimates and investigate potential biases in methods and/or systematic errors in geodetic products.
- To study the relative merit of geocenter motion data types (SLR, DORIS, GNSS, GNSS+LEOs). Special emphasis should be placed in evaluating the network-effect biases.
- To evaluate consistencies in methods used to retrieve geocenter motion (translational and inverse approaches, forward modelling).
- To assess the impact of errors in geocenter motion through variability in estimates for operational and scientific users.

Members

• *Kristel Chanard (France), Chair*
• *Xavier Collilieux (France)*
• *Alexandre Couhert (France), Vice-Chair*
• *Robert Dill (Germany)*
• *Suzanne Glaser (Germany)*
• *Christopher Kotsakis (Greece)*
• *Flavien Mercier (France)*
• *Laurent Métivier (France)*
• *Paul Rebischung (France)*
• *John Ries (USA)*
• *Ricardo Riva (Nehterlands)*
• *Krystof Sosnica (Poland)*
• *Dariusz Strugarek (Poland)*
• *Xiaoping Wu (USA)*
• *Radoslaw Zajdel (Poland)*

Activities during the period 2019-2023

Two papers, Meyssignac et al. (2019) and Blazquez (2020), relevant to this working group were recently published. Their work highlighted for the first time that the geocenter (with GIA) correction was the highest uncertainty in GRACE-based global water budgets and estimations of the Earth's Energy Imbalance. Such results further provide strong arguments towards the need to improve our understanding and modeling of this motion, especially to assess the current status of climate change and its future evolution.

Selected publications

Blazquez A (2020) "Satellite characterization of water mass exchange between ocean and continents at interannual to decadal timescales", Phd, Université Paul Sabatier - Toulouse III

Couhert A, Bizouard C, Mercier F, Chanard K, Greff M and Exertier P (2020) Self-consistent determination of the Earth's GM, geocenter motion and figure axis orientation. Journal of Geodesy, 94(12), pp.1-16.

Meyssignac Benoit, Tim Boyer, Zhongxiang Zhao, Maria Z. Hakuba, Felix W. Landerer, Detlef Stammer, Armin Köhl, et al. (2019) “Measuring Global Ocean Heat Content to Estimate the Earth Energy Imbalance”. *Frontiers in Marine Science* 6.

SG 1.2.1: Relevance of PSInSAR analyses at ITRF co-location sites

Chair: Xavier Collilieux (France)

Overview

The objective of the working group is to investigate if Permanent Scatterer Interferometric Synthetic Aperture Radar (PSInSAR) technique can be used to supplement local tie survey at ITRF multi-technique sites. The program of activities is the following:

- List strength and weakness of the PSInSAR technique for this application
- Collect all studies related to INSAR and more particularly PSInSAR at co-location sites
- If relevant, make an inventory of SAR images (for all missions) available at ITRF co-location sites
- If relevant, identify multi-technique co-location sites where PSInSAR processing should be performed and compare InSAR results from various software packages
- Compare results of free, but low-resolution, Sentinel-1 data with commercial high-resolution data (e.g. TerraSAR-X) where available; investigate whether a request for a supersite could be used to obtain additional high-resolution data (see https://www.earthobservations.org/documents/gsnl/20120918_GSNL_CEOSSelectionProcess.pdf)
- Investigate the relevance of installing corner reflectors or transponders at co-location sites
- Report conclusions and recommendations in IUGG2023 proceedings

Members

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- *Xavier Collilieux (IPGP/IGN/ENSG, France)*
- *Clément Courde (CNRS, France)*
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- *Davod Poreh (Universita degli Studi di, Napoli Federico II, Italy)*
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Corresponding Members

- *Ann Chen (UT Austin, USA)*
- *Ryan Hippenstiel (NGS, USA)*

Activities during the period 2019-2023

Strengths and weaknesses of the PSInSAR to monitor geodetic instrument point reference position at co-location sites have been investigated by the study group. They are summarized in the table provided below.

A PSInSAR analysis of Sentinel 1A/1B images spanning oct. 2016 to oct 2021 has been carried out at Wettzell co-location site by Rüsch et al. (2022). The resolution of Sentinel 1A/1B images images is about 3x22 m [rg x az] in Interferomeric Wide swath (IW) mode and 3x5 m [rg x az] in stripmap mode (SM). While numerous Persistent Scatterers (PS) have been obtained, no PS has been identified close to GNSS permanent stations in rural environment.

PS can be insured by installing corner reflector (CR) or transponders. Gruber et al. (2020) have studied transponders (active devices) for a project of height system unification named “Geodetic SAR for Baltic Height”. They reported that transponders are easy to install as they are much smaller than conventional CR. They can also be visible from both ascending and descending arcs. However some limitations have been pointed out: calibration, phase center correction, radio license constraint, software adaptation and possible interference with existing geodetic infrastructure (GNSS, DORIS, SLR, VLBI). While the positioning exhibits good repeatability at most sites, significant biases (up to 50 cm) have been noticed but not understood (possible instrument effects). Moreover, the tests carried out to determine reliable vertical velocities were not conclusive. As well-known alternative, Passive CR can be installed. At least five ITRF co-location currently hosts CR: Grasse (Collilieux et al., 2022), Metsähovi, O’Higgins, Wettzell, Yarragadee (Gisinger, 2022).

A few available services provide PSInSAR results based on Sentinel 1A/1B images at a national level (Germany, Italy, The Netherlands, Norway, Sweden) or at continental level for Europe with the European Ground Motion Service (EGMS) (Crosetto et al., 2020). EGMs results at all European ITRF co-location site have been studied. No clear displacement has been evidenced at any of the sites over the period February 2015 to December 2020.

Strengths	**Weaknesses**
Precise determination: 1 mm/yr (Ferretti et al., 2007)	1D line-of-sight or 2D measurements (when combining ascending and descending orbits); limited sensitivity in North/South direction
Independant information from current space geodetic techniques	Determine ground or monument motion and not the reference point position
Reliable reference PS can be created by dedicated radar target installations	All deformation measurements are relative to the selected reference PS point; the same point is often not visible in multiple orbits (ascending vs descending)
	Stability of a selected reference PS is usually unknown
Opportunistic results	No PS at some locations of interest
CR or transponders can be installed	CR cannot be installed to close to existing GNSS stations
High resolution images available	Limited spatial resolution
Provide relevant information mostly for large sites with available SAR images	
SAR data sometimes already available and sometimes free (ex: Sentinel 1A/1B).	Cost of some images
Already available PSInSAR products (ground motion services)	
In theory, atmospheric errors are limited for this application since they affect all stations similarly.	Atmospheric (mainly troposphere) phase screens have to be estimated with data driven methods; usage of standardized background models for troposphere / ionosphere / solid Earth dynamics not yet widely established with PSI InSAR processing chains

Table. Strengths and weaknesses of the PSInSAR technique to monitor geodetic instrument point reference position at ITRF co-location sites

It is possible to derive PSInSAR at a higher resolution using SAR images from other missions tha Sentinel 1A/1B. Poreh and Pirasteh (2020) studied ground deformation at Medicina co-location site from the end of 2009 to the end of 2011 using CosmoSkyMed X-band images in

StripMap/HIMAGE mode, resolution 2.5×2.5 m [rg x az]. At this site, a VLBI telescope and two GNSS stations are co-located. Unfortunately, the density of the Persistent Scatterers (PS) they obtained was not sufficient to investigate relative motion between instruments. No PS has been found on the VLBI telescope probably due to continuous VLBI telescope motions. But as shown by Parker et al. (2019), VLBI instruments can be efficient radar reflectors when oriented toward satellites.

TerraSAR-X (TSX) and TanDEM-X (TDX) missions are able to provide higher resolutions: about 0.6 x 1.0 m [rg x az] for High Resolution SpotLight (HS) and about 0.6 x 0.25 m [rg x az] for staring spotlight mode (Gisinger, 2022). The inventory of all images at ITRF co-location sites has been carried out. Five co-location sites show more than 15 TSX/TDX images at such resolution (Metsähovi, O'Higgins, Yarragadee, Wettzell, Wuhan) in ascending or descending arcs. The number of candidate sites is much larger using TSX/TDXstripmap mode, resolution 2 x 3 m [rg x az]. PSInSAR analyses of those X-band images would be worth investigating in the future.

Selected publications

Collilieux X, C Courde, B Fruneau, M Aimar, G Schmidt, I Delprat, M-A Defresne, D Pesce, F Bergerault and G Wöppelmann (2022) Validation of a Corner Reflector installation at Côte d'Azur multi-technique geodetic Observatory, Advances in Space Research, n. 360-370, doi:10.1016/j.asr.2022.04.050

Crosetto et al. (2020) "Interaction and cooperation between the European Ground Motion Service and national/regional Ground Motion Services", EGMS Technical Report, Version 3.0, 22/06/2020: https://land.copernicus.eu/user-corner/technical-library/

Gisinger, C. (2022) TerraSAR-X and DLR MF-SAR Activities at Geodetic Observatories, IAG WG on InSAR at ITRF co-location site WebMeeting, feb. 2022

Gisinger, C. and Libert, L.and Marinkovic, P.and Krieger, L.and Larsen, Y. and Valentino, A. and Breit, H.and Balss, U.and Suchandt, S. and Nagler, T.and Eineder, M.and Miranda, N., "The Extended Timing Annotation Dataset for Sentinel-1—Product Description and First Evaluation Results," in IEEE Transactions on Geoscience and Remote Sensing, vol. 60, pp. 1-22, 2022, Art no. 5232622, doi: 10.1109/TGRS.2022.3194216.

Gruber, T.; Ågren, J.; Angermann, D.; Ellmann, A.; Engfeldt, A.; Gisinger, C.; Jaworski, L.; Marila, S.; Nastula, J.; Nilfouroushan, F.; Oikonomidou, X.; Poutanen, M.; Saari, T.; Schlaak, M.; Światek, A.; Varbla, S.; Zdunek, R. Geodetic SAR for Height System Unification and Sea Level Research—Observation Concept and Preliminary Results in the Baltic Sea. Remote Sens. 2020, 12, 3747. doi:10.3390/rs12223747

Kotzerke, P (2022) End-to-End Implementation and Operation of the European Ground Motion Service (EGMS). Technical Report EGMS-D10.4-QCR-SC2-3.0-012.

Parker, A. L., McCallum, L., Featherstone, W. E., McCallum, J. N., & Haas, R. (2019). The potential for unifying global-scale satellite measurements of ground displacements using radio telescopes. Geophysical Research Letters, 46(21), 11841-11849

Poreh, D., Pirasteh, S. (2020). InSAR observations and analysis of the Medicina Geodetic Observatory and CosmoSkyMed images. Natural Hazards, 103(3), 3145-3161.

Rüsch L., Friedländer S., Liebsch G., PSInSAR at the Geodetic Observatory Wettzell, IAG WG on InSAR at ITRF co-location site WebMeeting, feb. 2022

Wang K. and Chen J. (2022) "Accurate Persistent Scatterer Identification Based on Phase Similarity of Radar Pixels," in IEEE Transactions on Geoscience and Remote Sensing, vol. 60, pp. 1-13, Art no. 5118513, doi: 10.1109/TGRS.2022.3210868.

Zerbini, S., B. Richter, F. Rocca, T. van Dam, and F. Matonti (2007), A Combination of Space and Terrestrial Geodetic Techniques to Monitor Land Subsidence: Case Study, the Southeastern Po Plain, Italy, J. Geophys. Res., 112, B05401, doi:10.1029/2006JB004338

Sub-commission 1.3: Regional Reference Frames

Chair: Carine Bruyninx (Belgium)

Overview

Sub-commission 1.3 contains six regional Sub-commissions (SC), namely

- Sub-commission 1.3a: Europe
- Sub-commission 1.3b: South and Central America
- Sub-commission 1.3c: North America
- Sub-commission 1.3d: Africa
- Sub-commission 1.3e: Asia-Pacific
- Sub-commission 1.3f: Antarctica

and one Working Group (WG) "Time-dependent transformations between reference frames in deforming regions".

This report gathers the contributions of the above regional sub-commissions and WG for the period 2019-2023. As stated in the Terms of Reference, IAG Sub-commission SC1.3 deals with the definitions and realizations of regional reference frames and their connection to the global International Terrestrial Reference Frame (ITRF). It offers a home for service-like activities addressing theoretical and technical key common issues of interest to regional organizations.

In addition to the specific objectives of each regional Sub-commission, the main objectives of SC1.3 as a whole are to:

- Coordinate the activities of the regional Sub-commissions focusing on exchange of data, competences and results;
- Promote operation of permanent GNSS stations, in connection with IGS whenever appropriate, as the basis for the long-term maintenance of regional reference frames;
- Promote open access to the GNSS data from permanent GNSS stations used for the maintenance of regional reference frames and scientific applications;
- Develop specifications for the definition and realization of regional reference frames, including the vertical component;
- Encourage and stimulate the development of the AFREF project in close cooperation with IGS and other interested organizations;
- Encourage and assist countries, within each regional Sub-commission, to re-define and modernize their national geodetic systems, compatible with the ITRF;
- Support the efforts of the United Nations Initiative on Global Geospatial Information Management (UN-GGIM) towards a sustainable Global Geodetic Reference Frame (GGRF).

The reports of all regional sub-commissions (except Africa) and the SC1.3 WG are presented hereafter.

Sub-commission 1.3a: Europe (EUREF)

Chair: Martin Lidberg (Sweden)

Introduction and Structure

The long-term objective of EUREF, as defined in its Terms of Reference is “the definition, realization and maintenance of the European Reference Systems, in close cooperation with the pertinent IAG components (Services, Commissions, and Inter-Commission projects) as well as EuroGeographics”. For more information, see http://www.euref.eu.

The results and recommendations issued by the EUREF sub-commission support the use of the European Reference Systems in all scientific and practical activities related to precise georeferencing and navigation, Earth sciences research and multi-disciplinary applications. EUREF applies the most accurate and reliable terrestrial and space-borne geodetic techniques available, and develops the necessary scientific principles and methodology. Its activities are focused on a continuous innovation and on evolving user needs, as well as on the maintenance of an active network of people and organizations, and may be summarized as follows:

- Maintenance of the ETRS89 (European Terrestrial Reference System) and the EVRS (European Vertical Reference System) and upgrade of the respective realizations;
- Refining the EUREF Permanent Network (EPN) in close cooperation with the International GNSS Service (IGS);
- Improvement of the European Vertical Reference System (EVRS);
- Contribution to the IAG Project GGOS (Global Geodetic Observing System) using the installed infrastructures managed by the EUREF members.

These activities are reported and discussed at the meetings of the EUREF Governing Board (GB), which take place three times a year, and the annual EUREF Symposia, an event that occurs yearly since 1990. The EUREF symposia have an attendance of about 100-120 participants from more than 30 European countries and other continents, representing mainly Universities, Research Centres, and NMCAs (National Mapping and Cadastre Agencies).

EuroGeographics (the consortium of the European NMCAs) supports the organization of the EUREF Symposia, reflecting the importance of EUREF for practical purposes.

EUREF and EPOS (the European Plate Observing System, https://www.epos-eu.org/) has formalized its cooperation in an MoU that was signed in 2022. EUREF and EPOS have common interest in increased knowledge and understanding of processes in the European plate. Cooperation is therefore already established since many years, so far primarily on GNSS.

Members

- *Elmar Brockmann (Switzerland)*
- *Carine Bruyninx (Belgium)*
- *Rolf Dach (Switzerland)*
- *Ambrus Kenyeres (Hungary)*
- *Karin Kollo (Estonia, EUREF secretary, ex-officio)*
- *Juliette Legrand (Belgium)*
- *Martin Lidberg (Sweden, EUREF chair, ex-officio)*

- *Tomasz Liwosz (Poland)*
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- *Martina Sacher (Germany)*
- *Wolfgang Söhne (Germany, GB chair)*
- *Christof Voelksen (Germany)*
- *Joaquin Zurutuza (Spain)*

A. Araszkiewicz (Poland), Z. Altamimi (France), A. Caporali (Italy), M. Poutanen (Finland), and J. Torres (Portugal) are regularly participating to the GB meetings as honorary members and invited guest, resp.

Activities during the period 2019-2023

EUREF Permanent GNSS Network (EPN) – Tracking Network, Network Coordination, EPN Central Bureau

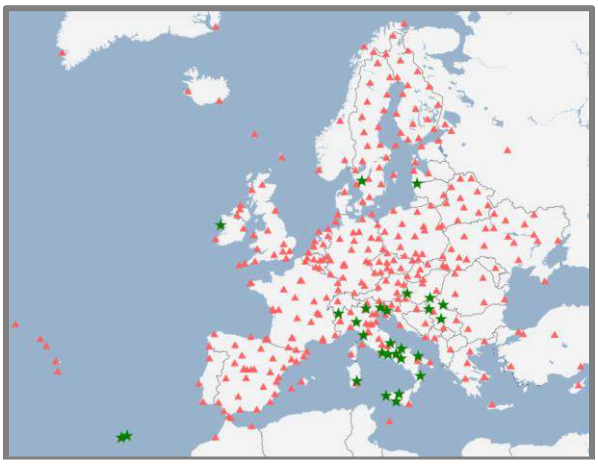
Most of the activities covering the EUREF Permanent GNSS Network (EPN) are reported on an annual basis in the Technical Reports of the International GNSS Service (IGS). In addition to the overview and summary given here, see Bruyninx et al. (2020, 2021, 2022, 2023) for more details.

EPN tracking network

The EPN network includes 405 stations (May 2023, compared to 341 in May 2019). In addition to GPS, the stations are also tracking:

- GLO: 97%
- GAL: 89%
- BDS: 78%

The EPN Central Bureau (CB, managed by the Royal Observatory of Belgium, https://www.epncb.oma.be/) continued to monitor operationally EPN station performance in terms of data availability, correctness of metadata, and data quality.



EPN tracking stations (status May 2023).
* indicates new stations included in the network in since June 2022.

The effort to move towards FAIR-aligned GNSS data continues with 97% of the EPN stations that have assigned a data license to their RINEX data in M3G (https://gnss-metadata.eu).

In order to comply with EU General Data Protection Regulation (GDPR), from Oct. 24 2022 on, all EPN site logs and GeodesyML files that can be retrieved from M3G (and EPN CB) have been stripped from any personal contact information coming from persons who have not given M3G the explicit permission to publish their personal information. Moreover, from that date on, M3G only allows to upload site logs that use non-personal contact information and emails in the "Prepared by" field (section 0), the "Primary contact" of the "On-Site, Point of Contact Agency Information" and the "Responsible Agency" (sections 11 and 12).

The EPN CB released version 2.0 of the ETRF/ITRF Coordinate Transformation Tool (ECTT) available from https://epncb.oma.be/_productsservices/coord_trans/. It now allows transforming coordinates from and to ITRF2020.

Encouraged by Resolution No 2 of the 2019 EUREF symposium in Tallinn, more than 81% of the EPN stations are sharing their daily RINEX data with the European Plate Observing System (EPOS). These EPN data are made available to EPOS through the ROB-EUREF EPOS data node built on top of the historical EPN data centre managed by the EPN CB.

In March 2022, The EUREF Governing Board also updated the Guidelines for EPN stations and Operational Centres making the submission of RINEX 3 data mandatory for EPN stations and encouraged the submission of high-rate RINEX data files.

EPN Analysis Centre Coordination

In the years 2019-2023 the EPN Analysis Centres Coordinator (ACC) continued to combine GNSS coordinate solutions (final, rapid and ultra-rapid) provided by currently 17 EPN Analysis Centres (AC).

The International GNSS Service (IGS) published the new terrestrial reference frame, IGS20, and the new antenna phase center variation/offset (PCV/PCO) model (igs20.atx) in July 2022. IGS changed from IGb14/igs14.atx to these new IGS20/igs20.atx and IGS repro-3 standards starting GPS week 2238 (November 27, 2022).

To be consistent with the IGS, the EPN decided switch to the new IGS20/igs20.atx and repro-3 standards at the same time as the IGS (GPS week 2238). In May 2023, 13 out of 17 ACs has been able to update their software, implement the new processing standards and provide final solutions in IGS20.

The change to IGS20 processing standards, also includes a change from individual calibrated receiver antenna PCV/PCO models to type mean models. The motivation is that many antennas in the EPN with individual PCV/PCO models, was calibrated at a time where calibrations was performed only for GPS and GLONASS. Therefor individual models for new frequencies from GAL and BDS (and GPS L5) are missing. Thus, type mean models provide better support for multi-GNSS signals, as well as better consistency with IGS analysis.

A specific antenna file has been compiled for use within EPN (epnc_20.atx). It is based on the igs20.atx and complemented with antenna/radom pairs not used at IGS stations.

To discuss the details regarding the switch to the IGS20 in EPN, the EPN Analysis Centres Workshop was organized on November 3, 2022.

EUREF Reference Frame Product

To maintain the ETRS89, EUREF releases, each 15 weeks, an update of the multi-year coordinates/velocities of the EPN stations in the latest ITRS/ETRS89 realizations (Legrand and Bruyninx, , 2019). The Reference Frame Coordinator (RFC) computes these EPN multi-year solutions with the CATREF software (Altamimi et al., 2007).

The latest EPN multi-year product including the SINEX files in Igb14 and ETRF2014, the discontinuity list and the associated residual position time series are available from https://epncb.oma.be/ftp/product/cumulative/latest/. Archives of the previous EPN multi-year product can be found at https://epncb.oma.be/ftp/product/cumulative/. In addition to the EPN multi-year product, extended time series are updated every day by completing the EPN multi-year solution with the most recent EPN final and rapid daily combined solutions. Together with the quality check monitoring performed by the EPN CB, these quick updates allow to monitor the behavior of the EPN stations and to react promptly in case of problems. In order to evaluate the quality of the EPN stations as reference stations, the "Tool for Reference Station Selection" is available on line and results are updated at each release of the Reference Frame Product: https://epncb.oma.be/_productsservices/ReferenceFrame/ (Legrand and Bruyninx 2021).

The latest multi-year coordinate/velocity solution is the C2235 (includes observations up to GPS week 2235), based on the Igb14. Development and release of multi-year solutions will be resumed as soon as remaining Acs has turned to IGS20 processing standards. This will be a large effort since it includes the work to harmonize previous solutions in Igb14 with new solutions in IGS20. This issue is a major argument for the up-coming EPN Repro3 effort (see below, WG EPN Reprocessing).

EPN Real Time

At the end of 2022, 219 EPN stations (i.e., mount-points) provided real-time data which corresponds to 55% of the EPN stations. Almost all varieties of RTCM 3.x messages are available from the EPN broadcasters, plus three stations still providing RTCM 2.3. The number of streams supporting the RTCM 3.3 Multi Signal Messages (MSM) has still been growing, resulting in many Galileo and BeiDou data streams available. The number of stations providing MSM4 messages (message types 1074 etc.) remains at 8 stations, MSM5 (message types 1075 etc.) is now 66 whereas the MSM7 (message types 1077 etc.) increased significantly to 127 data streams. Hence, the stations providing the old "legacy" messages 1004 (GPS) and 1012 (GLONASS) further reduced to 20. All streams are coming (directly) from the receiver.

The visibility, in particular availability and latency, of the real-time data streams and the monitoring of the three EPN broadcasters is maintained at the EPN CB (https://epncb.oma.be/_networkdata/data_access/real_time/status.php) as well as the meta-data monitoring (https://epncb.oma.be/_networkdata/data_access/real_time/metadata_monitoring.php). More than 96% of the real-time data is available at all three EPN casters at ASI, BKG and ROB.

Concerning real-time products, the EPN continues to follow the activities in the IGS and the standardization efforts in RTCM and in the IGS. The long product and broadcast ephemerides mount-point names have been completely introduced within the IGS, and consequently also the EUREF products were adapted: SSRA02IGS0_EUREF and SSRA03IGS0_EUREF for the RTCM SSR representation and SSRA02IGS1_EUREF and SSRA03IGS1_EUREF for the slightly different IGS SSR representation.

EPN Troposphere Products

Since June 2001, the EPN Analysis Centres operationally estimate tropospheric Zenith Path Delays (ZPD) in addition to station coordinates. These ZPD (available in daily SINEX TRO files) are used by the Troposphere coordinator to generate each week ('wwww') the combined EPN troposphere solution containing the combined troposphere estimates with an hourly sampling rate. The coordinates, as a necessary part of this file, are taken from the EPN weekly combined SINEX file. Hence, stations without estimated coordinates in the weekly SINEX file are not included in the combined troposphere solution.

As part of the EPN reprocessing activities, an updated series of combined EPN ZPD is also computed. This was done for EPN-REPRO1 (1996-2006) and EPN-REPRO2 (1996-2014). In 2020, the Integrated Water Vapor (IWV) was added in the EPN combined products. This require use of auxiliary data (pressure and temperature) from ECMWF.

The troposphere products are useful for applications in other disciplines, as well as quality check of the EPN GNSS processing. Among applications, improved Wet Trop Corrections for satellite altimetry can be mentioned. Climate research is also relevant since GNSS time series is approaching 30 years.

WG EPN Densification

The EPN Densification (EPND) is a collaborative effort of 30 European GNSS Analysis Centres providing series of daily or weekly station position estimates of the dense national and regional GNSS networks in SINEX format (Kenyeres et al., 2019). These are combined into one homogenized set of weekly SINEX series, then adjusted with the CATREF software to derive a regional station position and velocity product.

The most recent combination (D2200) covers the period from October 2008 to March 2022 (GPS week 1500-2200) using inputs expressed in IGS14. The complete solution includes 31 networks with positions and velocities of 3500 stations, well covering Europe. However, not all of them are published, stations with shorter than 3 years observation series are kept internally and also low-quality stations are removed. The positions and velocities are expressed in the ITRF2014 and ETRF2014 reference frames and are tied to the reference frame using minimum constraints on a selected set of reference stations. The description of the EPN Densification, station metadata, and results are available from the EPN Densification product portal (https://epnd.sgo-penc.hu). The EPND velocities are used as part of the EPOS GNSS products and for the generation of the European Velocity Model (Steffen et al., 2022). EPND is extended with the European part of the NGL (Nevada Geodetic Laboratory) global processing results in order to generate a unique reference velocity model for referencing the EGMS (European Ground Motion Service) InSAR ground motion model.

WG European Dense Velocities

Complementary to the EPN Densification, EUREF introduced a WG on dense velocities. The idea is to collect national or regional GNSS station velocity solutions presented in ETRF2000 (or possibly transformed to ETRF2000). In total, about 7900 individual station velocities are available for Europe. Almost half of the stations are included in 2 or more solutions. This provides good opportunity for evaluation of reference frame alignment between different national/regional solutions.

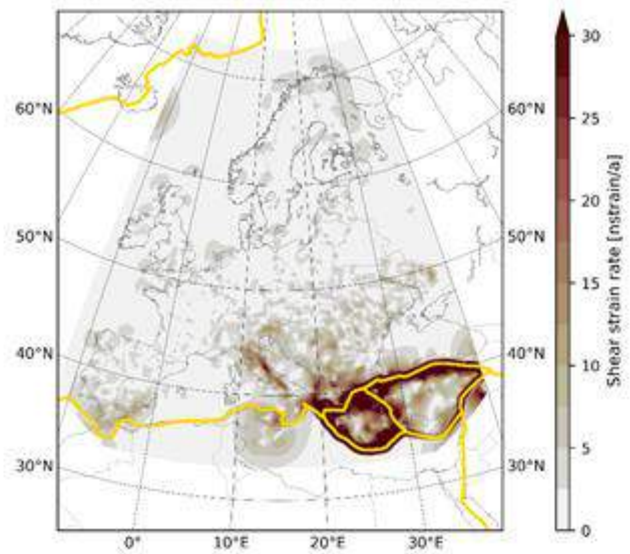
The description and detailed results are available at https://pnac.swisstopo.admin.ch/divers/dens_vel/index.html.

WG Deformation models

The precise knowledge of the crustal deformations within the EUREF area of interest is identified to be of vital importance from scientific perspective, for reference frame handling, and possibly as a tool for georeferencing of seamless ground motion products from InSAR (e.g. EGMS above).

A first version of a European velocity model, named EuVeM2022 (European Velocity Model 2022), has been developed based on the EPND2150 dataset. Horizontal and vertical velocities were determined on a dense grid covering Europe using a modified least-squares collocation method, which was published in Journal of Geodesy in January 2022 (**doi: 10.1007/s00190-022-01601-4**). The EuVeM2022 is available through https://doi.org/10.23701/euvem2022.

The horizontal gridded velocities have been used to obtain a strain rate map for Europe (see to the right). The velocity and strain rate models were presented at the REFAG2022 meeting in Thessaloniki (Greece).



Strain rate model from EuVeM2022

EuVeM2022 should be seen as a first version of a pan-European velocity model. So, first step after its release will be to evaluate and compare to other data sets and models.

WG EPN Reprocessing

EUREF plan to perform an EPN-Repro3, starting in 2023. The motivation is as follows:

- The global AC of the IGS have conducted their 3rd reprocessing campaign to provide consistent products that have been the input data for the computation of the ITRF2020
- Based on this new reference frame the EPN ACs had to switch in GPS week 2238 (27. Nov 2022) to the IGS20 for the operational computation of the EPN
- Consequently, previous operational products no longer match the actual analysis
- In order to obtain consistent products for the period from 1996 to the current generated products, a repeated processing of the old data is necessary
- This lead to the decision to initiate a new reprocessing campaign - ***EPN-Repro3***

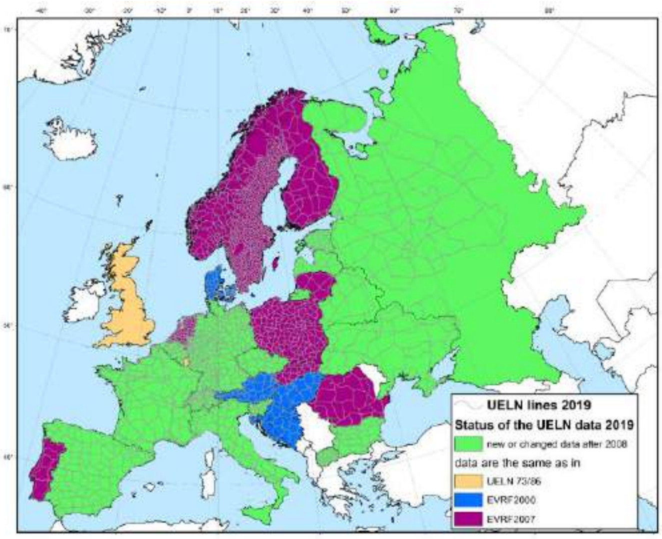
The EPN-Repro3 was discussed among the ACs at a virtual meeting on November 7 2022.

The result of the EPN-Repro3 is assumed to provide a firm base for the future maintenance of the European Terrestrial Reference Frame, ETRS89.

European Vertical Reference System (EVRS)
The European Vertical Reference System, EVRS, is realized in European Vertical Reference Frames, EVRFs This is performed by common adjustment of the United European levelling network (UELN). The latest solution is the EVRF2019 (Sacher and Liebsch 2020).

The work on EVRS is a continuous effort where a new country may be added to the UELN, or new levelling data may be added or replaced for another country. Revision of border connections between countries is another important task. Examples of countries with (some) updates of levelling data are Austria, Belgium, Bulgaria, Czeck Republic, France, Italy, Moldova, North Macedonia, Slovenia.

The UELN now includes the levelling data of 31 European countries (see below).



The UELN levelling lines as base for the EVRF2019.

The datum of EVRF2019 is realized by 12 datum points with their heights of the EVRF2007 adjustment. The measurements have been reduced to the epoch 2000 using the model of the land uplift for Fennoscandia and the Baltic region NKG2016LU_lev (Vestøl et al 2016) in Denmark, Sweden, Norway, Finland, Estonia, Latvia, Lithuania, Russia, Belarus and a velocity model for Switzerland. The heights of EVRF2019 are in the zero tidal system, according to IAG resolution No.16 adopted in Hamburg 1983 (Mäkinen, Ihde 2009). Additionally, the results of EVRF2019 have been provided in the mean-tide system – together with the comment to use these heights for tasks of oceanography as well as for clock rates. Furthermore, mean-tide heights can be used in the future for comparison with heights in the International Height System IHRS.

The heights of EVRF2019 are available at
https://evrs.bkg.bund.de/Subsites/EVRS/EN/EVRF2019/evrf2019.html.
Transformation grids between national European vertical reference frames and EVRF2019 are available at http://www.crs-geo.eu/.

WG European Unified Height Reference

The WG European Unified Height Reference was established through Resolution No. 1 at the EUREF 2021 Symposium. It aims to improve information about the national height coordinate frames within Europe and their transformations to the EVRS; to complement EVRS and ETRS89 with an official European height reference surface (EHRS, to be realized by a combined quasigeoid model); and thereby to enhance the European geodetic infrastructure.

To this end, three main tasks have been defined:

1. Establish a continuously updated inventory of official national height reference surfaces (geoid models) to be included in a redesigned CRS-EU database according to ISO 19111:2019 standards;
2. Work towards a new European GNSS/leveling dataset as a successor to EUVN_DA. In order to emphasize the relevance for the EHRS, a new title "European Height Reference Surface – Control Points" (EHRS_CP) was chosen.
3. Compute a seamless European combined quasigeoid model which is consistent with the latest EVRS and ETRS realizations.

A first online meeting of the WG took place on 1 Oct 2021. Meanwhile, a draft for a questionnaire on the national geoid models and a call for GNSS/leveling data has been finalized and sent out to the national contacts for the UELN. A first response was evaluated and presented at the EUREF Symposium 2023.

Organised Meetings

EUREF Governing Board meetings:
- October 15, 2019, in Warsaw, Poland, hosted by Warsaw University of Technology
- February 26-27, 2020, in Munich, Germany, hosted by Bayerische Akademie der Wissenschaften
- May 28, 2020, virtual
- November 9 and 19, 2020, virtual
- February 16, March 2, 2021, virtual
- May 4 and 7, 2021, virtual
- October 21 and November 4, 2021, virtual
- March 3 and 15, 2022, virtual
- May 4 and 11, 2022, virtual
- October 24 and December 2, 2022, virtual
- March 1-2, 2023, Frankfurt, Germany, hosted by the BKG
- May 22-23, 2023, Gothenburg, Sweden, hosted by the Chalmers technical University

EUREF Annual Symposia:
- May 26-28, 2021 on-line from Ljubljana, Slovenia, (> 100 participants)
- June 1-3, 2022 on-line from Zagreb, Croatia, (>100 participants)
- May 24-26, 2023 physical meeting in Gothenburg, Sweden, with a tutorial on AI/ML afternoon May 23. About 90 participants.

EUREF Analysis Workshop:
- October 16-17, 2019 Warsaw, Poland (approx. 30 participants)
- November 3, 2022, virtual

- November 7, 2022, virtual. Focus on EPN Re-processing no 3
- And several small virtual meetings from autumn 2022 to spring 2023 on the change to IGS20 standards and EPN-Repro3

Publications

Bruyninx, C., Legrand, J., Fabian, A., Pottiaux, E. (2019). GNSS metadata and data validation in the EUREF Permanent Network. GPS Solut 23:106, https://doi.org/10.1007/s10291-019-0880-9

Bruyninx C., Brockmann E., Kenyeres A., Legrand J., Liwosz T., Pacione R., Söhne W., and Völksen C. (2020). EUREF Permanent Network. *IGS Technical Report 2019*, eds. A. Villiger and R. Dach, University of Bern, Bern Open Publishing. 111–124. https://doi.org/10.7892/boris.144003

Bruyninx C., Brockmann E., Kenyeres A., Legrand J., Liwosz T., Pacione R., Söhne W., and Völksen C. (2021) EUREF Permanent Network. *International GNSS Service Technical Report 2020 (IGS Annual Report),* eds. A. Villiger and R. Dach, University of Bern, Bern Open Publishing. 121-133. https://DOI.org/10.48350/156425

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Legrand J. and Bruyninx C. (2021). Station Classification and Reference Station Selection, EGU General Assembly 2021, online, 19–30 Apr 2021, EGU21-14190, https://doi.org/10.5194/egusphere-egu21-14190

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Legrand J., Bruyninx C., Altamimi Z., Caporali A., Kenyeres A., Lidberg M. (2021). Guidelines for EUREF Densifications, Available from Royal Observatory of Belgium. https://doi.org/10.24414/ROB-EUREF-Guidelines-DENS, Lidberg M., Soehne W., Sacher M., Legrand J., Kenyeres A., (2020). EUREF – an Important Component of the European Geodetic Infrastructure. FIG Working Week 2020, 10-14 May. https://fig.net/resources/proceedings/fig_proceedings/fig2020/papers/ts03g/TS03G_lidberg_soehne_et_al_10687.pdf

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Steffen R., Legrand J., Ågren J., Steffen H., Lidberg M. (2022) HV-LSC-ex2: velocity field interpolation using extended least-squares collocation. J G 96:15, https://doi.org/10.1007/s00190-022-01601-4

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Sub-commission 1.3b: South and Central America

Chair: José Antonio Tarrío (Chile)
Vice-Chair: Demián Gomez (US)

Introduction and Structure

SIRGAS is the Geocentric Reference System for the Americas, in Spanish (Sistema de Referencia Geocéntrico para las Américas). Its definition corresponds to the International Terrestrial Reference System (ITRS), which is realized by regional densification of the International Terrestrial Reference Frame (ITRF). SIRGAS includes defining and realizing a vertical reference system based on ellipsoidal heights as a geometrical component and geopotential numbers (referred to as a global conventional W_0 value) as a physical component.

SIRGAS is a member of the Sub-commission 1.3 (Regional Reference Frames) of the Commission 1 (Reference Frames) of the IAG (International Association of Geodesy) and corresponds to a Working Group of the Cartography Commission of the PAIGH (Pan-American Institute for Geography and History).

SIRGAS is a non-profit organization that functions thanks to the voluntary contributions of scientific organizations and member countries' national geodetic, cartographic, or geographic agencies. The organizational flowchart of its operations is as follows:

SIRGAS organizational chart

Members

SIRGAS Executive committee

- *Sonia María Alves Costa , Chair (Brasil).*
- *Diego Alejandro Piñón, Vice-Chair (Argentina)*
- *José Antonio Tarrío, SIRGAS-WG1 Chair (Chile)*
- *Demián Gomez, SIRGAS-WG2 Chair (US)*
- *Gabriel do Nascimento Guimarães, SIRGAS-WG3 Chair (Brazil)*

SIRGAS Directing council

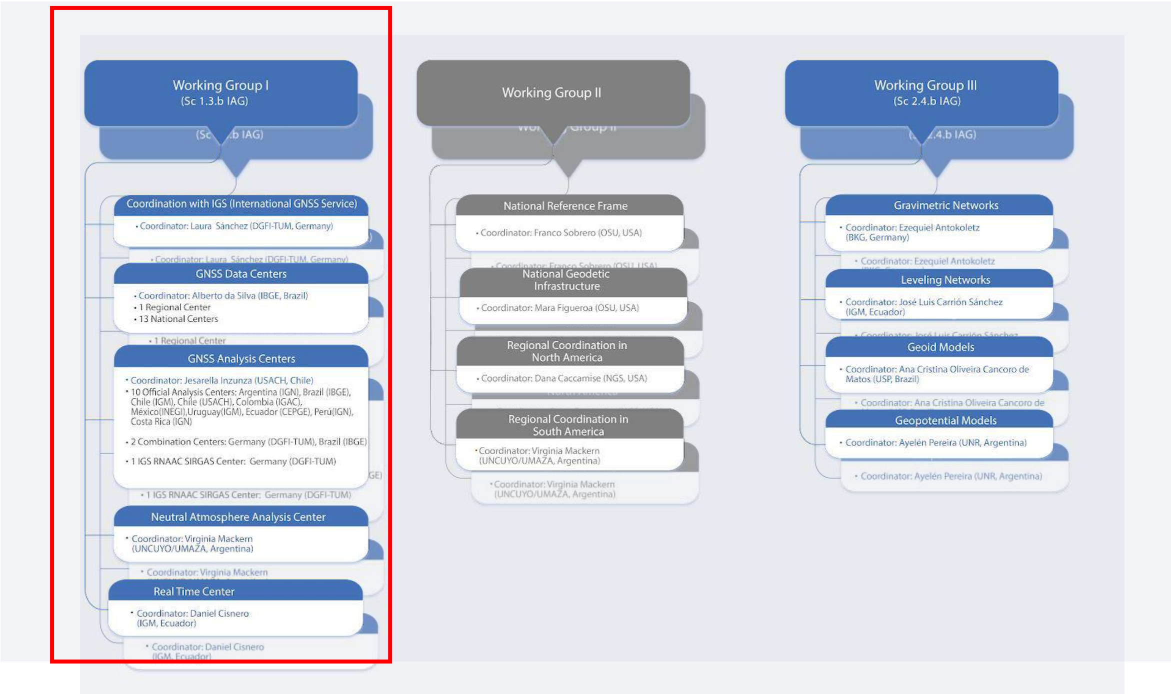
- *Hermann Drewes, Representative of IAG*
- *Nobertino Suarez, Representative of IPGH*
- *Juan Francisco Moirano; Demian Gómez (Argentina)*
- *Arturo Echalar Rivera; Mario Sandoval Nava (Bolivia)*
- *Luiz Paulo Souto Fortes; Sonia Maria Alves Costa (Brazil)*
- *Juan Pedro Harms; Sergio Rozas Bornes (Chile)*
- *Jose Ricardo Guevara Lima; Francisco Javier Mora Torres (Colombia)*
- *Max Lobo Hernández; Álvaro Álvarez Calderón (Costa Rica)*
- *Alejandro Jiménez Reyes; José Leandro Santos (Dominican Republic)*
- *Edgar Fernando Parra Cárdenas; Jose Luis Carrión (Ecuador)*
- *Carlos Enrique Figueroa; Wilfredo Amaya Zelaya (El Salvador)*
- *Óscar Cruz Ramos; Fernando Oroxan Sandoval (Guatemala)*
- *Rene Duesbury; Hilton Cheong (Guyana)*
- *Bruno Garayt; Alain Harmel (French Guyana)*
- *Luis Alberto Cruz (Honduras)*
- *Enrique Muñoz Goncen, Francisco Medina (Mexico)*
- *Wilmer Medrano Silva, Ramón Aviles Aburto (Nicaragua)*
- *Javier Cornejo, Melquiades Dominguez (Panama)*
- *Daniel Ariar, Joel Roque Trinidad (Paraguay)*
- *Julio Enrique Llanos Alberca, Julio Sáenz Acuña (Peru)*
- *Daniel Piriz (Uruguay)*
- *Dana J. Caccamise II, Daniel R. Roman (USA)*
- *Jose Napoleón Hernández, Melvin Jesús Hoyer Romero (Venezuela)*

SIRGAS Scientific Council

- *Denitzar Blitzkow (Brazil)*
- *Laura Sanchez (Germany)*
- *Hermann Drewes (Germany)*
- *Claudio Brunini (Argentina)*
- *M. Virginia Mackern (Argentina)*
- *Silvio Rogerio Correia de Freitas (Brazil)*
- *Melvin Jesús Hoyer Romero (Venezuela)*
- *Luiz Paulo Souto Fortes (Brazil)*

SIRGAS Working Group I

SIRGAS Working Group I (Reference System), also known as SIRGAS-WGI, is directly associated with the IAG Sub-commission 1.3b and it is responsible for coordinating the evaluation and processing of the continental geodetic network densifying the ITRF/IGS in Latin America to guarantee its long-term stability (i.e. ensuring the same quality over time) and uniform consistency (i.e. the same quality everywhere). To do this, a primary line of action is the regular processing of the SIRGAS continuous operation network (SIRGAS-CON) by applying criteria attached to standards and conventions on high-quality GNSS data processing. The general structure of SIRGAS-WGI is outlined in the following chart.



SIRGAS Working Groups

The coordinators of the SIRGAS-WGI activities are:

- *Chair of the SIRGAS-WGI, Jose Antonio Tarrío (Chile)*
- *Coordinator of the SIRGAS-CON Network, Alberto da Silva (Brazil)*
- *Coordinator of the SIRGAS-CON Network Combination, Jesarella Inzunza (Chile)*
- *Coordinator with IGS, Laura Sánchez (Germany)*

During the period 2021-2023 two additional CRI-PER processing centers have been established. Currently there are 10 official SIRGAS-WGI processing centers as follows:

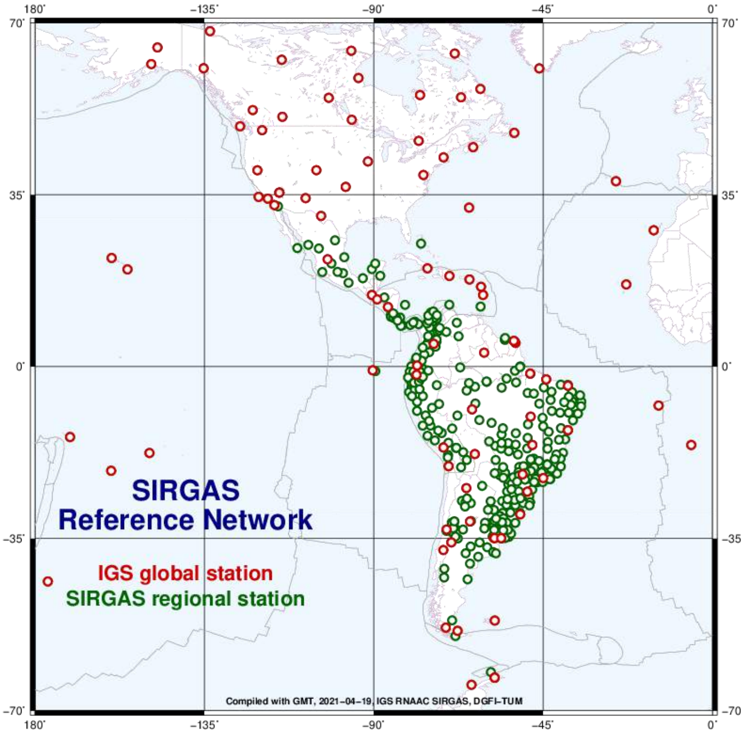
- Centro de Procesamiento de Datos GNSS del Ecuador (CEPGE) del Instituto Geográfico Militar (IGM, Ecuador).
- Centro de Procesamiento y Análisis Geodésico de la Universidad de Santiago de Chile (USC).
- Instituto Brasileiro de Geografía e Estatistica (IBGE, Brasil).
- Instituto Geográfico Agustín Codazzi (IGAC, Colombia).
- Instituto Geográfico Militar (IGM, Chile).
- Instituto Geográfico Militar (IGM, Uruguay).
- Instituto Geográfico Nacional (IGN, Argentina).
- Instituto Geográfico Nacional (IGN, Perú).
- Instituto Nacional de Estadística y Geografía (INEGI, México).
- Instituto Geográfico Nacional (IGN, Costa Rica)

Activities during the period 2019-2021

During the period 2019-2021, the following achievements associated with maintaining the SIRGAS' geodetic reference frame were obtained:

Network Processing

In 2020, SIRGAS incorporated 27 new GNSS stations, reaching close to 400 continuous stations (SIRGAS-CON) by the end of the year, of which 67 are included in the International GNSS Service (IGS) solution. This network realises the region's geodetic reference frame and is consistent with the International Terrestrial Reference Frame (ITRF). The network is operated and processed through the collaborative and continuous work of 13 data centres, 9 official processing centres, and two combination centres. Since august 2020 the Instituto Geográfico Nacional of Perú (IGN-PER) acts as a SIRGAS Experimental Processing Centre. With this new experimental processing centre, SIRGAS is approaching the goal of having a scientific GNSS processing centre in each region's country. Additionally, SIRGAS tropospheric products (tropospheric Zenith Path Delays (ZPD) with an hourly sampling rate) are computed by the SIRGAS Analysis Centre for the Neutral Atmosphere (CIMA), which is operated by the National University of Cuyo and UNCuyo / "Juan Agustín Maza" University.



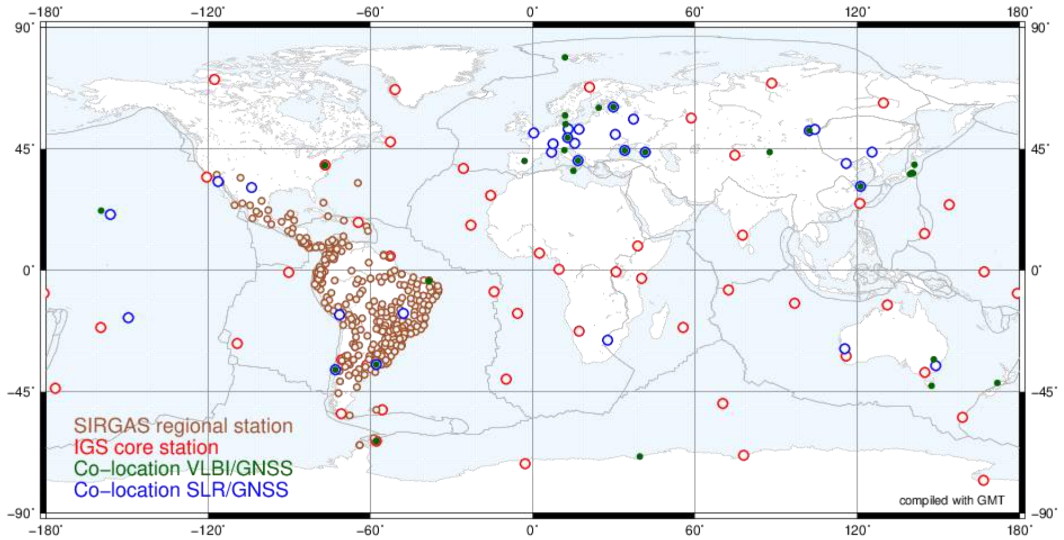
Current SIRGAS Reference Network with expansion to North-America

Reprocessing in ITRF2014

To ensure the reliability and stability of the SIRGAS reference frame, in November 2018, the IGS RNAAC SIRGAS (DGFI-TUM) started the reprocessing of the historical data of SIRGAS (from January 2000 to July 2020) using IGS14 (ITRF2014) as the reference frame with antenna model igs14.atx and satellite orbits and clocks in IGS14 set by the Jet Propulsion Laboratory (JPL) of NASA.

Together with the 500 (approximately) SIRGAS stations, IGS global stations co-located with VLBI and SLR were added to support the SIRGAS initiative involving SLR data in the Implementation of the reference frame. This initiative started with a workshop at the SIRGAS2017 Symposium (Mendoza, Argentina) and continued making progress at a second SLR workshop at the SIRGAS2019 Symposium (Rio de Janeiro, Brazil). Further details in

Sánchez L. (2020). SIRGAS Regional Network Associate Analysis Centre Technical Report 2019. Villiger A., Dach R. (eds.) International GNSS Service: Technical Report 2019, 125-136, 10.7892/BORIS.144003.



GNSS network configuration for the combination of GNSS, SLR, and VLBI normal equations in the realisation of a geocentric geodetic datum in the regional reference frame SIRGAS. VLBI/GNSS (green dots) and SLR/GNSS (blue circles) co-located stations are necessary for the normal equation combination. IGS core stations (red circles) are necessary for a high-quality GNSS data processing

SIRGAS stations included in ITRF2020

The IGS started, in mid-2019, the third reprocessing of its network (1994 - 2020), applying the updated standards and conventions for determining a new version of the ITRF (ITRF2020). The IGS RNAAC SIRGAS (DGFI-TUM), by mutual agreement with the managers/owners of some SIRGAS stations, proposed to the IGS adding 30 additional SIRGAS stations for the region to have available more reference stations for the calculation of the regional frame. The IGS RNAAC SIRGAS (DGFI-TUM), in agreement with the managers/owners of some SIRGAS stations, proposed to IGS add more than 30 SIRGAS stations to the region has more fiducial stations to calculate the regional frame.

National densifications of SIRGAS

In the 2019-2021 period at the national level, several activities were reported, among which the installation of several GNSS stations in Ecuador and Colombia stand out. The Instituto Geográfico Militar of Ecuador (ECU), through resolution No. 2019-037-IGM-JUR dated Dec 20, 2019, was resolved to adopt the Geocentric Reference System for the Americas (SIRGAS), in replacement of the PSAD56 Local Reference System, in order to provide support to cartographic and positional work in the country. In addition, 7 conversion parameters were made official for the transformation between systems. This resolution can be found together with several legal documents generated by the IGM(ECU) through the following link: *http://www.geoportaligm.gob.ec/wordpress/?page_id=511*

The Instituto Geográfico Agustin Codazzi in Colombia(IGA) densified its network in 15 stations to improve the geodetic infrastructure and the service provided to the community in general.

The Servicio Nacional de Geología y Minería de Chile, together with the geodetic analysis and processing centre of the University of Santiago, carried out the calculations and studies for the change from classical to modern datum (SIRGAS) in its mining cadastre. The above generates the first framework non-static reference for Chile; its name is REDGEOMIN(Red Geodésica para Minería) with EPSG CODE equal to 9694.

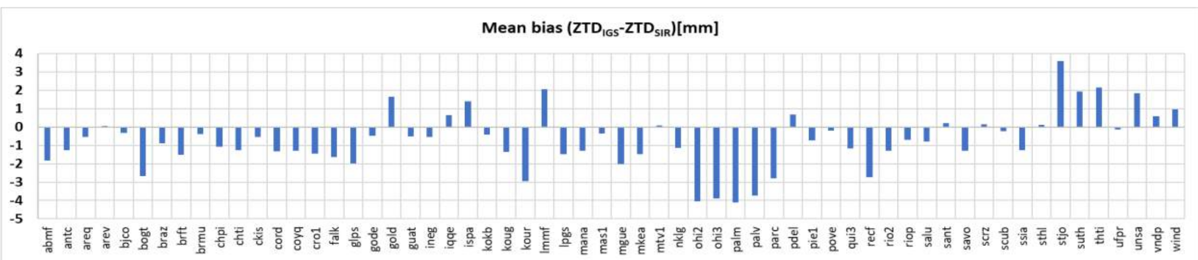
New GNSS stations in Ecuador and Colombia

Tropospheric Products in the GNSS SIRGAS Network

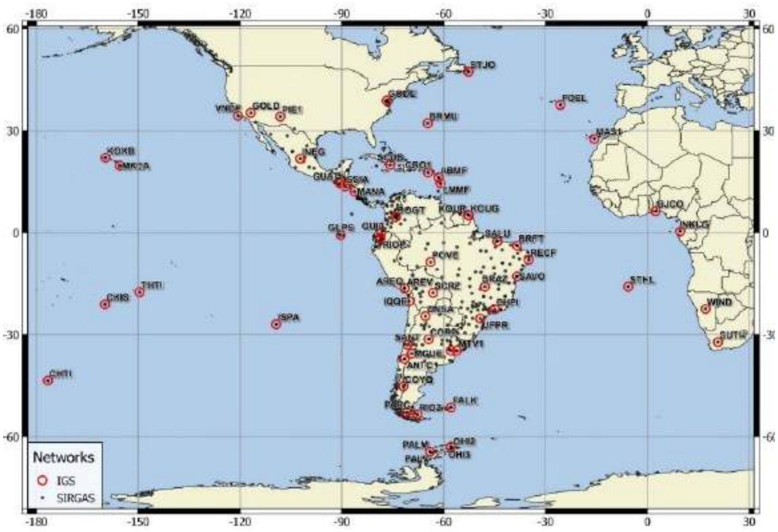
Within the SIRGAS Continuously Operating Network (SIRGAS-CON) weekly processing, Latin-American Analysis Centres operationally estimate tropospheric Zenith Total Delays (ZTD) with an hourly sampling rate. These ZTD are the input data for the weekly SIRGAS combined tropospheric products, computed by the Analysis Centre for the Neutral Atmosphere (CIMA). The Internal precision of SIRGAS final ZTDs is 1mm. They are generated and available in daily SINEX TRO files since January 2014, with a latency of 30 days. They can be downloaded from ftp://ftp.sirgas.org/pub/gps/SIRGAS-ZPD/.

ZTD_{SIRGAS} validation concerning IGS products

A comparison was made between the tropospheric products of SIRGAS (ZTD_{SIR}) and the corresponding ones of the IGS (ZTD_{IGS}) in 60 stations for a period of 7 years (2014 to 2020). The differences between both parameters (ZTD_{IGS}-ZTD_{SIR}) were calculated for each epoch, and the mean values of such differences (bias) were calculated. The Mean Bias resulted 0.76 mm with 6.6 mm of mean RMS.



Mean bias (ZTD_{IGS}-ZTD_{SIR}) for 60 GNSSSIR stations/IGS stations over a period of 7 years

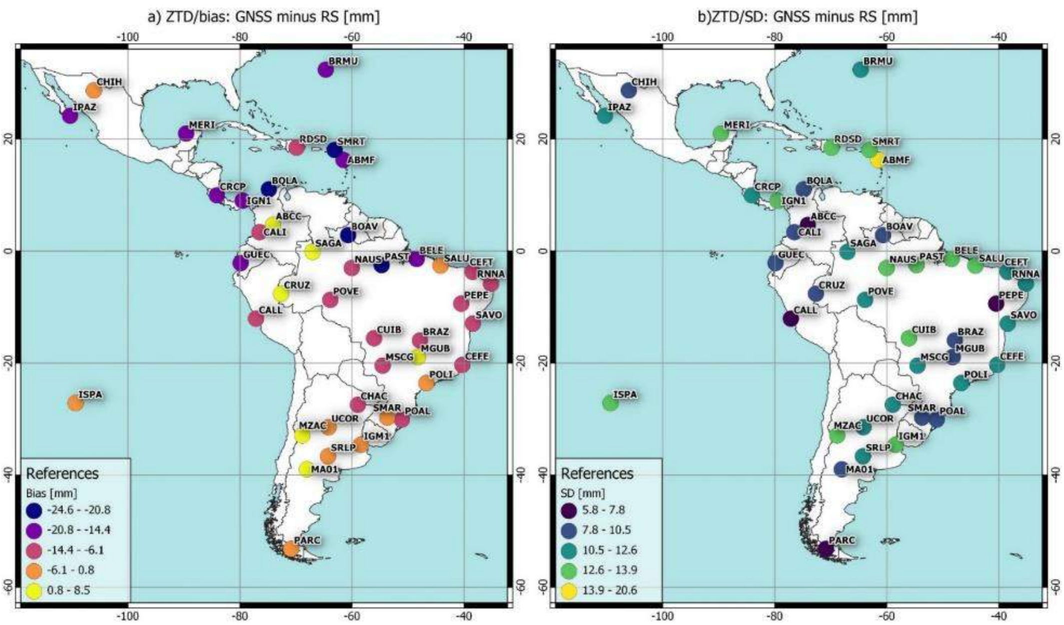


GNSS$_{SIR}$ stations / IGS stations (distributed in different regions)

ZTD$_{SIRGAS}$ validation concerning Radiosonde data

Another comparison was made between the ZTD$_{SIR}$ and the corresponding calculated from the Radiosonde data (ZTD$_{Rs}$). 42 GNSS$_{SIR}$ stations located within a maximum radius of 30 km from a radiosonde station were selected. This comparison could be performed for the 00 and 12 hrs UTC records due to limited availability of radiosonde records. The mean value and standard deviation were calculated as statistical indicators for the 7 years sampled. The mean bias resulted - 8.6 mm with a mean standard deviation of ± 11.4 mm, Mackern et al. (2021).

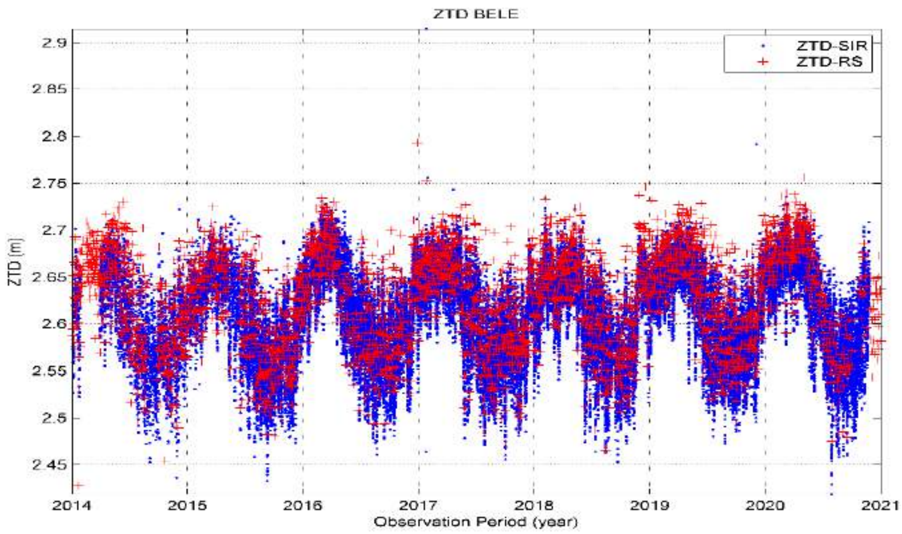
These results show that the ZTDs estimated at the SIRGAS-CON stations, distributed from South America, Central America, and the Caribbean region, are consistent throughout the region and provide reliable time series of troposphere parameters, which can be used as a reference in future research.



Mean bias (ZTD$_{SIR}$-ZTD$_{Rs}$), b) Mean Standard deviation for 42 GNSS$_{SIR}$ stations/RS over period of 7 years

Time series of ZTD_{SIRGAS} parameters

The ZTD final SIRGAS products are available from 2014, with an hourly interval, with a latency of 28 days. There is a corresponding ZTD time series, from 2014 (or since its incorporation) to date, for each of the SIRGAS-CON stations,



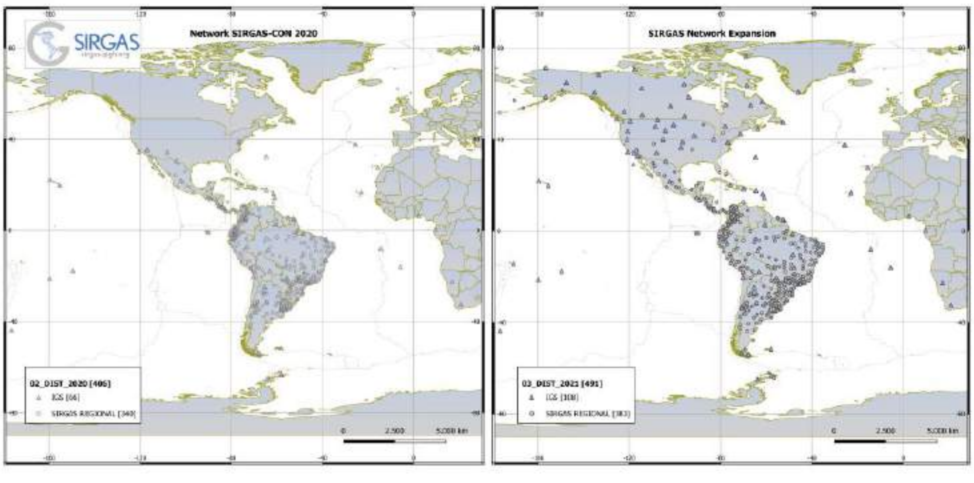
ZTD time series (2014-2020) from BELE, Brasil

Activities during the period 2021-2023

During the period 2021-2023, the following achievements associated with maintaining the SIRGAS' geodetic reference frame were obtained:

Expansion and redistribution of the SIRGAS Network

The network was extended to North America, adding new fiducial points, and the SIRGAS network was redistributed. The GNA-USC processing centers supported this extension, and DGF processes the SIRGAS-C network.



Current SIRGAS Reference Network with Expansion to North America

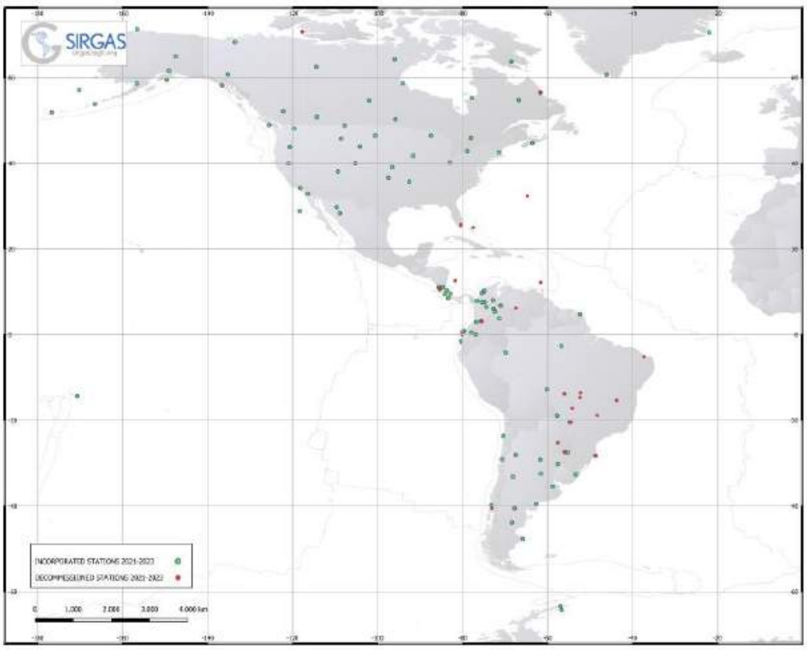
In summary, between 2021-2023 period, 108 stations were added, 23 stations were removed from the SIRGAS-CON network and 7 stations were added to IGS.

Incorporated stations 2021-2023 SIRGAS-CON Network.

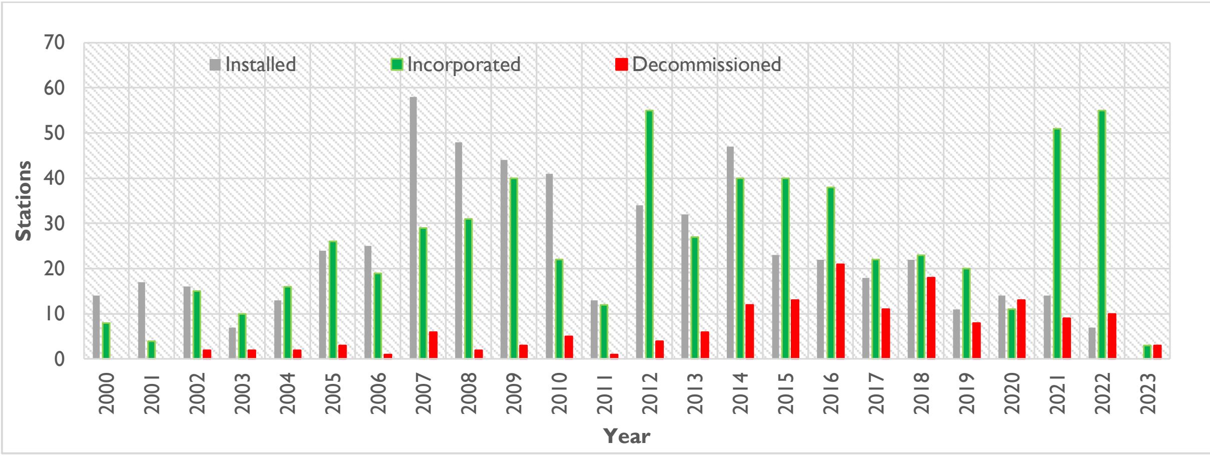
EBY100ARG, LROS00ARG, TOSF00ARG, SMDM00ARG, PELU00ARG, SICO00ARG, OBRA00ARG, ALTA00ARG, TGTA00ARG, PDE300ARG, MZAE00ARG, MBIO00ATA, SPRZ00ATA, PUS200BOL, ROVI00BRA, SCIM00BRA, MSGR00BRA, AMPT00BRA, AMTG00BRA, KUJ200CAN, IQAL00CAN, EUR200CAN, HLFX00CAN, BAKE00CAN, INVK00CAN, SCH200CAN, DUBO00CAN, WHIT00CAN, FLIN00CAN, UCLU00CAN, WILL00CAN, CHUR00CAN, PRDS00CAN, YELL00CAN, ALGO00CAN, TEJA00CHL, CMPN00CHL, ANTF00CHL, SDTA00COL, SUAN00COL, LIPA00COL, SOCB00COL, TARZ00COL, EBPT00COL, SUES00COL, SJNE00COL, SONE00COL, RUBI00COL, APTO00COL, BERR00COL, YOPA00COL, LBRA00CRI, PJMZ00CRI, CAPO00CRI, QUEP00CRI, BRBR00CRI, CHLS00CRI, LCRZ00CRI, LAEC00ECU, ESEC00ECU, PIEC00ECU, MUEC00ECU, JNEC00ECU, SCOR00GRL, QAQ100GRL, THU200GRL, CYNE00GUF, YESX00MEX, USMX00MEX, GUAX00MEX, UYBU00URY, UYRB00URY, TMG200USA, UTQI00USA, P80200USA, AC5800USA, P77700USA, P38900USA, AC4300USA, AB4300USA, P05300USA, ACSO00USA, AC2400USA, KSU100USA, AB2100USA, P01200USA, P04300USA, P05100USA, MIMQ00USA, AV0900USA, BFNY00USA, SG2700USA, NIST00USA, BREW00USA, ASPA00USA, SGPO00USA, ATW200USA, MONP00USA, JPLM00USA, NLIB00USA, WES200USA, FAIR00USA, QUIN00USA, FLF100USA, HOLM00CAN, NAIN00CAN, AEPL00COL, GUUG00GUM.

Decommissioned stations 2021-2023 SIRGAS-CON Network.

GRE100GRD, OSOR00CHL, MSCG00BRA, GUUG00GUM, MTNM00BRA, MTIT00BRA, EBYP00ARG, AEPL00COL, CANO00COL, IMBT00BRA, NAS000BHS, JAMG00BRA, MTNX00BRA, RNMO00BRA, UBE100BRA, LIBE00CRI, BRMU00GBR, ANDS00COL, HOLM00CAN, NAIN00CAN, FLF100USA, MTCN00BRA, PAEC00ECU.



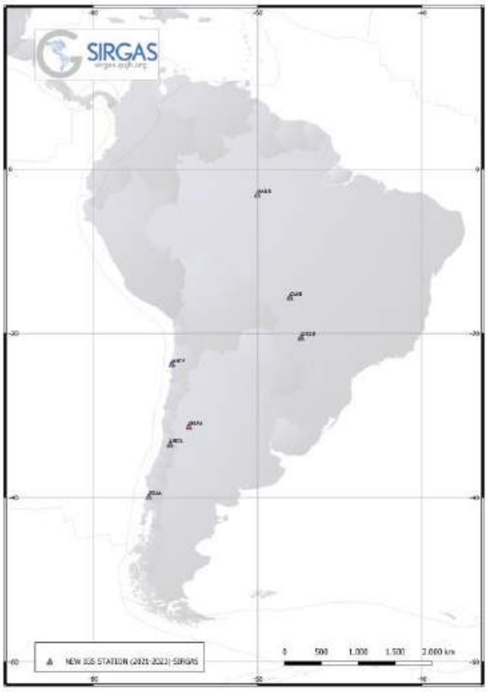
New stations SIRGAS and decommissioned stations (2021-2023)



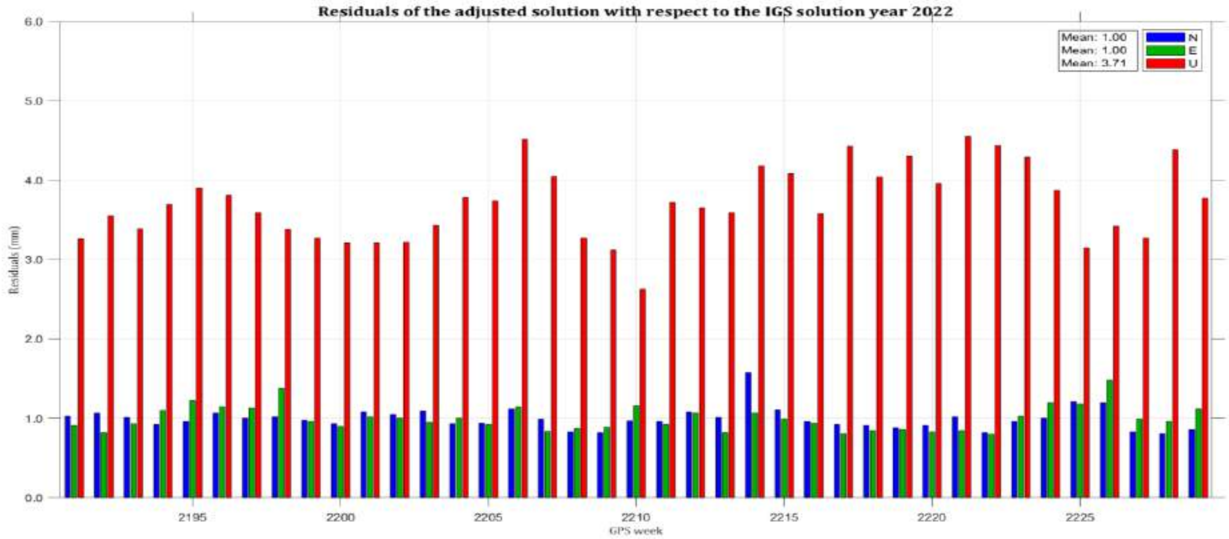
Time evolution of SIRGAS network

<u>Incorporated stations 2021-2023 IGS Network</u>
USCL00CHL, ANTF00CHL, OAFA00ARG, TEJA00CHL, CUIB00BRA, NAUS00BRA, MSCG00BRA.

Currently, the consistency of the network is as follows: the internal accuracy of the SIRGAS-CON network is set at 1.0 mm, 1.0 mm, and 3.0 mm in E, N, and U, respectively. The external accuracy of the SIRGAS-CON network, ITRF(IGS) densification, is set at: 2.0 mm, 2.0 mm, and 5.5 mm in E, N, and U, respectively.



New stations IGS (2021-2023)



External consistency of the SIRGAS-CON network

Updating technical guidelines

A coordination figure with the IGS was created. The SIRGAS guidelines were revised and updated in conformity with the IGS and IERS guidelines. The new guidelines are outlined below:

GUIDE01: COORDINATION OF THE SIRGAS-CON NETWORK
This document describes the functional organization chart of the SIRGAS-CON network, establishing the responsibilities and obligations of all the organizations involved and the coordination and the people in charge of them (Tarrío Mosquera, Costa, et al., 2021a).

GUIDE02: INSTALLATION, OPERATION, AND REGISTRATION OF SIRGAS-CON STATIONS
This document establishes the indications to install, operate and register a station in the SIRGAS-CON geodetic network (Tarrío Mosquera, Costa, et al., 2021b).

GUIDE03: PROCESSING OF SIRGAS-CON ANALYSIS CENTERS
This document provides guidelines for processing GNSS observations at the SIRGAS Analysis Centers (Official Processing Centers, Experimental Processing, and Combination Centers) for weekly processing of the SIRGAS-CON network (Tarrío Mosquera, Sánchez, et al., 2021).

Grid transformation between SIRGAS95, SIRGAS2000 and SIR17P01 solutions

A transformation grid between the SIR95, SIR2000, and SIR17P01 solutions is calculated to provide a transformation tool between the 3 SIRGAS realizations for use in geodetic and geomatics projects, which will be distributed together with an application guide. (Tarrío Mosquera, Inzunza, et al., 2021)

Geodetic Infrastructure, processing, and analysis

Geodetic infrastructure (data and metadata) consulting services were provided to HDN, VEN, CRI, and USA, in addition to a workshop on the new SIRGAS guidelines for geodetic infrastructure, processing, and analysis. Perú (PER) is included as official center as of week 2191.

IBGE and IGS-RNAAC-SIR analysis of the weekly combined weights and monitoring of the weekly solutions of all the centers. Meetings with IGS CAs about REPRO3 and GAL processing parameters and analysis of the distribution.

SIRGAS2022: the latest SIRGAS reference frame solution

SIRGAS2022 is based on the SIRGAS-Repro2 SINEX product series and includes the weekly normal equations between January 2000 (GPS week 1043) and March 2022 (GPS week 2200). SIRGAS2022 contains 573 stations with 1302 occupations. It includes post-seismic approximations for the first time in a SIRGAS reference frame solution. The SIRGAS2022 station positions refer to the IGb14 reference frame and are given at the epoch 2010.0. Their accuracy is estimated to be ±0.8 mm in N/E and ±1.8 mm in h at the reference epoch. The accuracy of the velocities is estimated to be ±0.6mm/year in N/E and ±1.0mm/year in U; for more details see (Kehm et al., 2022)

Training

- "Determination of accurate geodetic reference frames accurate geodetic reference frames, using the scientific processing software GPS/GNSS GAMIT/GLOB-K."
- Workshop "Vertical Reference Systems."
- Workshop "Heights and Gravity Systems."
- Workshop "Installation and operation of permanent GNSS stations: how to include them in SIRGAS-CON."
- GNSS processing capabilities update.
- Updating of processing standards to be included in IGS20. IGb14/IGS20 transition.
- In July 2023, the eighth SIRGAS School in Reference System was held in Costa Rica. The school covered reference systems and frames, GNSS processing in scientific software, network adjustment, and altitude system.

New CRDA (Alternate Regional Data Center) - Universidad de Santiago de Chile-USC

According to the SIRGAS Executive Committee meeting held on January 5, 2023, it was unanimously agreed to create an Alternate Regional Data Center (CRDA), which serves as a backup to the DGFI Regional Data Center (CRD)-TUM (Deutsches Geodätisches Forschungsinstitut, Technische Universität München, Germany), to collect and store the observations (RINEX files) from SIRGAS-CON stations, using these data for network reprocessing when necessary. The CRDA is currently located at the University of Santiago de Chile- USC; To make the transfer of information effective, the request and authorization were made to the different National Data Centers for the transfer of data and metadata related to the stations owned by them.

The Alternative Regional Data Center resources are as follows:
NAS/QNAP:

- Capacity of 8 or more disks
- Total storage of at least 50 TB
- Raid 5 or Raid 6 storage configuration
- Processor

Currently, 819539 files have been transferred, corresponding to 402 stations (766 GB).

Processing Centers

Restart activities of Real-Time SIRGAS group, responsible Daniel Cisneros (comments Melvin Hoyer) and Costa Rica (CRI) is included as official center as of week 2243.

Actions to be agreed (2023)

- Repro 3 SIRGAS
- Inclusion of GAL constellation processing of the SIRGAS-CON network.
- PSD - ERF.

SIRGAS Working Group III

SIRGAS Working Group III (Vertical datum), also known as SIRGAS-WGIII, was established during the IAG Scientific Assembly in Rio de Janeiro in 1997. Its main objectives are to define a modern unified vertical reference system for SIRGAS, to establish the corresponding reference frame, and to transform the existing classical height datums into the new system. As a fundamental SIRGAS-WGIII activity, a diagnostic of the current height datum was carried out. The main conclusions are:

- The reference level of the American height datums is realized by the mean sea level registered at individual tide gauges over different periods, i.e., they refer to different epochs,
- The vertical networks were extended over each country using mainly spirit leveling methods, but in general, the leveled heights have not been corrected by the gravity effects,
- They do not take into account the variation of heights and reference levels with time, i.e., they are static, and therefore
- These vertical datums present big discrepancies between neighboring countries, do not permit data exchange on a continental or global scale, and need to be able to support practical height determination with GNSS techniques in combination with precise geoid models.

The coordinators of the SIRGAS-WGIII activities are:

- *Chair of the SIRGAS-WTIII, do Nascimento Guimarães (Brazil)*
- *Geopotencial Models Coordinator, Ayelen Pereira (Argentina)*
- *Gravimetric Network Coordinator, Ezequiel Antokoletz (Germany)*
- *Geoid Models Coordinator, Ana Cristina O. C. de Matos (Brazil)*
- *Coordinator Spirit-Levelling Networks, José Luis Carrión Sánchez (Ecuador)*

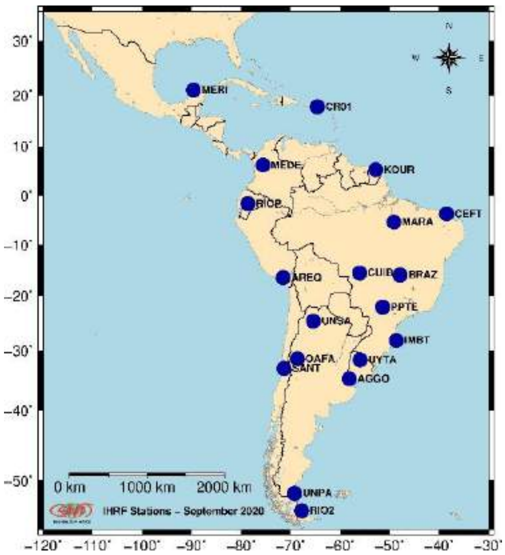
Activities during the period 2019-2023

During the period 2019-2021, the following achievements were obtained in relation to the SIRGAS vertical datum:

Advances related to the International Height Reference Frame (IHRF)

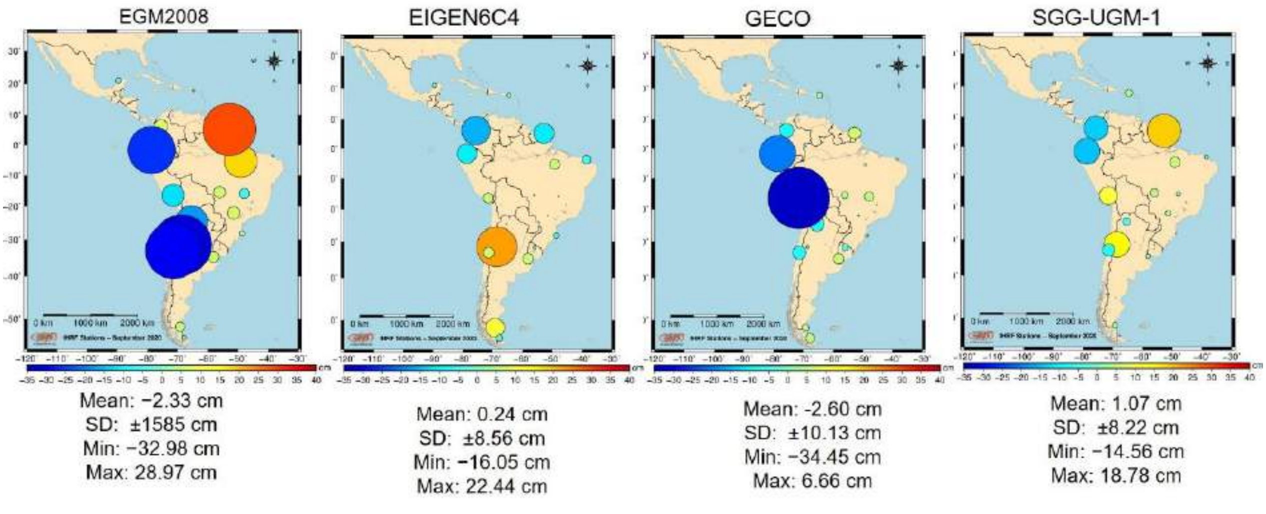
Concerning the SIRGAS Vertical Reference System (SVRS), there has been substantial progress made involving the incorporation of physical heights, the connection to the geometric components of SIRGAS, the integration of the national vertical networks, their links to the value of the reference potential W_0 of the IHRS, the definition for a specific epoch and the consistent connection with the ITRF.

In the context of the integration to the IHRS/IHRF, SIRGAS has proposed a set of 19 stations in Latin America and the Caribbean and has made progress in implementing these stations.



Proposal for IHRF stations in the region

A diagnostic analysis has been started in the IHRF stations based on the calculation of the potential values using the global gravity models (comparison with the XGM2019 model). This diagnosis is essential to consider which station(s) should be concentrated efforts in terms of studies and improvements of the gravimetric distribution.



Comparison of GGMs with XGM2019

Besides that, in 2021, the SIRGAS WG-III has been started the computation of geopotential values from the geoid or quasi geoid models available in the continent. Finally, the SIRGAS WG-III has been carrying out a scientific project together with the Technical University of Munich (TUM) called *Contributions of high-resolution gravity models in Latin America*. The goal of the project is to assess the geoid models and the levelling/GNSS stations available in Latin America using gravity field models of high resolution and of combining satellites to contribute to the potential calculation at the IHRF stations.

In the last four years, numerous investigations have been conducted by several scientists related to the objectives of SIRGAS-WGIII. Guimarães et al. (2022) presented preliminary results for computed geopotential values using Least Squares Collocation and Numerical Integration. In this study the geopotential model GOCO05s (n=m=200 and 100) was adopted as a reference gravitational field. Tocho et al. (2023) presented a preliminary computation of geopotential values based on the current official geoid model from Argentina, GEOIDE-Ar16. Currently, the first realization of the IHRS is in preparation by the IHRF working group, where these stations are included. In 2021, the SIRGAS Working Group III started computing geopotential values from the geoid or quasi-geoid models available in the continent. A meeting involving the GGOS Focus Area Unified Height System chair was carried out to plan the computation. Gómez et al. (2022) and Oliveira Cancoro de Matos et al. (2022) presented results regarding geopotential values in the Colorado Experiment. Ribeiro et al. (2022, 2023) inferred marine gravity data around IHRF stations in Brazil.

Besides the above activities, several countries have been dedicated to densifying the IHRF stations. For example, Colombia has scheduled for 2023 to measure 150 gravity points around the MEDE station. Ecuador has proposed that the RIOP station belongs to realizing the IHRS. In the last years, IGM/EC has collected around 500 gravity points. The CORS UYPT is the selected station to implement the IHRF in Uruguay. Four concentric circles contain a total of 106 densification stations. All those stations already have gravity and ellipsoidal height, and 67% have been connected to the vertical network. These surveys are planned to finish by the end of 2024.

Due to the objectives that SIRGAS carries out through its Working Group III to contribute to the development of regional geodesy, two technical guides on the International Heights Reference Frame (IHRF) have been published. The first document developed by Working Group III is called “Guidelines for IHRF station selection” and describes requirements and recommendations for selecting and implementing an IHRF station. The guide is aimed at institutions that already have a station planned in the calculation of the first IHRF implementation and at agencies that wish to propose new stations to integrate into the IHRF. The second document is entitled “Guidelines for performing gravimetric measurements around IHRF stations”. It describes the relevant requirements and recommendations for making land gravimetric measurements around IHRF stations using relative gravimeters.

WG GRFA: "Geodetic Reference Frame for the Americas"

The Authorities of SIRGAS coordinated the development of the Terms of Reference of the new UN: GGIM: America's working group naming "Geodetic Reference Frame for the Americas" (GRFA). These terms were approved through Resolution 2019/6 of the Seventh Session of UN-GGIM: Americas.

GRFA working group meeting

The main objectives of the GRFA are:

a) to support the Nations of the Americas so that they respond to the Global Geodetic Reference Frame for Sustainable Development (A/RES/69/266) resolution;
b) coordinate the efforts of the Member States to guarantee the sustainability and improvement of the regional geodetic reference frame, acting as a key facilitator of spatial data interoperability, the mitigation of hazards from disasters and sustainable development; and
c) to act as an interface between SIRGAS and the Member States to implement plans that push the development of the regional geodetic infrastructure, the geodetic reference frame of the Americas, and the geodetic capabilities of professional and technical specialists forwards. The Terms of Reference are published in the Spanish and English languages on the UN-GGIM:

   http://www.un-ggim-americas.org/assets/modulos/grupoTrabajo.html?grupo=3.

The Authorities of SIRGAS participated in the Eighth and Ninth Sessions of UN-GGIM: Americas contributing with strategic resolutions for geodesy in the region aligned to the resolution "A global geodetic reference frame for sustainable development," as follows:

Urging Member States of the Americas to implement open sharing of Global Navigation Satellite System (GNSS) data, to contribute to the GGRF and regional densifications through relevant national mechanisms and intergovernmental cooperation, and in coordination with SIRGAS.

Urging Member States to make the necessary efforts to link and align their national geodetic infrastructures towards the ITRF, IHRF, and ITGRF, to ensure the development, sustainability, and promotion of the GGRF.

Urging Member States and regional organizations relevant to supporting the strengthening of the Center of Excellence Global Geodetic (GGCE) of the United Nations, located in Bonn, Germany, and participate actively to guarantee the exchange of experiences and better practices that facilitate the implementation of the GGRF in the countries of the Americas and the Caribbean, as so also at world level.

WG GRFA supports the region's countries to include GNSS stations in the SIRGAS continuous operating network and height and gravity stations throughout the Americas and the Caribbean, with the objective of GGRF implementation in all member states.

Organised SIRGAS Symposia

The activities, advances, and new challenges of SIRGAS are reported, discussed, and evaluated in the annual SIRGAS Symposia, which have been held since 1993. During the period 2019-2023 SIRGAS organised the following annual symposia:

SIRGAS Annual Symposium 2019

In 2019, thanks to the kind invitation extended by the Brazilian Institute of Geography and Statistics (IBGE) and the Rio de Janeiro State University (UERJ), the SIRGAS Symposium was held in Rio de Janeiro, Brazil, between Nov 11 and 14, 2019. It was organised with the support of the International Association of Geodesy (IAG) and the Pan-American Institute for

Geography and History (PAIGH). In the frame of this Symposium, two additional activities were programmed:

1. "GGOS Days 2019" (Global Geodetic Observing System) was held simultaneously in the same venue and a joint session between the SIRGAS community and GGOS expert representatives was developed on Nov 12; and
2. The 2nd SLR (Satellite Laser Ranging) Workshop in Latin America took place from Nov 6 to 8, 2019. The main objective was to continue the integration between SIRGAS community (professionals and scientists) with the group of SLR experts. This effort was the continuation of actions initiated during the 1rst SLR SIRGAS workshop held in 2017 in Mendoza, Argentina; which aim was the promotion of the specialisation in the SLR technique, as well as data processing and its combination with GNSS (Global Navigation Satellite System) in the Latin American and international geodetic community context.


Participants to GGOS Days 2019

Participants of the SIRGAS Symposium 2019, IBGE Rio de Janeiro, Brazil, Nov 11-14

The SIRGAS Symposium 2019 was attended by 164 participants from 16 countries (Argentina, Austria, Bolivia, Brazil, Chile, Colombia, Costa Rica, Dominican Republic, Ecuador, Germany, Mexico, Panama, Spain, United States, Uruguay and Venezuela). The main topics addressed during the Symposium included SLR in Latin America, colocation techniques (4 presentations); Studies of the Atmosphere and analysis of the Earth System based on SIRGAS Infrastructure (18 presentations); SIRGAS-GGOS Session (18 presentations); the improvement and maintenance of the SIRGAS reference frame (12 presentations); practical applications aimed at the adoption of SIRGAS at the sub-regional and national level and Infrastructure SIRGAS in Real-Time (12 presentations); advances in SIRGAS Unified Vertical Reference System (9 presentations); gravity and geoid (12 presentations); and general reports (4 presentations). In total, 75 oral contributions and 18 posters were presented.

During the meeting of Directing Council held on Nov 13 2019, the results of the elections for president and vice president were reported, who formally assumed at the closing ceremony of the Symposium. Other issues discussed during this meeting will be available on the SIRGAS webpage, section "SIRGAS: Resolutions".

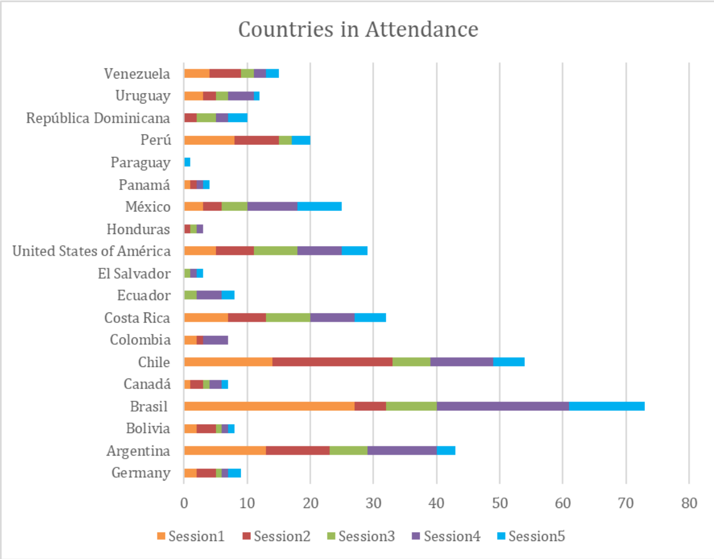
New SIRGAS Executive Committee: Sonia Costa from IBGE (Instituto Brasileiro de Geografia e Estatística) Brazil (president) and Diego Piñón from IGN (Instituto Geográfico Nacional) Argentina (vice president)

SIRGAS Annual Symposium 2020

Considering that all in-person activities in 2020 were cancelled due to the COVID-19 pandemic, SIRGAS promoted Webinars from May to September, 2020 with subjects related to geodetic activities in the region. The records and presentations from all Webinars are available on SIRGAS homepage (www.sirgas.org).

For October, SIRGAS organised a series of Webinars in the place of the annual SIRGAS Symposium, every Friday at 15:00 UTC. Each Webinar has 3 presentations with topics related to:

- Atmosphere studies and the Earth System analysis (Oct 2)
- SIRGAS reference frame's development and maintenance (Oct 9)
- Practical applications oriented to the adoption of SIRGAS at a sub-regional and national level (Oct 16)
- Height Systems (Oct 23)
- Gravimetry and geoid (Oct 30)



Attendees for each country at SIRGAS2000 symposium

The Directing Council and Working Groups meetings were organised in the week between 16 to Nov 19 at 2020. The new SIRGAS Statute was approved during the Directing Council meeting, with the approval of all SIRGAS members, including all countries in North America. During the Working Groups meetings were presented the new structures and coordinators of GT II and GT III and future work for 2021.

SIRGAS Annual Symposium 2021

Between November 29 and December 1, 2021, a new edition of the SIRGAS Symposium took place. The central purpose of the SIRGAS 2021 Symposium was to convene the geodetic community of the Americas and the Caribbean to exchange experiences and progress, as well as formulate new projects related to the implementation, maintenance, and use of the region's reference geodetic infrastructure.

Due to the CoVID-19 pandemic, the SIRGAS 2021 Symposium was held virtually and transmitted through the Zoom platform. The event was free to participate in, and there was a simultaneous translation service into English and Spanish.

The organization of the SIRGAS 2021 Symposium was under the coordination of the Local Organizing Committee, which comprised the SIRGAS Executive Committee and representatives of the National Geographic Institute of Peru. As previously, it has the valuable support of the International Association of Geodesy and the Pan American Institute of Geography and History.

The symposium had the participation of more than 150 attendees from countries of the Americas and Europe. 24 oral presentations and 29 posters were presented and can be consulted on the SIRGAS website https://sirgas.ipgh.org/eventos-sirgas/simposios/

SIRGAS Annual Symposium 2022

The 2022 SIRGAS Symposium was held between November 7th and 9th, 2022, in Santiago, Chile, in hybrid mode. Following the new SIRGAS events´ regulation, this symposium had a simultaneous translation service between the English and Spanish languages during the technical sessions and the SIRGAS Working Groups meetings.

The organization of the 2022 SIRGAS Symposium was under the coordination of the SIRGAS Executive Committee and the Local Organizing Committee, the Instituto Geográfico Militar (IGM) of Chile. As previously, it had the valuable support of the International Association of Geodesy (IAG) and the Pan-American Institute of Geography and History (PAIGH).

Participants of the SIRGAS 2022 Symposium, IGM-Chile, Santiago, Chile, November 7th to 9th, 2022

The symposium's technical sessions had 59 presentations from the following countries: Germany, Argentina, Canada, the United States, Costa Rica, Colombia, Brazil, Ecuador, Bolivia, Chile, and Uruguay. There was an attendance average of 90 participants onsite and 130 remotes. All Symposium presentations are available at https://app.ign.gob.pe/simposio/programacion/. Five technical sessions were held during these three days, and the main topics addressed were:

Session 1: Report of the SIRGAS authorities: President of SIRGAS, Presidents of the SIRGAS Working Groups, and update of the GRFA of UN-GGIM: Americas.

Session 2: Development and maintenance of the SIRGAS reference framework.

Session 3: Modeling the Earth's gravity field (geoid, gravimetry, international reference system of heights).

Session 4: Applications of the SIRGAS framework (national reports, real-time applications, etc.).

Session 5: SIRGAS contributions to the modeling of the Earth System (troposphere, ionosphere, seismology, oceanography, and hydrography).

The next symposium will be in 2024 and will be held in Bogotá, sponsored by the Agustín Codazzi Geographic Institute.

Other organized meetings

SIRGAS regularly organizes courses, workshops, and webinars to promote knowledge and constant learning. The following meeting activities were carried out during the period 2019-2023.

Workshop SLR SIRGAS 2019

The 2nd SLR Workshop in Latin America was attended by 25 participants from 8 countries (Argentina, Brazil, Colombia, Costa Rica, Ecuador, Peru, Uruguay, and Venezuela). It was organised as an activity of the SIRGAS Working Group I. On this occasion, the instructor was Dr. Daniela Thaller from the BKG, Germany. The SIRGAS Executive Committee thanks the BKG for the possibility of Dr. Daniela Thaller qualifying SIRGAS community in the SLR data processing and analysis.

Participants of the 2nd SIRGAS SLR Workshop, IBGE, Rio de Janeiro, Brazil, November 6 to 8, 2019

International Workshop for the Implementation of the Global Geodetic Reference Frame

The International Workshop for the Implementation of the Global Geodetic Reference Frame in Latin America was held in Buenos Aires, Argentina, from Sep 16 to 20, 2019. This workshop is a capacity building activity of the project "Implementation of the United Nations' Resolution on the Global Geodetic Reference Frame (UN-GGRF) for Sustainable Development in Latin America" of the International Union of Geodesy and Geophysics (IUGG) within the special grants program to celebrate in 2019 the centennial year of the IUGG foundation. The International Association of Geodesy (IAG) is the primary applicant of this project, and the International Association of Seismology and Physics of the Earth's Interior (IASPEI) and the IUGG National Committees of Argentina, Brazil, Chile, Colombia, and Costa Rica supported it. In addition to the IUGG, IAG, and IASPEI support, the workshop counted on the sponsorship of the International Committee on Global Navigation Satellite Systems (ICG) of the United Nations Office for Outer Space Affairs (UNOOSA). Twenty-eight travel awards for colleagues from fourteen Latin American countries were covered with the money granted by the IUGG. ICG-UNOOSA provided six flight tickets for colleagues from Colombia, Peru, Chile, Brazil, Costa Rica, and Ecuador. The Instituto Geográfico Nacional (IGN) of Argentina and the Argentine-German Geodetic Observatory (AGGO) organised the logistics needed for the successful realisation of the meeting. The support of IUGG, ICG-UNOOSA, IGN, AGGO and all the experts participating in the workshop is highly appreciated.

In total, 130 participants from 20 countries (Argentina, Australia, Bolivia, Brazil, Chile, China, Colombia, Costa Rica, Dominican Republic, France, Germany, Guatemala, Italy, Mexico, Panama, Paraguay, Peru, United States of America, Uruguay, and Venezuela) attended the workshop. With 52 presentations distributed in eight sessions, the meeting brought together politics, international organisations promoting science, the highest level of expertise in Geodesy worldwide, and regional specialists in Geodesy. Jointly, they could provide the Latin American colleagues responsible for the national geodetic reference frames, the scientific and political arguments to convince policymakers about the necessity of investing in geodetic and geophysical infrastructure in their countries.

Participants to the International Workshop for the Implementation of the Global Geodetic Reference Frame (GGRF)

This workshop convened for the first time politics (UN-GGIM, UN-GGIM Subcommittee on Geodesy, GEO, ICG-UNOOSA), international organisations promoting science (ICS, IUGG, IAG, IASPEI, FIG, PAIGH), the highest level of expertise in Geodesy worldwide (IAG, IAG Services, GGOS), and regional specialists in Geodesy (SIRGAS, gravity field modelling, geodetic observatories) to identify appropriate strategies to make real the objectives of the UN-GGRF initiative. The topics presented along the five days and the conclusions/recommendations arising from the discussions surely represent the appropriate start point to face the required activities to advance in the establishment of the GGRF in Latin America. Presentations, a list of participants and conclusions of the workshop are available at *http://www.sirgas.org/en/ggrf/*. Laura Sánchez (Deutsches Geodätsiches Forschungsinstitut Technische Universität München, Germany) and Claudio Brunini (Science Director of AGGO) were in charge of carrying out the event.

SIRGAS School on Reference System

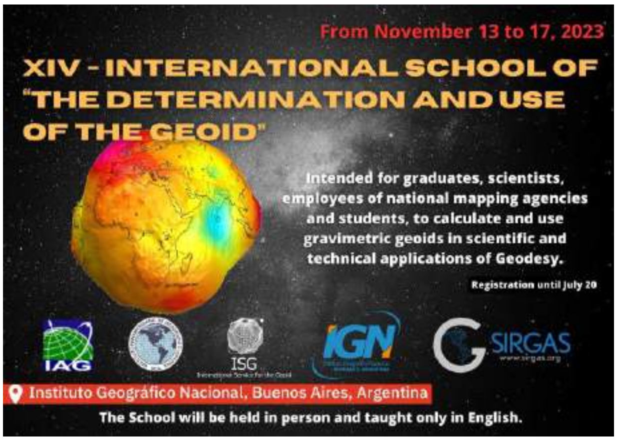
The 8th SIRGAS School on "Reference System" will be held from July 3 to 7, 2023. The School will occur at the University of Costa Rica and the National University of Costa Rica, in San José and Heredia, Costa Rica. In this opportunity, attendance will be in person, and SIRGAS Working Group Presidents will be responsible for the lectures.

The five-day course will cover the fundamental topics of physical and geometric geodesy and is aimed at advanced professionals, young scientists, and employees of national mapping agencies. The lectures will be divided into two blocks: theoretical (two and a half days) and practical (two and a half days). The instructor will impart GPS/GNSS network processing and adjustment topics during the practical block with BERNESE and GAMIT/GLOBK packages.

International School on The Determination and Use of the Geoid

From November 13 to 17, 2023 will be held the 14th International School on "The Determination and Use of the Geoid." The School will occur at the Instituto Geográfico Nacional in Buenos Aires, Argentina. The general purpose of the full-week intensive Geoid School is to prepare new graduate students, young scientists, and employees of national agencies to compute and use gravimetric geoids for scientific and technical applications in Geodesy. The School provides an excellent opportunity to familiarize with the latest geoid determination development and improve international contacts and collaborations among scientists dealing with gravity field modeling. In addition, the scientific community must be linked to the Cartographic Agencies responsible for implementing the Global Geodetic Reference Frame - GGRF in the country so that the research carried out in the scientific framework can be applied to develop regional and local geodesy.

The Geoid school will be organized in cooperation with the International Service for the Geoid of the International Association of Geodesy, and it is supported by the International Association of Geodesy and the Pan-American Institute of Geography and History (PAIGH).



International School on The Determination and Use of the Geoid

Several other workshops and webinars took place during the period 2021-2023 which are listed below:

2021

El nuevo Sistema de Referencia Internacional de Gravedad (IGRS) y su materialización (IGRF). H. Wziontek, Federal Agency for Cartography and Geodesy (BKG), Alemania; S. Bonvalot, International Gravimetric Bureau (BGI), Francia; E.D. Antokoletz, Facultad de Ciencias Astronómicas y Geofísicas –Universidad Nacional de La Plata, Argentina; Consejo Nacional de Investigaciones Científicas y Técnicas (CONICET), Argentina; Federal Agency for Cartography and Geodesy (BKG), Alemania. Webinar SIRGAS, 2021-03-05. Presentation also available in YouTube.

Venezuela, apuntando al restablecimiento del sistema geodésico nacional. Departamento de Ingeniería Geodésica y Agrimensura, Universidad Central de Venezuela. Webinar SIRGAS: Actividades Geodésicas en las Americas, 2021-07-29. Presentation also available in YouTube.

La red geodésica nacional: Un servicio continuo y esencial para la planeación y el desarrollo territorial en Colombia, Subdirección de Geografía y Cartografía, Instituto Geográfico Agustín Codazzi – IGAC. Webinar SIRGAS: Actividades Geodésicas en las Americas, 2021-07-09. Presentation also available in YouTube.

2022

Workshop on Reference Frames, H. Drewes, Universidad Técnica de Munich, Alemania, Representante de la Asociación Internacional de Geodesia en el Consejo Directivo y Miembro del Consejo Científico de SIRGAS. Webinar SIRGAS, 2022-02-07. The presentation is also available on YouTube.

Workshop Height systems and Gravity: Nivelación, números geopotenciales y la evaluación y propagación del IHRF. R. T. Luz, Instituto Brasileiro de Geografia e Estatísticas, Brasil. Webinar SIRGAS, 2022-05-06. Presentation also available in YouTube.

Workshop Height systems and Gravity: Definición del Sistema de Referencia Internacional de Gravedad (IGRS) y su materialización. E.D. Antokoletz, Facultad de Ciencias Astronómicas y Geofísicas – Universidad Nacional de La Plata, Argentina; Consejo Nacional de Investigaciones Científicas y Técnicas (CONICET). Webinar SIRGAS, 2022-05-05. Presentation also available in YouTube.

Workshop Height systems and Gravity: Gravimetría y Geoide en la región SIRGAS. D. Blitzkow, Centro de Estudos de Geodesia – CENEGEO, Brasil, Universidade de São Paulo, Brasil; A.C.O.C de Matos, Centro de Estudos de Geodesia – CENEGEO, Brasil. Webinar SIRGAS, 2022-05-04. The presentation is also available on YouTube.

Workshop Height systems and Gravity: Estado del IHRF en la región SIRGAS. G. N. Guimarães, Universidade Federal de Uberlândia, Brasil. Webinar SIRGAS, 2022-05-03. The presentation is also available on YouTube.

Workshop Height systems and Gravity: Sistema internacional de altitudes: definición (IHRS), realización (IHRF), estado actual. L. Sánchez, Technische Universität München, Alemania. Webinar SIRGAS, 2022-05-02. Presentation also available in YouTube.

Workshop "Installation and operation of permanent GNSS stations. How to include them in SIRGAS-CON?": Inclusion of SIRGAS-CON stations in the IGS (products and reference network). L. Sánchez, Technische Universität München, Alemania. Webinar SIRGAS, 2022-08-31. The presentation is also available on YouTube.

Workshop "Installation and operation of permanent GNSS stations. How to include them in SIRGAS-CON?": Evaluation of data and metadata from GNSS stations. Procedure for the inclusion of stations in the SIRGAS-CON Network. J.A. Tarrío, J. Inzunza, Universidad Santiago de Chile, Santiago de Chile. Webinar SIRGAS. 2022-08-30. The presentation is also available on YouTube.

Workshop "Installation and operation of permanent GNSS stations. How to include them in SIRGAS-CON?": Basic steps about receiver configuration. S. Costa, Instituto Brasileiro de Geografia e Estatísticas, Brasil. Webinar SIRGAS. 2022-08-29. The presentation is also available on YouTube.

Workshop "Installation and operation of permanent GNSS stations. How to include them in SIRGAS-CON?": Steps and details on the installation of a permanent GNSS station. A.

Zaino, UNAVCO – US. Webinar SIRGAS. 2022-08-26. The presentation is also available on YouTube.

Workshop "Vertical Reference System." Guimarães, H. Guagni, November 2 - 4, 2022. Santiago de Chile, Chile.

Outreach activities

During the 2019-2023 period, SIRGAS has carried out different outreach events, and also participated in the following international conferences:

2019

Report from developing countries Americas and Caribbean Region. S. Costa. International Association of Geodesy (IAG) Executive Committee Meeting. San Francisco, USA, Dec 7, 2019

Vinculación del marco de referencia nacional de Argentina con el global, la red continental SIRGAS. M.V. Mackern. XII Congreso Nacional de Agrimensura. Mendoza, Argentina. October 9 - 11, 2019.

SIRGAS: The Geocentric Reference System for the Americas. W. Martínez, M.V. Mackern, V. Cioce, R. Pérez Rodino, S.R.C. de Freitas. Workshop for the Implementation of the GGRF in Latin America. Buenos Aires, Argentina. September 16-20, 2019.

Status of the SIRGAS reference frame: recent developments and new challenges. W. Martínez, M.V. Mackern, H. Drewes, H. Rovera, C. Brunini, L. Sánchez, L.P.S. Fortes, E. Lauría, V. Cioce, R. Pérez, S.R.C. de Freitas, S.M.A. Costa, M. Hoyer, R.T. Luz, R. Barriga, W. Subiza. 27th IUGG General Assembly. Montreal, Canada. July 8 - 18, 2019.

Tropospheric products from high-level GNSS processing in Latin America. M.V. Mackern, M.L. Mateo, M.F. Camisay, P.V. Morichetti. 27th IUGG General Assembly. Montreal, Canada. July 8 - 18, 2019.

2020

Modelar el movimiento de la superficie terrestre: Velocidades continuas y coordenadas por etapas. H. Drewes, Webinar SIRGAS, agosto 20, 2020. Presentation also available in YouTube.

Procesamiento con NRCan PPP en entorno Windows Desktop. D. Gómez, Webinar SIRGAS, July 22, 2020. Presentation also available in YouTube.

Sistema internacional de Alturas IHRS. L. Sánchez, Webinar SIRGAS, June 25, 2020. Presentation also available in YouTube.

Procesamiento de datos GNSS con software libre, a partir de estaciones SIRGAS. B. Barraza, J.A. Tarrío, Webinar SIRGAS, May 29, 2020. Presentation also available in YouTube.

Actividades y productos de los centros de análisis SIRGAS. J.A. Tarrío, Universidad Santiago de Chile, Santigo de Chile. Webinar SIRGAS, May 14, 2020. Presentation also available in YouTube.

2021

SIRGAS and GRFA WG UN-GGIM: Americas. Sonia Costa, Diego Pinon, Jose Antonio Tarrio Mosquera, Demian Gomez, Gabriel Guimaraes. Tenth Plenary Meeting of Regional

Committee of United Nations Global Geospatial Information Management for Asia and the Pacific UN-GGIM-AP. WG1 – Geodetic Reference Frame Session. November 12, 2021.

Red geodésica SIRGAS-CON Acceso al Marco de Referencia Terrestre Internacional en las Américas. J.A. Tarrío, S.Alves, A. da Silva,L. Sanchez, Jesarella Inzunza, Fernando Isla, A. Martínez, Óscar Rodriguez, Emilio Aleuy, Hernán Guagni, Guido González, Gustavo Caubarrère. International Congress of the Brazilian Geophysical Society & Expogef 2021. Noviembre 8 – 11, 2021.

Actividades desarrolladas por SIRGAS y el grupo de trabajo GRFA de UN:GGIM: Américas para establecer y actualizar el Marco de Referencia Geodésico de las Américas. Sonia María Alves Costa, Diego Piñón, Demian Gómez, Gabriel Guimaraes. XIX Reunión científica virtual asociación argentina de geofísicos y geodestas «62 años aportando a la ciencia y tecnología argentina». Agosto 2 – 10, 2021.

Venezuela, apuntando al restablecimiento del sistema geodésico nacional. Departamento de Ingeniería Geodésica y Agrimensura, Universidad Central de Venezuela. Webinar SIRGAS: Actividades Geodésicas en las Americas, Julio 29, 2021. Presentación también disponible en YouTube.

La red geodésica nacional: Un servicio continuo y esencial para la planeación y el desarrollo territorial en Colombia, Subdirección de Geografía y Cartografía, Instituto Geográfico Agustín Codazzi – IGAC. Webinar SIRGAS: Actividades Geodésicas en las Americas, Julio 9, 2021. Presentación también disponible en YouTube.

SIRGAS and GRFA WG UN-GGIM: America's interactions for sustainable geodesy in the Americas. Sonia Costa, Diego Pinon, Jose Antonio Tarrio Mosquera, Demian Gomez, Gabriel Guimaraes. Asamblea Científica de la Asociación Internacional de Geodesia – IAG2021. Symposium 5, Session 6: Geodesy contributions to address societal challenges. Julio 2, 2021.

An overview of SIRGAS activities towards the IHRF. G.N. Guimarães, A.C.O. C. de Matos, A. Pereira, E.D. Antokoletz, J.L. Carrión Sánchez, L. Sánchez, and SIRGAS WG-III. International Association of Geodesy (IAG) Scientific Assembly 2021, Beijing, China, June 29, 2021.

South and Central America. J.A. Tarrío, D. Gómez. International Association of Geodesy (IAG) Scientific Assembly 2021, Beijing, China. June 28, 2021.

Recent achievements and current challenges in the maintenance of the geodetic reference frame of the Americas. J.A. Tarrío, L. Sánchez, S. Alves, A. Silva, J. Inzunza, G. Caubarrère, A. Martínez, O. Rodriguez, E. Aleuy, H. Guagni, G. González. International Association of Geodesy (IAG) Scientific Assembly 2021, Beijing, China. June 28, 2021.

Geodesy in the Americas (Geodesia en las Americas). Sonia Costa. Foro de Geodesia UN-GGIM: Américas. Geodesia para la Sustentabilidad de las Américas. Mayo 14, 2021.

La importancia de las redes GNSS permanentes en el mantenimiento de los Sistemas de Referencia Regional y Global. Sonia Costa. "Congreso Internacional de Geomática 2021", Instituto Geográfico Nacional (IGN) Perú. Abril 28, 2021.

Actividades del Grupo de Trabajo I de SIRGAS de la Torre Bilby a la Estación de Referencia de Operación Continua GNSS. J.A. Tarrío, S.Alves, A. da Silva, L. Sanchez, Jesarella Inzunza, Fernando Isla, A. Martínez, Óscar Rodriguez, Emilio Aleuy, Hernán Guagni, Guido González, Gustavo Caubarrère. Congreso Internacional Virtual de Geomática 2021. Abril 28, 2021. Presentación también disponible en YouTube.

Lineamientos para la implementación del Marco de Referencia Geodésico en las Américas. Diego Piñón. Escuela Regional – Facultad de Ciencias Astronómicas y Geofísicas de la Universidad Nacional de La Plata, Argentina. Abril 7, 2021.

Nuevas técnicas geodésicas para América Latina y El Caribe Sonia Costa. Escuela Regional – Facultad de Ciencias Astronómicas y Geofísicas de la Universidad Nacional de La Plata, Argentina. Abril 6, 2021.

Establecimiento de la Red Argentina de Monitoreo Satelital Continuo (RAMSAC). D. Piñón. Jornada "Hacia el establecimiento de la Red GNSS Continua de República Dominicana". Abril 6, 2021

Rede Brasileira de Monitoramento Contínuo dos Sistemas GNSS (RMBC): Complexidades e dasafios. A. Silva, G. Mantovani, M.A. de Almeida, N. Moura, S. Costa. Jornada "Hacia el establecimiento de la Red GNSS Continua de República Dominicana". Abril 6, 2021

Red SIRGAS-CON en Costa Rica. A. Álvarez. Jornada "Hacia el establecimiento de la Red GNSS Continua de República Dominicana". Abril 6, 2021

REDGEOMIN: Red geodésica para la minería en Chile. J.A. Tarrío, J. Inzunza, F. Isla, M. Caverlotti, G. Jeldres, C. Ferraz, R. Urrutia, J. Ojeda. Jornada "Hacia el establecimiento de la Red GNSS Continua de República Dominicana". Abril 6, 2021

Estado del Marco de Referencia SIRGAS: desarrollos recientes y nuevos desafíos. S. Costa, D. Piñón. Escuela Regional "Nuevas Técnicas Geodésicas para América Latina y El Caribe". Abril 6, 2021

Tropospheric products validation in the GNSS SIRGAS Network. M.V. Mackern, M.L. Mateo, M.F. Camisay, P. Rosell, G. Granados. Geodesy for Climate Research, Workshop of Inter-Commission Committee on "Geodesy for Climate Research" of the International Association of Geodesy. March 30, 2021 (video avaliable)

El nuevo Sistema de Referencia Internacional de Gravedad (IGRS) y su materialización (IGRF). H. Wziontek, S. Bonvalot, E.D. Antokoletz. Webinar SIRGAS, 2021-03-05. Presentatuon also available in YouTube.

2022

Status of the SIRGAS reference frame: recent developments and new challenges. S.M. Alves-Costa, L. Sanchez, D. Pinon, J.A. Tarrio-Mosquera, G. Guaimaraes, D. Gomez, H. Drewes, M.V. Mackern, E. Antokoletz, A.C.O.C de Matos, D. Blitzkow and A. da Silva. REFAG2022 – IAG Commission 1 "Reference Frames. October 17, 2022.

Contribuciones de la Tecnología para la construcción de una Geodesia Global. Sonia Costa. XVI Congreso Internacional de Topografía, Catastro, Geodesia y Geomática. San José, Costa Rica. Septiembre 22 – 24, 2022.

Processing a regional/continental dataset. Sonia Costa. Tour de l'IGS 3rd Stop: GNSS processing based on IGS products, International GNSS Service. February 17, 2022.

SIRGAS WG I (Sistema de Referencia) Sinergias actuales y retos a futuro en el Sistema de Referencia Geodésico para las Américas (SIRGAS). J.A. Tarrío, S.Alves, A. da Silva,L. Sanchez, Jesarella Inzunza, Fernando Isla, A. Martínez, Óscar Rodriguez, Emilio Aleuy, Hernán Guagni,Guido González, Gustavo Caubarrère. Jornadas Interdisciplinarias de Geociencias – IGM Chile. Julio 6, 2022. Presentación también disponible en YouTube.

Nuevo Sistema de Referencia Altimétrico Internacional IHRS/IHRF. L. Sánchez, E. Antokoletz, G. Guimarães. Webinar IGM-Chile. Marzo 17, 2022. Presentación también disponible en YouTube.

Training Processing and Adjustment of Gravimetric Networks. From September 21 to 23, 2022, to the Bolivian Military Geographic Institute. From October 6 to 7, 2022, the technical advice was carried out at the National Geographic Institute of Costa Rica. The presentation is also available on YouTube. The SIRGAS WG III Gravimetric Network Coordinator organized and delivered the training.

SIRGAS Social Media

SIRGAS has different accounts in social media:

- Facebook: https://www.facebook.com/SirgasAmericas/
- Twitter: https://twitter.com/SirgasAmericas/
- LinkedIn: https://www.linkedin.com/company/SirgasAmericas/
- YouTube channel: https://www.youtube.com/channel/UCHgFJJ6PPust08GKIlBtUAA

Publications

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Sub-commission 1.3c: North America (NAREF)

Co-Chairs: Michael Craymer (Canada), Daniel Roman (USA)

Introduction and Structure

In collaboration with the IAG community, its service organisations, and the national geodetic organizations of North America, the aims and objectives of this regional Sub-commission are to provide international focus and cooperation for issues involving the horizontal, vertical and three dimensional geodetic control networks of North America. Some of these issues include:

- Densification of the ITRF reference frame in North America and the promotion of its use;
- Definition, maintenance and future evolution of plate-fixed geometric reference frames for North America, including the North American Datum of 1983 (NAD83) and the forthcoming North American Terrestrial Reference Frame of 2022 (NATRF2022).
- Effects of crustal motion, including post-glacial re-bound and tectonic motions along, e.g., the western coast of North America and in the Caribbean;
- Standards for the accuracy of geodetic positions;
- Coordination of efforts with neighbouring IAG SC1.3b for Central and South America to ensure strong ties between each other's reference frames.
- Outreach to the general public through focused symposia, articles, workshops and lectures, and technology transfer to other groups.

Members

- *Michael Craymer (Canada)*
- *Daniel Roman (USA)*
- *Finn Bo Madsen (Denmark)*
- *Babak Amjadiparvar (Canada)*
- *Remi Ferland (Canada)*
- *Joe Henton (Canada)*
- *Mike Piraszewski (Canada)*
- *Dru Smith (USA)*
- *John Galetzka (USA)*
- *Phillip McFarland (USA)*
- *Theresa Damiami (USA)*
- *Lijuan Sun (USA)*
- *Don Haw (USA)*
- *Michael Bevis (USA)*
- *Geoff Blewitt (USA)*
- *Tom Herring (USA)*
- *Jeff Freymueller (USA)*
- *Corné Kreemer (USA)*
- *Richard Snay (USA)*

Activities during the period 2019-2021

The Sub-commission is currently composed of three working groups:

- SC1.3c-WG1: North American Reference Frame (NAREF)
- SC1.3c-WG2: Plate-Fixed North American Reference Frame
- SC1.3c-WG3: Reference Frame Transformations

The following summarizes the activities of each working group, followed by a report of other reference frame activities in Canada and the U.S., during the period 2019-2021. For more information and publications related to the working groups, see the regional Sub-commission web site at *http://www.naref.org/*.

Note: the acronyms "NAD83" (as used in Canada) and "NAD 83" (as used in the U.S.) will be used interchangeably throughout this report.

WG 1.3c.1: North American Reference Frame Densification (NAREF)
Chair: Michael Craymer (Canada)

The objectives of this working group are to densify the ITRF reference frame in the North American region by organizing the computation of weekly coordinate solutions and associated accuracy information for continuously operating GPS stations that are not part of the cur-rent IGS global network. A cumulative solution of coordinate and velocities will also be determined on a weekly basis. The working group will organize, collect, analyse and combine solutions from individual agencies, and archive and disseminate the weekly and cumulative solutions.

The Canadian Geodetic Survey (CGS) continues to produce weekly coordinate solutions of approximately 600 Canadian and northern U.S. public continuously operating Canadian Active Control System (CACS) stations in Canada, Greenland and the northern U.S. The data is processed using the Bernese GNSS Software v5.2 and final IGS orbits with about a 3 week latency. In addition, weekly solutions are also produced for over 750 commercial RTK stations in Canada. The time series of results for CACS and commercially operated stations are published online at *https://webapp.geod.nrcan.gc.ca/geod/data-donnees/cacs-scca.php* for public stations and *https://webapp.geod.nrcan.gc.ca/geod/data-donnees/rtk.php* for the commercial RTK stations.

CGS also continues to produce monthly-updated cumulative solutions of all of its weekly coordinate solutions using its own highly efficient combination software. A coordinates and velocities of nearly 900 current and discontinued public and over 1150 commercial stations are generated. In addition, periodic solutions with high accuracy campaign surveys of an additional 250 stations are included to densify the rather spare continuous network for generating an improved crustal deformation model for Canada. Figure 1.3c.1 gives a map of the vertical velocities from the last periodic solution with high accuracy campaign surveys. Several new CACS stations are planned for installation in strategic locations to improve network coverage but only a few new CACS stations could be installed due to COVID-19-related travel restrictions since early 2020.

Although NGS did not participate in the 2nd IGS reprocessing campaign, they have completed the reprocessing of their NOAA CORS Network (NCN) and IGS network stations. The newly reprocessed solution, called the Multi-Year CORS Solution 2 (MYCS2), is aligned to the ITRF2014 frame. MYCS2 supersedes the previous reference frame and realization, which was released in 2011 under the name MYCS1. The final alignment of the no-net-rotation SINEX files to ITRF2014 used 496 solutions from 194 ITRF2014 stations, not including any of the 26 IGS stations with post-seismic behavior. The MYCS2 generally implemented the IERS 2010 Conventions. Horizontal and vertical velocities from MYCS2 are shown in Figure 1.3c.2.

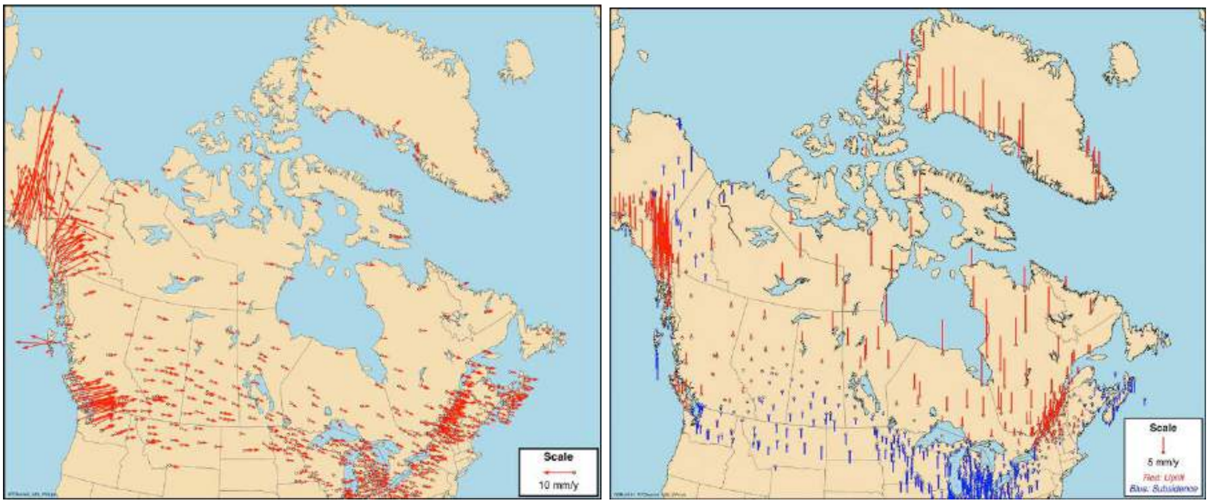

Figure 1.3c.1: *Horizontal (left) and vertical (right) velocities for combined CACS and high accuracy campaign stations in Canada forming the current realization of NAD83(CSRS). Velocities are with respect to the NAD83(CSRS) v7 reference frame where a residual plate motion is apparent in the horizontal plot.*

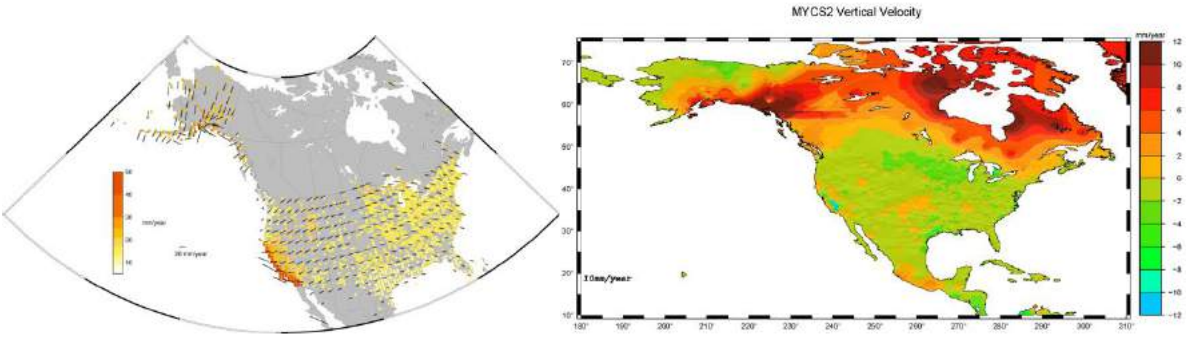

Figure 1.3c.2: *Horizontal (left) and vertical (right) velocities in ITRF2014 from final MYCS2 cumulative solution of "repro2" weekly solutions to GPS week 1933. In the vertical plot, warm colors represent uplift and cool colors represent subsidence.*

WG 1.3c.2: Plate-Fixed North American Terrestrial Reference Frame of 2022 (NATRF2022)
Chair: Daniel Roman

The objectives of this working group are to establish a high-accuracy, geocentric reference frame, including velocity models, procedures and transformations, tied to the stable part of the North American tectonic plate which would replace NAD83 and serve the broad scientific and geomatics communities by providing a consistent, mm-accuracy, stable reference with which scientific and geomatics results (e.g., positioning in tectonically active areas) can be produced and compared. In addition, similar plate-fixed reference frames will be established for U.S. states and territories on other tectonic plates in the Caribbean and Pacific regions.

Although NAD 83 was the best realization of a geocentric reference frame at the time it was introduced in 1986, it is now well known that it is offset from the actual geocentre (and thus ITRF) by about 2 meters. There is also a residual rotation with respect to North American tectonic plate of about 2 mm/yr at mid latitudes due to an inconsistency in the definition of the transformation from ITRF that now defines NAD 83. These problems make NAD 83 incompatible with modern geocentric reference frames used internationally and by all GNSS positioning systems. Additionally, the United Nations Global Geodetic Reference Frame (GGRF) also stipulates adoption of internationally accepted standards of which ISO 19161-1:2020 is the standard for the realization of the ITRS. Consequently, the U.S. has been making plans to replace NAD 83, along with its vertical datum, with a high accuracy geocentric reference frame called the North American Terrestrial Reference Frame of 2022 (NATRF2022). This high accuracy geocentric reference frame will likely be based on the forthcoming ITRF2020 at epoch 2020.0 and fixed to the North American plate. Discussions are also underway in Canada to adopt the same frame. Regardless whether or not the new frame is officially adopted in Canada, CGS will make coordinates and velocities available in both NAD83(CSRS) and NATRF2022, and provide a transformation between the two.

The new NATRF2022 reference frame will be defined by aligning it exactly with the latest realization of ITRF at an adopted reference epoch of 2020.0. It will then be kept aligned to the North American tectonic plate through an estimated Euler pole rotation. Discussions are presently underway on the selection of a set of reference frame stations representing stable North America and on the method of estimating an Euler pole rotation that either best represents the motion of the North American tectonic plate or that minimizes motions of stations outside the plate boundary zone. Investigations are also being made into methods of computing the Euler pole rotation, including a novel, robust approach developed by Kreemer et al. (2017). Remaining intra-frame motions will be modelled for propagating coordinates between epochs both horizontally and vertically.

In addition to defining a new regional reference frame for North America, the U.S. is also planning to define similar plate-fixed frames for the Caribbean and its territories on the Pacific and Mariana plates. The following names have been adopted for these reference frame:

- North American Terrestrial Reference Frame of 2022 (NATRF2022)
- Caribbean Terrestrial Reference Frame of 2022 (CATRF2022)
- Mariana Terrestrial Reference Frame of 2022 (MATRF2022)
- Pacific Terrestrial Reference Frame of 2022 (PATRF2022)

WG 1.3c.3: Reference Frame Transformations in North America
Chair: Michael Craymer

The objectives of this working group are to determine consistent relationships between international, regional and national reference frames in North America, to maintain (update) these relationships as needed and to provide tools for implementing these relationships.

This work primarily involves maintaining the officially adopted relationship between ITRF and NAD83 in Canada and the U.S. The NAD83 reference frame was re-defined in 1998 as a 7-parameter Helmert transformation from ITRF96 at epoch 1997.0. (Craymer et al., 2000) Transformations from/to other subsequent versions of ITRF are obtained by updating the NAD83-ITRF transformation with the official incremental time-dependent transformations between ITRF versions as published by the IERS (Soler and Snay, 2004). The NAD83-ITRF transformation was most recently updated to ITRF2014 in January 2017 just prior to adoption of ITRF2014 by the IGS. The updated transformation has been implemented in transformation software at the Canadian Geodetic Survey and U.S. National Geodetic Survey. The transformation will be updated to the forthcoming ITRF2020 once it is released.

To enable the propagation of coordinates between the various epochs adopted by different jurisdictions in Canada and the U.S., a velocity model and transformation software for North America was developed by Snay and others in 2016. The model integrates velocity fields from various sources to provide North American coverage. The resulting interpolation grid of velocities has been implemented in TRANS4D, an update to the HTDP software that models and predicts horizontal motion for the U.S. Trans4D will likely serve as the initial Intra-Frame Velocity Model (IFVM) for NATRF2022 in the U.S. Investigation has also begun on use of InSAR-based surface deformation modelling tied to the NCN and CACS to serve as a follow on IFVM.

Canada has developed its own national velocity model that incorporates a GIA model to better predict vertical crustal motions in the central and northern regions where GNSS stations are sparse (Robin et al., 2019a, b, c, 2021). The model uses the latest Canadian cumulative solution discussed in SC1.3c-WG1 together with a blending of the ICE-6G and LAUR16 GIA models. The blended GIA model was effectively distorted to fit the GPS velocities thereby providing a more reliable velocity interpolation grid for GIA areas with sparse GNSS coverage. Figure 1.3c.3 illustrates the resulting vertical velocity grid in the NAD83(CSRS) reference frame.

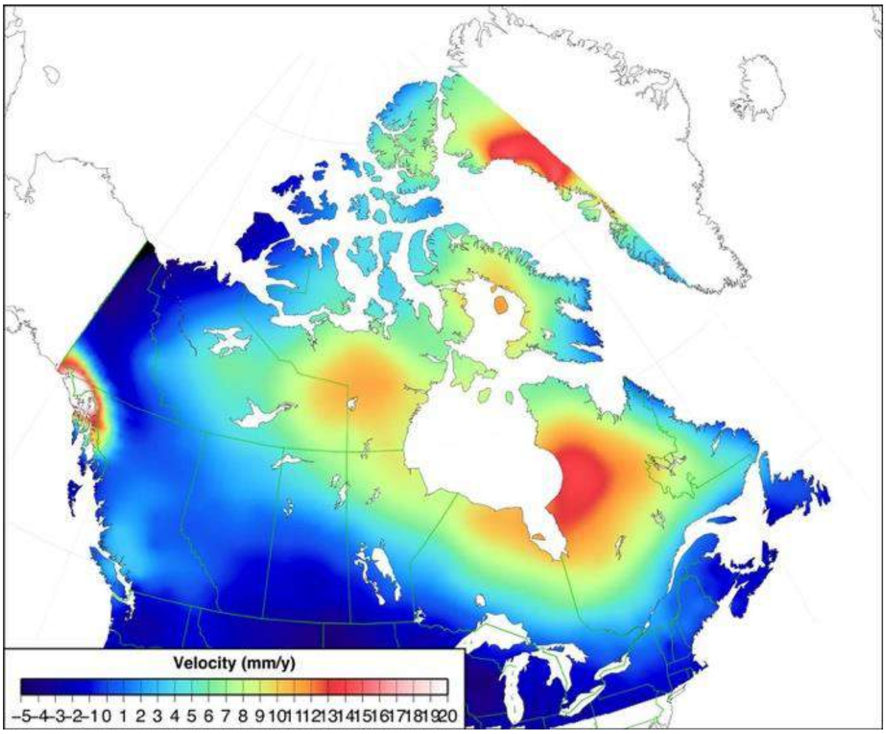

Figure 1.3c.3: *Canadian vertical velocity model in NAD83(CSRS) v7 obtained from an integration of GNSS velocities with a GIA model.*

Other Activities

NGS is creating a new high-level network of 36 highly stable, highly reliable GNSS tracking stations across the country at a spacing of approximately 800 km that will be contributed to the IGS and ITRF (see Figure 1.3c.4). These 36 stations include a minimum of 3 stations on each tectonic plate upon which the U.S. has significant populations (North American, Pacific, Caribbean, and Mariana) to enable computation of an Euler pole rotation (see SC1.3c-WG2). Of these 36, twenty six (26) are currently operational.

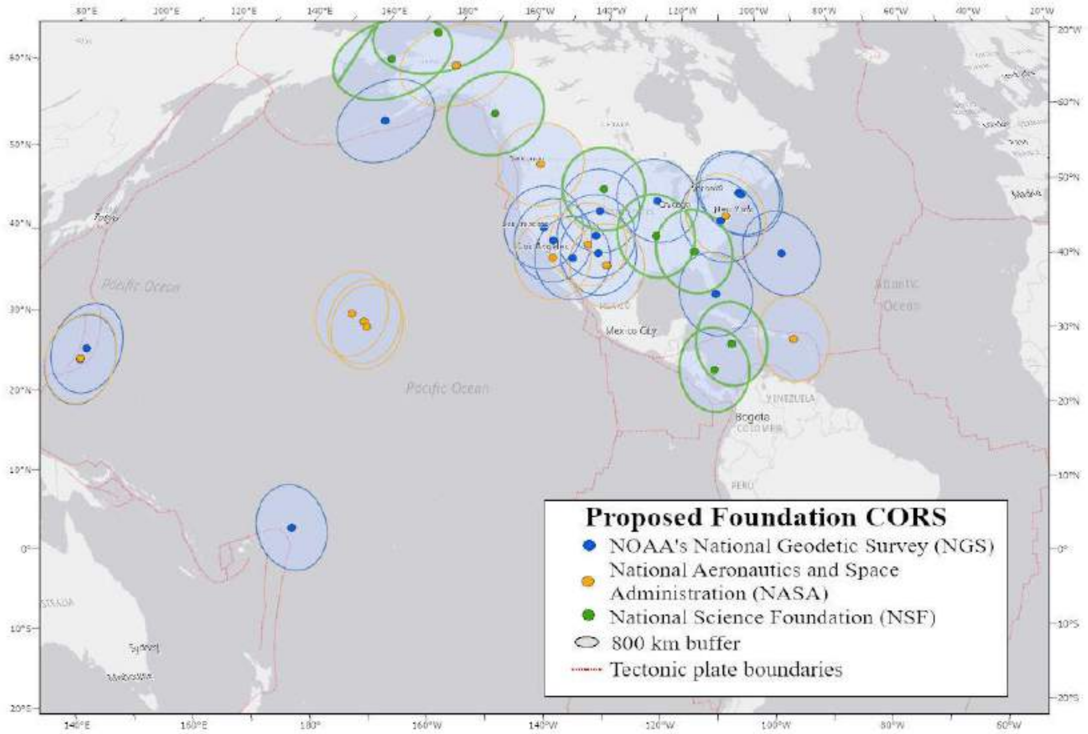

Figure 1.3c.4: *Proposed locations for NOAA Foundation CORS (NFCN) sites to serve as IGS stations and link ITRF solutions to MYCS solutions. Of these twnety six (26) are currently operational).*

Unlike most of the other stations in the NCN, these sites will be operated by the U.S. National Geodetic Survey (either through direct ownership or MOU's with other federal agencies) and will be built and operated to IGS standards. Referred to as the NOAA Foundation CORS Network (NFCN), this network is a subset of the larger NCN and will provide a more stable foundation for the reference frame in the U.S. Thirteen of these GNSS stations are already collocated with other techniques such as VLBI and SLR in order to create true GGOS stations. Another nine new collocated stations will be built at other GGOS sites lacking GNSS. The first of these sites was installed in Miami in late 2014 and the others will be built approximately two per fiscal year beginning the winter of 2019. When the project is completed, all NFCN stations will be fully GNSS capable, will support RINEX3, and will have local surveys ties between the different techniques performed to IERS standards about once every 5 years.

CGS has just recently received funding to enhance Canada's geodetic infrastructure to support future requirements for positioning services, the transportation industry (e.g., autonomous vehicle navigation) and weather modelling and forecasting. The primary objective of this five-year Space-Based Earth Observation (SBEO) project is to densify the existing network of continuously operating GNSS tracking station with about 22 or more real-time stations to support the work of the Canadian Geodetic Survey, Transport Canada and the meteorological branch of Environment and Climate Change Canada. Consideration will also be given to other non-geodetic uses of the GNSS data, such as reflectometry for determining snow depth and soil moisture.

Commercial real-time kinematic network (RTN) services and their networks of base stations have grown significantly over the years. They are effectively providing access to the NAD83 reference frame for many users independent of the public government networks in both Canada and the U.S. Because these networks are not always integrated into the same realization of NAD83, CGS began a program of validating the coordinates of these services to ensure they are properly integrated into the NAD83(CSRS) reference frame. CGS continues to provide on-going, monthly-updated multi-year cumulative solutions for 6 of the largest commercial RTN services in Canada; a total of nearly 900 stations (see Figure 1.3c.5). Compliance agreements have been signed with the five largest services where they have committed to using coordinates for their base stations that are generated in a consistent way by CGS. This ensures those RTN services are integrated into the latest realization of NAD83(CSRS). CGS is also monitoring the stability of RTN stations through time series of weekly coordinate solutions published on CGS's public website.

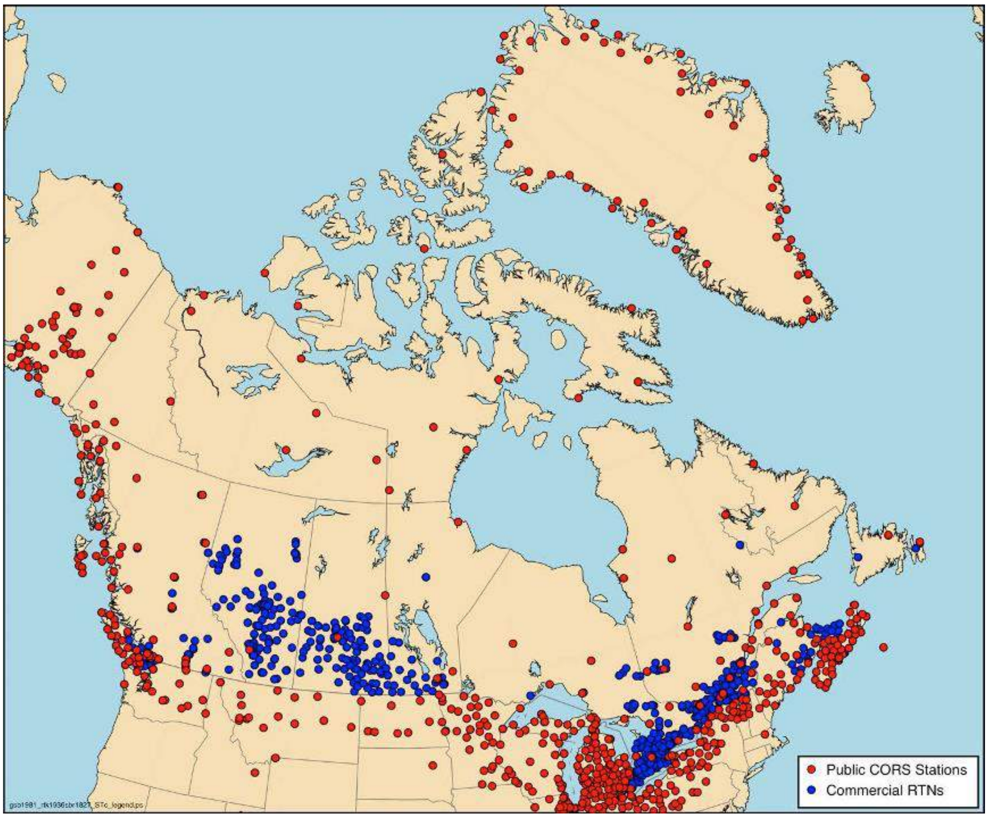

Figure 1.3c.5: *Distribution of the six largest commercial RTK networks in Canada (blue dots) in relation to public federal and provincial networks of permanent GNSS stations (red dots). The commercial RTN stations significantly densify the public network in the Prairies.*

NGS is also committed to developing an RTN Alignment Service (RAS) for RTN operators and users in the U.S. that will ensure RTN coordinates are consistent with the National Spatial Reference System (NSRS). This is intended to be a two-step procedure by first quantifying the alignment of base stations and then quantifying the alignment of rover positions relative to the NSRS.

Cooperation with other organizations and international integration

There has been much international coordination between NAREF and other groups. The most direct engagement has been with IAG 2.4c – gravity and geoid for Central and North America and the Caribbean. Canada has already adopted a geoid based vertical datum and the U.S. will soon do likewise. The North America-Pacific Geopotential Datum (NAPGD2022) is being jointly developed by Canada, the U.S. and Mexico to serve as a regional vertical datum, which will be accessed via the NATRF2022. As such, there is close cooperation between both 1.3c and 2.4c to ensure compatibility.

Additionally, NAREF is looking to foster closer cooperation and collaboration with the IAG Sub-commission 1.3b for South and Central America (SIRGAS). Although SC1.3b is still referred to as SIRGAS within the IAG, the SIRGAS organization recently implemented new terms of reference that defines itself as more of a separate scientific non-governmental organization serving all of the Americas. SIRGAS WG I (Reference System) expanded its focus to developing a reference frame for all of the Americas in support of the regional implementation of the UN-GGIM Global Geodetic Reference Frame for all of the Americas. As such, IAG 1.3b and 1.3c members actively participated to ensure that the SIRGAS Reference Frame is tied to the ITRF throughout all of the Americas. And members of NAREF SC1.3c are now official members of both SIRGAS and its WG I and the newly formed UN-GGIM:Americas Working Group 4 of the Geodetic Reference Framework for the Americas (GRFA).

Members of NAREF have also been contributing to the UN-GGIM Sub-Committee on Geodesy (SCoG) and its working groups. NGS and CGS are members of the SCoG. M. Craymer has served as Chair of the SCoG Working Group on Policies, Standards and Conventions until 2020 and D. Roman has recently assumed duties as the Chair of the SCoG Working Group on Education Training and Capacity Building, renamed as the Working Group on Geodetic Capacity Development.

Related to the SCoG standards working group are NAREF contributions to the development of ISO standards and the ISO Geodetic Registry (ISOGR). The Registry is an authoritative collection of definitions of international reference frames and the transformations between them, similar to the privately run EPSG registry. The primary purpose of the ISOGR is to provide an authoritative source of such information for other registries, including EPSG, as well as GIS software developers and end users. Both CGS and NGS have made a significant effort to populate and update the Registry with all current and historical reference frame realizations used in Canada and the U.S. along with the many transformations among them. The Control Body that approves and facilitates the entry of data into the Registry is presently chaired on behalf of the IAG by M. Craymer (Canada) and L. Hothem (U.S.). Under their leadership, registry software has been developed and implemented by Ribose Group. More recently, CGS has funded the migration of the ISOGR to a new, more efficient software platform. The Registry is available at the following link: *http://registry.isotc211org*.

Organised Meetings

2021 Geospatial Summit, Virtual, May 4-5, 2021. https://geodesy.noaa.gov/geospatial-summit/

Geodesy Forum for UN-GGIM:Americas, Geodesy for Sustainable Americas, virtual, May 14, 2021

2021 Annual General Meeting of the Canadian Geodetic Reference System Committee (CGRSC), Virtual, May 26-28, 2021.

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Robin C., Craymer M., Ferland R., Lapelle E., Piraszewski M., Zhao Y. (2019b). NAD83(CSRS) v7: A New Realization of NAD83(CSRS) for Canada. Presented at the 27th IUGG General Assembly, Montreal, July 8-18

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Sub-commission 1.3d: Africa (AFREF)

The IAG SC 1.3d has been inactive during the period 2019-2023

Sub-commission 1.3e: Asia-Pacific

Chair: Basara Miyahara (Japan)

Introduction and Structure

The objective of IAG Sub-commission 1.3e is to improve the regional cooperation that supports the realization and densification of the International Terrestrial Reference frame (ITRF). Its work is carried out in close collaboration with the Geodetic Reference Frame Working Group of the United Nations Global Geospatial Information Management for Asia and the Pacific (UN-GGIM-AP).

The specific objectives of the IAG Sub-commission 1.3e are:

- The densification of the ITRF and promotion of its use in the Asia Pacific region;
- To encourage the sharing of GNSS data from Continuously Operating Reference Stations (CORS) in the region;
- To develop a better understanding of crustal motion in the region;
- To promote the collocation of different measurement techniques, such as GNSS, VLBI, SLR, DORIS and tide gauges, and the maintenance of precise local geodetic ties at these sites; and
- To outreach to developing countries through symposia, workshops, training courses, and technology transfer activities.

Members

Guorong Hu (Australia)

Yamin Dang (China)

Asakaia Tabua (Fiji）

Upendra Nath Mishra (India)

Sidik Tri Wibowo (Indonesia)

Seyed Abdoreza Saadat Mirghadim (Islamic Republic of Iran)

Basara Miyahara (Japan)Ahmad Sanusi bin Che Cob (Malaysia)

Dalkhaa Munkhtsetseg (Mongolia)

Graeme Blick (New Zealand)

Jongsin Lee (Republic of Korea)

National geospatial information agencies of the Asia-Pacific region are listed here: https://www.un-ggim-ap.org/content/members

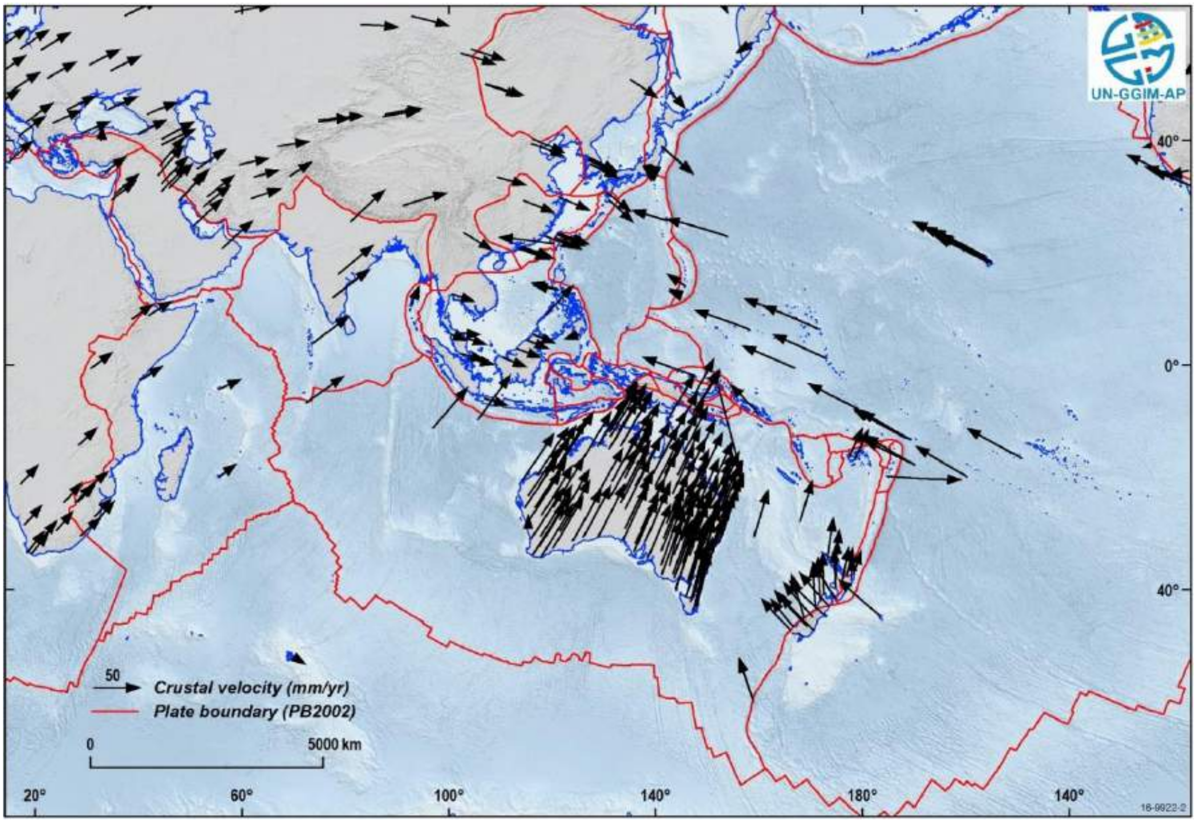
Activities during the period 2019-2023

The IAG sub-commission 1.3e has three focuses in the period; densification of ITRF, collaboration with global geodetic community, and geodetic capacity development in the region.

Asia-Pacific Reference Frame (APREF) Project

The purpose of the Asia-Pacific Reference Frame (APREF) project is to create and maintain an accurate geodetic framework to meet the growing needs of society including industries, science programs and the general public using positioning applications in the Asia-Pacific region. The project specifically is:

- Encouraging the sharing of GNSS data from Continuously Operating Reference Stations (CORS) in the region;
- An authoritative source of coordinates, and their respective velocities, for geodetic stations in the Asia-Pacific region;
- Establishing and maintaining a dense velocity field model in Asia and the Pacific for scientific applications and the long-term maintenance of the Asia-Pacific reference frame.



APREF GNSS stations

A large number of agencies have been participating in APREF. The following table summarizes commitments and contributions by member nations/organizations.

Country/Locality	Responding Agency	Proposed Contribution		
		Analysis	Archive	Stations
Afghanistan	National Geodetic Survey (USA)			2
Alaska, USA	National Geodetic Survey (USA)			7
American Samoa	National Geodetic Survey (USA)			1
Australia	Geoscience Australia	✓	✓	167
Australia	Curtin University			1
Australia	Department of Natural Resources, Mines and Energy, QLD			13
Australia	Department of Environment, Land, Water and Planning, Victoria	✓		161
Australia	Department of Infrastructure, Planning and Logistics, Northern			5

Country/Locality	Responding Agency	Proposed Contribution		
		Analysis	Archive	Stations
	Territory			
Australia	Department of Primary Industries, Parks, Water & Environment, Tasmania			4
Australia	Department of Finance, Services & Innovation, New South Wales			165
Australia	RTK NetWest			21
Australia	IPS Radio and Space Services			3
Australia	Department of Transport and Main Road, Queensland			45
Australia	Hexagon			89
Australia	UPG and Trimble			40
Australia	Position Partners Pty Ltd			100
Australia	Department of Environment and Science QLD			13
Australia	RPS Australia East Pty Ltd			5
Australia	Cody Corporation Pty Ltd			1
Australia	Gladstone Ports Corporation			1
Australia	Jet Propulsion Laboratory			1
Australia	National Geospatial-Intelligence Agency, USA			2
Australia	European Space Agency European Space Operations Centre			1
Brunei	Survey Department, Negara Brunei Darussalam			1
Brunei	Japan Aerospace Exploration Agency			1
Canada	Geodetic Survey of Canada			1
China	The Institute of Geodesy and Geophysics, Chinese Academy of Sciences	✓		
China	Helmholtz Centre Potsdam GFZ German Research Centre for Geosciences Geodes			1
China	Jet Propulsion Laboratory			3
China	National Institute of Metrology, China			1
China	Chinese Academy of Surveying & Mapping			1
China	Tibet Autonomous Regional Buerau of Surveying and Mapping			2
China	Urumqi Astronomical Observatory			1
China	Wuhan University			1
Cook Islands	Geoscience Australia and Lands Department of Cook Islands			1
Cook Islands	Geospatial Information Authority of Japan			1
Ethiopia	Ethiopian Mapping Agency			3
Federated States of Micronesia	Geoscience Australia and Weather Service of the Federated States of Micronesia			1
Fiji	Geoscience Australia and Lands Department of Fiji			1

Country/Locality	Responding Agency	Proposed Contribution		
		Analysis	Archive	Stations
French Polynesia	Geospatial Information Authority of Japan			1
French Polynesia	National Geospatial-Intelligence Agency, USA			1
French Southern Territories (the)	Centre National d'Etudes Spatiales			1
Guam, USA	National Geodetic Survey (USA)			1
Hong Kong, China	Survey and Mapping Office			18
India	Indian Institute of Technology Kanpur			1
India	Helmholtz Centre Potsdam GFZ German Research Centre for Geosciences Geodes			1
India	ISRO Telemetry, Tracking and Command Network, India			3
Indonesia	Bakosurtanal			8
Iran	National Cartographic Center, Iran			6
Iraq	National Geodetic Survey (USA)			6
Japan	Geospatial Information Authority of Japan			12
Japan	Helmholtz Centre Potsdam GFZ German Research Centre for Geosciences Geodes			1
Japan	Electronic Navigation Research Institute			1
Japan	Jet Propulsion Laboratory			1
Japan	Geographical Survey Institute			1
Japan	Space-Time Standards Laboratory National Institute of Information and Communications Technology, Japan			1
Kazakhstan	Kazakhstan Gharysh Sapary			2
Kazakhstan	Jet Propulsion Laboratory			1
Kiribati	Geoscience Australia and Weather Service of Kiribati			1
Kiribati	Geospatial Information Authority of Japan			2
Macau, China	Macao Cartography and Cadastre Bureau			3
Marshall Islands	Geoscience Australia and Weather Service of Marshall Islands			1
Malaysia	Department of Survey and Mapping Malaysia, JUPEM			7
Malaysia	Japan Aerospace Exploration Agency			1
Mongolia	Administration of Land Affairs, Construction, Geodesy and Cartography (ALACGaC)			6
Mongolia	Helmholtz Centre Potsdam GFZ German Research Centre for Geosciences Geodes			3
Nauru	Geoscience Australia and Lands Department of Nauru			1
New Zealand	Land Information New Zealand			48

Country/Locality	Responding Agency	Proposed Contribution		
		Analysis	Archive	Stations
New Zealand	Centre National d'Etudes Spatiales			1
New Zealand	National Geospatial-Intelligence Agency, USA			2
Northern Mariana Islands	National Geodetic Survey (USA)			1
Papua New Guinea	National Mapping Bureau, Papua New Guinea, and Geoscience Australia			2
Papua New Guinea	PNG Office of the Surveyor-General			2
Papua New Guinea	Porgea Joint Venture,PNG			2
Philippines	Department of Environment and Natural Resources, National Mapping and Resource Information Authority			6
Philippines	Jet Propulsion Laboratory			1
Philippines	Centre National d'Etudes Spatiales			1
Samoa	Geoscience Australia and Lands Department of Samoa			1
Samoa	Land Information New Zealand			1
Solomon Islands	Geoscience Australia and Weather Service of Solomon Islands			1
Tonga	Geoscience Australia and Lands Department of Tonga			2
Tuvalu	Geoscience Australia and Weather Service of Tuvalu			1
USA (Hawaii)	Jet Propulsion Laboratory			2
USA (Hawaii)	Federal Aviation Administration, USA			1
USA (Honolu)	National Weather Service, USA			1
USA	U.S. Coast Guard			3
USA	NOAA Earth System Research Laboratory			1
Vanuatu	Geoscience Australia and Lands Department of Vanuatu			2

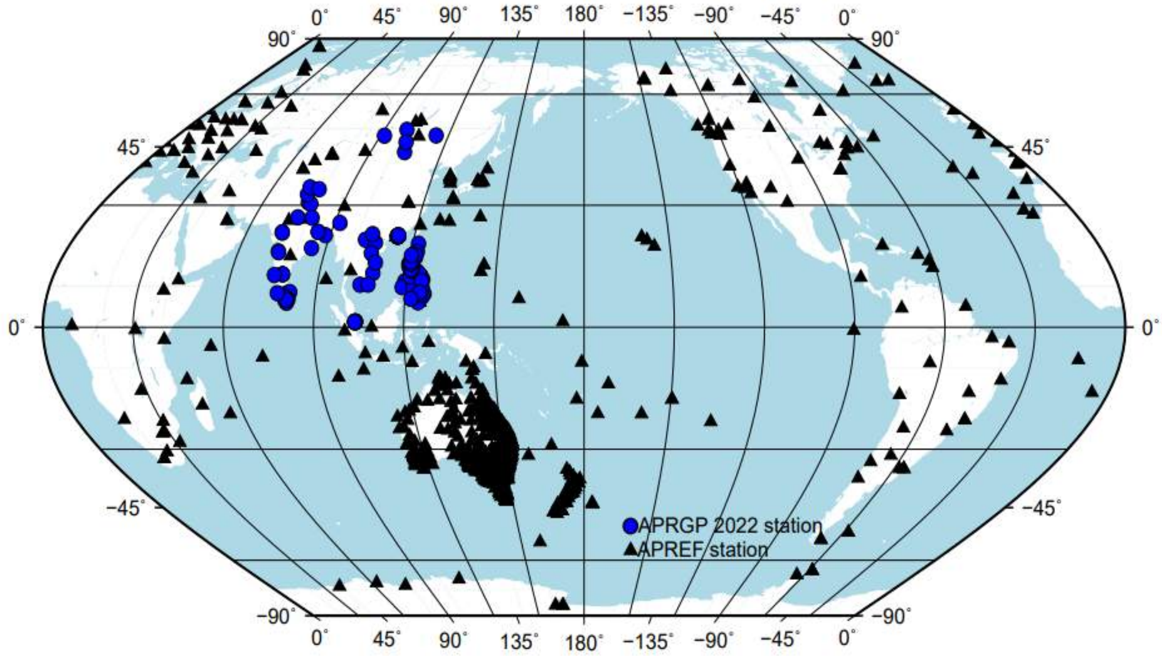
List of contribution to APREF

APREF data and products are provided with an open access data policy via the internet, following the practice of the International GNSS Service (IGS).

- Daily GNSS RINEX data, see https://data.gnss.ga.gov.au/docs/home/gnss-data.html
- Station log files, see https://data.gnss.ga.gov.au/docs/home/metadata.html
- Weekly coordinate estimates in SINEX format, see https://data.gnss.ga.gov.au/docs/home/products.html
- APREF network and time series plots, see https://gnss.ga.gov.au/network

Asia Pacific Regional Geodetic Project

For further densification and improvement of access to the ITRF, the sub-commission has continued to support the annual Asia Pacific Regional Geodetic Project (APRGP), which is a week-long GNSS campaign throughout the region. Campaigns were undertaken in every year from 2019 to 2022, and over ten countries participated in the past campaigns All data were processed and stations coordinates are available in the reports of each campaign. A campaign is planned for 2023.



Participating stations of the APRGP 2022 GNSS campaign.

Cooperation with other organizations and international integration

Sub-commission 1.3e made a contribution towards the development of two documents of the UN-GGIM Subcommittee on Geodesy reported to the Tenth Session of UN-GGIM which was held in virtual format. The most of members of Sub-commission 1.3e are participating in the Subcommittee as a member from the Member State. In addition, the sub-commission will support the work of the newly established UN Global Geodetic Center of Excellence in Bonn and pursue opportunities to collaborate with the center to develop geodetic capacity in the region and make the Global Geodetic Reference Frame more sustainable.

Outreach and capacity development

Several capacity development events were originally planned in the region, but the most of them were cancelled or postponed because of COVID-19 pandemic. The sub-commission contributed to the events through the organization and presentations. After long break caused by COVID-19, Sub-commission 1.3e is planning to hold a capacity development workshop on geodetic reference frame and its contribution to disaster risk reduction in conjunction with the UN-GGIM-AP 12th Plenary meeting which will be held in Bali, Indonesia on November 2023.

- UN-GGIM-AP, FIG, IAG "Positioning and Datum Modernisation Forum" in 3 November 2019 in conjunction with UN-GGIM-AP 8th Plenary Meeting. It was also the first opportunity to welcome a presentation from the geodetic working group of the UN-GGIM Arab States.

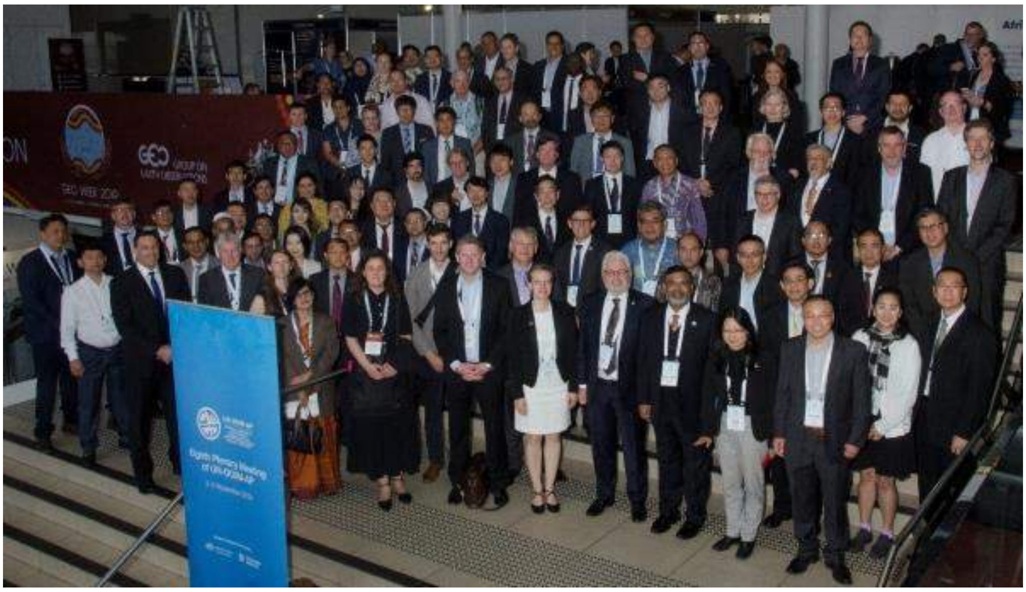
Positioning and Datum Modernisation Forum

- FIG Technical Seminar on Reference Frame in Practice: Reference Frames, Progress and Challenges in the Asia-Pacific Region was held in virtual format on 10 December 2020.

Organized Meetings

Sub-commission 1.3e usually has its annual session at the UN-GGIM-AP Plenary meeting in collaboration with the UN-GGIM-AP Working Group on Geodetic Reference Frame.

- The sub-commission 1.3e held its annual session at the 8th Plenary Meeting of UN-GGIM-AP on 3 November 2019 in Canberra, Australia. The national/regional/global issues and challenges on geodetic reference frame were discussed and resolution to tackle them were developed to table them to the Plenary Session.



8th Plenary Meeting of UN-GGIM-AP

- Annual sessions of the sub-commission 1.3e were held in 2022 and 2021 in virtual format in conjunction with UN-GGIM-AP 9th and 10th Plenary Meeting. Although these were the first and second opportunities for the sub-commission to hold online sessions, the sessions attracted a larger number of participants than the past sessions and around 70 and 80 people participated in the session respectively.

- After long break of COVID-19, the sub-commission 1.3e had its in-person meeting again together with the Geodetic Reference Frame Working Group of UN-GGIM-AP at the UN-GGIM-AP 11th Plenary Meeting on 14 November 2022 in Hyderabad, India, and plan to hold a meeting at the UN-GGIM-AP 12th Plenary Meeting on November 2023 in Indonesia.

12th Plenary Meeting of UN-GGIM-AP

Selected publications

Hu, G. 2020. Report on the analysis of the Asia Pacific Regional Geodetic Project (APRGP) GPS Campaign 2019. Record 2020/27. Geoscience Australia, Canberra. http://dx.doi.org/10.11636/Record.2020.02

Hu, G. 2021. Report on the analysis of the Asia Pacific Regional Geodetic Project (APRGP) GPS Campaign 2020. Record 2021/19. Geoscience Australia, Canberra. http://dx.doi.org/10.11636/Record.2021.019

Hu, G. 2022. Report on the analysis of the Asia Pacific Regional Geodetic Project (APRGP) GPS Campaign 2021. Record 2022/32. Geoscience Australia, Canberra. http://dx.doi.org/10.11636/Record.2022.032

Hu G., Jia M., Dawson J. 2019. Report on the Asia Pacific Reference Frame (APREF) Project. Record 2019/17. Geoscience Australia, Canberra. http://dx.doi.org/10.11636/Record.2019.017

Sub-commission 1.3f: Reference Frame in Antarctica

Chair: Martin Horwath (Germany)

Introduction and Structure

SC 1.3f deals with the densification of the ITRF in Antarctica and the application of geodetic GNSS measurements for geoscientific investigations, especially in geodynamics, geophysics, and glaciology. For this, the SC 1.3f promotes and supports all activities to realize geodetic GNSS measurements on bedrock sites in Antarctica. Therefore, a close linkage is maintained to the Scientific Committee on Antarctic Research (SCAR), especially to the SCAR Expert Group (EG) "Geodetic Infrastructure in Antarctica" (GIANT) and the SCAR Scientific Research Program "Instabilities and Thresholds in Antarctica" (INSTANT).

In terms of geodetic infrastructure Antarctica is a special case because it is not subject to sovereignty of any state. Instead, the Antarctic Treaty ensures freedom of research. Thus, geodetic markers and GNSS installations have been set up and are being maintained by a great number of different national Antarctic programs.

Members

The membership is mostly identical with that of SCAR EG GIANT. In that way, cooperation and coordination can best be pursued since all nations are represented who are involved geodetic GNSS activities in Antarctica.

Martin Horwath	TU Dresden *Chair of SC 1.3f*	Germany
Alessandro Capra	Universita di Modena e Reggio Emilia *Co-Chair of SCAR EG GIANT*	Italy
Mirko Scheinert	TU Dresden *Co-Chair of SCAR EG GIANT*	Germany
Manuel Berrocoso	Universidad de Cadiz	Spain
Graeme Blick	Linz	New Zealand
Jan Cisak	IGIK	Poland
Beata Csatho	University of Buffalo	USA
John Dawson	Geoscience Australia	Australia
Giorgiana De Franceschi	Istituto Nazionale di Geofisica e Vulcanologia	Italy
Koishiro Doi	National Institute of Polar Research	Japan
Rene Forsberg	DTU Space	Denmark
Angelo Galeandro	Universita di Modena e Reggio Emilia	Italy
Brendan Hodge	UNAVCO	USA
Larry Hothem	USGS	USA
Erik Ivins	JPL	USA
Thomas James	Government of Canada	Canada
Aspurah Kamburov	University of Mining and Geology Sofia	Bulgaria
Matt King	University of Tasmania	Australia
Christoph Knöfel	TU Dresden	Germany
Jeronimo Lopez-Martinez	Universidad Autonoma de Madrid	Spain

Jaakko Mäkinen	Finnish Geodetic Institute	Finland
Kenichi Matsuoka	Norwegian Polar Institute	Norway
Alexey Matveev	Aerogeodeziya	Russia
Gennadi Milinevsky	University of Kyiv	Ukraine
Monia Negusini	INAF	Italy
Elizabeth Petrie	University of Glasgow	United Kingdom
Markku Poutanen	Finnish Geodetic Institute	Finland
Goncalo Prates	Univ. Algarve	Portugal
Yves Rogister	Univ. Strasbourg	France
Kazuo Shibuya	NIPR	Japan
Lars Sjoberg	KTH Royal Institute of Technology	Sweden
Norbertino Suarez	Servicio Geografico Militar	Uruguay
Terry Wilson	Ohio State University	USA
Andres Zakrajsek	Instituto Antartico Argentina	Argentina

Activities during the period 2019-2023

Meetings, exchange of information, ongoing GNSS observations

A virtual group meeting took place on 28 July 2022 in the frame of the SCAR Meeting 2022, with a duration of about 1.5 hours. Further information were disseminated via email. To mention some highlights:

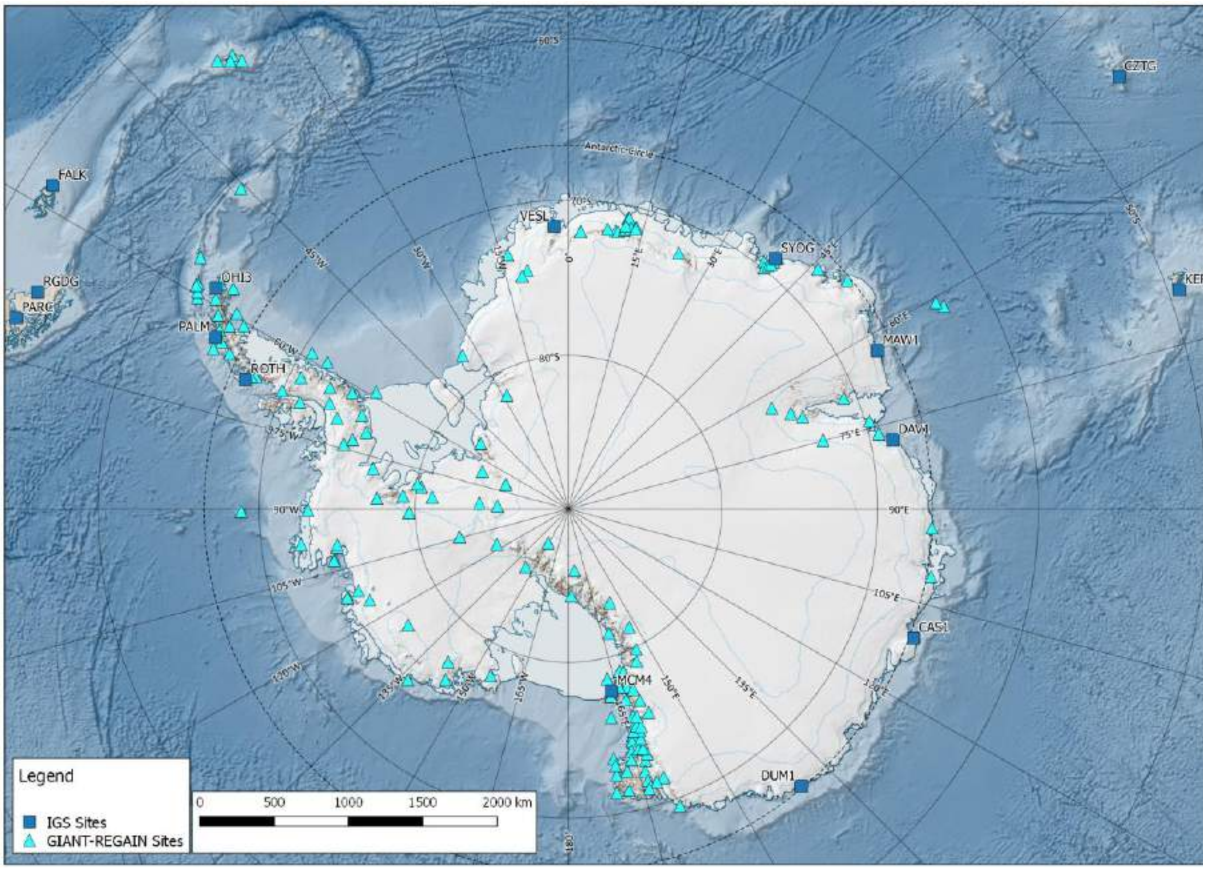
- At the Japanese station Syowa space geodetic observations including GNSS could be continued (comprising also VLBI, DORS and tide gauge time series).
- In the Australian sector of East Antarctica a number of permanently recording GNSS sites could be maintained at remote locations (King et al. 2022); additionally continuous GNSS was continued at the IGS sites of the Australian stations Mawson, Davies and Casey.
- TU Dresden realized repeated GNSS measurements at campaign sites in western Dronning Maud Land in 2019/2020 and 2022/2023 as well as in Enderby Land in 2021/2022. Additionally, two new permanent GNSS sites were set up in western Dronning Maud Land (Forstefjell and Kottas Mts.).
- Within the Italian program observations of the extensive GNSS network in Victoria Land could be continued, including upgrades of up to four permanent sites and set-up of a new permanent site at Mt. Melbourne, which will be valuable also for volcanology. Additionally, investigations have been undertaken to utilize permanent GNSS for atmospheric research in Antarctica (Negusini et al. 2021).
- Further permanent GNSS sites are being maintained, among others, by the Antarctic programs of Argentina and Spain. A new site was installed at Mt. Murphy in the region of the Amundsen Sea Embayment by the Korean program (KOPRI) in close cooperation with the US (UNAVCO, OSU).

SCAR GNSS Database

In close linkage with SCAR EG GIANT a database on geodetic GNSS in Antarctica (SCAR GNSS Database) is being maintained at TU Dresden. This is an ongoing activity (see data1.geo.tu-dresden.de/scar) and provides an important background support for the GIANT-REGAIN project (see below). New GNSS data could be incorporated, both of permanent and episodic sites.

Reprocessing of GNSS data in Antarctica (GIANT-REGAIN)

At the SCAR Meeting 2016 in Kuala Lumpur an initiative was launched by Mirko Scheinert (Germany) and Matt King (Australia) entitled "Geodynamics in Antarctica based on Reprocessing GNSS Data Initiative" (GIANT-REGAIN). This project aims to provide a consistent solution of coordinates and coordinate changes for the most complete set of GNSS bedrock stations in Antarctica for further applications in geodesy, geophysics and geodynamics (especially studies on glacial-isostatic adjustment). Huge efforts have been undertaken to collect and homogenize the necessary metadata. The observational data comprises now more than 280 GNSS sites on bedrock in Antarctica over a time span from 1995 to the end of 2021. Final results to be provided as consistent time series of coordinates at these ~280 sites as well as the respective publication can be expected in Q4 of 2023.



Overview of geodetic GNSS sites on bedrock in Antarctica utilized for the GIANT-REGAIN project, © TU Dresden / SCAR EG GIANT. See text for explanations. Map source: Quantarctica 3, QGIS 2.18. The final data set of GIANT-REGAIN now comprises more than 286 sites.

Linkage to SCAR Scientific Research Program INSTANT

Led by Mirko Scheinert (TU Dresden, Germany) and Weisen Shen (Stony Brook University, USA) a workshop of the SCAR INSTANT SC2.2 entitled “The Future of Geodetic-Geophysical Observational Networks in Antarctica” took place in Fort Collins (CO, USA) from September 29 to October 1, 2022. With geodetic GNSS on bedrock being one core technique the science rationale as well as logistics, infrastructure and coordination issues were discussed. A crucial question arose with regard to the planned decommissioning of large parts of the permanent GNSS infrastructure by the US and UK national programs (funding agencies NSF and NERC, respectively). It is (and will be) an ongoing task for the international science community to develop practical measures to maintain permanent GNSS sites Antarctica as far as possible. Here, the IAG together with SCAR will be of valuable support.

Participation in related meetings, conferences and workshops

Group members took part in relevant meetings, conferences and workshops although due to the Corona crisis most meetings took place in an online format or had to be cancelled at all. Besides the annual EGU General Assemblies and AGU Fall Meetings, the following meetings shall especially be mentioned:

- IUGG General Assembly, Montreal (Canada), 08 – 18 July 2019
- International Symposium on Antarctic Earth Sciences (ISAES) XIII, Incheon (South Korea), 28 July – 02 August 2019
- XXXVI SCAR Meeting and Open Science Conference (online, originally to take place in Hobart, Australia), August 2020
- IAG Scientific Assembly, 28 June – 2 July 2021
- XXXV SCAR Meeting and Open Science Conference (virtual), July 2022

Selected publications

King, M. A., Watson, C. S., & White, D. (2022). GPS rates of vertical bedrock motion suggest late Holocene ice-sheet readvance in a critical sector of East Antarctica. *Geophysical Research Letters*, 49, e2021GL097232. https://doi.org/10.1029/2021GL097232

Negusini, M. et al. (2021). Water Vapour Assessment Using GNSS and Radiosondes over Polar Regions and Estimation of Climatological Trends from Long-Term Time Series Analysis. *Remote Sensing*, 13(23), 4871; https://doi.org/10.3390/rs13234871

Rosado, B., Fernández-Ros, A., Berrocoso, M., Prates, G., Gárate, J., de Gil, A., & Geyer, A. (2019). Volcano-tectonic dynamics of Deception Island (Antarctica): 27 years of GPS observations (1991–2018). *Journal of Volcanology and Geothermal Research*, *381*, 57-82.

Samrat, N. H., King, M. A., Watson, C., Hooper, A., Chen, X., Barletta, V. R., & Bordoni, A. (2020). Reduced ice mass loss and three-dimensional viscoelastic deformation in northern Antarctic Peninsula inferred from GPS. *Geophysical Journal International*, *222*(2), 1013-1022.

Scheinert, M., O. Engels, E. J. O. Schrama, W. van der Wal and M. Horwath (2021). Geodetic observations for constraining mantle processes in Antarctica. In: A. P. Martin and W. van der Wal (eds.), The Geochemistry and Geophysics of the Antarctic Mantle. *Geological Society, London*, *Memoirs*, 56. doi: 10.1144/M56-2021_22

Turner, R. J., Reading, A. M., & King, M. A. (2020). Separation of tectonic and local components of horizontal GPS station velocities: a case study for glacial isostatic adjustment in East Antarctica. *Geophysical Journal International*, *222*(3), 1555-1569.

Whitehouse, P.L., Gomez, N., King, M.A. et al. (2019). Solid Earth change and the evolution of the Antarctic Ice Sheet. Nature Communication, 10, 503. https://doi.org/10.1038/s41467-018-08068-y

Zanutta, A., Negusini, M., Vittuari, L., Martelli, L., Cianfarra, P., Salvini, F., ... & Capra, A. (2021). Victoria Land, Antarctica: An Improved Geodynamic Interpretation Based on the Strain Rate Field of the Current Crustal Motion and Moho Depth Model. *Remote Sensing*, 13(1), 87.

Working Groups of Sub-commission 1.3

WG 1.3.1: Time-dependent transformations between reference frames in deforming regions

Chair: Richard Stanaway (Australia)

Introduction and Structure

The main aim of the WG has been to develop strategies to enable time-dependent transformations in deforming regions to support positioning and geodetic applications. Many different approaches and data formats have been used to enable transformation between reference frames within plate boundary zones and regions affected by glacial isostatic adjustment (GIA). These transformations are necessarily time-dependent to account for secular plate motion, interseismic strain and episodic seismic deformation. In these instances conformal transformations do not adequately model the complexity of the deformation field and other approaches are required to enable high precision transformations between source and target reference frames at different epochs. Deformation and other time-dependent transformation models provide linkages between global reference frames such as ITRF, regional reference frames and local reference frames commonly used for positioning, land surveying, mapping and GIS.

Since May 2020, the WG has worked closely collaborating with the Open Geospatial Consortium (OGC) Coordinate Reference System (CRS) Domain Working Group, Standards Working Group (SWG) and other regional reference frame working groups to develop a deformation model functional model (DMFM) for non-conformal time-dependent transformations, deformation models and a standardised open-source geodetic grid exchange format (GGXF). The functional model and grid specifications are currently progressing through the OGC standards review stage. It is anticipated that the OGC standard will be adopted by registries of geodetic parameters such as those hosted by ISO/TC 211 and IOGP/EPSG to assist geodetic agencies, positioning services and software developers. The WG has also worked closely with FIG Commission 5 (Positioning and Measurement), specifically FIG Working Group 5.2 (Reference Frames). WG members have comprised of a wide spectrum of researchers from different fields of geophysics, geodesy, land surveying, GIS and IT. The WG has attempted to be as inclusive as possible with the aim of involving geodesists from most countries that deal with and manage significant crustal deformation.

Members

- *Richard Stanaway* (Australia), Chair
- *Wan Anom Wan Aris* (Malaysia)
- *Elmar Brockmann* (Switzerland)
- *Miltiadis Chatzinikos* (Greece)
- *Yingyang Cheng* (China)
- *Michael Craymer* (Canada)
- *Chris Crook* (New Zealand)
- *Nic Donnelly* (New Zealand)
- *Kristian Evers* (Denmark)
- *Jeff Freymueller* (USA)
- *Pasi Häkli* (Finland)

- *Muzaffer Kahveci* (Turkey)
- *Kevin Kelly* (USA)
- *Martin Lidberg* (Sweden)
- *Roger Lott* (UK)
- *Niraj Manandhar* (Nepal)
- *Basara Miyahara* (Japan)
- *José Antonio Tarrío Mosquera* (Chile)
- *Chris Pearson* (New Zealand)
- *Susilo* (Indonesia)

Corresponding Members

- *Stylianos Bitharis (*Greece*)*
- *Graeme Blick* (New Zealand)
- *Carine Bruyninx* (Belgium)
- *Paul Denys* (New Zealand)
- *Patrick Forster* (South Africa)
- *Mark Greaves* (UK)
- *Leonid Lipatnikov* (Russia)
- *Craig Roberts* (Australia)
- *Hagi Ronen* (Israel)
- *Yoshiyuki Tanaka* (Japan)
- *Tatsuya Yamashita* (Japan)
- *Norman Teferle* (G.-D. Luxembourg)

Activities during the period 2019-2023

(a) Development of a deformation functional model and geodetic grid format for time-dependent transformations

The main product of the WG has been to work jointly with the OGC DWG and SWG to develop specifications for a deformation functional model (DMFM) and associated geodetic grid exchange format (GGXF). These are essential products to support development and consistency within spatial and positioning software for use in crustal deformation zones. Both products are currently in the final review stage and finalisation is expected by the end of 2023.

The repository websites for work content are located at:

https://github.com/opengeospatial/CRS-Deformation-Models

https://github.com/opengeospatial/CRS-Gridded-Geodetic-data-eXchange-Format

The current draft specifications can be accessed at:

https://github.com/opengeospatial/CRS-Deformation-Models/raw/master/products/specification/abstract-specification-deformation-model-functional-model.pdf

https://github.com/opengeospatial/CRS-Gridded-Geodetic-data-eXchange-Format/raw/master/specification/GGXF%20v1-0%20OGC-22-051r2_2023-01-09.pdf

Conformal time-dependent transformations are already in widespread use typically to accommodate secular plate rotation within a no-net-rotation (NNR) global frame. Plate motion models (PMM) can be simply represented within a 14 parameter model as rotation rate parameters with zeros for the other parameters. The 14 parameter Helmert transformation method is widely used for transformation between different realisations of ITRF, other TRF and plate-fixed RF such as the ETRF, NAD83 and GDA2020. This approach enables time evolution of parameters (rotation, translation and scale) from a defined reference epoch. PMM and time-dependent conformal transformations are suitable for transformation of points within stable portions of a tectonic plate but fail to accommodate intraplate (e.g. GIA) localised and plate boundary zone deformation. Conformal transformation models alone are not suitable for countries straddling plate boundaries. In these instances, geophysical, grid or triangulated velocity models can be used to estimate secular interseismic displacement of a crust-fixed RF as a function of time. Considerable work has been done to develop velocity grids for this purpose.

In addition to secular displacement, episodic seismic displacement models are required for transformation of spatial data (points, point clouds, vectors, strings, polygons and raster data) displaced by earthquakes. Local reference frames used for surveying and mapping often need to be updated to account for coseismic and postseismic deformation where displacements are significant and exceed certain positioning and dimensioning tolerances. Interseismic strain accumulation resulting in distortion of a crust-fixed RF can also require updates to the RF when the strain exceeds certain dimensional tolerances (e.g. across a locked fault). Displacement grids can be used transform spatial data within a consistent reference frame across these events (for example transformation of pre-earthquake spatial data sets to a post-earthquake epoch). A combination of secular velocity and episodic displacements is required to enable transformation between RF in seismically active areas and is especially important with the rapid uptake of GNSS-PPP, particularly by users with limited geodetic expertise. The combination of models is broadly termed a “deformation model” or “trajectory model” and is typically comprised of a suite of velocity grids, coseismic displacement grids and postseismic amplitude grids. The functional model approach dictates how the grid models are populated, aggregated and used to estimate time-dependent displacements and transformations within and between reference frames.

In June 2020, the Open Geospatial Consortium (OGC) Coordinate Reference System Domain Working Group (OGC CRS DWG) co-chaired by Keith Ryden (ESRI, USA) and Mark Hedley (UK Met Office) commenced biweekly virtual meetings to develop a deformation model functional model and associated geodetic grid format which are now both in the OGC standard review stage. This activity has been chaired by Roger Lott (IOGP, UK). The considerable overlap with the membership and aims of this OGC DWG project and the IAG WG has provided an ideal opportunity for these meetings to be mutually beneficial.

Chris Crook (LINZ, New Zealand) and Kevin Kelly (ESRI, USA) have co-chaired the deformation model functional model (DMFM) project of the OGC CRS DWG with monthly meetings between June 2020 and 2022.

Concurrently, Roger Lott has chaired the complementary OGC CRS DWG project developing a geodetic grid exchange format (GGXF). One of the main impediments to the uptake of time-dependent transformation models to date has been the lack of an accessible open-source grid format that can accommodate all of the requirements of the grids used in time-dependent transformations. The GGXF format is intended to support not only displacement and velocity grids but also a wider range of geodetic applications, for example as a standard format for geoid, quasi-geoid and hydroid models.

The importance of this work for datum modernisation, better alignment of GNSS positioning and data frames and the contribution by members of this IAG cannot be understated.

(b) Velocity models for kinematic to static/semi-kinematic RF transformations

In addition to the 14 parameter model, a gridded velocity model is now widely used for time-dependent transformations. Velocities (typically represented in a topocentric format) within a given reference frame are tabulated in a grid format and may be 1D (vertical or single component only), 2D (horizontal only) or 3D. Ideally, uncertainties and covariance information are also assigned to each node value in order to provide users of the model indicative uncertainties at different epochs. For any given point within the model coverage area, velocities and uncertainties can be estimated using a suitable interpolation method and variance propagation. This approach is ideal for transformations of GNSS-PPP positions (currently in the ITRF2020/IGS20 RF) to a local RF at a specific epoch.

A velocity grid is RF specific and provides a means of estimating displacements of points within a RF as a form of intraframe kinematic transformation or propagation. It could also be used directly for interframe transformations (e.g. between ITRF and a crust-fixed RF at a specific epoch) if there is a null-transformation between the velocity model RF and the target RF at the interframe transformation reference epoch. The velocity model alone has no episodic component, so any displacement of the target frame due to earthquakes or other phenomena would be implicit in the transformation for any epoch after a deformation event (assuming that the target frame is updated for these deformation events). Where uncorrected pre-earthquake spatial data is used with this approach, then a seismic displacement model (reverse sense) needs to be applied in addition to the velocity model to align post-earthquake positioning with pre-earthquake datasets.

Recent national and regional velocity model studies by WG members are now summarised. The WG also recognises the substantial efforts made recently by other geodesists in developing models to enable time-dependent transformations.

(c) National and regional velocity grids

Mike Craymer (NRCan, Canada) reports that Canada has recently updated its 3D velocity grid NAD83v70VG (Fig. 1) to support transformation of GNSS PPP positions (currently in the kinematic IGS14 RF) to the Canadian spatial reference system NAD83(CSRS)v7 (Robin, *et al*., 2021). The velocity grid is comprised of 3 grids with 0.25° spacing for each topocentric velocity component and associated uncertainties. The velocities are modelled in the IGS14 RF to enable kinematic PPP solutions in that RF to be transformed to NAD83(CSRS)v7 at the interframe transformation epoch.

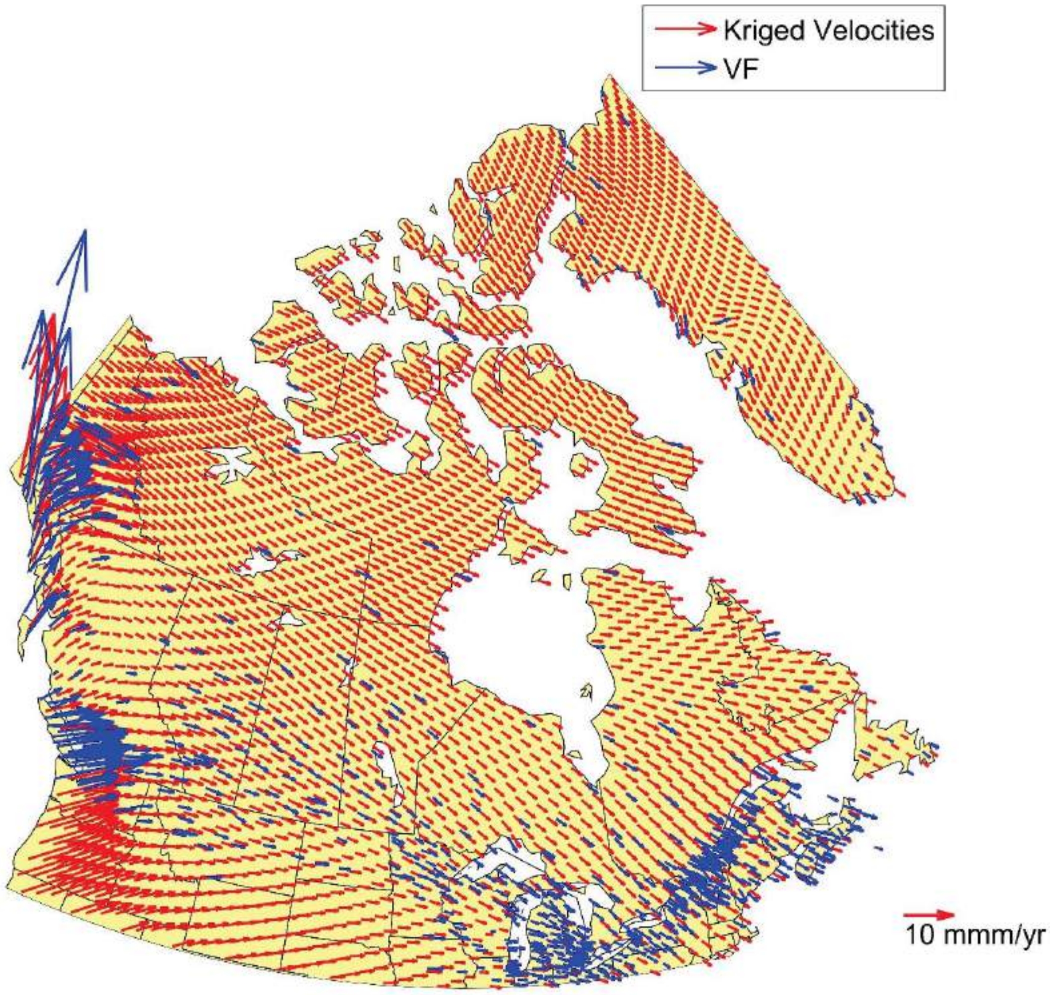


Fig. 1(a). NAD83v70VG, horizontal component, in NAD83(CSRS). The gridded model (red arrows) is decimated for easier visualisation. The model is estimated from the measured horizontal component of the velocity field (blue arrows) (Robin et al., 2020)

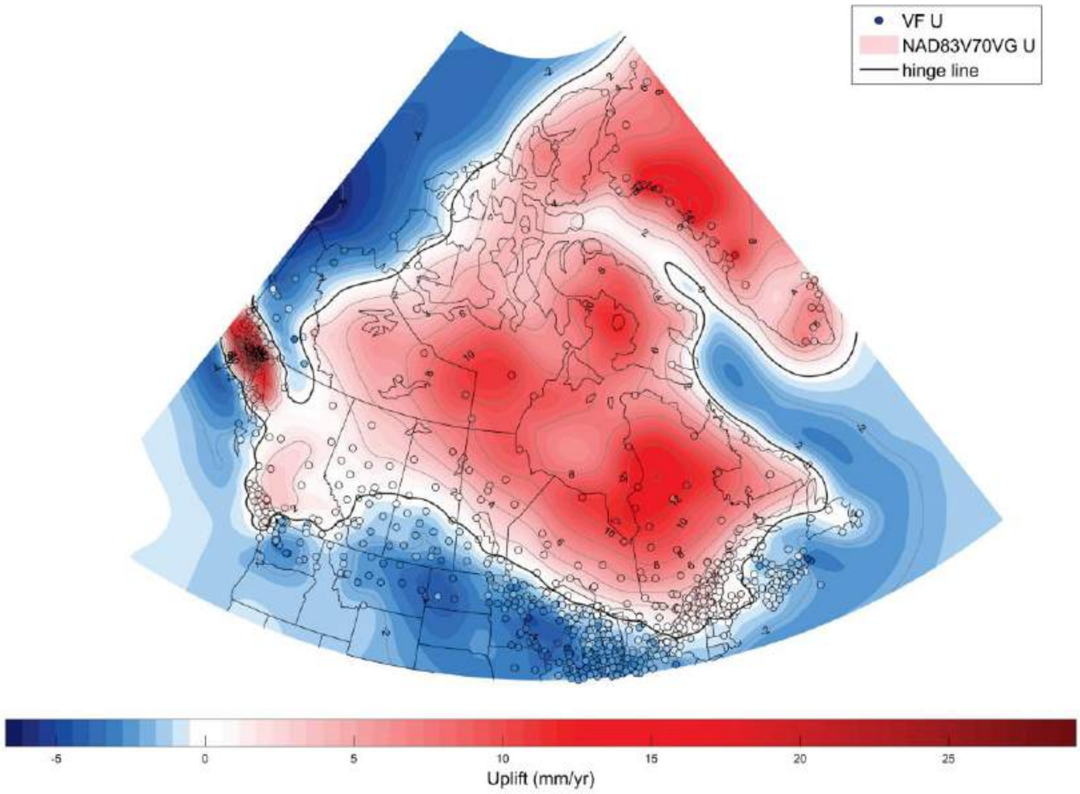


Fig. 1(b). NAD83v70VG, vertical component, in NAD83(CSRS). The observed velocity field is shown with coloured circles and shaded contours represents the hybrid velocity model which integrates both the observed velocity field and a combined geophysical model. (Robin et al., 2020).

The US is in the process of implementing a new national RF to supersede NAD83 and four intraframe velocity models (IFVM) will be an integral part of the new RF. The IFVM will model intraframe velocities within the four major plate-fixed reference frames within US jurisdiction (North America, Pacific, Caribbean and Marianas). Each plate-fixed frame will have a PMM and associated 14 parameter transformation to enable IGS14 (or later) transformations to each plate-fixed frame at a specified epoch.

Latin America has a long established geodetic framework SIRGAS. The current SIRGAS velocity grid (1 degree spacing), VEMOS2017 has evolved significantly since its first realisation in 2003. VEMOS2017 is defined in three reference frames (IGS14, South American Plate and Caribbean Plate). In the most tectonically active country in South America, Chile, José Antonio Tarrío (Universidad de Santiago de Chile) has indicated that the proposed new national dynamic datum for the resource sector REDGEOMIN will incorporate a denser velocity grid to better model interseismic secular velocities along the South America, Nazca and Antarctic Plate boundaries where a 1 degree resolution is insufficient to model the variability of plate boundary deformation along these highly active plate boundaries.

Yingyang Cheng (Chinese Academy of Surveying and Mapping) and colleagues have a developed gridded horizontal velocity model (1° grid interval overall with up to 0.25° interval denser grids in complex deformation zones) to model secular displacements within the Chinese Reference Frame CGCS2000 (Cheng *et al.*, 2021). China has a diffuse but nevertheless complex deformation field and 20 microplates have been identified within China. Tatsuya Yamashita (GSI, Japan) has reported that Japan was improving their secular deformation model (Fig. 2) to support PPP to JGD transformations (POS2JGD) to be precise enough for autonomous navigation tolerances (<3 cm). POS2JGD is a significant improvement on the current approach with a step-function applied at periodic intervals. Recent studies (Takagi *et al*. 2020) and (Tanaka *et al*. 2020) have tested the performance of an approach with a piecewise linear function and found that the new approach could be adequate for applications that require precision alignment of positioning with earlier (static) spatial data (e.g. autonomous driving, precision agriculture, and machinery control). In addition to improving the secular deformation model, Tatsuya has recently collaborated with WG colleagues Chris Crook and Nic Donnelly (LINZ, NZ) developing coseismic displacement grids after large earthquakes from SAR controlled by GNSS ground-truthing (Yamashita, 2020).

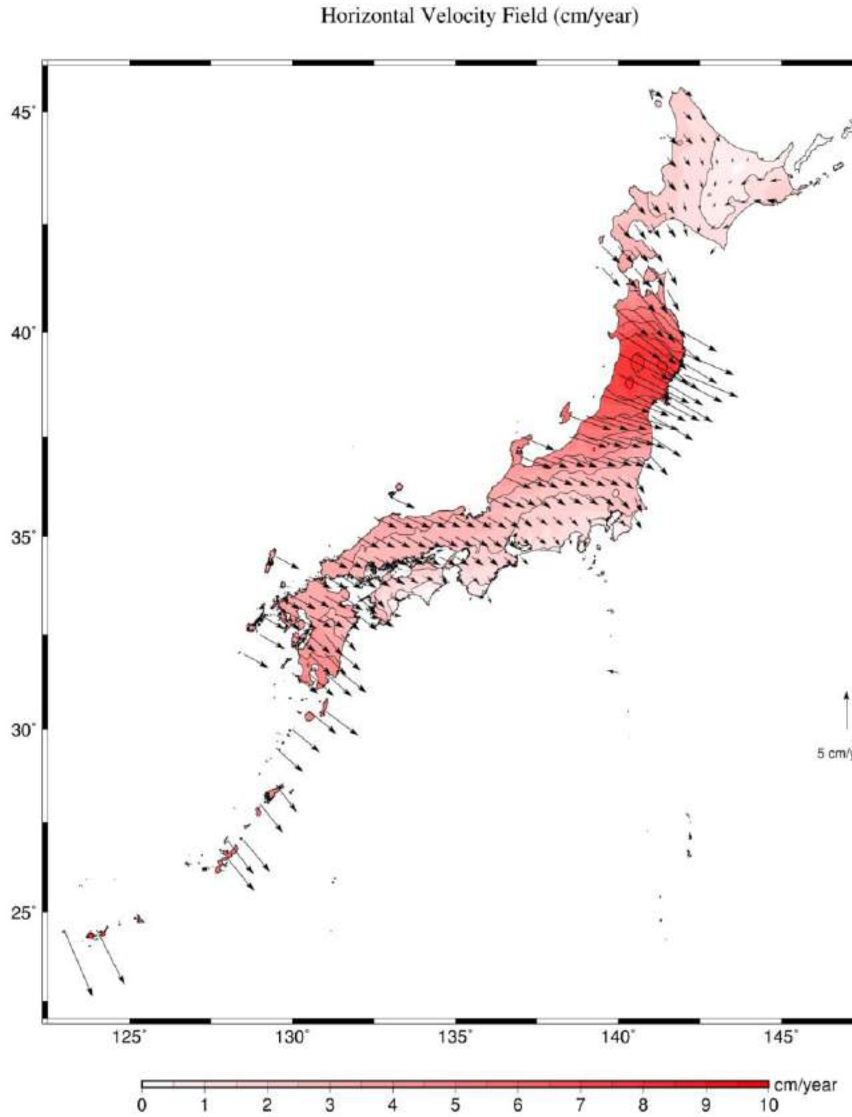


Fig. 2(a). The Japanese POS2JGD horizontal secular velocity field (in the IGS14 RF). The postseismic velocity correction after the Tōhoku 2011 earthquake is still significant (up to 8 cm/yr).

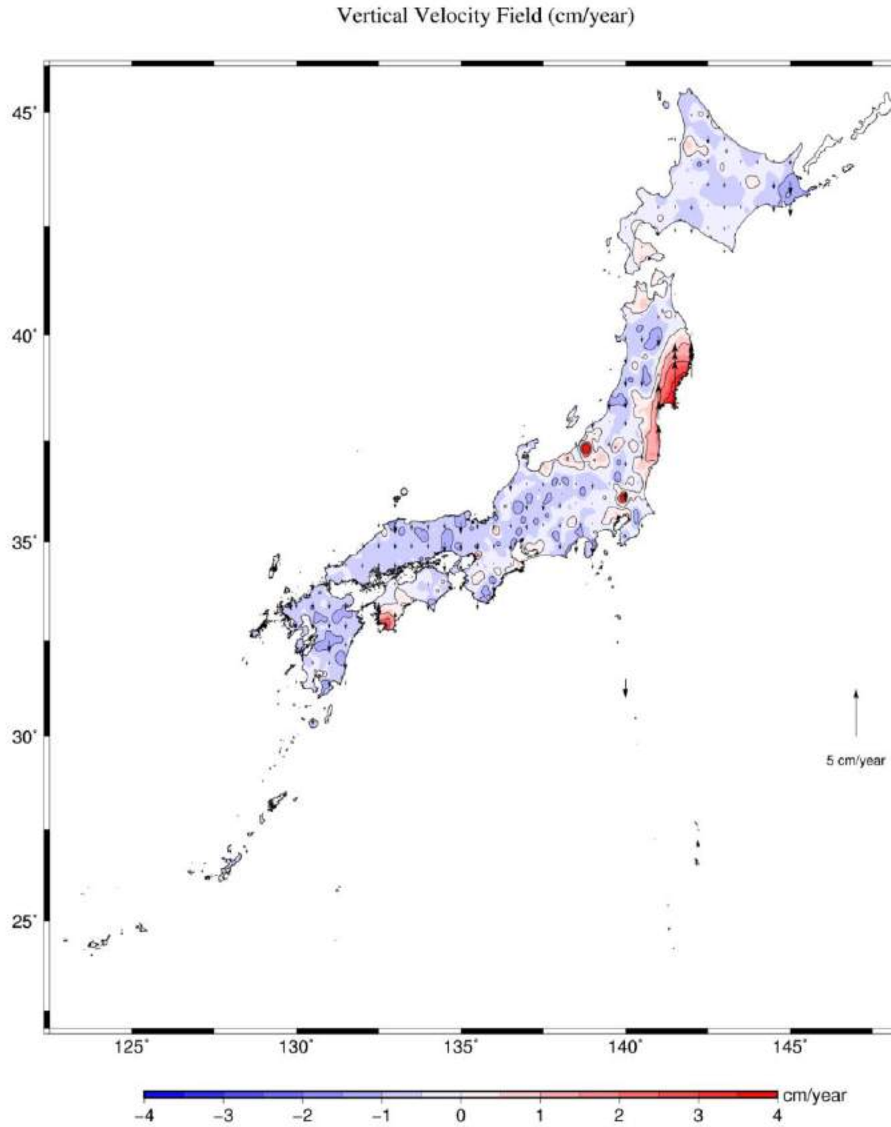


Fig. 2(b). The Japanese POS2JGD vertical secular velocity model. The postseismic uplift velocity correction after the Tōhoku 2011 earthquake is still significant (up to 4 cm/yr).

Wan Anom Wan Aris (UTM, Malaysia) and colleagues have developed coseismic displacement and postseismic amplitude grids to support maintenance of the GDM2000 datum in Malaysia and integrity of the MyRTK active geodetic network to account for deformation of the network due to recent large earthquakes in Sumatra (Wan Aris *et al.*, 2018).

Australia is fortunate not to have to deal with significant intraplate deformation apart from isolated intraplate earthquakes, far-field coseismic/postseismic deformation and localised deformation (e.g. from resource extraction, water abstraction and regolith creep). A 14-paramater transformation which embeds the Australian PMM (APMM) is used for ITRF2014 to GDA2020 (Australian plate-fixed) time-dependent transformations to support positioning services such as AusPOS (ICSM, 2020). Since January 2020, a time-dependent Australian Terrestrial Reference Frame (ATRF2014) has also been in use, providing Australia with a dual-frame geodetic reference system that accommodates the requirements of users of both kinematic and plate/crust-fixed reference frames. ATRF2014 is fully aligned with ITRF2014. A national deformation model to support ATRF is being considered to account for any intraplate and localised deformation.

The development of the European velocity model has been significant over the last four years. The EUREF WG on European Dense Velocities chaired by Elmar Brockmann (swisstopo, Switzerland) has currently compiled ~7000 estimated velocities over continental Europe, Turkey and Israel with half of these validated independently by at least 2 analysis centers. This work has been a very substantive collaborative effort involving input from geodetic researchers and agencies from most European countries, Turkey and Israel. This dense velocity field has been used to generate a grid model of velocities (Fig. 3) (swisstopo, 2021). The rapid increase in observed velocities has improved the uncertainty of modelled velocities across Europe. This work ties in closely with the goals of the EUREF WG on Deformation Models chaired by Martin Lidberg (Lantmäteriet, Sweden).

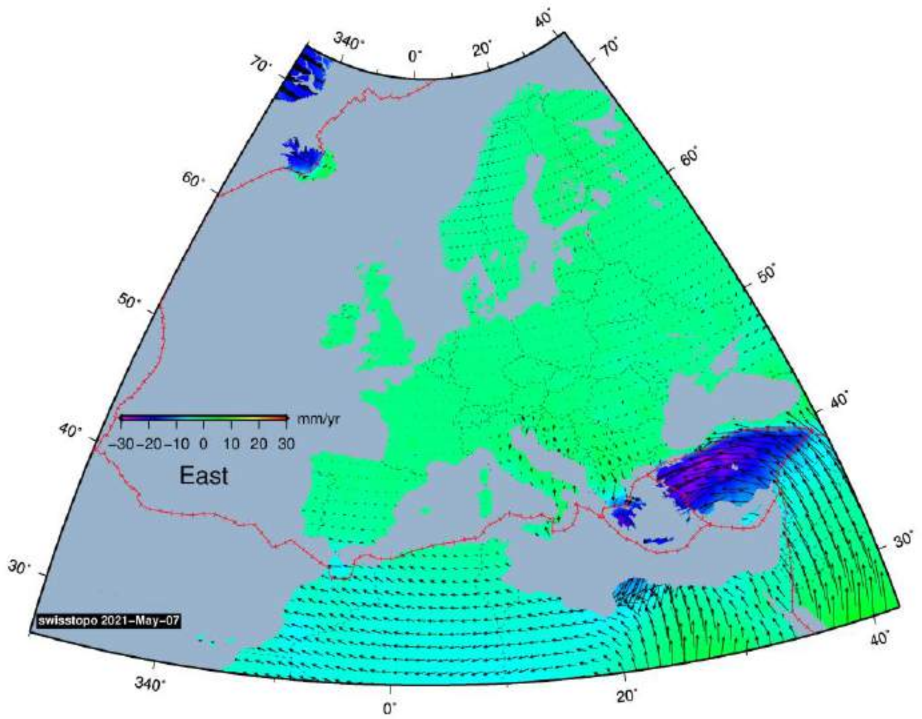


Fig. 3(a). European velocity field (East) in a stable Eurasian plate frame (swisstopo, 2021)

Pasi Häkli (NLS, Finland) along with many collaborators from the Nordic Geodetic Commission (NKG) has developed a horizontal intraplate (Eurasian plate fixed) velocity model for the Nordic and Baltic region to support time-dependent transformations (NKG2020) in the Nordic countries (Häkli *et al.*, 2023). The model accounts for the crustal extension component of GIA in the Fennoscandian/Baltic region. The current Nordic vertical velocity model (NKG_RF17) largely attributable to GIA is also used for reference (Fig. 4), (Vestøl et al., 2019).

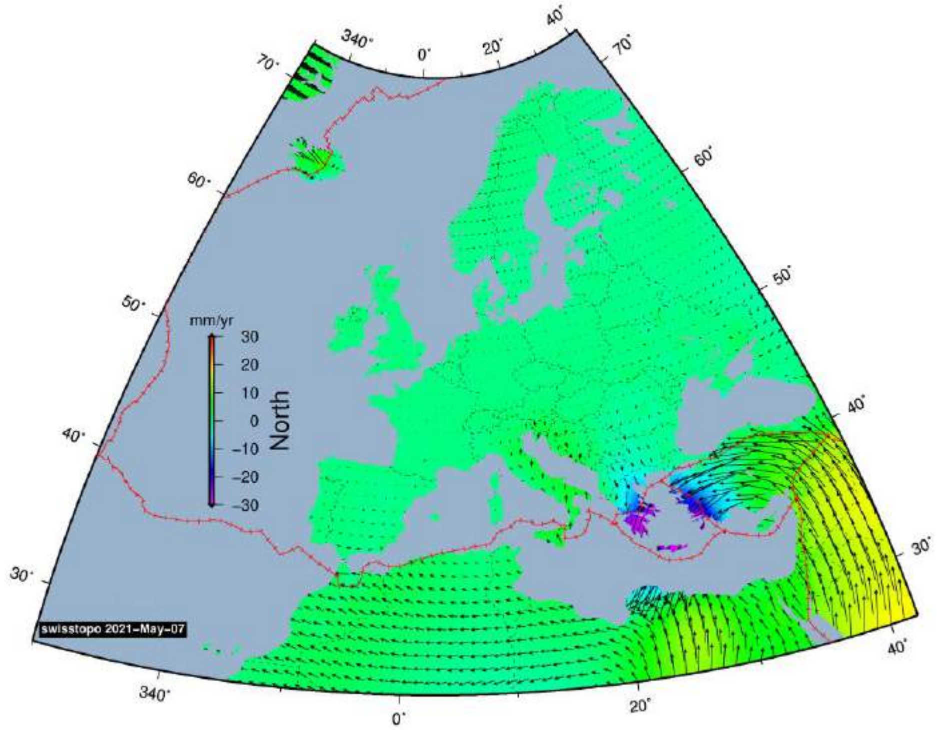


Fig. 3(b). European velocity field (North) in a stable Eurasian plate frame (swisstopo, 2021)

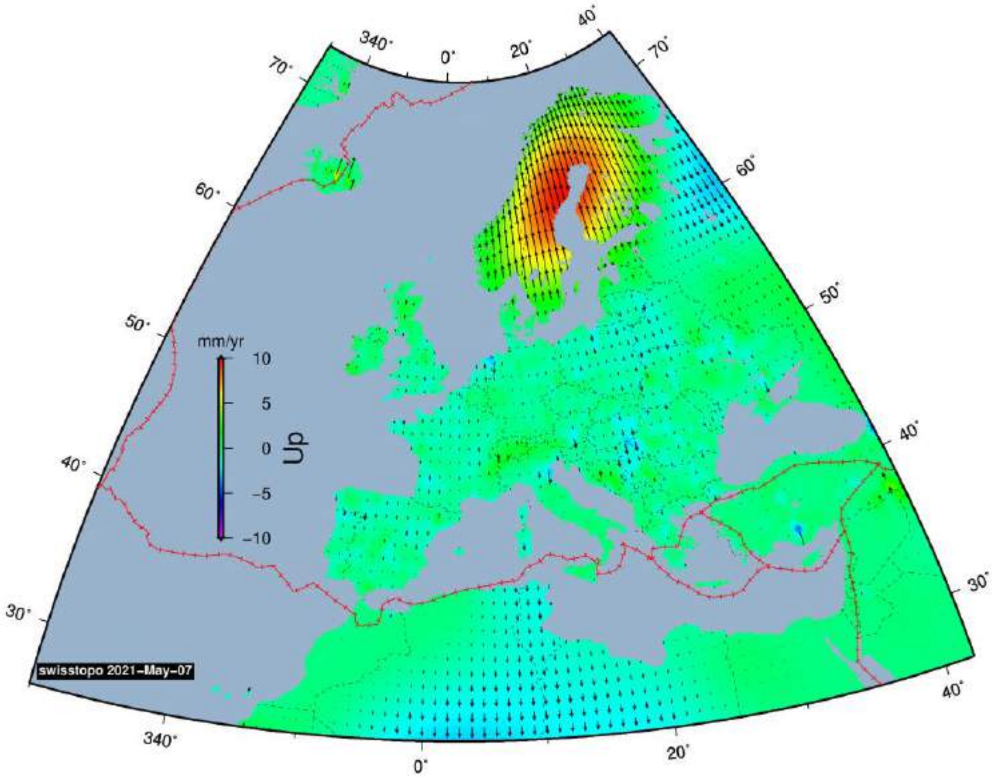


Fig. 3(c). European velocity field (Up) in a stable Eurasian plate frame (swisstopo, 2021)

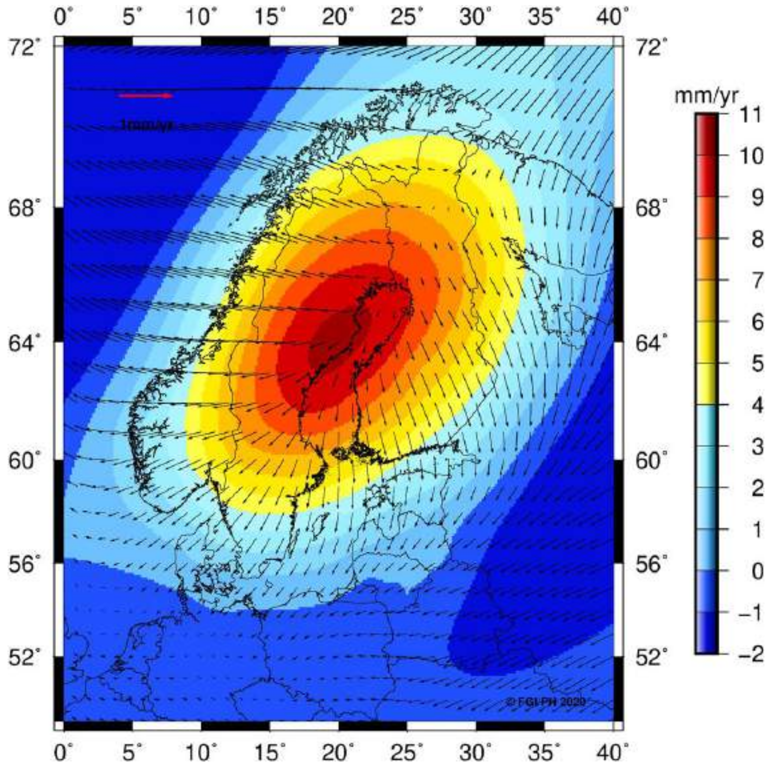


Fig. 4, NKG_RF17vel model intraplate velocities. Black vectors denote horizontal velocities in ETRF2014. Vertical velocities shown with the colourmap. Unit: mm/year.

Stylianos Bitharis (AUTh, Greece) and colleagues have undertaken considerable development of a velocity model for Greece (Bitharis *et al*., 2019) which has the most complex and active tectonic setting in Europe. This research has been provided to the EUREF WG.

Turkey shares the complex tectonic setting with Greece and Muzaffer Kahveci (KTUN, Turkey) has provided an update on velocity modelling in Turkey.

(d) Questionnaire on usage of time-dependent transformation and deformation models

In 2020, a questionnaire was distributed through the IAG WG and OGC CRS DWG to ascertain how different agencies and research institutions were defining, distributing and using deformation models and velocity grids. The response to the questionnaire was very encouraging with agencies from 29 countries providing information on their respective approaches. The questionnaire and supplied responses can be viewed at this github link (https://github.com/opengeospatial/CRS-Deformation-Models/blob/master/survey/Deformation%20survey%20responses.xlsx). The responses have assisted the IAG WG and OGC CRS DWG in developing a functional model and grid format that has flexibility to suit existing approaches to handling RF deformation and to support migration to a more standardised format.

(e) Glossary

A glossary of terms relevant to the WG or aide-memoire is being compiled to provide a useful reference for researchers, developers of standards, guidance notes and working documents. There is no full consistency between key organisations including the ISO, IERS, IOGP/EPSG with regard to terminology and this can to lead to confusion and misunderstandings. The aim of the glossary is to enable groups of users familiar with a specific terminology to translate definitions using plain English.

(f) Complex time-dependent transformations and velocity models in positioning services

Chris Pearson (University of Otago, NZ) has provided significant input into the improvement of Trimble's positioning products with the application of deformation models within the Trimble geodetic library (TGL) used by Trimble Access 2020.20 and Trimble Business Center 5.40 (Pearson, 2020). This work is of very great importance and it is expected that other positioning services will adopt a similar approach to enable more robust, consistent and repeatable localisation of GNSS positioning with an established local reference frame to enable better alignment with spatial data.

Organised Meetings

The covid-19 pandemic effectively ruled out face-to-face international meetings between 2020 and 2022. A WG meeting had been planned to coincide with the FIG Working Week in Amsterdam in May 2020. Fortuitously, the OGC initiated open-access biweekly webinars in June 2020 to develop a functional model for time-dependent transformations and a geodetic grid exchange format (GGXF) for the representation of time-dependent grid models (and geodetic data in general) in a more platform independent and standardised way. The considerable overlap of the goals and membership of the two WG and the opportunity to meet virtually every fortnight has been very collaborative and beneficial. A special note of thanks goes to Keith Ryden (ESRI), Roger Lott (IOGP), Chris Crook(LINZ) and Kevin Kelly (ESRI) for their support and impetus for these regular meetings.

The deformation model functional model concept was presented virtually at the IAG Scientific assembly in Beijing, China in mid 2021. A working group progress presentation was subsequently made at the IAG Commission 1 conference (REFAG) in Thessaloniki, Greece in October 2022.

The final WG meeting is planned for the IUGG in Berlin, July 2023 and oral presentations on aspects the work will be presented by both Richard Stanaway (for the DMFM) and Roger Lott (for the GGXF).

Publications

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Vestøl, O., Ågren, J., Steffen, H., Kierulf, H., and Tarasov, L., NKG2016LU: a new land uplift model for Fennoscandia and the Baltic Region. J Geod 93, 1759–1779, https://doi.org/10.1007/s00190-019-01280-8, 2019.

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Wan Anom Wan Aris, Tajul Ariffin Musa, Kamaludin Mohd Omar, Sohaimie Rasisi, Abdullah Hisam Omar, Non-Linear Crustal Deformation Modeling For Dynamic Reference Frame: A Case Study In Peninsular Malaysia, Proceedings of the FOG Working Week, Istanbul, Turkey, 2018.

Sub-commission 1.4: Interaction of Celestial and Terrestrial Reference Frames

Chair: Zinovy Malkin (Russia)

Overview

International terrestrial and celestial reference frames, ITRF and ICRF, respectively, as well as the tie between them expressed by the Earth Orientation parameters (EOP) are key products of geodesy and astrometry. The requirements to all the components of this triad grow steadily and the mm/μas level of accuracy is the current goal of the astronomic and geodetic community.

The current computation procedures for ITRF and ICRF are based on multi-stage processing of observations made with several space geodetic techniques: VLBI, SLR, GNSS, and DORIS. Not all of them provide equal contributions to the final products. The latest ITRF realizations have been derived from combination of normal equations obtained from all four techniques, whereas the ICRF is a result of a single global VLBI solution. The latter is tied to the ITRF using an arbitrary set of reference stations. However, VLBI relies on the ITRF origin provided by satellite techniques and shares responsibility with SLR for the ITRF scale. Finally, all the techniques contribute to positions and velocities of the ITRF stations.

This situation causes complicated mutual impact of ITRF and ICRF, which should be carefully investigated to improve the accuracy of both reference systems and the consistency between each other and EOP. The subject becomes more and more complicated when moving to millimeter accuracy in all components of this fundamental triad. Consequently, we face systematic errors involving the connection between the ICRF and ITRF realizations, which cannot be fixed by datum correction during the current solution.

There are several issues currently preventing the consistent realization of the terrestrial and celestial reference systems (TRF and CRF, respectively) at the mm/μas level of accuracy:

- Insufficient number and non-optimal distribution of active and stable stations (VLBI and SLR in the first place) and radio sources.
- Technological (precision) limitations of existing techniques.
- Incompleteness of the theory and models.
- Not fully consistent models applied during data analysis.
- Not fully understood and agreed-upon details of the processing strategy.
- Not fully understood and accounted for the systematic errors of different techniques.

These issues are subject of research activity of the IAG SC 1.4. All the three IAG SC 1.4 working groups are working in close cooperation with each other because there is clear interaction among their topics. To provide this, it was decided that each WG chair becomes a member of two other working groups, and the SC chair if a member of all the three groups.

SC 1.4 Meetings:
No SC 1.4 meeting was held in 2019–2023.

Other related meetings:
At the following meetings, the problems related to the IAG SC 1.4 topics were discussed:

- 27th IUGG General Assembly, Montreal, Canada, 08–18 July 2019
- Journées 2019 "Astrometry, Earth Rotation and Reference Systems in the Gaia era", Paris Observatory, 7-9 October 2019
- Solid Earth Team Meeting, La Jolla, CA, USA, 4–6 November 2019
- EGU General Assembly (online), 4–8 May 2020
- European VLBI Group for Geodesy and Astrometry (EVGA) 25th Working Meeting (online),
  15-18 March 2021
- EGU General Assembly (online), 19–30 April 2021
- IAG Scientific Assembly, June 28 - July 5, 2021, Beijing, China
- IVS General Meeting, March 27 - April 1, 2022, Helsinki, Finland
- EGU General Meeting, 23-27 May 2022, Vienna, Austria
- REFAG 2022, October 17-20, 2022, Thessaloniki, Greece

Working Groups of Sub-commission 1.4

WG 1.4.1: Improving and unification of geophysical and astronomical modeling for better consistency of reference frames

Chair: Dan MacMillan (USA)

Members
- *Robert Heinkelmann (Germany)*
- *Hana Krásná (Austria, Czech Republic)*
- *Sébastien Lambert (France)*
- *Zinovy Malkin (Russia)*
- *David Mayer (Austria)*
- *Lucia McCallum (Plank) (Australia)*
- *Tobias Nilsson (Sweden)*
- *Stanislav Shabala (Australia)*

Working Group 1.4.1 is concerned with the modeling of geophysical and astronomical effects and how they affect the consistent determination of the terrestrial and celestial reference frames. The work of the group generally falls into the following categories: 1) analysis and solution parametrization, 2) external models, and 3) internal inconsistencies within the VLBI technique. There clearly are overlaps between work done by the three Working Groups of IAG 1.4. Several of the group members (D. MacMillan, S. Lambert, H. Krásná, and Z. Malkin) also were in the IVS Aberration Working Group, which worked on a recommendation for a galactic aberration model for VLBI analysis and for use in the ICRF3 solution. S. Lambert, R. Heinkelmann, and Z. Malkin were also in the IAU ICRF3 working group.

Activities during the period 2019-2023

Modeling Source Structure Variation
In recent years, there has been considerable work done on the effect source structure in VLBI analysis. In the first significant investigation, Anderson, and Xu (2018) analyzed the VLBI

CONT14 continuous 2-week observing campaign data and concluded that source structure error amounts to half the VLBI error budget. Research continues how best to correct via imaging techniques the source structure error in the historical S/X data set (1980-present) as well as into the future and for next generation VGOS broadband observing.

Petrov et. al (2019) showed that the distribution of VLBI(S/X)-Gaia (optical) source position offset angles is nearly uniform over the sky. The offset directions were shown to be correlated with source jet direction; the distribution of the offset directions is correlated with the jet direction. Lunz et al. (2019) investigated the VLBI frequency dependence of the offsets and found similar behavior for K-band but not for X/Ka.

In an analysis of closure delays of 3417 celestial reference frame sources, Xu et al. (2019) found that the closure amplitude root mean square (CARMS) is a measure of how far away a source is from being compact and how much structure error contributes to residual delay errors in geodetic analysis.

Xu et al. (2021a) found that CARMS increases with the radio-optical distance, indicating that the structure is generally associated with a significant radio-optical offset. They also confirmed, for a reduced sample of sources, the finding of Y. Kovalev and his colleagues in earlier studies (e.g., Petrov et. al, 2019) that the radio-optical offset vectors are generally aligned with the direction of the radio jet.

ICRF3 and Other ICRF Accuracy/Precision Investigations

In 2018, the IAU ICRF3 working group created this new realization of the ICRS, which was then described in detail in Charlot et al. (2020). ICRF3 contains radio source positions for three different realizations of the ICRS at S/X-bands, X/Ka-bands, and K-band.

The IVS Working Group on Galactic Aberration completed its investigation and recommended a galactic aberration constant of 5.8 µas/yr for the ICRF3 solution. This constant was derived from a Calc/Solve solution using all data (1979 to 2018) that was to be used for the ICRF3 solution. Galactic aberration with this constant and with a reference epoch of 2015.0 was applied as an *a priori* model in the final ICRF3 solution. Applying the model has the effect of removing the decades long effect of aberration on VLBI source positions thus allowing better comparisons between VLBI and Gaia positions. The work of the IVS WG is summarized in MacMillan et al. (2019).

Mayer and Böhm (2020) investigated whether one can reduce the deformation between the VLBI CRF and the GAIA CRF by using different models (e.g., tropospheric raytracing, galactic aberration) and analysis strategies (gradient parameterization).

Modeling Troposphere Noise in VLBI Analysis

Nilsson and Balidakis (2021) investigated the impact of using tropospheric delays in the VLBI analysis obtained from raytracing though ERA5 model atmospheres. The results show that fixing the tropospheric delays to ERA5 makes the results (in terms of baseline length repeatability) much worse, except for the EURO sessions where a slight improvement could be seen in this case. However, when using a priori delays from ERA5, the tropospheric gradients can be fixed in the analysis without making the results worse and sometimes improving the results slightly.

Gravitational Antenna Deformation

A type of model that has recently been introduced into VLBI geodetic analysis is gravitational deformation of VLBI antennas, which mainly affects the height of the stations, typically at the centimeter level. At this time, deformation models have only been derived for six antennas, but there are efforts within the IVS to perform measurements of more antennas in the VLBI networks.

CONT17

Nilsson et al. (2019) investigated the precision and accuracy of Earth orientation parameters (EOP) from the CONT17 campaign.

MacMillan (2019) analyzed the differences between EOP estimated from the CONT17 simultaneous observing sessions of the two legacy (S/X) networks and the VGOS network. The EOP biases between the legacy networks were at the 1-sigma level. Based on the wrms differences of the EOP, the polar motion and UT1 precisions of the two networks were 20 µas and 2.3 µsec. Baseline length precision of the VGOS network was about 0.4 ppb compared with 0.8 ppb for the Legacy 1 network and 0.5 ppb for the Legacy 2 network.

Reference Frame Investigations

Karbon et al. (2019) examined the impact of using different TRF realizations on the CRF and the EOP. They found that using JTR2014, there were yearly signals and other artifacts in the EOP, compared to the EOP obtained using ITRF2014 or DTRF2014. However, the effect on the source coordinates were small.

Glaser et al. (2019) investigated the effect of local ties on the realization of terrestrial reference frames by performing simulations of VLBI, SLR, and GPS observations. VLBI is most affected by the size local tie uncertainties because of the inherent insensitivity of VLBI to the geocenter. In addition, local ties in the southern hemisphere were shown to be important for the realization of TRF scale.

VGOS Observing

Nilsson analyzed the performance of the VGOS sessions and compared their results to those obtained from simultaneous S/X sessions. The results show that the baseline length repeatability is slightly better for VGOS compared to the simultaneous R/R4 sessions. However, the EOP estimates were worse; this was probably due to the non-optimal network geometry of VGOS sessions.

T. Nilsson, E. Varenius, R. Haas at Onsala Space Observatory analyzed the local short-baseline experiments performed at Onsala (2019-2020) to determine the local tie vectors between the VGOS telescopes and the legacy S/X telescope (the ONETIE experiments). In this analysis, they investigated the impact of varying some of the modelling and parametrization, like thermal and gravitational deformation and the estimation interval of the tropospheric and clock parameters. There was a clear difference in the vertical components of about 5 mm when gravitational deformation of the ONSALA60 S/X antenna was not applied.
Xu et al. (2021b) evaluated the quality of VGOS broadband observations. Because the measurement noise of the VGOS system is so much less than for the S/X system, source structure effects are clearly visible in VGOS observations. Xu et al. (2021c) shows that it is possible to derive images directly from VGOS observations and to then derive structure corrections from these images. Applying the corrections can reduce CARMS by 80%.

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The impact of new estimates of models of stellar motion from VLBI on the alignment of the optically bright Gaia frame to ICRF3

D. S. MacMillan, A. Fey, J. M. Gipson, D. Gordon, C. S. Jacobs, H. Krasna, S. B. Lambert, Z. Malkin, O. Titov, G. Wang, M. H. Xu. Galactocentric acceleration in VLBI analysis – Findings of IVS WG8, Astronomy and Astrophysics, 630, A93, 2019. doi.org/10.1051/0004-6361/201935379.

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M. H. Xu, J. M. Anderson, R. Heinkelmann, S. Lunz, H. Schuh, and G. L. Wang. Observable quality assessment of broadband very long baseline interferometry system. Journal of Geodesy, 95:51, 2021b.

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WG 1.4.2 Improving VLBI-based ICRF and comparison with Gaia-CRF

Chair: Sébastien Lambert (France)

Members

- *Maria Karbon (Germany, now France)*
- *Daniel MacMillan (USA)*
- *Zinovy Malkin (Russia)*
- *François Mignard (France)*
- *Jacques Roland (France)*
- *Manuela Seitz (Germany)*
- *Stanislav Shabala (Australia)*

Since 2020, a global effort has been undertaken to improve the accuracy of VLBI solution and to understand the differences between the positions of the reference points at different wavelengths, both in terms of technique-dependent error (e.g., systematics) and astrophysics of AGN. The second item opens on a strong valorization of the radio and optical measurements for improving the modeling of the quasar machinery.

Activities during the period 2019-2023

Maintenance of the ICRF

As each year, new VLBI solutions provided by IVS analysis centers were assessed at the ICRS-PC of the IERS (Lambert & Arias 2021, 2022) to monitor the evolution of the VLBI CRF after the ICRF3. Recent VLBI catalog show no significant deformation, except rotations, with respect to the ICRF3. Against Gaia DR3, we notice significant quadrupolar deformations that are still matter of investigation on both VLBI or Gaia.

Liu et al. (2022) assessed the axis stability of the system on the basis of radio source position time series. They found a global spin of less than 1 microarcsecond per year and a scatter in the frame orientation of with 10 to 20 microarcsecond, which is still consistent with the expectations of the ICRF3, although two years of data were added.
Lambert & Malkin (2023) explored new methods for estimating robustly the deformations between frames, some based on the L1 norm. They propose several methods optimizing the detection of outliers and the deformation parameters estimates that will be used in next comparison campaigns at the ICRS-PC.

Gaia and around
The third data release of Gaia was published in 2022 (Gaia DR3, Vallenari et al. 2022). There is no change concerning astrometry with Gaia Early Data Release 3 (Gaia EDR3, Brown et al. 2021) but new products concerning quasars. Especially, the new release contains flags about the probability of being an AGN and being a variable AGN. In the meantime, the optical realization of the ICRF was published (Gaia-CRF3, Klioner et al. 2023) and the wording ICRF now comprises both the ICRF3 (Charlot et al. 2020) and the Gaia-CRF3, as expressed in the IAU resolution B3 (2022): (…) *as from 1 January 2022, the fundamental realization of the International Celestial Reference System (ICRS) shall comprise the Third Realization of the International Celestial Reference Frame (ICRF3) for the radio domain and the Gaia-CRF3 for the optical domain*.

The multifrequency-ICRF raises several questions about `stability': stability in position and stability in flux (or magnitude), given that the second has impact on the first by creating uncertainties in the coordinate determination. So that the maintenance of the ICRF should comprise both monitoring of VLBI positions but also monitoring of photometry.

New vision of AGNs
The AGN variability in Gaia DR3 is declined through the fractional variability in the G-band and in time series of about 800,000 AGN in RGB bands (Carnerero et al. 2023). Secrest (2022) showed that most variable sources were those exhibiting lowest radio-optical offsets, consistently with a paradigm where the ICRF sources are preferentially `blazars' in the sense they have their jet towards the observer, thereby boosting the photometry in average and in variations.

The astrophysical causes under the radio-optical offsets have been addressed in several recent works (post-Gaia DR2) suggesting that long radio-optical distances correspond to optical radiation emitted by a radio component of the jet, while short distances correspond rather to optical radiation emitted by the base of the jet and reinforced by the emission of the disk (Kovalev et al. 2017, Plavin et al. 2019, Lambert et al. 2021, Pierron et al. 2022). Moreover, the first category corresponds to sources whose jet contains stationary components (HBL-type blazar) while the second one corresponds to sources whose jet contains superluminal moving components (FSRQ). All these studies take – or will take – benefit from the numerous observations from the IVS and related programs, as well as from other non-astrometric measurements like, e.g., imaging at various wavelengths (Lister et al. 2021, de Witt et al. 2023). The consequences for frame realization as well as the existence (or not!) of subpopulations of sources more suitable (astrometric stability versus photometric stability) and their handling in the future realizations of the ICRF is under studies.

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JWG 1.4.3: Consistent Realization of TRF, CRF, and EOP

Chair: Robert Heinkelmann (Germany)
Vice-Chair: Manuela Seitz (Germany)

Overview

The International Astronomical Union / International Association of Geodesy / International Earth Rotation and Reference Systems Service (IAU/IAG/IERS) Joint Working Group (JWG) on the Consistent realization of TRF, CRF and EOP was created by IAU Commission A2, IAG Sub-commission 1.4 and IERS to continue the activity of the previous IAG Working Group 1.4.1 on 'Consistent Realization of ITRF, ICRF, and EOP that operated in the period 2015-2019.

Its purpose is to quantify the consistency of the current conventional reference frames and EOP as well as to assess the consistency of reprocessed and predicted EOP. The JWG strives to achieve this purpose through the computation of multi-technique CRF-TRF solutions together with EOP in one step, which can serve as reference solutions for comparisons. The JWG will investigate the impact of different analysis options, model choices and combination strategies on the consistency between TRF, CRF, and EOP. It will study the differences between multi-technique and VLBI-only solutions, study the possible contributions to EOP and frame determination by the LLR technique, study the differences between EOP derived by VLBI solutions at different radio wavelengths in cooperation with the IAU Division A WG on 'Multi-waveband Realizations of International Celestial Reference System', study the differences between EOP derived by VLBI solutions improved through Gaia (optical) data in cooperation with potential future IAU Division A WG(s) on VLBI – Gaia topics, study the effects on the results, when different data time spans are considered, compare the practically achievable consistency with the quality requirements deployed by IAG GGOS; and derive conclusions about future observing systems or analysis procedures in case the quality requirements cannot be met with the current infrastructure and approaches.

The webpage of the working group with an external and an internal area can be found here https://www.iers.org/IERS/EN/Organization/WorkingGroups/ConsistentRealization/consistentRealization.html.

Members

- *Claudio Abbondanza (US)*
- *Sabine Bachmann (Germany)*
- *Liliane Biskupek (Germany)*
- *Christian Bizouard (France)*
- *Xavier Collilieux (France)*
- *Aletha de Witt (South Africa)*
- *Anastasia Girdiuk (Germany)*
- *David Gordon (US)*
- *Robert Heinkelmann (Germany)*
- *Christopher Jacobs (US)*
- *Shuanggen Jin (China)*
- *Hana Krásná (Austria)*
- *Sebastien Lambert (France)*
- *Karine Le Bail (Sweden)*
- *Daniel MacMillan (US)*
- *Zinovy Malkin (Russia)*

- *David Mayer (Austria)*
- *Manuela Seitz (Germany)*
- *Benedikt Soja (Switzerland)*
- *Nicholas Stamatakos (US)*
-

Corresponding Members:
- *Grzegorz Bury (Poland)*
- *Alberto Escapa (Spain)*
- *Jose Ferrandiz (Spain)*
- *Juan Getino (Spain)*
- *Richard Gross (US)*
- *Florian Seitz (Germany)*
- *Krzysztof Sosnica (Poland)*
- *Jean Souchay (France)*
- *Daniela Thaller (Germany)*
- *Radoslaw Zajdel (Poland)*

Activities during the period 2019-2023

The kick-off meeting of the JWG was held as a video conference on June 9, 2020. Several presentations were made at the meeting including the Chair's introductory talk and reports on the latest activity of the group members and the plans for the nearest future.

The IERS ITRS Center, IGN, France, is working on the next ITRF release, ITRF2020, computed as a consistent TRF+EOP solution. IERS Rapid Service/Prediction Center (RS/PC), USNO (team leader N. Stamatakos), is planning to participate in the JWG activity to provide consistency between the JWG finding and recommendations and users of RS/PC products, including development of procedures and software used in the RS/PC. Research team of the Deutsches Geodätisches Forschungsinstitut, Technische Universität München, Germany (DGFI-TUM, M. Seitz, M. Bloßfeld, D. Angermann, M. Glomsda) is working on the problems of consistent realization of ITRS and ICRS in the framework of ITRF2020. The analysis is performed making use of the normal equations provided by the IVS Analysis Centers. The goal is to estimate for the first time EOP series and CRF solution consistent with DTRF (ITRS realization of DGFI-TUM). Two DTRF2020 solutions are planned: the first one will be EOP+TRF solution computed with the source coordinates fixed to ICRF3, and second one will be EOP+TRF+CRF solution. Several details of the analysis strategy is under investigation. The joint research team of Eidgenossische Technische Hochschule, Zürich, Switzerland, and Jet Propulsion Laboratory, USA (B. Soja, C. Abbondanza, T.M. Chin, R. Gross, M. Heflin, J. Parker, X. Wu) is working on the project aimed at joint consistent determination of EOP, TRF, and CRF. Two kinds of software are used. KALREF based on Kalman filtering is used for joint determination of EOP and TRF for JTRF2014. Software SREF based on square-root information filter is used for JTRF2020 and is capable of jointly estimating EOP, TRF, and CRF. SREF is currently under intensive development, so no definite EOP+TRF+CRF solution is available yet. Nevertheless, JPL plans to contribute a joint TRF/CRF solution to ITRF2020. Research team of the Institute for Geodesy of Leibniz Universität, Hannover (L. Biskupek and J. Müller) is working on the implementation of lunar laser ranging (LLR) to the joint solution. Research team of the Federal Office of Metrology and Surveying, Austria, is working on testing of models and analysis options on the TRF, EOP, and CRF with particular emphasis on new models included in the ITRF2020 and ray-tracing troposphere modeling.

Joint international team (A. de Witt, C. Jacobs, D. Gordon, J. Quick, J. McCallum, H. Krasna, B. Soja, K. Le Bail, S. Horiuchi) is working on extending and improvement of the K-band CRF solution with further perspective of computing independent K-band CRF+TRF+EOP solution. Collocation of GNSS receivers at all VLBA sites would allow a direct comparison of VLBI and GNSS TRF realizations.

The IVS Combination Center at Federal Agency for Cartography and Geodesy (BKG), Germany, (S. Bachmann, A. Girdiuk, D. Thaller) is working on consistent realization of CRF, TRF, and EOP as an IVS combined products. The main activities of this group include:

- Setting up BKG 2020 solution for IVS products w.r.t. ITRF2020 requirements;
- Extending routine IVS combination by source parameters for consistent determination along with station positions and EOP;
- Multi-technique combined solutions (VLBI, GNSS, and potentially SLR) with the full set of parameters related to the reference systems, i.e., TRF, CRF and EOP.

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Commission 2 – Gravity Field

https://com2.iag-aig.org/

President: Adrian Jäggi (Switzerland)
Vice President: Mirko Reguzzoni (Italy)

Structure

Sub-Commission 2.1:	Land, Marine and Airborne Gravimetry
Sub-Commission 2.2:	Geoid, Physical Height Systems and Vertical Datum Unification
Sub-Commission 2.3:	Satellite Gravity Missions
Sub-Commission 2.4:	Regional Geoid Determination
Sub-Commission 2.4a:	Gravity and Geoid in Europe
Sub-Commission 2.4b:	Gravity and Geoid in South America
Sub-Commission 2.4c:	Gravity and Geoid in North and Central America
Sub-Commission 2.4d:	Gravity and Geoid in Africa
Sub-Commission 2.4e:	Gravity and Geoid in Asia-Pacific
Sub-Commission 2.4f:	Gravity and Geoid in Antarctica
Sub-Commission 2.5:	Satellite Altimetry
Sub-Commission 2.6:	Gravity Inversion and Mass Transport in the Earth System
Study Group 2.1.1:	Developments in Gravity Instrumentation, Analysis and Applications
Study-Group 2.4.1:	Downward Continuation of Airborne Gravity Data for Local Geoid Improvement
Joint Working Group 2.1.1:	Establishment of the International Gravity Reference Frame
Joint Working Group 2.1.2:	Unified file formats and processing software for high-precision gravimetry frame
Joint Working Group 2.2.1:	Error assessment of the 1 cm geoid experiment
Working Group 2.6.1:	Geodetic observations and physical interpretations in the Tibetan Plateau

Overview

This report presents the activities of the entities of Commission 2 for the reporting period 2019- 2023. As shown above, Commission 2 consists of 6 sub-commissions (SC), whereby SC 2.4 is composed of 6 regional sub-commissions, and several Working Groups, Joint Working Groups and Study Groups. Most of these entities were very active and made significant progress in their specifically stated objectives and program of activities despite the severe impacts of Covid-19 during the first years. The corresponding reports can be found below, and the main achievements are summarized in the end of this overview section.

Activities during the reporting period 2019-2023

Commission 2 fostered and significantly supported main tasks and objectives of the present IAG period, such as the establishment of the International Height Reference Frame (IHRF; cf. IAG 2019 resolution no. 3), and the establishment of the Infrastructure for the International Gravity Reference Frame (IGRF, cf. IAG 2019 resolution no. 4).

Commission 2 was also very active in advocating mass transport from space by establishing the Combination Service of Time-variable Gravity Fields (COST-G) at the 2019 IUGG General Assembly as new Product Center of the IGFS that now operationally provides consolidated monthly global gravity models with improved quality, robustness, and reliability. Moreover, Commission 2 initiated a new Horizon 2020 project to increase the visibility towards EU/Copernicus by developing a prototype for a groundwater product based on the COST-G products as a new cross-cutting application of the existing product portfolio of in total three Copernicus core services.

Commission 2 also actively contributed to GGOS-related activities. As a voting member of the GGOS Executive Committee (EC) the president of the Commission 2 was participating in the monthly GGOS EC telecons.

Commission 2 was involved in the organization of several scientific conferences and workshops, as well as sessions at EGU and AGU. Naturally, however, all these activities were severely limited due to the Covid-19 pandemic situation during the first years of the IAG period 2019-2023.

Commission 2 and its components also triggered the submission of a new IAG resolution and a new IUGG resolution, which shall both be adopted at the IUGG General Assembly 2023 in Berlin, Germany:

- IAG resolution for the International Terrestrial Gravity Reference System (ITGRS)
- IUGG Resolution on Sustained Terrestrial Water Storage (TWS) Monitoring by Dedicated Gravity Satellite Constellations

Conferences and Meetings

Gravity, Geoid and Height Systems (GGHS) 2020/2022, Austin, Texas

The official Commission 2 symposium was originally planned as a joint symposium with the IGFS that should have been held in September 2020 in Austin, Texas, at the premises of the University of Texas. Due to the Covid-19 pandemic the GGHS had to be postponed to 2022 where it was eventually held from September 12-14, 2022 in a hybrid format at the Thompson Conference Center on the campus at the University of Texas at Austin. GGHS 2022 was composed by 7 sessions. With a total of 87 attendees (62 in-person, 25 remote), still relatively short after the Covid-19 pandemic, the program had to be shortened from 5 to 3 days. Related papers will be published as part of a special volume dedicated to the three IAG Symposia GGHS, REFAG and Commission 4, entitled "Gravity, Positioning and Reference Frames".

IAG General Assembly 2021, Beijing, China

Commission 2 was also deeply involved in the preparation of the scientific program of the virtual IAG General Assembly 2021, Beijing, China. The organization of the two main gravity- related sessions have been coordinated by the president ("Temporal gravity field") and vice-president ("Static gravity field") of Commission 2, and it also supported the preparation of several joint sessions.

IUGG General Assembly 2023, Berlin, Germany

Commission 2 contributed to the preparation of the scientific program of the IUGG General Assembly 2023, Berlin, Germany. The organization of the two main gravity-related sessions have been coordinated by the president (G03: Time-variable gravity field) and steering committee members (G02: Static gravity field and height systems) of Commission 2, and it also supported the preparation of several joint sessions.

Further theme-specific events

During the reporting period 2019-2021, commission 2 also fostered and supported several theme-specific conferences, meetings and workshops, which are presented in detail in the following individual reports of the respective entities of Commission 2.

Activities of the Sub-Commissions

SC 2.1 Land, Marine and Airborne Gravimetry

Though COVID-19 initially slowed down field activities, in-person meetings, and workshops, the second half of the 2019-2023 term saw a return to normal activity for SC 2.1 together with its associated joint working and study groups, JWG 2.1.1, and SG 2.1.1. In particular, we highlight the efforts of JWG 2.1.1, "Establishment of the International Terrestrial Gravity Reference System", whose proposal was formally presented to the IAG Executive Committee by the President of Commission 2 in April of 2021. A corresponding resolution shall be adopted at the IUGG General Assembly 2023 in Berlin, Germany.

SC 2.2 Methodology for Geoid and Physical Height Systems

During the reporting period, SC2.2 activities focused mainly on the publication of the results of the "1 cm geoid experiment", the realization of the International Height Reference System (IHRS) through the Implementation of the International Height Reference Frame (IHRF), the organization of a dedicated sessions within the 2021 European Geosciences Union, the 2021 IAG Scientific Assembly, 2022 European Geosciences Union, 2023 European Geosciences Union and the organization of the next Gravity Geoid and Height Systems (GGHS) conference. The SC2.2 JWG2.2.1 "Error assessment of the 1 cm geoid experiment" has started work to identify and quantify potential error sources, and to develop and improve methods for deriving realistic error estimates for the geoid models and the gravity potential values at the IHRS stations in the Colorado 1 cm geoid experiment.

SC 2.3 Satellite Gravity missions

The main activities of SC 2.3 include the promotion of scientific investigations regarding current and future gravity field missions. A new combination service for Level-2 and Level-3 time-variable gravity field solutions (https://cost-g.org), with the purpose to provide unique and user-friendly gravity products to a wider user community, originally developed in the frame of the Horizon 2020 Framework Program of the European Commission, has now become an integral component of the IGFS infrastructure. In the hydrological branch, one of the already established Essential Climate Variables (ECVs) of the Global Climate Observing System (GCOS) is groundwater. The Steering Committee of GCOS recommended in December 2020 to establish also Total Water Storage (TWS), the prime output of GRACE and GRACE-FO, as an additional ECV. This process was strongly supported by SC 2.3 members. Various SC 2.3 members are also involved in activities to realize future mass change missions which are currently discussed at various space agencies to guarantee gapless observations after GRACE-FO and to increase spatial and temporal resolution of mass transport data by dedicated future mission constellations.

SC 2.4 Regional Geoid Determination

SC 2.4 coordinates the activities of the 6 regional sub-commissions on gravity and geoid determination and supports the organization of conferences, workshops and schools. The focus of the reporting period was the collection, validation, and inclusion of new global and regional elevation models in the European database, the organization of outreach events like the SIRGAS webinar on the International Terrestrial Gravity Reference System (ITGRS) and its realization (ITGRF)", and the determination of a recent precise geoid models for the whole continent of Africa and South America. Further highlights were the release of the first North American geoid model that was jointly computed by NGS, NRCan, and INEGI, the organization of the first Asia Pacific geoid workshop, and investigations about the combination of the terrestrial gravity data in Antarctica with a high-resolution spherical harmonic models.

SC 2.5 Satellite Altimetry

Over the period of 2019-2023, the IAG sub-commission 2.5 mainly focused on the following research activities:

- New international team on mean sea surface (MSS) topography and marine gravity field for upcoming SWOT and existing missions.
- Significant publication contributions to ESA's "25 Years of Progress in Radar Altimetry" Symposium.
- Integrated use of altimetry and space geodetic techniques in monitoring global and coastal sea levels, inland surface water levels, and elevation changes over mountain glaciers.
- New applications that use altimeter-derived gravity to detect undersea volcano eruptions and submarine plate tectonic motions.
- New developments in data processing algorithms, validation and calibration.

SC 2.6 Gravity and Mass Transport in Earth System

SC 2.6 promotes and supports scientific research concerning spatial and temporal variations of gravity related to the dynamics of the Earth's interior, land surface, oceans, cryosphere, and atmosphere. A new international team supported by ISSI the International Space Science Institute (ISSI) and ISSI-Beijing was established in 2020 for gravity field modelling and its applications in the Earth system. The SC2.6 also co-organized the 19th International Symposium on Geodynamics and Earth Tides (G-ET) in Wuhan, China during 23-26 June 2021 with the sub-commission 3.1 Earth Tides and Geodynamics. Another important activity of SC2.6 was the initiation of WG2.6.1, aiming at the study on mass transport, geodynamic, and climate change of the Tibetan Plateau based on multiple geodetic observations.

Activities of Study Groups

Two SGs (SG 2.1.1 and SG 2.4.1) reporting to Commission 2 via SC 2.1 and SC 2.4, and Commission 2 is involved in ten JSGs as a partner, but none of these report directly to Commission 2. Their reports can be found in the ICCT section, and the Commission 1 and 3 sections.

Activities of Working Groups

One WG (WG 2.6.1) and 3 JWGs (JWG 2.1.1, 2.1.2, 2.2.1) are reporting to Commission 2. Their reports can be found in the corresponding chapters. Commission 2 is involved in nine further JWGs as a partner, but none of these report directly to Commission 2.

Sub-commission 2.1: Land, Marine and Airborne Gravimetry: Standards, Observations, and Innovation

Chair: *Derek van Westrum (United States)*
Vice Chair: *Przemyslaw Dykowski (Poland)*

Overview

General comment on the impact of COVID-19 in 2020 and early 2021

The severe impacts of COVID-19 on the activities of Sub-commission 2.1 and its members cannot be overstated. Each individual institution has almost surely been directly affected by the virus and the limitations it generated, but COVID-19 has also impeded scientific progress in the field of gravimetry in general.

One of the most visible impacts relates to conferences and symposia. Scientific meetings are the most important activity in terms of scientific development and increasing the outreach of scientific progress. Unfortunately, on-line meetings over the past year or so have been useful – but not ideal – conduits for communication.

The second major impact of COVID-19 was purely practical: Travel restrictions imposed significant limitations on gravity surveys worldwide. It also led to the cancellation or postponement of absolute instrument comparisons – activities crucial to the gravity reference distribution system.

As COVID-19 receded, we are pleased to report a return to near-normal levels of activity in the terrestrial gravity community: this includes in person meetings (including GGHS, and a workshop dedicated to the ITGRF in Leipzig), field activities, as well as formal instrument comparisons (NKG-CAG-2022).

General activities of the Sub-commission

Cooperation with the CCM on Instrument Comparisons and Traceability

The results of the 2018 European regional comparison of absolute gravimeters at Wettzell (EURAMET.M.G-K3) were published in 2020 (Falk et al., 2020). Other regional comparisons had to be cancelled or postponed due to COVID-19. In conjunction with the Consultative Committee on Mass (CCM), the Sub-commission 2.1 has secured the Table Mountain Geophysical Observatory in Boulder, Colorado, USA as the site of the next International Comparison of Absolute Gravimeters in August-September 2023.

A special issue of the Journal of Geodesy titled “Reference Systems in Physical Geodesy” was initiated in 2020 and finalized 2023 (Sánchez et al. 2023) which received 7 (out of 18) significant contributions related to SC2.1 and JWG 2.1.1: these document concepts for reference stations, evaluation of comparisons, and application for long-term monitoring of gravity changes.

Organization of Meetings and Conferences

While much “local” scientific work was able to continue during the pandemic, meetings, workshops, and conferences were greatly curtailed in 2020 and into 2021. However, virtual conferences like EGU and AGU did go forward, both with well attended sessions on terrestrial gravity and its applications: EGU Session G4 and AGU Session G016.

As post-COVID activities resumed, the Sub-commission actively supported meetings and workshops devoted to

- Static Gravity field at the IAG Scientific Assembly in June 2021

- Implementation of the International Gravity Reference System/Frame (Leipzig, April 2022)
- Gravity, Geoid, and Height Systems (GGHS, Austin, USA, September 2022)
- Metrology, and cooperation with the CCM (Vienna, May 2023)

Regional activities in gravimetry

Asia (reported by Wu Shuqing and Przemyslaw Dykowski)

- *China:* The past few years have seen a heavy emphasis on cold atom gravity meters in China. More than ten institutes or universities have developed such instruments (six Chinese instruments participated in the ICAG-2017 in NIM China Beijing). Efforts are also focused on the deployment of absolute gravimeters on moving platforms such as marine gravimetry, and institutes are investigating the use of quantum AGs as a replacement for superconducting gravimeters.
- *Indonesia:* Advanced activities related to new geoid development. Gravity activities include A10-049 gravimeter surveys on multiple stations. Among those stations several are used as reference for airborne surveys for consistently improving coverage of gravity surveys in Indonesia.

North America (reported by John Crowley, Derek van Westrum, and Przemyslaw Dykowski)

- *Canada:* The present focus is to update the Canadian Gravity Standardization Net (CGSN) from IGSN71 to IGRS. The project consists of re-adjusting the entire network of historical relative gravity ties with all absolute gravity measurements in Canada. The adjustment also includes relative gravity ties to primary stations (and excenters) in USA and Greenland. These are included to improve robustness of the network. The adjustment does not include absolute gravity measurements outside Canada.

  Adjusted gravity will represent epoch 2020.0. The epoch transfer is done using absolute and relative time series and a gravity model determined from the GRACE monthly data. The data clean-up is overall completed and preliminary results are available. The adjustment solved the following parameters: gravity, gravity velocity, scale, and factor and drift for relative meters. Gravity values are in the zero-tide system.

  In 2019, 14 sites of the CGSN were observed with the FG5. Field surveys were stopped due to COVID-19 in 2020. The focus is now to take monthly gravity measurements with the FG5 at the Canadian Absolute Gravity Site (CAGS, fundamental site for gravity) for a better understanding of the gravity variation (secular and seasonal). We plan to have the A10 back in operation soon in support of the national network. FG5 will be mostly limited to CAGS.

  We decommissioned our GWR superconducting gravimeter (Model TT70, serial T012) on May 3rd, 2023 due to a critical failure that resulted in a significant increase in helium loss and compounding issues that have been occurring over the past few years. A gPhoneX continuous relative gravity meter was installed at CAGS in March of 2022 and it has been running continuously since. We are working on a comparative analysis of the GWR and gPhoneX data using a one year period of overlap.

  We have a field deployable Absolute Quantum Gravimeter being built for us in

France and expect to receive it in January of 2024.

- *United States:* The National Geodetic Survey continues its Gravity for the Redefinition of the American Vertical Datum (GRAV-D) project, collecting airborne gravity over the United States and its territories. The project is currently ~98% complete, projected to finish data collection in late 2023. A paper by van Westrum et al was published in January 2021, describing a ground truth validation experiment in the rugged terrain of Colorado (van Westrum et al., 2021).

  Preparations are underway to get the Table Mountain Geophysical Observatory (TMGO) in Boulder, Colorado ready for the International Comparison of Absolute Gravimeters (ICAG) in August-September of 2023. The comparison will be operated in conjunction with the CCM-WGG and the U.S. National Institute of Standards and Technology. Approximately 40 instruments from over 20 countries are expected to participate.

  Though COVID-19 has slowed down most field activities, analyses of gravity instruments still continued. Relativistic effects in FG5 type instruments were investigated, as well as a side by side comparison of gPhoneX tidal gravimeters at the Table Mountain Geophysical Observatory (to be published).

  The Geoid Monitoring Service (GEMS) is beginning near Anchorage, Alaska, with A10-025 and CG6 measurements collected in summer 2021. Subsequent absolute gravity observations were also collected in the northeast U.S. (2022) and southeast U.S. (2023) as part of the time change project.

  One gPhoneX (#162) has been running continuously at TMGO since December 2019, and three more instruments (to be deployed elsewhere in the US) have been running on site since October 2022.

  Geopotential surveys (spirit leveling and absolute gravity) have been carried out at various optical clock laboratories at NIST and the University of Colorado to support gravity redshift observations.

- *Mexico:* A10 gravimeter (sn 056) has been delivered in 2021 to Instituto Nacional de Estadística y Geografía (INEGI) for works related to gravity reference frames in the country. Prior to 2021 absolute gravity surveys were performed with assistance of US institutions.

Europe (reported by Mirjam Bilker-Koivula, Przemyslaw Dykowski)

- *Finland:* Repeated absolute gravity measurements are continuing in all Nordic countries. Two papers analysing long time series were published this year: Bilker-Koivula et al (2020) and another by Olsson et al. (2019). To enable all Nordic Countries to obtain traceability to the SI units for their absolute gravimeters and compare their instruments to make sure they are compatible, a Nordic Comparison of Absolute Gravimeters, NKG-CAG-2022, was organized between May 9th and July 1st 2022 at the Onsala Space Observatory of Chalmers University in Sweden. It was organised under the umbrella of the Nordic Geodetic Commission by the Chalmers University, Lantmäteriet and the Finnish Geospatial Research Institute, that acted as the pilot laboratory for metrology. 15 instruments of 12 organisations participated. A report is under preparation.

  Marine gravity measurements in the Baltic Sea have been ongoing in order to calculate an improved geoid model for the Baltic Sea. Since the end of the FAMOS project (co-funded by the EU Connecting Europe Facility), the work on finalizing the FAMOS geoid model is continued under the supervision of the Chart Datum Working Group of the Baltic Sea Hydrographic Commission. The FAMOS geoid will define the reference height surface for the Baltic Sea Chart Datum, the new common height reference for the Baltic Sea. A follow-up project, BalMarGrav, funded by EU's Interreg Baltic Sea Region Programme for the period 2022-2024, aims to harmonize gravity data in the South and East Baltic Sea regions, which the goal to improve the marine geoid in these regions.

In the winter of 2019-2020 absolute gravity measurements were performed on the Finnish Antarctic Station Aboa. The measurements are part of a long time series that together with continuous GNSS observations and modelling of the ice field around the station will help us to better understand the Glacial Isostatic Adjustment (GIA) mechanisms in Dronning Maud Land.

- *Greece:* A10 and relative surveys regarding gravity contribution required to become a International Height Reference System (IHRS) station (Natsiopoulos et al., 2021).
- *Italy:* Gravity monitoring at Etna volcano currently includes 3 iGrav superconducting gravimeters, an Absolute Quantum Gravimeter, number of Scintrex CG-6 instruments as well as the development of a "gravity imager" based on multiple MEMS type instruments (Carbone et al., 2020, Greco et al., 2020, Carbone et al., 2021). This set of instruments is a perfect showcase how precise modern gravimeters can be used in a very practical manner.
- *Ireland/Northern Ireland:* In 2019 works continued on the establishment of the AGN Ireland gravity network with cooperation between Ordnance Survey Ireland and the Institute of Geodesy and Cartography, Warsaw, Poland (IGiK). During 2019 in total 90% of the surveys have been done with the A10-020 absolute gravimeter (by IGiK Poland). In 2020 further activities have been postponed due to the COVID-19 pandemic, yet both parties express interest to finish the works. Related to the project continuous tidal gravity record has been completed in early 2021 in order to evaluate ocean tidal loading effect models for the island of Ireland (Dykowski et al., 2021). Project was completed in late 2022.
- *Sweden:* final works concerning the gravity reference network in Sweden have been completed. The system is named the RG-2000 and is based on a combination of FG laboratory stations, A10 field stations and a densification network. Results have been published in Engfeldt et al. (2019).
- *Poland:* Activities in Poland include repeated surveys with A10-020 and FG5-230 absolute gravimeters at Borowa Góra and Jozefosław Observatories, respectively. Additionally, both instruments participate in 2 instrument AG comparisons at Borowa Góra Observatory in 2019, 2020 and early 2021. Joint surveys support the operation of the iGrav-027 superconducting gravimeter. The Borowa Góra Observatory is currently actively working in order to become and ITGRS reference and comparison station. In late 2021 an AQG-B07 absolute quantum gravimeter has been installed at BG Observatory of IGiK.

  Within the framework of EPOS-PL repeated absolute gravity surveys with the A10-020 gravimeter (IGiK) as well as relative densifications surveys with a Scintrex CG6 gravimeter are performed in the Silesian region on active mining areas (so called MUSE polygons - Mutke et al., 2019). In the years 2019-2021 4 additional campaigns have been performed (a total of 7 campaigns in 4 years). Also within the EPOS-PL project tidal gravity data is collected from multiple gPhoneX as well as other tidal gravimeters in Poland. The network of stations performing tidal gravity records has grown visibly in Poland in the last couple of years (Dykowski et al., 2021).

In 2020 first campaigns in the Polish shoreline were conducted with a MGS-6 seaborne gravimeter owned by Gdańsk Unversity of Technology (Pyrchla et al., 2020). Further surveys are expected to be done in the upcoming years.

Absolute quantum gravimetry

A visible growth in interest for the Absolute Quantum Gravimeter (AQG, manufactured by French company Exail, formerly iXblue and a while back originated as MuQuans) is observed. Currently more than 10 units are either already delivered or in delivery to scientific/academic institutions around the world. Instruments are delivered in two variants: A – laboratory type, B – field capable type (temperature stabilized). Already multiple presentations (Champollion et al., 2020, Vermeulen et al., 2020, Güntner et al., 2021) and several publications (Cooke et. al., 2021) had been published on the operation and results coming from those instruments. This subject is surely of great current interest in the gravity community. Additionally, Exail is developing and absolute quantum gradiometer. In principle, it is based on two AQG instruments in a single configuration (Janvier et al., 2020, Janvier et al., 2021).

A promising project is under way in Germany related to a very long baseline atom interferometer (VLBAI). A 10 meter atom interferometer is being built, which presents interesting potential in gravimetry and possible creation of a unique gravity reference site (Schilling et al., 2020).

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Joint Working Groups of Sub-commission 2.1:

JWG 2.1.1: Establishment of the International Gravity Reference Frame

Chair: *Hartmut Wziontek (Germany)*
Vice Chair: *Sylvain Bonvalot (France)*

Members

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- Przemyslaw Dykowski (Poland)
- Andreas Engfeldt (Sweden)
- Reinhard Falk (Germany)
- Jaakko Mäkinen (Finland)
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- Ilya Oshchepkov (Russia)
- Vojtech Palinkas (Czech Republic)
- Victoria Smith (UK)
- Ludger Timmen (Germany)
- Claudia Tocho (Argentina)
- Christian Ullrich (Austria)
- Michel van Camp (Belgium)
- Derek van Westrum (USA)
- Marc Véronneau (Canada)
- Leonid Vitushkin (Russia)
- Shuqing Wu (China)
- Toshihiro Yahagi (Japan)

Activities and publications during the period 2019-2023

Status of the International gravity reference system and frame

The IAG Joint Working Group 2.1.1 has further developed the International Gravity Reference System and Frame to achieve an accurate, homogeneous, long-term global recording of Earth’s gravity, while taking advantage of the potential of today’s absolute gravity measurements. The concept is documented in Wziontek et al. (2021), see also Fig. 1.

In early 2022, an unfortunate coincidence of the chosen acronym IGRF for the International Gravity Reference Frame was brought to attention. This acronym is already used by IAGA for the International Geomagnetic Reference Field since the 1960th. To avoid confusion within IUGG after a discussion in the IAG EC, the members of JWG 2.1.1 decided to change both, name and acronym to International Terrestrial Gravity Reference System/Frame, ITGRS/ITGRF. Therefore, the terms used in Wziontek et al. (2021) need to be updated in future use. Specifically, the IGRS conventions 2020, which cover substantial corrections for temporal gravity changes should now be referred to the ITGRS

The proposed definition of the International Terrestrial Gravity Reference System (ITGRS) is based on the instantaneous acceleration of free-fall, expressed in the International System of Units (SI). This quantity is measured by absolute gravimeters and plays an important role in particular in metrology (e.g. for the realization of the kilogram). By the correction of time depended effects due to tides, mass redistributions in atmosphere and polar motion, the conventional quantity „acceleration of gravity" is derived. To ensure the invariance of the system over time, the constant components of these time dependent corrections are part of the system definition: zero-tide system for the tidal correction, standard atmosphere ISO 2533:1975 and the reference pole of the International Earth Rotation and Reference Systems Service (IERS).

A draft resolution to adopt the ITGRS was prepared and will be proposed to the IAG resolution committee during the IUGG GA in Berlin, July 2023.

A set of conventional models (minimum requirements) for the correction of temporal gravity changes based on and compatible with International Absolute Gravimeter Base Network (IAGBN) Processing Standards is proposed with the IGRS Conventions 2020 (Wziontek et al., 2021).

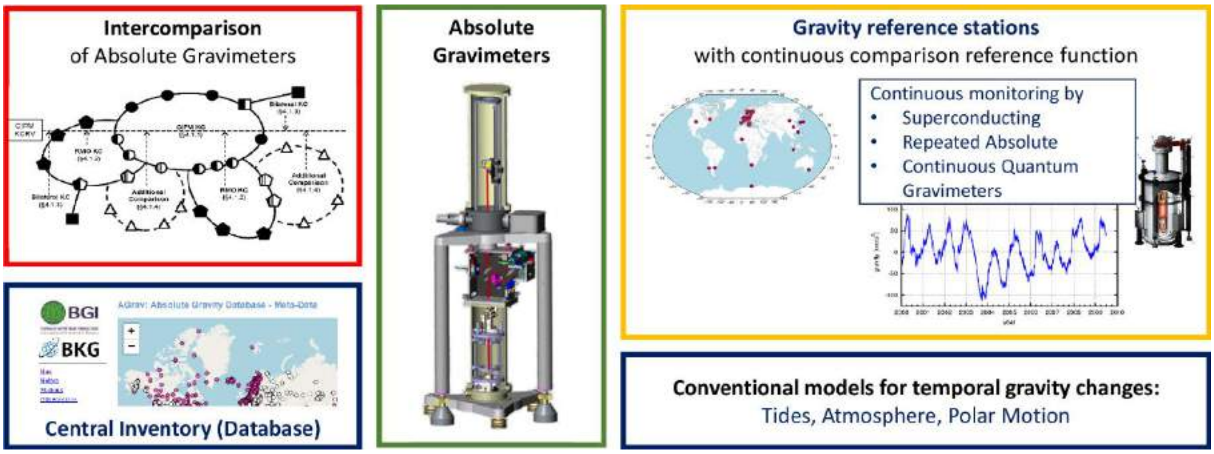

Fig. 1: Concept for the International Gravity Reference Frame.

The International Gravity Reference Frame (IGRF) is realized by measurements with absolute gravimeters (AGs) at the accuracy level of a few-µGal. A common reference level and the traceability to the SI of the AGs is ensured by key comparisons at the CIPM level and complemented by repeated regional comparisons. Comparison sites with extended facilities to compare AGs will therefore play an important role to ensure compatibility of AGs in long-term, needed for monitoring gravity variations at reference stations of the IGRF. Core stations with at least one available space geodetic technique will provide a link to the terrestrial reference frame. Continuous monitoring of temporal gravity variations and repeated absolute gravity observations are therefore recommended for GGOS core sites

In order to make the gravity system accessible to the users, efforts have been started to build up an infrastructure based of absolute gravity stations. This requires the support of and the cooperation with National agencies, which is encouraged by IAG resolution No. 4 of 2019. Compatible first order gravity networks have to be to established and information about existing absolute gravity observations needs to be provided. Such infrastructure should advantageously replace the previous IGSN71 network. The database AGrav at BGI and BKG will serve as a central archive for observations and all comparison results. Unfortunately, due to security issues, the database is not accessible since February 2022. However, efforts are taken by BGI and BKG to make this important service available again, based on a modern web application.

Reprocessing of comparisons of absolute gravimeters

Comparisons of absolute gravimeters (AGs) are essential for the IGRF. With a reprocessing and the analysis of recent comparisons (Pálinkáš et al. 2021), a concept for the evaluation of AG comparisons considering correlated observations and strictly applying the law of error propagation was published. All major AG comparisons from 2009 to 2018 were uniquely reprocessed, providing a frame for the elaboration of future comparisons. The significance of differences between FG5, FG5X and other types of gravimeters was assessed, concluding that both major groups of AGs can be described by the same normal distribution and that its standard deviation of 2.1 µGal represents the experimentally documented reproducibility of FG5/X.

Meetings and further activities

Due to the pandemic the first meeting of the JWG 2.1.1 with 43 participants was held online on Mach 17th 2021, where the concept of ITGRS and ITGRF was finally discussed and approved by the members prior to presentation at the IAG EC on March 26th by the president of Commission 2, Adrian Jaeggi.

The ITGRS was also presented at the Annual Meeting of the Indonesian Gravity Consortium (KGI) on March 31st 2021.

A collaboration with SIRGAS was initiated with the well-recognized online presentation "El nuevo Sistema de Referencia Internacional de Gravedad (IGRS) y su materialización (IGRF)" on March 5th 2021 held by E. D. Antokoletz in Spanish with more than 100 participants and a considerable outreach. The cooperation will be continued with SIRGAS working group WGIII (Vertical Datum).

With the relaunch of the GGOS web site, the IGRF was included in the section of geodetic reference frames: https://ggos.org/item/gravity-reference-frame

Several web meetings were held in January and February 2022, for the preparation of the workshop in April and to discuss solution about acronym and name.

The concepts of ITGRS/F were also presented to the space geodetic community at the GGOS Unified Analysis Workshop with two presentations (Wziontek et al. 2022a/b) and to the CCM-WGG (May 16 2023).

With two web meetings (Feb 22, May 11) in 2023 as well as during the Extended Workshop of CCM_WGG (May 16-17, 2023) a draft IAG resolution for the ITGRS was discussed and finalized and submitted to president of IAG commission 2.

A special issue in Journal of Geodesy titled "Reference Systems in Physical Geodesy" was initiated in 2020 and finalized 2023 (Sánchez et al. 2023) which received 7 (out of 18) significant contributions related to JWG 2.1.1., documenting concepts for reference stations, evaluation of comparisons and application for long-term monitoring of gravity changes and Scandinavia.

First IGRF workshop

A successful workshop dedicated to the ITGRF was held in Leipzig, Germany, April 11-13 2022, sponsored by the Federal Agency for Cartography and Geodesy (BKG). The main objective was to propose and develop national infrastructure, discuss best practices in gravimetric measurements, monitoring of absolute gravimeters, and time variable gravity

Fig. 2: Local participants of the "First IGRF Workshop", April 2022 in Leipzig, Germany.

corrections. It was the first meeting after the pandemic with local attendance (23 in person), but included remote participants (62 registered) too. Within 5 sessions the following topics were discussed:

Session 1: Establishment of the IGRF from national perspectives (8 local, 8 remote contributions)

Session 2: Standards in absolute gravimetry (2 contributions)

Session 3: Monitoring of Absolute Gravimeters (3 local, 4 remote contributions)

Session 4: Best practices (3 local, 3 remote contributions)

Session 5: Time variable gravity corrections (4 local, 1 remote contributions)

Practical aspects of the operation of FG5 absolute gravimeters were demonstrated on the example of FG5-101 on site, e.g. including an alternative drop acquisition system (Kren et al. 2016). In session 1, many reference station and compatible infrastructure worldwide were proposed, which are supposed to form the basis of a future ITGRF. Presentations were available for download in 2022 from the website of the workshop and are partially permanently accessible from Zenodo . JWG 2.1.1. highly appreciates the support and funding provided by BKG.

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Scherneck HG, Rajner M, Engfeldt A (2020) Superconducting gravimeter and seismometer shedding light on FG5's offsets, trends and noise: what observations at Onsala Space Observatory can tell us. J Geod 94, 80, https://doi.org/10.1007/s00190-020-01409-0.

Schilling M, Wodey É, Timmen L. et al. (2020) Gravity field modelling for the Hannover 10 m atom interferometer. J Geod 94, 122, https://doi.org/10.1007/s00190-020-01451-y.

Wziontek, H., Bonvalot, S., Falk, R., Gabalda, G., Mäkinen, J, Pálinkáš, V., Rülke, A., Vitushkin, L.: Status of the International Gravity Reference System and Frame. J Geod 95, 7 (2021), https://doi.org/10.1007/s00190-020-01438-9

Wziontek, H., Sylvain, B.; IAG Joint Working Group 2.1.1, Advances in the definition and realisation of a modern gravity reference system, 2022, UAW 2022 https://doi.org/10.5281/zenodo.7270578

Sub-commission 2.2: Geoid, Physical Height Systems and vertical datum unification

Chair: *Georgios S. Vergos (Greece)*
Vice Chair: *Rossen S. Grebenitcharsky (Kingdom of Saudi Arabia)*

Overview

The IAG Sub-Commission 2.2 (SC2.2) promotes and supports scientific research related to methodological questions in geopotential, geoid and height determination, both from the theoretical and practical perspectives. The former refers in particular on methodological questions and practical numerical applications contributing to the realization of IHRS with the required sub-centimeter accuracy, the combination of local/regional vertical reference frames and their unification to the IHRF. This includes (among others):

- Realization of the International Height Reference System.
- Height system unification at regional scales and unification to the IHRF.
- Studies on W0 determination.
- Studies on data requirements, data quality, distribution and sampling rate to reduce the omission error to the sub-centimeter level in different parts of the world.
- Contributions of alternate data sources, such as altimetry sea surface heights and GNSS geometric heights to geopotential modeling and geoid determination at reference benchmarks.
- Investigation of the theoretical framework required to compute the sub-centimeter geoid.
- Investigation of the error budget of potential determination and vertical reference frames unification.
- Investigation and benchmarking of alternative regional geoid determination methods and software.
- Studies on theoretical and numerical problems related to the solution of the geodetic boundary value problems (GBVPs) in geoid determination.
- Studies on time variations of the gravity field and heights due to Glacial Isostatic Adjustment (GIA) and land subsidence.
- Development of relativistic methods for potential difference determination using precise atomic clocks.
- Investigating the role of traditional levelling in future regional/local height system realizations, combined with all available data linked to Earth's geopotential determination.

Its main program of activities refers to:

- Organizing meetings and conferences.
- Organization of local/regional workshops for the promotion of IHRF related studies.
- Inviting the establishment of Special Study Groups on relevant topics.
- Reporting activities of SC2.2 to the Commission 2.
- Communication/interfacing between different groups/fields relevant to the realization of IHRS.
- Conceptual and methodological support to working groups for national & regional vertical datums and reference frames definitions as realizations of IRHS

SC2.2 consists of a steering committee, through which participation to the various research activities are promoted. Within SC2.2 a JWG, namely JWG2.2.1 "Error Assessment of the

1cm geoid experiment" has been established. It focuses, after the successful completion during the previous term 2015-2019 of JWG 2.2.2 (The 1 cm geoid experiment), on the validation of the results, to identify and quantify potential error sources, and to develop and improve methods for deriving realistic error estimates for the geoid models and the gravity potential values at the IHRS stations in the Colorado 1 cm geoid experiment.

During the reporting period, SC2.2 activities focused mainly on the publication of the results during the "1 cm geoid experiment", the realization of the International Height Reference System (IHRS) through the Implementation of the International Height Reference Frame (IHRF), the organization of a dedicated session within the 2021, 2022 and 2023 European Geosciences Union, the 2021 IAG Scientific Assembly and the organization of the Gravity Geoid and Height Systems (GGHS) 2022 conference in Austin, Texas.

One of the main on-going activities of SC2.2, especially in view of the forthcoming period 2024-2027, referred to the, in cooperation with the International Gravity Field Service (IGFS), Global Geodetic Observing System (GGOS) Focus Area (FA) Unified Height System (UAS) GGOS FA UHS and in particular GGOS-FA-UHS JWG0.1.3 "Implementation of the International Height Reference Frame (IHRF)", the realization of the IHRF as a service. This is a major component of the SC2.2 activities, as the system components and the realization of potential values for the selected stations are now to be realized as an IGFS service. The main activities focused on contributions to potential determination, organization of the service, and expansion of the reference/core stations to regions like Africa and the western part of Asia where voids exist.

The successful completion of past period (2015-2019) JWG2.2.2 activities resulted in a number of publications, within the current period, of SC2.2 members in the dedicated Journal of Geodesy Special Issue (SI) "Reference Systems in Physical Geodesy" (ISSN: 0949-7714 (Print) 1432-1394 (Online)) which is currently in its finalization phase (https://bit.ly/3bVdU2a). The organization of the SI and the preparation of the publications has been a major goal of SC2.2 activities as it provides an analytic presentation of the various methodological schemes for geoid/quasi-geoid and potential determination, given a common set of input land and airborne gravity data and a common digital terrain model for the evaluation of the topographic effects. Finally, the validation and cross-validation between the various solutions has been performed using the same set of GNSS/Levelling data acquired during the GSVS campaign by the U.S. National Geodetic Survey. This SI encompasses the joint work and research efforts of 14 research groups worldwide, creating a valuable reference for related studies.

Peer-reviewed publications from the "1 cm geoid experiment":

Claessens, S.J., Filmer, M.S. Towards an International Height Reference System: insights from the Colorado geoid experiment using AUSGeoid computation methods. J Geod 94, 52 (2020). https://doi.org/10.1007/s00190-020-01379-3

Grigoriadis, V.N., Vergos, G.S., Barzaghi, R., Vassilios N., Carrion, D., Koç, Ö. Collocation and FFT-based geoid estimation within the Colorado 1 cm geoid experiment. J Geod 95, 52 (2021). https://doi.org/10.1007/s00190-021-01507-7

Işık, M.S., Erol, B., Erol, S., Sakil, F.S. High-resolution geoid modeling using least squares modification of Stokes and Hotine formulas in Colorado. J Geod 95, 49 (2021). https://doi.org/10.1007/s00190-021-01501-z

Jiang, T., Dang, Y. & Zhang, C. Gravimetric geoid modeling from the combination of satellite gravity model, terrestrial and airborne gravity data: a case study in the mountainous area, Colorado. Earth Planets Space 72, 189 (2020). https://doi.org/10.1186/s40623-020-01287-y

Liu, Q., Schmidt, M., Sánchez, L., Willberg, M. Regional gravity field refinement for (quasi-) geoid determination based on spherical radial basis functions in Colorado. J Geod 94, 99 (2020).

https://doi.org/10.1007/s00190-020-01431-2
Sánchez, L., Ågren, J., Huang, J., Wang, Y.M., Mäkinen, J., Pail, R., Barzaghi, R., Vergos, G.S., Ahlgren, K., Liu Q. Strategy for the realisation of the International Height Reference System (IHRS). J Geod 95, 33 (2021). https://doi.org/10.1007/s00190-021-01481-0
van Westrum, D., Ahlgren, K., Hirt, C, Guillaume, S. A Geoid Slope Validation Survey (2017) in the rugged terrain of Colorado, USA. J Geod 95, 9 (2021). https://doi.org/10.1007/s00190-020-01463-8
Varga, M., Pitoňák, M., Novák, P., Bašić, T. Contribution of GRAV-D airborne gravity to improvement of regional gravimetric geoid modelling in Colorado, USA. J Geod 95, 53 (2021). https://doi.org/10.1007/s00190-021-01494-9
Wang, Y.M., Li, X., Ahlgren, K., Krcmaric, J. Colorado geoid modeling at the US National Geodetic Survey. J Geod 94, 106 (2020). https://doi.org/10.1007/s00190-020-01429-w
Wang, Y.M., Sánchez, L., Ågren, J. et al. Colorado geoid computation experiment: overview and summary. J Geod 95, 127 (2021). https://doi.org/10.1007/s00190-021-01567-9
Willberg, M., Zingerle, P. & Pail, R. Integration of airborne gravimetry data filtering into residual least-squares collocation: example from the 1 cm geoid experiment. J Geod 94, 75 (2020). https://doi.org/10.1007/s00190-020-01396-2

The next main activity of SC2.2 during the reporting period (2019-2023) refers to the involvement in the implementation of the IHRF. This is done through synergy with the International Gravity Field Service (IGFS), Global Geodetic Observing System (GGOS) Focus Area (FA) Unified Height System (UAS) GGOS FA UHS and in particular GGOS-FA-UHS JWG0.1.3 "Implementation of the International Height Reference Frame (IHRF)" and the Inter-Commission Committee on Theory (ICCT) JSGT2.26 "Geoid/quasi-geoid modelling for realization of the geopotential height datum". Based on the strategy paper (Sánchez et al., 2021) already published in the aforementioned Journal of Geodesy SI, the main steps for the determination of IHRF geopotential values at IHRF sites have been determined. The activities are based on a geopotential determination based on a) global geopotential and topography potential models and b) local/regional geoid/quasi-geoid models either available at the SC2.2 and GGOS-FA-UHS participating members and the International Service for the Geoid repository. Already, a number of presentations and a peer-reviewed journal paper have been prepared.

Presentations and publications:

Claessens, S.J., Filmer, M.S. Towards an International Height Reference System: insights from the Colorado geoid experiment using AUSGeoid computation methods. J Geod 94, 52 (2020). https://doi.org/10.1007/s00190-020-01379-3
Barzaghi, R., De Gaetani, C.I. & Betti, B. The worldwide physical height datum project. Rend. Fis. Acc. Lincei 31, 27–34 (2020). https://doi.org/10.1007/s12210-020-00948-0.
Barzaghi R., Sánchez L., Vergos G.: Operational infrastructure to ensure the long-term sustainability of the IHRS/IHRF. European Geosciences Union (EGU) General Assembly 2020, Vienna, Austria, 10.5194/egusphere-egu2020-7961, 2020.
Barzaghi R and Vergos GS (2022) Practical implementation of the IHRF employing local gravity data and geoid models. Presented at the 2022 EGU General Assembly, May 23 – 27, Vienna, Austria.
Sánchez, L.: Activities and plans of theGGOS Focus Area Unified Height System. GGOS Days 2020, Virtual Meeting, October 5-7, 2020.
Sánchez, L., Ågren, J., Huang, J., Wang, Y.M., Mäkinen, J., Pail, R., Barzaghi, R., Vergos, G.S., Ahlgren, K., Liu Q. Strategy for the realisation of the International Height Reference System (IHRS). J Geod 95, 33 (2021). https://doi.org/10.1007/s00190-021-01481-0.
Sánchez L., Barzaghi R.: Activities and plans of the GGOS Focus Area Unified Height System. European Geosciences Union (EGU) General Assembly 2020, 10.5194/egusphere-egu2020-8625, 2020.
Sanchez, L., Huang, J., Barzaghi, R., and Vergos, G. S.: Towards a Global Unified Physical Height System, EGU General Assembly 2021, online, 19–30 Apr 2021, EGU21-1500, https://doi.org/10.5194/egusphere-egu21-1500, 2021.
Sanchez, L., Huang, J., Barzaghi, R., and Vergos, G. S.: GGOS Focus Area Unified Height System: achievements and open challenges, IAG Sceintific Assembly 2021, online, June 28 – July 2, 2021.
Sanchez, L., and IHRF Computation Team: Status of the International Height Reference Frame (IHRF), IAG Sceintific Assembly 2021, online, June 28 – July 2, 2021.

Sánchez L, Huang J, Barzaghi R, Vergos GS (2022) Towards an international standard for the precise determination of physical heights. Presented at the 2022 EGU General Assembly, May 23 – 27, Vienna, Austria.

Sánchez L, Huang J, Barzaghi R, Vergos GS (2022) Advances in the determination of a global unified reference frame for physical heights. Presented at the IAG Commission 1 “Reference Frames for Applications in Geosciences” – REFAG2022 Conference, October 17-20, Thessaloniki, Greece.

Sanchez L, Barzaghi R, Vergos GS (2023) Operational infrastructure to ensure the long-term sustainability of the IHRS/IHRF. Presented at the 28th IUGG General Assembly, July 11-20, 2023, Berlin, Germany.

Sanchez L, Barzaghi R, Huang J, Ågren J, Vergos GS and the IHRF Computation Team (2023) A first solution for the International Height Reference Frame (IHRF). Presented at the 28th IUGG General Assembly, July 11-20, 2023, Berlin, Germany.

Sanchez L, Huang J, Barzaghi R, Vergos GS (2023) Advances in the determination of a global unified reference frame for physical heights. Presented at the 28th IUGG General Assembly, July 11-20, 2023, Berlin, Germany. Presented at the 2023 EGU General Assembly, April 23 – 28, Vienna, Austria.

Vergos GS, Grebenitcharsky RS, Al-Qahtani A, Natsiopoulos DA, Al-Shahrani S, Tziavos IN (2022) Development of the national gravimetric geoid model for the Kingdom of Saudi Arabia (KSA-GEOID21). Presented at the 3rd joint meeting of the International Gravity Field Service and Commission 2 of the International Association of Geodesy “Gravity Geoid and Height Systems 2022” – GGHS2022, Conference, September 12-14, Austin TX, USA

Dedicated Sessions during Conferences

During the reporting period, SC2.2 has participated in the organization of related sessions at the annual 2021, 2022, 2023 EGU General Assemblies and the 2021. During EGU2021 session G1.5 “Local/Regional Geoid Determination: Methods and Models” within the Geodesy Programme group has been organized, jointly with SC2.4 and the IGFS. 14 presentations have been given with virtual participation, referring to geoid/quasi-geoid determination, satellite data processing for geoid determination and theoretic aspects of geoid modeling. After the completion of the conference, it was decided that the session will be resubmitted for inclusion in the upcoming EGU2022, which was held in person. During EGU2022 the session was merged with G4.3 “Geoid determination, gravity and magnetic field data and their interpretation” with 9 oral and 6 poster presentations. During EGU2023 the session was merged with G1.5 “Recent Developments in Geodetic Theory and Gravity Field Estimation” with 9 oral and 5 poster presentations.

During the 2021 IAG Scientific Assembly, organized virtually in June 28 -July 2, 2021, a joint session (Session 2a.2 “Vertical Reference Systems: methodologies, realization, and new technologies”) with Commission 1, ICCT, GGOS-FA-UHS and Project QuGe was organized. This session focused on the unification of the existing height systems and vertical datums around the world, which can be achieved through the realization of an international vertical reference system that supports geometrical (ellipsoidal) and physical (normal, orthometric) heights with centimeter precision in a global frame. The session received 3 oral and 5 poster presentations.

Conference Organization and Planning

SC2.2 participated actively in the organization of the 3rd Joint IGFS and Commission 2 Meeting, Gravity Geoid and Height Systems, which was planned for Fall 2020, but due to the Covid-19 pandemic it was decided to be re-arranged. The conference was organized with both virtual and in person attendance in Austin, Texas between September 12-14, 2022. The GGHS2022 meeting encompassed seven sessions focusing on

- Current and future satellite gravity missions
- Global Gravity Field Modelling

- Local/regional gravity field modelling
- Absolute, Relative and Airborne Gravity - Instrumentation, Analysis, and Applications
- Height systems and vertical datum unification
- Satellite altimetry and applications
- Gravity for Climate & Natural Hazards: Inversion, Modeling, and Processes

The announcement and the call for abstracts resulted in 76 submissions, while the SC2.2 lead Session 3 "Local/Regional Gravity Field Modelling" was planned with 6 oral and 8 poster presentations. .

Joint Working Groups of Sub-commission 2.2:

JWG 2.2.1: Error assessment of the 1 cm geoid experiment

Chair: *Martin Willberg (Germany) (2019-2021.03)*
Tao Jiang (China) (2021.03-2023)
Vice Chairs: *Vassilios Grigoriadis (Greece) Matej Varga (Switzerland)*

Members

- Tao Jiang (China), Chair
- Vassilios Grigoriadis (Greece), Vice-chair
- Matej Varga (Switzerland), Vice-chair
- Laura Sánchez (Germany)
- Yan Ming Wang (USA)
- Marc Véronneau (Canada)
- Sten Claessens (Australia)
- Qing Liu (Germany)
- Rene Forsberg (Denmark)
- Hussein Abd-Emotaal (Egypt)
- Koji Matsuo (Japan)
- Bihter Erol (Turkey)
- Jonas Ågren (Sweden)
- Kevin Ahlgren (USA)
- Riccardo Barzaghi (Italy)
- Representative person USP (Brazil)

Activities and publications during the period 2019-2023

JWG 2.2.1 (Error assessment of the 1 cm geoid experiment) is the continuation of JWG 2.2.2 (The 1 cm geoid experiment) in the previous IAG period 2015-2019.

The objectives of this JWG are to validate the results, to identify and quantify potential error sources, and to develop and improve methods for deriving realistic error estimates for the geoid models and the gravity potential values at the IHRS stations in the Colorado 1 cm geoid experiment.

14 groups from 13 countries participated in the Colorado 1 cm geoid experiment. The groups have computed 14 gravimetric geoid models and 13 gravimetric quasigeoid models in the area of Colorado using terrestrial gravity, airborne gravity, digital elevation models and global gravity field models. The accuracy of each gravimetric quasigeoid model was independently evaluated by the National Geodetic Survey (NGS) of USA using the GSVS17 height anomalies. The quasigeoid models agree with the GSVS17 height anomalies from 2.1 cm to 3.6 cm in terms of the standard deviation (STD) of the differences. The median of the STD is 3.1 cm. The 14 groups are as follows:

- AUTh: Aristotle University of Thessaloniki, Greece
- CASM: Chinese Academy of Surveying and Mapping, China
- CGS: Canadian Geodetic Survey, Canada

- Curtin: Curtin University, Australia
- DGFI: Deutsches Geodätisches Forschungsinstitut, Technical University of Munich, Germany
- DTU: Technical University of Denmark, Denmark
- Minia: Minia University, Egypt
- NGS: US National Geodetic Survey, NOAA, USA
- GSI: Geospatial Information Authority of Japan, Japan
- IAPG: Institute for Astronomical and Physical Geodesy, Technical University of Munich, Germany
- ITU: Istanbul Technical University, Turkey
- KTH: University of Gävle, Lantmäteriet, Royal Institute of Technology, Sweden
- NTIS-GEOF: University of West Bohemia, Czech Republic & University of Zagreb, Croatia
- Polimi: Politecnico di Milano, Italy

The geoid computation methods, analysis and results of most groups have been published in Journal of Geodesy.
The NGS has released all the GSVS17 field data including spirit leveling, GPS, gravity, and deflection of vertical on its web page:
https://www.ngs.noaa.gov/GEOID/GSVS17/DataFiles.shtml.

An online meeting was organized on March 11, 2021, to discuss the aspects corresponding to the written terms of reference of this JWG. The main conclusions of the meeting were:

- The following aspects are the current main focus of this JWG:
  a) validate the geoid models by comparisons to the GSVS17 data
  b) identify and quantify potential error sources for geoid modeling
  c) analyze the differences of individual geoid results and find the most possible reasons
- Kevin Ahlgren from the NGS agreed to make an extended GSVS17 data file for this working group, which will be used by each group in this JGW for further and comprehensive geoid model validation and error analysis. Kevin Ahlgren has been working on preparing this GSVS17 data file.
- All groups should check their own solution for differences and similarities with the GSVS17 validation data from GPS/leveling and DoV
- The individual groups will try to find the discrepancies of various computation methods based on a unified and simplified data scenario.
- Due to personal reasons, Martin Willberg was not able to continue as a chair of the JWG. The JWG decided to select a new chair and two vice-chairs, and this was reported to Adrian Jäggi, the President of Commission 2:
  Chair: Tao Jiang
  Co-chairs: Vassilios Grigoriadis, Matej Varga

Peer-reviewed publications

Bjelotomić Oršulić, O., Markovinović, D., Varga, M., Bašić, T. The impact of terrestrial gravity data density on geoid accuracy: case study Bilogora in Croatia. Survey Review 52.373 (2020): 299-308. https://doi.org/10.1080/00396265.2018.1562747

Claessens, S.J., Filmer, M.S. Towards an International Height Reference System: insights from the Colorado geoid experiment using AUSGeoid computation methods. J Geod 94, 52 (2020). https://doi.org/10.1007/s00190-020-01379-3

Grigoriadis, V.N., Vergos, G.S., Barzaghi, R., Vassilios N., Carrion, D., Koç, Ö. Collocation and FFT-based geoid estimation within the Colorado 1 cm geoid experiment. J Geod 95, 52 (2021).

https://doi.org/10.1007/s00190-021-01507-7

Işık, M.S., Erol, B., Erol, S., Sakil, F.S. High-resolution geoid modeling using least squares modification of Stokes and Hotine formulas in Colorado. J Geod 95, 49 (2021). https://doi.org/10.1007/s00190-021-01501-z

Jiang, T., Dang, Y. & Zhang, C. Gravimetric geoid modeling from the combination of satellite gravity model, terrestrial and airborne gravity data: a case study in the mountainous area, Colorado. Earth Planets Space 72, 189 (2020). https://doi.org/10.1186/s40623-020-01287-y

Liu, Q., Schmidt, M., Sánchez, L., Willberg, M. Regional gravity field refinement for (quasi-) geoid determination based on spherical radial basis functions in Colorado. J Geod 94, 99 (2020). https://doi.org/10.1007/s00190-020-01431-2

Sánchez, L., Ågren, J., Huang, J., Wang, Y.M., Mäkinen, J., Pail, R., Barzaghi, R., Vergos, G.S., Ahlgren, K., Liu Q. Strategy for the realisation of the International Height Reference System (IHRS). J Geod 95, 33 (2021). https://doi.org/10.1007/s00190-021-01481-0

van Westrum, D., Ahlgren, K., Hirt, C, Guillaume, S. A Geoid Slope Validation Survey (2017) in the rugged terrain of Colorado, USA. J Geod 95, 9 (2021). https://doi.org/10.1007/s00190-020-01463-8

Varga, M., Pitoňák, M., Novák, P., Bašić, T. Contribution of GRAV-D airborne gravity to improvement of regional gravimetric geoid modelling in Colorado, USA. J Geod 95, 53 (2021). https://doi.org/10.1007/s00190-021-01494-9

Wang, Y.M., Li, X., Ahlgren, K., Krcmaric, J. Colorado geoid modeling at the US National Geodetic Survey. J Geod 94, 106 (2020). https://doi.org/10.1007/s00190-020-01429-w

Willberg, M., Zingerle, P. & Pail, R. Integration of airborne gravimetry data filtering into residual least-squares collocation: example from the 1 cm geoid experiment. J Geod 94, 75 (2020). https://doi.org/10.1007/s00190-020-01396-2

Sub-commission 2.3: Satellite Gravity Missions

Chair: *Frank Flechtner (Germany)*
Vice Chair: *Matthias Weigelt (Germany)*

Overview

SC2.3 shall promote and stimulate activities providing the scientific environment for the development of the next generation of static and temporal gravity field solutions based on observations from the satellite gravity missions CHAMP, GRACE, GOCE, and GRACE-FO, as well as optimum combination with complementary data types (SLR, terrestrial and air-borne data, satellite altimetry, etc.), developing alternative methods and new approaches for global gravity field processing with special emphasis on functional and stochastic models and optimum data combination, fostering the exchange of knowledge and data among processing entities, the communication and interfacing with gravity field model user communities (climatology, oceanography/altimetry, glaciology, solid Earth physics, geodesy, ...) as well as relevant IAG organizations such as the GGOS Committee on Satellite and Space Missions and the GGOS Bureau of Products and Standards. Finally, SC2.3 contributed to the identification, investigation and definition of enabling technologies for future gravity field missions such as observation types, technologies or mission architectures, and triggering new gravity field mission proposals and supporting their implementation.

Highlights throughout 2019-2023 (examples) were

COST-G: A new service to provide combined time-variable gravity field solutions

The International Combination Service for Time-variable Gravity Fields (COST-G) is the Product Center of the International Gravity Field Service (IGFS) for time-variable gravity fields. COST-G (https://cost-g.org) provides consolidated monthly global gravity models in terms of spherical harmonic (SH) coefficients and thereof derived grids by combining existing solutions or normal equations (NEQs) from COST-G analysis centers (ACs) and partner analysis centers (PCs). The COST-G ACs adopt different analysis methods but apply agreed-upon consistent processing standards to deliver time-variable gravity field models, e.g. from GRACE/GRACE-FO low-low satellite-to-satellite tracking (ll-SST), high-low satellite-to-satellite tracking (hl-SST), Satellite Laser Ranging (SLR).
COST-G continues the activities of the Horizon2020 project European Gravity Service for Improved Emergency Management (EGSIEM) to realize a long-awaited standardization of gravity-derived mass transport products and to improve the quality, robustness, and reliability of individual solutions and to enable hydrologists, glaciologists, oceanographers, geodesists and geophysicists to take full advantage of one well-defined, consolidated monthly gravity product.
A draft version of the COST-G terms of references (ToR) has been initially discussed at the IAG Executive Board meeting during the EGU General Assembly 2017 in Vienna, Austria. Finally, the International Union of Geodesy and Geophysics (IUGG) established COST-G as a new Product Center of IAG's International Gravity Field Service (IGFS) for time-variable gravity fields at its 2019 General Assembly.

COST-G performs a quality control of the individual contributions before combination and provides (see Fig 2),

- Combined gravity field solutions in SH coefficients (Level-2 products) derived from

a weighted combination of individual normal equations (NEQs) generate by the different ACs,
- Spatial grids and other high-level products (Level-3 products) of the Combined Solutions for hydrological, oceanic and polar ice sheets applications.

The Level-2 products are made available through the International Center for Global Earth Models (ICGEM, http://icgem.gfz-potsdam.de), the Level-3 products by the Information System and Data Center (ISDC, https://isdc.gfz-potsdam.de). The Level-3 products can be visualized at the COST-G Plotter (https://cost-g.org) and the Gravity Information Service (GravIS, http://gravis.gfz-potsdam.de) at GFZ Potsdam (see Fig 3).

The initial Analysis Centers (AC), in charge of computing time-variable gravity field solutions from GRACE and GRACE-FO, are (in alphabetical order) the

- Astronomical Institute, University of Bern (AIUB),
- Centre National d'Etudes Spatiales (CNES),
- German Research Centre for Geosciences (GFZ), and
- Institute of Geodesy, Graz University of Technology (IFG)

Current Partner Analysis Centers (PAC) are the

- Center for Space Research (CSR), and
- NASA's Jet Propulsion Laboratory (JPL)

In 2020 the Institut für Erdmessung of the Leibniz University of Hannover was selected to become also an AC (passing all tests as described in Lasser et al. (2020)). Discussions with various Chinese processing centers such as IGG, SUSTech, Tongji, HUST or Wuhan to be become COST-G ACs are still ongoing.

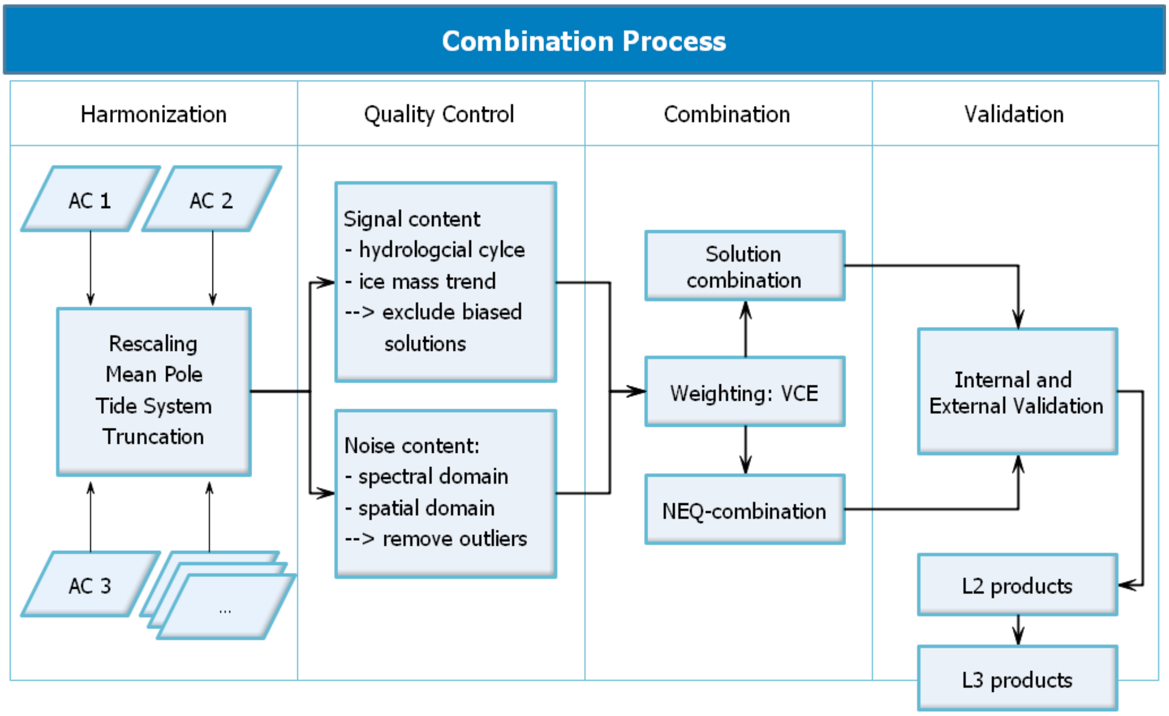


Figure 3: COST-G combination process.

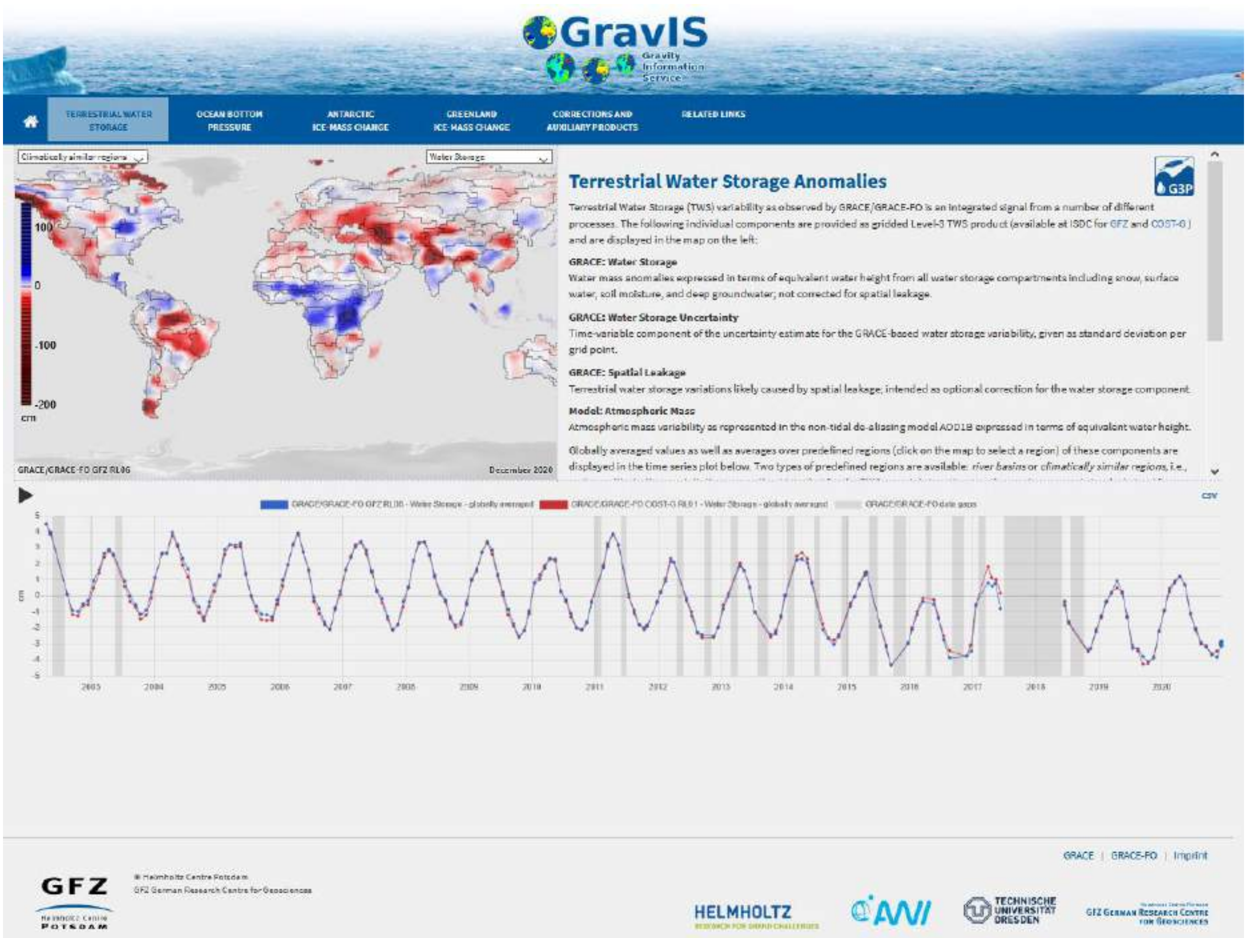


Figure 4: Screenshot of the GFZ Potsdam GravIS portal showing GFZ RL06 and COST-G based Level-3 global Terrestrial Water Storage Anomalies for climatically similar regions (more details on the webpage)

Total Water Storage became Essential Climate Variable

The Global Climate Observing System (GCOS) defines Essential Climate Variables (ECVs) as variables that are critical for characterizing the climate system and its changes. ECV datasets provide the empirical evidence needed to understand and predict the evolution of climate, to assess risks, to guide adaptation measures, to underpin climate services, among others. A list of ECVs is available at https://gcos.wmo.int/en/essential-climate-variables.

In the hydrological branch, one of the already established ECVs is groundwater. The Steering Committee of GCOS recommended in December 2020 to establish also Terrestrial Water Storage (TWS), the prime output of GRACE and GRACE-FO, as an additional ECV. This process was strongly supported by SC members. The official inclusion in the GCOS Implementation Plan happened in December 2022 (see https://www.eumetsat.int/essential-climate-variables-ecv-inventory-41-now-available).

Global Gravity-based Groundwater Product

While the European Union's Earth Observation Programme Copernicus does not yet provide data products for these ECVs, this gap is about to be filled by the EU research project G3P (Global Gravity-based Groundwater Product; www.g3p.eu) which was realized between 2020 and 2022 under leadership of GFZ Potsdam.

The G3P consortium combined key expertise from science and industry across Europe that optimally allows to (1) capitalize from the unique capability of GRACE and GRACE-FO satellite gravimetry as the only remote sensing technology to monitor subsurface mass variations and thus groundwater storage change for large areas, (2) incorporate and advance a wealth of products on storage compartments of the water cycle that are part of the Copernicus portfolio, and (3) disseminate unprecedented information on changing groundwater storage to the global and European user communities, including a European use case as a demonstrator for industry potential in the water sector. In combination, the G3P development can be seen as a novel and cross-cutting extension of the Copernicus portfolio towards essential information on the changing state of water resources at European and global scales.
The current version of the G3P prototype is v1.11. Gridded groundwater products can be downloaded from GFZ's ISDC archive in NetCDF format, visualization happens at GFZ´s GravIS portal. Necessary baseline gravity products have been provided by the COST-G service.

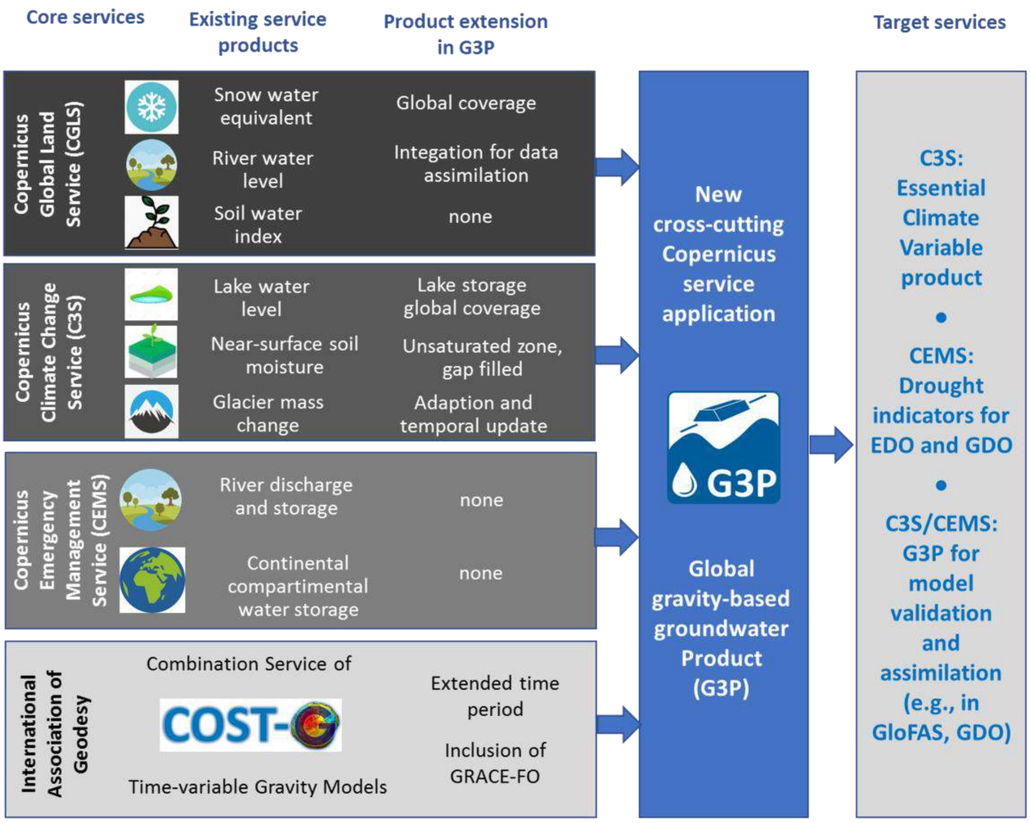


Figure 5: G3P overview (from https://www.gfz-potsdam.de/en/section/hydrology/projects/g3p-global-gravity-based-groundwater-product/). Note that the G3P time-variable gravity field models will be provided by the IAG COST-G Service (see above) via the Gravity Information Service GravIS at GFZ (see Figure 4)

GRACE and GRACE-FO

In April 2022, the community celebrated the incredible milestone of obtaining a 20-year climate data record of Earth system mass change through the combination of the NASA/DLR GRACE and NASA/GFZ GRACE-FO missions. Further, in May 2023, GRACE-FO celebrated 5 years of making mass change measurements, satisfying its baseline mission design lifetime. Additionally, the MOU between GFZ and NASA has been extended till December 2026 to guarantee continuation of the mass change data time series.

Towards realization of future gravity missions

Mass Change (MC)

Mass change (MC) was identified in the U.S. National Academies of Sciences, Engineering and Medicine (NASEM) 2017 Decadal Survey, "Thriving on Our Changing Planet: A Decadal Strategy for Earth Observations from Space" as a Designated Observable, and recommended a mass change observing system to continue, and potentially improve upon, the observational record established by the Gravity Recovery and Climate Experiment (GRACE) and GRACE Follow-On (GRACE-FO) missions. In response to the Decadal Survey, NASA chartered a multi-center 3-year study (2018-2021) led by JPL to examine implementation options for a mass change observing system.

The MC study had three main objectives (https://science.nasa.gov/earth-science/decadal-mc):

1. Identify and characterize a diverse set of high-value mass change observing system architectures responsive to the Decadal Survey's scientific and application objectives for mass change.
2. Assess the cost effectiveness of each of the studied architectures.
3. Perform sufficient in-depth design of one or two select architectures to enable rapid initiation of a phase-A study.

In addition, the study team considered synergies with other observation systems, pathways to accelerating research and applications, and strategic (international) partnerships. The status of the MC study has been presented at multiple meetings, e.g. AGU, EGU, GGHS, GRACE-FO Science Team Meetings.   full synthesis of the study, along with findings is available in open access form (https://doi.org/10.1029/2022EA002311). Major findings from the study include:

1. The lowest cost option to satisfy the science and applications objectives of the Decadal Survey, and provide the highest probability of providing gap-free continuity in the 20+ year mass change data record is a satellite-satellite tracking (SST) architecture consisting of a single in-line polar pair (see also GRACE-I below).
2. Attractive enhancement options to the single in-line pair include:
    a. The addition of a third trailing satellite performing pendulum motion relative to the in-line pair (see Marvel concept below)
    b. The addition of a second pair of satellites at a lower inclination (~70^{o}) (see NGGM/MAGIC below)

Upon the conclusion of the study in 2021, MC transitioned into Pre-Phase A with a baseline concept centered around a single in-line polar pair in partnership with DLR, relying significantly on heritage from GRACE and GRACE-FO. The baseline concept uses the Laser Ranging Interferometer (LRI) as the primary ranging instrument, taking advantage of the successful technology demonstration on GRACE-FO. The project successfully passed Mission Concept Review in 2022, allowing for transition into Phase A of formulation. The project has passed the System Requirements Review (April 2023) and has a planned Mission Design Review (MDR) in summer 2023. Phase B is expected to commence in the Fall 2023, with a planned launch in 2028.

GRACE-I

To realize a MCM NASA is seeking for international partnership. A future continuation of the very successful technological and scientific GRACE/GRACE-FO partnership between the U.S. and Germany is in the involved partners' highest interest and would be based on a strong heritage in the fields of satellite manufacturing, laser ranging interferometry (LRI) or science data utilization. The goal of a study, jointly performed in summer 2020 between German Aerospace Center (DLR), industry and Helmholtz Foundation (HGF) and Max-Plank-Foundation (MPG) scientists, was to bundle up an attractive scientific and technological German package for further discussions with NASA which 1) compares the cost and benefit of technical modifications with respect to GRACE-FO, 2) is not only attractive for a future MCM but also for the Laser Interferometer Space Antenna (LISA) and 3) strengthens at the same time Germany´s role towards ESA´s Next Generation Gravity Mission (NGGM) implementation. An ICARUS (International Cooperation for Animal Research Using Space) payload, currently successfully operated as a technology demonstrator onboard the International Space Station, on a future polar-orbiting GRACE-like "GRACE-ICARUS" (or short "GRACE-I") mission could provide a much-desired scientific extension of biodiversity monitoring, which is synergistic with the Surface Biology and Geology Designated Observable in NASA´s Decadal Survey.

In March 2021 a Phase-0 study has started at Airbus (Friedrichshafen) which has investigated till September 2021 the following realization options in close collaboration with NASA/JPL:

1. A GRACE-type single polar pair with Laser (LRI) redundancy @ 420 km (with drag compensation) or 490 km with a launch not later than 2027 to enable gap-free continuity to GRACE-FO (plus optional payloads such as ICARUS, spacecraft and LRI related enhancements or inclusion of technology demonstrators based on quantum technologies). "Bender constellation" demonstration via GRACE-FO / GRACE-I combination is an option, depending on health status of GRACE-FO.
2. Adding a 3rd pendulum satellite such as MARVEL (see below) could be an attractive companion to GRACE-I (if not a schedule driver).
3. GRACE-I combination with one or two advanced GRACE-type satellite pairs @ ca. 350 km developed in NASA/ESA collaboration such as NGGM/MAGIC (see below) due for launch ~2030/2037. The first pair could operate in a Bender constellation with GRACE-I, while the second pair could later replace GRACE-I and create a Bender constellation of two pairs both at lower altitudes."

Between March and October 2022 GFZ has performed a Phase-A study at Airbus which targeted to a) concretize the Phase 0 mission options and payload configurations, b) perform weighting of system-level options, c) derive a detailed design of required technical improvements w.r.t. GRACE-FO and d) derive a detailed schedule and cost estimation. The funding of the German elements of the baseline mission (GRACE-part of GRACE-I) has been secured on November 10, 2022, by the German Government. This includes, like for GRACE-FO, the optical components of the LRI, mission operations, launcher and launch services and contributions to the joint US-German Science Data System. Unfortunately, no funding was available for the optional ICARUS payload and necessary extension of the bus. As a consequence, ICARUS will not be implemented on the successor mission.

On the US-side JPL has successfully passed the System Requirements Review (SRR) on April 23, 2023. The Mission Definition Review (MDR) is planned for summer 2023. At the moment, NASA and DLR are working towards an implementation agreement to realize the GRACE-FO successor mission. Start of Phase B/C/D is planned for fall 2023 with a launch date in May 2028.

Marvel

The MARVEL (Mass And Reference Variations for Earth Lookout) concept was proposed to the 2019 CNES Seminar of Scientific Prospective and was ranked with the highest priority in the class of "large missions". This seminar takes place every four or five years and its recommendations serve CNES as a "roadmap" for the development of medium-term space science programming and associated programmatic decisions. One of the main driver and a key recommendation is international cooperation.

The initial concept of MARVEL aimed to achieve in a single mission two different and complementary scientific objectives:

i) Monitor mass transfers in the Earth system with improved accuracy w.r.t. current observing systems (GRACE/GRACE-FO), and
ii) Realization, at the millimeter level, of the International Terrestrial Reference Frame (ITRF).

This concept could be implemented by launching two constellations in a polar orbit: a low-flying one at 470 km and a higher one at 7000 km with a laser SST link between the two constellations. The reference frame objective would be reached by equipping the higher constellation with precisely collocated beacons of the four space geodetic techniques (GNSS, SLR, Doris, VLBI) on-board one of the satellites of the upper constellation.

A Phase-0 study started at CNES in January 2020. However, it soon became obvious that

1) the LEO/MEO concept had a low science value with the envisaged ranging accuracy between the lower and upper constellations and,
2) the cost associated with such a mission was unrealistic, particularly given the first point.

On the contrary, the "Pendulum" concept, also studied during the first stages of Phase-0, presented a high scientific benefit, on the same level as a Bender configuration (Fig. 6, right), with a very favorable cost/benefit ratio. The advantage of the Pendulum (or also Bender) concept is that it solves the problem of the strong anisotropy of the measurements which is one of the most handicapping points in the "polar in-line pair" concept of GRACE and GRACE-FO. A Pendulum pair is composed of two satellites in a polar orbit with a small offset of their ascending node and mean anomaly. In that way, the ranging measurement between the satellites oscillates alternatively from left to right between the ascending and descending tracks (Fig. 6, left). This concept was initially suggested in the "e.motion" proposal to ESA in the framework of the EE8 call. The Pendulum concept can also be associated with a classical in-line pair, in a 3-satellite configuration (Fig. 6, middle).

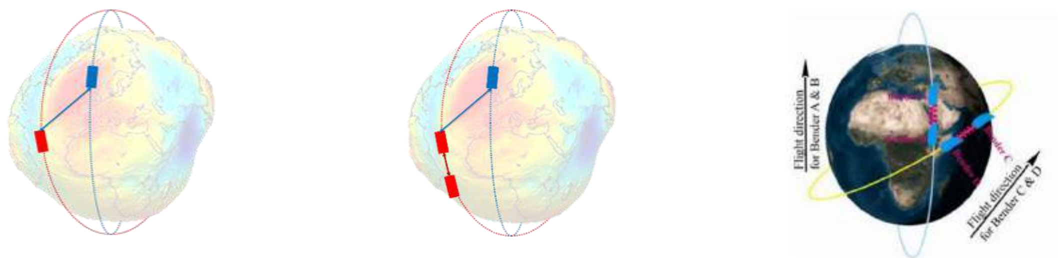


Figure 6: 2-satellite (left) and 3-satellite (middle) Pendulum and 2-pair Bender (right) configuration

The inter-satellite telemetry instrument being designed in Phase-0 is a chronometric laser link (i.e. a measurement of the time of flight of an optical signal, and not a laser interferometer). The target accuracy of this instrument in range and range-rate is 1 µm and 0.1 µm/s, respectively. This is about three orders of magnitude better than what is reached from the ground by SLR. It is based on existing telecom technologies, with a TRL of 9 on ground. The pointing mechanism enables a +/- 45° amplitude of pointing and is designed to generate extremely low levels of dynamical perturbations. The reflector part of the instrument can be totally static.

The second stage of Phase-0 started in September 2020, focusing on the Pendulum concept, and lasted until September 2021. During that time CNES on the one hand and NASA, ESA and DLR/GFZ on the other hand harmonized numerical simulation standards and performed numerous full-scale simulations to see whether MARVEL could fit into NGGM/MAGIC or GRACE-I projects. It turned out that a 2-pair Bender concept, as realized by MAGIC, outperforms the Pendulum concept. Therefore, MARVEL was no longer investigated.

NGGM/MAGIC

In the frame of the Missions of Opportunity enabled by international cooperation, ESA and NASA have coordinated studies of gravity monitoring constellations optimised to observe mass changes and transport in the Earth system. Already in 2016, the report from the ESA-NASA Interagency Gravity Science Working Group defined the benefits of such a unique cooperative effort. The objective of ESA-led NGGM (Next Generation Gravity Mission) is to provide an inclined second pair which could be combined in a staggered approach with the polar GRACE-I/MC pair to form a double pair constellation. This concept is also known as MAGIC (Mass-change and Geosciences International Constellation) and targets the long-term monitoring of the temporal variations of Earth’s gravity field at high resolution in time and space. NGGM/MAGIC will observe Earth mass change and reinforce services by monitoring hydrology, cryosphere, oceanography, solid Earth and climate change. This gravity mission evolution will provide continuity of science and services with respect to predecessor missions like GRACE, GOCE and GRACE Follow-On and will complement other ESA Earth Explorer programme and Copernicus missions.

The constellation concepts identified meet the goal of synergetic international collaboration fulfilling the needs of many user communities, including operational communities, in a way not achievable by a single agency. Given that a single pair of satellites will not meet (pre-) operational needs, since it cannot support key applications, e.g. ground-water and aquifer monitoring and management, at the required spatio-temporal resolution, a cooperation programme between ESA and NASA is necessary and timely. From a (pre-)operational standpoint, among current EO-enabled services, those for land, climate, ocean, and emergency management would especially benefit from improved mass change data as available only from a constellation, such as a double-pair Bender constellation (see Fig. 6, right) at very low altitude (e.g. 350-400 km) and with improved instrumentation (e.g. for accelerometry observing non-gravitational forces, drag compensation system, etc.).

In May 2021 ESA enabled two Phase A system studies, whose main objective are the determination of the programmatic, technical and technological feasibility of the mission within its boundary conditions. In parallel a science support study was initiated (TU Munich, GFZ, CNES, TU Delft) to simulate the gain in performance of different constellation scenarios and processing methods, (see Fig. 7). Intermediate results were obtained in September 2022 followed by corresponding industry and science extension phases till fall 2023. In parallel the ESA Ministerial Conference on November 25/26, 2022, gave already the green light to NGGM.

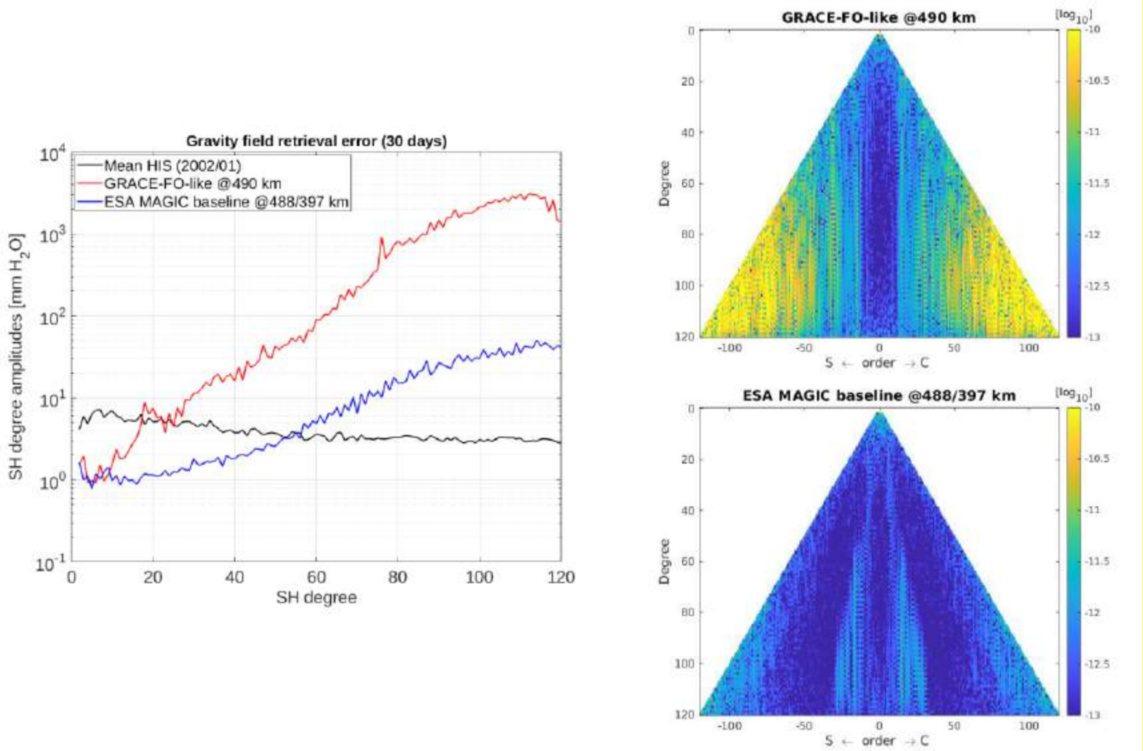


Figure 7: Exemplarily full-scale simulation result showing degree amplitudes (left) and error degree plots (right) for a GRACE-FO-like successor mission @490 km altitude and a MAGIC double pair scenario @ 488 (polar pair) and 397 (70 degrees inclined pair) km altitude assuming LRI for both mission scenarios and drag free as well as a ca. 10 times advanced accelerometer to measure non-gravitational forces for MAGIC.

Sub-commission 2.4: Regional Geoid Determination

Chair: Hussein Abd-Elmotaal (Egypt)
Vice Chair: Xiaopeng Li (USA)

Overview

The main purpose of Sub-Commission 2.4 is to initiate and coordinate the activities of the regional gravity and geoid sub-commissions.
Currently there are 6 of them:

- SC 2.4a: Gravity and Geoid in Europe (chair H. Denker, Germany)
- SC 2.4b: Gravity and Geoid in South America (chair G. Guimarães, Brazil)
- SC 2.4c: Gravity and Geoid in North and Central America (chair X. Li, USA)
- SC 2.4d: Gravity and Geoid in Africa (chair H. Abd-Elmotaal, Egypt)
- SC 2.4e: Gravity and Geoid in the Asia-Pacific (chair C. Hwang, China-Taipei)
- SC 2.4f: Gravity and Geoid in Antarctica (chair M. Scheinert, Germany)

These regional SC nominally cover the whole world with the exception of a larger region in the Middle East. But it is clear that not all countries which are listed as a member of a regional SC, are actively participating in international projects or data exchange agreements. This is especially true for some countries in Central America, the Caribbean, Africa and Asia.

Short summary of the activities of the regional SCs

SC 2.4a: European Gravity and Geoid

The main focus was on the update and of the digital elevation models. About 10 new global and regional elevation models were collected, validated and included in the European database. New global gravity field models and selected terrestrial gravity data sets were also added to the database. Furthermore, contributions were made to several projects related to optical clocks and chronometric levelling as well as to EUREF and the International Height Reference System (IHRS).

SC 2.4b: Gravity and Geoid in South America

In the last years, a big effort has been carried out by many different organizations to improve the absolute gravity measures over South America. As a result, more than 40 stations have been measured. At the same time, special attention has been given in terms of gravity densification, around IHRF stations. In South America, 17 stations were selected for the IHRF network. Some gravity measurements have been carried out around those stations.

SC 2.4c: Gravity and Geoid in North and Central America

The activities of the sub-commission 2.4c (Gravity and Geoid in North and Central America) is principally focused around the modernisation of the US National Spatial Reference System (NSRS) under the leadership of NOAA’s National Geodetic Survey (NGS). A geoid model, xGeoid20, was computed by NGS, NRCan, and INEGI. This is the first time that the three agencies generate a common geoid model for the entire North American area.

SC 2.4d: Gravity and Geoid in Africa

In Africa, a recent precise geoid model has been determined. Another geoid model using the shell layer method has been computed. Studies for the effect of the great lakes and depressions on the gravity and geoid have been carried out.

SC 2.4e: Gravity and Geoid in the Asia-Pacific

A first workshop was held to promote geoid modeling in the Asia-Pacific region and a special issue in the journal Terrestrial, Atmospheric and Ocean Sciences (TAO) was initiated to show recent gravity data processing and geoid modeling.

SC 2.4f: Gravity and Geoid in Antarctica (AntGG)

Due to the pandemic crisis the vast majority of re-search activities in Antarctica had to be cancelled especially for the season 2020/2021. But several aspects of the combination of the terrestrial gravity data in Antarctica with a high-resolution spherical harmonic model were successfully investigated and published.

Sub-commission 2.4a: Gravity and Geoid in Europe

Chair: Heiner Denker (Germany)

Overview

The primary objective of SC 2.4a was the development of improved regional gravity field models (especially geoid/quasigeoid) for Europe, which can be used for applications in geodesy, oceano-graphy, physics, geophysics and engineering.

The work concentrated mainly on the update and of the digital elevation models. About 10 new global and regional elevation models were collected. The data were converted into common formats and then compared with the previous global and national data sets available. Furthermore, new global gravity field models were collected and selected new gravity data sets were included in the European database, all this in cooperation with the national contacts, either new or existing from previous SC 2.4a cooperations. Several new regional quasigeoid updates were done in connection with new gravity measurements carried out around optical clock and metrology sites.

In addition to this, SC 2.4a contributed to several projects in Germany and Europe related to optical clock comparisons for chronometric levelling at the cm level, where the quasigeoid models together with GNSS measurements served for providing ground truth data by the so-called GNSS/geoid approach. Further contributions and cooperations of the sub-commission were related to the IAG enterprises EUREF and the International Height Reference System (IHRS), and the IAG Colorado test data set was analysed for checking the software and methodology used for Europe.

Short Summary

The main focus was on the update of the digital elevation models. About 10 new global and regional elevation models were collected, validated and included in the European database. New global gravity field models and selected terrestrial gravity data sets were also added to the database. Furthermore, contributions were made to several projects related to optical clocks and chronometric levelling as well as to EUREF and the International Height Reference System (IHRS).

Sub-commission 2.4b: Gravity and Geoid in South America

Chair: *G. Guimarães (Brazil)*
Vice Chair: *Ayelen Pereira (Argentina)*

Overview

This report intends to cover most of the activities in South America related to gravity field determination. Therefore, sub-commission 2.4b acknowledged Ezequiel Antokoletz (BKG - Germany), Denizar Blitzkow (EPUSP and CENEGEO - Brazil), Ana Cristina Oliveira Cancoro de Matos (CENEGEO - Brazil), Daniel Arana (UFPR - Brazil) Giuliano Sant'Anna Marotta (UnB - Brazil), José Luis Carrión Sánchez (IGM - Ecuador), Leidy Johanna Moisés Sepúlveda and José Ricardo Guevara Lima (IGAC - Colombia), Juan Croquis and Walter Subiza (IGM - Uruguay) for the contributions.

Improvements of gravity databases

Over the past four years, numerous organizations have worked hard to enhance gravity data coverage in South America. As a result, there are now around 922,077 gravity data points accessible for geoid determination. Figure X displays the new (blue points) and previous (red points) gravity data. The 12,204 latest gravity observations were conducted using LaCoste&Romberg and/or CG5 gravity meters. In addition, GNSS double-frequency receivers were utilized to determine the stations' geodetic coordinates.

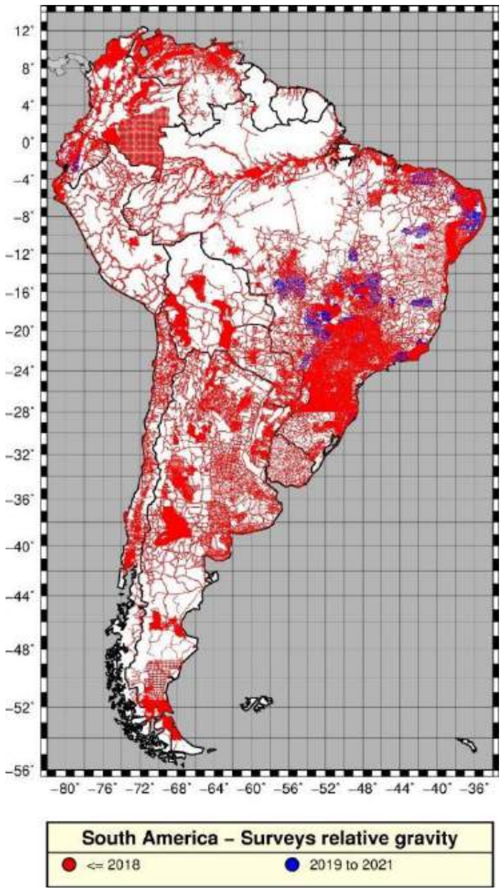
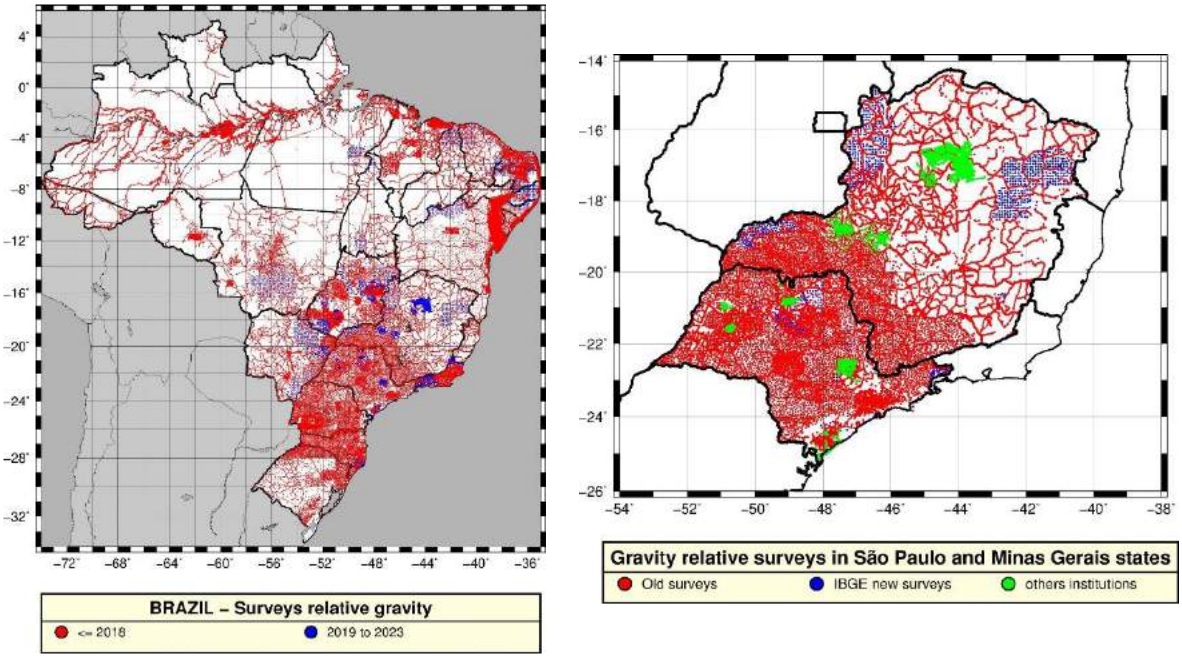


Figure 8 South America gravity data points.

Brazil

In the last four years, a total of 10,756 new gravity stations have been measured by the Brazilian Mapping Agency (IBGE), University of São Paulo, Polytechnic School, Department of Engineering Transportation (EPUSP-PTR), Federal University of Uberlândia (UFU), Geographic and Cartographic Institut of São Paulo (IGC) and Center of Studies of Geodesy (CENEGEO) (Figure 7a). Figure 7b shows the last gravity surveys in Minas Gerais and São Paulo states in Brazil.



(a) (b)

Figure 9 (a) Brazilian new gravity data; (b) Gravity data in Minas Gerais and São Paulo States in Brazil.

Colombia

Some improvements have been carried out in the Colombian gravity network. In the last four years, 746 stations (blues points in Figure 10) were collected by the Geographic Institute Agustín Codazzi (IGAC).

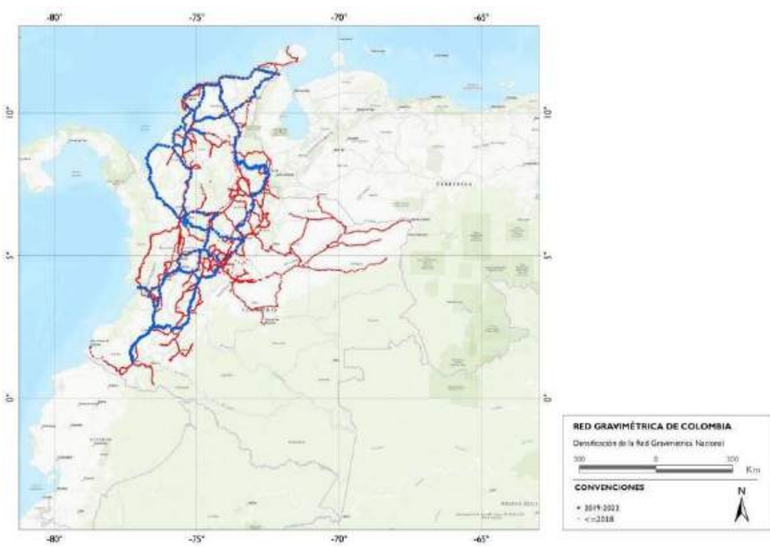


Figure 10 Gravity data in Colombia

Ecuador

From 2019 to 2023, gravimetric surveys carried out by the Military Geographic Institute (IGM/EC) in Ecuador, reached a total of 1,581 new points (Figure 10).
In addition, the gravity values of the densification surveys were connected to the Absolute Gravity Network (26 stations) established in 2017. The campaigns were a combined effort of IGM/EC and CENEGEO".

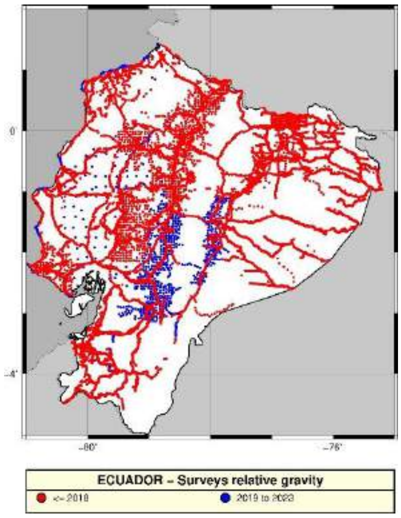


Figure 11 Gravity data in Ecuador.

Uruguay

Since 2017, gravimetric campaigns in Uruguay were increased by 321 new relative points. The gravity data were surveyed by Military Geographic Institute (IGM) using a Scintrex CG-5 and two Lacoste & Romberg gravimeters in the frame of several projects as IHRS. The new gravity surveys were connected to the Uruguayan National Gravimetric Network (UNGN), established in 1995 with three Jilag-3 absolute stations. A simultaneous readjustment of the UNGN was performed in December 2022 in cooperation with the IfE (Leibnitz University of Hannover, Germany), including 2,376 gravity stations, resulting in a mean standard deviation of 31 microgals. Another readjustment is planned for 2023, including the new absolute stations established by CENEGEO and three reoccupations of the previous ones measured with Jilag-3. Figure 12 shows the surveys until April 2023. The blue points are previous existing stations, and the red ones new surveys.

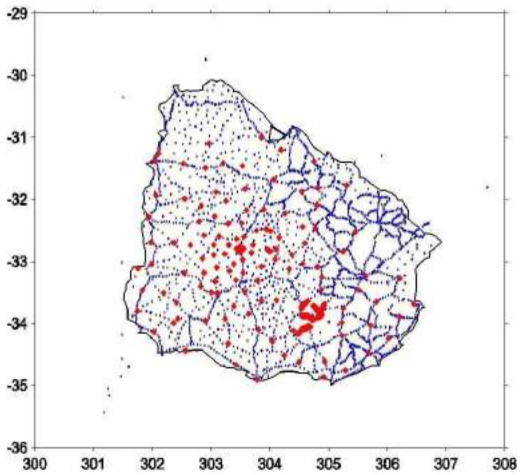


Figure 12 Gravity data in Uruguay.

Absolute gravity measurements

Argentina - Establishment of the International Gravity Reference Frame (IGRF)

The Argentinean-German Geodetic Observatory (AGGO) is a fundamental geodetic observatory located close to La Plata, Argentina. The observatory is operated jointly by the German Federal Agency for Cartography and Geodesy (BKG) and the National Scientific and Technical Research Council of Argentina (CONICET). All main space geodetic techniques are co-located: Very Long Baseline Interferometry (VLBI), Satellite Laser Ranging (SLR) and Global Navigation Satellite System (GNSS). Moreover, a gravity laboratory is established at AGGO where the superconducting gravimeter SG038 has been continuously recording gravity changes since December 16, 2015; and a FG5 absolute gravity meter was installed in January 2018. Figure 13 shows the gravity laboratory's floor plan and both installed instruments.

The gravity laboratory is also equipped with two auxiliary pillars, which will serve for absolute gravimeters comparisons in the International Terrestrial Gravity Reference System (ITGRS) frame. Antokoletz et al. (2020a) presented the gravity reference function for the observatory. This is based on the combination of the observations of the SG038 with the observations of the FG5. By this, a continuous and stable absolute gravity reference function was determined to serve for absolute gravimeter comparisons. With these results, AGGO has been established as the only station providing a continuous gravity reference function in South America and the Caribbean, suitable for AG comparisons. The station is now well qualified to become one of the core stations of the International Gravity Reference Frame (ITGRF), linked to the International Terrestrial Reference Frame (ITRF) and the International Height Reference Frame (IHRF).

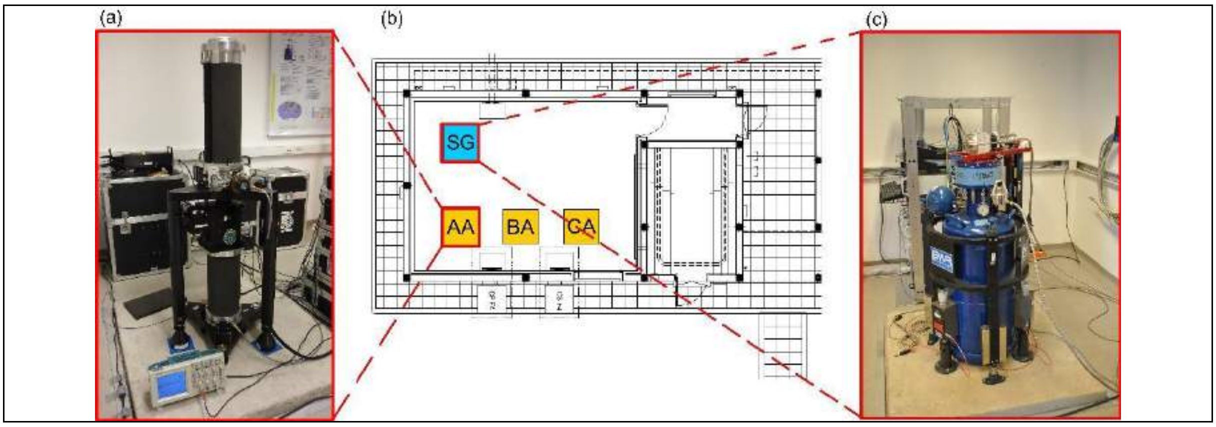


Figure 13 (a) FG5 absolute gravimeter. (b) Floor plan of the gravity laboratory. (c) SG038.

Brazil

The University of São Paulo is responsible for a gravity meter A-10 owned by the Institute of Geography and Cartography of the State of São Paulo in Brazil. The establishment of absolute stations in Brazil by year is presented in Figure 14.

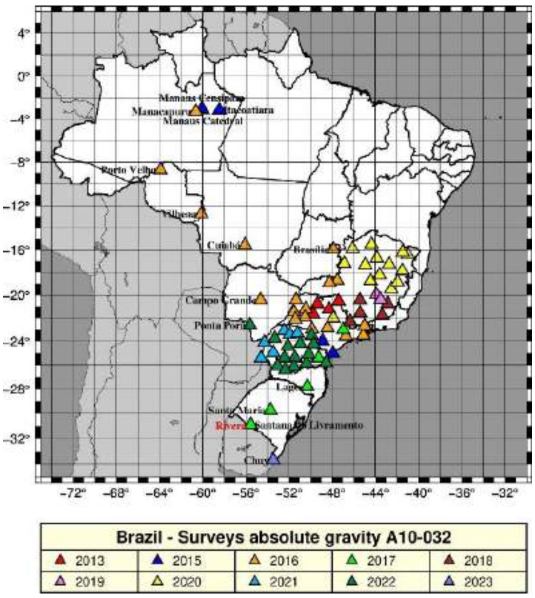
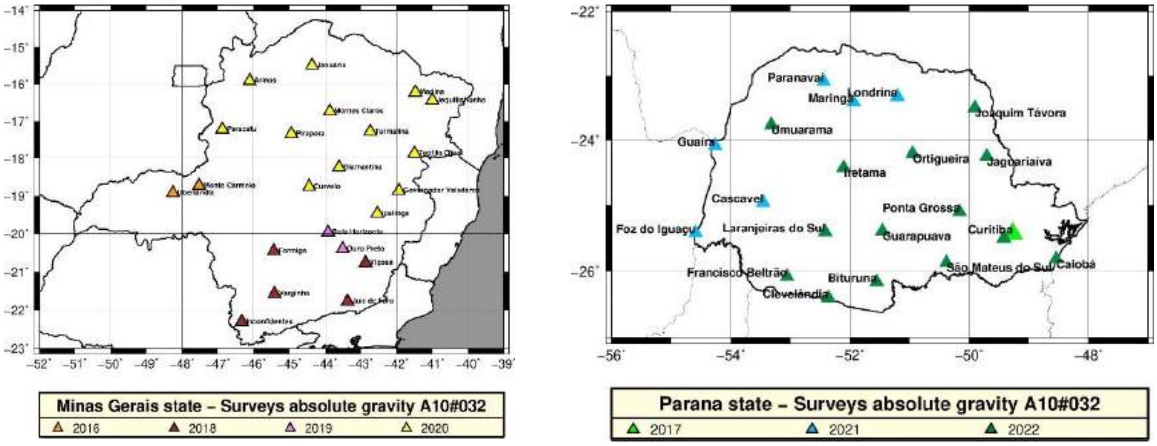


Figure 14 Absolute gravity stations in Brazil.

Figure 15a depicts 22 stations in Minas Gerais, with 15 being established from 2019 to 2020. The stations were measured by UFU and EPUSP-PTR and supported by the IGC and CENEGEO. In Figure 15b), it is illustrated that 21 absolute stations were established in the state of Paraná. Notably, 15 stations were measured between 2021 and 2022. The Water and Earth Institute (IAT), EPUSP-PTR supported by IGC and CENEGEO measured the stations.



(a) (b)

Figure 15 (a) Absolute gravity stations in Minas Gerais; (b) absolute gravity stations in Paraná.

Colombia

In 2022 the Colombian Geologic Service (SGC) and the International Gravimetric Bureau (BGI) carried out 25 absolute stations (Figure 16).

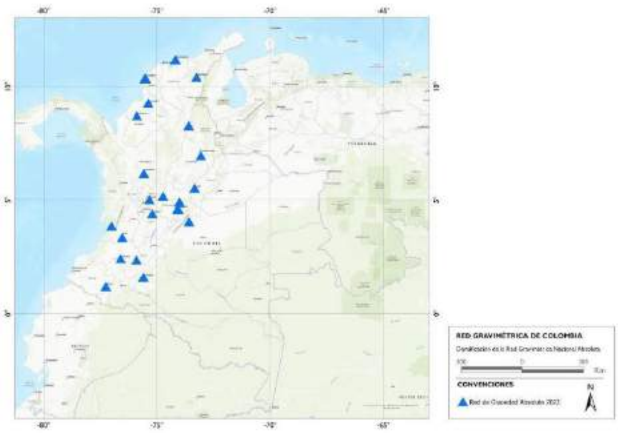


Figure 16 Absolute gravity stations in Colombia.

Paraguay

In Paraguay the establishment of 11 absolute stations (Figure 17) was carried out in 2022. The National University of Asunción (FIUNA/PY) and EPUSP-PTR supported by IGC and CENEGEO measured the stations.

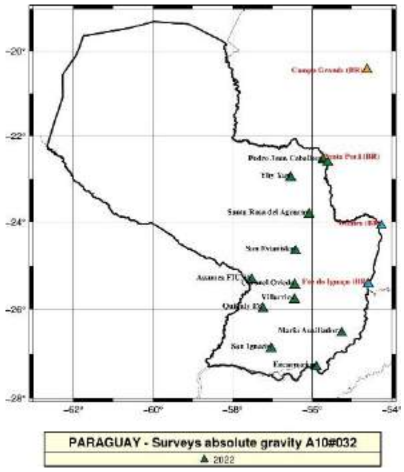


Figure 17 Absolute gravity stations in Paraguay.

Uruguay

Four new absolute stations were established and three were reoccupied in April 2023, adding up to 7 absolute stations. Figure 18 shows these stations, the date, and instruments for each occupation or reoccupation. The Military Geographic Institute (IGM/UY) and EPUSP-PTR supported by IGC and CENEGEO measured the stations.

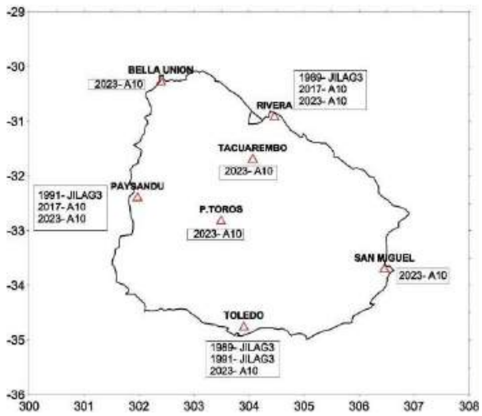


Figure 18 Absolute gravity stations in Uruguay.

Geoid Models

The South American gravimetric geoid and quasi-geoid models, named GEOID2021 (Figure 19) and QGEOID2021, respectively, were computed due to a collaboration of several institutions, companies and universities in South America. The models cover the area between 15°N and 60°S in latitude and 100°W and 30°W in longitude, with a grid resolution of 5' x 5' (Matos et al., 2021a,b).

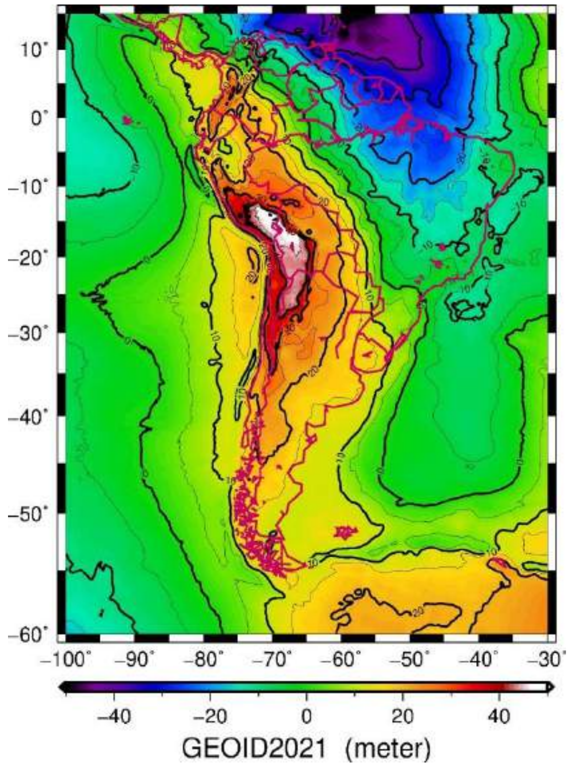


Figure 19 South American geoid model.

In Brazil, three regional/local geoid models were computed in the last four years. The models are the Federal District geoid model (Marotta; Almeida; Cherubim, 2019), São Paulo quasi-geoid model (Silva et al., 2021), and Minas Gerais quasi-geoid model (Guimarães et al., 2022). In Colombia, IGAC has been working on computing the national geoid model. Currently, the activities are concentrated on identifying and validating the existing gravimetric information. Currently, is available around 6,507,973 airborne gravity data carried out for geophysical purposes, besides marine and terrestrial data (Figure 20).

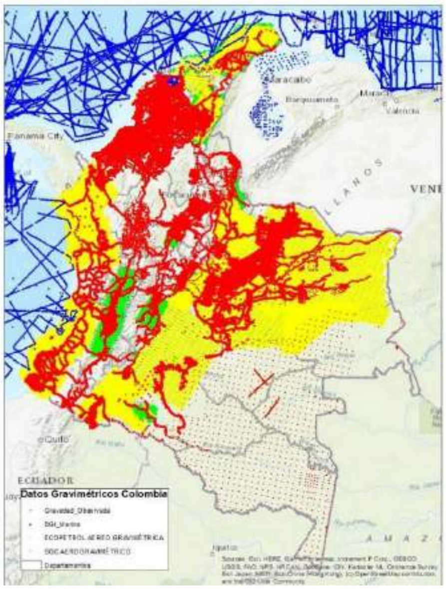


Figure 20 Gravity data available for the geoid model computation.

A new (quasi) geoidal and height transformation model is in its final calculation phase in Uruguay (Figure 21). This model replaces the previous 2007 version. A preliminary version was presented at the Symposium SIRGAS2022, Santiago de Chile (Piña, 2022). For this new model, a different approach to account for the gravity effects of the terrain was adopted, taking advantage of a Lidar DTM of high resolution (2.5 m) available for Uruguay.

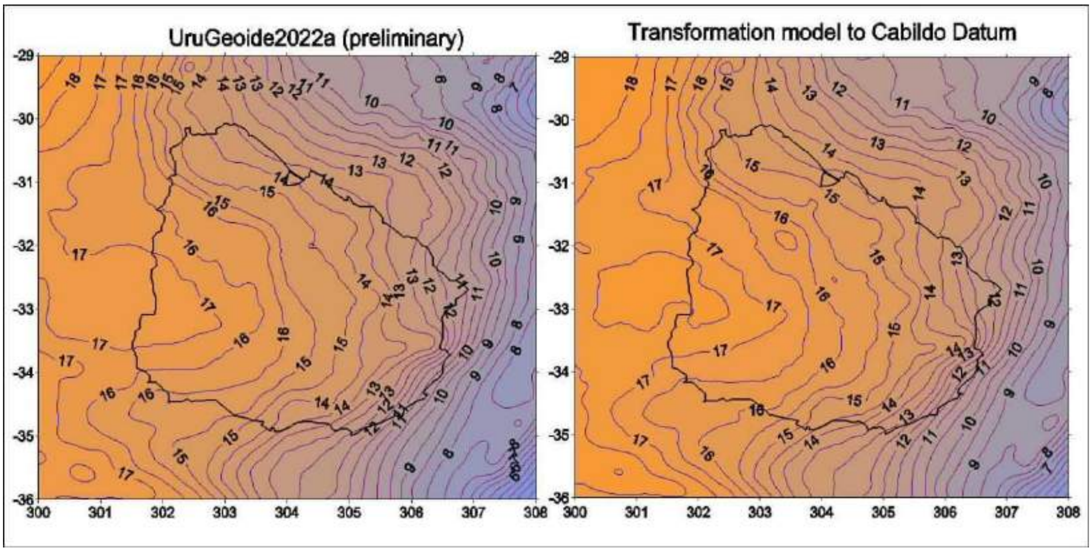


Figure 21 Geoidal and transformation model from the preliminary UruGeoide2022a.

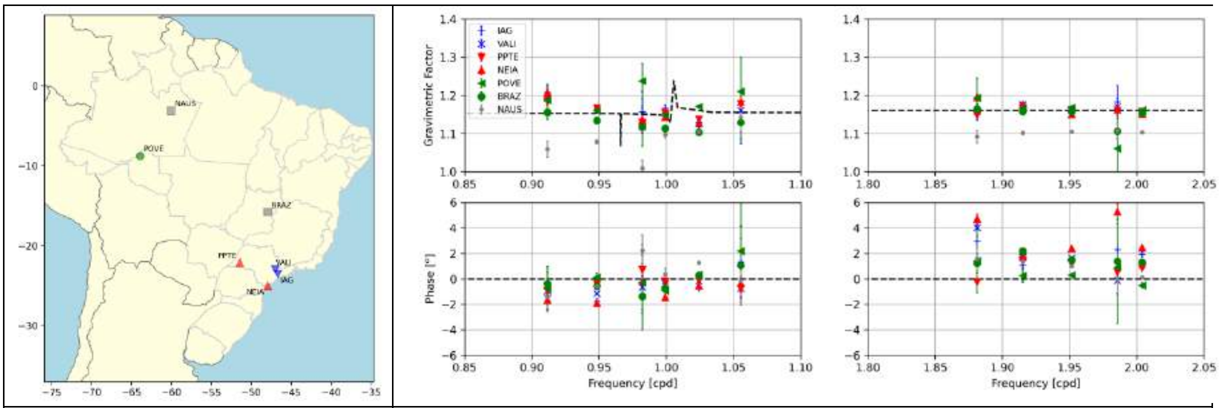
Earth tide model

New Earth tides model for the Argentinean-German Geodetic Observatory (AGGO)

A new Earth tides model was developed based on three years of continuous observations of the superconducting gravimeter SG038 located at the Argentinean-German Geodetic Observatory (AGGO). This model includes 55 tidal parameters determined from a tidal analysis made with the last version of the ETERNA ETA34-X software (http://ggp.bkg.bund.de/eterna/). Moreover, the impact of different ocean tide models on the parameters has been analyzed in order to separate the effects of Earth tides and ocean tide loading. Results are published in Antokoletz et al. (2020b).

Brazil

The collaborative effort of state and federal universities - University of São Paulo (USP), São Paulo State University (Unesp), Federal University of Uberlândia (UFU) and now the Federal University of Paraná - made it possible to carry out the Earth Tide Program in Brazil, successfully obtaining data from 7 stations, where field campaigns were carried out using two gPhones, Micro-g LaCoste. The studies involve three steps: (1) preprocessing, (2) processing of gravimetric observations, and (3) application of tidal models. The base stations for the study are VALI (Valinhos, SP), IAG (São Paulo, SP), PPTE (Presidente Prudente, SP), NEIA (Cananeia, SP), POVE (Porto Velho, RO), MANA (Manaus, AM), and BRAZ (Brasília, DF) – Figure 22 (Arana et al., 2020).



(a)	(b)

Figure 22 (a) Distribution of Earth Tide stations in Brazil; (b) Observed and Theoretical Earth Tide Model for Brazilian stations.

Gravity and Geoid Webinar and Events

SIRGAS Webinar "The new International Gravity Reference System (IGRS) and its realization (IGRF)"

On March 5, 2021, the SIRGAS Webinar "The New International Terrestrial Gravity Reference System (ITGRS) and its realization (ITGRF)" was organized by the Working Group III of SIRGAS, together with the support of the Federal Agency for Cartography and Geodesy (BKG), Germany. The Webinar took place online and about 150 people assisted from different countries belonging to SIRGAS.

In this Webinar, the main efforts of the Joint Working Group 2.1.1 "Establishment of a global absolute gravity reference system" were presented and the impact of the ITGRF at a regional level was analyzed.

Regional School "New geodetic techniques for Latin America and the Caribbean"

From 5 to April 10 2021, the Regional School "New geodetic techniques for Latin America and the Caribbean" took place at the National University of La Plata, Argentina, and gathered online. The school focused on the geodetic techniques operated at the Argentinean-German Geodetic Observatory (AGGO). In particular, two days were dedicated to introducing the concepts of the International Height Reference System (IHRS) and Frame (IHRF), the International Gravity Reference System (ITGRS) and Frame (ITGRF), and to the gravity techniques operated at AGGO. The school had 126 participants from 17 Latin America and the Caribbean countries.

Workshop "Height systems and Gravity"

From May 2 to 6, 2022, was held the virtual Workshop Height Systems and Gravity. The capacity building was aimed at the SIRGAS community, and the objective was to create capacity on height systems (IHRS/IHRF), gravity systems (IGRS/IGRF) and to update the practical activities about heights, gravity, and geoid in SIRGAS. The workshop had 105 participants from several different countries.

Workshop "Vertical Reference System"

From November 2 to 4, 2022, the Vertical Reference System Workshop explored topics related to the unification of the vertical datum for the SIRGAS country members, according to the guidelines and actions directed towards materializing the. The workshop main objective was to contribute to the training process of researchers, professionals, and technicians of the Americas who participate in the investigation, definition, and updating of national vertical reference frames and systems based on the processing of gravimetric and classical leveling information. The workshop took place in Santiago, Chile, and had 13 participants.

Capacity Building on "Processing and Adjustment of Gravimetric Networks"

From September 21 to 23, 2022, SIRGAS Working Group III provided technical advice to the Bolivian Military Geographic Institute. From October 6 to 7, 2022, the technical advice was carried out at the National Geographic Institute of Costa Rica.

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Sub-commission 2.4c: Gravity and Geoid in North and Central America

Chair: *Xiaopeng Li (U.S.A.)*
Vice Chair: *David Avalos (Mexico)*

Overview

During the period 2019 – 2023, the activities in North and Central America are mostly driven by the national geodetic agencies, with relevant contributions from the academia. The scientists in this region continue to develop some interesting advancements in the gravity field and geoid modeling at national and regional scale with promising results. Remarkably, the international collaboration has been promoted with a clear goal to construct a regional geoid model that can be used by a number of countries in the near future.

The sections below show some of the major activities that the sub-commission is working on from 2019 to 2023. The list is not necessarily exhaustive.

International collaboration.

The geodetic agencies from Canada, USA and Mexico maintain a close communication by meeting on a regular basis (once a month), where geoid specialists share and discuss the scope of geoid modeling processes. By the end of 2022, this collaboration yields the consolidation of data exchange, unification of fundamental computation parameters, building the first common vertical datum, and the release of experimental models for geoid and gravity field, which have been compared to learn their characteristics in depth. Great achievements in synchronization have been reached, specially between Canada and the USA.

Particularly the geoid team at US National Geodetic Survey (NGS) promotes the integration of all new results into a combined product. They have produced an experimental combination of Canada and US geoid models with promising results. This effort leads the way forward in the region.

Another collaborative effort is carried out between the geodetic agencies of Jamaica and Mexico. In order to support the future development of geodetic vertical control in Jamaica, the National Land Administration is receiving support from Mexico's INEGI to learn about the modern and practical aspects of geodetic control in general.

North American-Pacific Geopotential Datum

The largest project for modernization of the vertical datum in the region is the US National Spatial Reference System (NSRS) under the leadership of NGS. This modernisation includes not only the update of the NAVD 88 height reference system to a geoid-based height reference system (to be called NAPGD2022), but also the replacement of the NAD 83 (NSRS) geometric reference frame by a North American plate-fixed geocentric frame aligned with an IGS solution (to be called NATRF2022). Naturally, this project contributes to the vertical component of the modernisation. (https://www.ngs.noaa.gov/datums/newdatums/).

Under this project, the NGS continues to release an experimental geoid (xGEOID) model every year. On 2022 the models produced contain the gravity data from the latest satellite gravity models, the terrestrial gravity and most importantly, the airborne gravity from the Gravity for the Redefinition of the American Vertical Datum (GRAV-D) project.

The main product released on 2020 was the development of the experimental geoid model XGEOID20 for NAPGD2022. It is the first North American geoid model built with the external collaboration from INEGI and CGS. The consolidated models from independent geoid solutions were based on a common dataset organized by the three agencies (terrestrial gravity data, GRAV-D airborne gravity data, satellite altimetry-derived gravity data (DTU15), and a merged/corrected DEM from different models available). The independent models used the same underlay global Earth Gravity Models (EGMs) developed at NGS. The independent solutions from NGS and CGS show good agreement, in fact it is the best agreement ever between models developed at NGS and CGS. However, the discrepancies in some regions are still larger than expected for a unified geoid model. The three agencies are in the process of writing the technical report on the experimental model XGEOID20. More work is in progress to improve the national and continental solutions. In the meantime, CGS started a study of data requirement for determining temporal change of CGVD2013, and presented a poster at the AGU100 meeting in San Francisco.

During the course of the development of XGEOID20, NGS and CGS worked on different methods and procedures for downward continuation. A paper is in preparation. The gravity disturbance grids have been produced from 63 GRAV-D blocks at the mean flight level and on the reference ellipsoid. In addition, the two agencies worked on the transformation between geoid and quasi-geoid models by enhancing the topographical correction, i.e., taking care of the terrain roughness. The study also looked into the impact of the topographical density and downward continuation. This same procedure was also used to improve the calculation of the orthometric heights at benchmark (levelling) by estimating more precisely the mean gravity along the plumb line.

Then the models from different methods are weighted averaged to a common vertical datum, called xGeoid20. It is the first model of the joint effort of three agencies. For more information, please visit the xGeoid20 website at:

https://beta.ngs.noaa.gov/GEOID/xGEOID20/

The Colorado 1-cm geoid experiment

The Colorado experiment is an effort by the international geodetic community coordinated by IAG to examine (quasi)geoid disagreements caused by computation methods and software used by different groups. This study was coordinated within IAG, in particular, the IAG Sub-commission 2.2: Methodology for geoid and physical height systems (Ågren and Ellmann, 2019); the joint working group 2.2.2: The 1-cm geoid experiment in Colorado (Wang and Forsberg, 2019); the study group 0.15: Regional geoid/quasi-geoid modelling - Theoretical framework for the sub-centimeter accuracy of the IAG Inter-Commission Committee on Theory – ICCT (Huang and Wang, 2019), and the working group 0.1.2: Strategy for the realization of the IHRS of the Focus Area Unified Height System of the Global Geodetic Observing System - GGOS (Sánchez, 2019; Sánchez and Barzaghi, 2020). The data sets used in this experiment were provided by the U. S. National Geodetic Survey.

According to Resolution No. 1, 2015 of the International Association of Geodesy (IAG, Drewes et al. 2016, p. 981), the International Height Reference System (IHRS, Ihde et al. 2017) is defined in terms of geopotential numbers CP = W0–WP, where WP is the geopotential at a point of interest P, and W0 = 62,636, 853.4 m2s−2(Sánchez et al. 2016) as adopted by the IAG as the reference level for the IHRS. Since the W0 value is conventionally fixed, the primary value to be determined is the potential value WP. As absolute potential values cannot be measured directly, the value WP is to be determined from observable gravity field data by applying appropriate geoid or quasigeoid determination methods. In the (quasi)geoid computations, the primary quantity to be determined is the disturbing potential T = W − U, which is the difference between the actual gravity potential W and the normal gravity potential U generated by the adopted reference ellipsoid. Once TP is computed, the determination of WP is straightforward. However, the estimated value of the disturbing potential relies not only on available gravity data but also on gravity field modeling approaches. This includes different methods for handling terrain effects, filtering and combining gravity data, treating long-wavelength errors, formulating mathematical models to continue and transform gravity data and terrain effects, etc. Since there is no standardization in the computation of the disturbing potential and there are many parameter choices when handling gravity and terrain data, potential values estimated by different methods inevitably differ. Thus, different groups can generate quite different (quasi)geoid models from the same input gravity data.

To assess how much the results depend on applied computation methods, 14 groups from 13 countries working on regional geoid modeling agreed in August 2017 to determine geoid heights, height anomalies and geopotential values using the same input data and their own modeling strategies. For this purpose, NGS provided GPS/leveling data, terrestrial and airborne gravity data, and a digital terrain model for a test area of about 730km×560km in Colorado, USA. From 2018 to 2020, about 30 geodesists specialized in (quasi)geoid determination performed iterative computations of local (quasi)geoid models using these data, identifying their discrepancies and homogenizing to a large extent their different processing strategies. This initiative was successful in that the final models presented an agreement of around 2 cm in terms of the standard deviation of their differences. The contributing solutions represent the state-of-the-art in precise high-resolution gravity field modeling. The results of this experiment provide a benchmark for calibration of regional gravity field modeling methods and provide a basis for evaluation and further development of strategies and procedures to increase the achievable accuracy in determination of the regional gravimetric (quasi)geoid.

More than a dozen geoid modeling groups in the world participated this study where a variety of modeling approaches have been tested. The technical details and results of each successful methods can be found in a special issue, named reference systems in physical geodesy, in the Journal of Geodesy.

A summary paper describes key aspects of this joint international effort known as the Colorado 1-cm geoid experiment, the basic processing requirements agreed for the computation of the geoid and quasigeoid models, and the key aspects of the computation methods applied by the different groups, and discusses the main findings of the 1-cm geoid experiment and sets out recommendations for future research.

Geoid model for Mexico

By the end of 2020 INEGI produced an experimental geoid model for Mexico, based on an improved algorithm to calculate the contribution to geoidal height from satellite-only geopotential models. This result was further improved on 2022 with a study on the impact of implementing different algorithms of the Stokes integral. General good agreement has been achieved between geoid models over areas of the U.S. and now the focus is set on achieving similar agreement over Mexico and Central America.

CGS produces a new terrain correction for North America

CGS calculated a 30" x 30" grid of mean terrain corrections for North America using a 3" x 3" DEM. It makes use of the same DEM imbedded in the development of XGEOID20. This grids can contribute in the development of and the transformation between free-air, Bouguer, and refined Bouguer gravity grids. A new CGS experimental geoid model is also computed based on this new TC model.

CGS evaluated recent EGMs

CGS analysed recent EGMs that are augmented global topographic potential models such as GFZ's ROLI and Earth2014 against independent validation datasets (e.g., GPS on BMs). These EGMs were also used to develop experimental regional models for North America.

CGS analyzed new gravity data

CGS completed the validation of some 200,000 gravity points in Canada that we received from the U.S. National Geospatial-intelligence agency. This represents the largest increase in terrestrial gravity data in Canada in many years.

International Great Lakes Datum

CGS and NGS are working together with the U.S. and Canadian hydrographic services on the update of the International Great Lakes Datum (IGLD). This datum will rest on NAPGD2022, but the type of heights will be dynamic (opposed to orthometric) for proper management of water resources. Current activities include evaluation of geoid models at water gauges to demonstrate that each lake surface represents or is close to an equipotential surface.

vEGU21 session G1.5

The subcommittee SC2.4c is working together with SC2.4d and SC2.2 as well as IGFS for organizing and convening a local geoid session in vEGU21. Researchers from all over the world gathered together virtually in the G1.5 session, Local/Regional Geoid determination: Methods and Models on April 29th 2021. A total of 14 presentations were given in variety of issues related to local geoid quasi geoid computation. An extended break room discussions were kindly provided by vEGU to this session for some in-depth discussions.

This session focused on the practical solution of various formulations of geodetic boundary-value problems to yield precise local and regional high-resolution (quasi)geoid models. Contributions describing recent developments in theory, processing methods, downward continuation of satellite and airborne data, treatment of altimetry and shipborne data, terrain modeling, software development and the combination of gravity data with other signals of the gravity field for a precise local and regional gravity field determination are welcome. Topics such as the comparison of methods and results, the interpretation of residuals as well as geoid applications to satellite altimetry, oceanography, vertical datums and local and regional geospatial height registration are of a special interest.

Downward Continuation of Airborne Gravity Data

The working group SG2.4.1 is holding semi-yearly virtual meetings after its establishment at IUGG 27th at Montreal Canada. Extended discussions and computational tests have been carried to demonstrate the ill-posedness of the downward continuation problem and its stabilization. A paper entitled "Characterization and stabilization of the downward continuation problem for airborne gravity data" was published at Journal of Geodesy, volume 96, Article number 18 (2022).

In this study, we compare six commonly used methods for the downward continuation of airborne gravity data. We consider exact and noisy simulated data on grids and along flight trajectories and real data from the GRAV-D airborne campaign. We use simulated and real surface gravity data for validation. The methods comprise spherical harmonic analysis, least-squares collocation, residual least-squares collocation, least-squares radial basis functions, the inverse Poisson method and Moritz's analytical downward continuation method. We show that all the methods perform similar in terms of surface gravity values. For real data, the downward continued airborne gravity values are used to compute a geoid model using a Stokes-integral-based approach. The quality of the computed geoid model is validated using high-quality GSVS17 GPS-levelling data. We show that the geoid model quality is similar for all the methods. However, the least-squares collocation approach appears to be more flexible and easier to use than the other methods provided that the optimal covariance function is found. We recommend it for the downward continuation of GRAV-D data, and other methods for second check.

EGU23 session G1.5

Remarkable advances over recent years give evidence that geodesy today develops under a broad spectrum of interactions, including theory, science, engineering, technology, observation, and practice-oriented services. Geodetic science accumulates significant results in studies towards classical geodetic problems and problems that only emerged or gained new interest, in many cases as a consequence of synergistic activities in geodesy and tremendous advances in the instrumentations and computational facilities. In-depth studies progressed in parallel with investigations that mean a broadening of the traditional core of geodesy. The scope of the session is conceived with a certain degree of freedom, though it is primarily intended to provide a forum for all investigations and results of theoretical and methodological nature.

The contributions focused on problems of reference frames, gravity field studies, dynamics and rotation of the Earth, positioning. The presentations illustrated the use of mathematical and numerical methods in solving geodetic problems, demonstrated advances in mathematical modeling, estimating parameters, simulating relations and systems, using high-performance computations, and discussed methods for exploiting data of new and existing satellite missions. Presentations showed mathematical and physical research directly motivated by geodetic need, practice and tied to other disciplines.

The session also discussed the practical solution of various formulations of geodetic boundary-value problems to yield precise local and regional high-resolution (quasi)geoid models. Contributions described recent developments in theory, processing methods, downward continuation of satellite & airborne data, treatment of altimetry and shipborne data, terrain modeling, software development and the combination of gravity data with other signals of the gravity field for a precise local and regional gravity field determination. Topics were included the comparison of methods and results, the interpretation of residuals and geoid applications to satellite altimetry, oceanography, vertical datums & local and regional geospatial height registrations.

xGeoid22 is under construction

From 2014 to 2022, the National Geodetic Survey (NGS) published annual experimental geoid (xGEOID) models. As such, a new xGeoid model, xGeoid22, will be release later of 2023. A major update is on the use of re-processed GRAV-D data. NGS updated its airborne gravity processing method and re-processed all of its previous GRAV-D data with this newly revised method. xGeoid22 will use these newly processed GRAV-D airborne gravity data. The model will also contain the gravity data from the latest satellite gravity models, the terrestrial gravity. The associated DoV models will also be generated.

Gravity, Geoid, and Height Systems 2022 (GGHS2022)

The science of the earth's gravity field and its time variation is advancing rapidly. In addition to the classical disciplines of geoid determination, geodetic reference systems, navigation, satellite orbit determination, and geophysics and interior earth structure, the gravity field science has in the last decade provided unique insights into the cryosphere and hydrological changes, and general mass transports in the earth system, primarily from GRACE and GRACE-FO satellite missions. At the same time global knowledge of the gravity field details has improved significantly due to the GOCE mission, large-scale airborne gravity campaigns, and the coverage of the oceans by satellite altimetry. New technologies such as cold atom interferometry, miniature gravity sensors, strapdown IMU gravity sensors, and new satellite mission concepts are on the poise to further advance gravity field science.

The GGHS2022 symposium aims to bring together geodesists, geophysicists and space scientists who work with gravity field observations from space, airborne and surface, novel gravity field observation technologies, gravity field modelling, fundamental height systems, gravity networks, and gravity field change observations for climate change and hydrology.

NGS participated GGHS 2022 in Austin Texas Sept. 2022, and chaired sessions Session 3: Local/Regional Gravity Field Modelling, and Session 2: Global Gravity Field Modelling as well as presented research results on using bathymetric data to improve the precision of local geoid models: "Bathymetric Effects on Geoid Modeling: A Case Study in the Great Lakes".

International Federation of Surveyors (FIG) working week 2023

The National Society of Professional Surveyors (NSPS) co-hosted with FIG of the Working Week 2023 in Orlando, Florida from May 28th – June 1st, 2023. The FIG Working Week 2023 is the premier event for surveyors and geospatial experts. The theme is "Protecting Our World – Conquering New Frontiers" and is a great opportunity for the geospatial profession to expand its presence through technology, experience, and good will towards a better tomorrow. As our world and climate changes around us, we can leverage our knowledge base and tools for measuring, monitoring, and forecasting how to improve the outlook for our future generations.

This Working Week brought more than 1,000 surveyors and geo-spatialists from around the globe to share ideas, provide training for new techniques and methodologies, and offer attendees an opportunity to see the latest in technology from worldwide venders. The technical sessions offered many disciplines, including photogrammetrists, hydrographers, and land records professionals, opportunities to interact with fellow geospatial professionals on a wide range of topics in various settings.

NGS sent over 30 delegates to participate this working week and hosted a special NGS day to promote the NSRS modernization efforts, which aimed to give a pre-show of the upcoming national reference frame that also includes NAPGD2022. A presentation entitled “An Entire Spectrum Modernization of the Geoid Model ---- from data collection to modeling and customer services” summarized the major efforts during building the next vertical datum.

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Sub-commission 2.4d: Gravity and Geoid in Africa

Chair: Hussein Abd-Elmotaal (Egypt)
Vice-Chair: S.A. Benahmed Daho (Algeria)

Main activities (2019–2023)

Effect of Land Depression on Gravity and Geoid

Abd-Elmotaal and Kühtreiber (2020) have studied the effect of Qatara depression, Egypt, on the gravity anomalies and geoid. This effect is significant and extends over a large rejoin. The effect of Qattara Depression on the gravity anomalies reaches 20 mGal and is located only at the area of the depression. The effect of Qattara depression on the geoid exceeds 1 m and is not only limited to the area of the depression but rather spreads out all over the whole country (in a radius of about 1000 km). This shows its significance and importance to be taken into account for a precise geoid determination.

Effect of Great Lakes on Gravity and Geoid

Abd-Elmotaal et al. (2020a) have studied the effect of Victoria Lake on the gravity anomalies and the geoid. The study utilized two different techniques to determine the effect of the lake. The results proved that both developed approaches are capable to determine the effect of Lake Victoria on gravity anomaly and geoid undulation. Both approaches give practically the same results in all cases. The total topographic-isostatic effect of Lake Victoria on the gravity anomaly reaches about 4 mGal and is confined mainly to the area of the lake. The total effect of Lake Victoria on the geoid undulation has an isotropic behaviour attaining its maximum value at the lake, with a value of about 28 cm, and decreases with radial distance outwards. It practically vanishes outside a radial distance from the lake of more than 3o. Accordingly, the effect of Lake Victoria on the geoid is rather significant and should then be considered for precise geoid determination.

New AFRGDB_V2.2 Gravity Database for Africa

Abd-Elmotaal et al. (2020b) have established a new gravity database for Africa (AFRGDB_V2.2). The AFRGDB_V2.2 African gravity database has been established using a combination of real data on land and sea and an underlying grid filling the large data gaps. This underlying grid, used to fill-in the data gaps before the interpolation process, has been created using the GOCE Dir_R5 model up to degree and order 280. A 3′ grid filtering has been applied to the sea data to decrease their dominance on the solution. A 1′ grid filtering has been applied to the land data to improve the behaviour of the empirically determined covariance function, especially near the origin. The RTM remove-restore technique has been used with the GOCE Dir_R5 model, up to degree and order 280, representing the global model. An unequal weight least-squares prediction technique has been carried out to interpolate the reduced anomalies on a 5′ grid. The established AFRGDB_V2.2 gravity database for Africa has an internal precision of about 5.5 mGal.

The validation of the AFRGDB_V2.2 gravity database shows a similar quality as the previous AFRGDB_V2.0gravity database, measured with an external accuracy of about 7 mGal. This already indicates that establishing the gravity database for Africa has become robust to some extent.

The computation efforts and CPU-time needed for the AFRGDB_V2.2 gravity database are much less compared to those of the previous database (AFRGDB_V2.0).

Regional Geoid Determination for Africa

Abd-Elmotaal et al. (2020c) have computed a precise model for the regional geoid for the whole continent of Africa (cf. Fig. 23). This geoid model has utilized the AFRGDB_V2.1 gravity database of Africa.

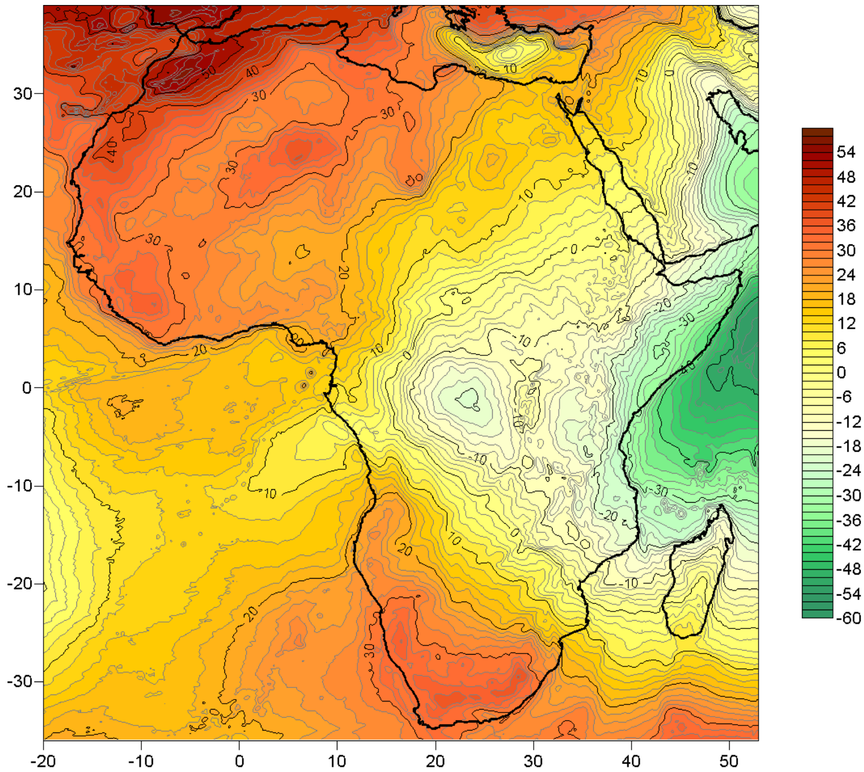

Figure 23 The African geoid model AFRgeo2019 (after Abd-Elmotaal et al., 2020c).

Optimal Terrain Correction Software for Window Remove-Restore Technique

Very powerful software for optimal terrain correction for the window remove-restore technique, with a case study for Africa, has been developed by Abd Elmotaal and Kühtreiber (2021c, 2022a). This software can save up to 99.5% of the CPU time required for computing the terrain correction for Africa.

Evaluation of the AFRGDB_V2.0 and AFRGDB_V2.2 African Gravity Databases

An assessment study of the previously created gravity databases for African has been carried out by Abd-Elmotaal et al. (2022a, 2023) employing new data set at the north-south area of the African window. This studt shows that the AFRGDB_V2.0 fits better than the AFRGDB_V2.2 to the new data. However, the computation efforts and CPU-time for the AFRGDB_V2.2 gravity database are much less compared to those of the AFRGDB_V2.0 gravity database. The validation, as an external check of the quality of the gravity databases AFRGDB_V2.x for Africa, shows reasonable accuracy of the established gravity databases considering the large data gaps in Africa. The performed validation of the so far used data for establishing the AFRGDB_V2.x databases shows significant discrepancy concerning the new data set for Sinai, which deserves deeper investigation.

Updated AFRGDB_V2.3 Gravity Database for Africa

Abd-Elmotaal et al. (2022b, 2023b) have established an updated gravity database for Africa (AFRGDB_V2.3). The available gravity data have large data gaps, particularly at the point gravity on land. The oceanic area is well covered with shipborne data and gravity anomalies derived from altimeter measurements. However, both are naturally measured along tracks. This makes it difficult to estimate a realistic empirical covariance function, which limits the performance of the used least-squares prediction technique. To get rid of this problem, the data is filtered and provided with individual weights. In doing so, the gravity data on land are weighted the highest. The shipborne and altimetry data, on the other hand, are introduced with somewhat less precision. The lowest weight is given to the gravity anomalies computed from the GOCE DIR_R5 geopotential model in order to fill the data gaps. The point gravity data from different sensors are smoothed by applying the widely used RTM reduction scheme. From the smoothed, weighted data, gravity anomalies are predicted on a uniform 5×5′grid by applying the weighted least-squares technique. After the final restore step, the AFRGDB (African Gravity Data Base) is obtained in the new version V2.3.

The new AFRGDB_V2.3 gravity database for Africa is discretized on a 5×5′and has an internal precision of about 5.6 mGal. The AFRGDB_V2.3 gravity database was compared to the previous AFRGDB_V2.0 gravity database. Both models, which were created using different methods, show a very good agreement with external accuracy of about 7 mGal. This makes it clear that the IAG Sub-Commission on gravity and geoid in Africa has already developed robust methods and will continue to work on them. The comparison also declares that the RTM method has significant advantages in terms of the required CPU time.
Of course, the new AFRGDB_V2.3 gravity database can not only be used for a corresponding calculation update of the geoid model. Free-air gravity anomalies reveal interesting geophysical signals which are of interest to all Earth system sciences.

Important Complementary Studies in Africa

Odera (2019) has accomplished an assessment study of the latest GOCE-based global gravity field models using height and free-air gravity anomalies over South Africa. Odera (2020) has evaluated the recent high-degree combined global gravity-field models for geoid modelling over Kenya, Africa. Ashry et al. (2021) have computed a geoid model for Africa employing the shallow layer method. This geoid model has been compared with the recent AFRgeo2019 geoid model. Compatabilities benween the two geoid models were concluded. Abd-Elmotaal and Kühtreiber (2021) have done a remarkable development within the used expressions for the window remove-restore technique, which will definitely contribute in a better geoid modeling for Africa.

A study of the optimum DTM resolution to be used within the window remove-restore technique for geoid determination in African has been carried-out by Abd Elmotaal and Kühtreiber (2021b). Ashry et al. (2022) have defined a unified height system for Africa using relativistic geodetic approaches. The effect of the gravity data coverage on the gravity field recovery has been studied by Abd Elmotaal and Kühtreiber (2022b). This study has proved that for the case of the large data-gaps, as the current situation in Africa, least-squares collocation method for geoid determination may lead to somewhat strange geoid behaviour. Instead, the Stokes approach, with modified Stokes kernel, behaves significantly better. Seitz et al. (2023) have nicely formulated the external gravitational field of a homogeneous ellipsoidal shell, with several computational tests. The developed formuals and approach can be used as a reference for benchmarking the gravity modelling software.

Future Activities

A study of the effect of the crustal density on the gravity interpolation at large data gaps in Africa is undertaken meanwhile and is going to be presented in the 28th IUGG General Assembly, Berlin, July 11–20, 2023, by Abd-Elmotaal et al. Odera is currently supervising 4 PhD students carrying out research related to geoid modelling and height systems in various countries in Africa (South Africa, Kenya, Zimbabwe, and Nigeria). Marijani is conducting a research on the validation of the African 3"×3" DTM (Abd-Elmotaal et al., 2017) in Tanzania. The African 3"×3" DTM for the window of Tanzaina has been made available to Marijani by Abd-Elmotaal.

Problems and Request

The IAG sub-commission on the gravity and geoid in Africa suffers from the lack of data (gravity, GNSS/levelling …). The great support of IAG is needed in collecting the required data sets. It can hardly be all done on a private basis. Physical meetings of the members of the sub-commission would help in solving the problems and would definitely contribute to the quality of its outputs. IAG is thus kindly invited to support that action.

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Sub-commission 2.4e: Gravity and Geoid in Asia-Pacific

Chair: *Cheinway Hwang (China-Taipei)*
Vice Chair: *Wenbin Shen (China)*

Activities from 2019 to 2023

The IAG SC2.4e, a subdivision of SC2.4, focuses on advancing gravity field modeling in the Asia Pacific area. In both October 2020 and October 2022, SC2.4e members and geoid modelers conducted two online workshops, which were accompanied by the launches of two journal special issues dedicated to these workshops. This paper presents the outcomes of IAG SC2.4e's activities from 2019 to 2023 and provides illustrations of gravity data collection, processing, and their application in geoid modeling across several locations including Australia, mainland China, Hong Kong, India, Indonesia, Japan, Malaysia, Nepal, New Zealand, Philippines, South Korea, Thailand, and Taiwan.

The two Asia-Pacific geoid workshops

The purpose of the two workshops was to promote SC2.4e. The first workshop took place on October 29, 2020, during the peak of the COVID-19 pandemic. Detailed information can be found on the website: http://space.cv.nctu.edu.tw/The-First-Asia-Pacific-geoid-workshop-4e. Initially, it was intended to be an in-person meeting, but due to the pandemic, an onsite gathering was not feasible. Subsequent to the first workshop, a special issue (SI) was launched in the Terrestrial, Atmospheric and Oceanic Sciences (TAO) journal (Hwang et al., 2021). A total of 13 papers were published in this SI. Fig.1 shows its cover image. This SI presented the most recent geoid models in Australia, mainland China, India, Indonesia, South Korea, Malaysia, Nepal, the Philippines, Taiwan, and Thailand. Some of the papers were not directly related to national geoid models. For instance, one paper presented a software package capable of effectively processing airborne gravity data in Java, Indonesia. Another paper used the land gravity values from the global gravity grid of the Scripps Institution of Oceanography to examine Bouguer anomalies and geological boundaries in mainland China. A paper demonstrated a gravity-geologic method for predicting oceanic depths around Malaysia. Lastly, a paper in the SI from the International Service for the Geoid highlighted some of the inventory geoid models in the Asia-Pacific region.

The 13 accepted papers in the SI of TAO can be freely downloaded from: https://drive.google.com/drive/folders/1Ijnl_bg9gKxApyUkxnjHZVN1F1sY7xYg?usp=drive_link.

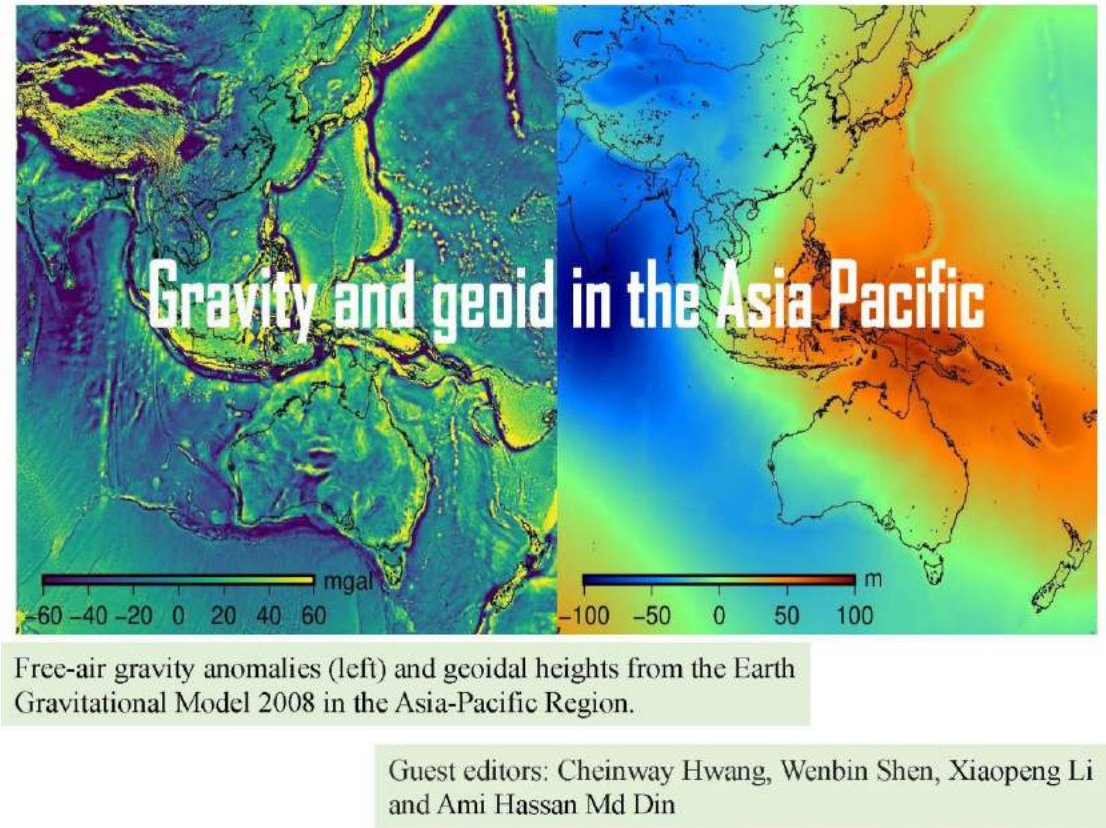

Figure 24 The cover image of the TAO special issue of gravity and geoid in the Asia Pacific

The second workshop took place online once again, on October 21, 2022. The speakers differed from those in the first workshop, but the representation of countries regarding geoid modeling was well maintained. For detailed information, please refer to the website: http://space.cv.nctu.edu.tw/The-Second-Asia-Pacific-geoid-workshop-4. Following the workshop, a special issue titled "Applications of New Techniques and Methods in Gravity Field Determination" was launched in the journal "Frontiers in Earth Science." As of June 2023, submissions to this special issue are still being accepted

Gravity data sharing in the Asia-Pacific region

In order to model a geoid in a specific country, it is typically necessary to use trans-national gravity data surrounding that country. Encouraging gravity data sharing among the members of IAG-SC2.4e is an important activity. One suggested approach for sharing is for individual countries to contribute their gravity data to an IAG service, such as the International Bureau of Gravity (BGI), and then retrieve the required trans-national gravity measurements from this service. Fig. 24 illustrates the distribution of land gravity measurements from BGI in the Asia-Pacific region. With the exception of Australia, New Zealand, South Korea, and Japan, most countries have limited availability of gravity data. It will require further efforts from the IAG to facilitate the provision of shared gravity data in the Asia-Pacific region.

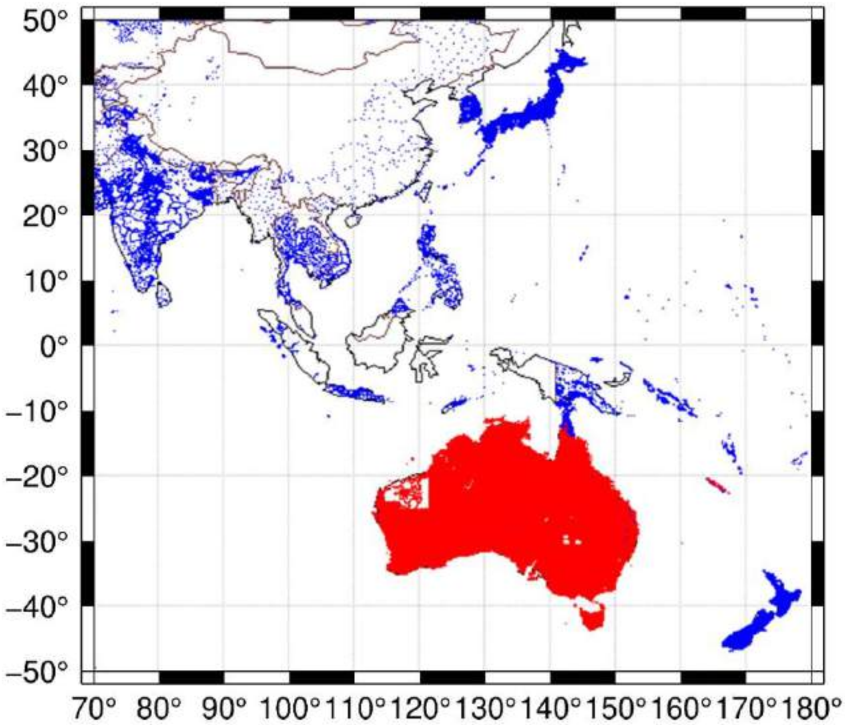

Fig. 25: The distribution of land gravity measurements from the International Gravimetric Bureau (BGI; https://bgi.obs-mip.fr) in the western Asia-Pacific region.

Prospect of geoid modeling

Ever since the publication of the lecture notes titled "Geodetic Boundary Value Problems in View of the One Cm Geoid" by Sanso and Rummel (1997), achieving cm-level accuracy has become the ultimate objective for geoid modelers worldwide. An example highlighting the pursuit of this cm geoid goal is the release of gravity and elevation data in Colorado by the National Geodetic Survey of the USA. In Colorado, 14 international teams developed their individual geoid models, known as the Colorado geoid models (Wang et al., 2021). Based on the findings of this experiment, the accuracy of these 14 Colorado geoid models is approximately 2 cm. This assessment was made by comparing the observed geoidal heights obtained from GNSS/leveling along a profile (highway) in Colorado (GSVS17).

In alignment with the Colorado experiment, SC2.4e announced that gravity data and elevation data for geoid modeling in Taiwan (Huang et al., 2021) are available for experimentation, free of charge. To request access for experiments, interested individuals can contact C. Hwang, at cheinway@nycu.edu.tw. Fig. 26a shows a digital elevation model (DEM) of Taiwan derived from LiDAR data. The DEM exhibits diverse terrains ranging from low-lying coastal areas to towering mountains, with elevations 3952 m. Fig. 26b shows the differences in elevation between the LiDAR-derived DEM and the 15" SRTM DEM. Accurate elevation data play a crucial role in accounting for the short wavenumber geoidal component, directly impacting the accuracy of the geoid model. Fig. 26b indicates substantial disparities of several hundred meters between the two DEMs, particularly in the mountainous regions of Taiwan. Fig. 26a also shows the locations of benchmarks with observed geoidal heights along a leveling route spanning Taiwan, with the highest elevation recorded at 3275 m. Similar to the GSVS17 assessments in Wang et al. (2021), the observed geoidal heights in Fig. 26a can be used to evaluate the accuracies of geoid models.

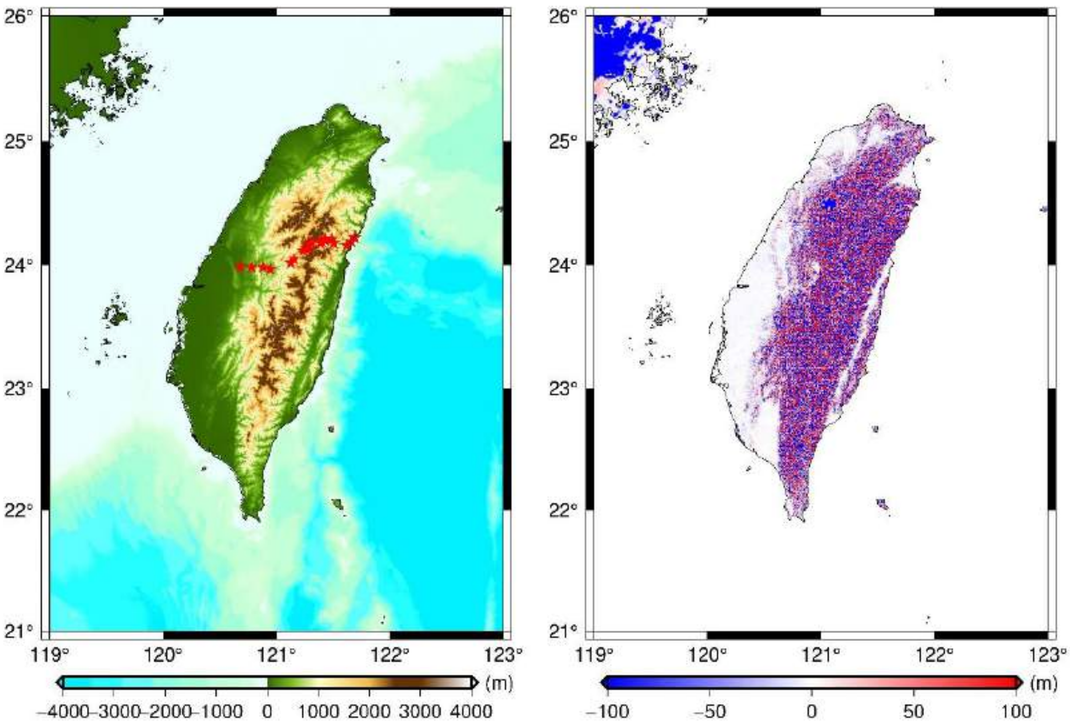

Fig. 26: (a) The latest digital terrain model around Taiwan from LiDAR (land) and multibeam measurements (oceans), and the distribution of GNSS/leveling points across a west-east provincial route in central Taiwan (red stars). (b) The differences between the elevations from LiDAR and from the SRTM DEM (15" resolution) in Taiwan.

Conclusion

Achieving a 1 cm-geoid model remains an ongoing endeavor within the geodetic community. The Asia-Pacific region stands out as a prime location for conducting geoid modeling experiments due to its rough gravity fields. The majority of SC2.4e members are persistently dedicated to pursuing the goal of attaining 1 cm accuracy in their respective nations. The support provided by IAG plays a vital role in ensuring their progress and eventual success.

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Sub-commission 2.4f: Gravity and Geoid in Antarctica

Chair: *Mirko Scheinert (Germany)*
Vice-Chair: *Fausto Ferraccioli (U.K.)*

Overview

The Sub-Commission is dedicated to the determination of the gravity field in Antarctica. In terms of observations, mainly airborne but also terrestrial campaigns have been and are being carried out to complement and to densify satellite data. Because of the region and its special conditions the collaboration extends beyond the field of geodesy – the cooperation is truly multidisciplinarily, especially incorporating experts from the fields of geophysics and glaciolo-gy. This is also reflected in the group membership (cf. below).

During the last period (2019 – 2023) new ground-based or airborne gravity data could not be incorporated into the AntGG database. Due to the pandemic crisis the vast majority of re-search activities in Antarctica had to be cancelled especially for the seasons 2020/2021 and 2021/2022.

In terms of the re-processing of all available terrestrial gravity data incorporating new data available since the publication of the first gravity anomaly grid (Scheinert et al. 2016) consid-erable progress could be made. Within a project funded by the German Research Foundation (DFG), led by Roland Pail (Munich, Germany) and Mirko Scheinert (Dresden, Germany), several aspects of the combination of the terrestrial gravity data in Antarctica with a high-resolution spherical harmonic model were successfully investigated and published (Zingerle et al. 2019, 2021). Preliminary results were presented at EGU 2021 (Scheinert et al. 2021a) and IAG 2021 (Scheinert et al. 2021b) as well as at the workshop of the SCAR Action Group RINGS (Scheinert et al. 2022). The grid spacing could be enhanced from 10 to 5 km. Also, the number of products could be enlarged to be provided with this updated AntGG solution w.r.t. the data published by Scheinert et al. (2016). Fig. 27 exemplarily shows preliminary re-sults in terms of gravity disturbances and height anomalies.

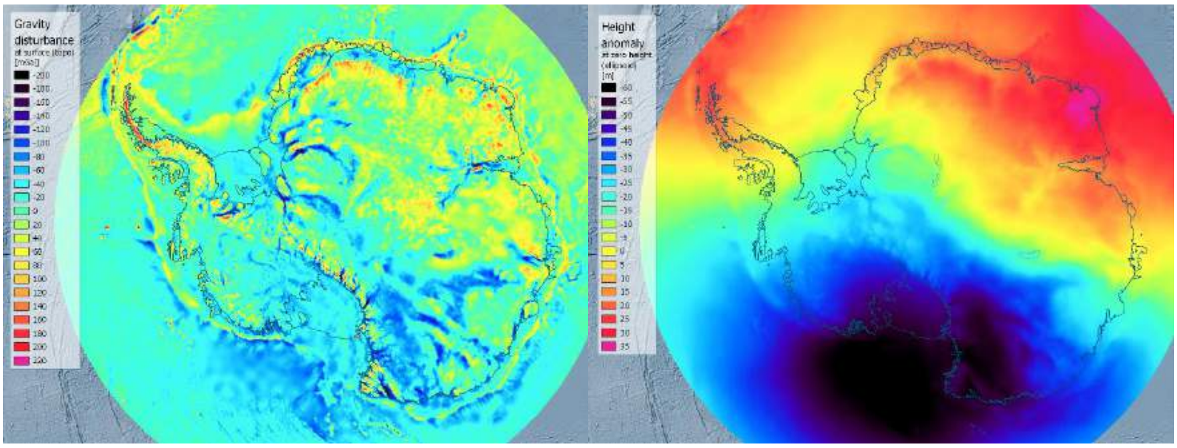

Figure 27 Preliminary results of the new processing of the regional gravity field in Antarctica. Left: Gravi-ty anomaly; right: height anomaly, as presented at IAG 2021 (Scheinert et al. 2021b).

In terms of outreach to the interested public, a contribution could be delivered (Eagles and Scheinert 2021) to the compilation *Antarctic Resolution* by Foscari et al. (2021) based on an exhibition at the Biennale Architettura 2021 in Venice.

Linkage

A close linkage is maintained to the Scientific Committee on Antarctic Research (SCAR) and its numerous groups and activities. The SCAR Expert Group on "Geodetic Infrastructure in Antarctica" (GIANT) serves as a counterpart of IAG SC 2.4f. M. Scheinert co-chairs GIANT as well as chairs the GIANT project "Gravity Field". The resulting datasets of AntGG are being consid-ered also in the science plan of the SCAR Action Group RINGS which primarily aims to im-prove models of subglacial (bedrock) topography in the transition zone from the Southern Ocean to continental Antarctica. There, the gravity dataset serves as a valuable input for an inversion of bedrock topography where direct measurements (radar) are not available or possible.
Furthermore, several group members are involved in the initiation and set-up of the new SCAR Scientific Research Program "Instabilities and Thresholds in Antarctica" (INSTANT). Within INSTANT regional gravity field information in Antarctica serves a number of questions to be investigated (e.g. paleo modelling, tectonic and geological interpretation, inversion for bathymetry and subglacial topography).

Future plans and activities

Future activities are well defined following the "Terms of Reference". Since any Antarctic activity call for a long-term preparation the main points to be focused on do not change. New surveys will be promoted, nevertheless, due to the huge logistic efforts of Antarctic surveys, coordination is organized well in advance and on a broad international basis. Within AntGG, the discussion on methods and rules of data exchange is in progress and has to be further pursued. Compila-tions of metadata and databases have to cover certain aspects of gravity surveys in Antarctica (large-scale airborne surveys, ground-based relative gravimetry, absolute gravimetry at coastal stations). The main goal to deliver a grid of terrestrial gravity data was fulfilled by the publica-tion of a first grid in 2016 (Scheinert et al. 2016). Updates and enhancements are anticipated as reported above.
With regard to new gravity surveys in Antarctica, aerogravimetry provides the most powerful tool to survey larger areas. In this context, airborne gravimetry forms a core observation technique within an ensemble of aerogeophysical instrumentation. Further airborne missions may help not only to fill in the polar data gap in its proper sense, but also all remaining gaps over Antarctica.

Selected conferences with participation of AntGG members / with relevance to AntGG

- IUGG General Assembly, Montreal (Canada), 08–18 July 2019.
- XIII International Symposium on Antarctic Earth Sciences, Goa, 13-17 July, 2015.
- International Symposium on Antarctic Earth Sciences (ISAES) XIII, Incheon (South Korea), 28 July – 02 August 2019
- XXXVI SCAR Meeting and Open Science Conference (online, originally to take place in Hobart, Australia), August 2020
- EGU General Assemblies 2020, 2021 (virtual conf.), 2022, 2023
- AGU Fall Meetings 2019, 2020, 2021, 2022
- IAG Scientific Assembly 2021
- Workshop of SCAR Action Group RINGS, Tromsö, June 2022
- XXXVII SCAR Meeting and Open Science Conference July/August 2022 (online, organized by India)

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Sub-commission 2.5: Satellite Altimetry

Chair: *Xiaoli Deng (Australia)*
Vice Chair: *C.K. Shum (U.S.A.)*

Summary

This report presents some of key activities that have marked the IAG sub-commission (SC) 2.5 over the period of 2019-2023. The various sections presented in this report provides specific details regarding the activities of individuals and teams within the SC2.5, which focus on integrated use of altimetry and space geodetic techniques and their applications in climate change analysis. These include:

- Determining marine gravity field, mean sea surface (MSS) and bathymetry,
- Monitoring global and coastal sea level changes,
- Reconstructing historic regional sea levels,
- Monitoring surface water levels over inland water bodies,
- New applications,
- Developing the retracking algorithm, validation and calibration of altimetry data from both conventional and new satellite altimetry missions,
- Contributed to establish new study and working groups, and
- Contributed to establish the international altimetry service (IAS).

The contributions below represent the group work by following members:

Prof Ole Andersen (DTU, Denmark)
Prof Li-Feng Bao (Chinese Academy of Sciences, China)
A/Prof Xiaoli Deng (The University of Newcastle, Australia)
Dr Luciana Fenoglio-Marc (University of Bonn, Germany)
Prof Cheinway Hwang (National Yang Ming Chiao Tung University, Taiwan)
A/Prof Tao-Yong Jin (Wuhan University, China)
Prof Chung-Yen Kuo (National Cheng Kung University, Taiwan)
Prof Jürgen Kusche (University of Bonn, Germany)
A/Prof Hyongki Lee (University of Houston, United States)
Dr Fukai Peng (Sun Yat-Sen University, China)
Prof David Sandwell (Scripps Institution of Oceanography, United States)
Prof C. K. Shum (Ohio State University, United States)
Dr Walter H. F. Smith (NOAA, United States)

Most members have made significant contributions to research and applications of satellite altimetry and been the co-authors of a publication by a large group of International Altimetry Team (2021). The publication provides a comprehensive description of interdisciplinary altimetry enabled science and applications, reporting on ESA's "25 Years of Progress in Radar Altimetry" Symposium, held at Ponta Delgada, São Miguel Island, Azores Archipelago, Portugal, 24-29 September 2018.

The SC2.5 has involved in following special issues:

1) Application of Satellite Altimetry in Marine Geodesy and Geophysics, in Frontiers in Earth Sciences. This special issue (Guo et al., 2022), edited by Guo, Deng, and Hwang, explores the applications of satellite altimetry in marine geodesy and geophysics, providing comprehensive insights into the field.

(https://www.frontiersin.org/research-topics/16136/application-of-satellite-altimetry-in-marine-geodesy-and-geophysics).

2) Advances in Satellite Altimetry, in Remote Sensing. This special issue, edited by Mertikas, Deng and Benveniste, presents recent advances in the field of radar and laser altimetry, their processing algorithms, calibration/validation, and their applications in the spatial-temporal monitoring of Earth's systems on all scales. (https://www.mdpi.com/journal/remotesensing/special_issues/satellite_altimetry).

The Mean Sea Surface (MSS) topography working group led by Prof David Sandwell started in September 2020. The group members include researchers from Scripps Institution of Oceanography, CLS, DTU, NOAA, SIO and NYCU. The regular meetings have been held to discuss several challenging issues of (1) cross-comparisons between MSS models from CLS, DTU and RADS, (2) understanding the large MSS difference between existing models in the Arctic and the Kuroshio and the Gulf Stream, and (3) the use of ICESAT-2 altimetry for the recovery of ocean topography.

Altimetry study and working groups

The SC2.5 sub-commission has established following four study/working groups:

- SC25.1: High-resolution altimetry for geodetic, oceanographic, cryosphere and hydrology studies (HRA), chaired by Dr Luciana Fenoglio-Marc and vice-chaired Prof Ole Baltazar Andersen.

  The HRA focuses on high resolution altimetry for geodetic, oceanographic, cryosphere and hydrology studies. It investigates the development allowed by high-resolution altimetry in 1-D and SWOT 2-D fields. It supports research projects in (1) enhanced processing of high-resolution altimetry along-track in SAR mode and comparison of available techniques (e.g., FF-SAR, LRMC, Unfocused SAR and Reduced SAR); (2) understanding of the SWOT signal with pre-launch simulation of future swath-like observations from model outputs and realistic errors, and post launch calibration/validation of the observations; (3) high resolution altimetry and assimilation in open seas to study eddy dynamics and related vertical processed with exchanges of heat and carbon between the ocean and the atmosphere, in coastal zones and estuaries to study dynamics of exchanges in the river-estuary and open ocean continuum, in rivers to study river dynamics and river discharge, and in lakes and wetland to study water mass change on land. It will provide a forum for discussion and to encourage innovative interdisciplinary scientific research and applications.

- SC25.2: Synergistic applications of satellite altimetry with other satellite sensors/physical models (SASA), chaired by A/Prof Hyongki Lee and vice-chaired by Chungyen Kuo.

  This group promotes innovative usage of altimetry data synergistically integrated with data obtained from other satellite sensors (e.g., optical/SAR imaging sensors, laser altimetry, GRACE/GRACE-FO and GNSS-R) and physical models in order to advance scientific studies and real-world applications. SASA will (1) study geophysical processes from merging multi-mission radar altimetry and laser altimetry (ICESat, ICESat-2), other geodetic data and SWOT interferometric altimetry; (2) support collaborations among scientific users of altimetry and other satellite sensors, merge altimetry-derived water levels with imaging sensor-derived river widths/inundated areas, in situ data, model outputs and GRACE/GRACE-FO data for river discharge estimation, reservoir monitoring and inundation mapping; (3) integrate altimetry data with hydrologic models to reduce uncertainties in model-derived streamflow, to isolate contributions from Glacial Isostatic Adjustment (GIA); (4) map land ice and mountain glacier elevations using multiple radar altimetry missions; and (5) use in-situ/SNR and spaceborne GNSS-R altimetry/radiometry for monitoring coastal sea levels, inland water bodies, soil moisture, snow elevation changes and land/water classifications.

- SC25.3: High Resolution Mean Sea Surface (MSS), chaired by David Sandwell and vice-chaired by Ole Andersen and Philippe Schaeffer.

  The group has been collaborating for the development of the high-resolution MSS by comparing largely independent developments. There are a number of important challenges including: the definition of the averaging time for the MSS; the methods of combining the short wavelength information from the high spatial density measurements with the sparse framework provided by the PO missions; and extending the MSS into the Arctic where the spatial and temporal coverage is less than optimal due to sea ice cover.

  The MSS study group aims to (1) support discussions and collaborations in the international scientific community on the development of a high resolution MSS; (2) develop a consensus global MSS by combining the long-term framework from exact repeat altimeter missions including: TOPEX/Jason, Envisat/SARAL and Sentinel-3 with the high spatial resolution data provided by Geosat, Cryosat-2, SARAL and Jason-1/2/3 (extension of life); (3) hold regular meetings to compare and contrast MSS models developed at CLS, DTU and SIO; (4) distribute the consensus MSS model(s) to the physical oceanography, geodetic, offshore industry and altimetry communities; and (5) focus, in particular, on the development of a MSS for the upcoming SWOT mission to provide calibration and validation early in its mission.

- SC25.4: International Altimeter Service (IAS) Planning Group, chaired by Prof C.K. Shum and A/Prof Xiaoli Deng.

  The IAS is to pool together international resources in satellite altimetry. It aims to (1) provide a forum for broad scientific consensus on intricate altimetry low to high level data processing algorithms; (2) complement existing altimetry data processing entities; (3) provide a mission- and agency-independent forum for potentially improved altimetry data processing and data product access; and (4) encourage innovative, new and interdisciplinary scientific research and applications of satellite altimetry. The IAS planning proposal and progress were presented by C.K. Shum, Xiaoli Deng, and Remko Scharroo during the 2019 IUGG Symposia in Montréal, Canada, July 9, 2019; and have been discussed in several IAG Executive Committee meetings since 2019. The group is calling geodetic and interdisciplinary researchers for participation in the IAS.

Marin gravity, MSS and bathymetry

Researchers from Scripps Institution of Oceanography, CLS, DTU, NOAA, SIO, NYCU and Wuhan have conducted research into:

- Assessed the ability of ICESat-2 (the Ice, Cloud and land Elevation Satellite 2) photon height data to recover oceanographic signals ranging from surface gravity waves to the marine geoid using data over a tropical Pacific box in both wavenumber and space domains (Yu et al., 2021). It found that ICESat-2 is a highly capable instrument with the potential to yield new information about along-track surface waves over distances of 10 km or less, but it will not provide major improvements for the geoid in the open ocean, where many years of radar altimeter observations are providing increasingly accurate global marine gravity maps approaching 12 km wavelength resolution. However, ICESat-2 data may be valuable in regions where surface gravity waves have low amplitude, and the broad radar altimeter waveforms are corrupted by land reflections in a 5 km radius.

- Reprocessed all the altimeter waveform data from the following satellites: Geosat, Envisat, Cryosat-2, Jason-1/2, and SARAL/Altika (~20 billion waveforms) to optimize the slope accuracy and spatial resolution (Yu et al., 2023). These data were used to refine global grids (V32) of the MSS, vertical deflection, gravity anomaly, and vertical gravity gradient (VGG). These grids are available at: https://topex.ucsd.edu/pub/global_grav_1min/.

- Investigated seasonal and interannual variability in sea surface slope (SSS) over the 30-100 km wavelength band. This is the band of wavelengths that will be more completely observed by SWOT. It shows that the seasonal components are generally small – about 10% of the mean variability. Through power spectral density analysis of the seasonal SSS variability, we find that the energy differences between local winter and summer are stronger at smaller scales (<100 km). The Ka-band radar interferometry instrument on the SWOT satellite mission will allow observation of ocean surface activities down to ~20 km at sub-monthly time scales, but wave-related errors (sea state bias, aliasing, wind-driven activities, etc.) will still be a major challenge.

- Continued the development of a high spatial resolution MSS in collaboration with scientists at CNES/CLS and DTU (Schaeffer et al., 2022). This grid was and delivered the global grid to the JPL SWOT project to use for removal of the time invariant effects to reveal the small-scale ocean dynamics.
  https://drive.google.com/drive/folders/10OlpkHq5G_FqqC78zfzrYX6kEQOu7imz

- Continued to refine the global seamount catalogue by identifying and modelling 8600 additional small seamounts observed in the latest VGG grids. The results are published in Gevorgian et al. (2023) and there have been several popular articles on this topic.
  https://www.science.org/content/article/it-s-just-mind-boggling-more-19-000-undersea-volcanoes-discovered
  https://www.sciencenews.org/article/satellite-data-unknown-oceans-sea-mountains
  https://www.livescience.com/planet-earth/rivers-oceans/mind-boggling-array-of-19000-undersea-volcanoes-discovered-with-high-resolution-radar-satellites
  https://www.vice.com/en/article/n7endd/gravity-anomalies-lead-to-discovery-of-vast-unknown-mountain-ranges-under-the-ocean

- Developing a new global predicted depth using a machine learning-based approach to train a neural network in a collection of 50 million depth soundings to predict globally using the latest altimeter-derived marine gravity models (Harper and Sandwell, 2023).

- A global marine gravity anomaly model SDUST2022GRA recovered from multi-satellite altimeter data (Zhen et al., under review). The study introduces SDUST2022GRA, a marine gravity anomaly model derived from laser and SAR altimetry data. This model significantly contributes to our understanding of global marine gravity variations.

- An improved triple collocation-based integration of multiple gravity anomaly grids from satellite altimeters: contribution of ICESat-2 (Chao et al., 2023). The paper presents an enhanced triple collocation-based approach for integrating multiple gravity anomaly grids from satellite altimeters, with a specific emphasis on the contribution of ICESat-2.

- Calibrating error variance and scaling global covariance function of geoid gradients for optimal determinations of gravity anomaly and gravity gradient from altimetry (Yu and Hwang, 2022). The study presents a calibration method for determining accurate gravity anomalies and gravity gradients from altimetry data by optimizing the error variance and scaling of geoid gradients.

- Advances in marine gravity measurement research conducted by Prof Bao and his colleagues. They overview the recent process and development in China in marine gravity field determination by satellite altimetry, seafloor topography inversion, underwater gravity-assisted navigation, and seafloor tectonic movement.

- Marine gravity recovery from Haiyang-2 (HY-2) altimetry missions by Dr Jin's team. The HY-2 missions have accumulated SSH observations on a global scale for more than 10 years. Four HY-2 satellites provide differently distributed data, which play a complementary role in marine gravity studies with other missions. Zhang et al. (2022) evaluated the performances of HY-2 in marine gravity modelling with respect to the SSH accuracy, geoid signal resolution ability, vertical deflections and gravity anomalies. The results show that HY-2 dataset can improve marine gravity anomalies and that the accuracy of NSOAS22 with incorporated HY-2 data is comparable to DTU21 and SS V31.1. The results also reveal different performance of HY-2 altimeters.

- Determining the best geoid gradients from SWOT altimetry using the Tikhonov-L-curve regularization method (Yu et al., under review) and the weighted least squares estimator (Jin et al., 2022). Both papers present the methods for accurately determining geoid gradients using SWOT altimetry simulated data, employing the Tikhonov-L-curve regularization approach and the weighted least squares estimator.

- Determining the Arctic MSS by Chen et al. (2022). A new Arctic MSS model, named SUST22, was developed by combining ICESat and Cryosat-2 data.

- Gravity recovery from SWOT altimetry using geoid height and geoid gradient (Yu et al., 2021). This research focuses on gravity recovery from SWOT altimetry data by utilizing geoid height and geoid gradient information, enabling improved understanding of Earth's gravity field.

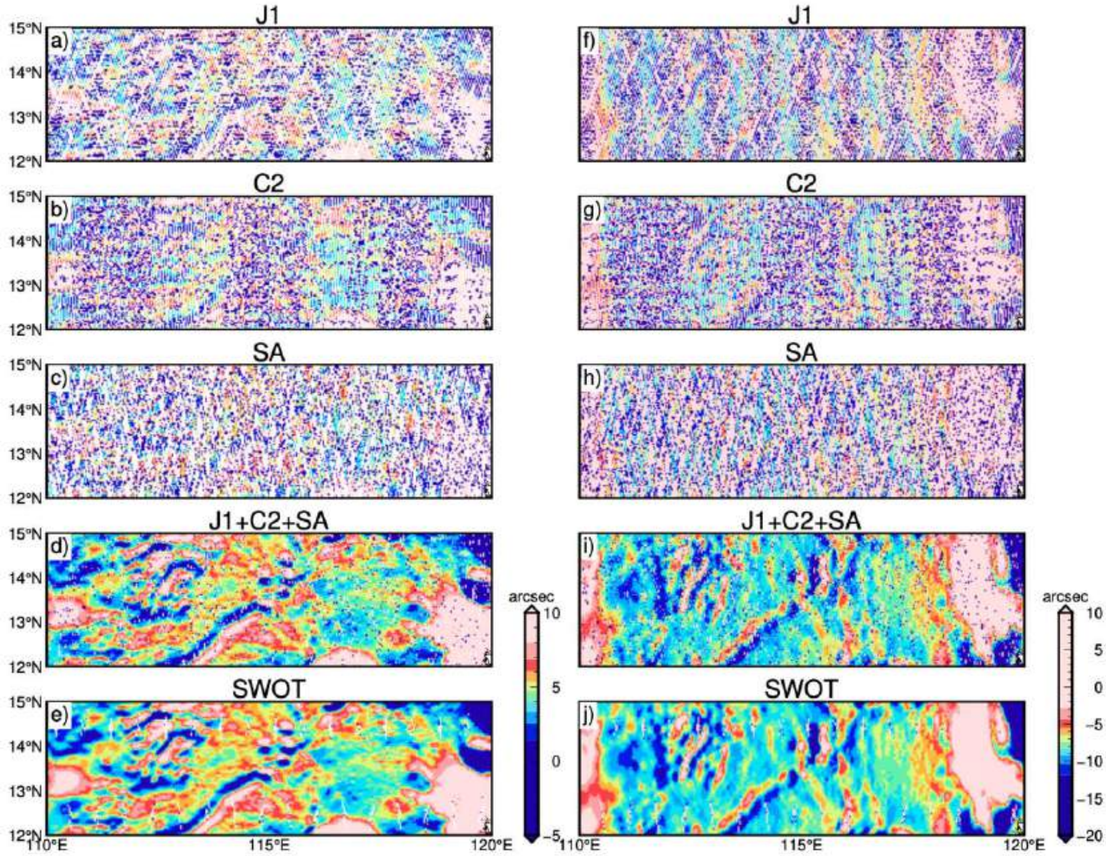

Figure 28. Vertical deflections from different SSH datasets. (a–e) North components; and (f–j) East components (Jin et al., 2022).

New applications of satellite altimetry

The following activities contribute to new applications of satellite altimetry:

- Altimeter gravity detection of undersea volcano eruptions. For the first time, altimeter-derived marine gravity field variations with high spatial resolution and accuracy were used to study the Nishinoshima volcanic activity. Prof Bao's team has computed three different periods with detrended Bouguer gravity anomalies, corresponding to before, during and after the volcanic eruption, and used a method called DEXP to interpret the magma distributions and motions beneath the Nishinoshima volcano (Li et al., 2021). This study shows that satellite radar altimetry provides an innovative and viable tool to study subaqueous volcanism, and demonstrates the methodology for the first time, on the study of the 2013 Nishinoshima volcanic eruption.

- Altimeter gravity detection of submarine plate tectonic motions. Submarine plate tectonic motions are important part of geodynamics and global change. According to the correspondence between mass migration and change of the Earth's external gravity field. Li et al. (2020) analyze the submarine plate motion characteristics using global marine gravity field variations from 1995 to 2019 calculated by the altimetry data of different periods. The results show that the gravity anomalies change significantly at plate convergent boundaries, aseismic ridges, seamount groups and fault zones, but not at plate divergent boundaries. The vertical gravity gradients vary significantly in the Southwest Indian Ridge, Atlantic ridge and Middle Indian Ridge, as well as in the subduction zone of the western Pacific Ocean and some aseismic ridges, which spatial distributions are basically consistent with the terrain.

- Altimeter detection of elevation changes over mountain glaciers. Hwang et al. (2021) developed an altimeter processing technique to detect long-term elevation changes near a glacier terminus and an icefield in Tanggula Mountains using altimeter data from the TOPEX/Poseidon (T/P), Jason-1 (J1), Jason-2 (J2), and Jason-3 (J3) altimeters. The altimeter-observed glacier thinning is confirmed by the direct elevation differences between the digital elevation models from the satellite missions TanDEM-X and SRTM, and by the glacier area losses from Landsat images. The Cryosat-2 result shows the altitude effect of glacier change: the higher the glacier, the less it melts. A repeat altimeter can provide time-lapsed elevation measurements as a virtual glacier station to monitor glacier melt caused by climate change. Tao et al. (accepted in May 2023) utilizes a novel glacier-threshold method with TOPEX/Poseidon and Jason-2 altimeter data to identify and monitor changes in Alaska glaciers.

Monitoring sea levels

Sea level trends

Satellite altimetry and tide gauges are used to monitor sea level changes in open oceans and coastal zones. Methods have been developed to characterize the nonlinear variations of sea levels.

- High-resolution sea level change around China seas revealed through multi-satellite altimeter data (Yuan et al., 2021). The study investigates high-resolution sea level changes in the China seas using multi-satellite altimeter data, contributing to a better understanding of regional sea level variations.

- Modelling sea levels from tide gauges. Jin et al. (2021) proposed a method called EMD-SSA, which effectively combines adaptive empirical mode decomposition (EMD) and singular spectrum analysis (SSA), to estimate the nonlinear trend of sea level change adaptively and accurately from tide gauge time series. Ding et al. (2021) used the optimal sequence estimation method to analyze global tide gauge sea level records. Yang et al. (2021) proposes a fusion approach of altimetry and tide gauge data based on a deep belief network (DBN) method.

- Estimated the sea level rise around Australia. Karimi and Deng (2020) estimated the sea level trend using a new approach that accounts for low frequency climate signals. They investigated the impact of climate modes on sea level variations and trends around Australia using altimetry data, climate indices, and sea level records from tide gauge stations. The average sea level trend for around Australia is estimated as 3.85±0.15 mm/year during the period of 1993-2018. Fukai et al. (2022) analyzes the variation of sea level trends along the Australian coast zone (0–100 km) using 16 years (2002–2018) of tide gauge records, reprocessed Jason data and European Space Agency (ESA) Climate Change Initiative (CCI) sea level product. The sea level trends from 20-Hz along-track points in the Australian coastal zone range from −2 to 12 mm/yr over the period January 2002–May 2018, with the trend uncertainties being smaller than 2 mm/yr.

- Sea-level budget, vertical motion and sea-level acceleration. Research on holistic sea-level budget adjustments using robust statistical models have been conducted (İz & Shum, 2020a, 2020b; İz, Yang & Shum, 2020a). Novel studies conflating altimeter and tide gauge records to estimate vertical land motion and geocentric coastal sea-level have been reported (İz et al., 2019; İz, Yang & Shum, 2020b). İz & Shum (2020c) reported on the certitude of the estimates of reported global sea-level uniform acceleration using satellite altimetry (1992–2020) and tide gauge data. The results of robust uncertainty analysis considered the unmodeled errors by prior studies including the long-period signals induced presumably by the 18.6-year lunar nodal tides induced sub-harmonics, with periodicities at 55.8-, 75.5-year, suggested that one should exercise prudence on the certainty of estimated uniform sea-level accelerations using satellite altimetry or tide gauge data during the altimetry era (İz & Shum, 2020c).

- Water level changes in the Ganges–Brahmaputra–Meghna delta. Becker et al. (2019) conducted a robust estimate of water-level changes in the Ganges–Brahmaputra–Meghna delta, the largest deltaic region and one of nations with the highest population density in the world. The deltaic regime is primarily driven by continental freshwater dynamics, vertical land motion, and sea-level rise. Through a dataset from 101 gauges, water-level evolution was reconstructed since the 1970s and the results show that the water-level variations across the delta increased slightly faster, at ∼3 mm/yr, than the global mean sea-level rise (∼2 mm/yr). By combining satellite altimetry and water-level reconstruction, that maximum expected rates of delta subsidence since the 1990s are estimated to be ranging from 1 to 7 mm/yr. By 2100, even under a greenhouse gas emission mitigation scenario (RCP4.5), the subsidence could double the projected sea-level rise, making it reaches 85 to 140 cm across the delta.

Monitoring inland water bodies

Model-aided Altimetry-based River Level Forecasting System for Mekong Basin

The research team led by A/Prof Hyongki Lee in Houston developed a freely accessible and model-aided satellite altimeter-based daily water level forecasting system for Mekong River (MR) and Mekong Delta (MD) (Chang et al., 2019). This system and toolkit have been delivered to SERVIR-Mekong and end-user agencies such Mekong River Commission (MRC). The daily forecasting system is developed using the forecasting rating curve generated from (1) 10-day repeat Jason-2 derived water level changes at upstream virtual stations and the Tonle Sap Lake, (2) daily river discharges at upstream Virtual Stations (VSs) obtained from VIC hydrologic model, and (3) historic in situ water levels at the locations where the forecasting is to be performed. In order to simulate ocean tide influences on water levels, a sum of 5-term sinusoidal function is used. They have performed 10-day or longer "pseudo-forecasting" at 11 locations in MD for the years of 2011 and 2012 and obtained promising forecasting skill with mean absolute error (MAE) of less than or about 0.10 m and excellent temporal agreement with observations from in situ gauges (Figure 29). The harnessing of freely available satellite altimetry data merged with easy to set up macroscale hydrologic model for flow prediction makes our model-aided satellite flood forecasting approach globally applicable for ungauged river basins and deltas.

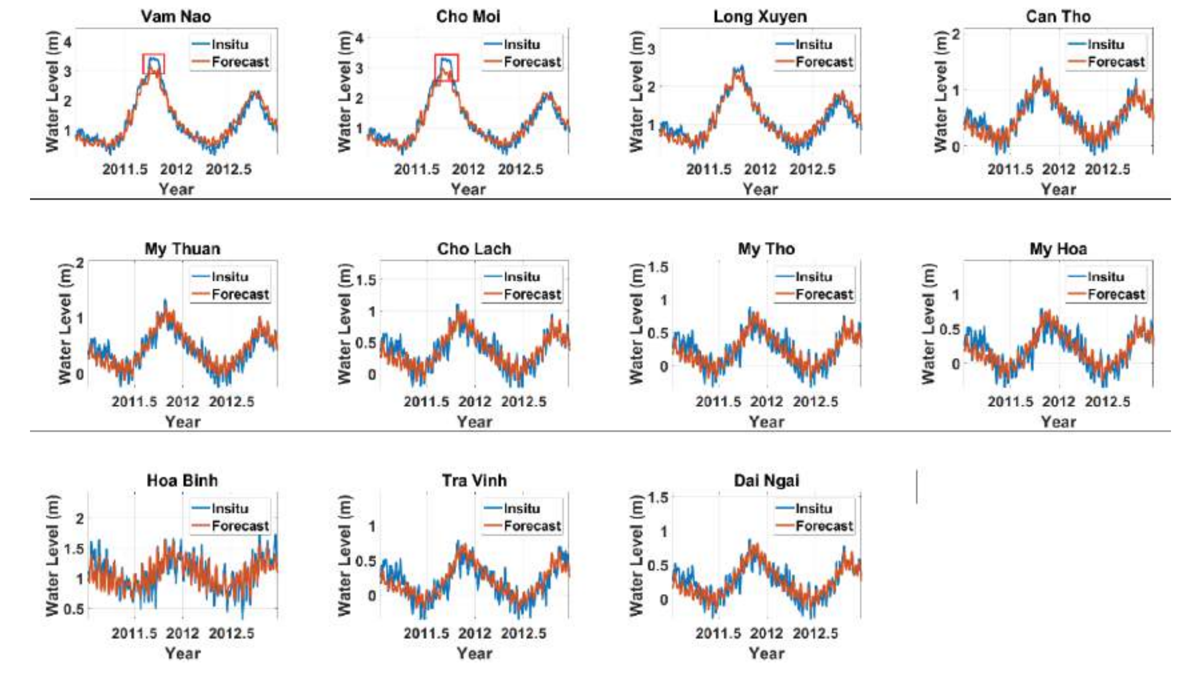

Figure 29. 10-day forecasted (orange) and in situ (blue) water levels from 2011 to 2012 at in-situ stations in MD.

Forecasting Inundation Extents using Rotated Empirical Orthogonal Function Analysis (FIER) and Altimetry-based River Level Forecasting System

FIER (Chang et al., 2020) has been developed to hindcast and forecast daily inundation extents using SAR images and historical and forecasted water levels or discharge. This video link (https://www.youtube.com/watch?v=J7jLpjd6KS0) animates forecasted daily inundation extents over Tonle Sap Lake (TSL) floodplains in Cambodia for Year 2019, generated with Sentinel-1 SAR imagery, Jason-2/3 altimetry, and multivariate ENSO index (Figures 30 and 31). It is expected that the inundation in Lower Mekong would be mainly governed by flooding in Tonle Sap Lake, Mekong mainstem, and Mekong Delta (Chang et al., 2019).

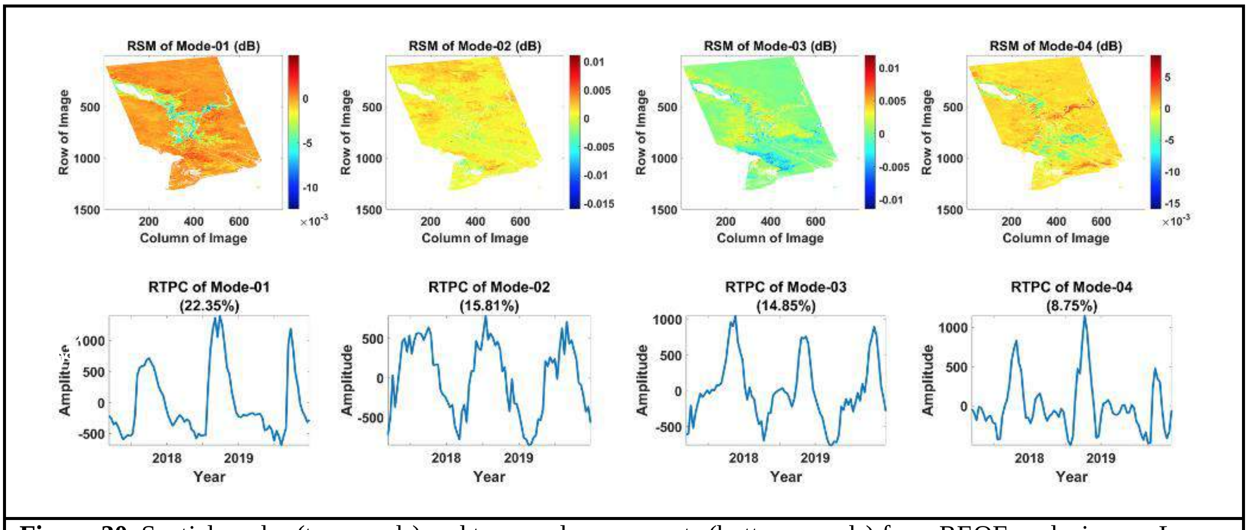

Figure 30. Spatial modes (top panels) and temporal components (bottom panels) from REOF analysis over Lower Mekong using Sentinel-1 images.

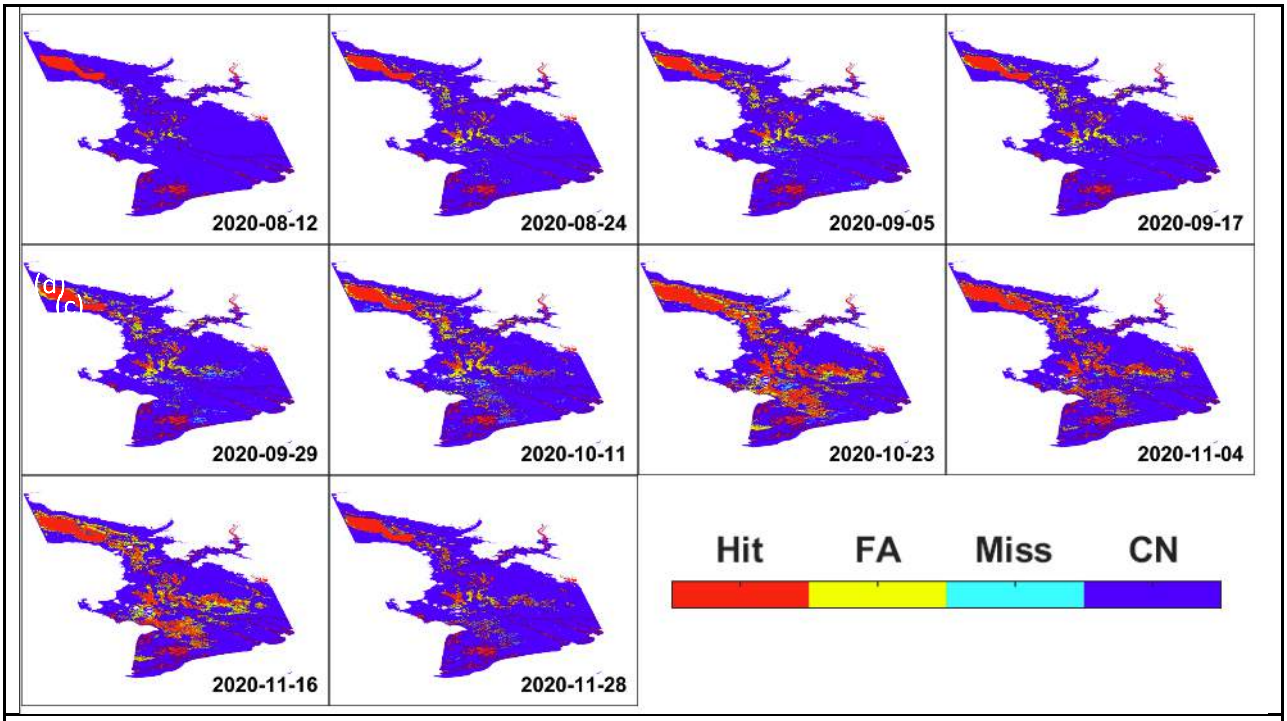

Figure 31. FIER-estimated flood inundation maps at selected dates over Lower Mekong compared with Sentinel-1 SAR-derived inundation maps. Altimetry-based river level forecasting system has been used with FIER.

Estimation of river discharges with Ensemble Learning Regression using altimetry data

Ensemble learning regression for estimating river discharges (ELQ) has been proven to be an effective method (Kim et al., 2019) and has been successfully applied to estimate the river discharges at the Brazzaville station in the Congo Basin using water level changes from multiple Envisat virtual stations. Similar to other continental river basins, the water management in the Mekong River Basin (Figure 32) has been experiencing difficulty due to insufficient stream gauges. Here, the ELQ is applied to the Mekong River in order to estimate daily discharges at decommissioned or temporarily discontinued in situ stations using Envisat altimetry data (Kim et al., 2020). The ELQ-derived discharges have been compared with a previous method based on a rating curve, which is $M_1 = a_1 \cdot (H - H_{min} + d_{min})^{5/3} + b_1$ (hereinafter Model 1) (Rantz et al., 1982), and a_i and b_i are parameters to be calibrated with in-situ discharges (Figures 32 and 33).
It is expected that this method can be used to provide discharge estimates at in situ stations along the Mekong River which are decommissioned or discontinued due to instrument failures.

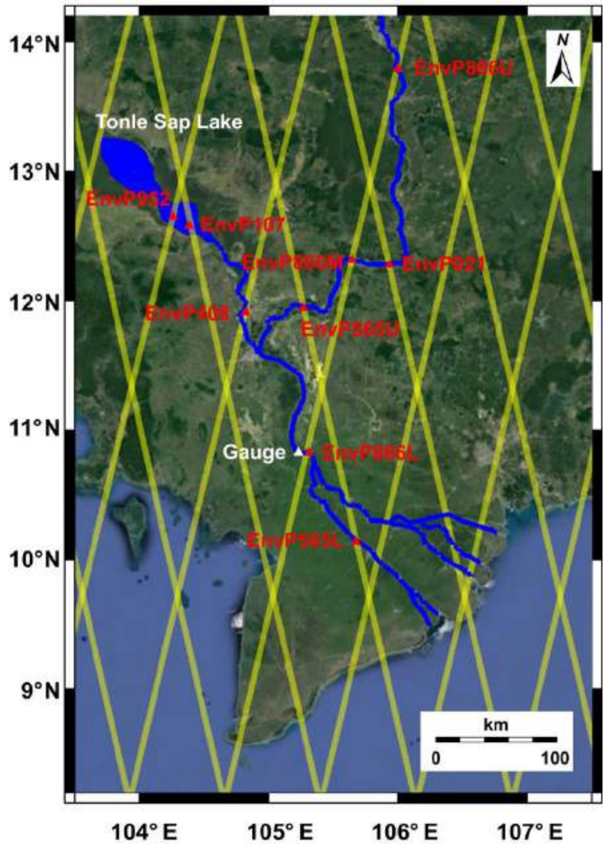

Figure 32. Map of the lower Mekong River with Envisat altimetry ground tracks. The white and red triangles indicate the in-situ gauge at Tan Chau and Envisat virtual stations, respectively. Yellow lines are Envisat altimetry ground tracks.

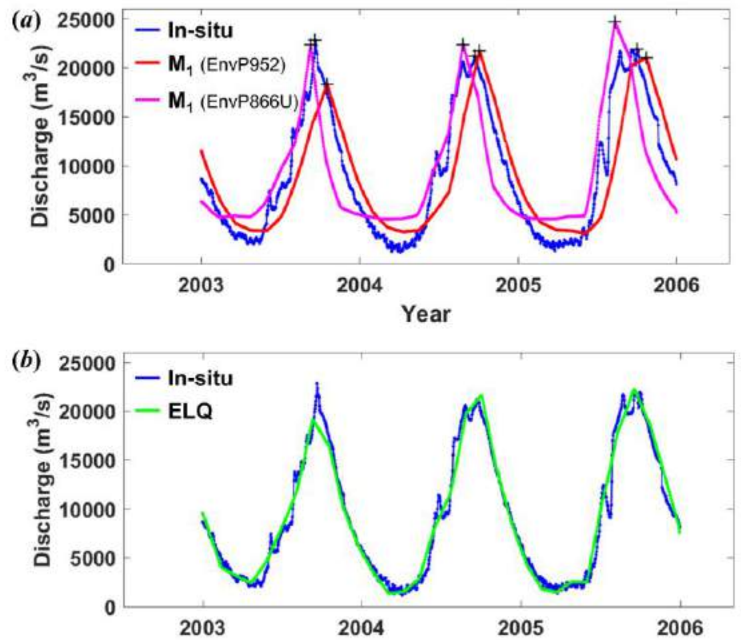

Figure 33. Comparison between the estimated *Q* and in-situ *Q* at Tan Chau station using (*a*) Model 1 and (*b*) ELQ. '+' signs in (*a*) indicate peak dates of discharges in Model 1-derived *Q* and in-situ *Q*.

Mapping Forested Floodplain Topography Using InSAR and Radar Altimetry

An accurate floodplain digital elevation model (DEM) is an essential input for the hydraulic modelling of water flows across the floodplain. A method by Yuan et al. (2019) is presented to map forested floodplain bare-earth topography with improved accuracy by combining InSAR and altimetry measurements (Figure 34). The floodplain bare-earth topography from our method outperforms the MERIT DEM and BEST DEM in capturing subtle elevation variations within the floodplain. The accuracy of the obtained floodplain topography is estimated to be 0.54 ± 2.6 m with respected to ICESat-derived elevations, which is close to the accuracy of the rectified DEM (0.4 ± 4.3 m) used for the hydraulic modeling of Amazon floodplain waters (Figure 35). We also performed qualitative hydraulic analysis using this floodplain bare-earth topography and the time series of water levels in the Congo River using Envisat altimetry measurements and found spatial complexity of the role of overbank flow in flooding the floodplains (Figure 36). This more accurate floodplain topography can be used to improve our understanding of the water flow hydraulics within the Cong floodplain and its role in storing water and retaining global river discharge.

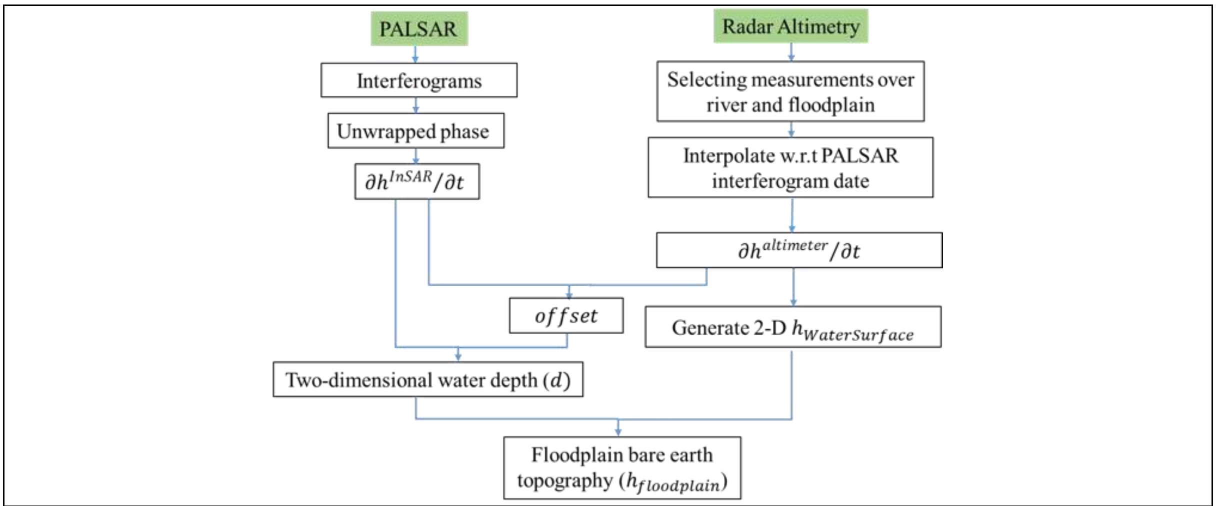

Figure 34. Flowchart of the data processing for generating floodplain bare-earth topography using ALOS PALSAR and Envisat radar altimetry.

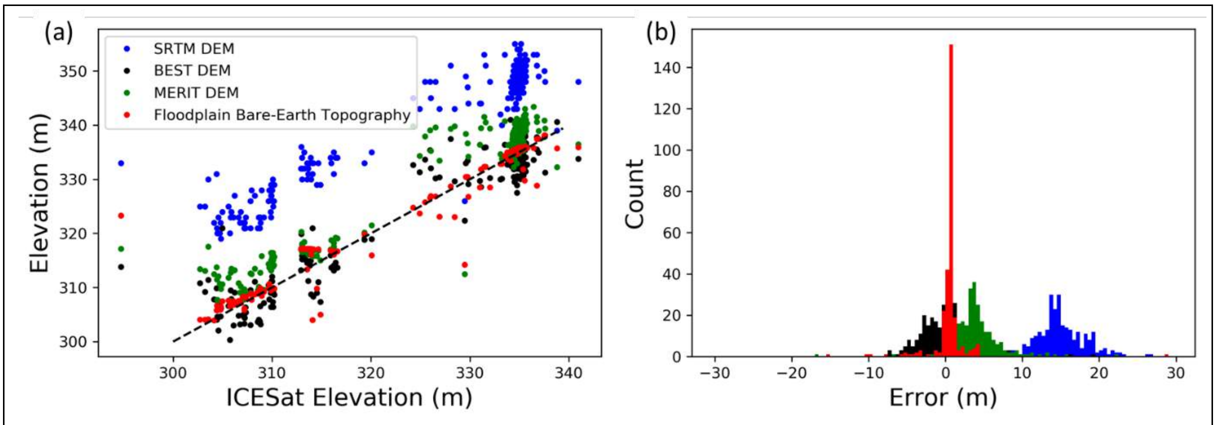

Figure 35. (a) Differences between ICESat-derived elevations and floodplain bare-earth topography from integration of InSAR and altimetry (red), SRTM DEM (blue), MERIT DEM (green), and BEST DEM (black). (b) histograms of the errors of our method (red), SRTM DEM (blue), MERIT DEM (green), and BEST DEM (black) with respect to ICESat-GLAS derived elevations.

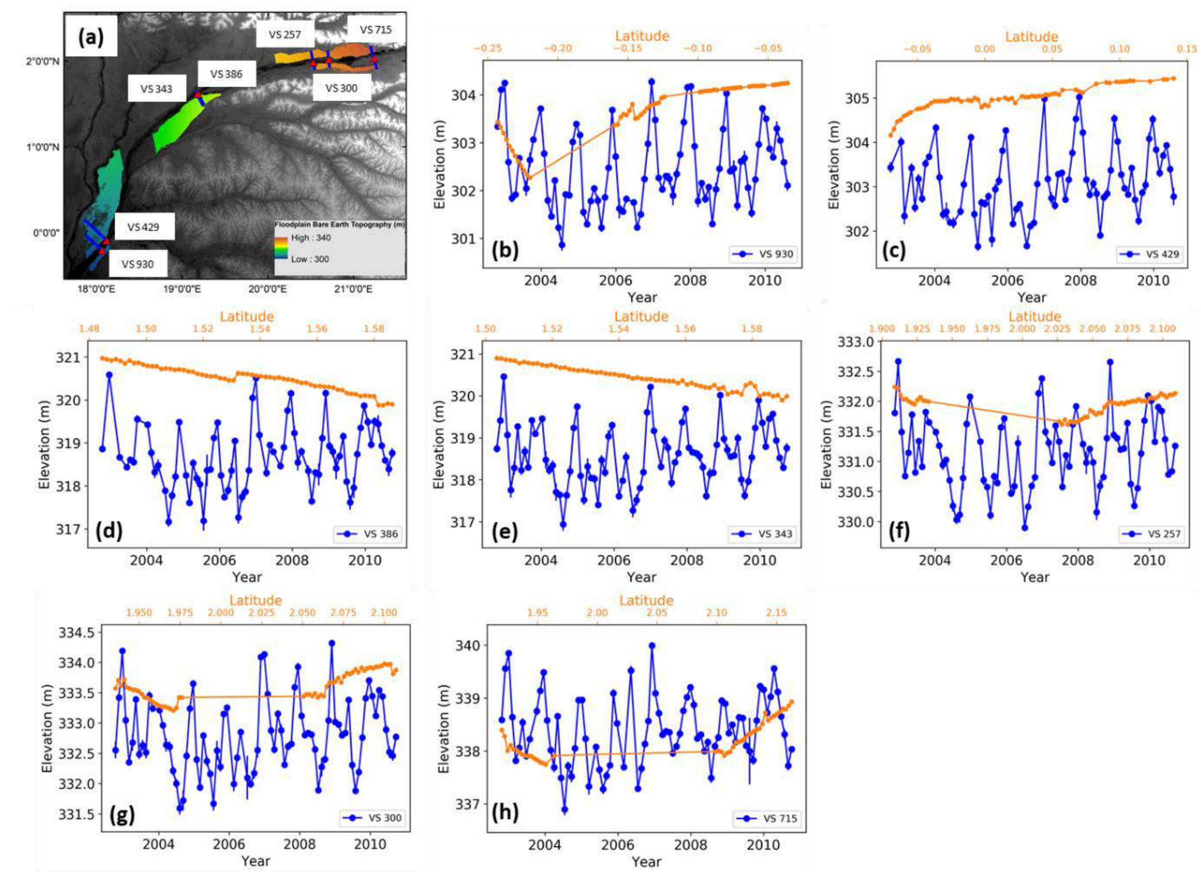

Figure 36. Comparison of floodplain bare-earth topography profile and time series of river level from Envisat altimetry. (a) shows the location of the seven virtual stations in the Congo River. (b)-(h) show the floodplain profile and time series of river level at the seven virtual stations. Note that virtual stations VS 343 and VS 386 are close to each other.

Estimating discharges for poorly gauged river basin using ensemble learning regression with satellite altimetry data and a hydrologic model

The Congo River is one of the least studied basins although it is the world's second largest in size (~ 3.7 million km2) and discharge (Q) (~ 40,600 m3s-1). Recently, Kim et al. (2019, 2021) have successfully applied the ensemble learning regression method, which is one of the machine learning techniques, to estimate Q (termed as ELQ) by linearly combining several rating curves over different locations. The study has estimated Q at the Brazzaville station with relative root-mean-square error (RRMSEs) of 7.17/5.53% for training/validation datasets whose temporal resolutions are 35-day for the period from 2002 to 2010. This study demonstrates that ELQ can provide more accurate daily Q using satellite altimetry data and a hydrologic model for poorly gauged river basins.

Streamflow prediction in "geopolitically ungauged" basins using satellite observations and regionalization at a subcontinental scale

This study uses a novel approach to combine regionalization and satellite observations of various hydrological variable to improve prediction of streamflow signatures at "geopolitically ungauged" basins (Du et al.,2020). Using the proposed step-wise physiography and climate-based regionalization approach, the model performance at ungauged basins reached 80% of performance of the ideal situation, where observed streamflow data were available for calibration, and significantly outperformed the global regionalization parameters using the

Koppen climate classification (Figure 37. It is expected that more satellite altimetry missions with a denser coverage in the future, together with macroscale hydrological model, either at continental scale or global scale with a wide variety of observed streamflow patterns could be benefited from this approach to further evaluate model performance in ungauged basins.

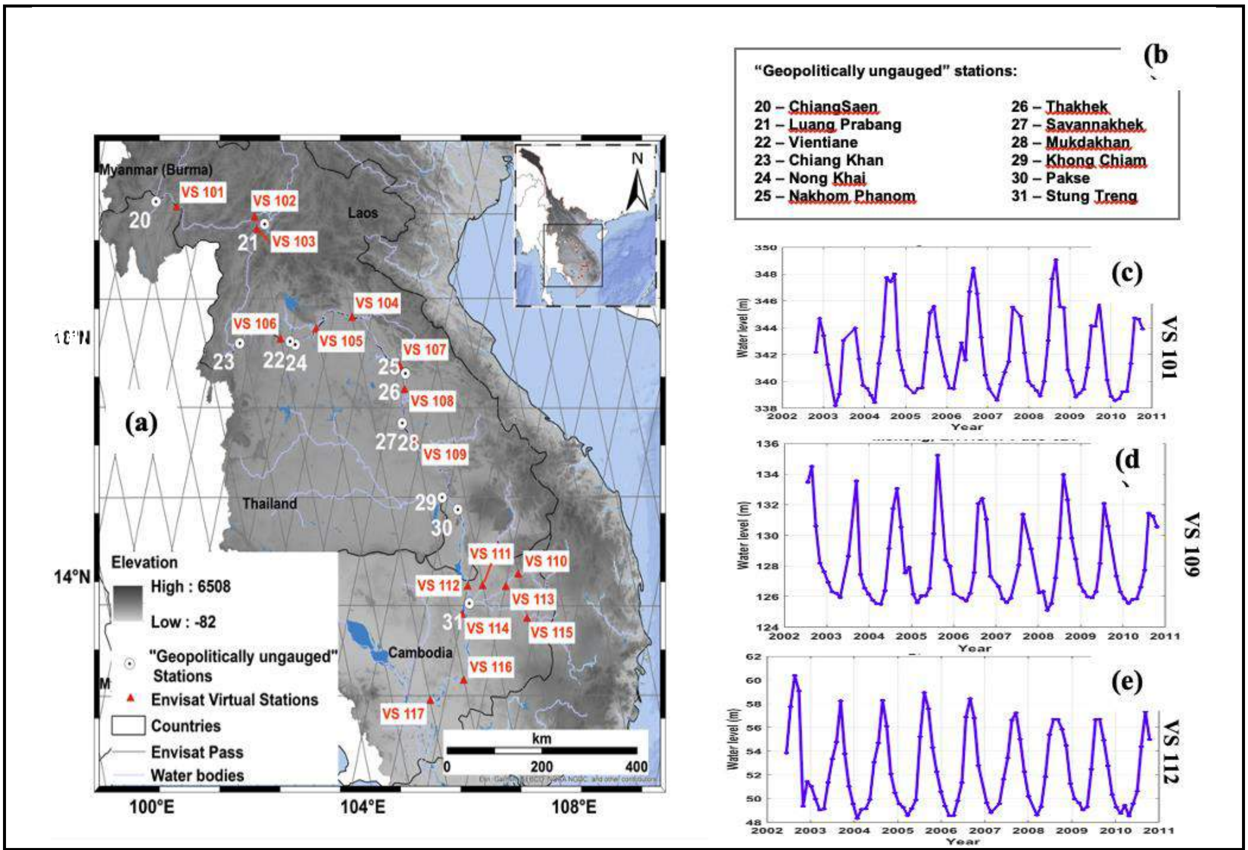

Figure 37. Spatial distribution of virtual stations (red triangles) and "geopolitically ungauged" stations (white circles) employed in the study (Figure 35a). The black lines denote the ground tracks of Envisat altimetry. Figure 35b shows the names of "geopolitically ungauged" stations. Time series of river elevation at three VS's are shown in the panels on the right (Figure 35c, 35d, 35f) (time series of all locations are not presented for reason of brevity).

Altimetry Data Processing for Inland Water Bodies Using Web Application

Markert et al. (2019) introduced an open-source web application (https://altex.servirglobal.net/) to access and explore Jason-2/3 altimetry datasets for use in water level monitoring, named the Altimetry Explorer (AltEx, Figure 38). The back-end of this web application is based on the automation method of Okeowo et al. (2017) led by Lee's group. This web application, along with its relevant REST API, facilitates access to altimetry data for analysis, visualization, and impact. The data provided through AltEx is validated using thirteen gauges in the Amazon Basin from 2008 to 2018 with an average Nash-Sutcliffe Coefficient and RMSE of 0.78 and 1.2 m, respectively.

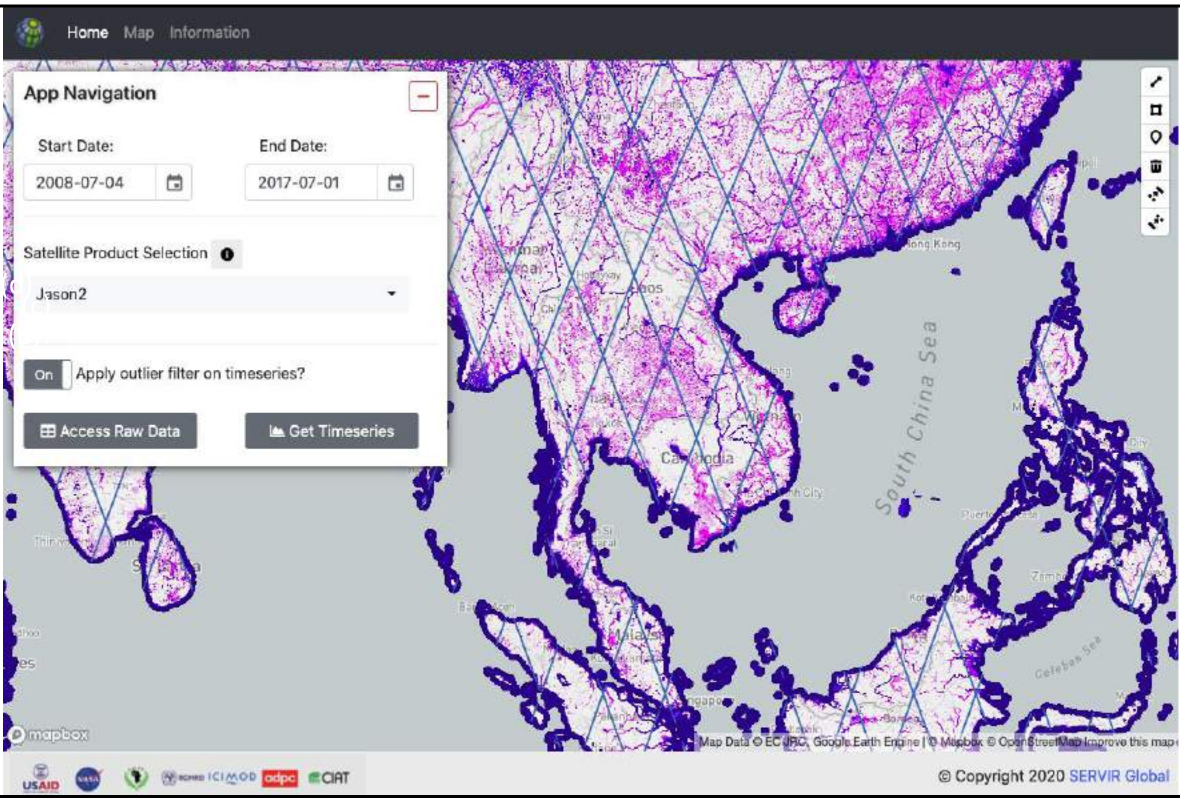

Figure 38 Interface of Altimetry Explorer (https://altex.servirglobal.net/)

Hydrodynamics of the River

In Germany, Dr Fenoglio's team used the improved altimeter heights and the river slope evaluated from two intersections of the same satellite track to study the hydrodynamics of the river. The river discharge is evaluated from water level and slope. Various methods have been used, included the empirical rating curve method which looks for a relationship between altimeter height and discharge from a nearby in-situ station, the semi-empirical Bjerklie method and the physically based method based on hydraulic equations. The normalized RMSE of altimetric and in-situ discharge is found to be between 3 and 7% for the rating curve methos, while using the altimeter-derived slope and heights the semi-empirical Bjerklie method the normalised RMSE is higher and around 20% (Fenoglio et al., 2021).

Satellite altimetry applications on lakes in China and on global rivers

1) Zhang et al. (2019; 2020a) studied regional differences of lake volume evolutions across China, and in refuting that the volume of China's lakes were under-estimated using Landsat images and altimetry. Zhang et al. (2020b) reviewed the trends, patterns, and mechanisms on the response of the Tibetan Plateau lakes to anthropogenic climate change.

2) A new and comprehensive decadal river elevation climate data records using multi-mission radar altimeter data, for global rivers wider than 1 km, were generated for the hydrologic community (Coss et al., 2020). The data product is hosted at the Ohio State University (https://go.osu.edu/altimeterVirtualStations) for visualizations and river water-level data download, and at NASA JPL/PODDAC.

3) Kao et al. (2019) assessed the performance of CryoSat-2 and SARAL/AltiKa radar altimetry retrieved water-level over Tibetan lakes and sea level in coastal region of

Taiwan. Lee et al. (2020) evaluated and improved *in situ* GNSS-Reflectometry altimetry sea level in coastal Taiwan.

4) Deng et al. (2021) tested the capability of retracked CryoSat-2 data (both SARIn mode and LRM) by different retrackers for monitoring surface water levels of plateau lakes. A case study has been conducted for two small lakes (<52 km^2 per lake) in Tibet and an inland lake in Yunnan, China. CryoSa-2 L2 LRM and L1B SARIn-mode data from 2011 to 2018 have been used to monitor water level variations of Dianchi Lake and two lakes of Gemang Co and Zhangnai Co in Tibetan Plateau (TP), respectively (Figure 39). The time series of lake levels has been generated and its trend has been estimated for each lake over the study period.

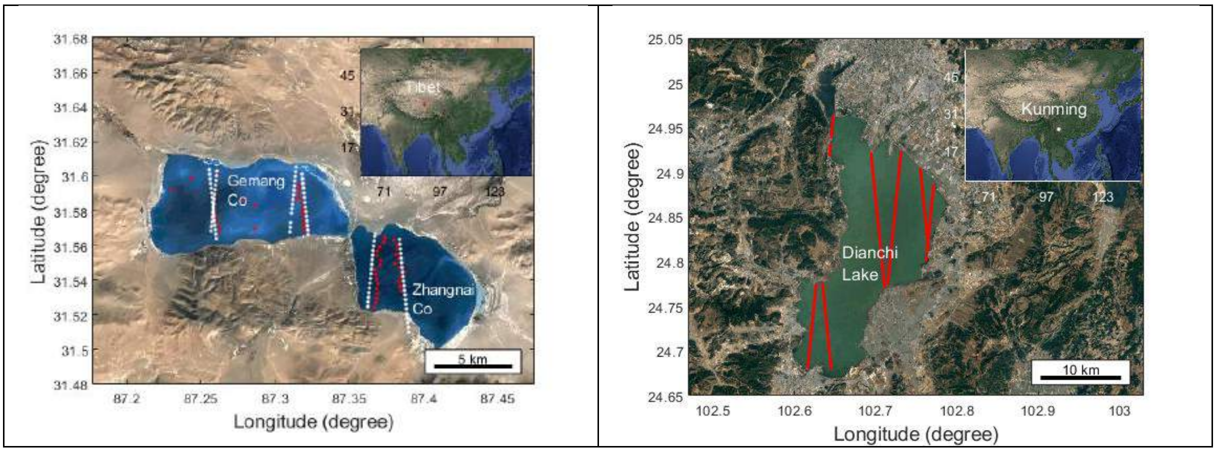

Figure 39. Top: TP lakes Gemang Co (left) and Zhangnai Co (right) overlapped with one cycle of CryoSat-2 SARIn-mode ground tracks in 2016. The white-dot lines are the nominal ground tracks, while the red dots are the corresponding slope-corrected ground tracks when considering off-nadir measurements. Note that some off-nadir measurements are located on land, but have been deleted during the data editing process. Bottom: Dianchi Lake, China, overlapped with one cycle of CryoSta-2 LRM ground tracks (in red) in 2011.

Retracking, calibrating and validating of altimetry data

Improved coastal altimetry data around Australia

Peng and Deng (2020a) examined the performance of their Brown-Peaky (BP) retracker on retrieving the backscatter coefficients and wind speeds, in coastal zones. Eight years of Jason-2 waveforms are reprocessed by the BP retracker. An empirical wind speed model is used to obtain the altimeter wind speeds based on the BP-derived backscatter coefficients. It is found that the altimeter wind speeds are significantly dependent on the sea state in the last 20-km distance to the coast, where the bias between altimeter and anemometer wind speeds increases remarkably and varies inversely with the offshore distance.

Peng and Deng (2020b and 2020c) conducted studies in validation of sea level anomaly (SLA) data from Jason-1/2/3 and Sentinel-3A missions against in-situ data, as well as improvement of SLA data through retracking processes and improving the corrections. They analysed the precision of 20-Hz SLA estimates with three sets of SSB corrections (i.e. 1-Hz, 20-Hz and composite SSB models) within 100 km to the Australian coastline using 16 years of retracked Jason-1/2/3 data, by modified Brown-Peak (MBP), and 3 years of SAMOSA+ retracked Sentinel-3A data.

Peng and Deng (2020b) validate the Synthetic Aperture Radar (SAR) mode sea level anomalies (SLAs) of Sentinel-3A altimetry mission around the Australian coastal region using eight tide gauge sea level records and retracked Jason-3 datasets from a modified Brown-peaky (MBP) retracker.

Peng et al. (2023) developed a SCMR (seamless combination of multiple retrackers) processing strategy to combine sea surface height (SSH) estimates from waveform retrackers of SGDR MLE4, ALES, WLS3 and MB4 for Jason-3 and Saral missions, and of SAMOSA and SAMOSA+ for Sentinel-3A mission in the Australian coastal zone. The validation results against tide gauge records demonstrate that the SCMR strategy is feasible and performs better than any single retracker used in this study.

Innovative processing and retracking for SAR mode waveforms

Dr. L. Fenoglio conducted research into water level change in coastal and inland water derived from an integrated use of space geodetic techniques and its application to climate change analysis. Innovative processing and retracking have been developed for SAR mode waveforms with the SAMOSA+ and SAMOSA++ retrackers (Dinardo et al. 2018, 2020) and with the Signal Model Involving Numerical Convolution (SINC/SINCS), a fast convolution based waveform model for conventional and unfocused SAR altimetry (Buchhaupt et al., 2018). Further on, the sub-waveform Spatio Temporal Altimetry Retracker (STAR) in LRM mode (Roscher et al., 2017) is adapted to the SAR mode retracker STARS (STAR for SAR) by using SINCS as the waveform model (Uebbing et al., 2021). The TUDaBo processor developed in-house and accessible in Earth Console (http://ui-ppro.earthconsole.eu) includes the Reduce Synthetic Aperture Radar (RDSAR), Synthetic Aperture Radar (SAR Delay Doppler) unfocused and Range Migration Compensation (RMC). The model SINCS-OV accounts in SINCS for the vertical Motion of Wave Particles (VMWP) and increases the precision of the retracked parameters compared to standard SAR processing, as SAR precision depends on SWH and wave period (T02) (Buchhaupt et al., 2020). In Figure 13, we notice an increased agreement between SAR and non-SAR processing when the SINCS-OV retracker is used. Buchhaupt et al. 2023 gives an analytical formulation of SAR altimetry signals that includes narrow banded nonlinear wave fields and conditional statistics between wave elevation displacements, horizontal wave slopes and vertical wave particle velocities. The FFSAR processing implemented in the SMAP code (CLS ESA contract) is extended to include the omega-kappa algorithm ((Guccione et al. 2018), less time consuming that the back projection algorithm (Egido and Smith 2019). The SAMOSA+ retracker is used for FFSAR waveforms.

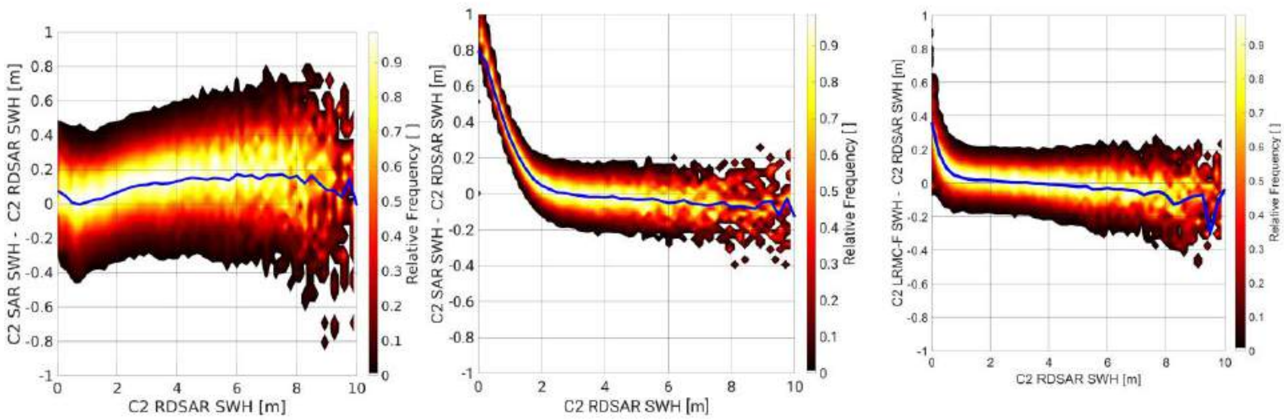

Figure 40. SWH 1-Hz differences between RDSAR and (left) Unfocused SAR CryoSat-2 SINCS, (middle) SAR SINCS-OV ZSK and (right) LRMC-F (right)

Cross-calibration of altimeter products and validation against in-situ and models

Dr Fenoglio's team has performed the cross-calibration of altimeter products and validation against in-situ and models. Dr Fenoglio is a member of validation teams and of study groups for current altimeter missions and of Mission Advisory Groups for future missions. The improvement near coast and in inland water of the SAR altimeter heights versus the LRM mode, was shown in Fenoglio et al., (2019, 2020) for CryoSat-2, Sentinel-3 and Sentinel-6. In coastal zone the dedicated retracker SAMOSA+ is the most accurate (Dinardo et al. 2018, 2020) for both USAR and FFSAR waveforms. With FF-SAR the along-track spatial resolution is at sub-meter level (Egido and Smith 2018). Accuracy and precision improve with the retracker choice of SAMOSA+. SAR and LRM waveforms and noise floor are different and the surface water slope is a new observable. Land contamination affects the geophysical parameters and causes a lower accuracy nearshore. SAMOSA+ and STAR products are the less noisy in the last 3 km from coast and in best agreement with the ocean models (Figure 41, Fenoglio et al. 2020). In estuaries and in the Wadden intertidal sea the STD difference (STDD) is larger. At Otterndorf, (Figure 13) in-situ and Sentinel-3A water heights fully corrected have 30 cm STDD. To build the time-series, data are binned along-track at a selected frequency, are then correlated with in-situ data to compute STDD at each location. Fig. 42 shows the STDD along-track and the radargram at one snapshot.

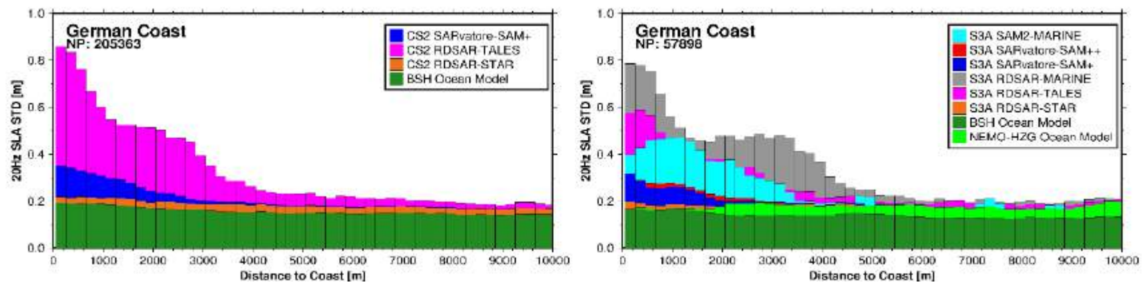

Figure 41. Standard deviation of CryoSat-2 (left) and Sentinel-3A (right) SLA in German Bight from products with SAMOSA+ and ++ retrackers and two ocean models until December 2018. The BSH (dark green) and the NEMO-WAM (light green) ocean models are corrected with ocean tide model TPXO8. NP is the number of common measurements selected for each dataset (Figure 3, Fenoglio et al., 2020).

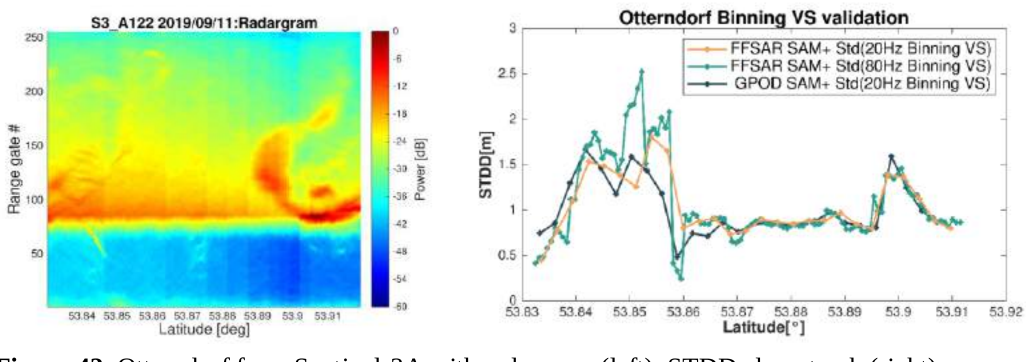

Figure 42. Otterndorf from Sentinel-3A with radargram (left), STDD along track (right).

Schröder et al. (2019) found that in rivers the SAMOSA+ products have higher accuracy than the standard Copernicus data. In the river Rhine for half of the 42 Sentinel-3 Virtual Gauges the STDD between water level at the VG and at the nearest gauge is between 0.10 m and 0.30 m, at the VG near Mainz the STDD is 10 cm (Figure 43). Chen at al. (2023) implement a multi-peak-detection retracker based on the SAMOSA+ retracker (AMPD-PF). Comparison of STDD obtained processing other data products show that the SAMOSA+ retracker is the most suitable retracker for both UFSAR and FFSAR processing. See the boxplot in Figure 43 bottom right, where the Copernicus Ocean and Ocog are used (Fenoglio et al., 2022, Chen et al. 2023). Fig. 43 top right shows that the rating curve evaluated by the three products are very similar. FF-SAR gives the best accuracy at high resolution. In UFSAR the mean STDD with in-situ data is 2-4 cm at sea, 10-30 cm in rivers and 30-50 cm in estuarine zone. In FFSAR the STDD at sea are larger than in UFSAR.

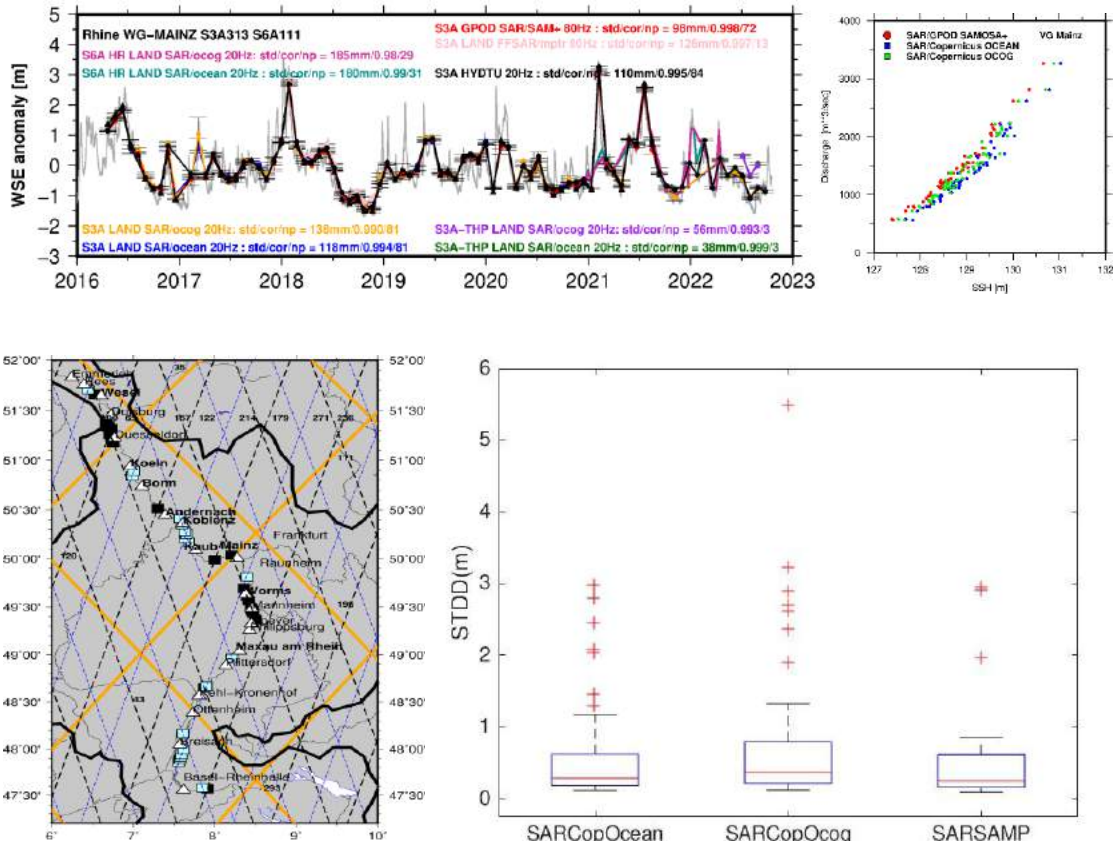

Figure 43. (top left) Water level anomalies and (top right) rating curve RC of in-situ discharge and VG water height in Mainz, (bottom left) River Rhine with in-situ (triangle) and virtual gauges of Sentinel-3A, 3B (squares); (bottom right) accuracy of WSE as standard deviation difference (STDD) with in-situ data

Sentinel-3A for oceans at Southeast Asia

Idris et al. (2021) assessed altimetric data from Sentinel-3A satellite operating in Synthetic Aperture Radar (SAR) mode for sea level research studies and applications over the largest archipelagos at Southeast Asia. Both qualitative and quantitative assessments are conducted by analysing the physical shapes of waveforms, comparing with quasi-independent geoidal height data and independent tide gauge measurements. The results identified the percentage of ocean like and non-ocean like waveforms are 91% and 9%, respectively (Figure 44).

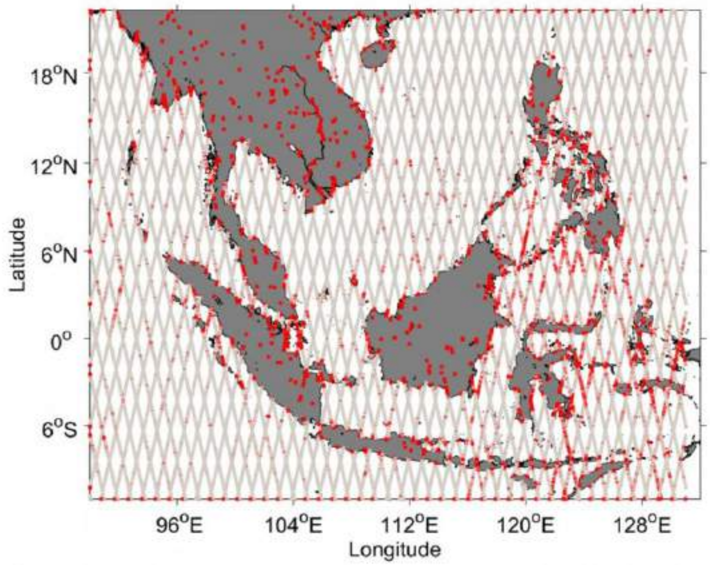

Figure 44. Spatial plot of waveform classes along the Sentinel-3A satellite tracks. The light grey and red colors show the ocean-like and non-ocean like waveforms, respectively. Note that the red marks on the land showing the waveforms over inland water.

SWOT mission

SWOT will provide new observations with high spatiotemporal resolution over inland water bodies. The accuracy of simulated SWOT monthly water surface heights (WSH) and its spatiotemporal characteristics were analyzed ovel lake Baikal in Du et at. (2021). Although SWOT has finer scale observations than nadir altimeter, the results show that the accuracy of the SWOT WSHs is difficult to be equivalent with that from nadir altimeter. WSHs from SWOT are affects by various factors, including the number of duplicated observations, the spatial location, and the time interval. Then, a local cross-calibration method was used to reduce the short wavelength roll error over lakes. As for river discharge from SWOT, a Constrained At-Many-Stations Hydraulic Geometry (CAMHG) method was proposed to optimize parameters of river discharge model. The performance of CAMHG is demonstrated in three stations of the Yangtze River using river widths derived from SWOT. The results show that CAMHG can significantly improves the accuracy of discharge estimations which is meaningful for upcoming SWOT data (Du et al. 2023). The goal of the SWOT mission is to detect small spatial scales in the ocean and to improve knowledge of hydrodynamic processes in the continuum coastal-estuary-rivers, which is not well observed from classical satellite altimetry.SWOT observations simulated at in-situ data locations from in-situ time-series were processed with the wavelet method to detect the signal registered by discrete SWOT observations. Figure 45 shows the signal in Helgoland and Ottendorf. SWOT 2D observations are from the JPL Ocean SWOT simulator using the ocean model SCHISM as input. Similarly, SWOT observations in the River Rhine were simulated by the Large Scale SWOT simulator using input water height of the hydrodynamic model Sobek. The simulated time-series in Mainz are denser than the Sentinel-3A altimeter time-series (Figure 46, right). Data resolution and decorrelation length scale of the on-board pre-processed estimates of SSH and spatially uncorrelated errors, are the dominant source of measurement errors on scales shorter than 100 km. Preparation is on-going for use of the 1-day fast repeat and the 21-day science phase within both CONWEST-DYCO (coastestuary), REFECCT (river) (https://swot.jpl.nasa.gov/people/142) and in "SWOT Multi-sensor and Modeling approaches for monitoring the Multi-scale Coastal hydrodynamics" - 3MC by B. Laignel (University of Rouen, France) projects.

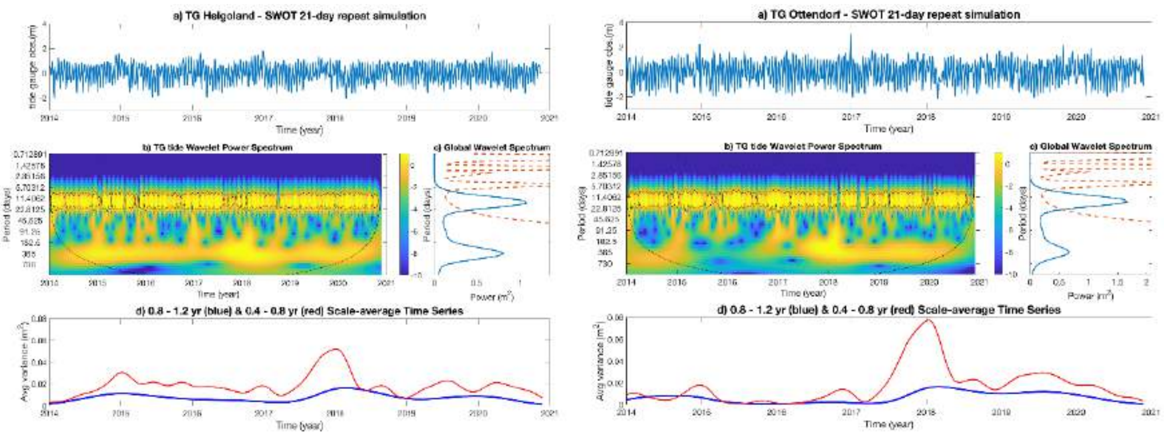

Figure 45. Wavelet analysis of 1D-SWOT 5-day simulated from Helgoland (top) and Ottendorf (bottom) in-situ gauge

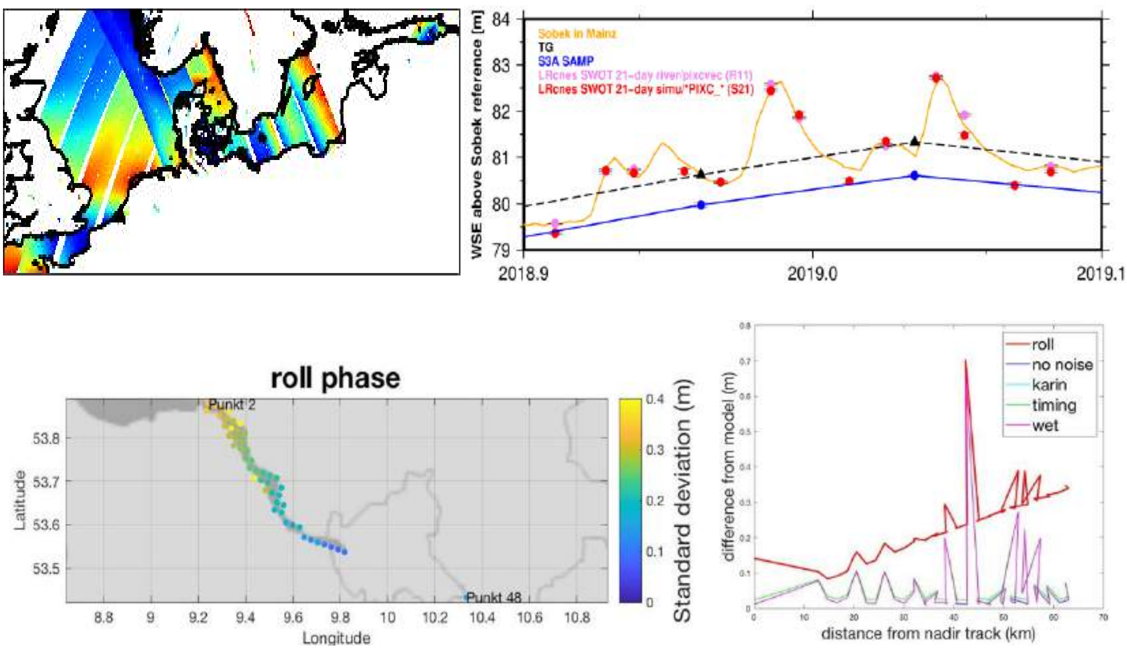

Figure 46 SWOT 2D simulation of WSE with input SCHISM model in JPL Ocean Simulator (top right). SWOT 1D simulation of WSE near the Mainz river gauge with Large Scale Hydrology simulator (top right). Standard deviation of the SWOT error simulated by JPL Ocean simulator for the 1-day cal/val with input SCHISM model (bottom right), simulated error dependence on distance from SWOT-nadir track (bottom right)

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Sub-commission 2.6: Gravity Inversion and Mass Transport in the Earth System

Chair: *Wei Feng (China)*
Vice Chair: *Roelof Rietbroek (Netherlands)*

Overview

Sub-commission 2.6 promotes and supports scientific research concerning spatial and temporal variations of gravity related to the dynamics of the Earth's interior, land surface, oceans, cryosphere, and atmosphere. The sub-commission is accompanied by a steering committee consisting of the members Cheinway Hwang, Vincent Humphrey, Jürgen Kusche, Maxime Mouyen, Jürgen Muller, John Reager, Wenbin Shen, Wenke Sun, and Bert Wouters. The members of the steering committee cover all relevant aspects from the various applications of space gravimetry on geodesy, hydrology, solid Earth, oceanography, and cryosphere, the mass transport inferred from terrestrial and space gravimetry. A working group focusing on the geodetic observations and physical interpretations in the Tibet has been established.

Activities and publications during the period 2019-2021

International Collaboration

A Sino-European international team (lead by the chair of SC2.6) supported by the International Space Science Institute (ISSI) and ISSI-Beijing was established in 2020 for gravity field modelling and improving our understanding of mass transport in the Earth system in the context of the GRACE and GRACE-FO missions. This international team project is an extension of the COST-G ISSI team supported by ISSI. A new version of COST-G GRACE products including the contributions from Chinese groups was planned to release.

Figure 47 First round table meeting for the Sino-European international team organized by the Commission-2 president in Bern (16-17 January, 2020)

Satellite Gravimetry

Several terrestrial water storage anomaly (TWSA) reconstruction methods were proposed to bridge the gap between GRACE and GRACE-FO or infer the TWSA in the pre-GRACE era, e.g. using SLR data (Löcher and Kusche, 2021), Swarm POD data (Richter et al.2021), or using statistical reconstructions (Li et al. 2021). Based on a statistical reconstruction method (Humphrey and Gudmundsson, 2019), the trends in TWS driven by precipitation and non-precipitation factors were separated for the Chinese mainland (Zhong et al., 2023). A recent study also tried to understand how, in the future, one could validate GRACE-FO or successor missions with optical clocks linked by fibre networks (Schröder et al., 2021). Another direction of recent work is creating a global reanalysis of terrestrial water storage via assimilating GRACE data into a hydrological model, with one of the final objectives being able to provide GRACE-based drought estimates (Gerdener et al., 2020) at 50 km resolution. In addition, the performance of GRACE mascon solutions was investigated for seismic studies (Zhang et al., 2019, Zhang et al., 2020).
In the framework of the Greenland Ocean ice sheet interaction project (funded by the German BMBF), S. Stolzenberger (with R. Rietbroek and J. Kusche), is working on modelling the effects of meltwater fluxes to the ocean circulation. A crucial aspect is the validation of the simulations with geodetic observations (Figure 48).

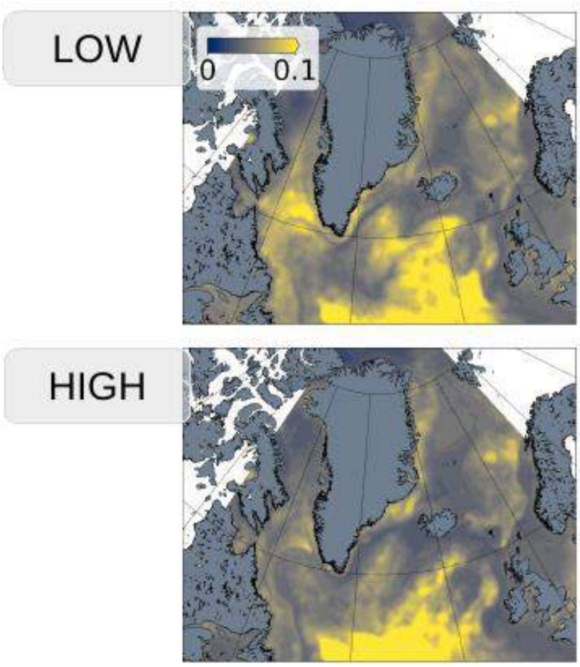

Figure 48 Root mean square error of sea surface height changes from an ocean model forced with meltwater (two different resolutions), and from a joint inversion (from B. Uebbing, Bonn) of GRACE and altimetry. Source: Stolzenberger et al. 2021 (EGU2021 https://doi.org/10.5194/egusphere-egu21-8225, 2021)

Ground gravimetry

Mouyen et al. (2019) conducted a preliminary investigation of the dual-Superconducting Gravimeter (SG) configuration in the Low Noise Laboratory in Rustrel (France) with a focus on groundwater redistributions in karstic aquifer. The two SGs are located about 400 m depth apart, one in an underground tunnel, the other one at the surface, roughly right above the underground SG. They evaluated the complementary attraction of the ground water on both SGs This work was continued under the lead of Séverine Rosat and Jacques Hinderer at Strasbourg. In addition, artificial intelligence methods, specifically deep neural networks, were used to predict groundwater level variations from rainfall and other meteorological data, and to explain gravity residual in SG time series recorded at the Onsala Space Obersvatory (Våge, 2020).

The group led by Cheinway Hwang contributed the following works. Overall, the contributions involve the application of gravity-based techniques to assess groundwater dynamics, quantify specific yields, and delineate aquifers in various geological settings in Taiwan. One study focused on estimating the groundwater mass balance in sandy aquifers affected by land subsidence (Chen et al., 2023). Absolute gravity data were utilized to assess the changes in groundwater storage and evaluate the impacts of groundwater extraction in the region. The findings contribute to understanding the dynamics of groundwater resources and addressing land subsidence issues. The second study delineated a volcanic aquifer using groundwater-induced gravity changes in the Tatun Volcano Group, Taiwan (Lien et al., 2022). This study aimed to identify and characterize a volcanic aquifer using gravity changes induced by groundwater variations, providing valuable insights into the hydrogeological features of volcanic aquifers and the risks posed by the ruptures of the aquifers. The third study estimated infiltration coefficient, percolation rate, and depth-dependent specific yields near a recharge lake in Pingtung, Taiwan using 1.5 years of absolute gravity changes (weekly observations) (Chen et al., 2021). The fourth study measured aquifer specific yields using absolute gravimetry in the Choushui River Alluvial Fan and Mingchu Basin, central Taiwan (Chen et al., 2020). This study provides valuable insights into the characterization of aquifers and their response to groundwater extraction, supporting sustainable water resource management practices.

In addition, inversion of sediment mass redistribution in a landsliding area was done in Taiwan from joint photogrammetry and gravimetry (Mouyen et al., 2020). Since only gravity can really sense mass, one can get more reliable quantification of erosion than with optic methods alone. However, the gravity survey remains a practical challenge. Small and cheap gravity sensors (MEMS gravimeter) may prove useful for such studies in the near future.

The continental-scale repeated gravity survey has been conducted in the Chinese Mainland for several decades. Chen et al. (2019) developed a dedicated terrestrial gravity data process method suitable for adjusting the absolute and relative gravimetric datasets. Han et al. (2021) determined a series of semiannual gravity field solutions up to degree 120 from 2011 to 2013 in North China solely using terrestrial survey campaign measurements. Zhang et al. (2020) and Yang et al. (2021) investigated the potential mass transport signal in the deep crust by analyzing terrestrial time-variable gravity measurements. After removing the contributions of surface displacement and subsurface mass effects, they examined the relationship between the derived residual gravity changes and precursors to the great earthquakes.

Meetings

Several members (R. Rietbroek, V. Humphrey, B. Wouters, J. Kusche) of the SC2.6 have contributed, both on an organizational level and in the forms of scientific content and keynote lectures, to the workshop initiated by the Inter-Commission Committee on Geodesy for Climate Research (ICCC) which was online held in March 2021. The workshop covered topics, closely related to the mass transport theme of the SC2.6, such as the use of (satellite) gravity and deformation data to study changes in hydrology, the cryosphere, and the ocean. Furthermore, during the 2021-2023 general assembly of the EGU, commission members have been active as session conveners and presenters.
The sub-commission also co-organized the 19th International Symposium on Geodynamics and Earth Tides (G-ET) in Wuhan, China during 23-26 June 2021 with the sub-commission 3.1

Earth Tides and Geodynamics. Due to the COVID-19 pandemic, the symposium was organized in an onsite-online hybrid mode. About 200 participants attended the symposium in Wuhan, with the same number of attendees online. The symposium covers the several sessions, including the session "Time variable gravity and mass redistribution". The SC also organized the session "Applications of Satellite Geodesy in Hydrology and Glaciology" in AOGS 2022 Annual Meeting.

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Commission 3 – Earth Rotation and Geodynamics

https://com3.iag-aig.org/

President: Janusz Bogusz (Poland)
Vice-President: Chengli Huang (China)

Structure

Sub-Commission 3.1:	Earth Tides and Geodynamics
Sub-Commission 3.2:	Volcano Geodesy (joint with IAVCEI)
Sub-Commission 3.3:	Earth Rotation and Geophysical Fluids
Sub-Commission 3.4:	Cryospheric Deformation (joint with IACS)
Sub-Commission 3.5:	Seismogeodesy (joint with IASPEI)
Joint Study Group 3.1:	Geodetic, Seismic and Geodynamic Constraints on Glacial Isostatic Adjustment (joint with IAG Commissions 1 and 2)
Joint Working Group 3.1:	Improving Theories and Models of the Earth's Rotation (joint with IAU)
Joint Working Group 3.2:	Global combined GNSS velocity field (joint with IAG Commissions 1 and 2)

Overview

This report presents the activities of the entities of Commission 3 for the reporting period 2019-2023. The Commission consists of 5 Sub-Commissions, 2 Joint Working Groups and Joint Study Groups. The purpose of Commission 3 is to promote, disseminate, and, where appropriate, to help coordinate research related to monitoring, explaining and numerically describing dynamic changed within Earth system. Sub-Commission 3.1 (Earth Tides and Geodynamics) addresses direct and indirect tidal phenomena that affect the position of fiducial sites and have to be corrected to provide accurate spatial referencing. Sub-Commission 3.2 (Volcano Geodesy) addresses explosion in the quality and quantity of volcano geodetic data, which has created a need for new approaches to data analysis, interpretation, and modelling required for data fusion and joint interpretation, both between geodetic datasets and with other types of volcano monitoring results. Sub-Commission 3.3 (Earth Rotation and Geophysical Fluids) addresses the space-time variation of atmospheric pressure, seafloor pressure and the surface loads associated with the hydrological cycle, and Earth's (mainly elastic) responses to these mass redistributions. Sub-Commission 3.4 (Cryospheric Deformation) addresses past and present changes in the mass balance of the Earth's glaciers and ice complexes which both induce present-day deformation of the solid Earth on a range of spatial scales, from the very local to global. Sub-Commission 3.5 (Seismogeodesy) addresses studying the plate boundary deformation zones and integration of geodetic and seismological monitoring of seismically active areas by increasing and/or developing infrastructures dedicated to broadband observations from the seismic wave band to the permanent displacement. Commission 3 interacts with Global Geodetic Observing System (GGOS), other Commissions and Services of the IAG as well as with other organizations such as the International Astronomical Union (IAU), International Association of Seismology and Physics of the Earth's Interior (IASPEI), International Association of Volcanology and Chemistry of the Earth's Interior (IAVCEI) and International Association of Cryospheric Sciences (IACS). Because of pandemic situation in 2019-2023 the on-site activities were limited, however on-line activities of the Commission 3 entities were significant and described in details in the following part of this report.

Sub-commission 3.1: Earth Tides and Geodynamics

Chair: Carla Braitenberg (Italy)
Vice-Chair: Séverine Rosat (France)

Terms of Reference

SC 3.1 addresses the entire range of Earth tidal phenomena and dynamics of the Earth, both on the theoretical as well as on the observational level. The Earth tide affects many types of high precision instrumentation, be it measurements of position, deformation, potential field or acceleration. The tidal phenomena influence both terrestrial and satellite-borne acquisitions. The tidal potential is a driving force that can be accurately calculated, and the tidal response observable as deformation and variations in Earth orientation and rotation parameters gives information on Earth's rheology. Instruments sensitive enough to detect the tidal signal, record a large range of periodic and aperiodic phenomena as ocean and atmospheric tidal loading, ocean, atmospheric and hydrospheric non-tidal effects, deformation related to the earthquake cycle and even to gravitational waves, as well as plate tectonics and intraplate deformation. The periods range from seismic normal modes over to the Earth tides and the Chandler Wobble and beyond, ending at the nutation period. Thus, the time scales range from seconds to years and for the spatial scales from local to continental dimensions. As tidal friction is affecting Earth rotation, all the physical properties of the Earth contribute to the explanation of this phenomenon. Therefore, the research on tidal deformation due to changes of the tidal potential as well as ocean and atmospheric loading are a prerequisite to constrain Earth's rheological properties. Further, direct and indirect tidal phenomena affect the position of fiducial sites and have to be corrected to provide accurate spatial referencing. Such referencing is needed for the observation and monitoring of changes of the Earth's surface at global, regional and local scales. Therefore, there is a considerable contribution of tidal research to global geodynamics and climate change by providing important constraints to geophysical models. Modern instrumental developments for which tidal phenomena are relevant are gravimeters and gradiometers based on superconductivity (SG), atom interferometry, micro-electromechanical-system (MEMS) gravimeters, Inertial Measurement Units, gravitational wave antennas, satellite gravimetry and atomic clocks. The improvements in gravimetric instrumentation leads to the use of gravimetry as a tool to detect underground mass changes, as naturally occurring hydrologic draughts or fluids injected into the underground for the purpose of temporary storage or for other purposes. The Earth must be studied as a dynamic system through the study of the global gravity field and its temporal variations, and the global and local deformation at the surface in order to define the Earth's internal structure and dynamics. In the next few years, instrumental developments in portable absolute gravimeters can be expected, and further innovations can be envisaged from the ring laser technology. The SC 3.1 follows the instrumental developments and infer innovative applications. These geophysical observations together with other geodetic observations and geological information provide the means to better understand the structure, dynamics and evolution of the Earth system. The existence of a network of superconducting gravimeters allows continuous monitoring of the gravity signal at selected stations with a precision of better than 10^{-10}. The range of applications of SGs has become very wide and applicable not only to Earth tides investigations, but also to support studies on Earth's seismic cycle and hydrological mass estimates. The SG network has had scientifically close relation to the SC 3.1 and IGETS (International Geodynamics and Earth Tide Service), which distributes the data. Therefore, the Chair of SC 3.1 is responsible for the close cooperation with the IGETS to provide effective service-with science coupling.

Summary of the Sub-commission's activities during the period 2019-2023

Meetings:

- Organization of the 19th International Symposium on Geodynamics and Earth Tides that will be held June 22-26, 2021 in Wuhan, China.
- Participation in the organization of the sessions
- Organization of the call and the committee for the assignment of the Melchior Medal 2021.

Website: http://get2020.csp.escience.cn/dct/

Sessions:

- **Session 1: Tides and non-tidal loading**
  - Conveners: Jean-Paul Boy, Heping Sun, Hartmut Wziontek, David Crossley
- **Session 2: Geodynamics and the earthquake cycle**
  - Conveners: Severine Rosat, Kosuke Heki, Thomas Jahr, Wenke Sun
- **Session 3: Variations in Earth rotation**
  - Conveners: Chengli Huang, Harald Schuh, Ben Chao, Janusz Bogusz
- **Session 4: Time variable gravity and mass redistribution**
  - Conveners: Cheinway Hwang, Carla Braitenberg, Holger Steffen, Wei Feng
- **Session 5: Monitoring of subsurface fluids**
  - Conveners: Jacques Hinderer, Jaakko Makinen, Yoichi Fukuda, Giuliana Rossi
- **Session 6: New technology and software development**
  - Conveners: Olivier Francis, Jürgen Müller, Hannu Ruotsalainen, Zhongkun Hu

Special sessions at international meetings:

EGU 2019, 2020, 2021, 2022
AGU 2019, 2020, 2021, 2022

Editorial activities: during the entire period of reference we have made support and promotion in the role as Editor of themes related to the SC 3.1 in the journal Pure and Applied Geophysics. In January 2023 the two special volumes dedicated to the 19th International Symposium on Geodynamics and Earth Tides (June 22-26, 2021) in Wuhan, China have been published in PAGEOPH and Geodesy and Geodynamics Journal. The papers give a good overview on the topics covered by the Symposium. The Symposium allows researchers working on precision measurements of deformation, gravity and earth rotation discuss observations and their modeling, as well as instrumental innovations and theory.

Figure 1. Illustration of the two special volumes on topics discussed at the 19th International Symposium on Geodynamics and Earth Tides (June 22-26, 2021) in Wuhan, China.

Online seminars in 2022 and 2023
Website of the seminars with recordings of the presentations https://iag-sc31.github.io/

List of 2022 seminars: https://iag-sc31.github.io/2022_seminars.html

- 21 June 2022, 1 PM CEST: Isabelle Panet, Pre-seismic signals in GRACE gravity solutions: application to the 2011 Tohoku and 2010 Maule earthquakes;
- 7 June 2022, 1 PM CEST: Alexandre Michel, GNSS inversion for surface loading;
- 24 May 2022: EGU and Living Planet Symposium;
- 10 May 2022 1 PM CEST: Tommaso Pivetta, Gravity measurements as a useful tool to model Karst hydrology.

List of seminars in 2023 (https://iag-sc31.github.io/)

- 23 May 2023, 1 PM CEST: Jiangcun Zhou, (State Key Laboratory of Geodesy and Earth's Dynamics, Innovation Academy for Precision Measurement Science and Technology, Chinese Academy of Sciences), Co/post-seismic deformation based on poroelastic theory;

- 6 June 2023, 1 PM CEST: Wei Feng, School of Geospatial Engineering and Science, Sun Yat-sen University, China, Separation of Earthquake and Hydrology Signals from GRACE Satellite Data via Independent Component Analysis: A Case Study in the Sumatra Region;
- 13 June 2023, 1 PM CEST: Antonella Amoruso, Luca Crescentini, Department of Physics, University of Salerno, Italy, A few looks at the dynamics of Campi Flegrei and Vesuvio volcanoes, Italy, from DInSAR data;
- 20 June 2023, 1 PM CEST: Hugo Lecomte, Institut Terre et Environnement de Strasbourg, France, GRACE and SLR, the gravity-field variations for new insights into the Earth's core;
- 27 June 2023, 1 PM CEST: Umberto Riccardi, Dipartimento di Scienze della Terra, dell'Ambiente e delle Risorse (DiSTAR), Università "Federico II" di Napoli, Italy, Catching the time-variable gravity at Mt. Somma-Vesuvius volcano by means of discrete and continuous relative gravity measurements.

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Sub-commission 3.2: Volcano Geodesy

Joint with IAVCEI

Chair: *Emily Montgomery-Brown (USA)*
Vice-Chair: *Alessandro Bonforte (Italy)*

Terms of Reference

Geodesy is an important tool for exploring the geometry and temporal evolution of magma plumbing systems, as well as for monitoring and hazards assessment during volcanic unrest and eruption. Geodetic techniques include measurements of both deformation (to determine the magnitude, location, and geometry of subsurface sources of pressure change) and gravity (to assess subsurface mass variations). Recent decades have seen an explosion in the quality and quantity of volcano geodetic data, which has created a need for new approaches to data analysis, interpretation, and modeling. In addition, geodetic data can have different temporal and spatial resolutions, as well as different origins (ground-, air-, and space-based), and they are best utilized in conjunction with other non-geodetic datasets, like seismicity and gas emissions. New tools are therefore needed for data fusion and joint interpretation, both between geodetic datasets and with other types of volcano monitoring results. This is especially relevant now given the expansion in GEO's Geohazard Supersites and Natural Laboratories initiative to volcanic sites around the globe. We feel that an IAVCEI (International Association on Volcanology and Chemistry of the Earth's Interior) Commission on Volcano Geodesy is needed to organize the diverse community and promote a better understanding of magmatic processes through geodesy.

Summary of the Sub-commission's activities during the period 2019-2023

A meeting of the Commission has been held in Portland on 7 and 8 October, 2020 together with the CONVERSE Research Coordination Network ("How to respond to (pre)eruptive volcanic activity for highest scientific return?"). During this meeting, the activities of the commission were discussed and future actions were planned. The pandemic reduced all the activities since the beginning of 2020. As a major effect, the pandemic forced the commission to cancel the plans for an October 2020 workshop in Yellowstone. However, the volcano-geodesy commission organized a virtual meeting on December 15 and 16 at two different times to meet colleagues participating from different time zones. The website was rebuilt from scratch in late 2020/early 2021 after it was corrupted. We contributed to the IAG Highlights report with a series of highlights featured on our website, including a discussion of volcano monitoring during the pandemic. In place of the in-person workshop that was cancelled due to covid, we developed and coordinated Phase 1 of the Drivers of Volcanic Deformation (DVD) community verification and validation exercises in 2021. Parts 1 and 2 of the exercises tested the most commonly used modeling software in the Volcano Geodesy community, and discovered fixed several bugs in multiple codes. Part 3 involved an inversion for an unknown source, and showed several examples of true uncertainties. Dozens of international collaborators participated in the exercises, and the results of the DVD exercises are in preparation with a plan for submission in July 2023. The commission met in-person at the 2023 IAVCEI meeting and elected new leadership.

Meetings and Special Sessions:

- 2019 October: Volcano Geodesy Meeting, Portland, OR;
- 2019 EGU General Assembly: From slow-spreading to rapid mass-movements in alpine and volcano-tectonic settings. Advances on monitoring, modelling and risk management (8 oral presentations, 16 poster presentations);
- 2019 EGU General Assembly: Volcanic Processes: Tectonics, Deformation, Geodesy, Unrest (20 oral presentations, 27 poster presentations);
- 2019 AGU Fall Meeting: Improving Volcano Deformation Interpretations with Integrated Multidisciplinary Data. (8 Abstracts);
- 2020 Cities on Volcanoes: Volcano deformation: data integration, models, ambiguities and implications for eruption forecasting;
- 2021 AGU Fall Meeting: Applications of Volcano Geodesy to Volcanic Systems;
- 2022 AGU Fall Meeting: Lessons learned from hypothetical exercises;
- 2023 IAVCEI Assembly: Global applications of Volcano Geodesy;
- 2023 IUGG Meeting: Volcano geodesy techniques and approaches for studying and monitoring volcanic processes.

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Sub-commission 3.3: Earth Rotation and Geophysical Fluids

Chair: *Jianli Chen (USA)*
Vice-Chair: *Michael Schindelegger (Germany)*

Terms of Reference

Mass transport in the atmosphere-hydrosphere-mantle-core system, or the “global geophysical fluids”, causes observable geodynamic effects on broad time scales. Although relatively small, these global geodynamic effects have been measured by space geodetic techniques to increasing, unprecedented accuracy, opening up important new avenues of research that will lead to a better understanding of global mass transport processes and of the Earth’s dynamic response. Angular momenta and the related torques, gravitational field coefficients, and geocenter shifts for all geophysical fluids are the relevant quantities. They are observed using global-scale measurements and are studied theoretically as well as by applying state-of-the-art models; some of these models are already constrained by such geodetic measurements.

Summary of the Sub-commission’s activities during the period 2019-2023:

Meetings and Special Sessions:

On behalf of SC3.3, we have organized several sessions related to Earth Rotation and Geophysical Fluids at various scientific meetings and workshops, which include:

- **Session G04 Earth Rotation and Geodynamics**, 2019 IUGG General Assembly in Montreal, Canada (July 8–18, 2019):
  - A joint session of SC3 sub-commissions
  - Convener: Manabu Hashimoto (Japan), Co-convener: Janusz Bogusz (Poland), Jianli Chen (USA), Matt King (Australia)
- **Session SE33 Global Mass Transport, Earth Rotation and Low-Degree Gravitational Change**, 2020 AOGS Annual Meeting to be held in Vivaldi Park, Hongcheon, Korea (June 28–July 4, 2020):
  - Convener: Jianli Chen (USA), Co-convener: Richard Gross (USA), Michael Schindelegger (Germany), Jolanta Nastula (Poland)
  - After much preparation, this meeting was cancelled due to the Covid-19 pandemic
- **Session 3.1 Earth rotation, low-degree gravitational change and mass transport in geophysical fluids**, 2021 IAG General Assembly in Beijing, China (June 28–July 2, 2021):
  - Jointly organized with IAG Inter-Commission Committee on "Geodesy for Climate Research" (ICCC)
  - Convener: Jianli Chen (USA), Co-convener: José Ferrándiz (Spain), Richard Gross (USA), Michael Schindelegger (Germany), Henryk Dobslaw (Germany), Jin Li (China)
- **Session SE03 Earth Rotation: Interpretation, Prediction, Uncertainty and Real-Time Geodesy**, 2022 AOGS Annual Meeting in Singapore (August 1–5, 2020):
  - Convener: Jianli Chen (USA), Co-Convener: José Ferrándiz (Spain), Richard Gross (USA), Michael Schindelegger (Germany)
  - Due to insufficient number of abstracts submitted, this session was later merged with SE05 General Contributions in Solid Earth

In addition, SC3.3 has actively participated the online workshop series organized by ICCC, led by Henryk Dobslaw (Germany) and Jolanta Nastula (Poland).

Selected peer-reviewed publications:

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Sub-commission 3.4: Cryospheric Deformation
Joint with IACS

IAG co-Chair: *Jeff Freymueller (USA)*
IACS co-Chair: *Bert Wouters (NDL)*
Vice-Chair: *Natalya Gomez (CDN)*

Terms of Reference

This sub-commission is a joint effort of IACS (International Association of Cryospheric Sciences) and IAG (International Association of Geodesy), which has built upon a history of separate activities in the two Associations. The overall goal of our sub-commission is to get a better understanding of the interaction between the cryosphere – in particular the ice sheets and glaciers – and the solid Earth. This SC has a long history as part of IAG. At the Montreal IUGG, it was decided to make this a joint sub-commission with IACS. Within IAG, SC3.4 historically has focused on resolving technical measurement issues. With the new cross-Association sub-commission, we will have a better opportunity to enhance collaboration and dissemination of these measurements within the glaciological community. Past and present changes in the mass balance of the Earth's glaciers and ice sheets induce present-day deformation of the solid Earth on a range of spatial scales, from the very local to global. Geodetic observations that validate, or may be assimilated into, models of glacial isostatic adjustment (GIA) and/or constrain models of changes in present-day ice masses through measurements of elastic rebound are of paramount importance, as are "paleo-geodetic" observations like the history of relative sea level. Present-day ice mass changes induce an immediate elastic deformation of the Earth, while the integrated history of mass changes induces an additional viscoelastic deformation. Traditionally, these have been considered separately, which is a good approximation for long-ago load changes and regions of high mantle viscosity. In regions of low mantle viscosity (e.g. West Antarctica and Iceland), the present-day and recent past load changes must be modeled together as the rapid viscoelastic relaxation is substantial and not easily separated from the immediate elastic changes. In all cases, present-day geometric measurements (e.g., uplift rates) measure the sum of elastic and viscoelastic deformations, and these components cannot be separated without additional models or observations. Present-day gravity changes have a different sensitivity to the elastic and viscoelastic components. In addition, it is now clear that 1-D Earth models are no longer sufficient for many problems, but 3-D models pose computational challenges, and careful inter-comparison of 3-D models is required to better understand model differences. Reference frames of GIA models are likely computed in the center of mass of the solid Earth frame, while the International Terrestrial Reference Frame (ITRF) is defined with origin at the center of mass of the Earth system (including all fluids). This means a frame origin transformation is required to allow direct comparison to measurements in ITRF and ambiguity currently exists over the exact transformation between the two.

Summary of the Sub-commission's activities during the period 2019-2023:

Most of our activities have been carried out in cooperation with other groups having similar goals, including Joint Study Group 3.1. In addition, the pandemic has hampered many of our plans, including the organization of workshops, however, we organized a highly successful online seminar series jointly with colleagues representing the World Climate Research Program (WCRP) and measurements of Paleo Sea-level (PALSEA). We also organized or co-organized several sessions at virtual or in-person scientific meetings. We co-sponsored the application of Joint Study Group 3.1 that was successful in obtaining funding for a GIA School to be held in

July 2023. There is also an ongoing effort together with other related groups to develop a 3D GIA benchmarking effort. A central activity of SC3.4 has been the organization of a virtual seminar series on sea Level, GIA and ice sheets. This highly successful monthly seminar series drew a consistent audience, with often over 100 participants worldwide to each seminar. It promoted cross-disciplinary discussions and collaborations across connected fields. Speakers included a number of early-career scientists, as well as established names. We recommend that cross-disciplinary virtual seminars continue in the next 4-year period, and the once per month frequency strikes a good balance, being regular enough to keep people engaged, but not so frequent as to be too routine. The series was first designed to lead up to a PALSEA workshop in fall 2021 (https://palseagroup.weebly.com/2021-meeting.html), which included a focus on topics of strong interest to SC3.4. In September 2021, the SERCE-PALSEA workshop took place (https://palseagroup.weebly.com/2021-meeting.html), where empiricists and modelers from the sea level and ice sheet communities together presented their work ~30 oral presentations and 2 poster session, including a number of presentations by members of sub-commission 3.4. The interest in the seminar series was strong enough that we resumed the series again in winter 2022, leading up to the next PALSEA workshop as well as the WCRP Sea Level Conference, both held in Singapore in July 2022. We chaired sessions at both conferences with speakers and discussions focused on Earth-ice-sea level interactions. The talks in the series were as follows, and have all been uploaded publicly here: https://mediaspace.msu.edu/playlist/dedicated/1_wic2n936/ (note that they are listed in reverse order, from most recent to oldest):

- March 2021 - Bob Kopp on the IPCC AR6 process, including the topic “What is needed from the paleo and GIA community to help refine projections of future sea-level change?”;
- April 13th 2021 - Future directions in GIA model intercomparison and benchmarking Wouter Van der Wal - GIA and benchmarking;
- May 11th, 2021: Perspectives from the modern sea level and ice sheet modeling communities. Aimée Slangen, a researcher at the Netherlands Institute for Sea Research (NIOZ) and a lead author of the IPCC AR6 report, will discuss advances in modern sea level research and coastal risk and Fiamma Straneo from SCRIPPS Institution of Oceanography (UCSD) will discuss the ISMIP6 effort and offer her perspective on how to facilitate cross-disciplinary collaboration;
- June 8th, 2021 - Records of paleo ice sheet variability;
- April Dalton from Charles University will discuss how “The marine d18O record overestimates continental ice volume during Marine Isotope Stage 3”, and Drew Christ from the University of Vermont will present “Camp Century revisited: an ecosystem under the ice reveals Greenland’s warmer past.”;
- July 13th 2021 - Holocene paleo sea level records Nicole Khan and (Stephen Chua) - Paleo sea level records;
- PALSEA – September 2021;
- March 2022 - theme: rates and amplitudes of Pleistocene ice sheet and sea level variations;
- Georgia Grant: “Continuous record of sea-level change during the intensification of North Hemisphere Ice Sheets (3.3 – 1.7 Ma)”;
- Jo Brendryen - “Rates of Deglacial Ice Sheet Retreat”;
- April 2022 - Nicholas Golledge, "Climate forced changes of the Antarctic Ice Sheet: Evidence, inference, and speculation";
- May 2022 - Terry Wilson and Doug Wiens on “Cryosphere – Solid Earth Interactions in Antarctica: Insights from Geodetic and Seismic Measurements”;

- June 2022 Sally Brown "Impacts and adaptation to sea-level rise" and Ivan Haigh "The impact of sea-level rise on storm surge barriers";
- PALSEA + WCRP July 2022.

Another key activity, jointly with colleagues representing the World Climate Research Program (WCRP) and measurements of Paleo Sea-level (PALSEA), has been to begin to organize a 3D GIA benchmark effort. Initial plans were presented to the community at the European Geoscience Union General Assembly. These were well received, which culminated in a GIA symposium at the upcoming IUGG 2023, where the benchmark efforts will be one of the main topics of discussion. Furthermore, members of sub-commission 3.4 were involved as organizers, session chairs and presenters in the 2021 and 2023 Geodesy for Climate Research symposia from IAG the Inter-Commission Committee on "Geodesy for Climate Research", which both featured several presentations on Earth-ice-sea level interactions. The IAG SC3.4 co-sponsored a proposal to IUGG to support the 2023 Glacial Isostatic Adjustment (GIA) Training School, which was led by another IACS-IAG joint working group. The proposal was successful, and US$5000 was awarded to support the participation of young scientists to this school, which will be held in Sweden in July 2023. We also had extensive discussions about organizing a GIA-focused meeting, likely to be held in Canada. The meeting calendar became very crowded after the end of the pandemic restrictions, so plans did not coalesce. Those discussions are ongoing, with the possibility of a meeting in 2024. We think such a meeting will be important and encourage further planning.

Below is a summary of sessions organized or co-organized at major international scientific meetings:

- AGU Fall meeting 2020: Sessions G012 (poster) and G013 (oral): Linking Cryosphere and the Solid Earth: From Sea Level Changes and Geodetic Time Series to Earth Rheology Session conveners: Rebekka Steffen, Jeff Freymueller, Natalya Gomez, Lambert Caron, 31 abstracts submitted. This session was organized together with JSG3-1;
- EGU General Assembly 2021 (vEGU21): Session 3.1: Geodesy for Climate Change, Session conveners: Roelof Rietbroek, Carmen Boening, Henryk Dobslaw, Anna Klos, Bert Wouters, 16 abstracts submitted;
- IAG Scientific Assembly 2021: Sessions 3.2: Observations and modeling of deformation related to changing ice, Session conveners: Jeff Freymueller, Natalya Gomez, Rebekka Steffen, Erik Ivins, Bert Wouters and Hansheng Wang, 12 abstracts submitted. This session is organized together with JSG3-1;
- Geodesy for Climate Research symposium 2021. Co-organized by Bert Wouters, 61 abstracts submitted;
- Geodesy for Climate Research symposium 2023. Co-organized by Bert Wouters, 46 abstracts submitted;
- IUGG General Assembly 2023: Session JG01 - Interactions of the Solid Earth With Ice Sheets and Sea Level (IAG, IACS, IASPEI). Session Conveners: Rebekka Steffen, Bert Wouters, Natalya Gomez, Lambert Caron, Doug Wiens. (organized jointly with Joint Study Group 3.1);
- IUGG General Assembly 2023: Session JG05 Geodesy for Climate Research (IAG, IAMAS, IACS, IAPSO, IAHS). Session Conveners: Annette Eicker, Bert Wouters, John T Reager, Adam Scaife, Benoit Meyssignac.

Sub-commission 3.5 : Seismo-Geodesy
Joint with IASPEI

In 2019-2021:
Chair: *Jean-Mathieu Nocquet (France)*
Vice-chair: *Takuya Nishimura (Japan)*
In 2021-2023:
Chair: *Takuya Nishimura (Japan)*
Vice-Chair: *Jean-Mathieu Nocquet (France)*

Terms of Reference

Space and terrestrial geodetic techniques provide key observations to investigate a broad range of geophysical processes, thanks to their high accuracy, precision, and reliable georeferencing. Thanks to both technological evolution and analysis improvement in the past decades, space geodesy can now monitor crustal movements of a few millimeters over time opening new prospects for the study of earthquakes. Among their many applications, geodetic measurements can now contribute to the study of the different phases of the seismic cycle, as they allow recording static and dynamic displacements during large earthquakes, as well as the slow postseismic and interseismic deformation. However, fully exploiting the potential of geodetic measurements is subject to their further integration with seismological analysis of conventional seismic sensors records and the development of a multidisciplinary approach to their interpretation. The joint IAG-IASPEI SC on Seismo-Geodesy aims to facilitate the cooperation between the geodetic and the seismological communities in order to both leverage the complementarity between geodetic and seismic data and improve our current understanding of the processes leading to earthquakes. The investigated phenomena range from large destructive events, to slow earthquakes and tremors with the aid of individual or collocated geodetic/seismic sensors. The works of the SC focus on both observational challenges and theoretical aspects. Particular effort is dedicated to identifying gaps of knowledge and opportunity for progress, particularly in the field of hazard assessment and early warning systems.

Summary of the Sub-commission's activities during the period 2019-2023

Meetings:

WEGENER Session at EGU 2019 (7-12 April 2019)

A session "Monitoring and modelling of geodynamics and crustal deformation: progress during 38 years of the WEGENER initiative" has been organized by the WEGENER group (Conveners: Haluk Ozener, Matthias Becker, Sara Bruni, Susanna Zerbini) together with the Geodynamics and Seismology divisions. It gathered 21 contributions (https://meetingorganizer.copernicus.org/EGU2019/session/30377)

WEGENER Session at EGU 2020 (4-8 May 2020)

Wegener session at EGU 2020 (Conveners: Sara Bruni, Takuya Nishimura, Jean-Mathieu Nocquet, Haluk Ozener, Susanna Zerbini) was hold virtual and gathered 22 presentations. https://meetingorganizer.copernicus.org/EGU2020/orals/35342. The session included contributions in new observational development, separation of contributions in geodetic time series, integration of active tectonics studies and geodesy to understand the role of faults at the regional scale and on the use of geodesy in seismic hazard assessment.

Seismo-geodesy Session at vEGU2021 (19-30 April 2021)

SC 3.5 organized a virtual session "Seismo-geodesy : integrating geodetic/seismological observations and analysis to probe the behavior of faults " co-sponsored by IUGG and the seismology division (https://meetingorganizer.copernicus.org/EGU21/session/39916). The session gathers 26 contributions addressing the following topics:

- Slow Slip Events: geodetic and seismological signatures
- Post-seismic slip and aftershocks
- Faults: from observation to models
- Improving geodetic analysis to probe fault behavior

Session at IAG2021 (28 June – 2 July, 2021) on Geodetic observations in volcanic and tectonically active areas.

The session was co-sponsored by SC 3.5 and SC 3.4 (Converners: Alessandro Bonforte, Emily Motgomery-Brown, Takuya Nishimura, Jean-Mathieu Nocquet, and Chengli Huang). There were 11 oral contributions and 17 poster contributions. Many studies on the crustal deformation in continental China and its surroundings were presented.

Wegener 20th general Assembly – Sousse, Tunisia, 24-27 October 2023.

Wegener is planned to continue its activities under the umbrella of IAG-IASPEI, as a meeting organized every two years offering a space for collaborative discussion and presentation of research. The meeting was at first planned to take place in Marrakech, Morocco, but was post-poned and finally cancelled by the local organizing committee. The National Office of Mine (OMN), Tunisia, together with the Office for Topography and Land Survey (OFT) and the National Institute for Meteorology (INM) will organize it in Sousse, Tunisia with support from IAG and IASPEI (https://congress-onm.tn/).

Session at EGU2022 (24 May 2022) on Active lithospheric deformation using space (GNSS, InSAR) and marine geodesy: Lessons from mountain belts and volcanic provinces down to earthquakes

The session was led by young scientists (P. Gonzales, L. Tunini & P. Sakic) with help from M. Meghraoui and T. Nishimura. It is co-sponsered by IUGG (https://meetingorganizer.copernicus.org/EGU22/session/42839) and included 33 abstracts. Popular topics include:

- Marine geodesy including GNSS/Acoustic measurements
- Combination of InSAR and GNSS for mapping high-resolution strain rate distribution
- Postseismic deformation of large megathrust earthquakes

Sub-commission 3.5 will organize the following session and scientific conference
Seismo-geodesy session at IUGG2023 General Assembly (July 11-20, 2023)

The session consists of 15 oral presentations and 7 poster presentations.

Web site.

A dedicated web site has been started https://iag-seismogeodesy.github.io/

Seismo-geodesy highlights & trends.

The contributions received at meeting session, together with feedbacks provided by the community highlight several trends in seismo-geodesy, that might help to define specific actions of SC 3.5 in future. Study of earthquakes is steadily improving thanks to the availability of high quality observations networks in place at the time of the earthquake. For crustal earthquakes, very rapid analysis of Synthetic Aperture Radar data and Optical images now makes earthquakes precise characterization significantly faster, within a few days, sometimes hours after the event. Similarly, both seismological and geodetic signatures of slow slip at faults are better documented both during the interseismic and post-seismic periods. Advances in seafloor observations also promote monitoring of slow slip in the subduction zone. Active research is carried out to develop new analysis methods. Among them Machine Learning approaches are rapidly growing and are promising. Separation of non-tectonic contributions in geodetic time series remains a challenge for longer term signals. In addition to geodesy and seismology, active tectonics also would deserve to be included in the general scope of the Seismo-geodesy sub-commission. Integrating active tectonic would allow to enlarge the time scale of fault behavior from the earthquake to 10^2-10^5 years. This contribution becomes even more important in the context where the use of geodetic data to probabilistic seismic hazard assessment is rapidly growing.

Selected peer-reviewed publications:

Baba, S., Takemura, S., Obara, K., & Noda, A. (2020). Slow earthquakes illuminating interplate coupling heterogeneities in subduction zones. Geophysical Research Letters, 47(14), e2020GL088089.

Bletery, Q., & Nocquet, J. M. (2020). Slip bursts during coalescence of slow slip events in Cascadia. Nature communications, 11(1), 2159.

Caballero, E., Chounet, A., Duputel, Z., Jara, J., Twardzik, C., & Jolivet, R. (2021). Seismic and aseismic fault slip during the initiation phase of the 2017 MW= 6.9 Valparaíso earthquake. Geophysical research letters, 48(6), e2020GL091916.

Cruz-Atienza, V. M., Tago, J., Villafuerte, C., Wei, M., Garza-Girón, R., Dominguez, L. A., ... & Kazachkina, E. (2021). Short-term interaction between silent and devastating earthquakes in Mexico. Nature communications, 12(1), 2171.

Fredrickson, E. K., Gomberg, J. S., Wilcock, W. S., Hautala, S. L., Hermann, A. J., & Johnson, H. P. (2023). Slow slip detectability in seafloor pressure records offshore Alaska. Journal of Geophysical Research: Solid Earth, 128(2), e2022JB024767.

Fukao, Y., Kubota, T., Sugioka, H., Ito, A., Tonegawa, T., Shiobara, H., ... & Saito, T. (2021). Detection of "Rapid" Aseismic Slip at the Izu-Bonin Trench. Journal of Geophysical Research: Solid Earth, 126(9), e2021JB022132.

Guo, Y., Zhuang, J., & Zhang, H. (2023). Detection and characterization of earthquake swarms in Nankai and its association with slow slip events. Journal of Geophysical Research: Solid Earth, 128(3), e2022JB025984.

He, B., Wei, M., Watts, D. R., & Shen, Y. (2020). Detecting slow slip events from seafloor pressure data using machine learning. Geophysical Research Letters, 47(11), e2020GL087579.

He, B., Wei, X., Wei, M., Shen, Y., Alvarez, M., & Schwartz, S. Y. (2023). A shallow slow slip event in 2018 in the Semidi segment of the Alaska subduction zone detected by machine learning. Earth and Planetary Science Letters, 612, 118154.

Huang, H., & Hawthorne, J. C. (2022). Linking the scaling of tremor and slow slip near Parkfield, CA. Nature communications, 13(1), 5826.

Itoh, Y., Aoki, Y., & Fukuda, J. (2022). Imaging evolution of Cascadia slow-slip event using high-rate GPS. Scientific reports, 12(1), 7179.

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Matraku, K., Jouanne, F., Dushi, E., Koçi, R., Kuka, N., Grandin, R., & Bascou, P. (2023). The 26 November 2019 Durrës earthquake, Albania: coseismic displacements and occurrence of slow slip events in the year following the earthquake. Geophysical Journal International, 234(2), 807-838.

Michel, S., Gualandi, A., & Avouac, J. P. (2019). Similar scaling laws for earthquakes and Cascadia slow-slip events. Nature, 574(7779), 522-526.

Mouslopoulou, V., Bocchini, G. M., Cesca, S., Saltogianni, V., Bedford, J., Petersen, G., ... & Oncken, O. (2020). Earthquake Swarms, Slow Slip and Fault Interactions at the Western-End of the Hellenic Subduction System Precede the Mw 6.9 Zakynthos Earthquake, Greece. Geochemistry, Geophysics, Geosystems, 21(12), e2020GC009243.

Nuyen, C. P., & Schmidt, D. A. (2021). Filling the gap in Cascadia: The emergence of low-amplitude long-term slow slip. Geochemistry, Geophysics, Geosystems, 22(3), e2020GC009477.

Nishikawa, T., Ide, S., & Nishimura, T. (2023). A review on slow earthquakes in the Japan Trench. Progress in Earth and Planetary Science, 10(1), 1-51.

Nishikawa, T., Matsuzawa, T., Ohta, K., Uchida, N., Nishimura, T., & Ide, S. (2019). The slow earthquake spectrum in the Japan Trench illuminated by the S-net seafloor observatories. Science, 365(6455), 808-813.

Nishikawa, T., Nishimura, T., & Okada, Y. (2021). Earthquake swarm detection along the Hikurangi Trench, New Zealand: insights into the relationship between seismicity and slow slip events. Journal of Geophysical Research: Solid Earth, 126(4), e2020JB020618.

Rousset, B., Bürgmann, R., & Campillo, M. (2019). Slow slip events in the roots of the San Andreas fault. Science advances, 5(2), eaav3274.

Watts, D. R., Wei, M., Tracey, K. L., Donohue, K. A., & He, B. (2021). Seafloor geodetic pressure measurements to detect shallow slow slip events: Methods to remove contributions from ocean water. Journal of Geophysical Research: Solid Earth, 126(4), e2020JB020065.

Weiss, J. R., Walters, R. J., Morishita, Y., Wright, T. J., Lazecky, M., Wang, H., et al. (2020). High-Resolution Surface Velocities and Strain for Anatolia From Sentinel-1 InSAR and GNSS Data. *Geophysical Research Letters, 47*(17).

Xie, S., Dixon, T. H., Malservisi, R., Jiang, Y., Protti, M., & Muller, C. (2020). Slow slip and inter-transient locking on the Nicoya megathrust in the late and early stages of an earthquake cycle. Journal of Geophysical Research: Solid Earth, 125(11), e2020JB020503.

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Yokota, Y., & Ishikawa, T. (2020). Shallow slow slip events along the Nankai Trough detected by GNSS-A. *Science Advances*, *6*(3).

Joint Study Group 3.1: Geodetic, Seismic and Geodynamic Constraints on Glacial Isostatic Adjustment

With IAG Commissions 1 and 2

Chair: *Rebekka Steffen (Sweden)*
Vice-Chair: *Erik R. Ivins (US)*

Terms of Reference

The solid Earth's memory of past glacial loading has been modelled throughout the past 100 years using much of the same formalism and attention to Earth structure that is found in the study of surface wave seismology. Glacial Isostatic Adjustment (GIA) models and geodynamics models use, as fundamental source of data, both seismologically based internal mantle structure models and geodetic time series. It is therefore the focus of this working group to allows cross fertilization of models, data and conceptual frameworks of these two communities, geodynamics and GIA, with the development of an interdisciplinary approach to better determination of the Earth's internal rheological structure. The compatibility of the spatial and time scales over which rheological frameworks operate effectively is essential. This JSG also tasks itself with analysis of the currently applied GIA modelling parametrizations, data constraints and emerging geodetic data sets, such as GPS, gravity change, and both relative and absolute sea-level variations. In this interdisciplinary study it will be essential to improve the operative definition of the lithosphere. We seek to identify critical assessments that can be performed to more tightly constrain the relationships between effective mantle viscosity for use in geodynamics and GIA models that are compatible with the results of advanced seismic imaging of 3-D mantle structure and geodetic time series. Consequently, this Study Group is joined between Commission 1 on Reference Frames, Commission 2 on Gravity Field.

Summary of the Group's activities during the period 2019-2023

Development of goals and establishment of group: The group was newly formed, and objectives had to be developed, which were approved at the IAG Council Meeting in December 2019. The objectives follow the goal of the JSG to increase collaboration between different geoscientific disciplines (geodesy, geodynamics, seismology, mineral physics, applied geophysics). As part of these goals, the JSG is involved in a new GIA modelling benchmark, which will focus on three-dimensional structures in the Earth models. This effort is led by SCAR-INSTANT (Scientific Community on Antarctic Research - INStabilities & Thresholds in ANTarctica) and several members of this JSG will contribute to this benchmark. In addition, the JSG will lead further GIA modelling benchmarks focusing on compressible material behavior and mantle rheologies. The JSG has a large focus on seismology and geodynamics. Thus, a strong connection with IASPEI (International Association of Seismology and Physics of the Earth's Interior) was planned. To achieve this, an article about the JSG was published in the IASPEI newsletter in February 2021 (http://download.iaspei.org/newsletters/2020-2029/2021-Feb.pdf). A further summary of the JSG was written for GIM International (Issue 3, 2021; https://www.gim-international.com/magazines/issue-3-2021). The goals of the JSG and some of the outstanding questions in GIA research were presented at several meetings in 2022. In addition, members of the JSG have contributed to the organization of sessions related to GIA at various geoscientific meetings (see list below; see figure below of a poster summarizing some outstanding questions in GIA research). We are also involved in the planning of a GIA meeting to be held in 2024 in Canada.

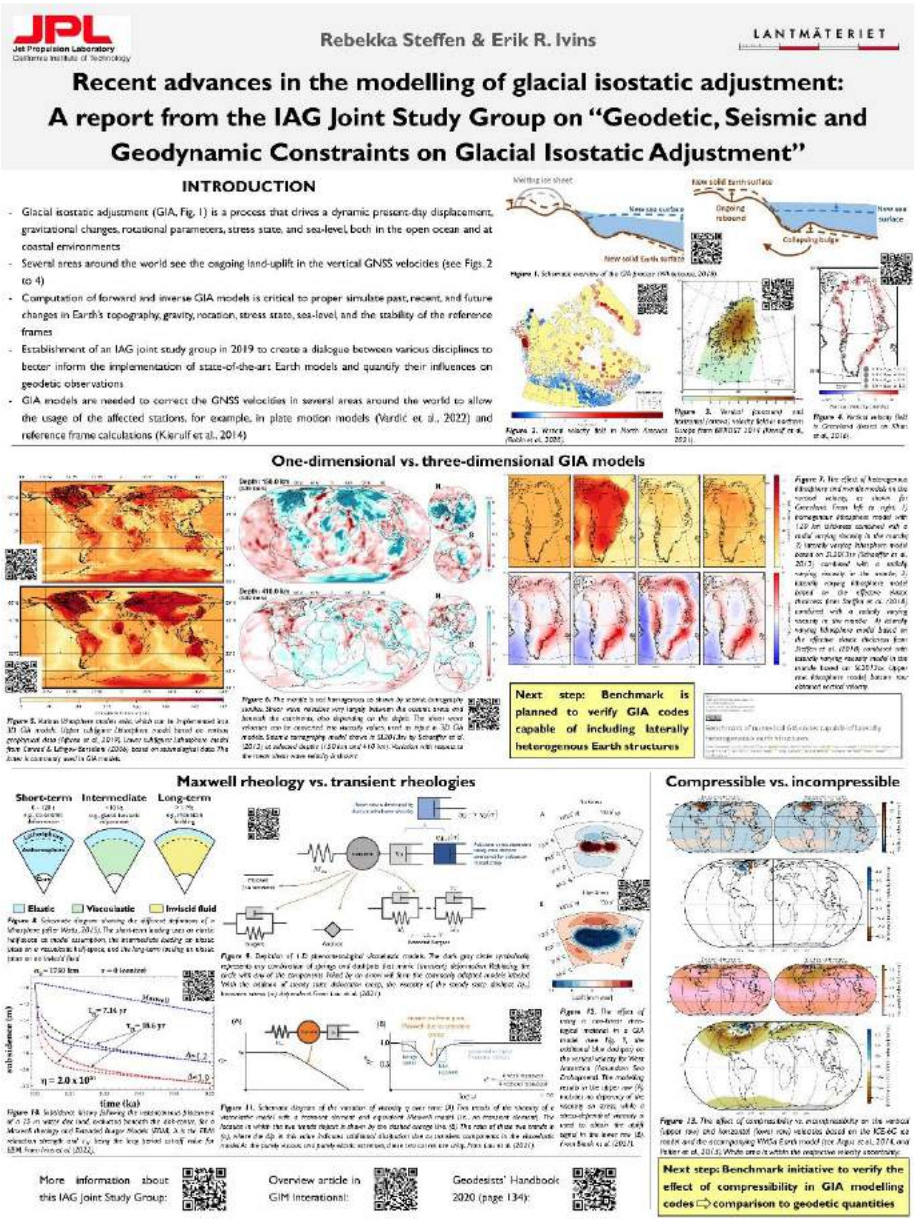

Figure 2. Poster about some of the outstanding questions within GIA research. Poster was presented at the General Assembly of the Nordic Geodetic Commission in Denmark (September 2022) and at the REFAG meeting in Greece (October 2022).

Organization of meetings/sessions:

- GIA Training School 2019: A Training School on GIA was organized by SERCE (Solid Earth Responses and influences on Cryospheric Evolution) as part of SCAR (Scientific Community on Antarctic Research) and POLENET (Polar Earth Observing Network) as part of the Antarctica Network (ANET) both funded by The National Science Foundation (NSF) with additional funding from the International Association of Cryospheric Sciences (IACS), the European Geosciences Union (EGU), and DTU Space. The training school was held at the headquarter of Lantmäteriet in Gävle (Sweden). The chair of the JSG was involved in the organization, and the chair, co-chair and several team members were invited as lectures. 42 students attended the Training School in-person (selected out of 120 researchers who applied) and several were able to attend the lectures virtually. The lectures during the Training School covered various topics on GIA modelling, ice sheet modelling and their observations. In addition, one day was dedicated to an excursion where the students were able to see the consequences of land uplift;

- AGU Fall Meeting 2020 Session: JSG 3.1 and SC 3.4 (Cryospheric Deformation) co-organized a session on "Linking Cryosphere and the Solid Earth: From Sea Level Changes and Geodetic Time Series to Earth Rheology" at the AGU Fall Meeting 2020. We received 30 abstracts and more than 100 participants attended the online session during the AGU Fall Meeting. Invited speakers were Kate Selway (Australia) and Volker Klemann (Germany);
- IAG General Assembly 2021 Session: JSG 3.1 and SC 3.4 (Cryospheric Deformation) co-organized a session on "Observations and modeling of deformation related to changing ice loads" at the General Assembly of the IAG 2021. In addition to the chairs and co-chairs of both IAG groups, Hansheng Wang from the Chinese Academy of Sciences in Wuhan was invited to join the convener team;
- GIA Training School 2023: Another GIA Training School is organized in Gävle (Sweden) by SCAR-INSTANT and POLENET as part of ANET funded by NSF. Additional funding was received by IACS, IUGG, NSF-project funds by Andrew Lloyd, EGU, University of Gävle and Lantmäteriet. The chair of the JSG is involved in the organization and contributes with teaching. In addition, Glenn Milne (member of this JSG) is invited as lecturer. The training school will be held in early July (3rd to 7th), before the IUGG2023 meeting. Almost 200 researchers applied for the training school and 40 were selected for in-person participation. All lectures will be streamed, and virtual participation is possible. One day is dedicated to an excursion where the students can see the consequences of land uplift;
- IUGG General Assembly 2023: Organization of the joint symposia "Interactions of the Solid Earth With Ice Sheets and Sea Level" (JG01) together with members of SC 3.4 and the SCAR-INSTANT group. We received 26 abstracts. Invited speakers are Terry Wilson (US) and Tanghua Li (Singapore) to highlight the data aspect of GIA modelling.

Selected peer-reviewed publications:

Adhikari, S., Ivins, E.R.., Larour, E., Caron, L., Seroussi, H. (2020): A kinematic formalism for tracking ice–ocean mass exchange on the Earth's surface and estimating sea-level change. *The Cryosphere* 14, doi: 10.5194/tc-14-2819-2020.

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Austermann, J., Hoggard, M.J., Latychev, K., Richards, F.D., Mitrovica, J.X. (2021): The effect of lateral variations in Earth structure on Last Interglacial sea level. *Geophysical Journal International* 227, doi: 10.1093/gji/ggab289.

Bagge, M., Klemann, V., Steinberger, B., Latinović, M., Thomas, M. (2021): Glacial-isostatic adjustment models using geodynamically constrained 3D earth structures. *Geochemistry, Geophysics, Geosystems* 22, doi: 10.1029/2021GC009853.

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Celli, N.L., Lebedev, S., Schaeffer, A.J., Gaina, C. (2020): African cratonic lithosphere carved by mantle plumes. *Nature Communications* 11, doi: 10.1038/s41467-019-13871-2.

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Gosselin, J.M., Audet, P., Schaeffer, A.J., Darbyshire, F.A., Estève, C. (2020): Azimuthal anisotropy in Bayseian surface wave tomography: application to northern Cascadia and Haida Gwaii. *Geophysical Journal International* 224, doi: 10.1093/gji/ggaa561.

Gradmann, S., Steffen, R. (2021): Crustal-Scale Stress Modelling to Investigate Glacially Triggered Faulting. In: Steffen, H., Olesen, O., Sutinen, R. (eds), On glacially triggered faulting. *Cambridge University Press*, doi:10.1017/9781108779906.030.

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Joint Working Group 3.1: Improving Theories and Models of the Earth's Rotation
With IAU

Chair: José Ferrándiz (Spain)
Vice-Chair: Richard Gross (USA)

Terms of Reference

The main purpose of this JWG is proposing consistent updates of the Earth rotation theories and models and their validation. The associated tasks will thus contribute to the implementation of the 2018 IAU Resolution B1 on Geocentric and International Terrestrial Reference Systems and Frames, and the 2019 IAG Resolution 5 on Improvement of the Earth's Rotation Theories and Models. The last resolution is the most specific for the WG assignment and mandates:

- to encourage a prompt improvement of the Earth rotation theory regarding its accuracy, consistency, and ability to model and predict the essential EOPs;
- that the definition of all the EOPs, and related theories, equations, and ancillary models governing their time evolution, must be consistent with the reference frames and the resolutions, conventional models, products, and standards adopted by the IAG and its components;
- that the new models should be closer to the dynamically time-varying, actual Earth, and adaptable as much as possible to future updating of the reference frames and standards.

The work has been performed in close cooperation other IAG components, particularly GGOS, the IERS, and current WGs dealing with the Earth rotation and standards from specific perspectives, as well as with the IAU Commissions A2 and A3.

Summary of the Group's activities during the period 2019-2023

For more than two years, the development of the JWG planned activities was affected by the COVID-19 pandemic declared in 2020, as were many other IAG and IAU activities. Despite this, the JWG played a relevant role in the procedure that culminated in the approval of IAU Resolution B2 on the Improvement of the Earth's Rotation Theories and Models, in September 2021. With the adoption of this resolution the IAU and the IAG have confirmed their willingness to work in the same direction to improve theories and models of the Earth's rotation. Also noteworthy is the participation of the chairs of SWG 1 and of the full JWG in the 2019 and 2022 IERS/GGOS Unified Analysis Workshops (UAW), presenting proposals that resulted in concrete recommendations for achieving short-term feasible improvements to the precession and nutation models.

Web site:

A website was established at the University of Alicante, Spain, to facilitate documenting the group activities: <web.ua.es/wgitmer>. JWG main reports and other material and links of interest can be found on-line on it. The web site also contains a link to an archive of the documents elaborated by the previous Commission 3 JWG on Theory of Earth rotation and validation, which operated in the period 2015-2019, and the JWG on Theory of Earth rotation, which operated in the period 2013-2015, both joint with IAU.

Meetings:

The JWG Chairs have organized splinter meetings and special sessions at conferences of particular relevance to its activity, open to the interested conference attendants. They have also co-convened sessions on Earth rotation - or including it – at large meetings, or served in scientific organizing committees, as have other JWG members. Of course, the pandemic situation seriously affected this kind of activity. It prevented holding in-person meetings in 2020 and 2021, due to the cancellation or change to on-line format of most of the relevant events. In 2022, some meetings have already begun to be held in mixed format, virtual and face-to-face, and only at the end of this term can it be said that normality has almost been restored in a large part of the world. 2020 was the toughest year. The chair of SWG 1, A. Escapa, was a convener of an Earth rotation session at the EGU general assembly which was changed to a virtual format with a great reduction of the time for oral presentations. Alberto was also involved in the organization of the Journées 2020 - the latest planned in a series of meetings supported for decades by the IAG and IAU and which were re-started in 2017 thanks to the stimulus of the precedent IAU/IAG JWG 3.1 on Theory of Earth rotation and validation (TERV) - which was postponed *sine die* (but will be held again in September 2023). The AGU 2020 Fall Meeting did not host a specific Earth rotation session organized with the participation of JWG members, unlike before; however, the GGOS session helped to fill the gap by welcoming Earth rotation modelling and other related topics. The sessions and events in whose organization the JWG has participated are:

- 2020 European Geosciences Union General Assembly (EGU 2020, virtual only). Session G3.1 “Earth Rotation: Theoretical aspects, observation of temporal variations and physical interpretation”. https://meetingorganizer.copernicus.org/EGU2020/session/35334;
- 2021 European Geosciences Union General Assembly (vEGU 2021, virtual only). 19-30 April 2021:
    - Session G3.3, “Earth Rotation: Theoretical aspects, observation of temporal variations and physical Interpretation”. Conveners: A. Escapa, S. Böhm, M Karbon, D. Salstein, F. Seitz. https://meetingorganizer.copernicus.org/EGU21/session/39900;
    - SPM7 Business Meeting of the IAU/IAG JWG on Improving Theories and Models of the Earth’s Rotation (ITMER). Conveners: J.M. Ferrándiz, R. Gross, April 30, 2021. https://meetingorganizer.copernicus.org/EGU21/session/41591;
- 2021 Scientific Assembly of the International Association of Geodesy (IAG 2021, virtual). Beijing 28 June - 2 July 2021. Symposium 3: Earth Rotation and Geodynamics, Convener J. Bogusz, Session 3.1 “Earth rotation, low-degree gravitational change and mass transport in geophysical fluids” (Joint with: ICCC). Conveners: JL. Chen, J.M. Ferrándiz, R. Gross, M. Schindelegger, H. Dobslaw, J. Li.;
- 2022 European Geosciences Union General Assembly (EGU 2022, in-person and virtual), Vienna, 23–27 May 2022. Session G3.5 "Earth Rotation: Theoretical aspects, temporal variability, physical interpretation, and prediction". Conveners: D. Salstein, S. Böhm, A. Escapa, F. Seitz, S. Bruni. https://meetingorganizer.copernicus.org/EGU22/session/43011;
- 2022 Asia Oceania Geosciences Society (AOGS 2022) annual meeting (virtual only) 1-5 Aug 2022. Session SE03, “Earth Rotation: Interpretation, Prediction, Uncertainty and Real-time Geodesy”. Conveners: JL Chen, J.M. Ferrándiz, R. Gross, H. Dobslaw. Merged with Session SE05 (Solid Earth General Session); https://www.asiaoceania.org/aogs2022/public.asp?page=sessions_and_conveners.asp
- 2022 XXI General Assembly of the IAU. Busan, Korea 2-11 August 2022 (in-person and virtual), Division A Meeting, Session 4 - Reference Frames and Rotations. Convener: A. Escapa. https://www.iau.org/science/scientific_bodies/divisions/A/meeting2022/
- First Workshop of Spanish and German IVS Analysis Centers, Alicante 5-6 October 2022 (in-person and virtual). Chairs: H. Schuh, J.M. Ferrándiz;
- 2023 European Geosciences Union General Assembly (EGU 2023, in-person and virtual) Vienna, 23-28 April 2023. Session 2.3 "Global Geodetic Observing System with a special

focus on Earth Rotation". Conveners: K. Heki, F. Seitz, A. Escapa, D. Salstein, A. Craddock, H. Wolf. https://meetingorganizer.copernicus.org/EGU23/sessionprogramme/4926;

- 2023 General Assembly of the International Union of Geodesy and Geophysics (IUGG 2023, in-person). Berlin 11-20 July 2023. IAG Symposium G04 "Earth Rotation and Geodynamics". Convener: J. Bogusz, CL. Huang, S. Rosat, M. Schindelegger. https://www.iugg2023berlin.org/iag/.

Cooperation with the IAU and the IAG components:

JWG 3.1 reports to the International Astronomical Union through its Commission A2, Rotation of the Earth. The cooperation has been tight and fruitful during the previous IAU term that ended in 2021 and the current term as well. In both terms, the Presidents, Vice Presidents and Secretaries of A2 have been affiliated with this JWG, and many members of the A2 Organizing Committees (OC) belonged to the JWG in both IAU trienniums. That fluent relation made it easier to share ideas and objectives related to Earth's rotation between IAU and IAG. A main result was that IAU Commission A2 (C.A2) proposed the said Resolution B2 on the Improvement of the Earth's Rotation Theories and Models. The process of approval of IAU resolutions newly introduced by the IAU was more complex than in previous occasions because, after a first phase in which the Resolutions Committee decided whether to accept a proposal, in a second phase, a remote discussion was opened which lasted about two months through the collaborative tool "Slack". Subsequently, at the IAU General Assembly, virtual and divided into two Business Sessions, the President of C.A2, F. Seitz, entrusted the Chair of this JWG with the task of presenting the resolution to the assembly, answering any questions that might arise and defending it or making changes if necessary, since the Chair of the Resolutions Committee had requested that these tasks be centralized in a single person. Prior to the second business session, at which the resolutions submitted for decision by the General Assembly were also presented again, there was, again for the first time in the history of the IAU, a remote discussion in which all IAU members could participate and which was intended exclusively for the presentation, discussion, defence and modification, if necessary, of the four resolutions that had been submitted. After this step, the text was considered definitive, and in the second administrative session, instead of voting directly on the resolutions as had been done in the former assemblies, an electronic voting period was opened to all members, which began on August 26 and ended on September 10. We refer to in this approval process here to record the strength of IAU support for the new C.A2 resolution that reinforces the 2019 IAG Resolution 5 proposed by the previous ITMER JWG. Records of the sessions are available at https://www.iau.org/science/meetings/general_assemblies/ga2021/. Finally, the editors of the IAU outreach magazine The Catalyst asked C.A2 for an article explaining the meaning and scope of the two resolutions adopted in 2021 on terrestrial rotation, in a way that would be intelligible without the possession of specific technical knowledge. The other resolution is B1, which supports the protection of geodetic radio astronomy against radio frequency interference. The article was published in the first issue of 2022, (https://www.iau.org/static/publications/iau-catalyst-06.pdf, pp. 18-21), its co-authors being all members of JWG3.1 - its chairpersons but one and the President of C.A2.

The interaction with the IAU has not been limited to C.A2, but has been extended to Commission A3, "Fundamental Standards". The relationship with C.A3 is important for the better fulfilment of the JWG's assignment, as it deals with astronomical standards in general. The JWG Chair ran for the last election with a proposal emphasizing the improvement of the standard Earth rotation models and was elected Vice President for the term 2021-2024.

Cooperation with GGOS was mandatory according to the Terms of Reference (ToRs) and has developed closely and smoothly. Maintaining good coordination is to be expected because the Vice Chair is the Immediate Past President of GGOS, the Chair is a member of the scientific panel and the Chair of SWG 3 belongs to the GGOS Bureau of Products and Standards (BPS), which is the component of GGOS in charge of standards. Therefore, the BPS must be aware of any proposed change of standards in Earth rotation models.

Strong cooperation has also been maintained with IERS, as foreseen in the TORs. Again, this smooth relationship has been facilitated by the existence of common members. In fact, the SWG3 Chair is the current IERS Analysis Coordinator, and among the members of the JWG are the Directors of the Central Bureau, three Product Centers (Earth Orientation, Rapid Service/Prediction and Conventions) and two Special Bureaus (Ocean, Atmosphere). In addition, the JWG and SWG Chairs are collaborating in the editing of Chapter 5 of the upcoming renewed IERS Conventions that will supersede the IERS Conventions (2010) currently in force (Petit & Luzum 2010). Bridges of these kinds have performed satisfactorily, and we believe that they are highly suitable for achieving the highest levels of consistency, given today's stringent accuracy requirements.

Among the collaboration activities with GGOS and IERS, participation in the IERS/GGOS Unified Analysis Workshops (UAW) held in 2019 and 2022 deserves special mention. In each of them, J. Ferrándiz and A. Escapa gave a presentation on the current situation and the prospects for improvement of the precession and nutation models in the short and medium term. The presentation at UAW 2022 included a proposal for some specific corrections to the current precession and nutation models that could be used to improve their performance in the short term. The proposed corrections are currently undergoing an external assessment by the IVS Analysis Coordinator.

Finally, the JWG has kept a good level of coordination with other WGs dealing with Earth rotation issues, in particular with the IAU/IAG/IERS JWG on the Consistent realization of TRF, CRF, and EOP and with the IERS WG on the Second EOP Prediction Comparison Campaign (EOPPCC2, http://eoppcc.cbk.waw.pl/). Both WGs have several members in common with the JWG. It should not be forgotten that the predictive capability of a given deterministic model, such as that for precession and nutation, is an intrinsically different concept from the capability of any algorithm to predict signals that have stochastic components, so that the tasks of ITMER and EOPPCC2 do not overlap, but rather their respective results help each other.

Progress of research and outcomes:

1. Short-term improvement of the official precession-nutation models

Following the above two IAG and IAU Resolutions, the main and most urgent objective of the JWG is to contribute to the prompt improvement of the theories and models of the Earth's rotation regarding their accuracy, consistency and ability to model and predict the essential EOP. The current conventional models endorsed by the IAG/IUGG and IAU are IAU2000 nutation and IAU2006 precession ones. The deviation of the values provided by these models with respect to those observed by VLBI is on the order of 200 micro-arcseconds (mas) in terms of WRMS of celestial pole offsets (CPO) time series. This is still too far from the general target of 33 mas set by GGOS. Thus the JWG should propose updates to both, trying to have a good ratio of effectiveness and cost of implementation, both in the short and medium term. Recall that IAU2006 consists of two parts expressed by polynomials of degree 5, the precession of the ecliptic, obtained from planetary theories, and that of the equator. The latter is empirical and includes a linear variation, fitted to observations until 2003 or so, of the dynamical ellipticity (or oblateness) H, which is instead assumed constant in IAU2000. On the other hand, IAU2000 has two blocks. The major components are formed by the lunisolar terms, whose amplitudes are obtained by convolution of the corresponding part of the REN2000 Hamiltonian rigid earth solution with the MHB2000 transfer function, fit to a set of VLBI-derived periodic terms in the period 1979-1999. The other block is that of the planetary terms, which contain both the direct effects of the planets and the indirect ones. The second block consists of more terms than the first one (687 vs. 678), but they are much smaller and so it was taken directly from REN2000, without applying any transfer function.

Shortly after the creation of the JWG by the IAG and before its formal approval by the IAU (which happened in February 2020), an IERS/GGOS UAW took place in October 2019, in Paris. The session on Conventions and Standards, co-organized by D. Angermann (GGOS) and N. Stamatakos (IERS), discussed the question of how to improve the current IAU2006 and IAU2000 precession and nutation models and how to better target the JWG activity for this purpose. Consensus was reached on recommending that the task of building such models should include as a matter of priority:

- updating the amplitudes of the leading nutations of IAU2000 and testing shortened series for certain operational purposes,
- correcting the inconsistencies already known in precession-nutation models,
- testing the available free core nutation (FCN) models and helping the relevant bodies consider whether or not the IERS should recommend FCN models for general purposes.

It was deemed that the development and publication of completely dynamically consistent theories capable of fully supporting and justifying next generation models that have precision and stability closer to the goals set by GGOS for the reference frames was a very demanding task that would require the maintenance of a targeted activity at least until the end of the current 4-year mandate.

The above indicated lines of work are the most important for the achievement of the main scientific objective of the JWG and will therefore be dealt with in more detail in this report. In the following years there has been a number of conference presentations and journal articles that sought to derive improvements to the precession and/or nutation theories. These specific investigations have been carried out by members of the JWG and their collaborators, highlighting the results obtained independently at a few centers, namely the Paris Observatory, the Royal Observatory of Belgium, and the University of Alicante in collaboration with GFZ.

These investigations are all complex and cannot be described in detail. In brief, the results obtained at the Belgian center include obtaining corrections to the amplitudes of the main lunisolar nutations by re-evaluating the basic earth parameters (BEP) of the IAU2000 theory and evaluating the effect of such corrections (named Fits20), alone or together with an FCN model, on the WRMS of two well-known CPO time series; without FCN, the WRMS decrease was less than 10% (Zhu et al 2021). The French team, in addition to also considering lunisolar nutations and variations of BEP, contributed with the development of alternative FCN models based on multiple periods, and also worked with their own VLBI solutions specifically obtained for these purposes (Nurul-Huda et al 2020, 2021). The German-Spanish group dealt with a wider set of CPO solutions from VLBI and has been the only one to investigate the mutual consistency of several corrections of the precession parameters obtained from different solutions and to derive theoretic and empirical corrections to nutations of planetary origin (Ferrándiz et al 2022).

More precise information about the above results and their comparative usefulness can be found in the presentation "Update on nutation issues" made by J. Ferrándiz and A. Escapa at the UAW 2022 held in October 2022 (https://zenodo.org/record/7352364). The analysis of a set of 9 main VLBI solutions produced by individual analysis centers or by the combined BKG center, all of them with more than 4,000 points in the period 1984-2022 and referenced to ICRF3 (Charlot et al 2020) and ITRF14 (Altamimi et al 2016), evidenced the existence of significant trends of the order of a few mas/y in dX and dY. Moreover, the linear corrections for some of them were statistically compatible with those derived for almost all the others as well as with the daily series IERS EOP14C04 (Bizouard et al 2019) and USNO finals. This remains the case with solutions referred to ITRF2000 (Altamimi et al 2023). It was proposed at UAW 2022 to discuss the possibility of recommending the use of linear corrections derived from the combined ivs19q4X series, which reduced the WRMS to about 150-160 mas and had maximal compatibility. Note that the variation of the precession rate induces a variation of the dynamic ellipticity H. Furthermore, let us recall that some other effects not included in IAU2000 induce a variation in H of a few ppm and the resulting "indirect" corrections to nutations (Escapa et al 2016) are not negligible and exceed 50 μas for a few terms (Ferrándiz et al 2017, Baenas et al 2017, 2019). Besides such update, it is necessary to precise unambiguously to which tidal system is referred that value of H (Escapa et al. 2020, 2022a). The revision of the value of H, and of its modeling for use in the terrestrial rotation theory where appropriate, was also proposed at the last UAW and will be studied by an IAU C.A3 WG.

Regarding the correction of lunisolar nutations, the derivation of empirical corrections to a reduced set of 11 periods provides a reduction of the WRMS that is about 20 μas greater than the reduction achieved with Fits20.

The empirical fit of the planetary nutations is more difficult because among them there are quite a few terms with periods close to each other and close to those of the FCN or of some larger lunisolar terms. An alternative to deal with this problem is to refrain from including in the fit any problematic period, even if this forces us to exclude several whose theoretically derived amplitudes are larger than 10 μas (Ferrándiz et al 2020). By correcting the amplitudes of a set limited to only 5 periods free of such problems, the decrease of the WRMS is as large as that achieved with the lunisolar corrections. Furthermore, the WRMS decreases obtained by using both lunisolar and planetary corrections are almost additive. It was therefore proposed in UAW 2022 to also consider the near-term adoption of a small set of corrections of planetary and lunisolar terms amplitudes. The joint use of the three previous corrections allows a 30% reduction in the WRMS of the above-mentioned ivs19q4X series, down to around 120 μas - although the figures are higher for other CPO series. In the final discussion, it was agreed that these proposed updates would be submitted for external evaluation to John Gipson, the IVS Analysis Coordinator, which is currently underway.

2. Advances in FCN modeling

FCN is a component of the nutations arising from a resonance at the nearly diurnal retrograde frequency due to the existence of the Earth's fluid core and excited by geophysical sources whose variations are not as predictable as the astronomical forces that excite the forced nutations. The use of FCN models allows a large reduction of the unexplained WRMS, but models depend on past observations and require periodic updating. For reference, using an update of the Belda 2016 FCN approach, the WRMS of the ivs19q4 solution can be lowered to 84 μas (115 μas for IERS14C04), which is about a 50% reduction.

Models are mainly derived following two quite different approaches: (1) Fitting a time-varying amplitude to the FCN oscillation, whose period is assumed constant, by a sliding window. This is the most common approach (e.g., Lambert 2007, Malkin 2013 or Belda et al 2016) and provides insight into the underlying geophysical process. For example, some JWG members have shown a relation with geomagnetic jerks (Vondrák and Ron 2020, Belda et al 2022). (2) Fitting constant amplitudes to a chosen set of a few fixed frequencies distributed in a band around the FCN (e.g., Petrov 2007 or Nurul-Huda et al 2020). In general, their computational cost is less and the WRMS reduction is only slightly worse, but they lack connection with the physics.

At the last EGU, a novel approach was introduced by Belda et al (2023) that behaves better in preliminary tests. The differences in performance among the most extended FCN models are rather small and the assessment might not be conclusive enough, but it seems reasonable that e.g., IERS, IVS, or GGOS assess the quality of and facilitate access to a few selected models instead of recommending only one. The recommendation made at the UAW 2022 was that users may decide on FCN models.

In summary, with the use of appropriate corrections for precession and some forced nutations, with or without FCN models, CPO models could achieve an accuracy better than 5 or 3 mm respectively.

3. Effects of ancillary geophysical models on EOP

The IAU2000 theory was developed using the latest geophysical models available at the time. They are therefore different from the current conventional models used in data processing, which is a source of inconsistency noted in the cited IAG and IAU resolutions. However, the needed update is not immediate, because that theory did not provide such effects separately, but embedded in the total amplitudes - probably as they were calculated numerically from the dynamic equations and not from the resonance formulas, as described in Section 6.1 of Mathews et al. 2002. Some recent investigations of new effects associated to mass redistribution with current models for the anelastic solid earth and oceans have shown that there are appreciable differences between different models, both in nutation and length-of-day (LOD) (Baenas et al 2021, 2022, Escapa et al 2022b).

4. Exploring further the effects of the Earth's interior on its rotation

The RotaNut team at the Royal Observatory of Belgium has extensively studied the diverse effects on nutations arising from the core-mantle boundary, which are very intricate, although estimates of their magnitude suggest that they are currently undetectable (Triana et al 2021).

Guo and Shen (2020) formulated a triaxial three-layered anelastic Earth rotation theory assuming various core-mantle couplings, including pressure and gravitational couplings acting on the elastic inner core (IC) by the fluid outer core (FOC) and mantle, and the visco-electromagnetic coupling between the FOC and mantle and between the outer and inner cores. They estimated that the effects on the periods of the Chandler Wobble (CW) and Inner Core Wobble (ICW) were about 4 and 95 days, respectively. In a later paper, Zhang and Shen (2021) proposed a parametric approach to the topographic coupling between the mantle and outer core for refinement of the former theory and obtained a slight decrease of the ellipticity of the outer core compared to the one assumed in IAU2000.

Shih and Chao (2020) obtained further results on the axial torsional libration of the IC under the gravitational attraction of the mantle and applied them to investigate some geophysical implications on the characteristics of the lower mantle. Their approach used a multipole expansion that was discussed in more detail in another paper (Chao and Shih 2021). Duan and Huang (2020) also addressed the study of IC oscillations under gravitational and electromagnetic torques, as well as the strong rotational coupling between FOC and IC near their boundary.

Finally, let us recall a recent survey by Riker et al (2022) that examines some relationships between the properties of the Earth's interior and its observed rotation. The above studies show that it seems unlikely that a treatment of all the effects originating in the Earth's interior in a way that integrates them into a unified rotation theory can be completed in the short term.

5. Time-variations of the Earth's dynamical parameters and Earth rotation

Future theories should try to adapt to the time-varying Earth according to the IAG and IAU recommendations. The often-called dynamic ellipticity H and the oblateness parameter J_2, basically proportional to each other, play a fundamental role in Earth rotation theory since they are present as a factor in the precession rate and forced nutations and in the CW period, all this understood in a first order of approximation of solutions. As mentioned above, the IAU2006 theory includes a hypothesis of linear variation of J_2, which at present cannot be maintained (e.g., Chao et al 2020). The difference between the assumed and observed variations of the Earth's oblateness produces some effects on precession and nutation, the largest of which have been estimated and reach a magnitude of 150 μas in dX over the entire period of VLBI observations (Ferrándiz et al 2022). The introduction of some corrections to the precession model would also provide a good opportunity to include also in the models the effect on the nutations of the known inconsistencies between IAU2000 and IAU2006, which include several so-called Poisson or secular-mixed terms, whose amplitudes are factorized by time (Escapa et al 2017, Escapa and Capitaine 2018; Ferrándiz et al 2020, 2022; Ferrándiz and Escapa 2022).

On the other hand, another of the basic hypotheses of IAU2000, concerning the existence of a set of principal axes of inertia that are supposed to be fixed to the solid Earth, has also been proven not to be exactly fulfilled, since the calculation of the position of these axes from the temporal variations of the observed Stokes coefficients shows that they are drifting with respect to a supposed mean equilibrium position (Ferrándiz et al 2020). Another research related to the variation of the Stokes coefficients and the motion of the equatorial axes is that of Chao and Yu (2020) on the 6-year westward wave-2 motion in the Earth.

6. Miscellaneous

In addition, many advances in different aspects of the theoretical formulations or explanation of the observed variations in the Earth's rotation have been published or are in an advanced stage of development over this term, and it is reasonable to expect that they will lead to a better understanding of the underlying physics, and thus help to improve the theory of the Earth's rotation and help to predict the EOP on a more solid basis.

Among them, the Hamiltonian method has recently been extended to derive the second order contributions to nutations (i.e., quadratic in H) for a Poincaré Earth model, confirming that the transfer function method is not precise enough for computing such small effects at the GGOS accuracy level (Getino et al 2021).

Polar motion and LOD have been addressed in so many studies that we cannot cite them in this report, investigating many features, as their trends, decadal variations, some specific observed periods of unclear origin, relations with geophysical phenomena and climate, etc. A selection of them is listed in the bibliography.

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Joint Working Group 3.2: Global combined GNSS velocity field

With IAG Commissions 1 and 2

Chair: *Alvaro Santamaría-Gómez (France)*
Vice-Chair: *Roelof Rietbroek (Netherlands)*

Terms of Reference

This Working Group aims at combining and comparing available GNSS velocity fields obtained by different groups from both network and PPP solutions. It continues the activities of former JWG3.2 "Constraining vertical land motion of tide gauges" with the inclusion of the last reprocessed solutions derived or related to the ITRF2020 realization while also extending the scope to the horizontal component of the velocity field. GNSS velocities estimated by different groups usually differ due to the choices made concerning the GNSS data processing (corrections applied and noise level of the series), the completeness of the series, the removed position discontinuities and the alignment to a terrestrial reference frame. The position discontinuities that populate the GNSS time series have probably the biggest impact on the velocity estimates. Even when using exactly the same series, it is common that different groups provide different velocity estimates and uncertainties mainly due to the different choices of position discontinuities. The main outcome of the Working Group is a combined velocity field that takes into account the repeatability of the estimates by the different groups. It is expected that the combined GNSS velocity field will be useful for the scientific community in the areas of tectonics, sea-level change and GIA modeling among others. The differences of the combined GNSS velocity field with respect to velocity fields obtained from other techniques (other space geodetic techniques, TGs, satellite altimetry) was assessed since observations from gravimeters, InSAR and other space geodetic techniques (e.g., DORIS) have the potential to provide valuable information on the velocities.

Summary of the Group's activities during the period 2019-2023

The IAG combined GNSS velocity field has been computed from several GNSS velocity field solutions that have been compared, combined and aligned to the ITRF2020. The velocity fields used in the combination include solutions from the Regional Reference Frame Commissions (APREF, EUREF, SIRGAS) and global velocity fields computed from different groups (see details in Table 1).

Solution	#sites	Coverage	Contributors
APREF	720	Global	John Dawson et al.
EOST	986	Europe	Alexandre Michel et al.
EPND	2391	Europe	https://epnd.sgo-penc.hu
EUREF	351	Europe	https://epncb.oma.be
INGV	594	Europe/Africa	https://gnssproducts.epos.ubi.pt
ITRF2020	901	Global	https://itrf.ign.fr
JPL	2468	Global	https://sideshow.jpl.nasa.gov
LTK	581	Europe/Africa	https://gnssproducts.epos.ubi.pt
NCL	965	Global	Katarina Vardic et al.
NGL	10100	Global	http://geodesy.unr.edu
NGS	1748	Global	Phillip McFarland et al.
NRCAN	593	Canada	Michael Craymer et al.
SIRGAS	89	Central & South America	https://www.sirgas.org
SOPAC	978	Global	https://cddis.nasa.gov

Each input velocity field was checked for anomalous velocity estimates, including station names and locations, and then weighted following their agreement with respect to the combined velocity field. The estimated variance factors differ among the input velocity fields up to one order of magnitude, but the average a posteriori (weighted) 3D formal velocity uncertainty ranges between 0.2 and 0.4 mm/yr, meaning that all solutions, after their alignment and weighting, contributed almost equally to the IAG combined velocity field. In total, the IAG combined GNSS velocity field includes 3D velocity estimates for 12,000 sites globally distributed and having at least five years of observations. For those sites having at least four different velocity estimates among the input solutions, the standard repeatability of the velocities obtained is 0.1 and 0.3 mm/yr, for horizontal and vertical components respectively.

Selected peer-reviewed publications:

Santamaría-Gómez A., Rietbroek R., Frederikse T., Rebischung P. (2022). Towards an IAG combined global GNSS velocity field. EGU General Assembly 2022.

Commission 4– Positioning and Applications

http://iag-comm4.survey.ntua.gr

President: Allison Kealy (Australia)
Vice President: Vassilis Gikas (Greece)

Structure

Sub-Commission 4.1:	Emerging Positioning Technologies and GNSS Augmentation
Sub-Commission 4.2:	Multi-Frequency Multi-Constellation GNSS
Sub-Commission 4.3:	Atmospheric Remote Sensing
Sub-Commission 4.4:	GNSS Integrity and Quality Control
Special Study Group 4.1.1:	Positioning using smartphones
Joint Study Group 4.4.4:	Assessment and validation of IGS products and open-source scientific software
Joint Working Group 4.3.1:	Real-Time Ionosphere Monitoring and Modelling
Joint Working Group 4.3.4:	Validation of VTEC Models for High-Precision and High Resolution Applications

Overview

The primary mission objective of Commission 4 is to promote research that leverages current and emerging positioning techniques and technologies to deliver practical and theoretical solutions for GNSS smartphone positioning technologies, multi-frequency, multi-constellation GNSS, positioning integrity and quality, alternatives and backups to GNSS, sensor fusion, atmospheric sensing, modelling, and applications based on geodetic techniques. Commission 4 will carry out its work in close cooperation with the IAG Services and other IAG entities, as well as via linkages with relevant entities within scientific and professional organizations the International Federation of Surveyors (FIG), International Society for Photogrammetry and Remote Sensing (ISPRS) and the Institutes of Navigation (ION & RIN).

Recognizing the central role of Global Navigation Satellite Systems (GNSS) in providing the positioning requirements today and into the future, Commission 4 will focus on research for improving models and methods that enhance and assure the positioning performance of GNSS-based positioning solutions for an increasing diversity of end-user applications. It also acknowledges the increasing levels of threat and vulnerabilities for GNSS-only positioning and investigates technologies and approaches that address these. A significant part of Commission 4 activities is oriented towards the development of theory, strategies and tools for modeling and/or mitigating the effects of interference, signal loss, and atmospheric effects, as they apply to precise GNSS positioning technology. In addition, technical and institutional issues necessary for developing backups to GNSS, integrated positioning solutions, automated processing capabilities, and quality control measures, are also being addressed. Commission 4 also deals with geodetic remote sensing using Synthetic Aperture Radar (SAR), Light Detection And Ranging (LiDAR), and Satellite Altimetry (SA) systems for geodetic applications.

The reader is referred to the Geodesist's Handbook 2020 for further details on the objectives of Commission 4 and the descriptions of its entities. As shown above, Commission 4 consists of four Sub-Commissions (SC), with SC 4.3 by far the largest, composed of five SCs, one Joint Study Group not led by Commission 4, five Working Groups (led by Commission 4, SC 4.3) and two Joint Working Groups: (led by Commission 4, SC 4.3), and five additional Joint Working Groups not led by Commission 4. Most of these entities have been closely interacting with other IAG components including Commissions, Services, ICG, ICCM, ICCT, ICCC and GGOS, where positioning and the associated applications are of major concern. This report presents the activities performed during the period 2019-2021 by the various entities of Commission 4, most of which were very productive and made significant progress in their stated objectives and program of activities despite the severe impacts of the Covid-19 pandemic.

Activities during the reporting period 2019-2021

In addition to the work performed by the sub-components of Commission 4, the following list summarizes major activities in 2019-2023 that were pursued on behalf of the entire Commission:

- A new web site for Commission 4 was established at http://iag-comm4.survey.ntua.gr which is hosted by the School of Rural and Surveying Engineering, National Technical University of Athens
- The terms of reference and structure of Commission 4, as well as the membership and the descriptions of its sub-components were detailed in our contribution to the Geodesist's Handbook 2020.
- A new Steering Committee was formed, which is composed of the President and Vice-President, the Chairs of the four Sub-Commissions, one representative from IGS (Sharyl Byram), one representative from IVS (Robert Heinkelmann) and two IAG members-at large (Ana Paula C. Larocca (Brazil), and Jiyun Lee (Korea))
- During the 2019-2021 period, the Commission 4 Steering Committee did not meet physically due to travel restrictions imposed by the Covid-19 pandemic. Commission-related business were mostly conducted through email discussions and electronic exchange of information. One remote meeting was held in May 2021 and the next business meeting of the Steering Committee took place during the IAG Scientific Assembly, Beijing, China in late June 2021.
- During the period 2019-2023 Commission 4 was represented at all IAG Executive Committee Meetings, at which brief progress reports were presented.
- Commission 4 is represented in the Steering Committees of various IAG components, including the Inter-Commission Committee on Theory (ICCT), the Inter-Commission Committee on Climate Change (ICCC), the Inter-Commission Committee on Marine Geodesy (ICCM) and the IAG Project "Novel Sensors and Quantum Technology for Geodesy". Commission 4 is also represented in the ICG and the GGOS Committees.
- *IAG Scientific Assembly 2021, Beijing, China*. Commission 4 was strongly involved in the preparation of the scientific program of the virtual IAG Scientific Assembly 2021. The organization of Symposium 4 "Positioning and Applications" was coordinated by the President and it is divided into 9 different sessions, with a total number of about 63 presentations.
- *Other events.* During the reporting period 2019-2023, Commission 4 was involved in the organization of several scientific conferences and workshops, including ION, FIG, MGA, EGU, AGU and COSPAR meetings, which are presented in detail in the following activity reports. Naturally, however, some of these activities were severely limited due to the Covid-19 situation.
- *The 2nd International Symposium of Commission 4* was held from 5th to 8th September 2022 at Wissenschaftsetage Potsdam. This symposium was carried out in close cooperation with the

International GNSS Service (IGS), the IAG Global Geodetic Observing System (GGOS) Focus Area "Geodetic Space Weather Research", as well as via linkages with relevant entities within scientific and professional sister organizations. The Symposium was co-sponsored by the International Association of Geomagnetism and Aeronomy (IAGA) Inter-Division Commission on Space Weather and Working Group IIC "Meteorological Effects on the Ionosphere". Further partners are the Institute of Navigation (ION), the SGI Workshop Organizers of Technische Universität Berlin, and the GFZ Potsdam. There were around 75 participants, of whom 45 participated in person and the rest online. The proceedings will be published in IAG Symposia by Springer.

Participants at the Second International Symposium of Commission 4, Potsdam, Germany, 5th- 8th September 2022

- *Selected research highlights include*:
    - Novel gait analysis techniques (WG 4.1.2),
    - Development of new positioning infrastructure for autonomous vehicles in Asian urban canyons (WG 4.1.5),
    - Measurements of Covid-19 contact tracing (SSG 4.1.1),
    - New low-cost systems for GNSS (WG 4.2.2),
    - LEO-augmented GNSS positioning (WG 4.2.3),
    - Development of a road map to disseminate real-time ionospheric information (JWG 4.3.1),
    - Enhanced dynamical models of the ionosphere (WG 4.3.2),
    - Development of automatic detection techniques for plasma depletions (WG 4.3.3),
    - Validation of vertical total electron content using JASON and GNSS data (JWG 4.3.4),
    - Development of new tools to visualize the troposphere in real-time (WG 4.3.5),
    - Creation of the benchmark datasets preceeding the Central European floods of summer 2021 (WG 4.3.6),
    - An inventory of GNSS-R stations (WG 4.3.7),

- Progress towards decimetre and sub-decimetre accuracy for self driving cars (WG 4.4.1),
- New techniques for leveraging the properties of Android smartphones for GNSS (WG 4.4.3),
- An assessment of open-source products for clock precision (JSG 4.4.4), and
- Crowd-sourcing techniques to detect GNSS spoofing (WG 4.4.5)

Activities of Working and Study groups

The following pages provide individual reports for all IAG components that are primarily affiliated with Commission 4 and its Sub-Commissions.

Sub-Commission 4.1: Emerging positioning technologies and GNSS augmentation

Chair: Laura Ruotsalainen (Finland)
Vice Chair: Ruizhi Chen (China)

Overview

IAG Sub-Commission 4.1 comprises five Working Groups in total (i.e., WG4.1.1, WG4.1.2, WG4.1.3, WG4.1.4 and WG4.1.5), and one Special Study Group (SSG4.1.1). During the term 2019-21, SC4.1 activities were coordinated remotely via electronic means due to the Covid-19 pandemic.

Working Groups of Sub-commission 4.1:

WG 4.1.1: Multi-Sensor Systems

Chair: Allison Kealy (Australia)
Vice Chair: Günther Retscher (Austria)

Activities and publications during the period 2019 – 2023

During the FIG Congress held in September 2022 in Warsaw, Poland, it was proposed to establish a new follow-up WG with different terms-of-references and a different main focus. For this new group it was discussed to find new chairs in their early stage of their carreer. This proposal should be further discussed at the upcoming IUGG Congress in July 2023.

Activities of the WG concentrated on participation at conferences, such as the aforementioned FIG Congress, and just recently the Mobile Mapping Symposium held in May 2023 in Padova, Italy. The main focus of discussions was the use of smartphone sensors for seamless ubiquitous positioning.

A major activity with involvement of the WG is the Erasmus+ Capacity Building in Higher Education project LBS2ITS. This is a joint project in EU Erasmus+ Programme Capacity Building in Higher Education, coordinators Gunther Retscher (Austria), Vassilis Gikas (Greece). The kick-off was held on March 2021. Due to the delays caused first by the Covid-19 pandemic and then by the economical crises in the partner country Sri Lanka an extension of 11 months has been granted for the project now lasting until mid December 2024. Training of the teachers is carried out with the last of the six train-the-teachers courses on smartphone positioning to be held in end of August 2023. After the training, new courses and course modules dealing with the project are implemented at the four Sri Lankan partner Universities.

Meetings and Conferences

Participation in key roles in the

- ION GNSS+ conference (2020 virtual)
- ISPRS, Nice (Postponed)
- virtual ION ITM (2021)
- FIG eWW (2021)

Publications

Journal Publications

- Retscher, Guenther; Kealy, Allison; Gabela, Jelena; Li, Yan; Goel, Salil; Toth, Charles K; Masiero, Andrea; Błaszczak-Bąk, Wioleta; Gikas, Vassilis; Perakis, Harris; A benchmarking measurement campaign in GNSS-denied/challenged indoor/outdoor and transitional environments, Journal of Applied Geodesy, 14 (2), 215-229, 2020
- Retscher, Guenther; Kealy, Allison; Gikas, Vassilis; Gabela, Jelena; Goel, Salil; Li, Yan; Masiero, Andrea; Toth, Charles K; Perakis, Harris; Błaszczak-Bąk, Wioleta; A Benchmarking Measurement Campaign to Support Ubiquitous Localization in GNSS Denied and Indoor Environments, 2020
- Masiero, A; Perakis, H; Gabela, J; Toth, C; Gikas, V; Retscher, G; Goel, S; Kealy, A; Koppányi, Z; Błaszczak-Bak, W; INDOOR NAVIGATION AND MAPPING: PERFORMANCE ANALYSIS OF UWB-BASED PLATFORM POSITIONING, The International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences, 43, 449-555, 2020
- Retscher G. (2020): Fundamental Concepts and Evolution of Wi-Fi User Localization: An Overview Based on Different Case Studies. Sensors, 2020:20; 36 pgs.

Conference Publications

- Bai, Yuntian Brian; Kealy, Allison; Retscher, Guenther; Hoden, Lucas; A Comparative Evaluation of Wi-Fi RTT and GPS Based Positioning, Proceedings of the International Global Navigation Satellite Systems IGNSS 2020 Conference, Sydney, Australia, 5-Jul, 2020
- Gabela, Jelena; Majic, Ivan; Kealy, Allison; Hedley, Mark; Li, Shenghong; Robust Vehicle Localization and Integrity Monitoring Based on Spatial Feature Constrained PF, IEEE/ION Position, Location and Navigation Symposium (PLANS), 661-669, 2020
- Goel S., J. Gabela, G. Retscher, C. K. Toth, A. Masiero, A. Kealy (2020): UWB Cooperative Localization of Pedestrians along a Constrained Building Hallway. in: Papers presented at the International Global Navigation Satellite Systems (IGNSS) 2020 Conference, February 5-7, 2020, Sydney, Australia.
- Retscher G., Y. Li, A. Kealy, V. Gikas (2020): The Need and Challenges for Ubiquitous Positioning, Navigation and Timing (PNT) Using Wi-Fi. FIG Working Week 2020, Amsterdam, The Netherlands; 10.05.2020 - 14.05.2020; paper-No. 10335, 18 pgs.
- Cheng W., Y. Dai, N. El-Sheimy, C. Wen, G. Retscher, Z. Kang, A. Lingua (2020): ISPRS Benchmark on Multisensory Indoor Mapping and Positioning. ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences, Nice, France, pp. 117 - 123.
- Retscher G., V. Gikas, R. Gerike (2021): Curricula Enrichment for Sri Lankan Universities Delivered through the Application of Location Based Services to Intelligent Transport Systems FIG eWorking Week 2021, paper-No. 10865, 16 pgs.

WG 4.1.2: Autonomous Navigation for Unmanned Systems

Chair: Ling Pei (China)
Vice Chair: Giorgio Guglieri (Italy)

Members:

- You Li, University of Calgary, Canada
- Laura Ruotsalainen, University of Helsinki, Finland
- Margarida Coelho, University of Aveiro, Portugal
- Marko Ševrović, University of Zagreb, Croatia

Activities and publications during the period 2019 - 2023

The main activities carried out by WG 4.1.2 during the period were:

- Actively collecting data in various data campaigns, commit research visits and publishing joint papers. The plan is to establish a ResearchGate portal for disseminating and sharing the outputs widely for the whole WG, SC and wider public.
- Organisation of the Shanghai Space Information Conference – Satellite Navigation Forum
- Research visit of Prof El-Sheimy
- Research activities on PPP based Multi-Sensor Fusion Localization in challenging environments
- S-Cube

The Shanghai Space Information Conference - Satellite Navigation Forum (aka Shanghai Navi Forum since 2005) was held at the Lingang Center in China (Shanghai) on April 15, 2023. The forum, under the principle of serving the national strategy based in Shanghai and themed with "Empowerment through Time and Space, Convergence through Smart Solutions", aims to explore the trends and future blueprint of the digital industry, to seek out space information industry scenarios and solutions, and to open up a new pattern for the integrated development of the spatial information industry. Attendees included Yang Changfeng, academician of the Chinese Academy of Engineering and chief designer of the China BeiDou system, Gong Jianya, Wang Jianyu, and Wu Yirong, academicians of the Chinese Academy of Sciences, Gong Huixing, Luo Xiwen, and Zhang Ping, academicians of the Chinese Academy of Engineering, Zhao Wenbo, chief engineer of the National Remote Sensing Satellite Application, Cao Chong, chief scientist of the Chinese Satellite Navigation Location Association, as well as experts in the field of Beidou satellite navigation, officials from relevant municipal government agencies, and industry leaders.

Prof. Ling Pei hosted an academic talk session. Seven invited talks were included.

(1) **Key Technologies and Practices of Smart Agriculture**, Luo Xiwen (Academicians of the Chinese Academy of Engineering)
(2) **Design and Research Progress of Open Earth Space Engine**, Gong Jianya (Academicians of the Chinese Academy of Sciences)
(3) **Construction of National Major Science and Technology Infrastructure for Aerial Remote Sensing Systems**, Wu Yirong (Academicians of the Chinese Academy of Sciences)
(4) **Research on the International Development Trends of Positioning, Navigation, and Timing (PNT) and Industry**, Cao Chong, (Chief scientist of the Chinese Satellite Navigation Location Association)

(5) **From Satellite Navigation to PNT with Space-Ground Cooperation**, Bofeng Li (Tongji University)
(6) **Key Technologies and Future Development for Improving the Service Performance of Beidou**, Junping Chen, (Shanghai Astronomical Observatory, Chinese Academy of Sciences.)
(7) **User-Side Open-Source Hardware Platform and Practice in PNT System**, Ling Pei (Shanghai Jiao Tong University)

You Li has co-organized a session of Autonomous driving perception, motion planning, and control for the conference 2023 IEEE/RSJ International Conference on Intelligent Robots (IROS 2023), together with Xin Xia, University of California at Los Angeles, USA, Wei Liu, Purdue University, USA, Peng Huang, Tongji University, China, and Dongmei Wu, Wuhan University of Technology, China. The IROS 2023 conference will be held on Oct 1-5, 2023, Detroit, Michigan, USA.

The objective of this session is to compile the recent R&D efforts related to autonomous driving, including

(1) Autonomous driving perception (object detection, semantic segmentation, object tracking, motion forecasting),
(2) Multi-sensor-based vehicle state estimation,
(3) Data-driven/model-based planning for autonomous driving,
(4) Echo-driving and safety control of autonomous driving,
(5) Simulation and testing for autonomous driving.

Publications

Journal Publications

- Y. Li et al., "Toward Location-Enabled IoT (LE-IoT): IoT Positioning Techniques, Error Sources, and Error Mitigation," in IEEE Internet of Things Journal, doi: 10.1109/JIOT.2020.3019199.

- Multi-sensor integrated navigation/positioning systems using data fusion: From analytics-based to learning-based approaches, Yuan Zhuang, Xiao Sun, You Li*, Jianzhu Huai, Luchi Hua, Xiansheng Yang, Xiaoxiang Cao, Peng Zhang, Yue Cao, Longning Qi, Jun Yang, Nashwa El-Bendary, Naser El-Sheimy, John Thompson, Ruizhi Chen. Published in Information Fusion vol. 95, no. 3, 2023.

This article describes a thorough investigation into multi-sensor data fusion, which over the last ten years has been used for integrated positioning/navigation systems. Different navigation/positioning systems are classified and elaborated upon from three aspects: (1) sources, (2) algorithms and architectures, and (3) scenarios, which we further divide into two categories: (i) analytics-based fusion and (ii) learning-based fusion. For analytics-based fusion, we discuss the Kalman filter and its variants, graph optimization methods, and integrated schemes. For learning-based fusion, several supervised, unsupervised, reinforcement learning, and deep learning techniques are illustrated in multisensory integrated positioning/navigation systems. Design consideration of these integrated systems is discussed in detail from several aspects and their application scenarios are categorized. Finally, future directions for their research and implementation are discussed.

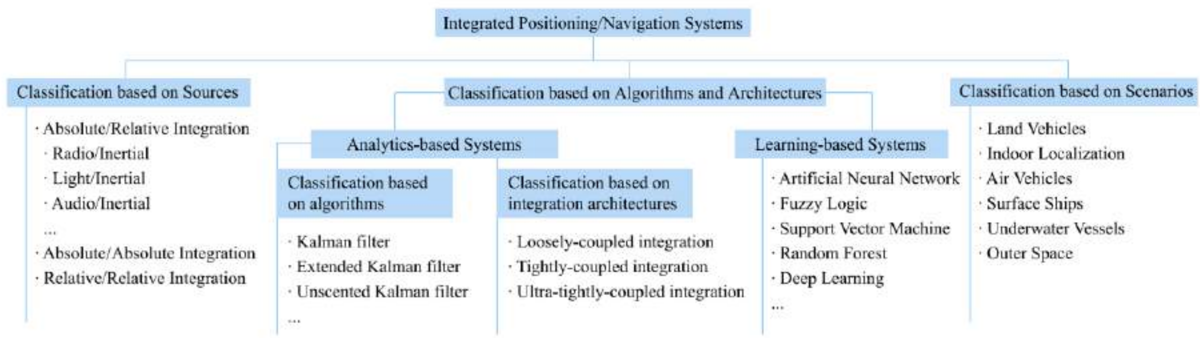

Fig. 1. Investigation of integrated positioning/navigation systems.

- Peng Zhang, You Li*, Yuan Zhuang, Jian Kuang, Xiaoji Niu, Ruizhi Chen, "Multi-level Information Fusion with Motion Constraints: Key to Achieve High-Precision Gait Analysis Using Low-Cost Inertial Sensors", Information Fusion, vol. 89, no. 5, pp. 603-618, Jan, 2023.

This paper achieves an improved gait-analysis system that provides stride-length and foot-clearance accuracy of 1.5 cm and 1.0 cm, respectively. Such accuracy is state-of-the-art for low-cost inertial systems and is even competitive with those from visual-sensor-based gait-analysis systems. A key to the proposed method is a new multi-level information fusion architecture and the extraction of human-walking constraints. The information-fusion architecture involves data fusion from the sensor, single-foot, and dual-foot levels. Two gait-characteristic-based motion constraints are presented to achieve such fusion, including the toe-heel constant distance constraint and the dual-foot flexible distance constraint. To implement these constraints, a constrained Kalman filter is constructed. The corresponding hardware system has been designed using multiple dollar-level inertial measurement units.

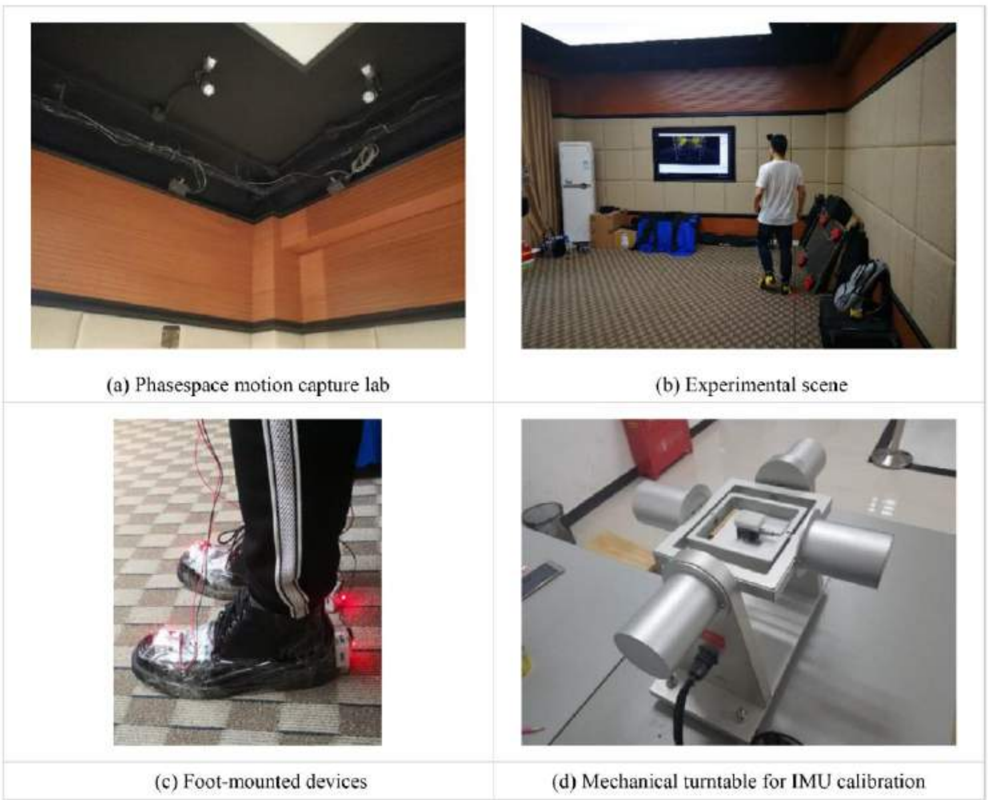

Fig 2. Test environment and devices for multi-level constrained navigation

Research activities on PPP based Multi-Sensor Fusion Localization in Challenging environments. This research was carried out by Ling Pei, Tao Li, Tong Hua, Wenxian Yu of Shanghai Jiao Tong University, Shanghai, China

Motivation

The coupling of PPP (Precise Point Positioning) will enable the SLAM (Simultaneous Localization and Mapping) system to provide more robust localization and mapping results in large-scale scenarios without an extra reference station. In turn, GNSS (Global Navigation Satellite System) is heavily influenced by multipath and NLOS in urban canyon environment, resulting in poor performance. SLAM always performs well in urban canyon environment and gets a relative positioning result. So, it is meaningful to fuse PPP and SLAM: SLAM can speed up the initialization procedure and improve the availability of PPP. On the other hand, PPP can provide the positioning result of SLAM in a local coordinate system to the global one. Recent years, we have investigated diverse extended Kalman Filter (EKF) based or optimization based fusion frameworks to integrate GNSS/PPP, camera, IMU (inertial measurement unit), LiDAR (Light Detection and Ranging), or wheel odometry according to specific applications.

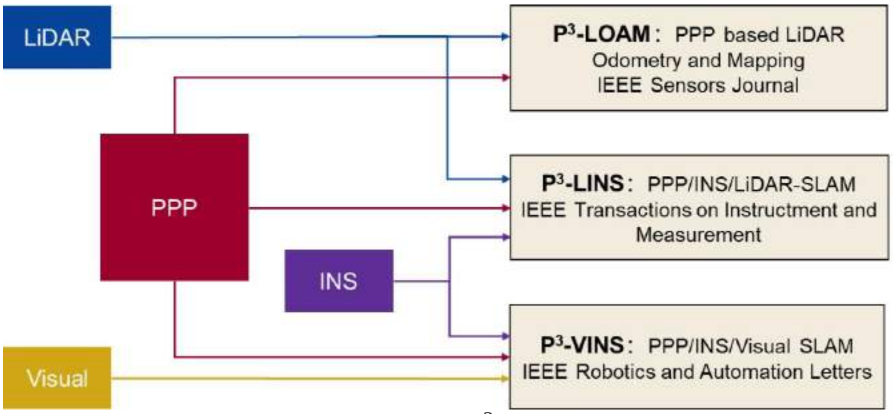

Fig. 3. Structure of P^3-SLAM series.

Contribution

P^3-LOAM: PPP based LiDAR Odometry and Mapping. LiDAR-SLAM has drawn increasing interests in autonomous driving. However, LiDAR-SLAM suffers from accumulating errors which can be significantly mitigated by GNSS. PPP as an accurate GNSS operation mode independent of base stations, gains growing popularity in unmanned systems. Considering the features of the two technologies, LiDAR-SLAM and PPP, this paper proposes a SLAM system, namely P^3-LOAM which couples LiDAR-SLAM and PPP. For better integration, we derive LiDAR-SLAM positioning covariance by using Singular Value Decomposition (SVD) Jacobian model, since SVD provides an explicit analytic solution of Iterative Closest Point (ICP), which is a key issue in LiDAR-SLAM. A novel method is then proposed to evaluate the estimated LiDAR-SLAM covariance. In addition, to increase the reliability of GNSS in urban canyon environment, we develop a LiDAR-SLAM assisted GNSS Receiver Autonomous Integrity Monitoring (RAIM) algorithm.

P^3-LINS, a navigation system tightly coupling PPP/ INS/ LiDAR with the DRANSAC- RAIM and the doppler iterative closet point algorithm (DICP) as its initialization procedure is established for accurate and reliable positioning in urban environments. The position initialization of P^3-LINS is completed by the static PPP with the DRANSAC-RAIM algorithm. The yaw is initialized through the proposed DICP algorithm which relies on the quadratic constraint least-squares problem built by Doppler speed, LiDAR-SLAM poses, and GNSS positions. After dealing with the initialization issue, the fusion framework of P^3-LINS is constructed to handle the heterogeneous sensor data spatial–temporal consistency problem with the three-phase extended Kalman Filter (EKF)-based estimator.

P^3-VINS, we propose a tightly-coupled PPP/INS/Visual SLAM system. It fuses GNSS raw measurements (pseudorange, carrier phase, and Doppler) with visual and inertial information for accurate and robust state estimation. All raw data is modelled and optimized under a factor graph framework. To eliminate ionospheric effects and utilize carrier phase measurements, P^3-VINS uses the ionosphere-free (IF) model by dual-frequency observations and adds phase ambiguity into the estimated states.

In addition, Invariant Extended Kalman Filter (IEKF) has been successfully applied in Visual-inertial Odometry (VIO) as an advanced achievement of Kalman filter, showing great potential in sensor fusion. we propose partial IEKF (PIEKF), which only incorporates rotation-velocity state into the Lie group structure and apply it for Visual-Inertial-Wheel Odometry (VIWO) to improve positioning accuracy and consistency. Specifically, we derive the rotation-velocity measurement model, which combines wheel measurements with kinematic constraints. The model circumvents the wheel odometer's 3D integration and covariance propagation, which is essential for filter consistency. And a plane constraint is also introduced to enhance the position accuracy. A dynamic outlier detection method is adopted, leveraging the velocity state output.

S-cube

The team led by Prof. Ling Pei from Shanghai Jiao Tong University has developed an electronic system called S-Cube, which combines RTK capabilities, industrial cameras, high-precision inertial sensors, and multi-beam lidar as in Figure 2. The system is well suitable for academic research, particularly for the development and testing of SLAM algorithms. All sensors on the device are synchronized with a self-developed hardware platform, resulting in millisecond-level time differences between each sensor. Furthermore, the device can also plug in different other sensors, like panoramic camera. To benefiti the multi-sensors navigation community, the code and hardware design will be open-sourced at: https://github.com/DreamWaterFound/S-Cube.git.

Figure 4 S-Cube: Plug-and-Play All-source Navigation Platform

Research Projects and Data Sets

- SJTU and Politecnico di Torino applied together to a grant MAECI-MOST for navigation in smart city scenarios.
- SJTU and NetEase Ltd. released an open dataset "NEAR: The NetEase AR Oriented Visual Inertial Dataset"in 2019 IEEE International Symposium on Mixed and Augmented Reality Adjunct (ISMAR-Adjunct). The full dataset with calibration parameters and ground truth is publicly available via https://github.com/EZXR-Research/ NEAR-VI-Dataset.
- SJTU added semantic saliency information to the Euroc dataset to generate an open-source saliency SLAM dataset. More details could be found from a preprint on aXiv "Attention-SLAM: A Visual Monocular SLAM Learning from Human Gaze".

Research Visits

- Giorgio Guglieri, Fabio Dovis, Politecnico di Torino, Italy hosted by Ling Pei, Shanghai Jiao Tong University, China
- Prof. Elisa Capello Politecnico di Torino, Italy came to SJTU to teach the 1 week course "Flight control system design for multirotor UAVs".
- Two master students from Politecnico di Torino, Italy came to complete their master thesis at SJTU Shanghai, hosted by assistant professor Daniele Sartori.
- Dr. Gabriele Ermacora graduated from Politecnico di Torino, Italy is working as post-doctor offered by Prof. Ling Pei
- SJTU and Politecnico di Torino officially signed a memorandum of understanding for cooperation between the department of mechanical and aerospace engineering of Politecnico and the lab.
- May 28 to June 2, You Li has invited Prof. Naser El-Sheimy to visit and give a presentation of "25-Years of Inertial Navigation at University of Calgary: State of the Art and Future Trends". Dr. Naser El-Sheimy is Professor and former Head of the Department of Geomatics Engineering, the University of Calgary. He holds a Tier-I Canada Research Chair (CRC) in Geomatics Multi-sensor Systems. His research expertise includes Geomatics multi-sensor systems, GPS/INS integration, and mobile mapping systems. He is the founder and president of Micro Engineering Tech Inc (METI) and Profound Positioning Inc. (PPI).

Cooperation with other Organizations

- SJTU has utilized the dataset from WG 4.1.5 Positioning and Navigation in Asian Urban Canyons. A paper based on the dataset has been submit to IEEE Sensors Journal
- Planned: Cooperation with other IAG SC 4.1 WGs in Commission 4.1 Symposium via Internet.

WG 4.1.3: 3D Point Cloud based Spatio-temporal Monitoring

Chair: Jens-Andre Paffenholz (Germany)
Vice Chair: Corinna Harmening (Austria)

Activities and publications during the period 2019-2023

The WG has set-up a project corresponding to the WG at the social networking site ResearchGate (www.researchgate.net) and is intensifying its use for exchange as well as preparing actively for FIG WW2020.

Meetings and Conferences

- Joint session of FIG Commission 6 and IAG WG 4.1.3., Working Week in Amsterdam in May 2020
  - five talks plus a talk dealing with the topics "point cloud-based monitoring in engineering surveying"
  - all papers are available via the FIG website.
- Preparing for FIG WW2020, planned to be held in 2021 in Utrecht

Publications

Journal Publications

- Joint journal paper under preparation
- Submitted a paper (2020) for a conference in Austria about "Spatio-temporal monitoring of soil erosion by means of 3D point clouds", joined work with a colleague form the Institute of Physical Geography and Landscape Ecology, Leibniz University Hannover.

Conference Publications

- Paffenholz and Harmening (2021), paper submitted for the FIG

Cooperation with other Organizations

- ResearchGate portal used for collaboration among other WGs, SC, and wider IAG community
- Trying to find ways to get more in touch with the other WGs at least the chairs about general aspects of the WGs and the Commission.

WG 4.1.4: Computer Vision in Navigation

Chair: Andrea Masiero (Italy)
Vice Chair: Kai-Wei Chiang (Taiwan)

Activities and publications during the period 2019-2023

The Working Group 4.1.4 has actively been collecting data, sharing data with all WG members and using that for joint research resulting in publications. The WG has also been actively participating and collaborating in different meetings. Investigation on the integration of RGB camera information, LiDAR measurements with radio-based positioning, such as UWB. Such investigation has been conducted considering sensors both on ground platforms and on Unmanned Aerial Vehicles, in particular dealing with the collaborative positioning case. In the collaboration with JRC, a specific case has been considered: collecting vision-based information in order to track ground vehicles from UAV data, aiming at providing a dataset on the human driving behavior.

Meetings and Conferences

The WG presented the goals and actions of the group in the following events:

- ISPRS World Congress, Nice, France, in June 2021
- IAG Assembly, June-July 2021, online
- IPIN 2021, Barcelona, Spain, in October 2021
- MMT International Symposium in Padua, Italy, in May 2022
- ISPRS World Congress, Nice, France, in June 2022
- IAG Commission 4 "Positioning and Applications Symposium" in Postdam, Germany, in September 2022
- Gi4DM Urban Geo-Informatics, Beijing, China, in November 2022
- Mobile Mapping Technology (MMT), Padua, Italy, in May 2023
- ION PLANS 2023

Cooperation with other Organizations

- JRC and other stakeholders in activities related to the SARA project (September-October 2020).
- Cooperation with ISPRS WG I/2, "Mobile Mapping Technology"

Research Visits

- Charles Toth, The Ohio State University, USA, Paolo Dabove and Vincenzo Di Pietra, Polytechnic of Turin, Italy hosted by Andrea Masiero, University of Florence, Italy, May 2023
- Charles Toth, The Ohio State University, USA hosted by Andrea Masiero, University of Florence, Italy, November 2022
- Andrea Masiero, University of Florence, Italy hosted by Charles Toth, The Ohio State University, USA, May 2022
- Paolo Dabove and Vincenzo Di Pietra, Polytechnic of Turin, Italy hosted by Andrea Masiero, University of Padua, Italy
- Paolo Dabove and Vincenzo Di Pietra, Polytechnic of Turin, Italy hosted by Andrea Masiero, University of Padua, Italy

Data Collections

- Columbus, USA, May 8-18, 2022: pedestrian, bicyclists, ground vehicles and UAV collaborative positioning
- Padua, Italy, March 25-25, 2022: pedestrian and UAV collaborative positioning
- Padua, Italy, October 19-21, 2020: pedestrian and UAV collaborative positioning
- Ispra, Italy, September 29-30, 2020: ground vehicle tracking, collaboration with JRC

Publications

Journal Publications

- Masiero, A.; Toth, C.; Gabela, J.; Retscher, G.; Kealy, A.; Perakis, H.; Gikas, V.; Grejner-Brzezinska, D. Experimental Assessment of UWB and Vision-Based Car Cooperative Positioning System. Remote Sens. 2021, 13, 4858

Conference Publications

- M. Gurturk, A. Masiero, C. Toth, P. Dabove, V. Di Pietra, A. Vettore, A. Guarnieri, F. Mugnai, M. Soycan (2023). DATASET FOR POSITIONING AND TRACKING CARS AND PEDESTRIANS FROM UAV IMAGERY AND STATIC LIDAR, Int. Arch. Photogramm. Remote Sens. Spatial Inf. Sci., XLVIII-1/W1-2023, 161–165
- Masiero, Andrea, Toth, Charles, Remondino, Fabio, "Vision and UWB-Based Collaborative Positioning Between Ground and UAS Platforms," 2023 IEEE/ION Position, Location and Navigation Symposium (PLANS), Monterey, CA, April 2023, pp. 748-754
- Masiero, A., Dabove, P., Di Pietra, V., Piragnolo, M., Vettore, A., Guarnieri, A., Toth, C., Gikas, V., Perakis, H., Chiang, K.-W., Ruotsalainen, L. M., Goel, S., and Gabela, J. (2022): A COMPARISON BETWEEN UWB AND LASER-BASED PEDESTRIAN TRACKING, Int. Arch. Photogramm. Remote Sens. Spatial Inf. Sci., XLIII-B2-2022, 839–844
- Mugnai, F., Masiero, A., and Ciuffo, B. (2022): ON THE ESTIMATION OF VEHICLE TRAJECTORIES WITH A MINI-UAS, ISPRS Ann. Photogramm. Remote Sens. Spatial Inf. Sci., X-3/W2-2022, 23–28
- Jelena Gabela, Guenther Retscher, Andrea Masiero, and Charles Toth (2022). Seamless Indoor-Outdoor Transitioning of Pedestrian Platforms, IAG 2nd International Symposium of Commission 4
- Masiero et al. "A CASE STUDY OF PEDESTRIAN POSITIONING WITH UWB AND UAV CAMERAS", ISPRS Archives, 2021
- "Towards collaborative positioning of pedestrian and UAS platforms by integrating vision, UWB, and IMU data", IAG Assembly, 2021
- Masiero, A., Perakis, H., Gabela, J., Toth, C., Gikas, V., Retscher, G., ... Li, Y. (2020). Indoor Navigation and Mapping: Performance Analysis of Uwb-Based Platform Positioning. The International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences, 43, 549-555.

WG 4.1.5: Localization at Asian urban canyons

Chair: Li-Ta Hsu (Hong Kong)
Vice Chair: Kubo Nobuaki (Japan)

Activities and publications during the period 2019-2023

The Working Group 4.1.5 has actively been collecting data, sharing data with all WG members and using that for joint research resulting in publications. WG builds an integrated dataset collected in diverse challenging urban scenarios in Hong Kong and Tokyo, that provides full-suit sensor data, which includes GNSS, INS, LiDAR and cameras. The open-source data, UrbanNav collection campaign is in two-stages. Stage one: Pilot Dataset collected by Tokyo and Hong Kong The pilot data collected by both teams are online available through the link https://www.polyu-ipn-lab.com/urbannav. The GitHub page is also maintained to allow the user to ask questions on the use of the open-source data. Several conference and journal papers are published using this pilot dataset. ION is working with the WG to invite papers that used the open-source data to submit to ION Pacific PNT 2021. Stage two: Pilot Dataset collected by Tokyo and Hong Kong. The Hong Kong team is preparing a complete sensor-kit (See the figure below.). The new setup will include, Smartphone, commercial Geodetic level GNSS receivers, two 16 channel LiDARs and one 32 channel LiDAR and one stereo camera with a baseline of 30 cm. 5 new routes are designed to include various urban environments in Hong Kong.

Members

- Taro Suzuki, Chiba Institute of Technology, Japan
- Junichi Meguro, Meijo University, Japan
- Wu Chen, PolyU, Hong Kong
- Zhizhao Liu, PolyU, Hong Kong

Grants

1. *Internal Grant from Smart Cities Research Institute, PolyU:*

Project Title: Urban Positioning Infrastructure for Autonomous Vehicles
Project Investigator: Prof Wu CHEN, PolyU

Co-Investigators: Dr Li-Ta HSU, PolyU, Dr Wei YAO, PolyU, Dr Bin XIAO, PolyU , Dr Yiping, JIANG, PolyU, Dr Wang Hei HO, PolyU, Prof. Xiaoli DING, PolyU, Prof. Ruizhi CHEN, Wuhan University
Funding nature: Research Grant (Competitive)
Period: 30 Apr 2021 - 29 Apr 2023
Amount: HK$ 1,000,000
Aims:
1) Establish a testbed for autonomous vehicle navigation system;
2) Develop an open architecture for multi-sensor vehicle navigation system;
3) Investigate algorithms for the integration of vehicle sensors and road infrastructures.

2. External Grant from Germany/Hong Kong Joint Research Scheme (RGC/DAAD)

Project Title: Collaborative Navigation for Smart Cities
Project Investigators: Dr Li-Ta Hsu, PolyU (Hong Kong Side), Prof. Schön Steffen, Leibniz, Universität Hannover (Germany Side)
Funding nature: Travelling Grant (Competitive)
Period: 1 Jan 2021 - 31 Dec 2022
Amount: HK$ 57,200 (Hong Kong Side) EU€ 10, 616 (Germany Side)
PhD Students participated: Mr Guohao, Zhang, PolyU (Hong Kong), Ms Lucy Icking, Leibniz Universität Hannover (Germany)
Aims:
In recent years, the possibility for communication from vehicle-to-participants (V2X) has enabled exchanging information between traffic participants as well as elements of the environment. In this context, collaborative positioning has become a widely noticed topic and shows great potential for improved accuracy and integrity for navigation in urban areas. Global Navigation Satellite Systems (GNSS) is the only navigation sensor that provides absolute positioning. However, urban areas form the most challenging environment for GNSS to achieve a reliable position. Because of the reduced satellite visibility and signal disturbances like diffraction and multipath, the resulting position has a reduced accuracy and availability. Multipath is the error arising by an incoming reflected signal, making it hard to determine the actual signal path length. The overall research objective of this project is to reduce these shortcomings through collaboration.
1) Develop strategies for improved GNSS based navigation using 3D building models.
2) Investigate collaboration between nodes to share GNSS observations information.
3) Evaluate similarities and differences in challenges and solutions for GNSS based positioning in the urban areas Hong Kong and Hannover.

Publications

Journal Publications

- Qian Meng, Li-Ta Hsu (2020) A New Kalman Filter based Solution Separation for Integrity Monitoring of Multi-Sensor Integrated Navigation System, IEEE Sensors Journals, (online available)
- Xiwei Bai, Wen Weisong, Li-Ta Hsu (2020) Robust Visual-Inertial Integrated Navigation System Aided by Online Sensor Model Adaption for Autonomous Ground Vehicles in Urban Areas, Remote Sensing, vol. 12, pp. 1686-1701.
- Wen Weisong, Xiwei Bai, Zhang, Guohao, Shengdong Chen, Feng Yuan, Li-Ta Hsu (2020) Multi-Agent Collaborative GNSS/Camera/INS Integration Aided by Inter-ranging for Vehicular Navigation in Urban Areas, IEEE Access, vol. 8, pp. 124323-124338
- Yue J., Wen W., Han J., Hsu L.T. (2021) 3D Point Clouds Data Super Resolution Aided LiDAR

Odometry for Vehicular Positioning in Urban Canyons, IEEE Transactions on Vehicular Technology,(Accepted)
- Luo H., Li Y. , Wang J., Weng D., Ye J., Hsu L-T, Chen W. (2021) Integration of GNSS and BLE Technology With Inertial Sensors for Real-Time Positioning in Urban Environments, IEEE Access, 9:15744.
- Wen W., Pfeifer T., Bai X., Hsu L.T., (2021) Factor Graph Optimization for GNSS/INS Integration: A Comparison with the Extended Kalman Filter, Navigation, Journal of Institute of Navigation (Accepted).

Conference Publications

- Bing Xu, Li-Ta Hsu, Taro Suzuki Intermediate Frequency Level GPS Multipath/NLOS Simulator based on Vector Tracking and Ray Tracing, ION ITM 2020, San Diego, California, USA.
- Weisong Wen, Tim Pfeifer, Xiwei Bai and Li-Ta Hsu, GNSS/LiDAR Integration Aided by Self-adaptive Gaussian Mixture Model in Urban Scenarios: An Approach Robust to Non-Gaussian Noise, IEEE/ION PLANS 2020, Portland, Oregon, USA.
- Xiwei Bai, Weisong Wen, Li-Ta Hsu and Huiyun Li, Perception-aided Visual/Inertial Integrated Positioning in Highly Dynamic Urban Areas, IEEE/ION PLANS 2020, Portland, Oregon, USA
- Weisong Wen, Yiyang Zhou, Guohao Zhang, Saman Fahandezh-Saadi, Xiwei Bai, Wei Zhan, Masayoshi Tomizuka, and Li-Ta Hsu, UrbanLoco: A Full Sensor Suite Dataset for Mapping and Localization in Urban Scenes, ICRA 2020, Paris, France.
- Li-Ta Hsu, Nobuaki Kubo, Wu Chen, Zhizhao Liu, Taro Suzuki and Junichi Meguro, "UrbanNav: An Open-Sourced Multisensory Dataset for Benchmarking Positioning Algorithms Designed for Urban Areas," ION GNSS+ 2021 (Virtually) on Sept 2021.

Research Visits

- Taro Suzuki, Chiba Institute of Technology, Japan, hosted by Li-Ta Hsu, PolyU, Hong Kong (2020)
- Li-Ta Hsu, PolyU, Hong Kong, hosted by Nobuaki Kubo, Tokyo University of Marine Science &Technology, Japan (2020)
- Tim Pfeifer, Chemnitz University of Technology, Germany, hosted by Li-Ta Hsu, PolyU, Hong Kong (2020)

Meetings and Conferences

- ION Pacific PNT 2019, Oral Presentation, Honolulu, Hawaii
- ION GNSS+ 2019, Oral Presentation, Miami, Florida
- International Workshop on Autonomous Guidance 2020, Navigation and Control of Unmanned System, Nanjing, China (Virtual Talk)
- Dr Li-Ta Hsu gives talk on the topic "3D LiDAR Aided GNSS and Its Tightly Coupled Integration with INS Via Factor Graph Optimization," at Aerospace Information Research Institute, Chinese Academy of Sciences (virtually) on 9 April 2021
- Dr Li-Ta Hsu gives talk on the topic "3D LiDAR Aided GNSS and Its Tightly Coupled Integration with INS Via Factor Graph Optimization," at Research Theme Group on Integrity and Collaboration in Dynamic Sensor Networks (i.c.sens), Leibniz Universität Hannover (virtually) on 21 May 2021

Cooperation with other Organizations

The group has established links between the following stakeholder for improved dissemination of the action deliverables and input of different user needs for the work:

- ION in the Council meetings in 2019 and 2020.
- The session "Challenging Navigation Problems" on ION Pacific PNT is inviting papers that used the open-source dataset, UrbanNav, to develop their algorithm

SSG 4.1.1: Positioning using smartphones

Chair: Guenther Retscher (Austria)
Vice Chair: Ruizhi Chen (China)

Activities and publications during the period 2019-2023

The SSG4.1.1 has committed the following actions during the reporting period.

- Continuation of investigation of the application of Wi-Fi for indoor and urban positioning using smartphones
- Development of an library navigation and guidance system at TU Wien
- Analyses of urban positioning with smartphones along a public transport route in Vienna
- Analyses of the new Google Pixel 5 dual frequency GNSS smartphone in Vienna
- Investigation of Bluetooth RSSI measurements for covid-19 contact tracing with an international measurement campaign of TU Wien, Ghent University and KU Leuven: https://www.youtube.com/watch?v=x6y8W80qH8M

Meetings and Conferences

- Give a keynote speech in the 12th China Satellite Navigation Conference entitled "Precise Ubiquitous Positioning-Extending From Outdoor to Indoor", in May 26th, Nanchang, China.
- Pariticipating the Google "Smartphone Decimeter Challenge", and will present in ION GNSS+ 2021. https://www.ion.org/gnss/sessions.cfm?sessionID=1318

Publications

- Retscher G. (2020): Fundamental Concepts and Evolution of Wi-Fi User Localization: An Overview Based on Different Case Studies. Sensors, 2020:20; 36 pgs.
- Retscher G., A. Bekenova (2020): Urban Wi-Fi Fingerprinting Along a Public Transport Route. Journal of Applied Geodesy, 14:4, pp. 379 – 392.
- Retscher G., A. Leb (2021): Development of a Smartphone-based University Library Navigation and Information Service Employing Wi-Fi Location Fingerprinting. Sensors 2021: 21; 37 pgs.
- Retscher G., A. Leb (2021): Development of a Navigation and Information Service for a University Library. 2021 International Technical Meeting ION ITM, virtual; 25.01.2021 - 28.01.2021; paper-No. 19, 14 pgs.
- Y. Yu, R. Chen, L. Chena, W. Li, Y. Wu and H. Zhou, A Robust Seamless Localization Framework Based on Wi-Fi FTM / GNSS And Built-in Sensors, in IEEE Communications Letters, doi: 10.1109/LCOMM.2021.3071412.
- Y. Yu, R. Chen, L. Chen, W. Li, Y. Wu and H. Zhou, Autonomous 3D Indoor Localization Based on Crowdsourced Wi-Fi Fingerprinting And MEMS Sensors, in IEEE Sensors Journal, doi: 10.1109/JSEN.2021.3065951.
- Y. Yu et al., A Novel 3-D Indoor Localization Algorithm Based on BLE and Multiple Sensors, in IEEE Internet of Things Journal, vol. 8, no. 11, pp. 9359-9372, 1 June1, 2021, doi: 10.1109/JIOT.2021.3055794.
- Peng X, Chen R, Yu K, Ye F, Xue W. An Improved Weighted K-Nearest Neighbor Algorithm for Indoor Localization. Electronics. 2020; 9(12):2117. https://doi.org/10.3390/electronics9122117
- Z. Liu, R. Chen, F. Ye, G. Guo, Z. Li and L. Qian, Improved TOA Estimation Method for Acoustic Ranging in a Reverberant Environment, in IEEE Sensors Journal, doi:

10.1109/JSEN.2020.3036170.

- Z. Liu, R. Chen, F. Ye, G. Guo, Z. Li, L. Qian (2020). Time-of-arrival estimation for smartphones based on built-in microphone sensor, in Electronics Letters, Vol. 56, Issue 23, p. 1280-1283.
- Y. Yu et al., "Precise 3-D Indoor Localization Based on Wi-Fi FTM and Built-In Sensors," in IEEE Internet of Things Journal, vol. 7, no. 12, pp. 11753-11765, Dec. 2020, doi: 10.1109/JIOT.2020.2999626.
- Li, M.; Chen, R.; Liao, X.; Guo, B.; Zhang, W.; Guo, G. A Precise Indoor Visual Positioning Approach Using a Built Image Feature Database and Single User Image from Smartphone Cameras. Remote Sens. 2020, 12, 869. https://doi.org/10.3390/rs12050869
- G. Guo, R. Chen, F. Ye, X. Peng, Z. Liu and Y. Pan, "Indoor Smartphone Localization: A Hybrid WiFi RTT-RSS Ranging Approach," in IEEE Access, vol. 7, pp. 176767-176781, 2019, doi: 10.1109/ACCESS.2019.2957753.
- F. Ye, R. Chen, G. Guo, X. Peng, Z. Liu and L. Huang, "A Low-Cost Single-Anchor Solution for Indoor Positioning Using BLE and Inertial Sensor Data," in IEEE Access, vol. 7, pp. 162439-162453, 2019, doi: 10.1109/ACCESS.2019.2951281.
- S. Xu, R. Chen, Y. Yu, G. Guo and L. Huang, "Locating Smartphones Indoors Using Built-In Sensors and Wi-Fi Ranging With an Enhanced Particle Filter," in IEEE Access, vol. 7, pp. 95140-95153, 2019, doi: 10.1109/ACCESS.2019.292738

Sub-commission 4.2: Multi-Frequency Multi-Constellation GNSS

Chair: *Safoora Zaminpardaz (Australia)*
Vice Chair: *Sunil Bisnath (Canada)*

Overview

SC 4.2 is composed of four Working Groups. Besides, several of SC 4.2 members participate in other IAG Joint Study Groups and Working Groups related to GNSS PNT methods, integrity and control, e.g., WG 4.4.3: Reliability of Low-cost & Android GNSS in navigation and geosciences and SG 4.1.1 Positioning Using Smartphones.

SC4.2 coordinates activities to promote and deliver practical and theoretical solutions for engineering and scientific applications and also will stimulate strong collaboration with the IAG Services (IGS) and relevant scientific and professional sister organizations such as FIG, ION and IEEE.

In joint effort with SC 4.4, the SC 4.4. organized dedicated session at The Scientific Assembly of the International Association of Geodesy from June 28th to July 2nd, 2021, specifically session 4.3: Techniques and Applications in High Precision GNSS (http://www.iag2021.com/en/web/index/1646_)

Working Groups of Sub-Commission 4.2

WG 4.2.1: Interoperability of GNSS Precise Positioning (Joint WG between IAG and IGS)

Chair: Allison Kealy/Suelynn Choy TBA (Australia)
Vice Chair: Sharyl Byram (USA)

The objective of this WG is to promote interoperability of GNSS precise positioning to support a wide range of science and engineering applications, which will benefit society. Activities include: (1) encourage sharing and dissemination of knowledge of satellite parameters and receiver properties, which are essential for high precision GNSS applications; and (2) investigate new techniques and algorithms to ensure interoperability of correction products for precise point positioning (PPP).

This WG will work in close scientific collaboration with IGS, FIG and ICG.

Activities and publications during the period 2019-2023

ICG WG-D

In 2019, the WG 4.2.1 was formed in collaboration with the IAG, IGS and FIG as results of the work of WG-D within the United Nations International Committee on GNSS (UN ICG). Meetings took place in June and December 2019 together with members of the ICG and GNSS/RNSS System Providers to discuss opportunities and challenges of interoperability of GNSS precise point positioning (PPP) services.

In June 2019, a special technical session on GNSS PPP services was organized at the UN ICG Workshop on the Applications of GNSS, Suva Fiji, 24-28 June 2019. The aim of the workshop was to share ideas and promote the use and interoperability of GNSS PPP services. The link to the presentations of the workshop on the applications of GNSS is here: https://www.unoosa.org/oosa/en/ourwork/psa/schedule/2019/2019-workshop-on-global-navigation-satellite-systems_-presentations.html

Subsequently in December 2019, WG 4.2.1 met at ICG-14 in Bangalore, India, to progress the discussion of interoperability of GNSS PPP services. Based on the outcome of the workshop, a recommendation to establish a Task Force on PPP interoperability was adopted by the ICG. The Task Force will be co-chaired by Australia, the EU and Japan, and will prepare a workshop in 2020 to continue the discussion and address the issues raised at the 2019 workshop. The IGS, FIG and IAG are members of the Task Force. For more information about ICG-14, refer to: https://www.unoosa.org/oosa/en/ourwork/icg/meetings/ICG-2019.html

In February 2020, the International Global Navigation Satellite Systems (IGNSS) Conference hosted presentation sessions and specifically a panel discussion on the “Future of GNSS Precise Point Positioning”, in which interoperability of the GNSS PPP services were discussed. The panel was represented by members from government, industry and academia.

Selected publications during the period 2019-2023:

- R. Hirokawa and I. Fernandez-Hernandez, "Open Format Specifications for PPP/PPP-RTK Services: Overview and Interoperability Assessment," Proceedings of the 33rd International Technical Meeting of the Satellite Division of the Institute of Navigation (ION GNSS+ 2020), pp. 1268-1290, 2020.
- R. Hirokawa, "Recent Activity of International Standardization for High-Accuracy GNSS Correction Service," Coordinates, vol. 15, no. 11, pp. 10-17, November 2019.

WG 4.2.2: Ambiguity resolution for low-cost GNSS positioning

Chair:	Prof. Xiaohong Zhang (China)
Vice-Chair:	Dr Robert Odolinski (New Zealand)

Members
- Yang Gao, Calgary University (Canada)- TBD
- Wu Cheng, the Hong Kong Polytechnic University (China)
- Amir Khodabandeh, Melbourne University (Australia)
- Dinesh Manandhar, The University of Tokyo (Japan)
- Nacer Naciri, York University(Canada)
- Baocheng Zhang, Institute of Geodesy and Geophysics, CAS(China)

The research conducted by WG 4.2.2 will focus on algorithms and methods for integer ambiguity resolution on low-cost handheld devices, to facilitate optimal modelling of precise positions and atmospheric delays (ionosphere and troposphere), to investigate the quality control methods for low-cost GNSS precise positioning, to develop a robust algorithms of integration GNSS with MEMS and other low-cost sensors.

Activities and publications during the period 2019-2023 relevant to the above objectives

(1) Frequency Division Multiple Access (FDMA) ambiguity resolution applied to short and long baseline GLONASS data

Teunissen and Khodabandeh (2019) and Hou et al. (2020) studied and applied the new GLONASS FDMA ambiguity resolution model, as developed by Teunissen (2019), for short- and long-baseline data. This FDMA model is also applicable to low-cost GNSS receivers able to track FDMA GLONASS signals, such as the ublox ZED-F9P receivers, as explicitly demonstrated in Teunissen and Khodabandeh (2019). Zaminpardaz et al. (2021) performed a Code Division Multiple Access (CDMA) and FDMA combination of GLONASS-only satellites for real-time kinematic (RTK) positioning, and analyzed its performance using the future GLONASS constellation.

(2) Best Integer Equivariant (BIE) estimation applied to low-cost multi-GNSS data, with comparison to the commonly used Integer Least Squares (ILS) estimator

Odolinski and Teunissen (2020a) analyzed the normal distribution-based BIE estimation for low-cost single-frequency (SF) multi-GNSS RTK positioning. Odolinski and Teunissen (2020b) analyzed subsequently also the corresponding BIE performance for low-cost dual-frequency (DF) long baseline multi-GNSS RTK positioning. It was shown that the BIE estimator outperforms ILS and the float solutions in terms of their positioning mean squared errors (MSEs).

(3) Single-station precise point positioning RTK (PPP-RTK) that can enable low-cost positioning infrastructures

Khodabandeh and Nadarajah (2020) studied a single-receiver constant-velocity setup with which a reference receiver can act like a PPP-RTK correction provider. Khodabandeh (2021) further demonstrated how the ambiguity resolution performance for single-station PPP-RTK is driven by the correction latency and therefore by the uncertainty involved in the time-prediction of single-station PPP-RTK corrections. Supported by numerical results, Khodabandeh (2021) showed that the number of satellites and number of frequencies work in tandem to enable one to increase the correction latency, yet ensuring successful single-receiver ambiguity resolution.

(4) Single-receiver stochastic modeling of multi-frequency GNSS observables

In alignment with the single-station concept above, Zhang et al. (2020) applied the least-squares variance component estimation (LS-VCE), as developed by Teunissen and Amiri-Simkooei (2008), to the geometry-free functional model. This so as to facilitate the stochastic properties of multi-frequency GNSS observables at the undifferenced level and a single-receiver.

(5) On the temperature sensitivity of multi-GNSS intra- and inter-system biases (ISBs).

Mi et al. (2020) analyzed the temporal variability of the intra- and inter-system biases (ISBs), including the receiver-dependent differential code and phase biases (DCBs and DPBs, respectively). RTK positioning evaluations were further conducted to assess the performance improvement one can gain by modeling this time-variability in comparison to the commonly used models of time-invariant receiver DCBs, DPBs and ISBs. This is particular important in the context of optimal RTK performance while using low-cost multi-GNSS receivers, where further studies can be conducted. The short-term variability of receiver code biases was further mitigated in Wang et al. (2019) to improve the ambiguity resolution performance for PPP.

(6) Low-cost GNSS receiver integration with MEMS Inertial Measurement Units (IMUs)

Vana et al. (2019) studied the MEMS IMU and low-cost GNSS receiver data integration for dual-frequency PPP. Such integration can be particular beneficial for unmanned aerial vehicles (UAVs), pedestrian navigation, and autonomous vehicles. Zhu et al (2019 fused dual-antenna GNSS and MEMS to acquire heading, pitch, and roll with high accuracy in GNSS challenged environments. Instead of a Euler angle representation, the misalignment is used to build the state model in the integrated Kalman filter. Attitudes derived from dual-antenna GNSS and smoothed acceleration are adopted as measurements. It can be found that this filtering architecture is actually a subset of loosely coupled GNSS/MEMS integration. Therefore, the proposed module can be easily embedded into loosely coupled integration. In addition, due to the disadvantage that GNSS is sensitive to signal interference and obstacles, the fault detection and exclusion strategy was proposed to avoid the filtering divergence and to improve the reliability of attitude determination. Zhu et al (2019) introduces a dedicated android smartphone application called Walker that integrates the GNSS navigation solution and MEMS (micro-electromechanical systems) sensors to enable continuous and precise pedestrian navigation. The kinematic experiment verifies that the proposed method is capable of obtaining accuracy within 1–3 m for smooth and continuous navigation.

(7) New progress of PPP/PPP-RTK

Zhang et al (2020) summarized a brief review of the current state of development of precise point positioning (PPP) in recent years, with a focus on summarizing the latest research progress of several hot spots such as real-time rapid estimation of high-rate satellite clocks, multi-GNSS PPP ambiguity resolution, multi-frequency GNSS PPP models and ambiguity resolution, rapid initialization of PPP and PPP-RTK. The evaluation of positioning performance of single/multi-GNSS PPP with latest observation of GPS, GLONASS, Galileo and BDS, especially the positioning accuracy, convergence time and time to first fix of BDS-2+3, is given.

(8) Integer-estimable FDMA model as an enabler of GLONASS PPP-RTK

Zhang et al (2021) studied the GLONASS PPP-RTK that takes advantage of the integer-estimable FDMA (IE-FDMA) model developed by Teunissen (2019) to guarantee rigorous integer ambiguity resolution and simultaneously takes care of the presence of the inter-frequency biases (IFBs) in homogeneous and heterogeneous network configurations. When conducting GLONASS PPP-RTK based on a network of homogeneous receivers, code and phase observation equations were used to construct the IE-FDMA model, in which the IFBs were implicitly eliminated through reparameterization. For a network consisting of heterogeneous receivers, the code observables were excluded and a phase-only IE-FDMA model was developed, thereby circumventing the adverse effects of IFBs. Supported by numerical results, Zhang et al (2021) succeeded in fixing both GPS and GLONASS ambiguities, shortening the convergence time to 0.5 (3) minutes, compared to 8 (9) minutes of ambiguity-float positioning in the case of a homogeneous (heterogeneous) network with a data sampling rate of 30 seconds. Compared with GPS-only positioning, the integration of GPS and GLONASS yielded an improvement of 8%-34% in accuracy and leaded to a reduction of 25%-50% in convergence.

(9) Instantaneous ambiguity resolution in some Android smartphones

Yong et al. (2021) studied the ambiguity resolution performance of Google Pixel4 and Samsung S20 smartphones. The instantaneous single-baseline RTK performance in Dunedin, New Zealand was analyzed. The effects of locating the smartphones in an upright and lying down position were evaluated, and they showed that the choice of smartphone configuration can affect the positioning performance even in a zero-baseline setup. They also found that the two assessed smartphones have different antenna gain pattern and antenna sensitivity to interferences. In this contribution, they demonstrated, for the first time, a near hundred percent (98.7% to 99.9%) instantaneous RTK integer least-squares success rate for one of the smartphone models and cm level positioning precision while using short-baseline experiments with internal and external antennas, respectively. Finally, for the first time, Yong et al. (2022) employed the best integer equivariant (BIE) estimator for a short-baseline RTK experiment using Google Pixel4 smartphones, and showed that BIE always gives a superior positioning performance than other commonly used estimators (integer least square and float counterparts) in the mean squared error (MSE) sense.

Special issues

- A Special Issue "Multi-GNSS Precise Positioning and Applications" in Sensors on the objectives of the WG 4.2.2 (ed. R. Odolinski and A. Khodabandeh).

Selected publications

- Hou, P., Zhang, B., Liu, T. (2020) Integer-estimable GLONASS FDMA model as applied to Kalman-filter-based short-to long-baseline RTK positioning. GPS Solutions 24 (4), 1-14
- Khodabandeh A. (2021). Single-station PPP-RTK: correction latency and ambiguity resolution performance. Journal of Geodesy, https://doi.org/10.1007/s00190-021-01490-z
- Khodabandeh A. & Nadarajah N. (2020). State-space Positioning Corrections via Single-receiver GNSS Data. ION GNSS+ 2020, pp. 2676–2685
- Mi, X., Zhang, B., Odolinski, R., & Yuan, Y. (2020). On the temperature sensitivity of multi-GNSS intra- and inter-system biases and the impact on RTK positioning. GPS Solutions, 24, 112. doi: 10.1007/s10291-020-01027-5
- Odolinski, R., & Teunissen, P. J. G. (2020a). On the best integer equivariant estimator for low-cost single-frequency multi-GNSS RTK positioning. Proceedings of the International Technical Meeting of the Institute of Navigation (ION). (pp. 499-508). Institute of Navigation. doi: 10.33012/2020.17158
- Odolinski, R., & Teunissen, P. J. G. (2020b). Best integer equivariant estimation: Performance

analysis using real data collected by low-cost, single- and dual- frequency, multi-GNSS receivers for short- to long-baseline RTK positioning. Journal of Geodesy, 94, 91. http://dx.doi.org/10.1007/s00190-020-01423-2

- Teunissen, P.J.G., Khodabandeh, A. (2019) GLONASS ambiguity resolution. GPS Solut 23, 101. https://doi.org/10.1007/s10291-019-0890-7
- Vana, S., Naciri, N., Bisnath, S. (2019) Low-cost, Dual-frequency PPP GNSS and MEMS-IMU Integration Performance in Obstructed Environments. Proceedings of the 32nd International Technical Meeting of the Satellite Division of The Institute of Navigation (ION GNSS+), Miami, Florida, September 2019, pp. 3005-3018.
- Wang, J, Huang, G, Yang, Y, Zhang, Q, Gao, Y, Zhou, P (2019). Mitigation of short-term temporal variations of receiver code bias to achieve increased success rate of ambiguity resolution in PPP, Remote Sensing, 12(5):796. doi:10.3390/rs12050796
- Zaminpardaz S, Teunissen PJG, & Khodabandeh A (2021), “GLONASS-Only FDMA+CDMA RTK: Performance and Outlook”, GPS Solutions, https://doi.org/10.1007/s10291-021-01132-z
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- Zhu, Feng, Hu, Zengke, Liu, Wanke, Xiaohong Zhang(2019). Dual-antenna GNSS integrated with MEMS for reliable and continuous attitude determination in challenged environments [J]. IEEE Sensors Journal, 19(9): 3449-3461.
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- Xiaohong Zhang, Xianlu Tao, Feng Zhu, Xiang Shi, Fuhong Wang (2018). Quality assessment of GNSS observations from an Android N smartphone and positioning performance analysis using time-differenced filtering approach[J]. GPS Solutions, 22:70
- Xianlu Tao, Xiaohong Zhang, Feng Zhu, Fuhong Wang, Weizheng Teng(2018). Precise Displacement Estimation from Time-differenced Carrier Phase to Improve PDR Performance[J]. IEEE Sensors Journal, 20(18):8238-8246.
- Zhang, Xiaohong, Hu, Jiahuan, Ren, Xiaodong(2020). New progress of PPP/PPP-RTK and positioning performance comparison of BDS/GNSS PPP[J]. Acta Geodaetica et Cartographica Sinica,49(9):1084-1100. DOI:10.11947/j. AGCS. 2020.20200328
- Zhang, Baocheng, Hou, Pengyu, Zha, Jiuping, Liu, Teng (2021). Integer-estimable FDMA model as an enabler of GLONASS PPP-RTK [J]. Journal of Geodesy.
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Meeting and communications during the period 2019-2023

- Xiaohong Zhang gave a invited talk'A New Ionospheric Product：High precision Ionospheric STEC from IGS Network' at CSNC-ION joint Panel, Nanchang, China, 27, June, 2021
- Xiaohong Zhang gave a invited talk 'Opportunities and Challenges of PPP-RTK' at CSNC, Nanchang, China, 27, June, 2021
- Yang Gao gave a keynote talk 'Precision GNSS to the masses' at CSNC, Nanchang, China, May 26, 2021
- Yang Gao gave a panel talk 'Precision GNSS for AI-Enabled Autonomous Systems' at ION GNSS+, September 23, 2020.
- Sunil Bisnath gave a keynote, International Global Navigation Satellite Systems conference 2020, Sydney, Australia – "GNSS use in autonomous vehicles: Challenges and opportunities"
- Sunil Bisnath gave an invited talk, 2019 International Workshop Joint International Research Laboratory of Modern Geodesy and Geodynamics, School of Geodesy and Geomatics, Wuhan University, Wuhan, China – "Assessment of GNSS PPP positioning performance for error analysis and positioning improvement"
- Sunil Bisnath gave a speaker's seminar, German Geoscience Center (GFZ), Potsdam, Germany – "The potential of PPP augmentation for next-generation, low-cost GNSS receivers"
- Sunil Bisnath gave a speaker's seminar, Germany Aerospace Center (DLR), Munich, Germany – "Precise Point Positioning (PPP) with mass market GNSS sensors"
- Sunil Bisnath gave an international speaker's seminar, Center for Space Research, University of Texas, USA – "Advancement of the Precise Point Positioning (PPP) GNSS technique and its evolving utility in science and engineering"

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- Zhiyu Zhang, Fei Guo, Xiaohong Zhang, Lin Pan. (2022) First result of GNSS-R-based sea level retrieval with CMC and its combination with the SNR method. GPS Solutions, 2022, 26(1):1-14.
- Xiaodong Ren, Hang Liu, Dengkui Mei, Pengxin Yang, Zhiyu Zhang, Mohamed Freeshah, Xiaohong Zhang. (2022) Leveraging the CYGNSS spaceborne GNSS-R observations to detect ionospheric irregularities over the oceans: Method and verification. Space Weather, 2022, 20, e2022SW003141.
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- Zheng Li, Fei Guo, Fade Chen, Zhiyu Zhang and Xiaohong Zhang. (2023) wind speed retrieva1 using gnss r technique with geographic partitioning. Satellite Navigation, 2023, 4(1).
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- Vana S, J Aggrey, S Bisnath, R Leandro, L Urquart, P Gonzalez (2019) "Analysis of GNSS correction data standards for the automotive market." Navigation. 66(3): 577-592.
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WG 4.2.3: GNSS and LEO constellation

Chair: Prof. Xingxing Li (Germany)
Vice-Chair: Dr. Safoora Zaminpardaz (Australia)

Members

- Bofeng Li (China)
- Maorong Ge (Germany)
- Oliver Montenbruck (Germany)
- Yansong Meng (China)
- Xiaohong Zhang (China)
- Lang Bian (China)
- Denise Dettmering (Germany)
- Jan Dousa (Czech Republic)
- Inigo del Portillo (USA)
- Xiaodong Ren (China)
- Tyler G. R. Reid (USA)
- Adrian Jäggi (Switzerland)
- Qile Zhao (China)
- Jose van den Ijssel (Netherlands)
- Da Kuang (USA)
- Daniel Koenig (Germany)
- Wenhai Jiao (China)
- Rothacher Markus (Switzerland)
- Baoguo Yu (China)
- Xinyuan Mao (Netherlands)
- Qianxin Wang (China)
- Zak Kassas (USA)

Activities and publications during the period 2019-2023

1. Integrated Precise Orbit Determination of GNSS and LEO satellites

Onboard GNSS observations from multiple LEO satellites have been used to investigate the LEO-augmented GNSS precise orbit determination (POD). The introduction of LEO satellites can effectively improve the orbit accuracy of GNSS satellites, whose effects are closely related to the number and the distribution of ground network. Based on a global 40-station network, the differences between the estimated GPS satellite orbits and the official IGS products decrease from 19.4 to 16.7 mm (13.9% improvement) in 1D-mean RMS when adding eight LEOs. The benefit of incorporating LEO satellites is more prominent in case of the regional network. With a regional 12-station network, the orbit accuracy of GPS satellites gets improved from about 68.4 to 19.5 mm (71.5% improvement) in 1D-mean RMS after integrating the eight LEOs. Our results also demonstrate that the orbit diversity of introduced LEO satellites has a significant impact on the GPS satellite orbits. By including three LEOs in three different orbital planes, the GPS satellite orbits improve more than from adding seven well-selected additional stations to the network.

Thanks to the availability of BDS-2 observations collected by FY-3C and FY-3D satellites, we got a great opportunity to study the contribution of LEO to BDS-2 POD, which generally suffers from the limited observation geometry when only using a ground network. Our results indicate that the inclusion of FY-3D contributes to the orbit precision improvement about 72% for the BDS-only solution. The most pronounced benefit can be observed in BDS GEO orbits, which is improved by 44% for the regional solution and 41% for the global solution. The further inclusion of FY-3C improves the orbit precision by 3%, 3%, and 1% for BDS GEO, IGSO, and MEO satellites respectively.

Considering the limited number of available LEO satellites, the simulated GNSS observations from large LEO constellation have also been applied to fully explore the potential of LEO satellites in the integrated POD. The accuracy improvement percentage with respect to the ground-based POD results can reach over 70% for all the integrated POD schemes with 60-, 66-, 96-LEO satellites. The largest orbit accuracy improvement of over 98% can be recognized for BDS GEO satellites. Compared with the 60- and 66-LEO schemes, a slightly better orbit quality is observed in the 96 LEO scheme due to the introduction of more LEO satellites. The impact of the LEO orbit type on the integrated POD has also been evaluated. With the same number of LEO satellites, the sun-synchronous-orbiting constellation presents a stronger enhancement to GNSS orbits than the polar-orbiting constellation. The results with partial LEO constellation demonstrate that introducing part of a LEO constellation can be an effective way to balance the conflict between the orbit accuracy and computational efficiency.

2. LEO-augmented GNSS Precise Positioning

We investigated the precise point positioning (PPP) performance of the LEO constellation-augmented full operational capability multi-GNSS. With the augmentation of 60-, 96-, 192- and 288-satellite LEO constellation, the multi-GNSS PPP convergence time can be shortened from 9.6 to 7.0, 3.2, 2.1 and 1.3 min, respectively, in midlatitude region. For LEO-augmented GPS- and BDS-only PPP, the improvement is more significant with the convergence time dramatically shortened by 90% from about 25 to within 3 min with 192- or 288-satellite constellation. To achieve better performance of LEO-augmented multi-GNSS precise positioning, the designing of hybrid LEO constellation using a genetic algorithm has been studied. With 100 LEO satellites, the average numbers of visible satellites during a regression period are 5.49, 5.44 and 5.47, with standard deviations of 0.44, 0.18 and 0.28, for the optimized hybrid polar-orbit/Walker, orthogonal circular-orbit/Walker and Walker/Walker constellations, respectively. For coverages with four and five visible satellites with an elevation mask angle of 7°, the required numbers of satellites are 90 and 93, respectively.

Furthermore, we built the model of multi-frequency PPP AR with the augmentation of different LEO constellations. The estimated results of uncalibrated phase delay (UPD) products of GNSS and LEO show that the performance of estimated LEO UPD is comparable to that of GNSS UPD. Based on the UPD products, LEO-augmented multi-GNSS PPP AR can be achieved. The augmentation performance is more remarkable in the case of increasing LEO satellites. The time to first fix (TTFF) of the GREC fixed solution can be shortened from 7.1 to 4.8, 1.1, and 0.7 min, by introducing observations of 60-, 192-, and 288-LEO constellations, respectively. The positioning accuracy of multi-GNSS fixed solutions is also improved by about 60%, 80%, and 90% with the augmentation of 60-, 192-, and 288-LEO constellations, respectively. Compared to the dual-frequency solutions, the triple-frequency LEO-augmented PPP fixed solution presents a better performance. The TTFF of GREC fixed solutions is shortened to 33 s with the augmentation of 288-LEO constellation under the triple-frequency environment. The averaged TTFFs are 71.8 s and 55.2 s for the 288-satellite LEO-only PPP AR in dual-frequency and triple-frequency modes respectively.

Apart from LEO-augmented PPP AR, the GNSS real-time kinematic (RTK) positioning with the augmentation of LEO constellation has also been investigated. The results of 68.7 km baseline indicate that the RTK convergence time can be shortened from 4.94 to 2.73, 1.47, 0.92, and 0.73 min with the introduction of 60, 96, 192, and 288 polar-orbiting LEO satellites respectively. Results also confirm that LEO satellites do helpfully obtain faster convergence and fixing, especially in the case of long baselines, using large LEO constellations. The averaged TTFF for long baselines decreases from 12 to 2 min approximately by combining with the larger LEO constellation of 192 or 288 satellites.

3. LEO-GNSS meteorology and ionospheric sounding methodology

An approach to generating a global topside ionospheric map (GTIM) using dual-frequency GPS data from multiple LEO satellites at different orbital altitudes is presented. NeQuick2 is employed to normalize LEO data to the same observation range, and 13 LEO satellites from 2015/01/01 to 2015/09/27 are used to generate GTIM-500 (with an ionospheric range from 500 km to 20,200 km) and GTIM-800 (with an ionospheric range from 800 km to 20,200 km). The coinciding pierce point technique is used to study the error induced by altitude normalization. The results show that the relative bias error is approximately 1%. Then, the performance and accuracy of the GTIMs as well as the differential code bias (DCB) of GPS receivers onboard LEO and GPS satellites are compared and analyzed. The statistical results of the differences between the official LEO-DCB products and the LEO-DCBs estimated by different solutions show an RMS improvement of 23% and 41% for GTIM-500 and GTIM-800, respectively. The improvement in RMS of GPS-DCBs for the proposed method is approximately 20%. Moreover, the accuracy of GTIM is evaluated by the dSTEC assessment method. The results show that the RMS of GTIM-500 is 0.50 TECU (total electron content unit) for both methods. In terms of GTIM-800 estimated by the proposed method, the RMS has an improvement of 24%. In addition to the research on generating GTIM by LEO satellites, the ionospheric modelling with both GNSS and LEO satellites is also investigated. Two approaches are proposed to combine GNSS and LEO observation data for ionosphere modeling, which are single-layer normalization (SLN) method and dual-layer superposition (DLS) method, respectively. The results exhibit a significant improvement of ionospheric model accuracy by combining LEO and GNSS observation data based on proposed methods compared with that using GNSS data only, with a reduction in root mean square (rms) error of about 25% and 21% for SLN method and DLS method, respectively. The relations between the performance of ionospheric model estimated by the SLN method and LEO ionospheric observations with different observation accuracy and different satellite cut-off elevations are also highlighted. The results indicate that ionospheric model estimated by GNSS/LEO using SLN method improves at least 25% compared with that by GNSS only. The improvement of ionospheric model estimated with the cut-off elevation of 50° is the best, followed by 70°, and then 20°.

Selected publications during the period 2019-2023:

- Huang W, Männel B, Sakic P, Ge M, Schuh H. (2020) Integrated processing of ground- and space-based gps observations: improving gps satellite orbits observed with sparse ground networks. Journal of Geodesy, 94(10).
- Huang W, Männel B, Brack A, Schuh H. (2020) Two methods to determine scale-independent GPS PCOs and GNSS-based terrestrial scale: comparison and cross-check. GPS Solutions, 25:4
- Li X, Zhang K, Ma F, Zhang W, Zhang Q, Qin Y, Zhang H, Meng Y, Bian L. (2019) Integrated Precise Orbit Determination of Multi-GNSS and Large LEO Constellations. Remote Sensing, 11(21):2514.
- Li X, Zhang K, Meng X, Zhang Q, Zhang W, Li X, Yuan Y. (2020) LEO–BDS–GPS integrated precise orbit modeling using FengYun-3D, FengYun-3C onboard and ground observations. GPS Solutions, 24(2).
- Su M, Su X, Zhao Q, Liu J. (2019) BeiDou Augmented Navigation from Low Earth Orbit Satellites. Sensors, 19(1).
- Li B, Ge H, Ge M, Nie L, Shen Y, Schuh H. (2019) LEO enhanced Global Navigation Satellite System (LeGNSS) for real-time precise positioning services. Advances in Space Research, 63(1).
- Li X, Li X, Ma F, Yuan Y, Zhang K, Zhou F, Zhang X. (2019) Improved PPP Ambiguity Resolution with the Assistance of Multiple LEO Constellations and Signals. Remote Sensing,

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- Ma F, Zhang X, Li X, Cheng J, Guo F, Hu J, Pan L. (2020) Improved PPP Ambiguity Resolution with the Assistance of Multiple LEO Constellations and Signals. GPS Solutions, 24:62.
- Li X, Lv H, Ma F, Li X, Liu J, Jiang Z. (2019) GNSS RTK Positioning Augmented with Large LEO Constellation. Remote Sensing, 11(3):228.
- Li X, Ma F, Li X, Lv H, Bian L, Jiang Z, Zhang X. (2019) LEO constellation-augmented multi-GNSS for rapid PPP convergence. Journal of Geodesy, 93:749-764.
- Ren X, Zhang J, Chen J, Zhang X. (2021) Global Ionospheric Modeling Using Multi-GNSS and Upcoming LEO Constellations: Two Methods and Comparison. IEEE Transactions on Geoscience and Remote Sensing, 99:1-15.
- Ren X, Chen J, Zhang X, Schmidt M, Li X, Zhang J. (2020) Mapping topside ionospheric vertical electron content from multiple LEO satellites at different orbital altitudes. Journal of Geodesy, 94(9).
- Ren X, Chen J, Zhang X, Yang P. (2020) Topside ionosphere of NeQuick2 and IRI-2016 validated by using on-board GPS observations from multiple LEO satellites. Journal of Geophysical Research: Space Physics.
- Ren X, Zhang X, Schmidt M, Zhao Z, Chen J, Zhang J, Li X. (2020) Performance of GNSS Global Ionospheric Modeling Augmented by LEO Constellation. Earth and Space Science, 7, e2019EA000898.
- Li X, Qin Y, Zhang K, Wu J, Zhang W, Zhang Q, Zhang H (2022) Precise orbit determination for LEO satellites: single-receiver ambiguity resolution using GREAT products, Geo-spatial Information Science, 25:1, 63-73, DOI:10.1080/10095020.2021.2022966

Meetings and communications during the period 2019-2023

- A Special Issue of Remote Sensing on “High-precision GNSS: Methods, Open Problems and Geoscience Applications”.
- A Special Issue of Applied Sciences on “Recent Advances in GNSS High-Precision Positioning and Applications”

WG 4.2.4: Multi-GNSS in Asia

Chair: Prof. Chalermchon Satirapod (Thailand)
Vice-Chair: Prof. Hung-Kyu Lee (Korea)

Members
- Toshiaki Tsujii (Japan)
- Hyung Keun Lee (Korea)
- Ben K.H. Soon (Singapore)
- Horng-Yue Chen (Taiwan)
- Michael Moore (Australia)
- Dudy Darmawan Wijaya (Indonesia)
- Trong Gia Nguyen (Vietnam)

Activities and publications during the period 2019-2023

As the Asia Oceania GNSS downstream market continues to grow rapidly, the role of the WG is to further promote GNSS scientific research, development and applications in the region. It will also focus on education and capacity building such as training, research, and networking activities to encourage the next generation of GNSS researchers. The working group will work in close cooperation with Multi-GNSS Asia (MGA) to promote applications of GNSS and SBAS such as in surveying, construction, agriculture, transportation and logistics, as well as emergency response and disaster management.

Dr. Horng-Yue Chen and Prof. Chalermchon Satirapod attended the IUGG2019 conference in Montreal, Canada in July 2019. Prof. Satirapod attended the Multi-GNSS Asia conference 2019 and gave one keynote presentation in Bangkok, Thailand. Several members (Prof. Chalermchon Satirapod, Prof. Hung-Kyu Lee, Prof. Hyung-Keun Lee, Prof. Toshiaki Tsujii, Dr. Horng-Yue Chen and Dr. Ben K.H. Soon) joined the International symposium on GPS/GNSS 2020 held in Bangkok during 17-19 January 2020. It was a great opportunity to exchange ideas and discuss some potential research collaborations.

Technical work on developing a new IGS multi-GNSS orbit combination is being developed at Geoscience Australia. The software is currently being tested to create IGS multi-GNS repro 3 products. Preliminary reprocessing results show that Galileo perform just as well as GPS from mid 2019, QZSS, Beidou have a way to go in terms of improving their orbit modelling. Geoscience Australia is also developing it's own inhouse GNSS processing engine called with the intention of being released for as open-source package. Furthermore, some related publications from the group members are as shown in the publication section.

Prof. Chalermchon Satirapod attended the Multi-GNSS Asia conference 2021 and moderated one panel talk on Thailand-Japan session, in Phuket, Thailand during 10-11 March 2021. Prof. Satirapod was also invited as a judge for the Rapid Prototype Development (RPD) challenge at the MGA. Several members (Prof. Chalermchon Satirapod, Prof. Hung-Kyu Lee, Prof. Toshiaki Tsujii, Dr. Horng-Yue Chen and Dr. Ben K.H. Soon) joined the Multi-GNSS Asia conference 2022 held in Chiangmai, Thailand during 30 January-2 January 2022. Prof. Satirapod was appointed as a new MGA steering committee member. It was a great opportunity to exchange ideas and discuss some potential research collaborations at the MGA2023 in Chiangmai, Thailand. Furthermore, some related publications from the group members are as shown in the publication section.

Selected publications during the period 2019-2023:

- Trakolkul, C., and Satirapod, C. (2020) Variations of Precipitable Water Vapor Using GNSS CORS in Thailand. Survey Review, https://doi.org/10.1080/00396265.2020.1713611.
- Trakolkul, C., and Satirapod, C. (2020) Analysis of PWV derived from the GNSS CORS stations for determining the onset of the southwest monsoon in Thailand, International Journal of Geoinformatics, 16 (2), 71-78.
- Charoenphon, C. and Satirapod. C. (2020) Improving Accuracy of a Real-Time Precipitable Water Vapor using the local meteorological models with Precise Point Positioning in Thailand, Journal of Spatial Science, https://doi.org/10.1080/14498596.2020.1758969.
- Jongrujinan, T. and Satirapod. C. (2020) Stochastic modeling for VRS network-based GNSS RTK with residual interpolation uncertainty, Journal of Applied Geodesy, 14(3), 317-325.
- Uaratanawong V., Satirapod C. and Tsujii T. (2020) OPTIMISATION TECHNIQUE FOR PSEUDORANGE MULTIPATH MITIGATION USING GNSS SINGLE POINT POSITIONING MODE, Artificial Satellites, 55 (2), 77-86.
- Uaratanawong V., Satirapod C. and Tsujii T. (2021) Evaluation of multipath mitigation performance using signal-to-noise ratio (SNR) based signal selection methods, 15(1),75-85.
- Yun, S., Lee, H., Nguyun, D.H. (2019) A study on status of multi-GNSS constellation and its positioning performance on SPP mode, Journal of the Korea Academia-Industrial Cooperation Society, 20(8), pp.622-673.
- Yun, S., Lee, H. (2020) Influence of radome types on GNSS antenna phase center variation, Journal of the Korean Society of Surveying, Geodesy, Photogrammetry and Cartography, 38(1), pp.11-21.
- Nguye, D.H, Lee, H., Yun, S. (2020) A study on simultaneous adjustment of GNSS baseline vectors and terrestrial measurements, Journal of the Korean Society of Surveying, Geodesy, Photogrammetry and Cartography, 38(5), pp.415-423.
- Yun, S., Lee, H. (2021) Quality assessment of GPS L2C signals and measurements, Journal of Positioning, Navigation, and Timing, 10(1), pp.13-20.
- Horng-Yue Chen, Hsin Tung, Ya-Ju Hsu and HungKyu Lee (2019) Evaluation of Single-frequency Receivers for Studying Crustal Deformation at the Longitudinal Valley Fault, Eastern Taiwan, Survey Review, 52, 374, Page 454-462. https://doi.org/10.1080/00396265.2019.1634340.
- Hsin Tung, Horng-Yue Chen, Ya-Ju Hsu, Jyr-Ching Hu, Yo-Ho Chang, and Yu-Ting Kuo (2019) Triggered slip on multifaults after the 2018 Mw 6.4 Hualien earthquake by continuous GPS and InSAR measurements, Terr. Atmos. Ocean. Sci., 30, 285-300, doi: 10.3319/ TAO.2019.04.03.01.
- Le Huy Minh, Vu Tuan Hung, Jyr- Ching Hu, Nguyen Le Minh, Bor- Shouh Huang, Horng-Yue Chen, Nguyen Chien Thang, Nguyen Ha Thanh, Le Truong Thanh, Nguyen Thi Mai, and Pham Thi Thu Hong (2020) Contemporary movement of the Earth's crust in the Northwestern Vietnam by continuous GPS data, September 2020, Vietnam Journal of Earth Sciences 42(4) DOI: 10.15625/0866-7187/42/4/15282.
- Horng-Yue Chen, Ryoya Ikuta*, Ya-Ju Hsu, Toshiaki Tsujii, Masataka Ando, Yoko Tu, Takeru Kohmi, Kiyomichi Takemoto, Koto Mizuno, Hsin Tung, Chin-Shang Ku and Cheng-Horng Lin (2021) A Decade of Global Navigation Satellite System/Acoustic Measurements of Back-Arc Spreading in the Southwestern Okinawa Trough, Front. Earth Sci., 10 February 2021, https://doi.org/10.3389/feart.2021.601138.
- W. J. Yoo, L. W. Kim, Y. D. Lee, and H. K. Lee, "A Coarse-Time Positioning Method for Improved Availability," GPS Solutions, GPS Solut 24, 2. https://doi.org/10.1007/s10291-019-0919-y, 2019
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- Trong N. (2020) The method for connecting CORS station into VN-2000 reference coordinate system, University report, Hanoi University of Mining and Geology, Vietnam.
- Thari P., Kriengkraiwasin S. and Satirapod C. (2021) Evaluation of GNSS Positioning Accuracy from Satellite-Based Augmentation Systems in Thailand, Engineering and Applied Science Research 49 (2), 209-217.
- Kriengkraiwasin S., Charoenphon C., Butwong K., Kovitpongkajorn V., Yomwan P., Thongtan T. and Satirapod C. (2021) UNIFICATION OF GNSS CORS COORDINATES IN THAILAND, Survey Review 54 (387), 534-542.
- Paijitprapaporn C., Thongtan T. and Satirapod C. (2021) Accuracy assessment of integrated GNSS measurements with LIDAR mobile mapping data in urban environments, Measurement: Sensors, 18, 100078, https://doi.org/10.1016/j.measen.2021.100078.
- Thongtan T., Sawatdiaree S. and Satirapod C. (2022) GNSS time and frequency transfers through national positioning, navigation and timing infrastructure, Journal of Applied Geodesy, 16(2), 123-130.
- Trakolkul, C., Charoenphon, C. and Satirapod, C. (2022) Impact of El Niño–Southern Oscillation (ENSO) on the Precipitable Water Vapor in Thailand from Long Term GPS Observation, International Journal of Geoinformatics, 18 (3), 13-20.
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- Dumrongchai, P., Patsadutarn, J. and Satirapod, C. (2023) Performance tests of geodetic receivers with tilt sensors in obstructed environments using the NRTK GNSS technique, Journal of Applied Geodesy, 17(1), 39-52.
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- Y. D. Lee, L. W. Kim, and H. K. Lee, "A tightly-coupled compressed-state constraint Kalman Filter for integrated visual-inertial Global Navigation Satellite System navigation in GNSS-degraded environment," IET Radar, Sonar & Navigation, Vol. 16, No. 8, pp. 1344-1363, https://doi.org/10.1049/rsn2.12265, 2022.
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- Narayan K.P., Yun, S., Lee, H., Nguyen D.H. (2021) Impact of multi-GNSS measurements on baseline processing for control surveying applications, J. of Positioning, Navigation and Timing, 10(2), pp.103-111.

Sub-commission 4.3: Atmosphere Remote Sensing

Chair: Michael Schmidt (Germany)
Vice Chair: Ehsan Forootan (Denmark)

Overview

The SC 4.3 is composed of five Working Groups (WG) and two Joint Working Groups (JWG). Besides, several SC 4.3 members participate in other IAG and GGOS Joint Study Groups (JSG) and JWGs related to atmosphere remote sensing, for instance, the GGOS Focus Area "Geodetic Space Weather Research" (FA-GSWR) which is chaired by Michael Schmidt and Ehsan Forootan, too.

Due to the Corona pandemic many of the planned activities at conferences and workshops did not work out during the reporting period and had to be postponed to the second half of 2021 or to an even later time moment. As one example we want to mention the EGU General Assembly 2020, where we have postponed all SC 4.3 activities by one year to the virtual EGU 2021 which was running in the second half of April 2021. For this online conference we installed the Session G5.1 "Ionosphere, thermosphere and space weather: monitoring and modelling" lead by the main convener Ehsan Forootan. Another example is the 2nd IAG Commission 4 Symposium, which was originally scheduled for September 2020 in Potsdam, Germany, but then was post- poned. It finally took place from September 5th to 8th, 2022, at Wissenschaftsetage Potsdam. The Symposium website (https://www.iag-commission4-symposium2022.net/) created by Co- pernicus Gesellschaft mbH will be available at least for a five-year timeframe.

Altogether 74 participants have been registered, of which 28 were taking part remotely and 46 met at site. Among the registered, we had 14 students and six IAG Members, who received the obligatory 10% discount for registration.

The scientific program of the 2nd IAG Commission 4 Symposium included nine sessions. Some of them were arranged according to the IAG Commission 4 structure

- Emerging Positioning Technologies and GNSS Augmentation (SC4.1)
- Multi-frequency multi-constellation GNSS (SC4.2)
- Atmospheric Remote Sensing of the troposphere and GNSS reflectometry (SC4.3)
- Atmospheric Remote Sensing of the ionosphere (SC4.3)
- GNSS integrity and quality control (SC4.4).

51 orals and seven posters were presented within these sessions. It was decided to accept presentation slides and posters as part of the open access Symposium Proceedings at Zenodo (https://zenodo.org/communities/iag-comm4-symp-2022/).

Apart from these scientific sessions, we held opening and closing sessions and a Special Session with a video presentation. An IAG Sub-Commission 4.3 Splinter Meeting, a Business Meeting of IAG Commission 4 and an IAG + IAGA (International Association of Geomagnetism and Aeronomy) Splinter Meeting on the specific topic of "Space Weather Research" have been organized.

Many papers related to the scientific content of the SC 4.3's WGs and the JWGs have been written in the last years. Significant progress has also been made in third-party funded national and international projects; the work within these projects is often strongly coupled with the objectives of individual WGs and JWGs of the SC 4.3.

On the next pages the different WGs and JWGs of the SC 4.3 give an overview about their work within the last four years, i.e. the reporting period 2019 to 2023.

Working Groups of Sub-commission 4.3: Atmosphere Remote Sensing

JWG 4.3.1: Real-time Ionosphere Monitoring and Modelling

(joint with IGS and GGOS)

Chair: Zishen Li (China)
Vice Chair: Ningbo Wang (China)

Members

- Alberto Aarcia-Rigo (Spain)
- Alexis Blot (France)
- Andre Hauschild (Germany)
- Andreas Goss (Germany)
- Andrzej Krankowski (Poland)
- Attila Komjathy (USA)
- Cheng Wang (China)
- Eren Erdogan (Germany)
- German Olivares (Australia)
- Kenji Nakayama (Japan)
- Libo Liu (China)
- Manuel Hernández-Pajares (Spain)
- Nicolas Bergeot (Belgium)
- Qi Liu (China)
- Qile Zhao (China)
- Raul Orús (The Netherlands)
- Reza Ghoddousi-Fard (Canada)
- Wookyoung Lee (Korea)
- Xingliang Huo (China)
- Yunbin Yuan (China)
- Zhizhao Liu (China Hongkong)

Activities and publications during the period 2019-2023

Discussing the roadmap of real-time ionospheric information dissemination

To mitigate the ionospheric delay errors in real-time GNSS applications, the spherical harmonic expansion up to degrees 15 is defined in RTCM v3 standard for the dissemination of real-time global ionospheric vertical total electron content (VTEC) messages. Working together with the IGS real-time working group, the "IGS-SSR Task Force" was launched in late 2019 to design different types of IGS-SSR messages in support of real-time scientific applications in current multi-frequency and multi-constellation GNSS environment. The "Ultra-rapid", "Rapid" and "Final" time scales for delivering IGS ionospheric SSR messages have been designed. In the "Ultra-rapid" time scale, it is suggested to implement exactly the same type of existing RTCM ionospheric message, but increase the maximum degree of the spherical harmonic expansion as much as possible. This has been fixed in the released IGS-SSR format v1.0. In the "Rapid" time scale, it is suggested to consider a second IGS-SSR ionospheric message directly implanting the IONEX format, i.e., based on a pixel- or voxel- basis function. This extends the well-known IONEX format from post-processed to real-time applications, allowing in particular high resolution VTEC information at given regions, and also allowing to broadcast in the same format other useful information, such as effective height or topside electron content fraction among other many possibilities. In the "Final" time scale, it is suggested to broadcast both ionospheric corrections and associated quality indicator (QI), as such information is of importance in designing the stochastic model of RT-PPP algorithm in case RT global ionospheric corrections were used as constraints. It is still now under discussion the possibility of increasing the degree of spherical harmonic expansion and adding the ionospheric accuracy information in IGS-SSR message within the community, which might take two more years to achieve an agreed format for distributing the ionospheric accuracy information associated to the provided real-time VTEC or STEC corrections.

Real-time regional and global ionospheric modeling

As of June 2023, there are 6 analysis centres providing real-time global ionospheric maps (RT- GIMs). Aside from CAS, CNES and UPC-IonSAT, three additional contributors, i.e., DGFI- TUM, NRCan and Wuhan University (WHU) also started RT-GIM computation and distribu- tion. At CAS, A predicting-plus-modelling approach is employed for its RT-GIM computation using multi-GNSS streams of the IGS-RTS (Li et al. 2020). At CNES, the spherical harmonicexpansion up to degree 12 is directly used for global VTEC representation. At UPC-IonSAT, the Tomographic model with spherical harmonic interpolation was used to replace the original Kriging interpolation in September 2019. And then, a new interpolation technique, i.e. Atomic Decomposition Interpolation of GIMs (ADGIM, Yang et al. 2021) interpolation, has been im- plemented for its RT-GIM computation in the beta test phase.

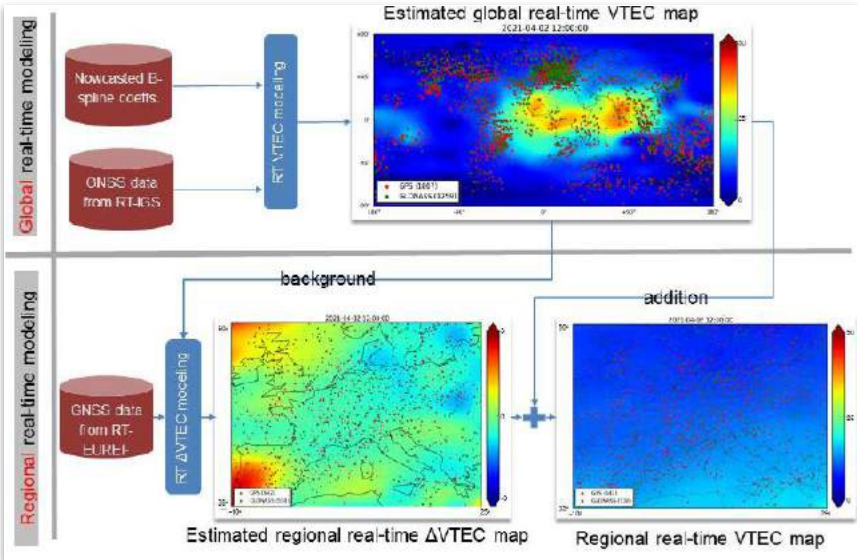

Figure 1: Process chain of DGFI-TUM to generate RT regional and global VTEC maps

The current implementation of the VTEC modelling approach of DGFI-TUM relies on both a global and a regional sequential estimator (Kalman filter) running in a parallel mode. The global VTEC estimator produces VTEC maps with B-splines using real-time data from global IGS network (Schmidt et al. 2015, Erdogan et al. 2020). The regional estimator makes use of the VTEC product of the real-time global estimator as background information and generates high- resolution VTEC maps using real-time data from the EUREF Permanent GNSS Network. The concept that was carried out for the regional ultra-rapid VTEC modelling approach of the DGFI- TUM (Goss et al. 2019, 2020a) are applied to the regional real-time modelling approach using real-time GNSS data. Following the

RTCM-SSR standard, NRCan distributes the real-time ion- ospheric corrections at a 30 second rate, whereas WHU at 1 minute rate.

The influences of different spectral, spatial and temporal resolutions on the performance of RT- GIMs were examined in detail by UPC-IonSAT (Liu et al. 2021a) and DGFI-TUM (Goss et al. 2020b) colleagues. A high accuracy 4-D regional ionospheric electron density model was re- ported by GA colleagues (Olivares-Pulido et al. 2019), and its usage in GNSS high precision positioning, i.e., PPP-RTK, was also analysed. For easy use, a satellite-based method for direct ionospheric STEC modelling and correction is proposed (Li et al. 2021). This algorithm is well applicable to regional and local GNSS networks within several hundred kilometres. Adapted from the adjusted spherical harmonic expansion proposed for real-time regional ionospheric map (RT-RIM) computation (Li et al. 2019), a Spherical Harmonic function Add Kriging Ion- ospheric Near real-time model (i.e., SHAKING) is used for RT-RIM generation over China (Liu et al. 2022). SHAKING model has been successfully applied in the pre-operational BDSBAS system to generate Grid Ionospheric Vertical Delay (GIVD) and Grid Ionospheric Vertical Error (GIVE) information over China and its surrounding region. In addition, an open- source tool to estimate precise ionospheric estimates, namely ESA UGI (Unified-GNSS-Iono- sphere), was undocumented by ESA-ESTEC colleagues (Orus-Perez et al. 2020), which should largely benefit the research of real-time regional and global ionospheric modelling within GNSS ionosphere communities.

Real-time Global Ionospheric Map combination

To provide a more stable real-time ionospheric correction stream, UPC-IonSAT adapted its post-processing GIM combination method, which has been successfully applied in the combi- nation of IGS rapid and final GIMs, and used to combine the experimental IGS RT-GIM since October 2018. Note that such experimental IGS RT-GIM is transmitted in RTCM-SSR message type 1264 and available from the caster of UPC-IonSAT itself. With the transition of UPC's RT-GIM from spherical harmonic interpolation to the newly developed ADGIM interpolation, a new version of IGS combined RT-GIM (i.e., IRTG) was developed at UPC-IonSAT, adapting to the updated RT-GIM of UPC-IonSAT (Liu et al. 2021b). The steps for generating UPC com- bined RT-GIM is shown in Figure 2. The combined RT-GIM is generated using RT ionospheric streams from 4 centres, i.e. CAS, CNES, UPC-IonSAT and WHU, which is presently broad- casted in the IGS-SSR standard (IONO00IGS1). In addition to RT data streams, the latest IGS RT-GIMs are also archived at the FTP site of UPC-IonSAT (http://chapman.upc.es/irtg/ar- chive/).

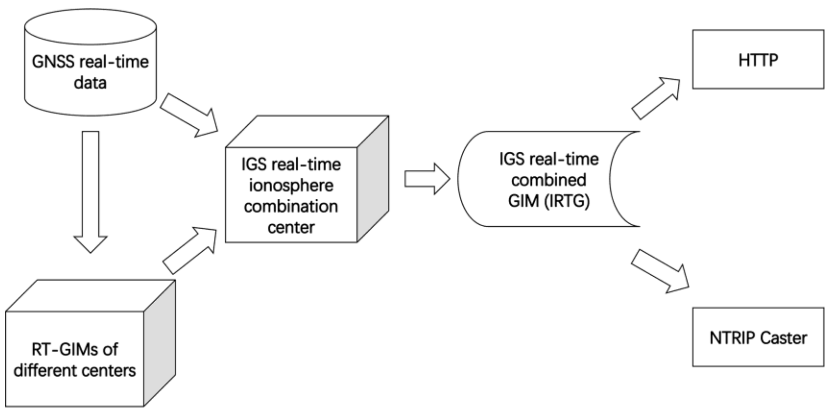

Figure 2: The flowchart for generating UPC combined RT-GIM (IRTG)

Following UPC's RT-GIM combination activity, CAS also started the RT-GIM combination since late-2021. A time-varying GNSS dSTEC analysis method was proposed to evaluate the quality of RT-GIMs from different ACs in real-time (Wang et al. 2022a). Compared to the conventional dSTEC assessment referring to the first epoch or the epoch with highest satellite elevation angle across the whole phase observation arc, the proposed time-varying dSTEC anal- ysis requires limited computation load, which is also free of higher noises of those observation data with lower satellite elevation angles. A total of 40 RT-GNSS stations from the IGS-RTS network are selected for RT-dSTEC analysis. CAS combined RT-GIMs are transmitted in both RTCM-SSR (IONO01IGS0) and IGS-SSR (IONO01IGS1) standards, which are freely acces- sible from the IGS data streaming server since January 2022. An overview of those provided real-time ionospheric correction streams is summarized in Table 1.

Table 1 Status of those generated real-time ionospheric correction streams (as of June 2023)

Analysis centers	Caster	Mountpoint	Interval / s	Format
CAS	products.igs-ip.net:2101	SSRC00CAS1	60	IGS-SSR
CNES	products.igs-ip.net:2101	SSRC00CNE1	60	IGS-SSR
UPC	products.igs-ip.net:2101	IONO00UPC1	15	IGS-SSR
WHU	58.49.94.212:2101	IONO00WHU0	60	RTCM-SSR
UPC-combined	products.igs-ip.net:2101	IONO00IGS1	15	IGS-SSR
CAS-combined	products.igs-ip.net:2101	IONO01IGS1	60	IGS-SSR
		IONO01IGS0	60	RTCM-SSR

The performance of global VTEC representation in all of the RT-GIMs has been assessed by VTEC directly measured from JASON3 altimeter. During the recent testing period (see Fig. 3), the accuracy of most IGS RT-GIMs is close to post-processed GIMs. These results indicates that the IGS RT-GIMs turn out to be reliable sources of real-time global VTEC information.

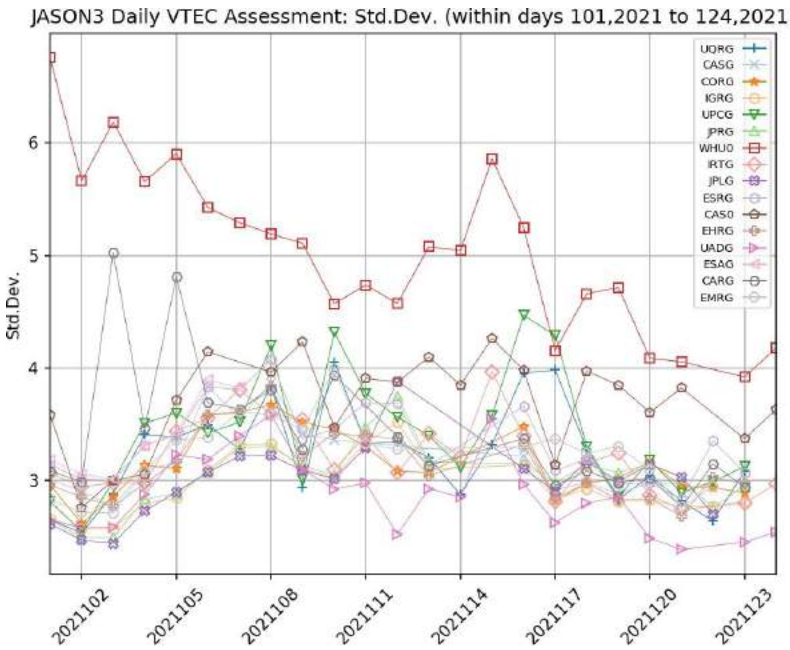

Figure 3: Daily standard deviation of GIM VTEC versus measured Jason3-VTEC (in TECU), from April 11 to May 04 in 2021, including the updated IGS RT-GIM, the rapid IGS GIM and the rapid IGS GIM.

Real-time global ionospheric map combination using NRT DORIS data

Although primarily developed for precise orbit calculation, the high-quality dual-frequency phase measurements of DORIS system provide valuable opportunities to examine the Earth’s ionosphere. For some time now, DORIS data from the Jason-3 satellite has also been available in near real time (NRT) with a delay of a few hours. Compared to GNSS station network, DO- RIS beacon network provides a more uniform coverage of global ionosphere over both conti- nental and oceanic regions.

These data are perfectly suited for an independent validation of RT- GIMs derived from GNSS measurements with a latency of a few seconds.

The present combined RT-GIM is generated by a RT-GNSS dSTEC weighting method. Obvi- ously, GNSS observation data is used to evaluate the performance of GNSS derived global ionospheric maps themselves. To independently validate the quality of RT-GIMs, the concept of DORIS dSTEC is proposed (Liu et al. 2023). Benefitting from the large relative frequency ratio between DORIS L1 (2 GHz) and L2 (400 MHz) frequencies, the theoretical precision of DORIS derived dSTEC is much higher than that of GNSS L1/L2 generated dSTEC. In addition to providing an indication of the accuracy of individual RT ionospheric models, the NRT DO- RIS data can also be used to weight the models of individual data centres for combination. Wang et al (2022b) presents first results of such a weighting (see Figure 4), i.e., DORIS-dSTEC combined RT-GIM generated using real-time ionospheric streams of CAS, CNES, UPC and WHU. As shown in Figure 5, the new combination achieves a better performance than the com- bination based on classical methods through a validation with independent altimeter data from the Jason-3 mission.

In the near future, it is envisaged that DORIS data can be directly incorporated into NRT or RT ionosphere modelling. To this end, it is planned to make NRT DORIS data available for addi- tional satellite missions (e.g., Sentinel-3) and possibly also to further reduce the latency times. This would then result in numerous further applications for ionospheric modelling

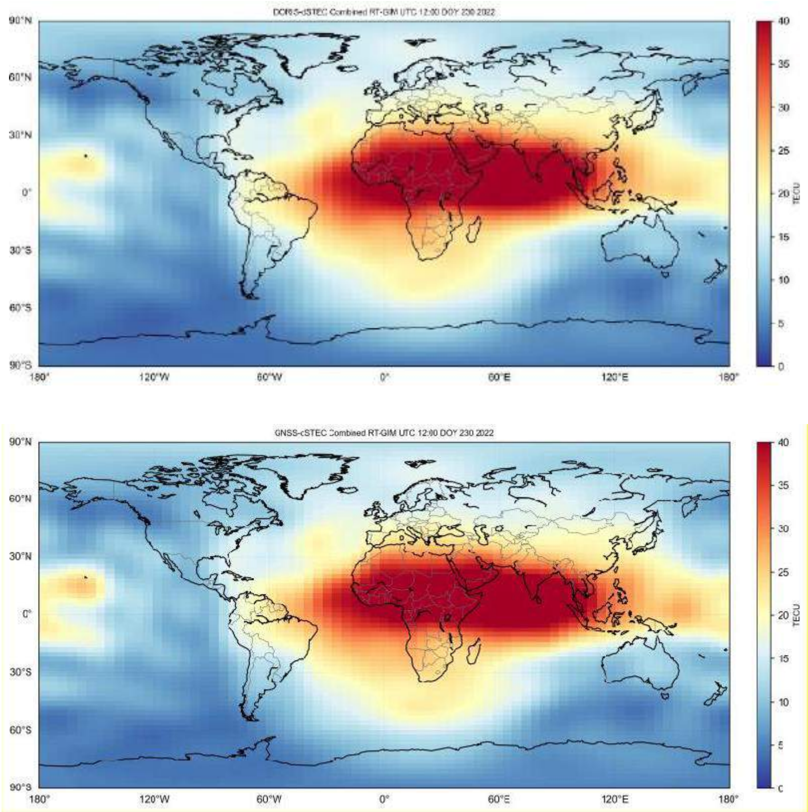

Figure 4: Distribution of global total electron contents generated by DORIS-dSTEC combined RT- GIM (top) and GNSS-dSTEC combined RT-GIM on UTC 12:00 of DOY 230, 2022.

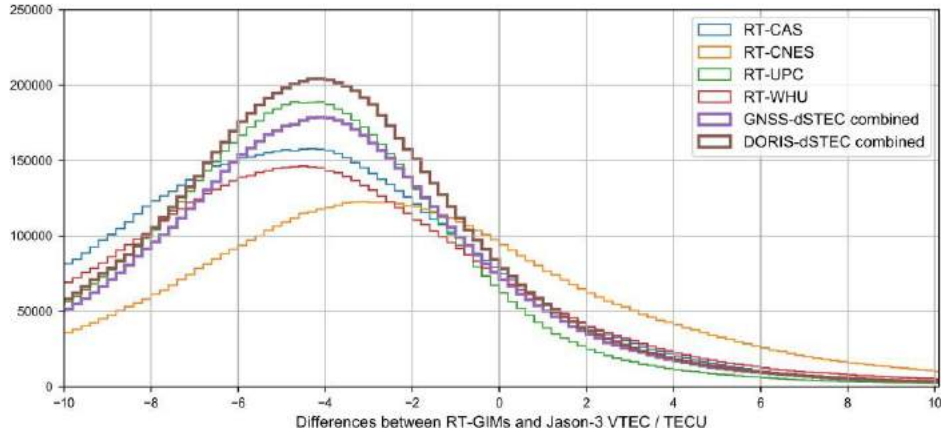

Figure 5: Histogram of differences between RT-GIM derived VTECs and Jason-3 altimeter VTEC ob- servables during DOY 001–270, 2022.

Real-time ionospheric irregularity monitoring

The ionospheric irregularities have a strong impact on many applications of GNSS and other space-based radio systems. The rate of ionospheric total electron content (TEC) change index (ROTI, TECU/min), defined as the standard deviation of rate of TEC change (ROT) within a short time (e.g. 5 minutes), has been used to describe the ionospheric irregularities and associ- ated scintillations. Since 2017, the ionospheric ROTI map covering the northern hemisphere has been routinely generated at UWM, Poland in post-processing mode, which is a helpful scientific data set for the climatology characteristics analysis of ionospheric irregularities (Kotulak *et al*. 2020). The availability of RT GNSS data streams from regional and global networks of GNSS stations also support the ionospheric irregularity monitoring in real-time. The global RT ROTI map has been generated at UPC-IonSAT and CAS using real-time GPS data from the IGS Network. At NRCan, ionospheric irregularities as sensed by 1Hz GPS and GLONASS phase rate measurements continued to be monitored in near-real-time and have been used to study geomagnetic storms (Ghoddousi-Fard *et al*. 2020, Prikryl *et al*. 2019, 2020). Additionally, an ionospheric climate index based on GNSS was proposed by BUAA colleagues (Wang *et al*. 2020). We will continue the work with the IGS ionospheric WG on developing ionospheric TEC gradient indicators as well as the associated real-time monitoring products, which are of the great interest of the GNSS community.

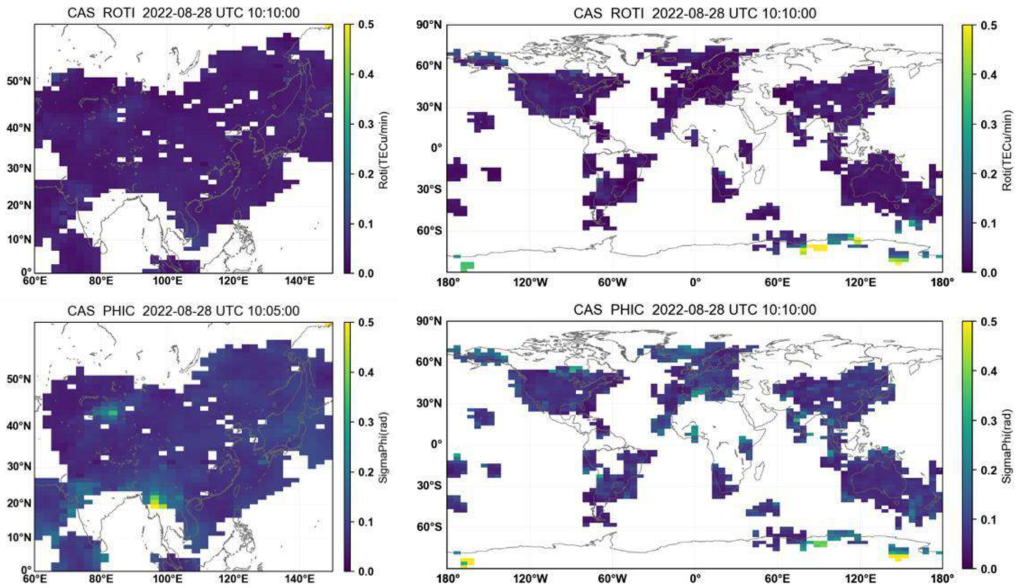

Figure 6: Regional and global ionospheric disturbance maps generated using 1 Hz real-time GNSS observation data

Generation and broadcasting of real-time ionospheric accuracy information

The possibility of generating and broadcasting the accuracy information of RT-GIM has been discussed within the WG. Such information is of importance in designing the stochastical model of uncombined PPP algorithm in the case RT global ionospheric corrections were used as con- straints. According to the IGS questionnaire for improved real-time ionosphere correction mes- sages, the real-time ionospheric accuracy information (AI) is highly required for GNSS com- munity especially for precise positioning applications (see Figure 7). It is agreed to define a preliminary data format and broadcast the RMS map associated to the provided RT-VTEC product.

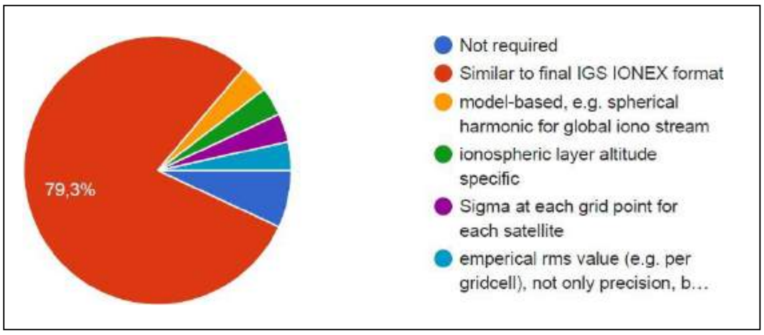

Figure 7 IGS questionnaire for real-time ionosphere accuracy information messages

At CAS, it has been tried to fit the RT ionospheric residuals to express VTEC error estimates using spherical harmonics and, broadcasting those spherical harmonic coefficients by adding one additional message type temporally (message body similar to VTEC). An example of CAS RT-GIM and associated quality indicator is presented in the left plot of Figure 8. A method based on the high-quality dual-frequency GNSS phase measurements is developed to indirectly analyse the reliability of RMS maps of post-processed GIMs (Zhao et al. 2021). The method is then extended to check the reliability of global ionospheric QIs provided in CAS RT-GIM (see right plot of Figure 8). The discussion on the generation and dissemination of RT ionospheric QI message is still on-going with close collaboration with IGS real-time working group, which would hopefully reach an agreed format for broadcast real-time RMS or accuracy information for the next two years.

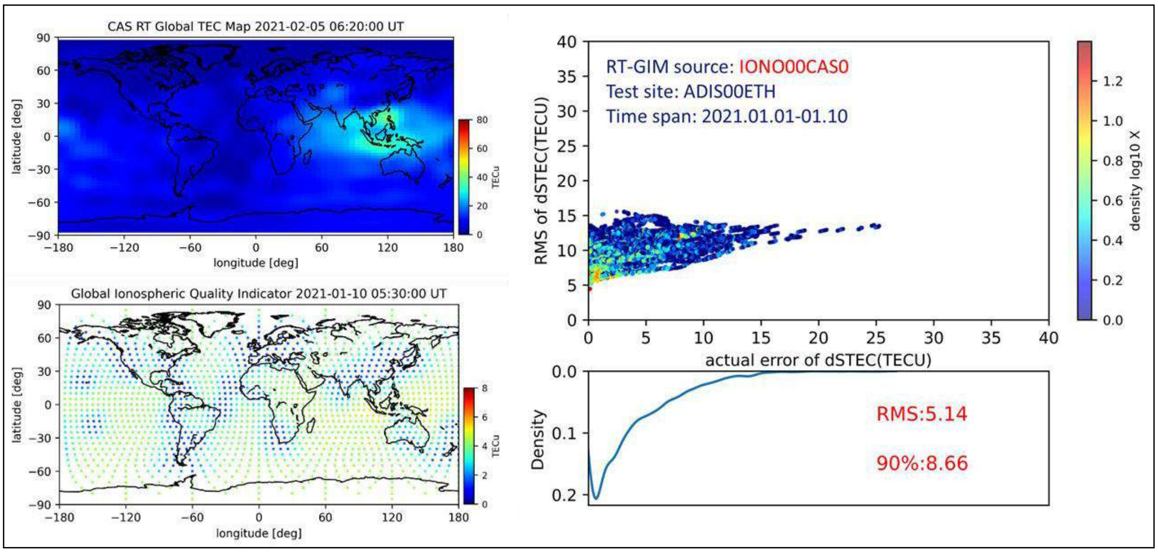

Figure 8: An example of CAS RT-GIM as its quality indicator (QI) map (left plot) and assessment of RT-GIM QI at one equatorial site ADIS00ETH.

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WG 4.3.2: Prediction of Ionospheric State and Dynamics

Chair: Mainul Hoque (Germany)
Vice Chairs: Eren Erdogan (Germany/ USA) / Murat Durmaz (Turkey)

Members

- Mahdi Alizadeh (Iran)
- Enric Monte (Spain)
- Fabricio Prol (Finland)
- Liangliang Yuan (China)
- Adria Rovira Garcia (Spain)
- Ningbo Wang (China)
- Cheng Wang (China)

Activities and publications during the period 2019-2023

To realize WG 4.3.2 objectives and goals, group members accomplished individual activities as well as worked in cooperation with other group members. The progress during the period 2019-2023 is briefly described below.

Real-time Ionosphere Modelling, Nowcasting and Forecasting using B-splines

At DGFI-TUM, two approaches for VTEC forecasting/nowcasting have been studied: 1) sum of a linear model, a series expansion in terms of trigonometric basis functions and an ARIMA model, as well as 2) a machine learning technique trained with historical VTEC maps. The first approach was updated, and is operationally in use.

The first approach makes use of the VTEC maps represented by a series expansion in tensor prod- ucts of polynomial B-splines in latitude and trigonometric B- splines in longitude (Schmidt et al. 2015). The VTEC products, feed- ing the forecast/nowcast model, are ultra-rapid products of the DGFI-TUM and generated with a delay of 2–3 hours (Goss et al. 2019, 2020, Erdogan et al. 2020). The unknown parameters of the forecast model are recomputed at the end of every hour using a time series in a moving window consisting of estimated ultra-rapid B-spline coefficients from the last 30 days. Later forecasted VTEC maps are computed for the next days. Besides, the approach was recently used to provide nowcasted supplementary information to global real-time ionosphere modelling. The concept is illustrated in Figure 1 and operationally runs in the context of the OPTIMAP project.

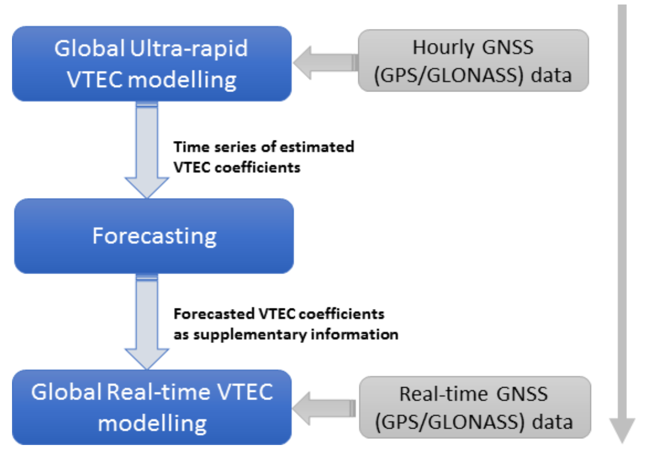

Figure 1: Processing chain for global real-time VTEC modelling in support of forecasted VTEC products

The second approach is based on Machine Learning (ML) tools. In a study applied at DGFI- TUM, an artificial recurrent neural network (NN), based on a Long Short-Term Memory (LSTM) approach has been applied to a time series of historical VTEC (global mean value) data to forecast values for different future horizons (1h, 24h, 120h). Figure 2 provides the real global mean VTEC values (red) and the corresponding forecasted values, based on the NN for different horizons. The forecast of 1h hour provides with a RMS value of 0.32 TECU w.r.t the real data a high forecast accuracy. With increasing horizons, i.e., 24h and 120h the forecast accuracy decreases and provides RMS values of 0.86 TECU and 1.23 TECU, respectively.

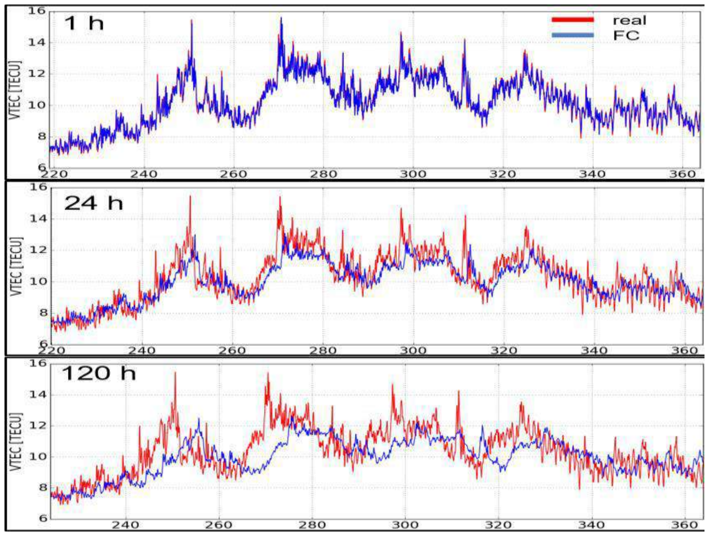

Figure 2: Mean VTEC Forecasting using machine learning tools; the real global mean VTEC values (red) and the cor- responding forecasted values based on the method of neural network.

Ionospheric prediction algorithm for Galileo single frequency users

Hoque et al. (2019, 2020) proposed an alternative ionospheric correction approach for single frequency Gali- leo users. In the proposed approach the broadcasted coefficients are used to drive the Neustrelitz Total Elec- tron Content (TEC) Model (NTCM) instead of the standard Galileo iono- sphere model NeQuick-G. The NTCM-based correction approach uses 12 model coefficients, the solar radio flux index F10 and a few em- pirically fixed parameters. The re- quired TEC values can be computed at any location and time without us- ing any spatial or temporal interpo- lation of parameters. This makes NTCM very fast running in operational applications. The presented approach performs well when fed with the same Az parameter as NeQuick-G. The global performance analysis with reference Vertical Total Electron Content (VTEC) data from the International GNSS Service (IGS) shows that the performance of the NTCM was better than that of NeQuick-G. A compar- ison with reference Slant TEC (STEC) data shows that there is no significant difference between both models performance in terms of residual statistics such as Root Mean Square (RMS), mean and Standard Deviation (STD). An improved mapping function could even reduce correspond- ing errors when transforming NTCM derived VTEC to STEC values used for comparison. When comparing the computational time, it is found that the NTCM use is in average 65 times faster than the NeQuick-G operation.

The model residuals ($VTEC_{model}$ – $VTEC_{igsg}$) are determined and corresponding mean, Standard Deviation (STD), and Root Mean Squares (RMS) are computed and enlisted in the Table 1 for the years 2014 and 2015. Additionally, we compared the model performance for the low latitude region 30° N – 30° S covering all longitude and the hours of 06:00-18:00 local time. Ionospheric effects are most dominant in the low latitude region during day time hours. The model residual statistics are given in Table 1.

Table 1: Statistics of model residuals with respect to the reference igsg data showing their perfor- mances for global day and nighttime and low latitude daytime analysis.

Residual error statistics in TECU	NeQuick-G		NTCM	
	2014	2015	2014	2015
global RMS	9.6	7.8	7.8	6.4
global mean	-3.3	-2.7	-1.5	-0.6
global STD	9.0	7.4	7.7	6.4
regional RMS	17.0	10.7	13.8	9.6
regional mean	-9.1	1.2	-6.8	0.8
regional STD	14.4	10.6	12	9.5

By comparing the values in Table 1, we find that NTCM residual statistics are less than the corresponding NeQuick-G values for both global and regional (low latitude day time) cases during 2014 and 2015.

In the Figures 3 and 4 the RMS residuals over the globe are shown for different local time (LT) periods in 2014 and 2015. Figure 3 shows the error distribution when all local times (0-24 LT) are considered, whereas Figure 4 shows the error distribution for the daytime hours 12-15 LT. In each case the RMS residuals are determined separately at each grid location (2.5° and 5° latitude and longitude grid) considering a full year of data and shown in the global map.

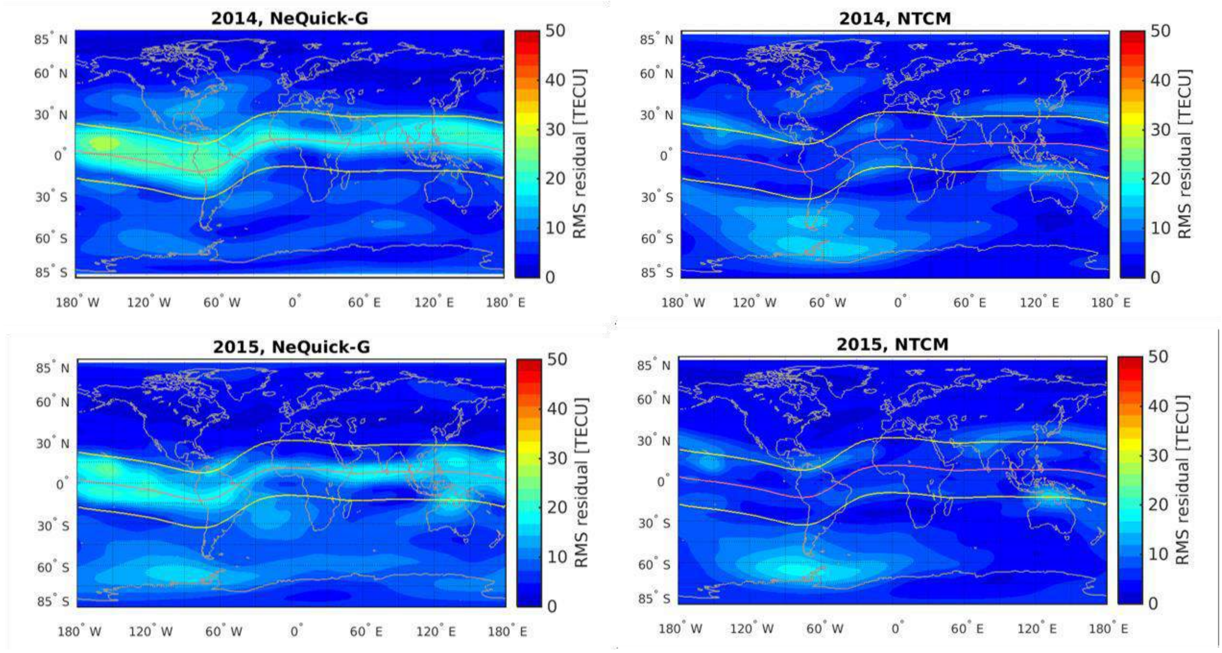

Figure 3: VTEC RMS residual error distribution in 2014 (top panel) and 2015 (bottom panel) for Ne-Quick-G (left panel) and NTCM (right panel) considering all local time.

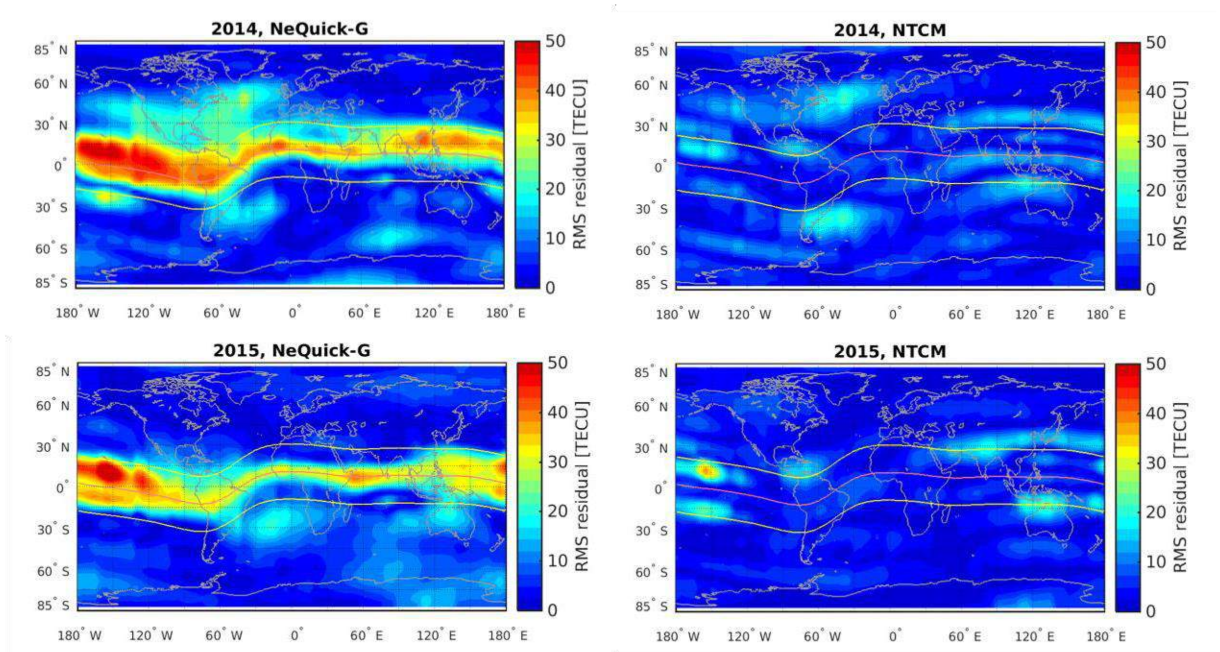

Figure 4: VTEC RMS residual error distribution in 2014 and 2015 for daytime hours 12-15 LT for Ne- Quick-G (left panel) and NTCM (right panel).

Figure 3 shows that at the equatorial regions on both sides of the geomagnetic equator NeQuick- G shows larger RMS errors when compared to the NTCM model. By comparing NeQuick-G errors in Fig. 4 and Fig. 3, we see that RMS errors are much higher for the local noon case (12- 15 LT) compared to the all local time case. On the contrary, the NTCM errors are slightly increased for the local noon case.

Cahuasquí et al. (2022) performed a global statistical validation of the NTCM-G model in the position domain by comparing its results with the results of the Klobuchar and NeQuick-G models for the first time. For this purpose, we used the GNSS analysis tool gLAB and its customization capabilities in the Standard Point Positioning (SPP) mode. The data used for model validation corresponds to a one-month period of perturbed solar and geomagnetic activity (December 2014) and another one-month period of quiet conditions (December 2019). The data has a worldwide coverage with up to 73 IGS stations. The statistical analysis of the hourly average 3D position error shows that whereas the root mean squared (RMS) values of the Klobuchar model are 6.71 and 2.75 m for the perturbed and quiet conditions, respectively, the NeQuick-G model has RMS values of 4.61 and 2.35 m. In comparison, the corresponding RMS values of 4.36 and 2.32 m of the NTCM-G model confirm its better positioning performance for both periods (see Figures 5 and 6).

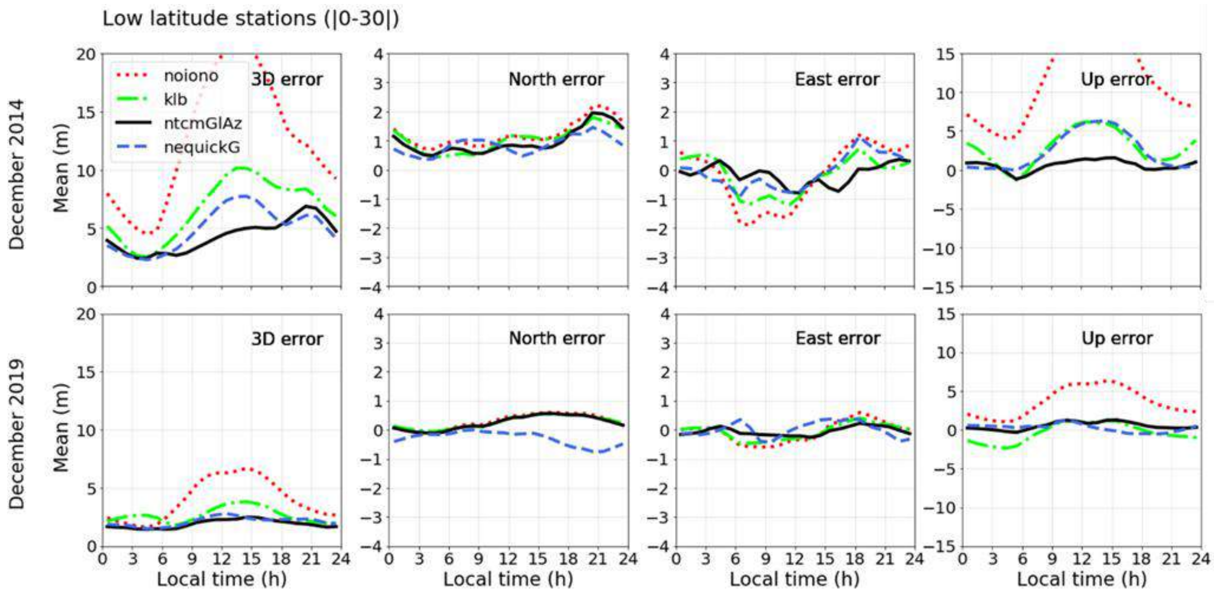

Figure 5: Hourly mean of the 3D, North, East and Up position errors for the total sample of low-latitude stations. The panels depict a comparison between the positioning performance of the four tested ionospheric correction models for perturbed (top panels) and quit (bottom panels) conditions.

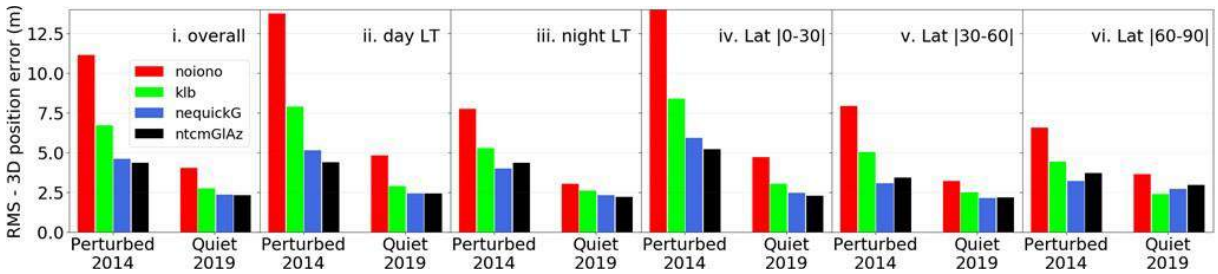

Figure 6: Graphical comparison between RMS values of the 3D position error achieved with the four modelling approaches for perturbed and quiet periods. The panels display the results for subsets organized by local time and latitude range.

As summary of this novel validation of the NTCM ionospheric model driven by Galileo ioni- zation coefficients we can state that, in the position domain, the NTCM-G clearly outperforms the Klobuchar model and slightly surpasses the accuracy of NeQuick-G model on a global scale.

NTCM G is now available on the European GNSS Service Centre (GSC) website (https://www.gsc-europa.eu/news/) for the Galileo Open Service. It will be used as an alterna- tive of NeQuick G model for correcting ionospheric delay of single-frequency Galileo signals.

Recently GSA published the NTCM G algorithm description in details to be implemented at user receivers (see https://www.gsc-europa.eu/sites/default/files/NTCM-G_Ionospheric_ Model_Description_-_v1.0.pdf) which compliments the Galileo OS SISICD [2021]. The doc- ument also includes the implementation guidelines for user receivers, and data for the verifica- tion of independent implementations. The source code of NTCM G recommended for imple- mentation in user equipment is also available at https://www.gsc-europa.eu/support-to-devel- opers/ionospheric-correction-algorithms/ntcm-g-source-code. The software package provides a portable and validated C/C++ implementation (Matlab and Simulink implementations are also available), including testing functions and testing vectors.

Investigation shows that NTCM G algorithm is less complex compared to NeQuick G and thereby requires less computational resources while providing a good performance to single- frequency Galileo users. Such a fast and robust model is considered as highly beneficial in particular for mass-market receivers (e.g. smartphones) since they have limited capacity in terms of hardware. Safety of Life (SoL) applications would certainly also benefit from the re- duced complexity of the algorithm that would facilitate the required certification of the equip- ment (e.g. certification of the avionics receiver).

It is noted that NTCM G offers an alternative to NeQuick G (users are free to implement either one) with reduced computational load and complexity for certain users. The NTCM G model was developed by the German Aerospace Centre (DLR) and validated by the Joint Research Centre (JRC) of the European Commission with the support of the European Space Agency (ESA). The description of the source code and its implementation were carried out jointly be- tween DLR and JRC, with the European Union Agency for the Space Programme (EUSPA) supporting the review and the publication of the model description.

Global equivalent slab thickness model of the Earth’s ionosphere

Jakowski and Hoque (2021) presented a prediction model for the equivalent slab thickness (Neustrelitz equivalent Slab Thickness Model – NSTM, see Figure 7). The model approach is similar to a family of former model approaches successfully applied for Total Electron Content (TEC), peak electron density NmF2 and corresponding height hmF2 at DLR. The model de- scription focuses on an overall view of the behaviour of the equivalent slab thickness as a func- tion of local time, season, geographic/geomagnetic location and solar activity on a global scale.

The equivalent slab thickness of the ionosphere that characterizes the width of vertical electron density profiles is an important parameter for a better understanding of ionospheric processes under regular as well as under perturbed conditions. The equivalent slab thickness is defined by the ratio of the vertical total electron content over the peak electron density and is therefore easy to compute by utilizing powerful data sources nowadays available thanks to ground and space based GNSS techniques. They used peak electron density data from three low earth or- biting (LEO) satellite missions, namely CHAMP, GRACE and FORMOSAT-3/COSMIC, as well as total electron content data obtained from numerous GNSS ground stations.

In conclusion, the model agrees quite well with the overall observation data within a RMS range of 70 km. There is generally a good correlation with solar heat input that varies with local time, season and level of solar activity. However, under non-equilibrium conditions, plasma transport processes dominate the behaviour of the equivalent slab thickness. It is assumed that night-time plasmasphere-ionosphere coupling causes enhanced equivalent slab thickness values like the pre-sunrise enhancement. The overall fit provides consistent results with the mid-latitude bulge (MLB) of the equivalent slab thickness, described for the first time in this paper. Furthermore, the model recreates quite well ionospheric anomalies such as the Night-time Winter Anomaly (NWA) which is closely related to the Mid-latitude Summer Nighttime Anomaly (MSNA) like the Weddell Sea Anomaly (WSA) and Okhotsk Sea Anomaly (OSA). Further model improve- ments can be achieved by using an extended model approach and considering the particular geomagnetic field structure.

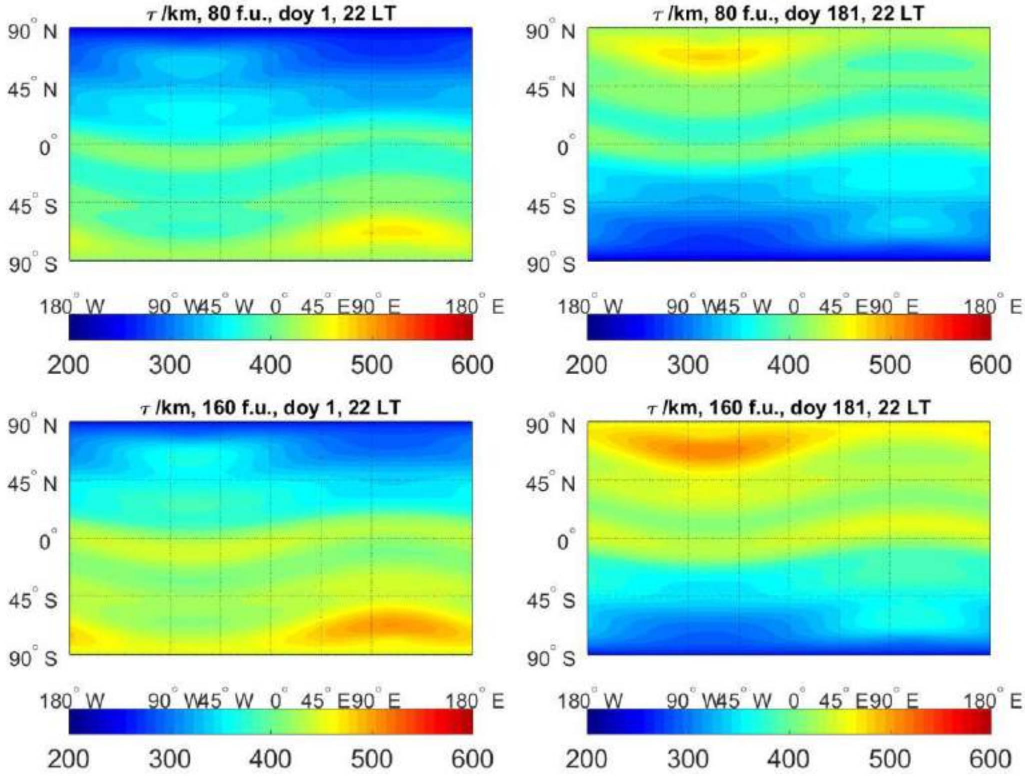

Figure 7: Global maps of NSTM at 22 LT for days 1 (left) and 181 (right) under low and high solar activity conditions (F10= 80 and F10=160, respectively).

A new climatological electron density model for supporting space weather services

The Neustrelitz Electron Density Model (NEDM2020) is a three-dimensional electron density model developed at German Aerospace Center (DLR) for supporting space weather services and mitigation of propagation errors for trans-ionospheric signals (Hoque et al., 2022). The 3D electron density distribution is modelled by combining a Chapman layer representing the iono- spheric F-layer, an E-layer model and a plasmasphere model (see Figure 8). The F-layer param- eters such as the peak density, peak height and TEC resulting from the Chapman layer are precomputed from already existing empirical models Neustrelitz Peak Density Model (NPDM, Hoque and Jakowski 2011),

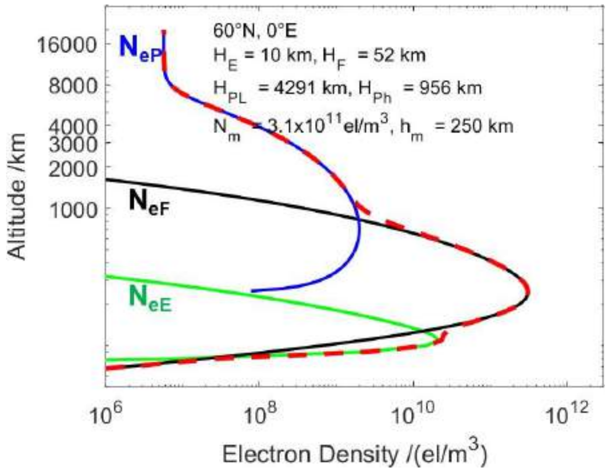

Figure 8: Total electron density distribution superposed by contributions from the NPSM- (blue), F-layer (black) and E-layer (green).

Neustrelitz Peak Height Model (NPHM, Hoque and Jakowski, 2012) and Neustrelitz TEC Model (NTCM, Jakowski et al., 2011), respectively.

The topside ionosphere is modelled by superposing the Neustrelitz Plasmasphere Model (NPSM, Jakowski and Hoque, 2018) to the F-layer and E-layer models. The same driving pa- rameter namely the solar radio flux index F10.7 is used for running sub-models. The combined model describes the ionosphere and plasmasphere up to GNSS orbit height of about 20,000 km. Knowing the F10.7 in advance NEDM2020 can predict the electron concentration at any given location and time in the ionosphere for trans-ionospheric applications. Use of a limited number of model coefficients (< 100) and no interpolation for model parameters makes NEDM2020 a fast running model, suitable for operational use.

Use of CAS rapid GIM for global total electron content prediction

CAS rapid GIM is computed by spherical harmonic expansion using a global network of GNSS stations. A maximum posterior estimation-based method is proposed to predict the variation of global ionospheric total electron contents using CAS rapid ionospheric products. CAS 1-, 2- and 5-day predicted GIMs are routinely generated by predicting each spherical harmonic coef- ficient using the proposed algorithm. In case individual spherical harmonic coefficients are de- rived, the predicted GIM is then reconstructed by spherical harmonic expansions. The quality of CAS predicted GIMs as well as those from CODE, ESA and UPC-IonSAT was evaluated during 2008-2020. Results show that the performance of CAS predicted GIM is on the same level with CODE product, which is notably better than ESA and UPC predicted ones. While CAS predicted GIMs have not yet been provided to the IGS, the products are downloadable from CAS repository itself (ftp://ftp.gipp.org.cn/product/ionex/). Note that predicted models are commonly computed by either extrapolation technique or physical model using historical ionospheric observation data, the pronounced performance degradation can be foreseen in the occurrence of ionospheric disturbances or perturbances.

Use of CAS predicted GIM for RT-GIM generation

To enable GNSS applications with low or no latency, the real-time service (RTS) of the IGS was launched in 2013. IGS RTS provides real-time data streams with typical latencies of up to few seconds, containing multi-frequency and multi-constellation GNSS measurements from a global network of high-quality GNSS receivers. The availability of RT-GNSS data streams is being explored to generate the experimental global ionospheric maps in real-time. Considering the discontinuous real-time data streams in some cases, CAS 2-day predicted GIM is introduced to provide priori ionospheric information to support the reconstruction of real time ionospheric maps. A predicting-plus-modeling approach is employed at CAS for the routine computation of its RT-GIM, which is provided in RTCM-SSR and IGS-SSR streams via CAS caster (cas- ip.gipporg.cn:2101) in real time, and IONEX files (ftp://ftp.gipp.org.cn/product/ionex/) for post-processing applications. Details on the generation and validation of RT-GIM are reported in Li et al. (2020). It is planned at CAS to shorten the time span of the prediction model from 2 days to few hours to support the generation of more reliable real-time global ionospheric models.

Ionospheric forecasting activity at Beihang University

Since the beginning of 2018, the daily prediction of GIMs has been implemented in routine operation at Beihang University (Wang et al. 2018, 2020). The 1-d ahead and 2-d ahead pre- dicted GIMs are provided with temporal resolution of 1 hour. The predicted GIMs products are available at http://pub.ionosphere.cn/prediction/daily/. Also, the TEC maps of the latest predic- tions can be found on the web page: http://ionosphere.cn/page/daily_gim_prediction. The per- formance of the predictions (B1PG, 1-d ahead) is investigated by comparison with our final GIMs (BUAG) from Jan. 22 in 2018 to Apr. 22 in 2021. The following Figure 9 shows the daily bias and RMS of the differences between the B1PG and BUAG.

Wang et al. (2021) performed the prediction of ionospheric climate index (ICI) indicating the general state of the ionosphere. And the ICI predictions are calculated from the predicted GIMs (B1PG and B2PG). The comparison between the final ICI and predictions is depicted in Figure 10. The data source of ICI and predictions is public access at http://pub.iono- sphere.cn/space_weather/

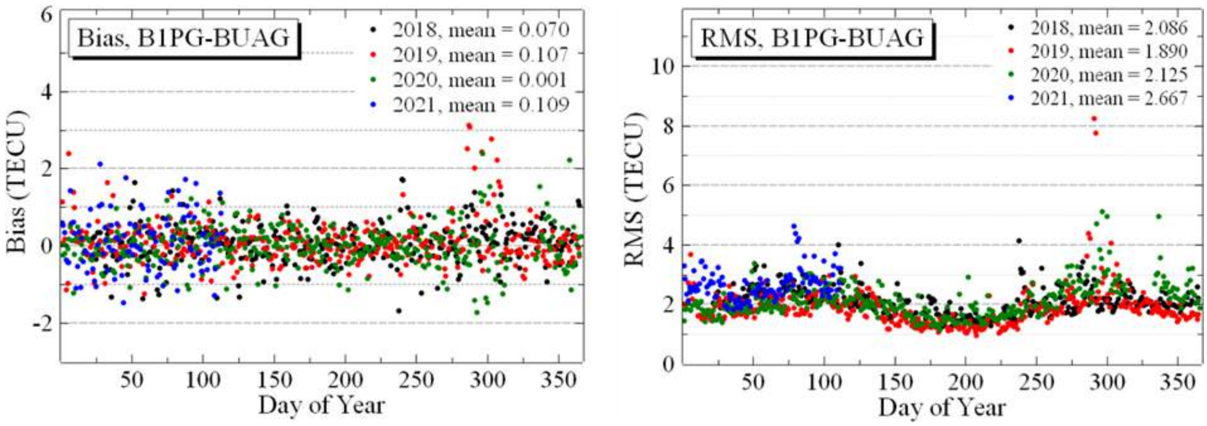

Figure 9: daily bias and RMS of the differences between the 1-d ahead predicted B1PG and final BUAG from Jan. 22 in 2018 to Apr. 22 in 2021.

Recently, ICI is introduced as a new driving parameter for the NeQuick model (Wang et al. 2023). In comparison, the ICI-driven NeQuick model has a better performance than the Az-driven NeQuick G model at both low and high latitudes. In addition, only one GNSS station at low latitudes is required to calculate the ICI, which would save maintenance costs and improve the efficiency of updating the broadcast coefficients. The performances of the NeQuick model using different driving parameters were investigated by comparing the global ionosphere TEC maps derived from the models with the final GIMs of the CODG. The results indicate that the ICI-driven NeQuick model performs better than the official Ne- Quick G model at both low and high latitudes. In addition, using the ICI as the driving parameter of the NeQuick model requires only one GNSS station at low latitudes. Therefore, it would be profitable to save the cost of maintaining multiple stations and improve the efficiency of updat- ing the broadcast coefficients.

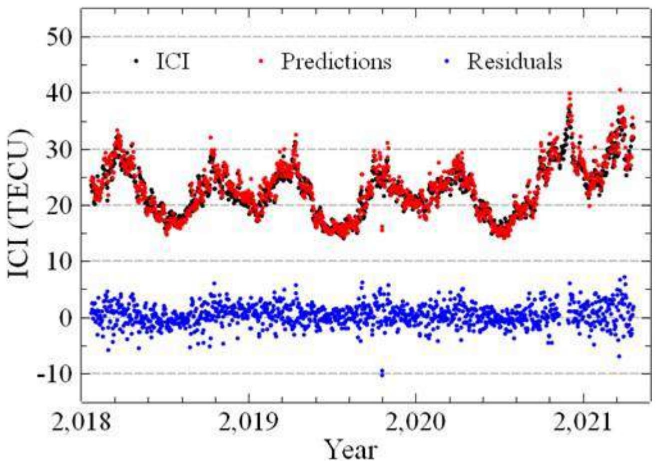

Figure 10: The final ICI, predictions and re- siduals from Jan. 22 in 2018 to Apr. 22 in 2021.

A simplified worldwide ionospheric model (SWIM) is proposed for satellite positioning. By comparison, SWIM model has better performance than the Klobuchar model in terms of accu- racy at both low and high solar activity, and is comparable to the NeQuick G and BDS iono- spheric models. At the same time, the SWIM model (Wang et al. 2022) has high efficiency because of the simple calculation process. It has great potential for ionospheric delay correc- tions in satellite navigation and positioning.

Ionospheric Scintillation Prediction on S4 and ROTI Parameters using Artificial Neutral Net- work and Genetic Algorithm

Atabati et al. (2021) studied ionospheric scintillation prediction on S4 and ROTI Parameters using Artificial Neutral Network and Genetic Algorithm. Irregularities in electron density usu- ally correlate with ionospheric plasma perturbations. These variations making radio signals fluctuations, in response, generate ionospheric scintillations that frequently occur in the low latitude regions. In this research, the combination of Artificial Neural Network (ANN) with Genetic Algorithm (GA) is implemented to predict the ionospheric scintillations. The GA method is considered for obtaining the ANN model's initial weights. This procedure is applied to GNSS observations at GUAM (13.58°E, 144.86°N, 201.922H) station to the daily prediction of Ionospheric amplitude scintillations via predicting the signal to noise ratio (S4) or via pre- diction of Rate of TEC Index (ROTI). 30-day modelling was carried out for three months of January, March, and July, representing different seasons of the winter solstice, equinox, and summer solstices during three different years of 2015, 2017, and 2020 with different solar ac- tivities. The models, along with ionospheric physical data, were used for the daily prediction of ionospheric scintillations for the consequent day after the modelling. The prediction results are evaluated using S4 derived from GNSS observations at the GUAM station. The designed model has the ability to predict daily ionospheric scintillations with an accuracy of about 81% for S4 and about 80% for ROTI (Atabati et al. 2021).

Other relevant activities by WG members

Aragon-Angel et al. (2021) conducted an optimization study of NeQuick-G which is used as Galileo ionospheric correction algorithm. Aragon-Angel et al. (2019) integrated Galileo Iono- spheric Correction Algorithm into the Open-Source GNSS Laboratory Tool Suite (gLAB). They released NeQuick-G into the open source gLAB software tool. Rovira-Garcia et al. (2020) assessed the quality of ionospheric (prediction) models through GNSS positioning error. Timoté et al. (2020) studied the impact of medium-scale traveling ionospheric disturbances on net- work real-time kinematic services.

Juan (2022) addresses an important topic for the GNSS community that routinely uses the com- bination L1-L2. Depending on the receiver type, the ionospheric content that is extracted with such combination might be contaminated. Nie (2022) investigated the effect of different space weather phenomena in the positioning domain. Mainly the effect on the signal and the cycle slip detection. Yin et al. (2022) performs a climatological study of the anomalies in the Electron Content (i.e. an excess of TECUs) that occurs at night time. For this study, we used Radio Occultation data at different Solar Cycle conditions. Rovira-Garcia et al. (2021) presented the developments of our two-layer ionospheric model that has been chosen as a baseline model for the service level 2 of the Galileo HAS. The contribution shows the modifications that we had to perform to our model to adapt to the HAS.

An ongoing joint activity of WG members: Comparison of Global Ionosphere Forecasting Techniques

The main objective of the Prediction of Ionospheric state and Dynamics Working Group has been studying the inter-dependency of different space-weather parameters during quiet and per- turbed conditions and developing global and regional prediction approaches to handle varia- tions on different parts of the globe in different times. During the last few years different groups have developed algorithms to meet objectives provided. The results have been presented/pub- lished in scientific events or journals.

The comparison of these models in a common setting is necessary to understand the advantages and disadvantages of the developed models. In a common test scenario different models can be compared and with their associated characteristics in different space weather situations. In ad- dition, an ensemble of the models can be generated and tested.

Starting from the last quarter of 2022 a comparison study of different Ionospheric state predic- tion models has been conducted within the working group activities. The common test scenario contains two consecutive quiet and perturbed days within 2022. The days are selected to be the 14th and 15th of April 2022 by considering DST index for geomagnetic storm conditions and the 29th and 30th of July for quiet Ionospheric states. The training data for ML/DL methods has been any interval of GIMs between 2000 and 2021. The models are compared to IGS final maps on the given dates by means of RMSE, mean and bias calculated over North and South hemi- sphere a well as globally. Here the preliminary results from four contributing members are listed where more results are expected to arrive in the continuation of the comparison effort. The current results are from German Aerospace Center - Institute for Solar Terrestrial-Physics (DLR), Universitat Politècnica de Catalunya (UPC), Department of Civil and Geomatic Engi- neering-ETH Zurich (ETH) and Department of Geomatics Engineering – Hacettepe University (HUN). The individual model summaries are given below with associated published articles.

UPC

The method is based on searching the historical database for the dates of the GIMs closest to the current map and using as a prediction the maps in the database that correspond to time shifts on the prediction horizons. In contrast to other methods of machine learning, the implementa- tion only requires a distance computation and does not need a previous step of model training and adjustment for each prediction horizon. Also provides confidence intervals for the forecast. The method has been analysed for two full years (2015 and 2018), for selected days of 2015 and 2018, i.e., two storm days and two non-storm days and the performance of the system has been compared with CODE (24- and 48-hour forecast horizons). This technique, allows predic- tors to be implemented without the need to train a model (such as a deep neural network, or similar machine learning techniques), which makes the system flexible to changing or previ- ously unseen conditions. It is based on a Linear Combination of GIMs from a historical data set that spans over two Solar Cycles. It also provides confidence intervals for the forecast, namely the RMSE. The computational time is of the order of milliseconds and can be implemented in real time (Monte-Moreno et.al., 2022).

DLR

A fully connected neural network was trained with Global Ionosphere Maps (GIMs) from the Center for Orbit Determination in Europe (CODE) during the last two solar cycles. Instead of training the model with daily data, we downscaled the dataset by taking Carrington rotation averages at each hour, where one Carrington rotation is approximately 27 days. Using Carring- ton rotation averages instead of daily data the computational complexity was reduced. The day of year, universal time, geographic longitude, geomagnetic latitude, solar zenith angle, and solar activity proxy, F10.7, are used as the input parameters for the model and the output is Vertical Total Electron Content (VTEC). The model was tested with unseen data during a high solar activity period, 2015, and a low solar activity period, 2020. The model was able to show large- and small-scale features of the ionosphere and it was outperforming the Neustrelitz TEC Model (NTCM) by approximately 1 TEC unit (Adolfs and Hogue, 2021).

ETH

The models use the solar geomagnetic coordinate system for forecasting GIMs where the fore- casted GIMs are transformed back to the geographic coordinate system. IGS GIMs are interpo- lated to obtain 1-hour interval maps. The training phase of all models utilized IGS GIMs span- ning the period from

Table 2. Architecture of convLSTM model

Layer	Channel number I	Channel number O	Kernel size
convLSTM	1	64	5 x 5
convLSTM	64	32	5 x 5
convLSTM	32	16	3 x 3
conv	16	25	3 x 3

2004 to 2021, while the testing phase involved data exclusively from 2022. For the first solution (LSTM), we combined PCA (spatial) and LSTM (temporal) to forecast GIMs. Initially, the IGS GIMs are decomposed into 135 principal components through principal component analysis (PCA). Subsequently, individual LSTM models are trained to predict the 135 PC components, which are then utilized to reconstruct the GIMs. The proposed LSTM architecture contains one input layer, three hidden layers and one output layer. The number of units for the hidden layers are 96, 48 and 24, respectively. The inputs are the past 14 days' IGS GIMs and the outputs are the predicted GIMs for the next day (from 00:00 to 24:00, 24 hour ahead predictions). Compared to the LSTM model, the hours of day, day of year and other space weather indices are added as auxiliary input features in the second solution (LSTM_aux). The space weather indices including the interplanetary magnetic field (Bz) and disturbance storm time (Dst), solar wind (SW) plasma speed, sunspot number (R) and solar radio flux are also included. The third solution (convLSTM) utilizes a convolutional LSTM (convLSTM) model for GIM forecasting. The convLSTM architecture, as described in Table 2, takes as input the past 2 days' IGS GIMs and predicts the GIMs for the next day (00:00 to 24:00, 24h ahead predictions).

HUN

IGS final GIM maps are represented as coefficients of Trigonometric B-Splines in a solar geo-magnetic reference frame (Yildiz, 2021). In this setting IGS final GIM maps from 2006 to 2022 are converted to a time series of Trigonometric B-spline coefficients by Least-Squares estima- tion procedure. The resulting B-spline coefficients provide a low-resolution representation of GIMs. The proposed model architecture is similar to an Auto Encoder where the coefficients of Trigonometric B-Splines are used as an image with size of (18 x 26). Training dataset con- tains coefficients between 2006 and 2021 with a test-validation split of 20%. Inputs for both 24 hours ahead forecasting and 1 hour ahead forecasting can be represented as [N, time_step, height, width, 1] where N is batch size (64) and time step is selected as 6. Height and width are 18, 26, respectively. Output shape is (N, 1, 18, 26, 1) representing the forecast GIM coefficients. The last 6 hours are used to forecast 1 hour ahead GIMs such that [t-5, t-4, t-3, t-2, t-1, t] are the inputs and [t+1] is the output for 1 hour forecast. Similarly, the same hour of day in the last 6 days are used as input to forecast 24h ahead GIMS, such that [t-120, t-96 t-72, t-48, t-24, t] are used as input and [t+24] is the output. For both models three ConvLSTM2D layers with node sizes of 32, 16 and 32 respectively are used. The activation function is selected as "relu" and Batch Normalization layers are used between each ConvLSTM2d layers. The last layer is a Conv3D layer to provide the forecast coefficients. The kernel size is selected as 3x3.

Combined Model - COM

The comparison study also tries to investigate the potential of an ensemble forecast model where individual models are combined with associated weights. The weights of the combination are currently based on the mean RMSE values of each model on the first day (doy 210 for quiet and doy 104 for storm days). The reciprocal of mean RMSE values is used as weight for each model. However, different weighting schemes such as hourly RMSE or region-based combina- tion techniques may also be considered in the continuation of the activities.

Forecast results

For the results of 1h forecasts only HUN and UPC results are shown here since the other models provide 24h forecasts for the time being. The results are shown for 1h and 24h forecast GIMs difference from the IGS final maps using the Mean, Std and RMSE of global VTEC values. The global statistics for each hour in the given days are plotted with a label indicating the model. In addition, combined maps are shown with a label COM.

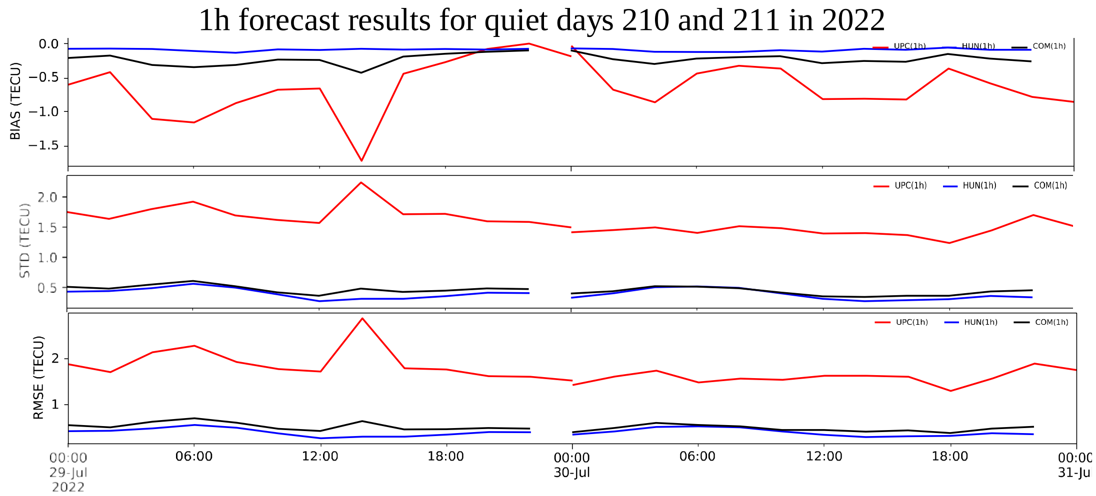

Figure 11: One hour ahead forecast errors of UPC (red), HUN (blue) and COM (black) with respect to IGS final maps on quiet days of 210 and 211 in 2022

Quiet Days

One hour forecast results for the quiet days of 210 and 211 in 2022 are given in Figure 11. It can be seen that HUN results provide closer results to the IGS final maps with very low bias. The low RMSE values for HUN compared to the nearest neighbour averaging of UPC can be due to very slow change of ionospheric state on quiet days which results in high correlation with the previous hour given as input to the HUN forecast model. The combined model COM is using the inverse of RMSE for weighting thus the results are closer to HUN forecast results.

One day ahead forecast results for quiet days are presented in Figure 12. One immediate obser- vation from the figure is that forecast provided by DLR has an almost constant bias of -2 TECU. This may be a result of DLR using CODE GIMs rather than the IGS final GIMs in their training procedure (Adolfs and Hoque, 2021). Another observation is that the results of all ETH models start with a very low RMSE values for the beginning of each day. This is due to the fact that the model is using all hours from the previous day to forecast the next day starting from midnight. Thus, the first hour in a given day can be considered as one hour forecast. If compared to the one-hour forecasts in Figure 11, then the results for these hours can be considered comparable to the one-hour results provided by HUN models. As the hours advance all models tend to provide similar results. The combined model (COM) shows

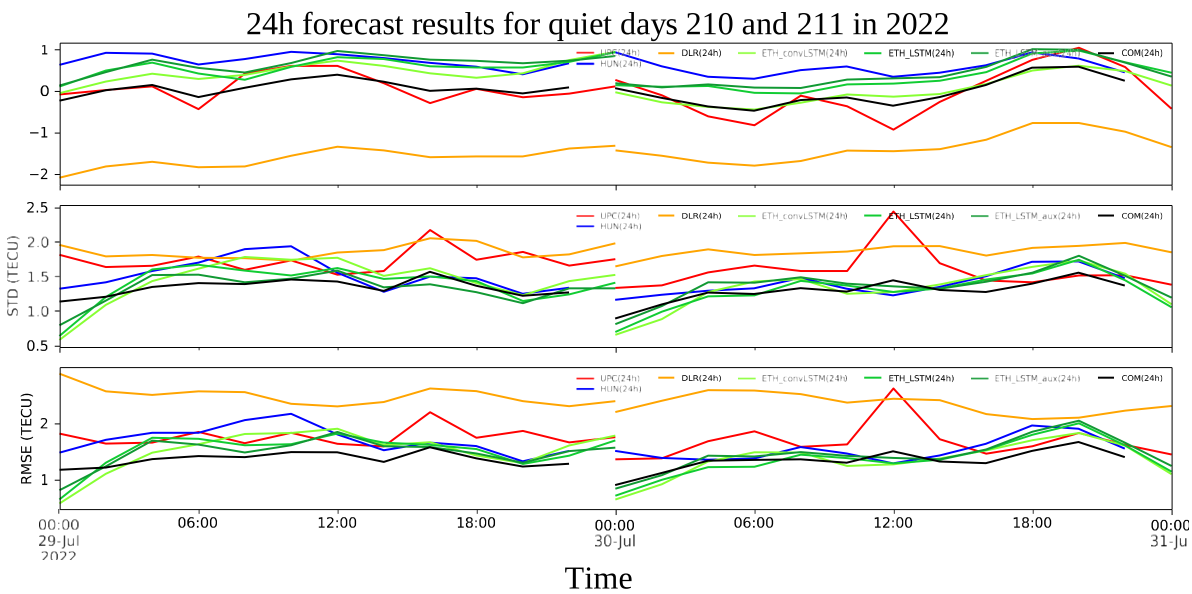

Figure 12: One day ahead forecast errors of UPC (red), HUN (blue), DLR (orange), ETH models (shades of green) and COM (black) with respect to IGS final maps on quiet days of 210 and 211 in 2022.

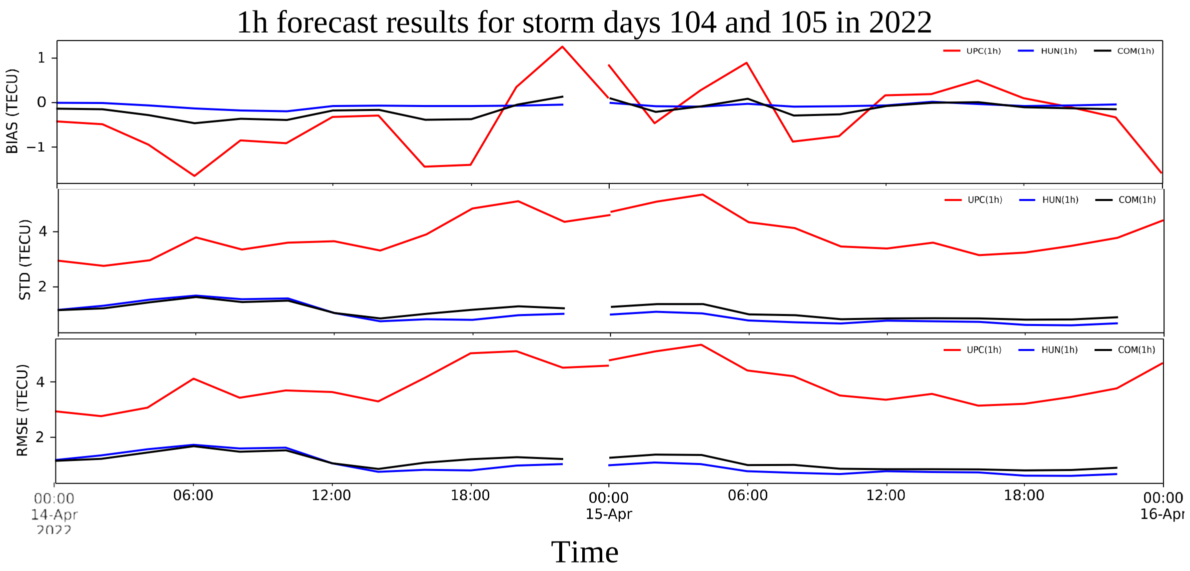

Figure 13: One hour ahead forecast errors of UPC (red), HUN (blue) and COM (black) with respect to IGS final maps on storm days of 104 and 105 in 2022.

consistent behaviour of RMSE and bias indicating a promising result for a motivation of ensemble model for Ionosphere fore- cast. All ETH model results are very close results where LSTM_aux model providing slightly better performance among the three. The HUN model results are close to the ETH models which use similar forms of DL techniques, however, the HUN model forecast the B-spline coefficients rather than GIM maps.

Storm Days

One hour forecast results for the storm days of 104 and 105 in 2022 are given in Figure 13. The UPC results provide consistent results compared to the quiet days showing a stable behaviour of forecasting. It can be seen that HUN results provide lower bias and variance as is the case for quiet days. However, the variance is increased to over one TECU. The combined model COM is using the inverse of RMSE for weighting thus the results are closer to HUN forecast results.

The 24 hour forecast results of all models on the storm days of 104 and 105 in 2022 are given in Figure 14. Similar to the quiet days, ETH model results for the first hours of each day are lower since

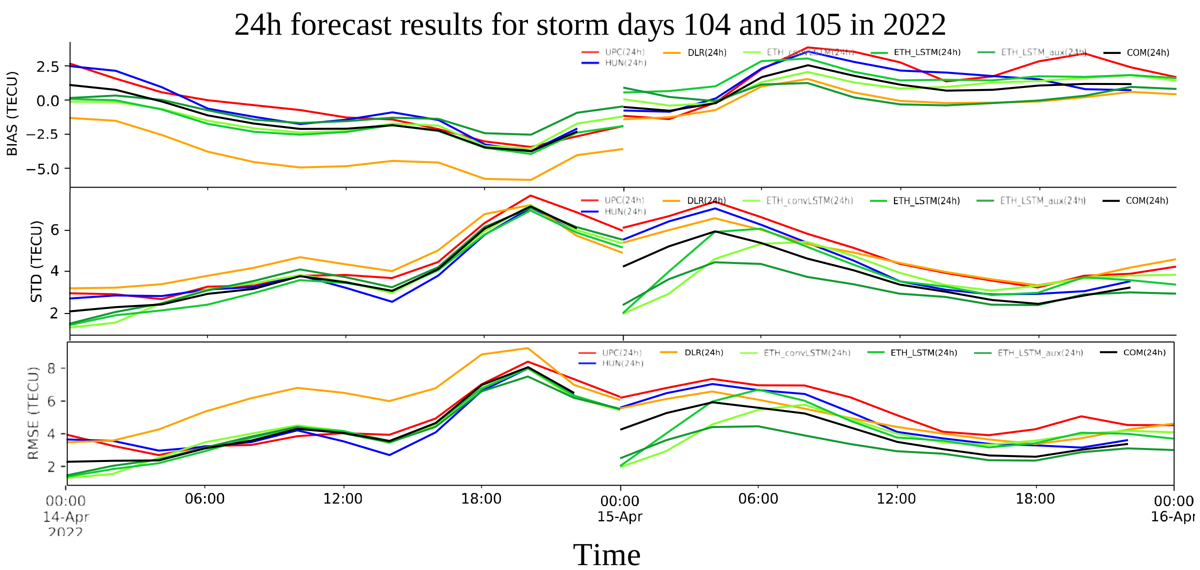

Figure 14: One day ahead forecast errors of UPC (red), HUN (blue), DLR (orange), ETH mod- els (shades of green) and COM (black) and COM (black) with respect to IGS final maps on storm days of 104 and 105 in 2022.

they can be considered as 1h ahead forecasts due to the modelling of inputs. The results for the first hour of each day are consistent again with the 1h forecasts provided by HUN. The results from all models except the DLR provide similar results for doy 104 where again the difference can be related with the higher bias of DLR results on that day. All model results show a general tendency to provide higher variances in the second half of the day which may be attributed to underestimating the global VTEC on those hours. The HUN, ETH and UPC results show a general consistency. HUN results are lower for 10:00 to 18:00 UTC on doy 104.

On the other hand, on doy 105, the ETH LSTM_aux model provides generally better results. Again, a consistent behaviour can be observed from UPC model for each day. The combined model also provides consistent behaviour on each day having a tendency of low variance and low bias. The results for storm days for a combined model are also promising.

Conclusion and Future study directions

The results presented here are preliminary results from the comparison study. Different models trained with different ML/DL architectures and inputs may provide changing success for quiet and storm days. The preliminary results indicate that different techniques have pros and cons for different Ionospheric states. An ensemble model may provide promising results having both lower bias and variance. The weighting strategy applied in the preliminary results use the re- ciprocal of RMSE of each model in the first day of quiet and storm days. A better weighting strategy can be built considering the pros and cons of each model on different regions and time of day. A focus on regional structures, additional insight can be achieved on the success of the individual forecast models. The results will also provide a basis for active discussion on the type of improvements and combination techniques. The initial results are promising to motivate joint efforts on producing sustainable, reliable and accurate forecast on Ionospheric state for both perturbed and quiet conditions. In addition, the efforts for combination strategies for online near real-time combination of the Ionospheric state may potentially be possible.

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WG 4.3.3 Ionosphere scintillations

Chair: Jens Berdermann Germany)
Vice-Chair: Lung-Chih Tsai (Taiwan)

Members

- Charles L. Rino (USA)
- Michael Schmidt (Germany)
- Rui Fernandes (Portugal)
- Chi-Kuang Chao (Taiwan)
- Alexei V. Dmitriev (Russia)
- Yoshihiro Kakinami (Japan)
- Suvorova Alla (Russia)
- Sudarsanam Tulasiram (India)
- Chinmaya Kumar Nayak (India)
- Shin-Yi Su (Taiwan)
- Felix Antreich (Brazil)
- Michael Felux (Swiss)
- Dmytro Vasylyev (Germany)

Activities and publications during the period 2019-2023

The activities of this WG are

1. understanding the climatology of ionospheric scintillations, namely, its variation with latitude, season, local time, magnetic activity and solar cycle,

- *Study the relationship between low latitude scintillation onset in respect to changes of the sunset terminator over Africa*

A method for automatic detection of plasma depletions by using GNSS measurements have been developed and tested at several GNSS stations in the equatorial region [Mer- sha et al, 2020]. The method has been applied to study the relationship between low latitude scintillation onset in respect to changes of the sunset terminator over Africa [Mersha et al, 2021].

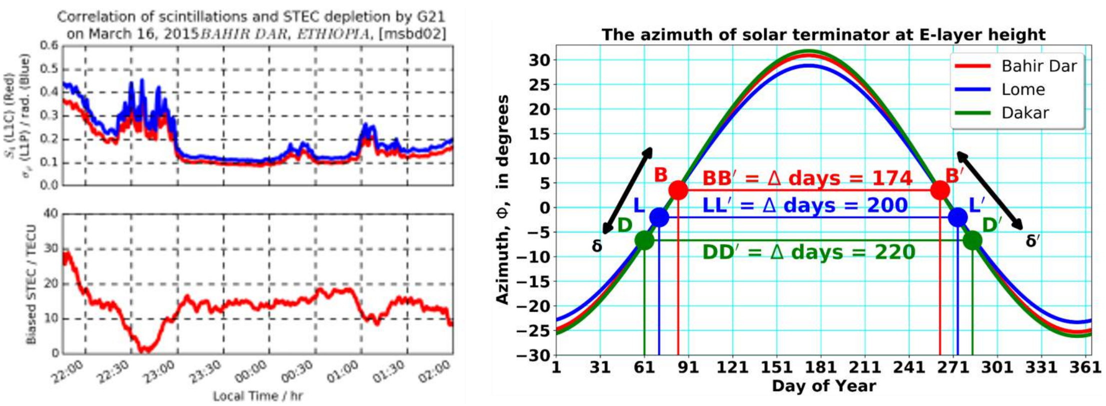


Figure 1: (left) scintillations indices (top panels) and STEC depletions (bottom panels) observed by GPS G21 and GLONASS R20 satellite at measurement station Bahir Dar 02 (msbd02)/Ethiopia, on 16 March 2015 [Mersha et al, 2020]; (right) seasonal variation of the azimuth of the day-night terminator at GNSS stations in Dakar, Lomé and Bahir Dar. The indicated dots are days of azimuth coincidence with geomagnetic declination (horizontal lines) at these three selected stations.

Due to its permanent change, the solar terminator is in line with the geomagnetic decli- nation line twice a year, providing optimal conditions for the rapid changes in the elec- tromagnetic coupling processes especially in the E-region ionosphere. In the vicinity of the solar terminator, essential parameter like S4 index measurements have been analyzed to monitor and analyze perturbations in the ionosphere. The results give an insight into the underlying physical processes and will improve the model and forecast capa- bilities.

Storm-time scintillations associated with intense fluxes of energetic protons at low latitudes

Satellite experiments at low latitudes have shown that energetic (tens of keV) electrons and protons can penetrate from the Earth's radiation belt near the equator into the iono- sphere. The effect of the fluxes of these particles on the upper atmosphere and iono- sphere is investigated during a magnetic storm of July 22, 2009 [Golubkov et al., 2020]. Local variations in the concentration of ionospheric ions were investigated in the regions of injection of energetic electrons and protons with energies higher than 30 keV into the low-latitude ionosphere. Ion density and scintillations in the low-latitude ionospheric F- region were investigated using experimental data acquired from C/NOFS satellite [O. de la Beaujardiere et al., 2004]. The energetic particle fluxes were measured by NOAA/POES satellites at heights about 850 km [Evans and Greer, 2004]. It was shown a relationship between additional ionization by energetic electrons and an increase in the concentration in the F layer in the morning sector.

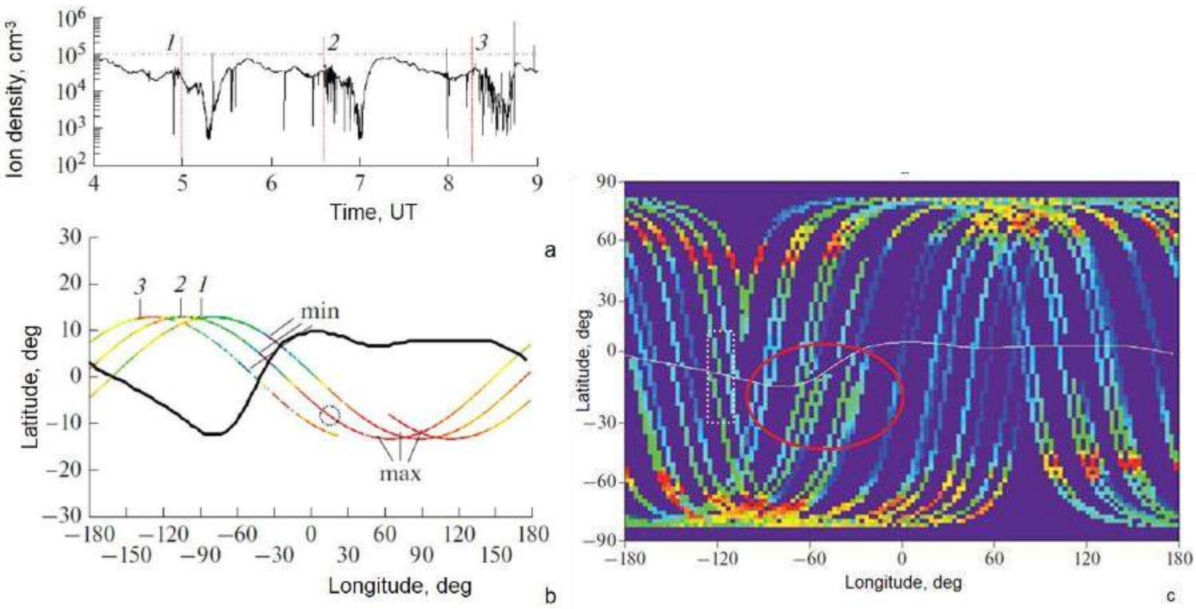


Figure 2: disturbances in the night-time low-latitude ionosphere during magnetic storm on July 22, 2009. Ionospheric ion density variations were measured by C/NOFS satellite: (a) time pro- file and (b) geographic map of three successive satellite orbits. Strong variations in the ion density are indicated by numbers 1, 2 and 3 corresponding to the satellite orbits. Panel (c) shows geographic distributions of fluxes of energetic protons with energies > 30 keV observed by NOAA/POES satellites. The vicinity of South Atlantic Anomaly (SAA) with continuous proton precipitation at low latitudes is bounded by the red oval and the region of storm-time precipitation of protons is indicated by white dotted rectangle. It can be seen that both strong ion density fluctuations and intense energetic proton fluxes occur simultaneously at low lati- tudes in the longitudinal region around -120 deg.

The ionospheric inhomogeneities observed in the night sector in the form of strong con- centration fluctuations are associated with the action of protons. The Figure 2 shows strong variations of the ion density observed by C/NOFS satellite in the nighttime low- latitude ionosphere in westward vicinity of the South Atlantic Anomaly (SAA) in the longitudinal sector around -120 deg. At the same time, NOAA/POES satellites observed in the same region intense fluxes of energetic protons with energies >30 keV. Those protons penetrated from the storm-time ring current to the ionospheric heights due to charge-exchange interactions. One can clearly see that the region of strong ion densityfluctuations coincides in time and space with the region of intense energetic fluxes that might indicate their close relationship.

Early development of shorter (3m) scale irregularities at the top of EPB

The Equatorial Plasma Bubbles (EPBs), once developed, grow nonlinearly into topside ionosphere and simultaneous secondary instabilities lead to the development of shorter scale irregularities. The altitudinal growth and generation of smaller scale irregularities determines the spatio-temporal occurrence and the intensity of ionospheric scintillations at wide spectrum of radio waves and have significant implications on the GNSS/Satellite Based Augmentation Systems. As the bubble grows into topside ionosphere, the signif- icant reduction of ion-neutral collisions and increased ratio of F- to E-region field-line integrated conductivities give rise to more rapid development of intermediate-to-shorter scale irregularities at topside compared lower altitudes. The larger structuring of EPBs in the topside ionosphere is found to be one of the important factors explaining the much stronger L-band scintillations at low-latitudes compared to equatorial latitudes besides the higher background density and larger density gradients. Here, we present a unique EPB observation from Equatorial Atmosphere Radar (EAR) that provides hitherto un- disclosed evidence for the smaller (3-meter) scale irregularities initially developing at higher altitudes and subsequently developing to lower altitudes which would have sig- nificant impact on the latitudinal development of L-band scintillations.

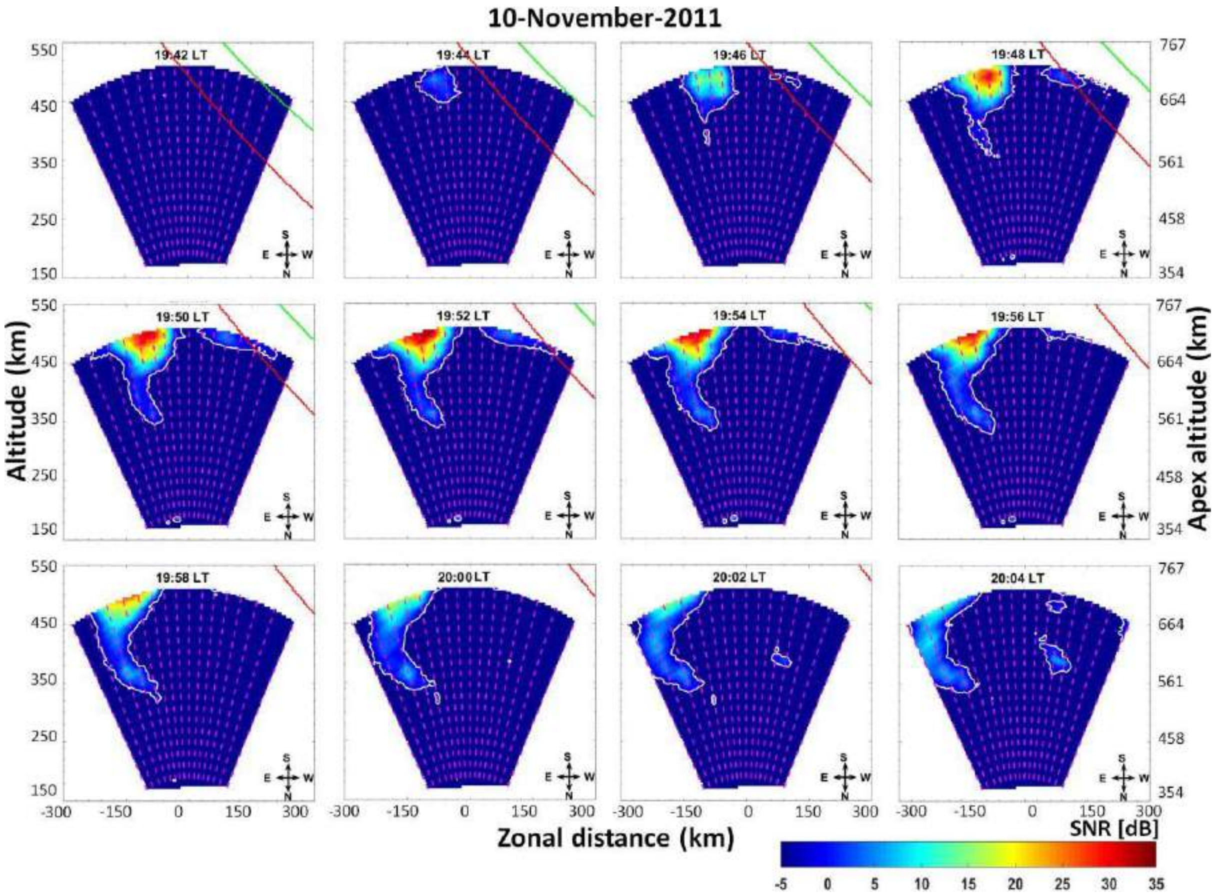


Figure 3: unique observational evidence for the early development of 3-m scale irregularities initially at the topside region of an Equatorial Plasma Bubble and subsequently at lower alti- tudes.

- *Periodic development of EPBs due to grav- ity waves originated from a Tropical Cy- clone*

The interesting cases of intense and peri- odic EPBs observed during 08 and 09 April 2013 by the 47 MHz Equatorial Atmos- phere Radar at Kototabang, Indonesia have been thoroughly investigated in view of its possible connection with the tropical cy- clone Victoria. The periodic EPBs are sep- arated by about 200-250 km and were found to initiate before the sunset. The pre- sunset onset and development of these pe- riodic EPBs were discussed in light of the gravity waves (GWs) excited in connection with the deep convection due to the tropical cyclone Victoria. The outgoing long-wave radiation measurement by very high-reso- lution radiometer (VHRR) onboard Indian meteorological satellite Kalpana-1 shows the occurrence of deep convective activity during these days. The presence of upward propagating gravity waves from the deep convective region associated with TC Vic- toria were confirmed using the GPS radio occultation observations. The GW signatures at ionospheric altitudes were also observed from the Ionosonde observations over magnetic equator and medium scale (~300 km) GWs were observed from the GPS- TEC data near to the magnetic equator and cyclone center. From the GW parameters observed from GPS-TEC and GPS-RO, we surmise that the secondary GWs generated by the dissipation of primary GWs associated with TC Victoria could have served as a seeding source on the generation of periodic EPBs during these two consecutive days.

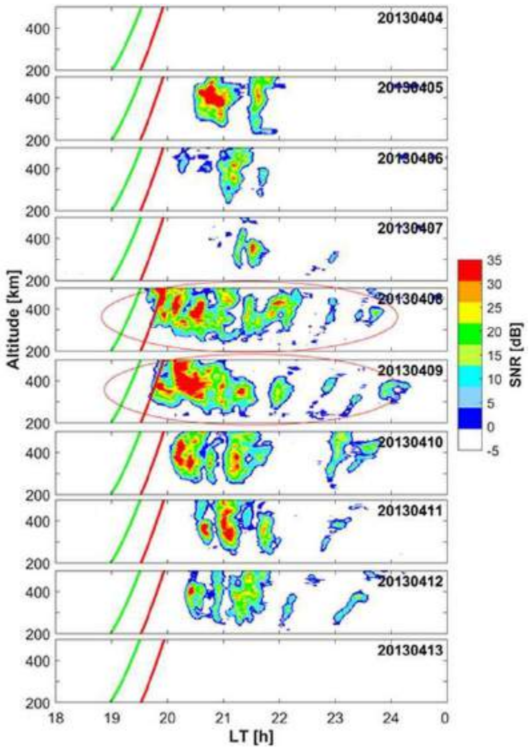


Figure 4: intense and periodic development of several equatorial plasma bubbles over Southeast Asian region in connection with the gravity waves originated from deep con- vective region associated with the tropical cyclone, Victoria

2. *investigation of the GNSS signal frequency and receiver impact on signal loss and phase cycle slips during scintillation events*

The impact of spatial and temporal ionospheric gradients as caused by small scale ion- ospheric irregularities or ionospheric storms is a threat for GNSS augmentation systems as well as for onboard GNSS receivers. Strong disturbances are able to produce severe scintillations or even can cause disruption of communication and data links, whereas strong ionospheric plasma gradients may lead to hazardous misleading information for the positioning domain, especially for differential GNSS applications [Berdermann et al, 2020].

Scintillation occurrence and its impact on the tracking performance of GNSS receivers has ben analyzed, based on data from two high rate GNSS receiver stations at the north- ern crest region during the last solar maximum (2013-2015). The results show that scin- tillation occurrence time and statistics as well as the impact on GNSS signals are similar, which can be used for future development of improved nowcasts and forecasts for GNSS-related services. Furthermore, the impact on the different receiver types used is similar and a simple mathematical model has been derived able to estimate the Loss of Lock probability under disturbed ionospheric conditions at the equator. Such models might allow a better assessment of GNSS performance for aviation in the Equatorial region and can contribute to the definition of technical standards for GNSS aided inertial systems. In order to verify the robustness of different GNSS receiver under ionospheric scintillation conditions in detail the elaboration and validation of Bitgrabber data is needed. In the next step we plan to setup Bitgrabber-technique which enables us to in- vestigate the effect of small scale ionospheric irregularities on different GNSS receivers.

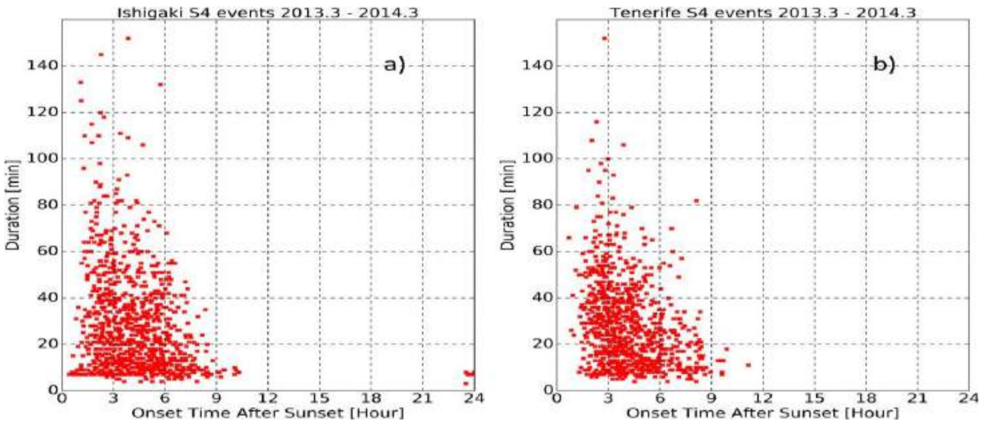


Figure 5: occurence and duration of amplitude scintillation events at Ishigaki (3a) and Tenerife (3b) from March 2013 till March 2014. Scintillation events are based on a S4 index > 0.2 us- ing an 20° (Ishigaki) and 30° (Tenerife) elevation cut-off to remove multipath effects [Berder- mann et al, 2020]. Shown are the duration of the scintillation event versus local time after sun- set (18:00 LT). In both regions' scintillation events start around 19:00 LT.

- In order to enhance robustness and monitoring capabilities of GNSS receiver with re- spect to ionospheric scintillation effects advanced mitigation and monitoring algorithms have to be developed. Also measures like S4 and the standard deviation of the phase tracking error are not sufficient to really characterize ionospheric effects and especially to study and evaluate GNSS receiver performance. It is desirable to separate the influ- ence of the ionosphere on the amplitude and the phase of the received signal from other effects and from the dynamic of the satellite movement. Thus, it is possible provide estimates or observables of the scintillation phase and amplitude. An example for such advanced mitigation and monitoring algorithms was developed in [Fohlmeister et al., 2018] and was tested with bit-grabber data and GNSS receiver prompt-correlator data in [Fohlmeister et al. ,2018] and [Fohlmeister et al., 2019]. Hence, in the future receiver behavior can exactly be studied based on such observations or estimations and also es- pecially correlation among different frequencies can be studied in detail and without any correlation introduced by the monitoring receiver.
- Transient fluctuations of electron content inside regions of the ionosphere interact with propagating radio waves causing scintillation. Ionospheric scintillation can significantly impact the availability, accuracy, continuity, and integrity of GNSS positioning. The signal processing channels in a GNSS receiver perform carrier and code delay tracking of GNSS satellite signals. Regarding the received signal carrier, ionospheric irregulari- ties are a source of amplitude and phase scintillations adding up to the line-of-sight dy- namics, introducing disturbances to GNSS tracking algorithms in the receiver that, in many cases, cause a reduction of precision in the positioning and eventually the loss of lock of GNSS signals. Two adaptive Kalman phase locked loop (PLL) structures for ionospheric

scintillation mitigation for GNSS receivers are proposed, employing radial basis function networks to model the scintillation phase and amplitude. The Kalman PLL structures employing the RBF networks present reduced errors compared to the structures using autoregressive models. Work is in progress and a paper has been re- cently submitted.

3. Global modelling and forecasting of scintillations considering temporal and regional (Polar and Equatorial region) differences.
   - The Global Ionospheric Scintillation Model (GISM) is used to model phenomena rele- vant for the GNSS applications and provides the amplitude and phase scintillation indi- ces. Due to the 3-dimensional nature of the GISM model it is capable to describe a variety of communication geometries such as satellite-ground station or satellite-satel- lite communication link. Moreover, it is able calculate scintillation maps at specific al- titudes (see also Figure 6a) below for an example of the GISM output). At present first steps for further development, extension and validation of GISM has been started. We work on the upgraded version of the model that extends its applicability to several new user-cases and incorporates the improvements in physical model of randomly inhomo- geneous ionosphere. For example, in the case of planning of cubesat communication satellite missions one can calculate the expected scintillation levels over specified geo- graphical location and use them for determination of communication outage risks [Fer- reira et al., 2022], see also Figure 6b) below. This information can be used further for optimization of satellite mission parameters during the planning phase. For better mod- eling of anisotropic scintillation-associated inhomogeneities, the phase screen genera- tion method has been updated. This allows one to model the effect of scintillation en- hancement caused by propagation geometry, namely the relative position of the signal propagation link and the field-aligned anisotropic irregularities. An effect of such geo- metrical enhancement of scintillation is shown in Figure 6c) for communication links between the earth surface and geostationary satellite over the equator. The ongoing work concerns the modeling of scintillation due to refractive scattering on edges of de- pleted/enhanced ionospheric regions such as SEDs, TOIs, equatorial plasma bubbles, polar patches, etc.
   - Ionosphere Sounding in the Central Arctic (see Figure 7): An experiment was conducted during the expedition of the Multidisciplinary Drifting Observatory for the Study of Arctic Climate (MOSAiC) in 2019 and 2020 [Semmling et al., 2022]. Signals of global navigation satellite systems (GNSS) were recorded during 12 months aboard the Ger- man research icebreaker Polarstern that drifted with a sea ice floe over the Arctic Ocean. We published the preliminary results of an ionosphere sounding experiment from a 5 month measurement period in the central Arctic (>85° N). The results indicate that ion- ospheric variations in the Arctic cusp region can be detected using GNSS data from a ship. A masking of relative bearing is required to mitigate the impact of ship-based structures (mast and chimney). The resolved ionosphere-related anomalies of about 0.15 rad to 0.2 rad indicate a moderate level of ionospheric disturbance, as expected in this period of low solar activity. The anomaly around noon local time, indicating particle precipitation in the cusp region, is found at high elevations. An increased level also appears at medium elevations. At a lower elevation, this feature no longer occurs. A deeper analysis of phase data for the resolution diffractive or refractive effects is planned for a future study.

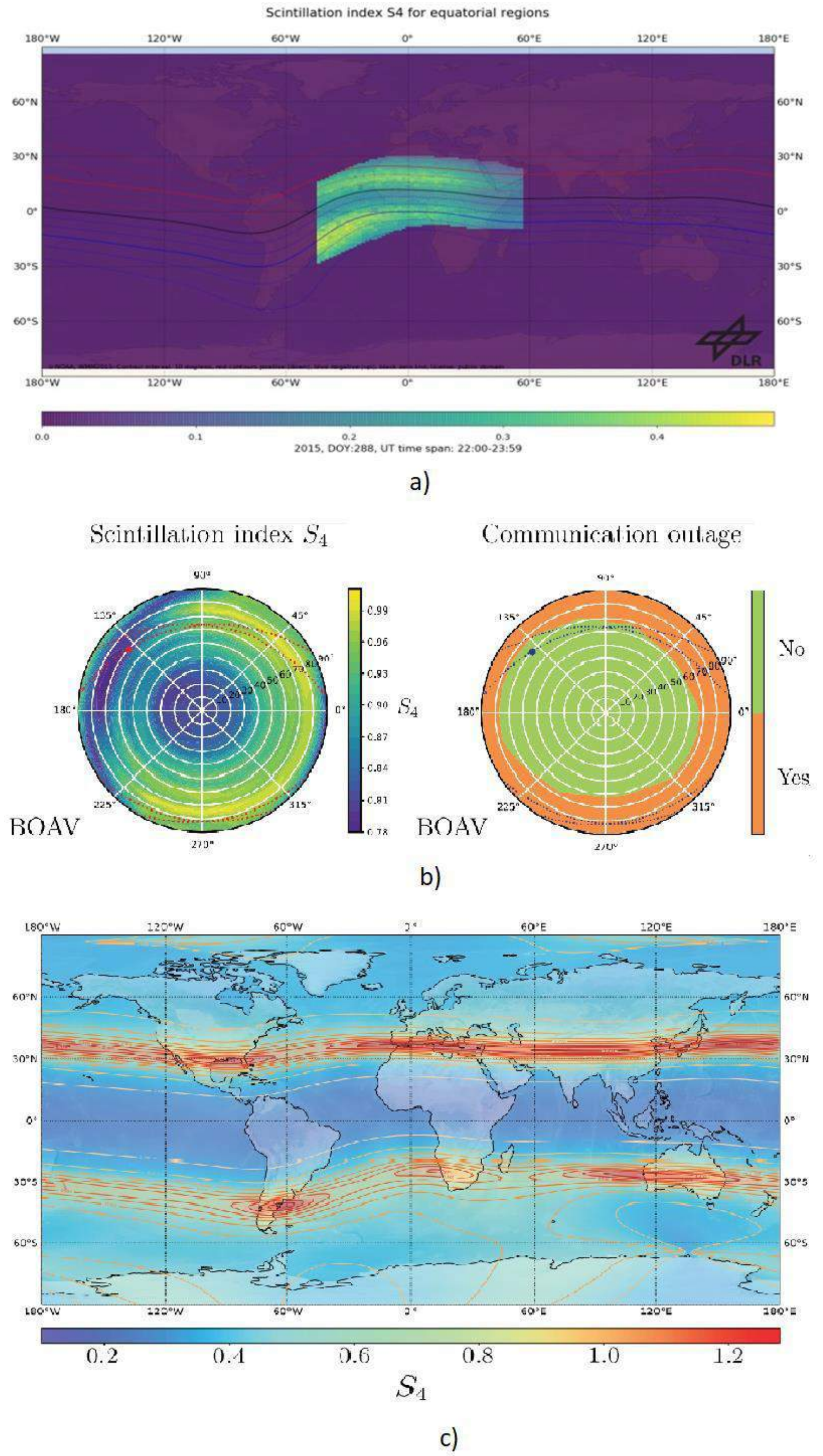


Figure 6: a) Excerpt of a scintillation map for the equatorial region obtained with the GISM model. b) The sky plot of scintillation index calculated for Boa Vista station (Brazil) and the corresponding communication outage risk regions. Scintillation along other factors impacts the UHF communication at low elevation angles. c) Regions of geometrically enhanced scin- tillation for geostationary communication satellite over the equator. In order to demonstrate the geometric enhancement effect, the parameter, that describes the strength of irregular struc- tures, is set to constant.

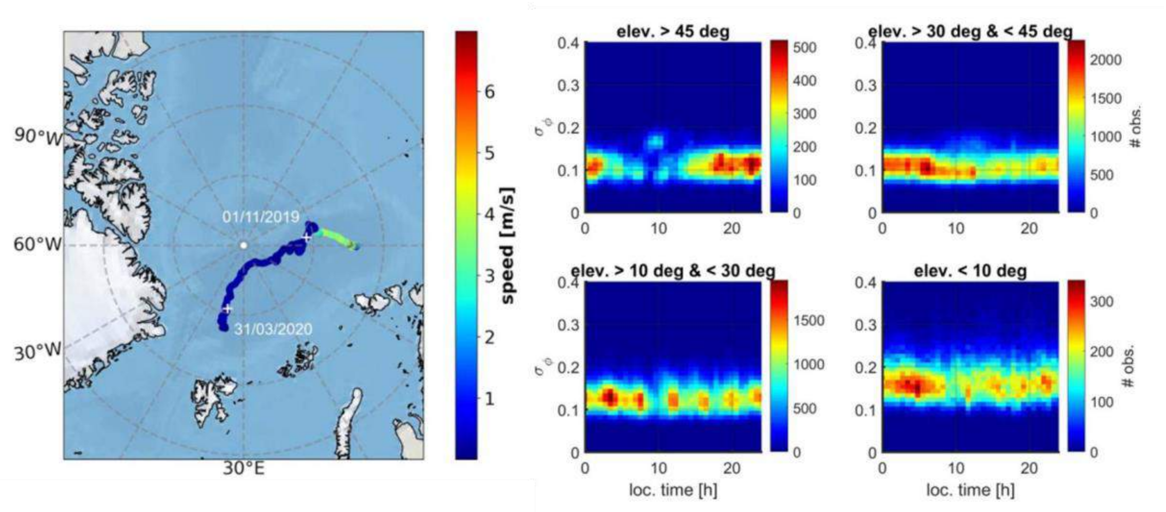


Figure 7: Ionosphere sounding in the Central Arctic

4. Multi-station and multi-instrument observations of F-region irregularities in the Taiwan-Philippines sector
   - A multi-station and multi-instrument system, organized and proposed for ionospheric scintillation and equatorial spread-F (ESF) specification and their associated motions in the Taiwan–Philippines sector, has been developed. We first indicate the existence of a plasma bubble in the Taiwan–Philippines sector by using the FS7/COSMIC2 GPS/GLONASS radio occultation observations. We verify the latitudinal extent of the tracked plasma bubble using the recorded ionograms from the Hualien VIPIR. We fur- ther discuss the spatial and temporal variabilities of two-dimensional vertical scintilla- tion index VS4 maps based on the simultaneous GPS L1-band signal measurements from 133 ground-based receivers located in Taiwan and the surrounding islands. We also operate two high-sampling, software-defined GPS receivers and characterize the targeted plasma irregularities by carrying out spectrum analyses of the received signal. As a result, the derived plasma irregularities moved eastward and northward. Further- more, the smaller the irregularity scale, the higher the spectral index and the stronger the scintillation intensity were at lower latitudes on the aimed irregularity feature.

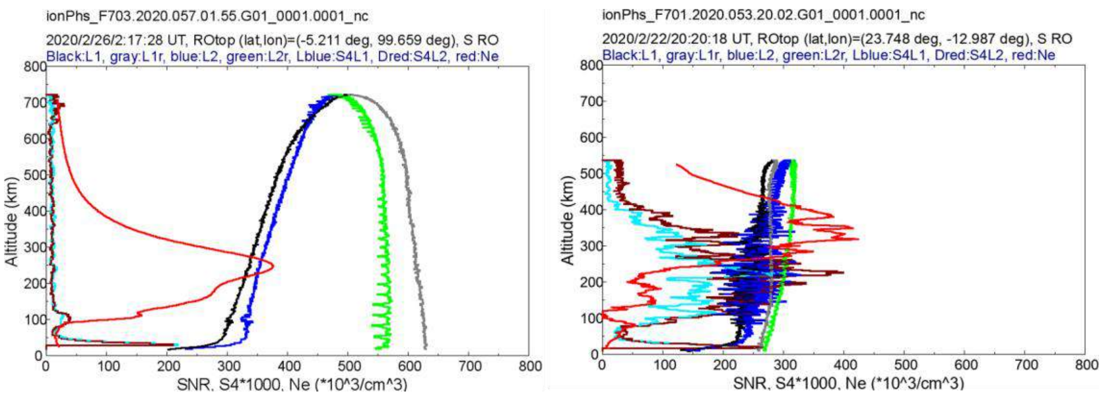


Figure 8 Two examples of FS7/COSMIC2 RO observations at quiet time (without amplitude scintillation as shown in the left panel) and disturbed time (with amplitude scintillation as shown in the right panel) separately, which shows the limb-viewing SNR amplitude profiles at the occulting side in black and blue for L1 and L2 bands respectively and the resulting under- sampling S4 profiles in cyan and dark red. The retrieved electron density profile is shown in red. It also shows the limb-viewing SNR amplitude profiles at the auxiliary side in gray and green for L1 and L2 bands respectively.

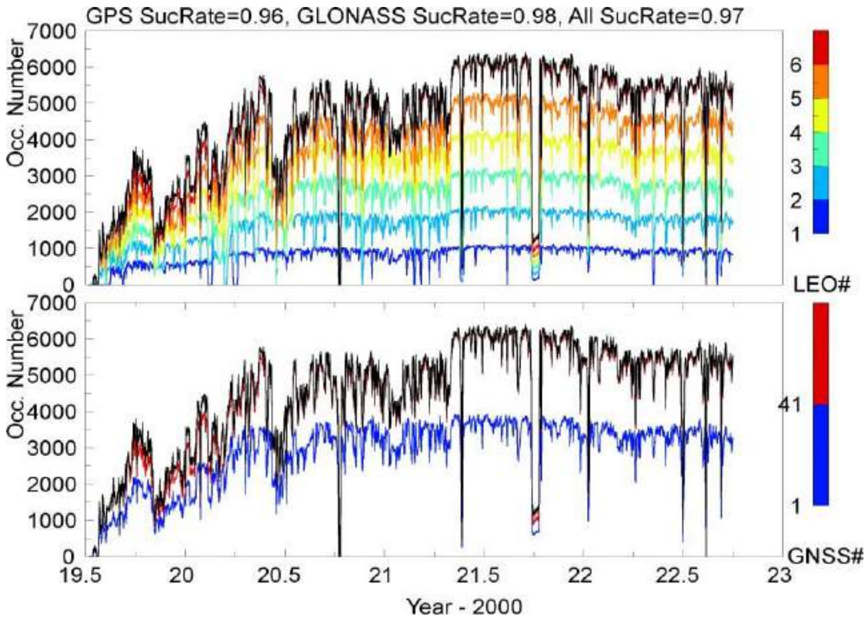


Figure 9: Daily numbers of FS7/COSMIC2 RO observations from 2019 to DOY 275, 2022 are shown as the black lines in the both panels, and daily accumulated and retrieved Ne profile numbers from different LEO satellite (in the top panel) and GPS and GLONASS satellites (in the bottom panel) are shown as the colored lines.

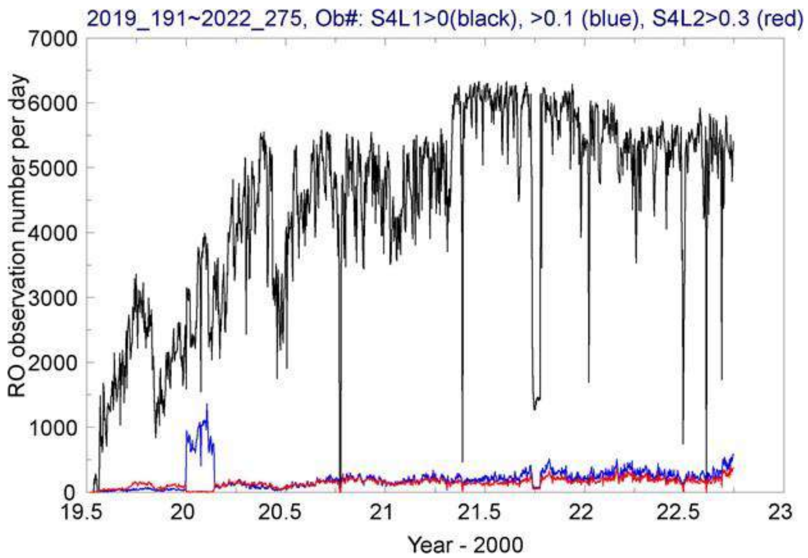


Figure 10: Daily numbers of the FS7/COSMIC2 RO observations from 2019 to 2022 are shown in black for complete observations, and in blue (red) for observations with F-layer scin- tillation events at L1 (L2) band which are defined at the corresponding maximum S4L1 (S4L2) larger than 0.1 (0.3).

- The sources of validation systems for ionospheric Ne specification and modelling in- clude a Vertical Incidence Pulsed Ionospheric Radar (VIPIR) network located in east Asia. The East-Asia VIPIR network includes nine systems allocated at Wakkanai/Sa- robetsu (45.16°N, 141.75°E), Kokubunji (35.71°N, 139.49°E), Yamagawa (31.20°N, 130.62°E), Okinawa/Ogimi (26.68°N, 128.15°E), Geosan (36.77°N, 127.82°E), Jeju (33.50°N, 126.53°E), Hualien (23.89°N, 121.55°E), Longquan (22.67°N, 120.60°E), and Malina (14.61°N, 120.96°E). Each VIPIR is actually a high-frequency ionospheric sounding radar, i.e. ionosonde. The variation of the virtual height of reflection h'(f) as a function of the radio frequency is the fundamental ionosonde data product, and the records of these measurements are known as ionograms. The following figure shows an example of spread-F ionogram obtained from the Hualien VIPIR at 13:49UT on DOY 299, 2021. We completed the soundings using the Hualien VIPIR from the mid to DOY 301, 2021, and DOY 43 to DOY 275 in 2022. The corresponding raw data can be ftped at IP:140.115.111.237 and port:21.

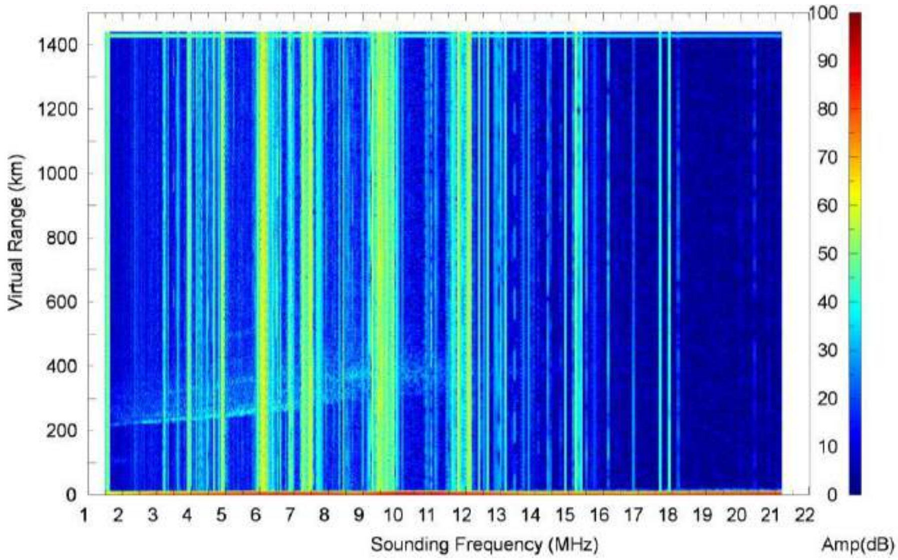


Figure 11: An example of spread-F ionogram obtained from the Hualien VIPIR at 13:49UT on DOY 299, 2021.

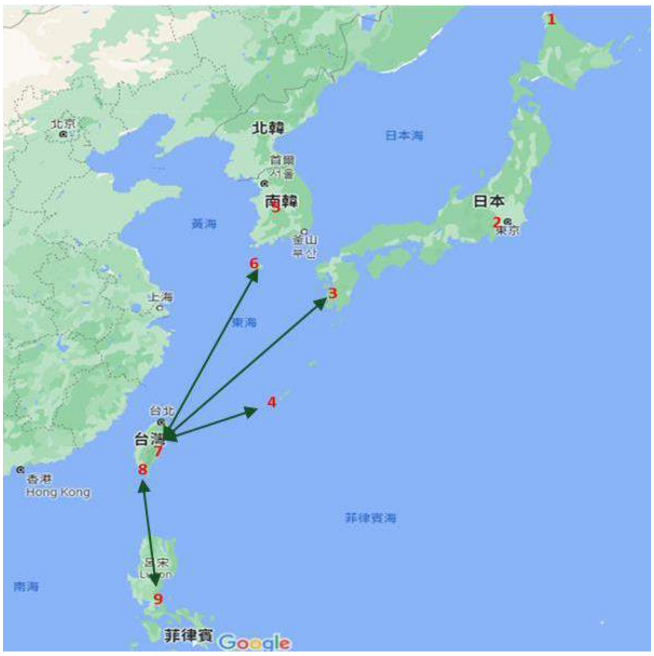
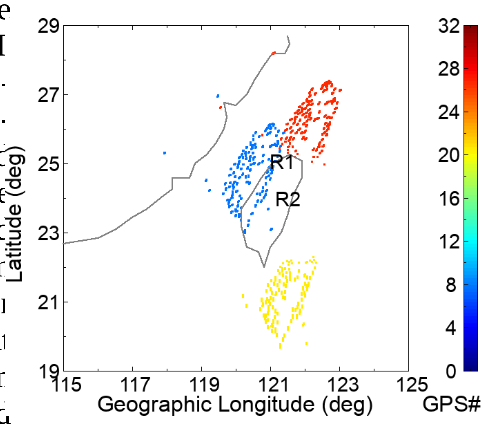


Figure 12: The East-Asia VIPIR network includes nine systems allocated at Wakkanai/Sa-robetsu (#1; 45.16°N, 141.75°E), Kokubunji (#2; 35.71°N, 139.49°E), Yamagawa (#3; 31.20°N, 130.62°E), Okinawa/Ogimi (#4; 26.68°N, 128.15°E), Geosan (#5; 36.77°N, 127.82°E), Jeju (#6; 33.50°N, 126.53°E), Hualien (#7; 23.89°N, 121.55°E), Longquan (#8; 22.67°N, 120.60°E), and Malina (#9; 14.61°N, 120.96°E).

- The sources of validation system for ionospheric Ne specification and modelling also include more than 130 local ground-based GNSS receivers in Taiwan. These local GNSS receivers are operated and maintained by the Central Weather Bureau (CWB) of Taiwan. The following figure shows an example distribution of ionospheric pierce point (IPP) positions of lines of viewing from GPS satellites to the 130s ground-based GPS/GNSS receivers. We completed the spatial and temporal variabilities of two-di- mensional vertical scintillation index VS4 maps on the equatorial plasma bubbles (EPB) and ESF feature observed on 26 October 2021, and based on the simultaneous GPS L1- band signal measurements from 133 ground-based receivers located in Taiwan and the surrounding islands. The following figure also shows the derived ESF feature in two- dimensional VS4 map taken at 14:42 UT on 26 October 2021.

Figure 13: Geographical geometry of the IPPs of the simultaneous GPS signal measurements at 14:42 UT on 26 October 2021, and from 133 ground-based re- ceivers located in Taiwan and the surrounding is- lands. The dots colored in light blue, yellow, and red show the IPP positions at 300-km altitudes for the lines of sights connecting GPS satellite #8, #21, and #27, respectively, which have a minimum elevation angle of 45° from receivers. The positions of another two software-defined GPS receivers located at Chungli (24.97°N, 121.19°E) and Hualien (23.89°N, 121.55°E), Taiwan, are shown and labeled by “R1” and “R2”, respectively.



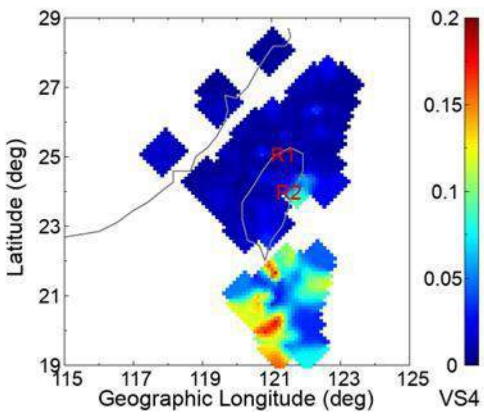
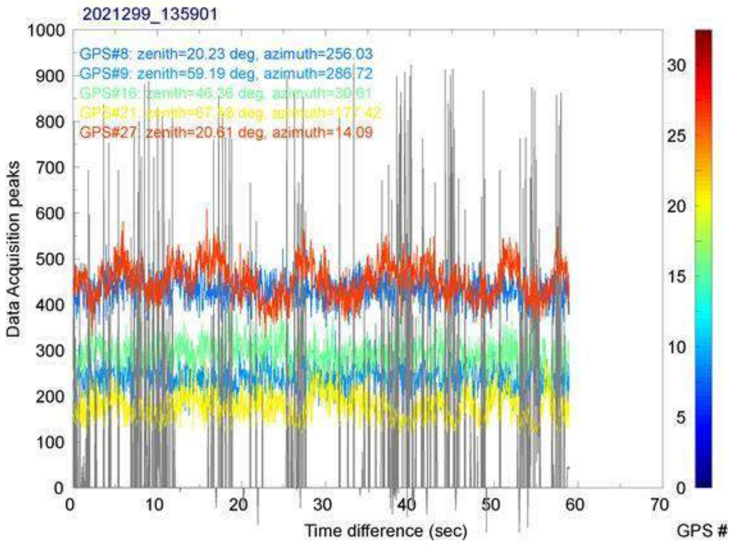


Figure 14: An example of EPB and ESF feature in two-dimensional VS4 map taken at 14:42 UT on 26 October 2021, and derived by the simultaneous GPS signal measurements from the CWB GPS re- ceiving network.

- Ionospheric scintillation characteristic determination based on signal spectrum analysis from GPS&SBAS software-defined receiver (SDR): we have built four SDRs in Tai- wan, which can receive not only GPS but also SBAS satellite L1-band signals for iono- spheric scintillation observations and for the comparison with FS7/COSMIC2 scintilla- tion observations. SDRs offer added flexibility and versatility by implementing most functions in software. Another advantage of a GPS&SBAS SDR has a maximum sam- pling rate of 1000 Hz due to the L1-band Coarse Acquisition (C/A) code duration at 1 millisecond. The 1000-Hz sampling rate is much higher than that of a typical commer- cial GPS receiver and can solve the problems of underestimated S4s and signal phase aliasing. The following figure shows example time-series records of L1-band C/A code signal acquisition (in SNR) obtained on DOY 299, 2021, from the Chungli-E system. We note the time-series amplitude profiles of GPS #21 & 27 represent wave structures caused by ionospheric irregularities. The log-log plot and their spectral index p values of the normalized power spectra of the GPS#8, #21, and #27 time-series signal ampli- tudes of the ionospheric scintillation event on October 26 2021 are shown as follows.

Figure 15: Example time-se- ries record of L1-band C/A code signal acquisition (in SNR) obtained on DOY 299, 2021, from the Chungli-E system. The col- ored temporal profiles repre- sent the maximum signal ac- quisition results from visible GPS satellite numbers 8, 9, 16, 27. We note the time-series amplitude profiles of GPS #21 & 27 represent wave structures caused by ionospheric irregularities.



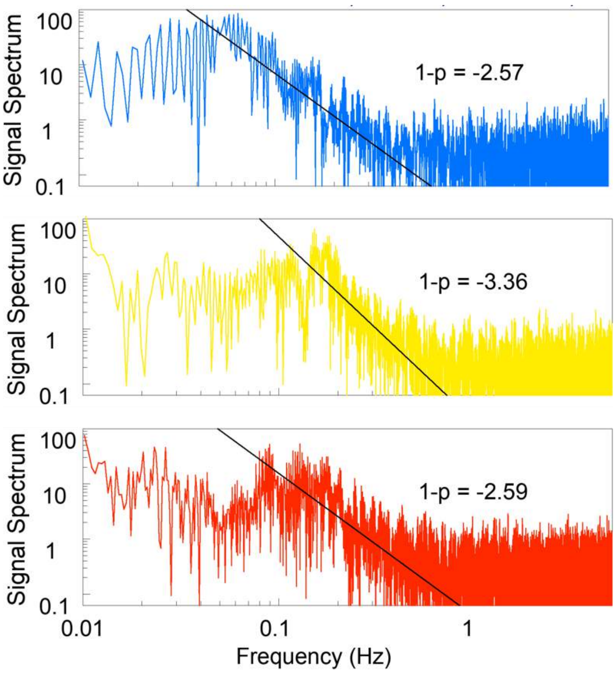


Figure 6: Power spectrums and their spectral index p values of the L1-band signal scintillation patches recorded by the Chungli software-defined GPS re- ceiver from GPS satellites #8 (upper panel), #21 (middle panel), and #27 (lower panel). Three data segments are from 13:29 to 13:44 UT, 14:29 to 14:49 UT, and 13:44 to 14:19 UT on 26 October 2021, for GPS satellites #8, #21, and #27 signal observations, respec- tively**.**

5. International Workshops and Dissemination
   - *3rd International Workshop on GNSS Ionosphere* (IWGI2022) September 26-28, 2022, at DLR Neustrelitz, 45 presentation.

The IWGI2022 provided a platform for scientists and engineers to communicate and exchange their views on ionospheric observations, new methods, retrieval techniques, data fusion, applications and future challenges. The workshop was open to all scientists who may have the latest results and developments in ionosphere reconstruction, model- ling, monitoring techniques and prediction methodologies as well as **ionospheric scin- tillation and propagation effects** on microwave space-based geodetic techniques (e.g. GNSS, SLR, VLBI, DORIS etc.) and their mitigation using multi-frequency, multi-sen- sors observations.

Publications (related to the activities)

Activity 1

Mogese Wassaie Mersha, Norbert Jakowski, Volker Wilken, Jens Berdermann, Martin Kriegel, Elias Lewi and Baylie Damtie, A method for automatic detection of plasma deple- tions by using GNSS measurements Radio Science, 55, e2019RS006978 (2020)

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J. Berdermann, H. Sato, M. Kriegel, T. Fujiwara and T. Tsujii, "Effects Of Equatorial Iono- spheric Scintillation For GNSS Based Positioning In Aviation," 2020 European Navigation Conference (ENC), Dresden, Germany, 2020, pp. 1-8, doi: 10.23919/ENC48637.2020.9317407.

F. Fohlmeister, F. Antreich, V. Wilken, M. Kriegel, J. C. M. Mota, A. L. F. de Almeida, F. G.

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Activity 3

Global Ionospheric Scintillation Model: current status and further development strategies Dmytro Vasylyev, Yannick Beniguel, Volker Wilken, Martin Kriegel, and Jens Berdermann EGU21-9441 solicited talk

D. Vasylyev, Y. Bèniguel, V. Wilken, M. Kriegel, and J. Berdermann, Further development of the Global Ionospheric Scintillation Model (GISM) : Perspectives and prospective URSI GASS 2021

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Other related Papers

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JWG 4.3.4 Validation of VTEC models for high-precision and high resolution applications

(Joint with IGS)

Chair: *Anna Krypiak-Gregorczyk (Poland)*
Vice-Chair: *Attila Komjathy (USA)*

Members

Andreas Goss (Germany)
Bruno Nava (Italy)
Dieter Bilitza (USA)
Eren Erdogan (Germany)
Gu Shengfeng (China)
Heather Nicholson (Canada)
Mainul Hoque (Germany)
Reza Ghoddousi-Fard (Canada)
Shuanggen Jin (China)
Wojciech Jarmołowski (Poland)
Yunbin Yuan (China)
Manuel Hernández-Pajares (Spain)
Haixia Lyu (Spain)
Qi Liu (Spain)
Raul Orus-Perez (The Netherlands)
Tam Dao (Australia)
Beata Milanowska (Poland)

Activities during the period 2019-2023

Group members realized the goals of JWG 4.3.4 in their individual activities as well as in co-operation with other group members.

VTEC validation with external data (JASON) and GNSS

Global ionosphere maps (GIM) computed from dual-frequency GNSS measurements have been widely used for monitoring ionosphere as well as providing ionospheric corrections in Space Geodesy since 1998. Due to the inhomogeneous global distribution of GNSS real-time stations and especially due to the large data gaps over oceanic areas, the global VTEC models are usu- ally limited in their spatial and spectral resolution. Most of the GIMs are mathematically based on globally defined radial basis functions, i.e., spherical harmonics (SH), with a maximum de- gree of 15 and provided with a spatial resolution of 2.5∘×5∘ in latitude and longitude, respec- tively. Regional GNSS networks, however, offer dense clusters of observations, which can be used to generate regional VTEC solutions with a higher spectral resolution.

In Goss et al. (2020), a two-step model (TSM) comprising a global model as the first step and a regional model as the second step was introduced. The authors apply polynomial and trigo- nometric B-spline functions to represent the global VTEC. Polynomial B-splines are used for modelling the finer structures of VTEC within selected regions, i.e., the densification areas. The TSM provides both, a global and a regional VTEC map at the same time. In order to study the performance, the authors apply the developed approach to hourly data of the global IGS net- work as well as the EUREF network of the European region for St. Patrick storm in March 2015. For the assessment of the generated maps, it was used the dSTEC analysis and compare both maps with different global and regional products from the IGS Ionosphere Associated Analysis Centers, e.g., the global product from CODE (Berne, Switzerland) and from UPC (Barcelona, Spain), as well as the regional maps from ROB (Brussels, Belgium) **(**Figure 1**)**. The assessment shows a significant improvement of the regional VTEC representation in the form of the generated TSM maps. Among all other products used for comparison, the developed regional one is of the highest accuracy within the selected time span.

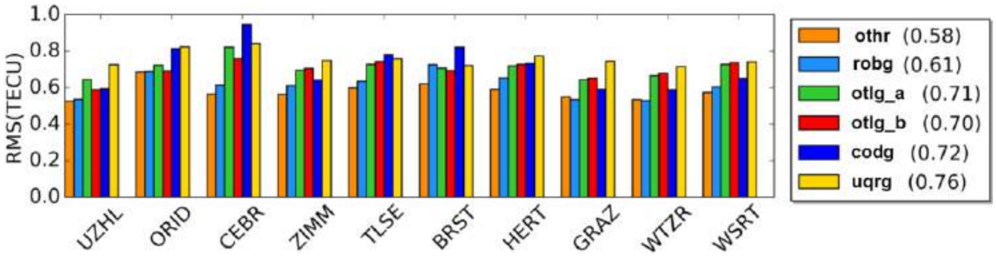

Figure 1: RMS values computed at the 10 stations for the products listed in the legend; the two global products 'otlg_a' and 'otlg_b' as well as the regional product 'othr', the external regional product 'robg' and the external global products 'codg' and 'uqrg' of the IAACs CODE and UPC are used for comparison. The values in the parantheses are the average RMS values over all 10 receiver stations for the entire test period between 8 March and 23 March 2015. *(Goss et al., 2020)*

UWM team analyzed the GIMs accuracy in relation to their temporal resolution and solar ac- tivity level. The accuracy evaluation was based on GIM-TEC comparisons to differential STEC derived from GNSS data and VTEC derived from altimetry measurements. The results show that temporal interval has no significant impact on the overall, annual map RMS during both high and low solar activity periods. However, during geomagnetic storms, when reducing map interval, the map accuracy improves by almost 25% (Milanowska et al. 2020, 2021). The dSTEC analysis showed that during high solar activity period, when increasing GIM interval from 15 minutes to 60 and 120 minutes, STEC accuracy decreases by 3% and 21%, respec- tively. During low solar activity period 60-minute interval presents a good accuracy, and when increasing map interval to 120 minutes, the accuracy degrades by ~2% to 13%. Under disturbed conditions, GIMs with 60-min. interval are less accurate by ~3-5%, and 120-min. maps are less accurate by even ~30% (comparing to 15-minute interval). In case of CASG GIM there is a little influence of map interval on STEC accuracy, this may suggest that intrinsic interval of the underlaying model is longer than 30 minutes (Figure 2).

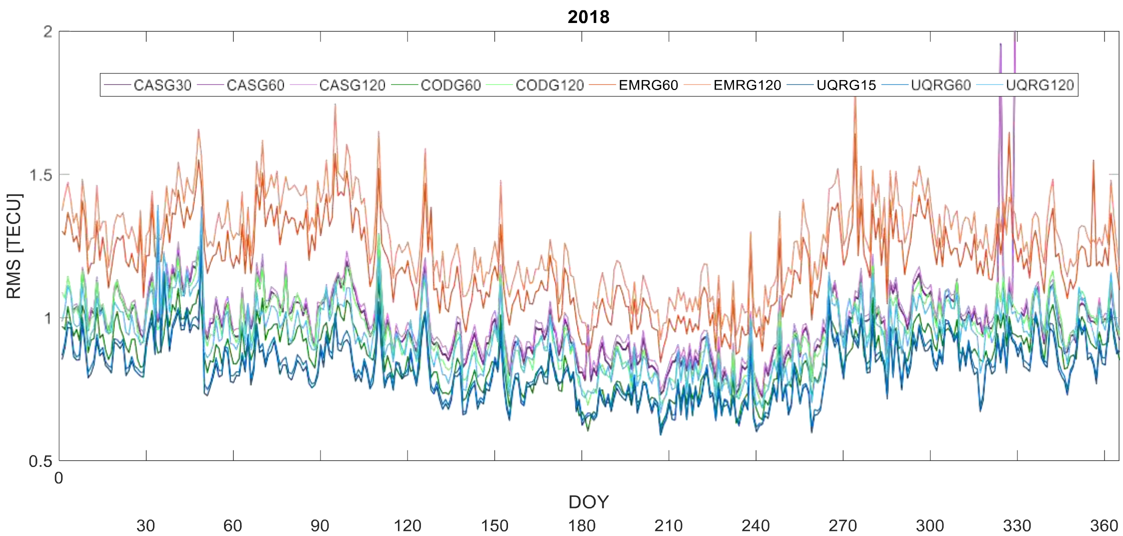

Figure 2: Daily RMS distribution for GIMs with different time resolution (year 2018) *(*Milanowska et al., 2020*)*

Liu et al. (2021) presented the influence of temporal resolution on the performance of global ionospheric maps (UQRG). The performance of the GIMs has been assessed by directly com- paring with external vertical total electron content (VTEC) measurements from Jason altimeters over oceanic regions. In order to perform a complete assessment and analysis of involved GIMs, the influence of geographical position and solar and geomagnetic activities was also taken into account during more than one solar cycle. The assessment shows that discrepancy among GIMs with different time resolutions becomes more apparent at low latitudes and also at the high solar-geomagnetic activity. The results also suggest that the accuracy for GIMs with time res- olution smaller or equal to 60 min is consistent during the period from 2002 to 2019 and is more accurate than other GIMs with lower temporal resolution **(**Figure 3**)**. Accordingly, high time resolution (including 15, 30, 45 and 60 min) is recommended for the application of GIMs with the highest accuracy.

The scope of another study is on the evaluation the accuracy and consistency of the IAAC GIMs during high (2014) and low (2018) solar activity periods of the 24th solar cycle (Wielgosz et al. 2021). In this study, two different evaluation methods were applied. First, the authors carried out a comparison of the GIM-derived slant TEC (STEC) with carrier phase geometry-free com- bination of GNSS signals obtained from 25 globally distributed stations. Second, vertical TEC (VTEC) from GIMs was compared to altimetry-derived VTEC obtained from the Jason-2 and Jason-3 satellites and complemented for plasmaspheric TEC. The analyzed GIMs obtained STEC RMS values reaching from 1.98 to 3.00 TECU and from 0.96 to 1.29 TECU during 2014 and 2018, respectively. The comparison to altimetry data resulted in VTEC STD values that varied from 3.61 to 5.97 TECU and from 1.92 to 2.78 TECU during 2014 (Figure 4) and 2018, respectively. The results show that among the IAACs, the Center for Orbit Determination in Europe (CODE) global maps performed best in low and high solar activity periods. However, the highest accuracy was obtained by a non-IGS product - UQRG GIMs provided by the Uni- versitat Politècnica de Catalunya (UPC) (Figure 5). It was also shown that the best results were obtained using a modified single layer model mapping function (Table 1) and that the map time interval has a relatively small influence on the resulting map accuracy.

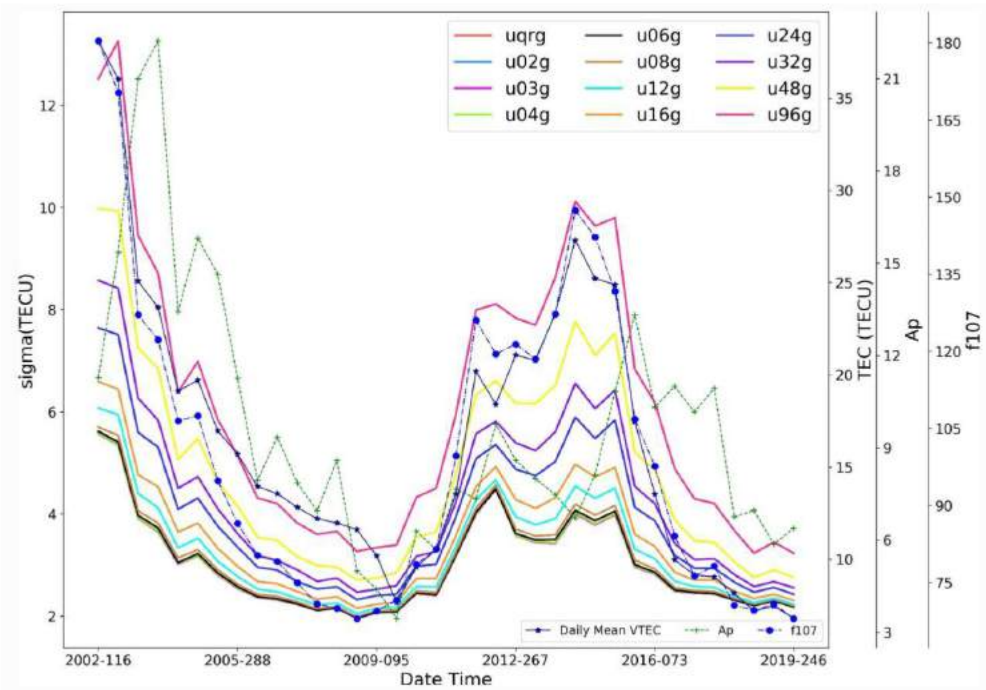

Figure 3: The evolution of standard deviation of the discrepancy of GIM VTEC versus measured al- timeter VTEC, in TECUs, from day 26 of 2002 to day 335 of 2019, represented simultaneously to Ap geomagnetic activity and F10.7 solar flux indices (green crosses and blue bullets, respectively) *(*Liu et al., 2021*)*

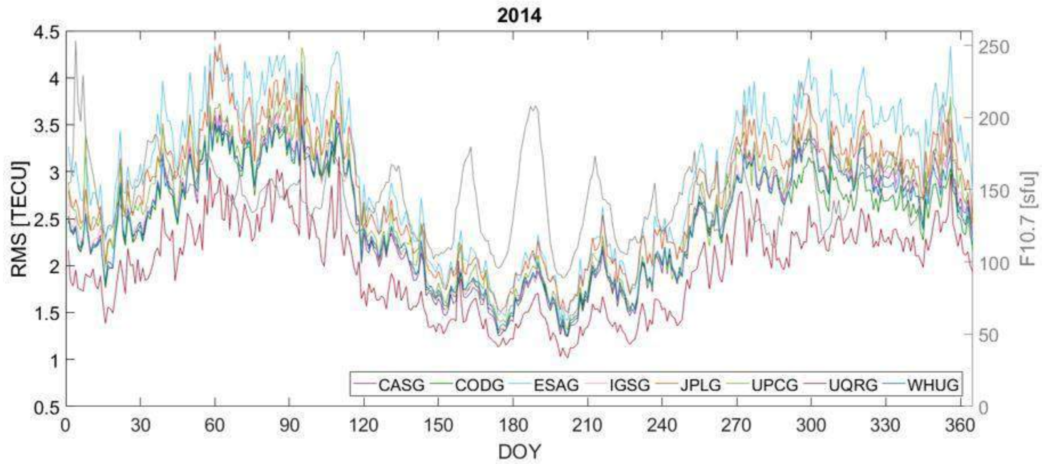

Figure 4: F10.7 index and daily GIM-derived STEC RMS distribution based on a comparison with ground GNSS observations from 25 stations in 2014 (Wielgosz et al., 2021)

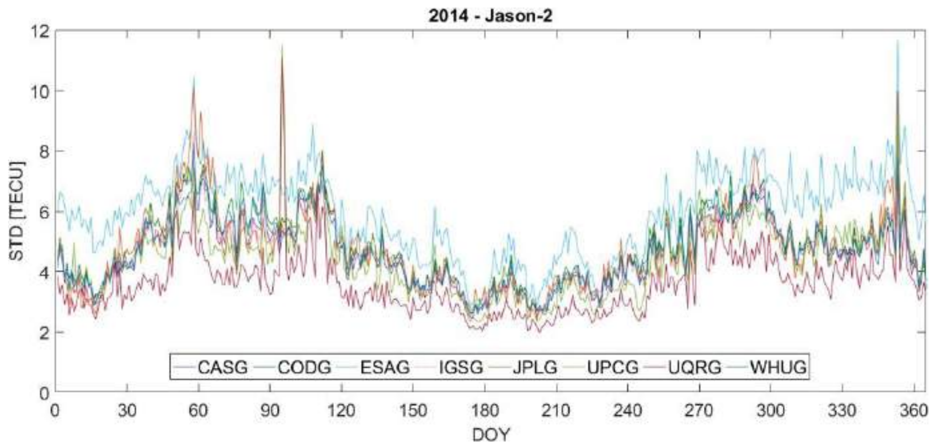

Figure 5: Daily GIM-derived VTEC STD distribution based on a comparison with the Jason-2 data in 2014 (Wielgosz et al., 2021)

Table 1: Annual RMS [TECU] for all analyzed GIMs in 2014 (left) and 2018 (right) obtained with the use of SLM and MSLM mapping functions. The superscripts mean: [a] EMRG is available since April 2015; [b] UQRG is not an official International GNSS Service (IGS) product (Wielgosz et al., 2021)

GIMs	Mapping Function	
	SLM	MSLM
CASG	2.49	2.41
CODG	2.44	2.36
EMRG[a]	-	-
ESAG	3.00	2.95
IGSG	2.54	2.44
JPLG	2.80	2.64
UPCG	2.62	2.57
UQRG[b]	1.98	1.93
WHUG	2.50	2.43
UQRG[b] (2h)	2.30	2.24

GIMs	Mapping Function	
	SLM	MSLM
CASG	1.10	1.09
CODG	1.00	0.98
EMRG[a]	1.29	1.28
ESAG	1.25	1.23
IGSG	1.12	1.08
JPLG	1.24	1.16
UPCG	1.15	1.13
UQRG[b]	0.96	0.93
WHUG	1.12	1.10
CASG (2h)	1.12	1.11
CODG (2h)	1.09	1.07
EMRG[a] (2h)	1.38	1.37
UQRG[b] (2h)	1.06	1.04

The investigations of the seven analysis center models (Wielgosz et al. 2021) were comple- mented with new results for a ionosphere model from DGFI-TUM denoted OTHG. This new model is based on tensor products of trigonometric B-spline functions in longitude and polyno- mial B-spline functions in latitude for a global representation (Goss et al. 2019). For these in- vestigations, the validation methodology presented in Krypiak-Gregorczyk et al. (2017) was used. This methodology is based on GIM-derived slant TEC (sTEC) comparison with carrier phase geometry-free combination of GNSS signals. In the presented study (Krypiak-Gregor- czyk et al. 2022), one year of GNSS data collected by 25 globally distributed stations was used; see Figure 6. For each product, the overall, yearly RMS value is calculated, based on all 365 days of continuous observations from all stations. The results in Figure 7 show that the overall RMS of the tested GIMs ranges from 0.93 TECU to 1.29 TECU. OTHG GIMs performed as one of the best, with RMS of 1,10 TECU. In addition, Jason-2 and Jason - 3 altimetry comparisons are applied.

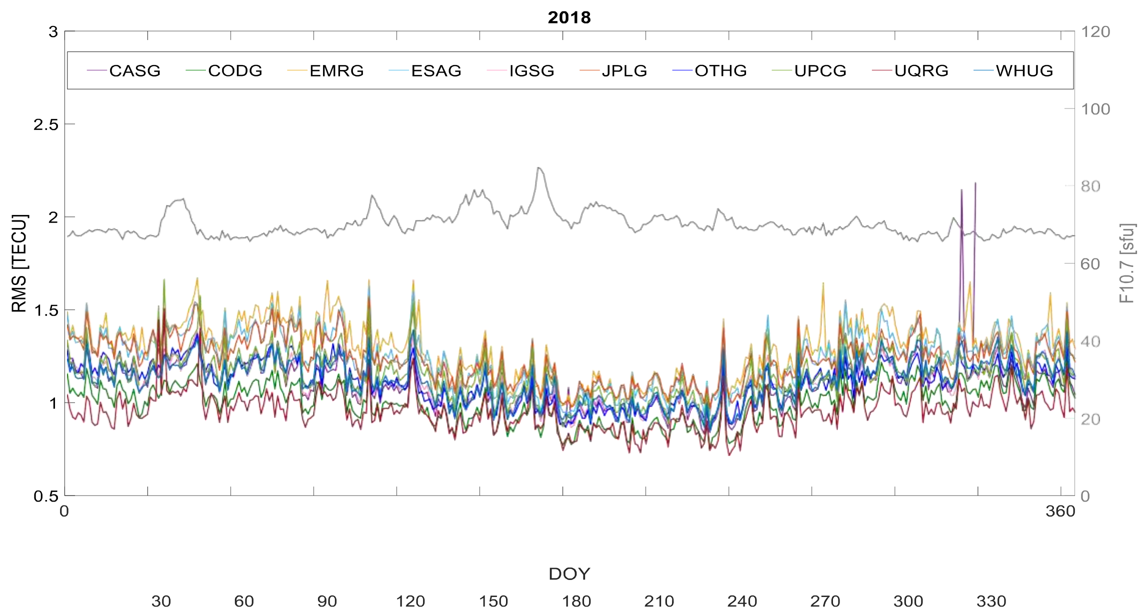

Figure 6: Daily RMS distribution for all analysed GIMs in 2018 [TECU] (Krypiak-Gregorczyk et al. 2022a)

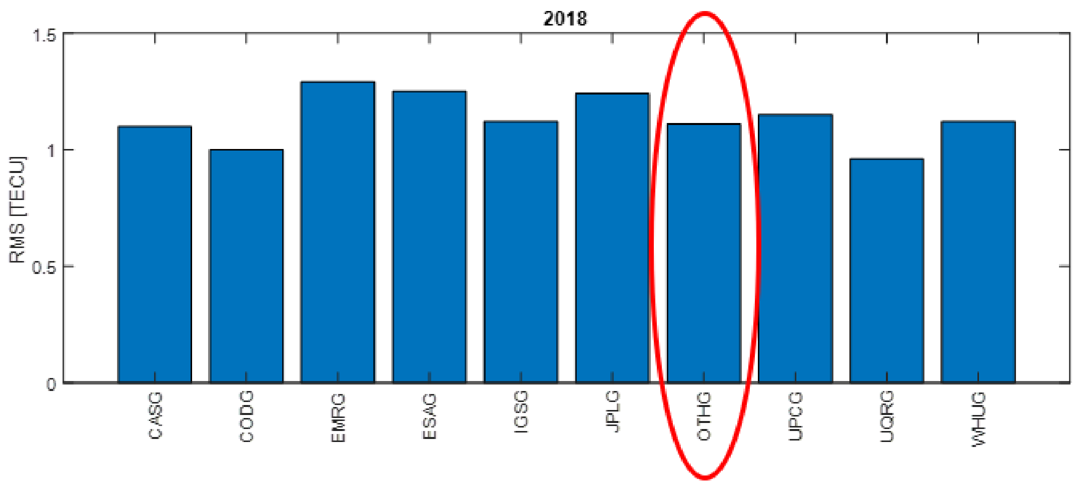

Figure 7: Overall RMS from self-consistency tests in 2018 (Krypiak-Gregorczyk et al. 2022a)

In the next step, a new global ionosphere total electron content (TEC) model developed at UWM in Olsztyn was analyzed. This model is based on un-differenced multi-GNSS precise carrier phase data from 260 globally distributed stations and stochastic modeling using the kriging technique (Wielgosz et al. 2022). The model performance was evaluated during the most severe geomagnetic storm of 2018, which took place on August 26th. The derived iono- spheric TEC estimates were compared to the broadly used global ionosphere models provided by the International GNSS Service (IGS) -IGSG GIMs, the Center for Orbit Determination in Europe (CODE)-CODG GIMs and a non-IGS product - UQRG GIMs provided by Universitat Politècnica de Catalunya (UPC) (Figure 8). The maps were also validated by the self-con- sistency analysis technique using GNSS data from 23 globally distributed stations. The valida- tion results confirmed that the applied stochastic TEC modeling properly reflects variations in the ionospheric TEC induced by the geomagnetic storm. In all cases, the UWMG maps presented better accuracy than the IGS product (Figure 9). UWMG has the best accuracy in the high and mid latitude regions, while in low latitude regions the accuracy of the UWMG is slightly lower than UQRG. The accuracy of the UWMG model is the lowest for ocean regions with less data availability - which indicates the need to complete the measurement data set.

UWMG model can be provided publicly with a delay of 12 hours, a time resolution every 10 minutes and a spatial resolution of 1x1 degree.

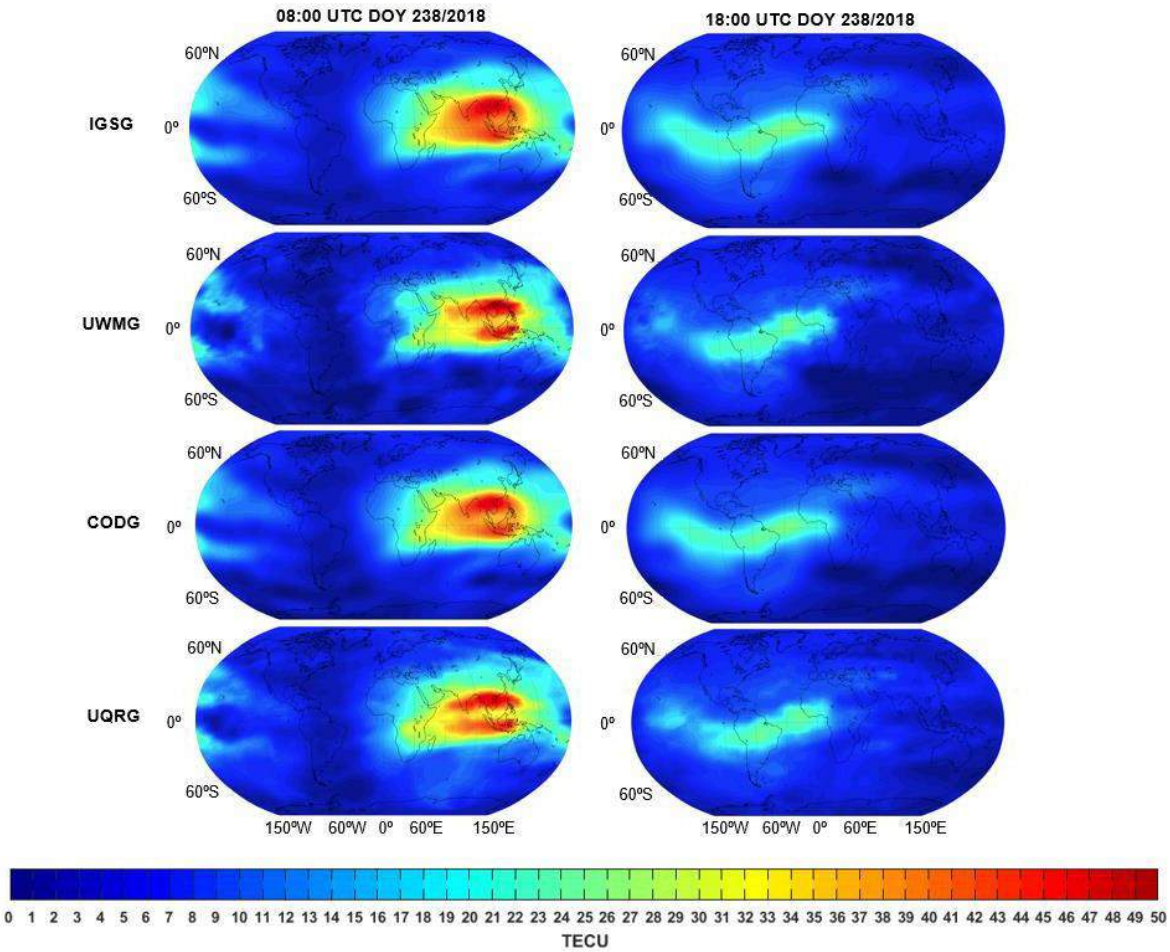

Figure 8: Example TEC maps derived from IGSG, UWMG, CODG, UQRG models on the stormy day (DOY 238) at 08.00 UTC (left) and 18.00 UTC (right) (Krypiak-Gregorczyk et al. 2022b)

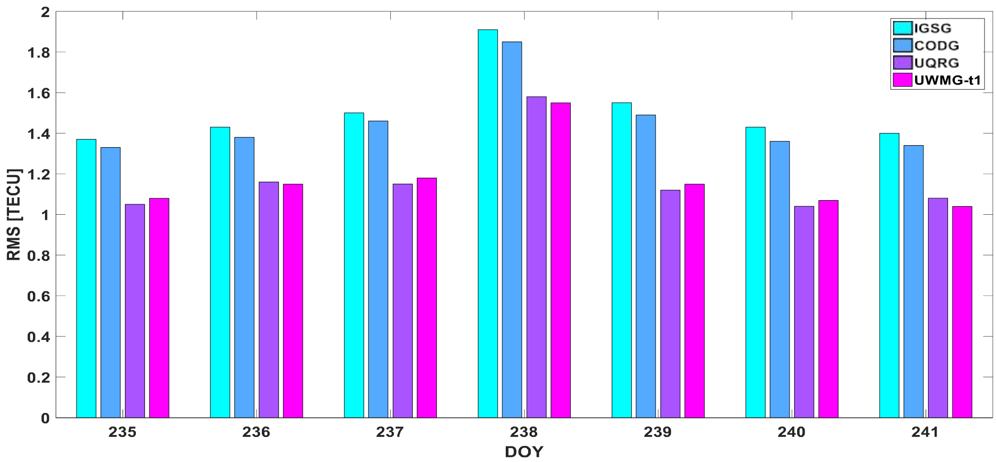

Figure 9: Daily RMS distribution for all analysed GIMs [TECU] (Krypiak-Gregorczyk et al. 2022b)

As the RMS maps are commonly used as the accuracy indicator of GIMs to optimize the sto- chastic model of precise point positioning algorithms, investigating the reliability of RMS maps involved in GIMs of different IAACs (the integrity of GIMs) has become important. Zhao et al. (2021) presented the reliability of the RMS maps in seven rapid IGS GIMs (UQRG, CORG, JPRG, WHRG, EHRG, EMRG and IGRG) and six final GIMs (UPCG, CODG, JPLG, WHUG, ESAG and IGSG) by assessing the bounding relationship between the actual dSTEC error and the dSTEC RMS derived from the RMS maps in the GIM products under the zero-mean normal distribution assumption.

The study was examined under the maximum and minimum solar activity conditions as well as the geomagnetic storm period. The analyses showed that the reliability of the RMS maps is significantly different for GIMs from different IAACs. The rapid and final GIMs from CODE, JPL and WHU provide quite reasonable RMS maps, and the distribution of the actual error is properly bounded by the normal distribution derived from the RMS map, as well as EMRG. The RMS map of UQRG is the most conservative, because it has been calibrated to a large value to ensure its integrity as a sort of ionospheric protection level. In contrast, the RMS map of UPCG is slightly more optimistic than GIMs from CODE, JPL and WHU. EHRG and ESAG reveal highly optimistic estimated RMS values, which indicates a quite low integrity fulfill- ment. For IGSG and IGRG as combined products, the RMS bounding performance differ greatly for different stations.

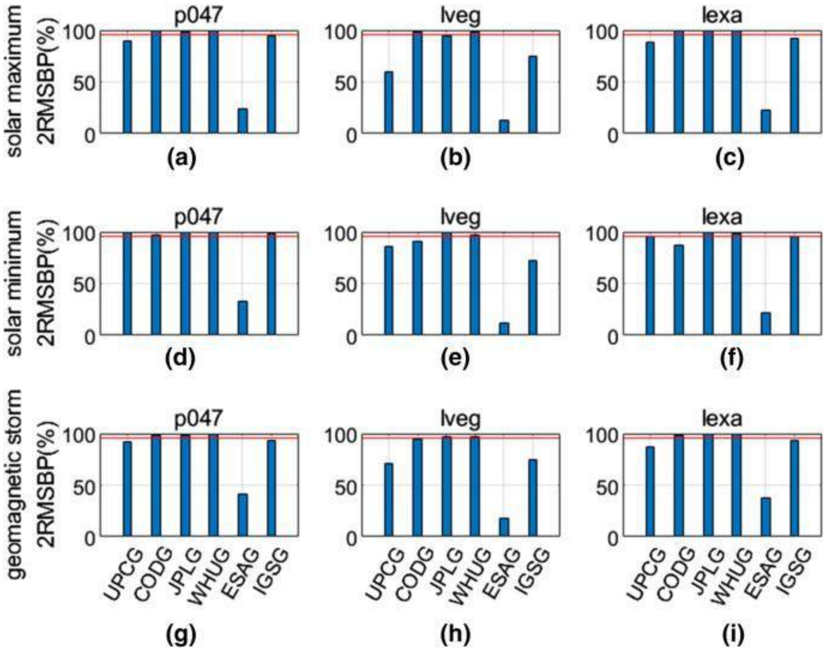

Figure 10: RMSBP values of different final GIMs for the select stations, where the red line in the pan- els represents the reference percentage of 95.45% (Zhao et al. 2021)

VTEC validation in precise GNSS positioning

The ionosphere delay is the major issue in the undifferenced and uncombined observable model (Zhao et al. 2019). Though several ionosphere delay parameterization approaches have been promoted, the team from Wuhan argues that the functional model with only deterministic char- acteristic may not follow the irregular spatial and temporal variations. Thus, the deterministic plus stochastic ionosphere model (DESIGN) was developed, in which the deterministic part was expressed as a second-order polynomial and the stochastic part was estimated as random. Based on two-year data collected by about 150 stations, the second-order polynomial coeffi- cients of the deterministic part was modeled with Fourier series, while, the constrains of the stochastic part was evaluated with variogram. From the statistic studies, it was concluded that the main frequency components are identical for different coefficients, different stations, as well as different ionosphere activity status, but with varying amplitude. Thus, in the Fourier series expression of the deterministic part, the frequency was fixed and the amplitude was esti- mated as daily constant unknowns.

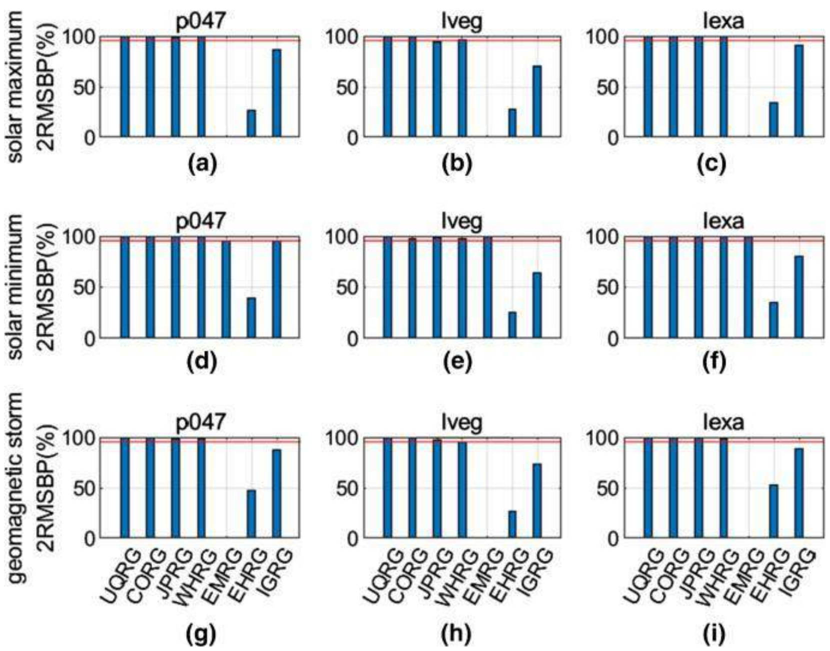

Figure 11: RMSBP values of different rapid GIMs for the selected stations, where the red line in the panels represents the reference percentage of 95.45% (Zhao et al. 2021)

Concerning the stochastic component, the variation of variogram was both, geomagnetic lati- tude and ionosphere activity status dependent. Thus, the Gaussian function was used and Ep- stein function to model the variation of geomagnetic latitude and ionosphere activity status, respectively. Based on the multi-GNSS zero-baseline observation, the ionospheric delay de- rived from PPP constrained with DESIGN was then compared to the result of the smoothed geometry-free observation model **(**Figure 12**)**. Moreover, the undifferenced ionospheric delay was also evaluated in the wide area PPP-RTK over Europe (Figure 13).

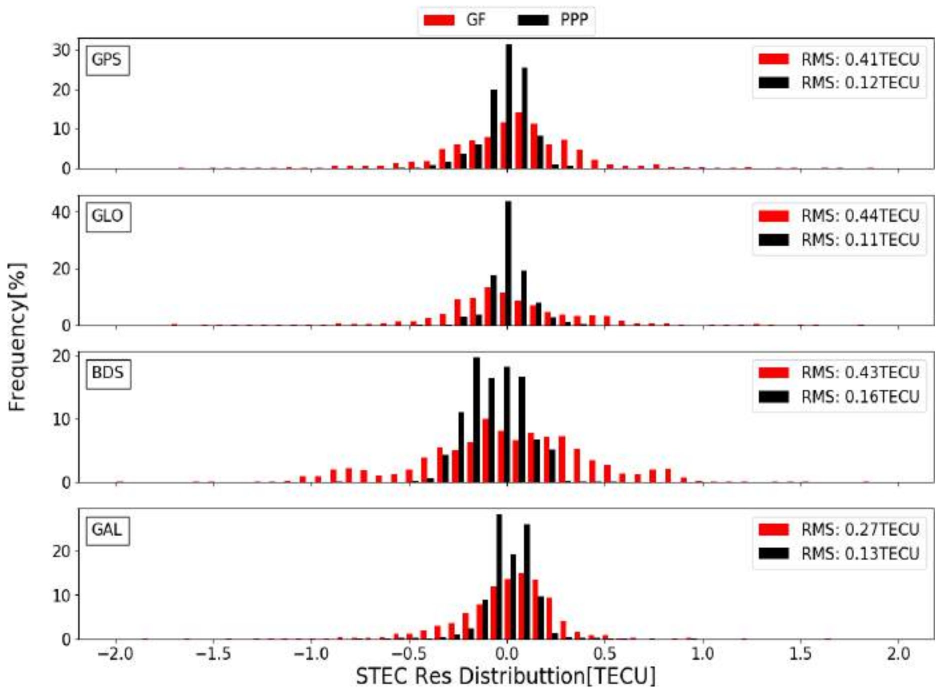

Figure 12: Comparison of the ionospheric delay estimation based on smoothed geometry-free observation model and the undifferenced and uncombined PPP model with zero-baseline

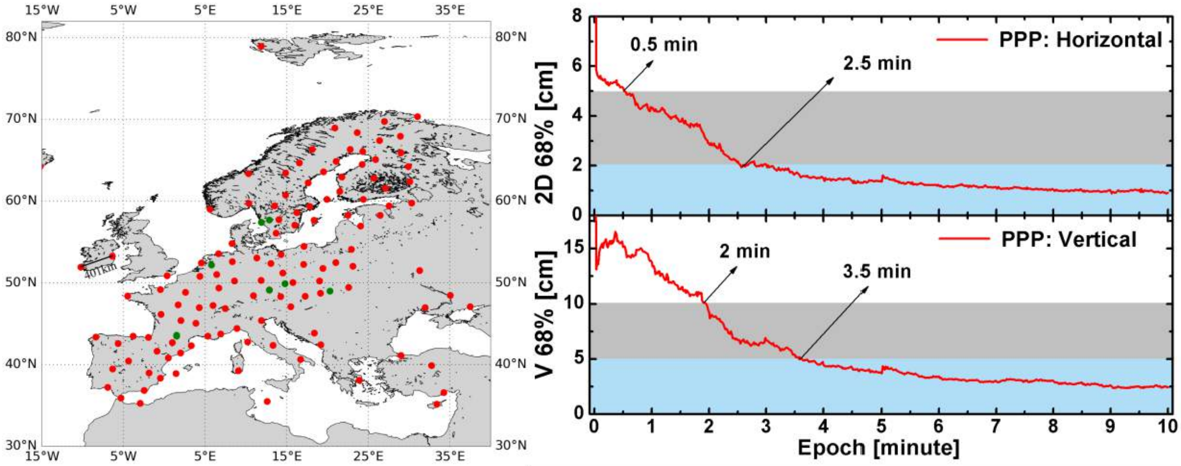

Figure 13: Application of undifferenced ionospheric delay modeling in wide area PPP-RTK over Europe

In another study, Goss et al. (2020) applied a single-frequency PPP using the RTKLIB software. They compared their high-resolution global B-spline ultra-rapid product (latency of approx 3 hours) with the final GIM `codg' (CODE) and the rapid GIM `uqrg' (UPC). What they see is an improvement in position when they use the high-resolution VTEC maps to correct for the ion- ospheric delay on the PPP.

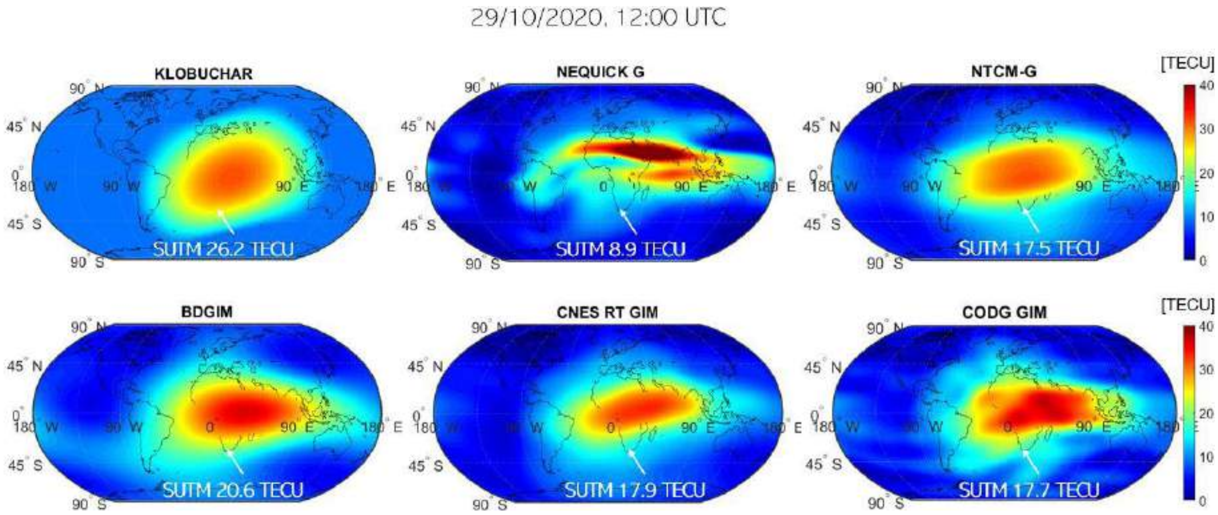

Figure 14: Evaluated ionospheric delay correction models (Wielgosz et al. 2023)

Team of scientists from UWM and Mainul Hoque (Institute for Solar-Terrestrial Physics, Ger- man Aerospace Center, Neustrelitz, Germany) jointly evaluated ionospheric delay correction models in single-frequency GNSS navigation (Milanowska et al. 2022, Wielgosz et al. 2023). Figure 14 presents maps of total electron content (TEC) derived from six analyzed ionospheric delay correction models. It is an example of the state of the ionosphere on 29 October 2020 at 12:00 UTC. The CODG GIM serves as a reference. Since CODG maps are the final product, we can assume that these GIMs show the actual state of the ionosphere. From the general view, one can observe that NTCM-G, BDGIM, and CNES real-time maps present similar TEC values. However, the NeQuick G two-dimensional model presents a different shape of TEC. It is also clearly visible that the Klobuchar model, broadcast by the GPS satellites, is the simplest one. In addition, the TEC values for the southern station SUTM were indicated. According to the reference map (CODG GIM), TEC value should be around 17 TECU at this station. The NTCM-G and CNES present similar values of 17.5 and 17.9 TECU respectively. There are two models that overestimate TEC over SUTM station – BDGIM with 20.6 TECU, and Klobuchar with 26.2 TECU. However, the NeQuick G clearly underestimates TEC value over the whole southern hemisphere and obtains only 11.3 TECU at the SUTM station.

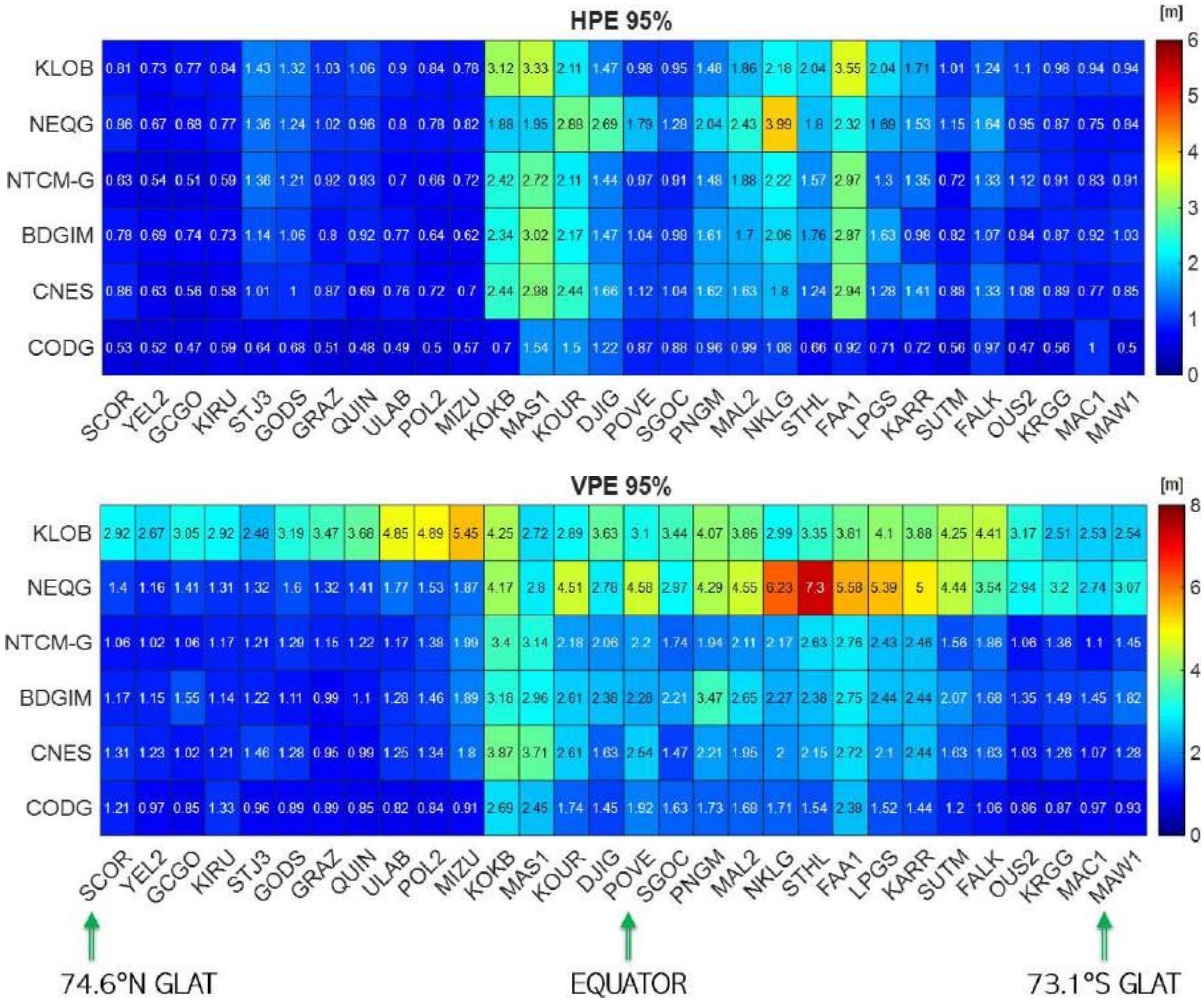

Figure 15: Single point positioning results with the application of analyzed models. The horizontal position error (HPE, top) and the vertical position error (VPE, bottom) with a 95% confidence level (Wielgosz et al. 2023)

The positioning results presented in Figure 15 are derived from the single-frequency single- point positioning mode using the evaluated ionospheric delay correction models. For the pro- cessing, the observation from four satellite systems was used – GREC. The results are presented for all analyzed stations in geomagnetic order, from the most northern station to the most south- ern one. The differences between the models are more visible in the vertical component. The application of the Klobuchar model achieves the worst positioning results. However, the Ne- quick G model in the southern hemisphere was even worse than the Klobuchar. The poor per- formance of the NeQuick G in this region was also evident in Figure 13. BDGIM model adopted by the BDS system performed better than the GPS and Galileo ionospheric correction algo- rithms (ICAs). The NTCM-G model, developed by DLR (German Aerospace Center) is a very good alternative for Nequick G. These two models are driven by the same effective ionization parameters broadcast in Galileo navigation message. The analyzed real-time GIM from CNES, transmitted as SSR corrections, also achieved good positioning results, being close to the ref- erence CODG GIM.

In another study, the impact of the use of the VTEC uncertainties for the interpolation procedure was applied to the GIMs of different centers and assessed in the positioning domain (Jerez et al. 2022). The VTEC values and the corresponding standard deviations are routinely provided to users in GIMs, to correct the ionospheric disturbances for GNSS positioning, with a typical time resolution of 2 h (and up to 15 min) on regular grids with 2.5º resolution in latitude and 5º resolution in longitude. To determine the ionospheric corrections from the GIMs for positioning applications, an interpolation has to be applied to the VTEC grid values, which generally de- generates the final VTEC accuracy. In this context, Jerrez et al. (2022) have presented the in- fluence of VTEC uncertainties in the calculation of VTEC from GIM in the positioning domain in terms of a new associated hybrid weighting approach. The analysis was done with four Bra- zilian stations in challenging regions. All analyses considered four cases: one week with a ge- omagnetic storm, one week with low solar flux and two weeks with high solar flux (equinox and solstice). Three ionospheric products were used: CODG, UQRG and UQ-6. The influence of VTEC in terms of the uncertainties weighting approach led to significant improvements compared to the performance with GIMs without taking into account their uncertainties. Most significant rates of improvement were observed in cases with high solar flux, especially for stations SAVO and PPTE (located close to geomagnetic latitude − 15°.

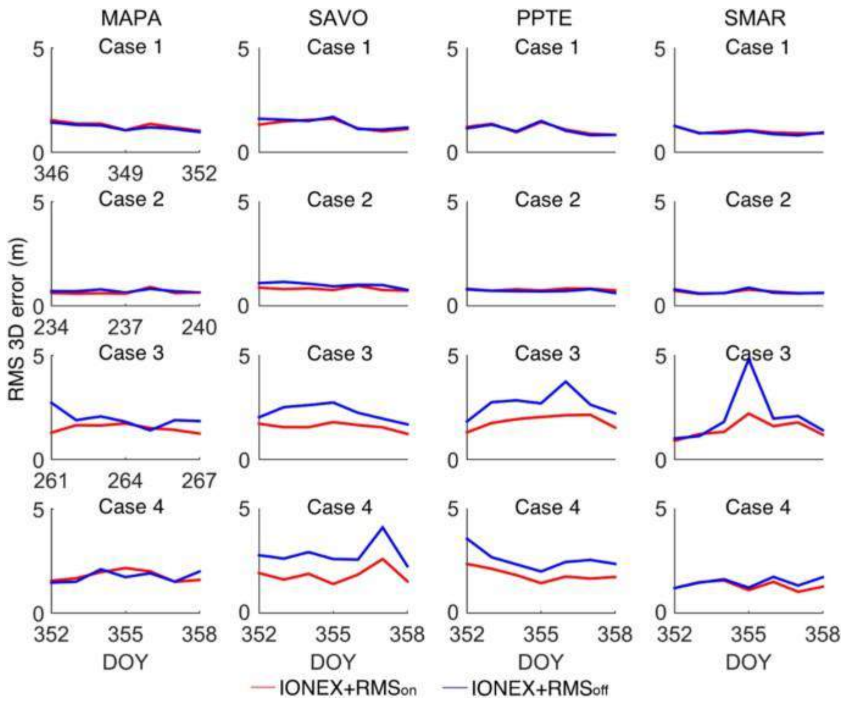

Figure 16: RMS of 3D error using CODG, stations: MAPA, SAVO, PPTE and SMAR (Jerez et al. 2022)

The mean 3D error with CODG presented mean errors at the positioning about 5 cm larger than UQRG, considering the strategy without RMS (Figure 16). With the use of VTEC RMS, CODG obtained mean errors about 7 cm smaller than UQRG and 10 cm smaller than UQ-6. The mean rates of improvement considering all cases and stations for CODG, UQRG and UQ-6 were 23%, 14% and 15%, respectively. Consequently, the authors recommend the usage of the VTEC uncertainties from ionospheric maps in IONEX format for positioning applications, in particu- lar when low latitude regions and periods of high solar flux are considered.

Comparison of GNSS-derived VTEC maps and empirical models

Commonly used two-dimensional ionospheric models for GNSS positioning applications, in- cluding Total Electron Content (TEC) maps, require a mapping function (obliquity factor) which is used for conversion between vertical and slant TEC at ionospheric pierce points. In Ghoddousi-Fard (2020), NeQuick - a three-dimensional semi-empirical model -, was used to simulate the level of uncertainties that one may expect from more simplified approaches. In order to evaluate the performance of mapping functions on GNSS vertical TEC estimation, coinciding pierce points from mixed stations and receivers from stations over North America are analyzed. A fit to the NeQuick derived mapping function values resulted in an empirical mapping function which performed slightly better than commonly used mapping functions dur- ing the studied periods and locations.

Hoque et al. (2019) developed and published an ionospheric correction model namely NTCM G for single frequency Galileo users. NTCM G is recently adopted by the European Commis- sion (EC) as an alternative ionosphere model for Galileo Open Service. The model is rigorously validated against IGS TEC maps and altimeter TEC data. Very recently Cahuasquí et al. (2022) validated NTCM G in position domain considering many GNSS stations distributed over the globe. Its results were compare with the results of the Klobuchar and NeQuickG models for the first time. in the position domain, the NTCM-GlAzpar clearly outperforms the Klobuchar model and slightly surpasses the accuracy of NeQuickG model on a global scale (Figure 17).

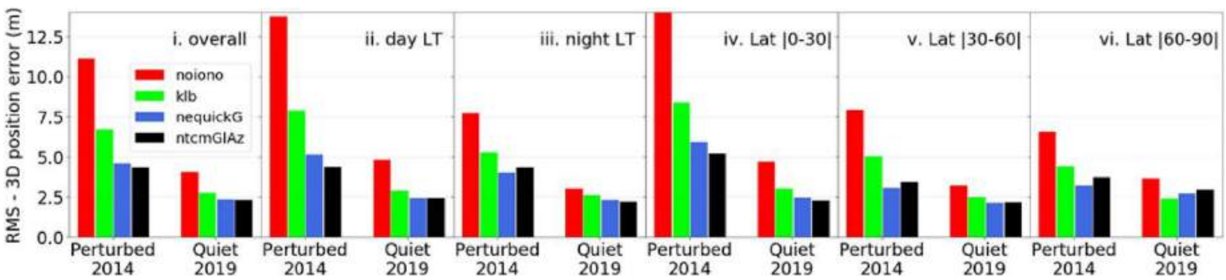

Figure 17: Graphical comparison between RMS values of the 3D position error achieved with the four modeling approaches for perturbed and quiet periods. The panels display the results for subsets orga- nized by local time and latitude range (Cahuasquí et al. 2022)

Su et al. (2019) investigated the performance of NTCM model in mitigating ionospheric delay effects on multi-GNSS combined positioning applications. Telmo dos Santos Klipp (2019) evaluated the performance of NTCM model over Central and South Americas by comparing model data with TEC reconstruction and found very good results. Su et al. (2021) developed a technique of estimating ionospheric VTEC and satellite DCB from single-frequency BDS ob- servations with multi-layer mapping function. Adolfs and Hoque (2021) developed a Neural Network-Based VTEC model capable of reproducing Nighttime Winter Anomaly (NWA). The model uses the SYM-H, Hp30, DOY, UT, storm time, solar flux index F10.7 and the 27-day median TEC as input parameters in order to predict the relative TEC. The model was trained with UQRG GIM data from the UPC analysis center during storms. The model performs well when compared with NTCM model and IGS VTEC data. Yuan et al. (2021) derived a method to estimate VTEC and GPS satellite and receiver differential code biases using a network of LEO satellites. Hoque et al. (2022) developed a new climatological electron density model for supporting space weather services. The 3D electron density model is extensively validated against IGS GIMs during low and high solar activity conditions and the model performs better or at least similar to the NeQuick2 model. Adolfs et al. (2022) developed a storm-time relative TEC model using machine learning techniques based on IGS GIMs. The model is validated with independent IGS data which are not used during the training and testing procedures.

During the 4 years of the Joint Working Group's JWG 4.3.4 activities, the scientists evaluated the performance and quality of existing IGS ACs ionosphere models. The new global iono- sphere models were also validated.

The main objectives have been achieved. However, there is a need for continued research. In the future, there should be more focus on validation of existing solutions and new VTEC models in modeling disturbed states of the ionosphere, during which there are rapid changes of various magnitudes in electron concentration, which makes it difficult to model. In addition, there should put more emphasis on the development of new validation techniques.

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WG 4.3.5 Real-time Troposphere Monitoring

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Chair: *Galina Dick (Germany)*

Members

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Junping Chen (China)
Jan Douša (Czech Republic)
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Andrea Stürze (Germany)
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Pavel Václavovic (Czech Republic)
Henrik Vedel (Denmark)
Karina Wilgan (Germany)
Kefei Zhang (Australia)
Florian Zus (Germany)

Activities during the period 2019-2023

To develop, optimize and assess new real-time or ultra-fast GNSS tropospheric products, and to exploit the full potential of multi-GNSS observations in weather forecasting has become one of the focuses in the field of GNSS meteorology (Dousa et al., 2015). Tropospheric zenith total delays, tropospheric linear horizontal gradients, slant delays, integrated water vapor (IWV) maps or other derived products in sub-hourly cycles are foreseen for future exploitation in nu- merical and non-numerical weather nowcasting or severe weather event monitoring (Guerova et al., 2016; Lu et al., 2016). The use of the Precise Point Positioning (PPP) processing strategy plays a key role in developing new products as it is an efficient and autonomous method, it is sensitive to absolute tropospheric path delays, it can effectively support real-time or ultra-fast production, it may optimally exploit data from all GNSS multi-constellations, it can easily pro- duce a full variety of parameters such as zenith total delays, horizontal gradients or slant path delays and it may also support as reasonable as high temporal resolution of all the parameters. In particular, PPP is supported with global orbit and clock products provided by the real-time service of the International GNSS Service (IGS, Dow et al., 2009; Caissy et al., 2012).

The main objectives of the IAG WG 4.3.5 'Real-Time troposphere monitoring' are: (1) Develop real-time multi-GNSS processing algorithms and strategies for high-resolution, rapid-update NWP and nowcasting applications, (2) Develop new/enhanced GNSS tropospheric products and exploit the full potential of multi-GNSS (GPS, GLONASS, Galileo and BeiDou) observations for use in the forecasting of severe weather, (3) Evaluate the benefit of new/enhanced GNSS products (real-time, gradients, slants…) for numerical and non-numerical nowcasting,

(4) Stimulate the development of application software for supporting routine production, (5) Demonstrate real-time/ultra-fast production, assess applied methods, software and precise orbit and clock products, and (6) Setup a link to the potential users, review product format and re- quirements.

Under the framework of the working group objectives, the main achievements during the period 2019-2023 focused on the establishment of GNSS real-time processing software and provide tropospheric products for climate and weather research (objective 1 & objective 4 & objective 6), the evaluation of new/enhanced GNSS tropospheric products for applying in numerical and non-numerical weather now-casting (objective 2 & objective 3), e.g., the atmospheric parame- ters retrieved from the Galileo and BDS-3 constellations, so as the assessment on the applied real-time methods, precise orbit and clock products offered by different ACs in terms of their effects on the performance of the derived tropospheric products (objective 5).

Developing real-time/ultra-fast application software

Different software has been developed continuously by the working group members to produce real-time/ultra-fast tropospheric products with high accuracy, spatial-tempo resolution and re- liability. Among these are the EPOS-RT Software (Li et al., 2014) developed by GFZ, the G- Nut/Tefnut software provided by Geodetic Observatory Pecny (GOP) (Douša and Václavovic et al., 2013), GNSS-WARP from Wroclaw University of Environmental and Life Science (WUELS, Hadaś, 2015), the real-time troposphere monitoring software of GREAT-Trop estab- lished by Wuhan University (Li et al., 2021) and the BKG Ntrip Client (Weber et al., 2016). Besides the provision of real-time ZTDs, gradients and STDs estimates can also be expected from this software. As examples, real-time STDs are able to be obtained from G-Nut/Tefnut of GOP (Dousa et al., 2016), and high-resolution tropospheric gradients as well as an ambiguity- fixed resolution for tropospheric parameters derivation are also offered by the GREAT-Trop software.

The Real-Time Demonstration campaign

Geodetic Observatory Pecný

The Geodetic Observatory Pecný of the Research Institute of Geodesy, Topography and Car- tography has been developing the G-Nut/Tefnut software since 2013, and since 2018 continued in a collaboration with the G-Nut Software s.r.o. The latest G-Nut/Tefnut-RT is capable of es- timating of all tropospheric parameters (ZTD, linear horizontal gradients and slant tropospheric delays) in real-time, near real-time, and post-processing mode using PPP method when sup- porting all the GNSS constellations. During 2015-2019, the GOP coordinated the Real-Time GNSS Troposphere Demonstration Campaign (Douša and Dick, 2017), it was a first contributor which has continued to the present time. In 2018, the real-time processing has been enhanced to a new all-in-one strategy enabling a simultaneous real-time and near real-time processing (Douša et al. 2018), the latter exploiting a backward smoother in addition to the Kalman Filter (Václavovic and Douša, 2016). In 2019, the un-combined and undifferenced processing strat- egy has been implemented and evaluated. In 2020, the real-time demonstration has been ex- tended to about 200 stations, majority in Europe and some others in the world. The ZTD and horizontal tropospheric gradients are estimated in a 5-min sampling continuously with a RMS better than 10 mm and 0.5 mm, respectively. A quality of the real-time solution reached almost the quality of the traditional near real-time product. The monitoring web is available at https:/www.pecny.cz/RT-TROPO/ where the time-series of estimated parameters can be visu- alized and compared. In particular, a comparison of independent results from collocated stations provides a good indicator of the quality in real-time, see GOPE and GOP6 in Figure 1.

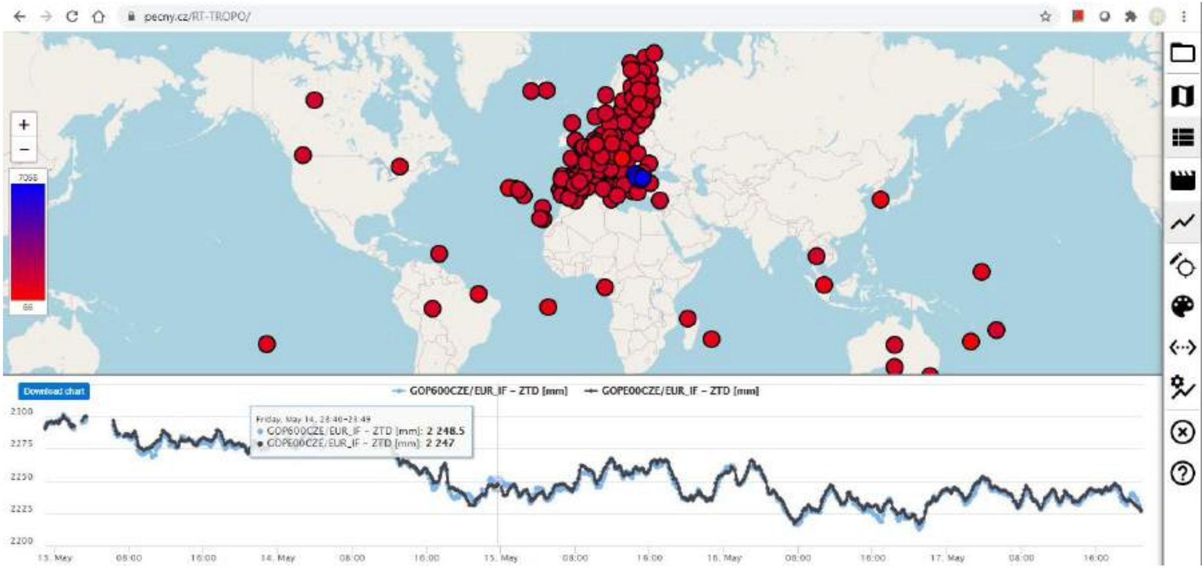


Figure 1: Web visualizing ZTD and gradients estimated in real-time at GOP. Example time-series of GOPE and GOP6 collocated stations, May 13-18, 2021.

A validation from the GOP real-time products against the EUREF combined tropospheric prod- uct is displayed in Figure 2. The RMS of ZTD is plotted on a monthly basis for 9 selected stations. Note offsets of +10 mm for each individual stations. The mean bias, standard deviation and RMS over all the stations and months is below 5 mm, 8 mm, and 10 mm, respectively.

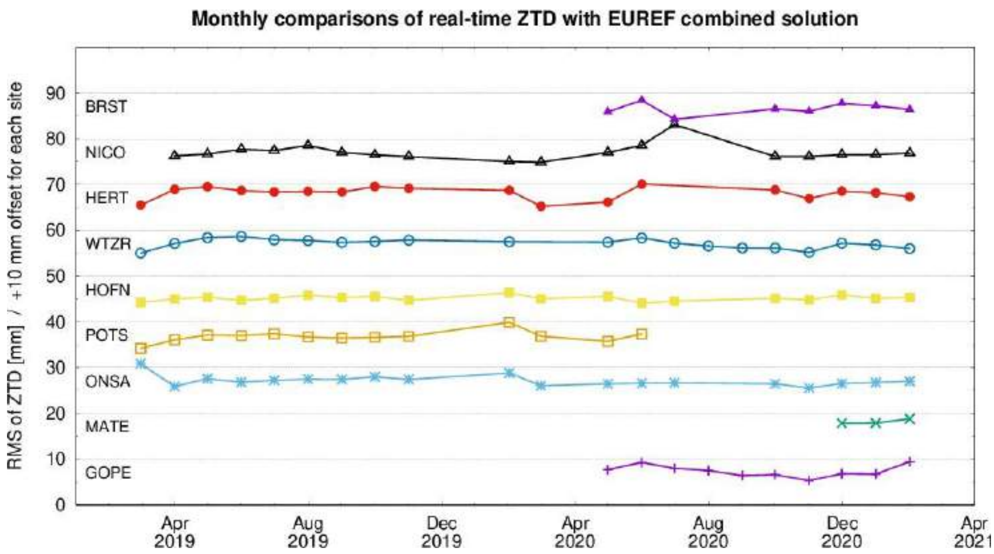


Figure 2: Monthly RMS of real-time ZTDs produced at GOP with respect to combined EUREF product.

UK Met Office

Sub-hourly GNSS data collection

The **B**KG (*Bundesamt für Kartographie und Geodäsie* – i.e. the German Federal Agency for Cartography and Geodesy) **N**trip (Networked Transport of RTCM via Internet Protocol) **C**lient (BNC, https://igs.bkg.bund.de/ntrip/bnc), is installed on the Met Office DMZ server GPSRT, for the collection of real-time (NTRIP) GNSS raw data streams, and for the subsequent writing of 15-minute RINEX files. The 15-minute RINEX are then pulled in through the Met Office firewall by the Met Office sub-hourly GNSS processing servers (see below).

BNC connects to specific ntrip broadcasters (i.e. casters) by way of ip address (or DNS name), username, password and port number. Once connected to the individual NTRIP caster, the in- dividual GNSS sites (i.e. mountpoints) are selected for download.

Currently the Met Office has 5 separate instances of BNC running 24/7, collecting data from 5 NTRIP casters. Having separate instances of BNC running concurrently eliminates the risk of all data input failing if a problem arose with one caster's stream.

The BNC streams:

Bnc.os	Retrieving data from Ordnance Survey GB
Bnc.osi	Retrieving data from Ordnance Survey of Ireland
Bnc.osni	Retrieving data from Ordnance Survey of Northern Ireland
Bnc.eu	Retrieving data from EUREF
Bnc.igs	Retrieving data from the IGS

RINEX header information (e.g. antenna make/model etc) is critical to GNSS processing. When RINEX files are created using BNC, header information is not always available via the stream. As such, RINEX header information is added to the incoming streamed RINEX by way of skeleton (.skl) files. Skeleton files are (mostly automatically) collected from 3rd party data pro- viders and uploaded to GPSRT. Once RINEX (with correct header) is created, it is then Ha- tanaka compressed, Unix compressed and moved to an archive, ready for download by the pro- cessing servers.

Met Office sub-hourly GNSS Data Processing

The Met Office currently operates five 24/7 GNSS processing services (each with a stack of Production, Test and Development servers, i.e. 15 servers in total), two services derive space weather products (i.e. TEC data), with the remaining three deriving tropospheric delays (i.e. ZTD and IWV). Of the GNSS tropospheric servers, one stack (METR) is dedicated to the pro- cessing of 15 minute RINEX data for delivery of ZTD and IWV products in real-time.

On the METR server, two 15 minute GNSS processing systems are running, METR (Bernese v5.0 solution) and MTRS (Metoffice Tropospheric Regional Subhourly) which is a Bernese v5.2 processing solution. 15 minute RINEX is downloaded from GPSRT every 15 minutes and Bernese estimates the ZTD at the start and end of the 15 minute file (e.g. for a 00-15min file, estimates of ZTD at 00:00 and 14:59). Data download and processing campaign setup takes 10 minutes and processing time of ~2 minutes, thus the most real-time ZTD/IWV estimate is around 12 minutes old by the time they are made available to customers. Bernese output files are converted to COST716 format (ASCII) which are uploaded to the E-GVAP server and also into binary BUFR format which are then ingested into the Met Office database (MetDB) and disseminated on the Global Telecommunication System (GTS) for use by other National Me- teorological and Hydrological Services (NMHSs).

At the current time, data from the 15 minutes processing systems (METR and MTRS) is not operationally assimilated in any Met Office numerical weather prediction models as latency from other Met office GNSS processing systems is adequate. However, as NWP model assim- ilation progresses (e.g. to 4DVar) and with ever higher temporal and spatial resolution models, the 15 minute processed data will be operationally assimilated in the near future, with trials already underway.

Additionally, a separate script collects surface meteorological (SYNOP) data (temperature, pressure and dew point temperature) from the MetDB for conversion of ZTD to Integrated (Precipitable) Water Vapour. The IWV data is then plotted onto maps and animations for oper- ational forecaster use in the

Met Office operations centre. Additionally, the forecasters in the operations centre also use the IWV data with a nomogram to estimate maximum potential rain- fall from a given air mass.

School of Geodesy and Geomatics, Wuhan University

The School of Geodesy and Geomatics of Wuhan University is dedicated to exploring the po- tential of multi-GNSS signals and providing a set of real-time products and services. For this purpose, real-time precise point positioning (RTPPP) software was developed to serve GNSS high-precision satellite navigation and positioning. The RTPPP software is composed of the server side and the user side. The server side aggregates real-time data streams from the ground- based reference network to the data processing center via network transmission. The data center processes real-time data streams and broadcasts precise orbit, clock, and tropospheric delay products to users. The RTPPP software mainly includes the following functions:

(1) Support SPP, PPP, PPP-AR, and PPP-RTK solutions for GPS, BDS, and Galileo sys- tems
(2) Support GNSS static and dynamic solutions
(3) Support tropospheric delay modeling and broadcasting
(4) Support real-time monitoring of data transmission status and display of data processing results

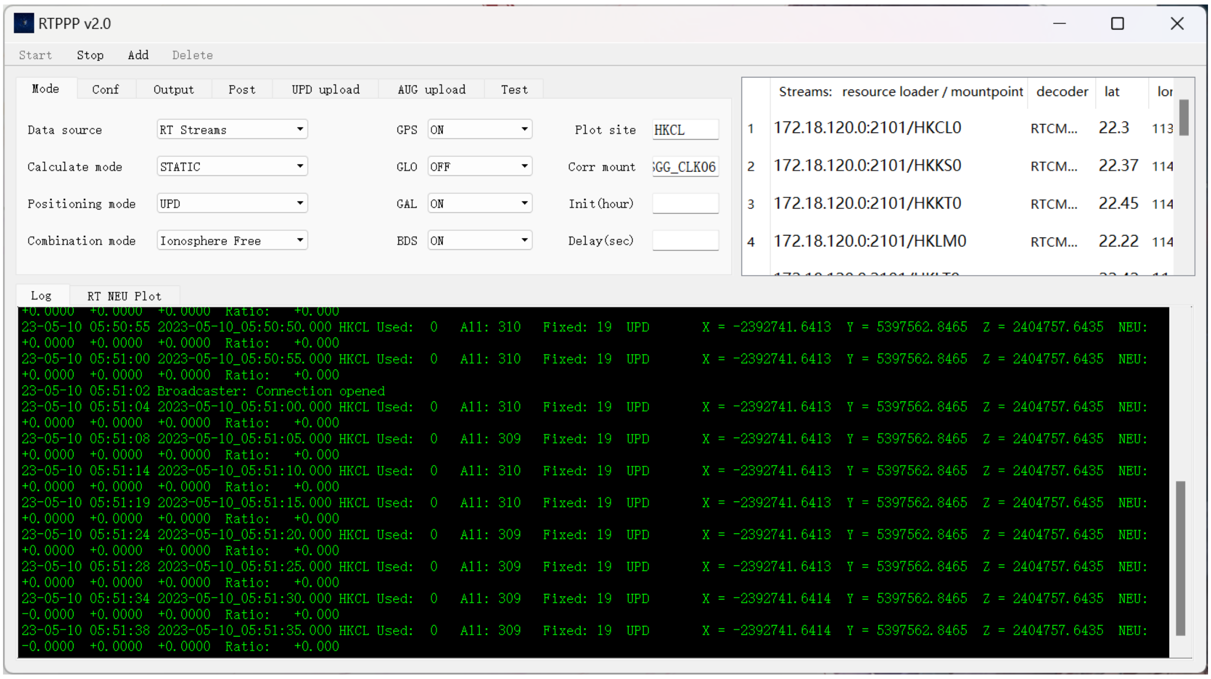


Figure 3: Real-time GNSS (RT-GNSS) data processing of RTPPP

To evaluate the accuracy of tropospheric delay products broadcasted by RTPPP software, GNSS data streams from 2023-04-24 00:00:00 to 2023-04-24 23:59:30 of the Hong Kong CORS network were selected for testing. A total of 14 stations were selected in the experiment. The distribution of the stations is shown in Figure 4, among them 11 stations are used for trop- ospheric delay modeling and 3 stations are used as user stations.

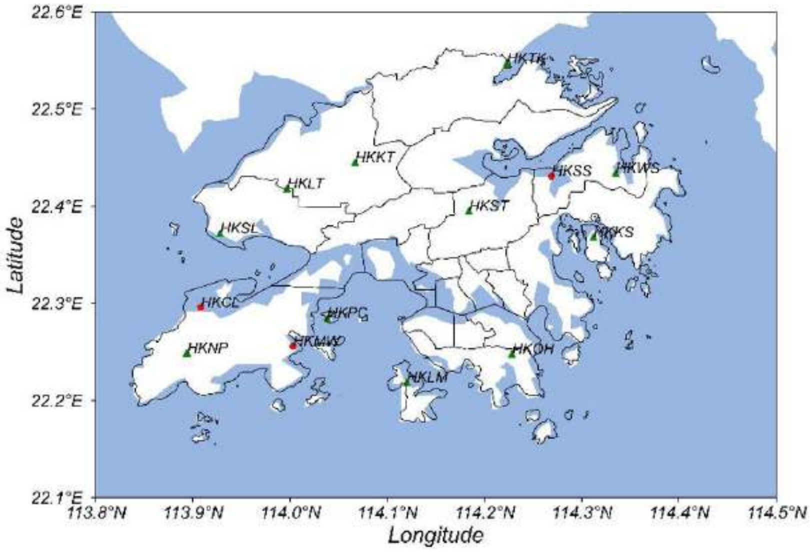


Figure 4: Map of Hong Kong CORS stations

Figure 5 demonstrates the statistical results of the tropospheric delay precision broadcast by the RTPPP software. The results show that the RMS values of the difference between the broad- casted and solved tropospheric delays for three user stations are 6.7 mm, 6.2 mm, and 2.5 mm, respectively, which are all less than 1 cm.

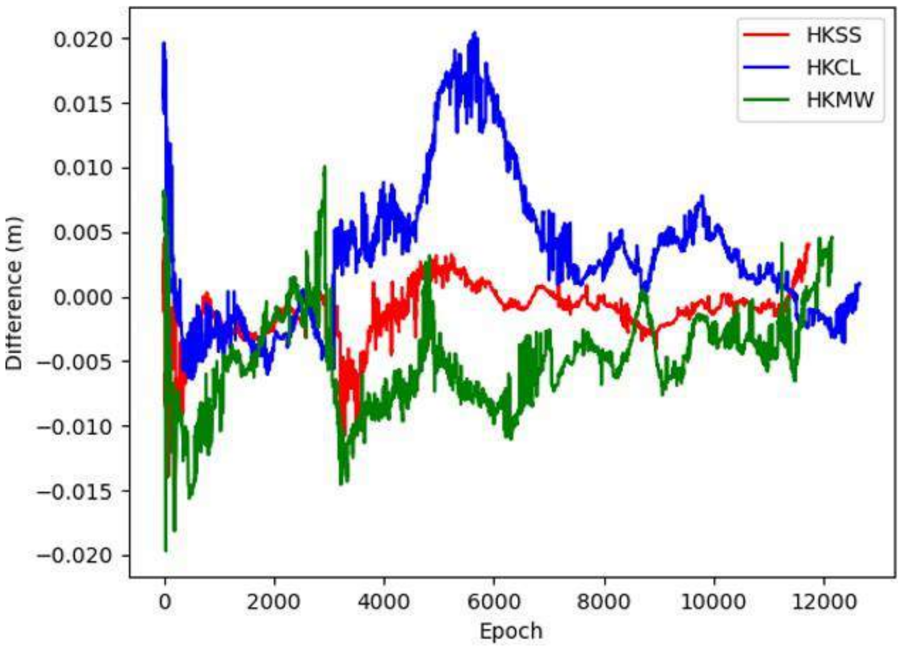


Figure 5: Tropospheric delay accuracy of CORS stations in Hong Kong

Real-time tropospheric products and validation

The rapid development of the European Galileo system and the Chinese BeiDou Navigation Satellite System (BDS) brings a great opportunity for the real-time retrieval of atmospheric parameters, including time-critical meteorological applications. Studies were carried out by em- ploying Galileo observations to retrieve real-time water vapor based on the PPP technique, where the benefit of ambiguity resolution on water vapor sensing was also investigated (Lu et al., 2020). The ZTDs retrieved from Galileo are compared with post-processing GPS ZTDs, and Galileo PWV values are validated with ECMWF PWV products. Statistics reveal that the derived Galileo PWVs display good agreement with the ECMWF PWVs in general. The aver- aged RMS value of PWV from the Galileo float solution for all stations is 1.9 mm, and that of the fixed solution is 1.7 mm, revealing an improvement of 10.5%. In addition, the initialization time is shortened from 27.4 min to 20.8 min by applying the ambiguity fixed solution in com- parison to the float solution.

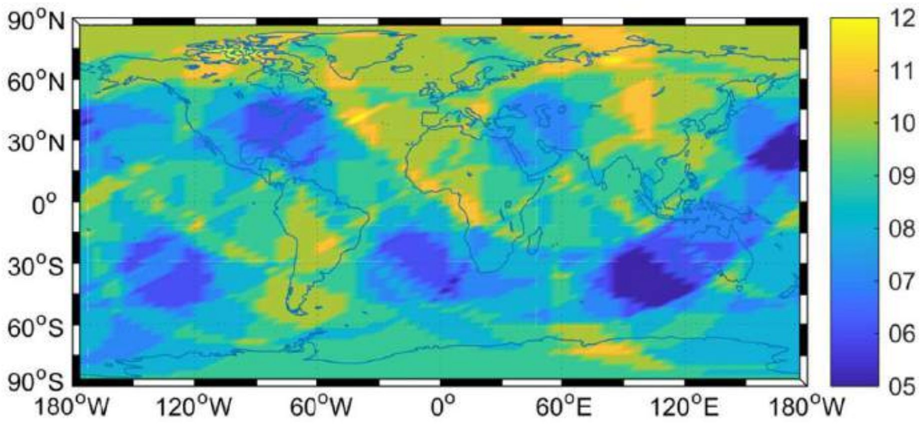


Figure 6: Averaged number of visible Galileo satellites with an elevation cutoff of 5 degrees on DOY 120, 2019.

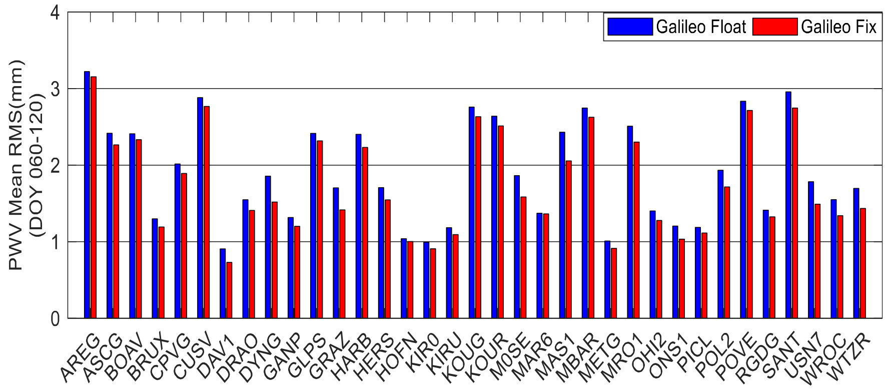


Figure 7: Averaged initialization time of the real-time Galileo ZTDs derived from float (blue) and fixed (red) solutions during DOY 060–120, 2019.

Within the transpolar drifting expedition MOSAiC (Multidisciplinary drifting Observatory for the Study of Arctic Climate), the Global Navigation Satellite System (GNSS) was used among other techniques to monitor variations in atmospheric water vapor (Männel et al., 2021). Based on 15 months of continuously tracked GNSS data including GPS, GLONASS and Galileo, epoch-wise coordinates and hourly zenith total delays (ZTDs) were determined using a kine- matic precise point positioning (PPP) approach. The derived ZTD values agree to 1.1 ± 0.2 mm (root mean square (RMS) of the differences 10.2 mm) with the numerical weather data of ECMWF's latest reanalysis, ERA5, computed for the derived ship's locations. This level of agreement is also confirmed by comparing the on-board estimates with ZTDs derived for ter- restrial GNSS stations in Bremerhaven and Ny-Ålesund and for the radio telescopes observing very long baseline interferometry in Ny-Ålesund.

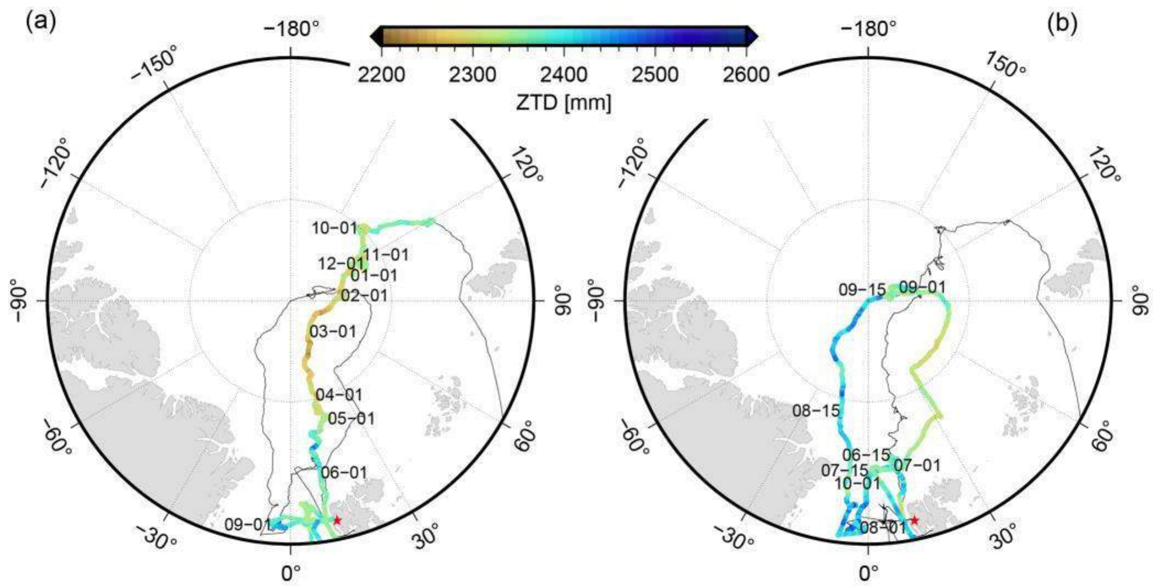


Figure 8: Ship track with hourly ZTD values (color coded according to the ZTD); panel (a) shows the ZTD series for August 2019 to 5 June 2020, panel (b) shows the ZTDs for 6 June to 3 October 2019; selected time stamps are added; the red star marks Ny-Ålesund.

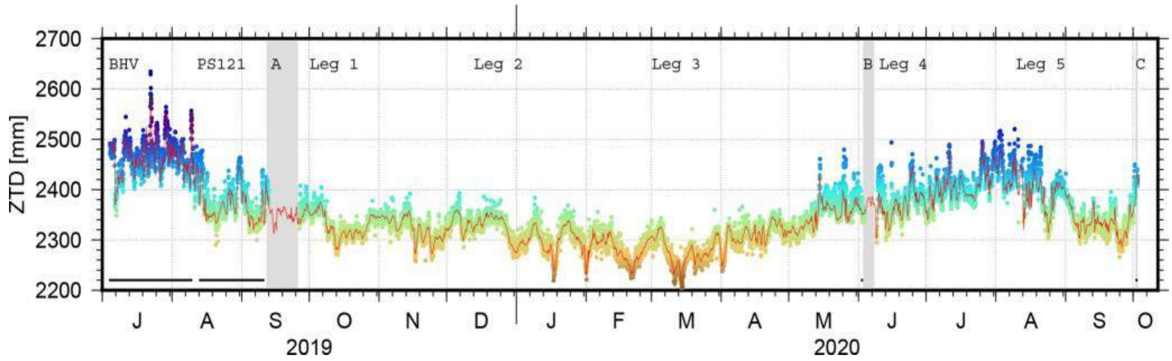


Figure 9: ZTD time series: hourly ZTD values (color coded according to the ZTD) and 3-hourly ERA5-based ZTDs (red line).

In addition to the ZTD and PWV, the slant total delays (STDs) derived from GNSS are also evaluated. "Advanced MUlti-GNSS Array for Monitoring Severe Weather Events" (AMUSE) is a current research project performed in cooperation of TUB (Technische Universität Berlin), GFZ (German Research Centre for Geosciences) and DWD (Deutscher Wetterdienst). The main objectives of the project are: 1) developments to provide multi-GNSS instead of GPS-only data, including GLONASS, Galileo and BeiDou; 2) developments to provide high quality advanced tropospheric products, i.e. slant tropospheric delays (STD); 3) developments to shorten the de- lay between measurements and the provision of the products to the meteorological services.

At the moment, three multi-GNSS solutions are being calculated: GPS-only, GPS/GLONASS and GPS/GLONASS/Galileo based on a dense German network SAPOS and a global network (GFZ/IGS). The STDs are calculated every 2.5 minutes. The obtained parameters were com- pared with two global Numerical Weather Models (NWM): ERA5 reanalysis and a forecast model ICON. Figure 10 shows that all three solutions exhibited a similar level of agreement with the NWMs although, the GRE solution had slightly higher agreement with ERA5. When only the Galileo observations are considered, the biases were reduced by ~25% compared to the GPS-only solution (Wilgan et al., 2022).

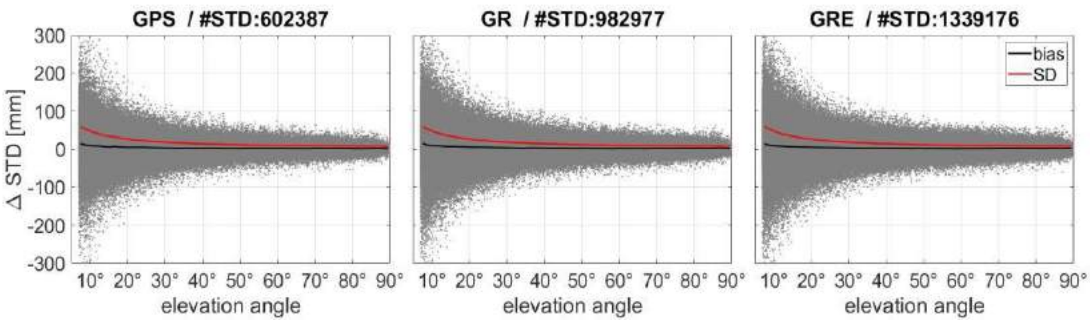


Figure 10: Differences between STDs from ERA5 and three GNSS solutions: GPS only (left), GPS/GLONASS (middle) and GPS/GLONASS/Galileo (right). Data period is October 2020.

The Vienna Mapping Function 1 (VMF1) model, based on continuous updates of Numerical Weather Prediction (NWP) data from the European Centre for Medium-Range Weather Fore- casts (ECMWF), is recommended for the accurate modeling of tropospheric path delay in post- processing. The VMF1 coefficients determined from forecast data of the ECMWF are now readily and freely available. A study investigates the performance of the VMF1-FC model in terms of its three components which are critical for the modeling of tropospheric path delay: the Zenith Hydrostatic Delay (ZHD), the Zenith Wet Delay (ZWD) and mapping functions (Yuan et al. 2019). All three components are assessed in the context of GNSS Precise Point Positioning (PPP) using 28 global stations over a 70-day period. The Zenith Total Delays (ZTD) derived with the VMF1-FC (implemented in real-time PPP) are shown to agree well with the tropospheric delay product from the Center for Orbit Determination Europe (CODE). Root mean square (RMS) errors associated with these ZTD estimates are < 10 mm at all 28 stations. The results shown in Figure 11 also show that the VMF1-FC model performs better than empirical models such as the widely used Global Pressure and Temperature 2 (GPT2) and GPT2 wet (GPT2w), with smaller RMS errors associated with the ZTD estimates. It is recommended that VMF1-FC be applied for future tropospheric delay modeling in real- time GNSS and VLBI applications.

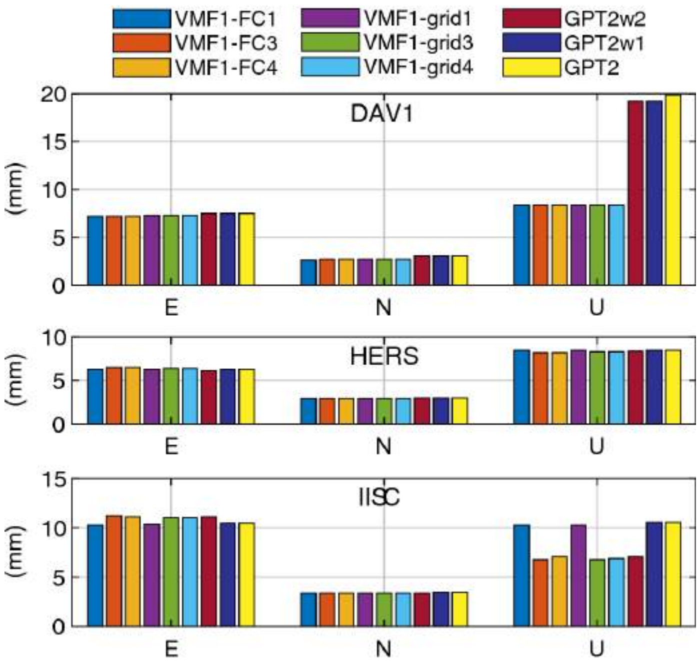
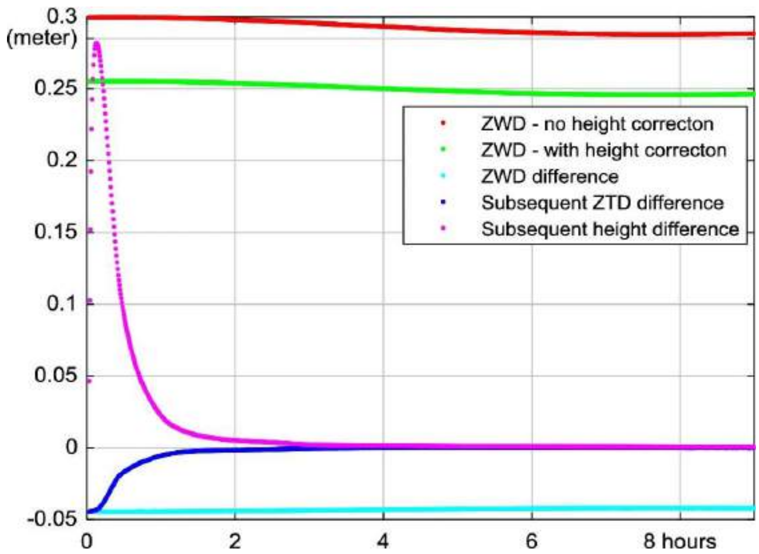


Figure 11: RMS errors of the three components of station coordinates at stations DAV1 (in polar regions), HERS (in extratropical region) and IISC (in tropical region). In this scenario, VMF1-FC mapping functions are held constant while different a priori ZHDs are used in PPP:

Figure 12: Changing of ZTD and height estimated from PPP at station IISC when different



Current achievements of tropospheric modeling

In addition to the main objectives of this working group mentioned previously, some members have also worked on several related aspects of tropospheric modeling. These include regional or global atmospheric modeling, the establishment of local real-time water vapor monitoring systems, the emerging implementation of machine-learning methods in GNSS meteorology (Lu et al., 2023a; Shamshiri et al., 2020; Zheng et al., 2022), applications of GNSS tropospheric products in numerical weather prediction or weather now-casting (Guerova et al., 2022; Hadas et al., 2020), and GNSS water vapor retrieval from ocean regions based on ship-born platforms (Ikuta et al., 2022; Männel et al., 2021).

Recently, a tropospheric delay model that integrates tropospheric delays derived from the Eu- ropean Centre for Medium-Range Weather Forecasts' fifth-generation global atmospheric rea- nalysis and the Continuously Operating Reference Station (CORS) network observations in mountainous areas is established, which is then applied to improve GNSS precise point posi- tioning (Lu et al., 2023b).

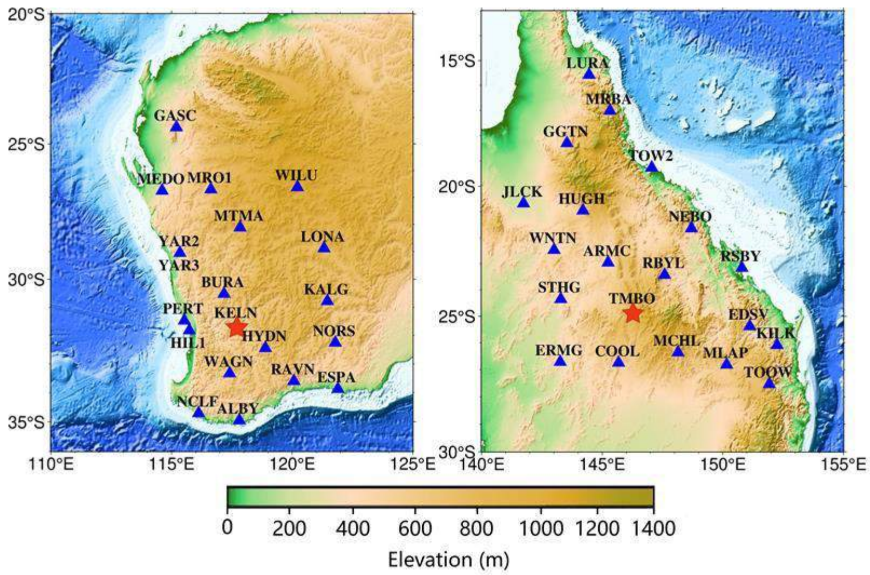


Figure 13: Geographical distribution of the 40 selected Australia CORS stations**.**

Observations of GNSS stations in the Great Dividing Range of eastern Australia are selected for the experiments. The performance of zenith wet delay (ZWD) retrieved from the integrated tropospheric model is evaluated with comparisons to precise point positioning (PPP) es- timated ZWD values. Results show that the average root-mean-square value for ZWDs of the integrated tropospheric model is 8.03 mm for the eastern Australian CORS network, showing an improvement of 14.0% compared to that of the CORS inter- polation model.

Besides, the proposed tropospheric model is applied to regional augmentation precise position- ing. Results present that the average positioning accuracy of the tropospheric model- corrected PPP solutions is 1.42 cm, 1.39 cm and 2.90 cm for the east, north and vertical components, respectively, revealing an improvement of 14.5%, 11.5% and 18.6% compared to the PPP so- lutions with regional CORS corrections. Meanwhile, almost all stations can achieve a faster solution convergence by performing the integrated tropospheric model-corrected PPP. All these results demonstrate the promising potential of the proposed tropospheric model in enhancing precise positioning as well as facilitating applications in the meteorological fields.

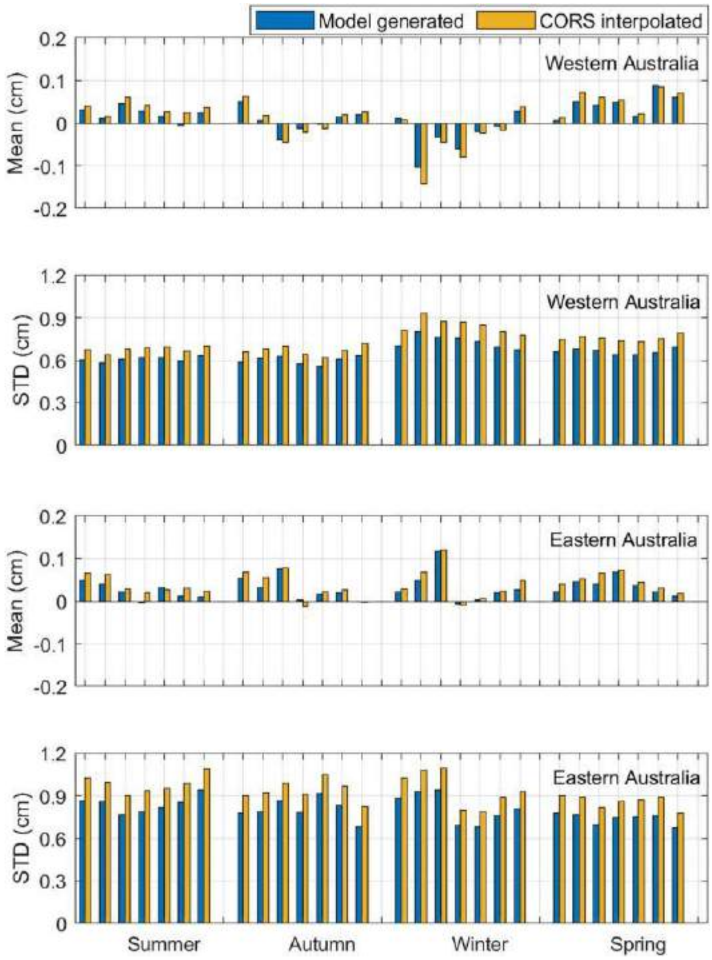


Figure 14: Mean and STD of the ZWD differences for Western Australia (top panels) and Eastern Australia (bottom panels) for four seasons, i.e., from DOY 001 to 007 in summer, from DOY 090 to 096 in autumn, from DOY 180 to 186 in winter and from DOY 270 to 276 in spring. The blue and yellow histograms denote the model-generated solutions and CORS-interpolated solutions, respectively.

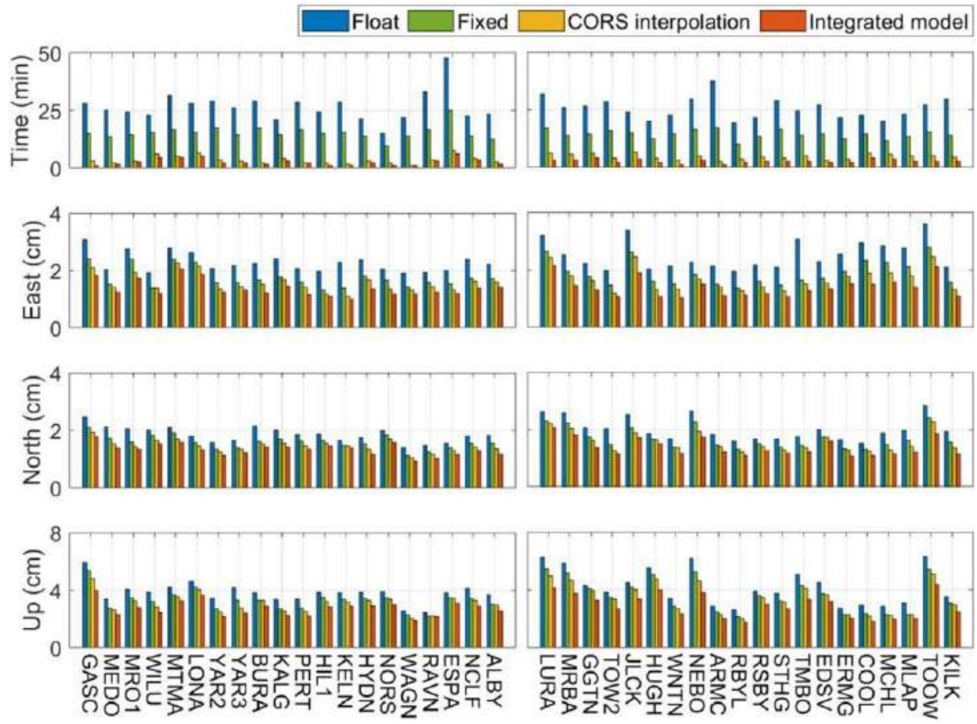


Figure 15: Statistical results of the convergence time (top two panels) and positioning RMS values of the float PPP (blue bars), fixed PPP (green bars), interp-PPP (yellow bars) and model-PPP solutions (red bars) for four weeks. The left panels denote results for stations in Western Australia and the right panels denote results for stations in Eastern Australia.

In this context, authors from Wuhan University formed a multi-source real-time local tropo- spheric delay model that uses polynomial fitting of ground-based GNSS observations, meteor- ological data and empirical GPT2w models (Yao et al., 2019), where the ZTDs were verified with a RMS of 1.48 cm in active troposphere conditions and 1.45 cm in stable troposphere conditions, which is superior to the conventional tropospheric GPT2w and Saastamoinen mod- els. A pilot transnational severe weather service exploiting GNSS tropospheric products to en- hance the safety, the quality of life and environmental protection in the Balkan-Mediterranean region was developed by a project “BalkanMed real-time severe weather service” (2017-2019, Guerova et al., 2020).

Since March 2021, Sofia University “St Kliment Ohridski” is leading a project to exploit the added value of GNSS tropospheric product for nowcasting of convective storm by building Storm Demonstrator (Storm Demo) in support of public weather and hail suppression services in Bulgaria. As a part of the Storm Demo real-time PPP processing will be conducted with G- Nut software for the first time in Southeast Europe for the hail suppression season May-Sep- tember 2021.

Authors from the Chinese Academy of Sciences Institute of Geodesy & Geophysics proposed a method to establish a real-time GNSS-PWV monitoring system using the national GNSS net- work of China (Zhang et al., 2019). The agreement between the real-time GPS-PWV and NCEP-II-PWV is approximately 2.0 mm in terms of RMS and has a mean bias of -0.8 mm. Authors from the Chinese Academy of Sciences Shanghai Astronomical Observatory proposed a regional zenith tropospheric delay (ZTD) empirical model SHAtropE, which is developed and provides tropospheric propagation delay corrections for users in China and the surrounding areas with improved accuracy (Chen et al., 2020). The model combines the exponential and periodical functions and is provided as regional grids with a resolution of 2.5◦ × 2.0◦ in longi- tude and latitude. Moreover, SHAtropE also provides the predicted ZTD uncertainty, which is valuable in Precise Point Positioning (PPP) with ZTD being constrained for faster convergence. And the modeling quality control method for such models is proposed to establish the basis for the establishment of global ZTD models based on GNSS data (Ding et al., 2020). The accuracy and accuracy spatial-temporal properties of the latest model of the GPT series, GPT3, were analyzed, containing ZTD, eastward gradient and northward gradient (Ding and Chen, 2020).

In addition, exploration on GNSS water vapor sensing over the ocean regions were attempted. As an example, experimental observations of precipitable water vapor derived using GNSS receivers mounted on autonomous surface vehicles for real-time monitoring applications were reported by Fujita et al. (2020). PWV retrieval using kinematic PPP method with shipborne GNSS observations was also carried out during a 20-day experiment in 2016 in Fram Strait, the region of the Arctic Ocean between Greenland and Svalbard (Wang et al., 2019). Results showed that the shipborne GNSS PWV shows an agreement of similar to 1.1 mm with numer- ical weather model data and radiosonde observations.

Within the transpolar drifting expedition MOSAiC (Multidisciplinary drifting Observatory for the Study of Arctic Climate), GNSS was used among other techniques to monitor variations in atmospheric water vapor (Männel et al., 2021). The derived ZTD values agree to 1.1 ± 0.2 mm (RMS of the differences 10.2 mm) with the numerical weather data of ECMWF's latest reanal- ysis, ERA5, computed for the derived ship's locations. The overall difference for integrated water vapor of 0.08 ± 0.04 kg m^{-2} (RMS of the differences 1.47 kg m^{-2}) demonstrates the good agreement between the GNSS and radiosonde data (Figure 16).

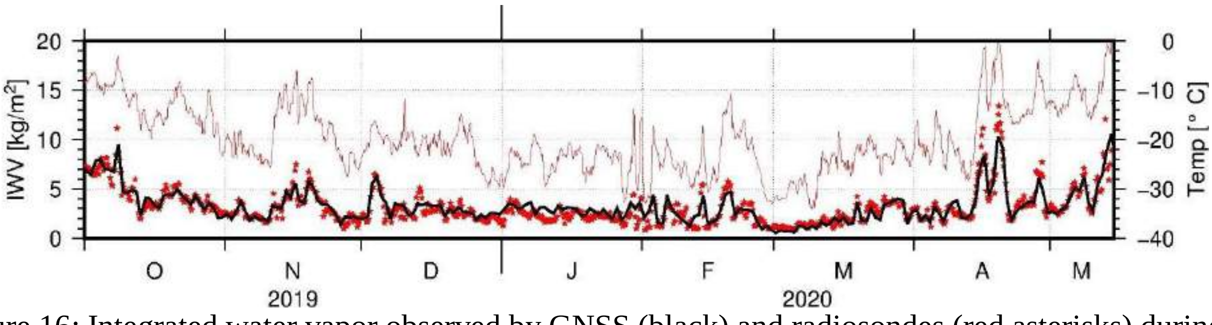


Figure 16: Integrated water vapor observed by GNSS (black) and radiosondes (red asterisks) during the MOSAiC campaign (October 2019 to May 2021), air temperature curve (thin red line, secondary axis).

Moreover, the machine-learning method was introduced to solve the current related issues in the GNSS/Met attributing to its dramatic developments. Exemplarily, a generalized regression neural network (GRNN) was applied (Zhang et al., 2021) to fuse PWVs from GNSS, the Mod- erate-Resolution Imaging Spectroradiometer (MODIS) and the European Centre for Medium- Range Weather Forecasts Reanalysis 5 (ERA5). Additionally, a tropospheric delay network (TropNet) model is developed based on deep learning method to forecast the zenith wet delays (ZWD) by combining information provided by the Geostationary Operational Environmental Satellite-R series and the global forecast system (GFS) (Lu et al., 2023c).

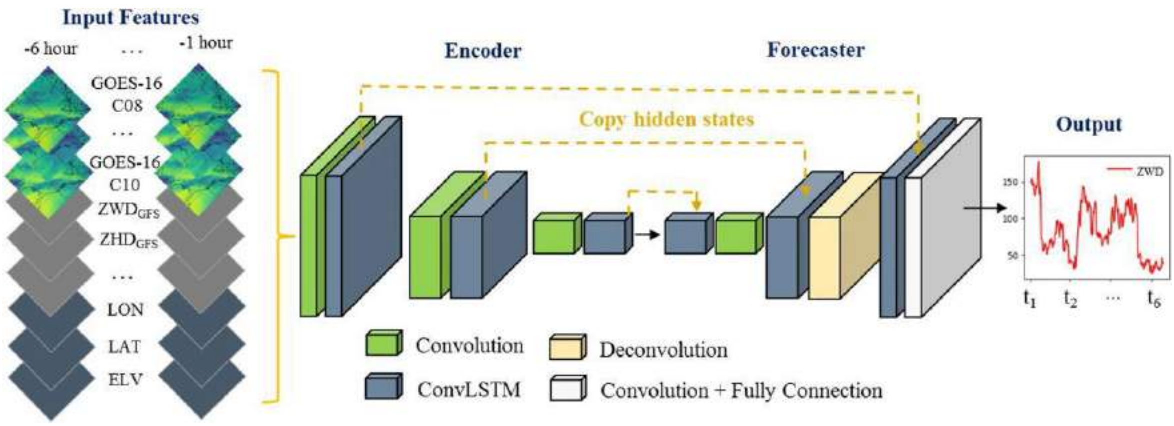


Figure 17: The encoding-forecasting framework of TropNet.

The performance of the tropospheric delays predicted from TropNet is assessed with tropo- spheric products derived from GNSS. The results demonstrate that the TropNet predicted ZWD agree well with the GNSS-derived ZWD, and an accuracy of better than 11 mm is achieved for all the forecast lead times, showing an overall improvement of 15.5% when compared to the GFS ZWD. Moreover, intercomparisons with ZWD derived from radiosondes and Vienna Map- ping Functions 3 (VMF3) are performed to further evaluate the performance of the TropNet model. Averaged RMS values equal to 14.9 mm and 13.9 mm are obtained when compared to radiosondes and VMF3. Furthermore, the TropNet model is able to forecast high-quality ZWD up to 6 h at a spatial resolution of 2 km and a temporal resolution of 1 h, which indicates a prospective potential for time-critical applications.

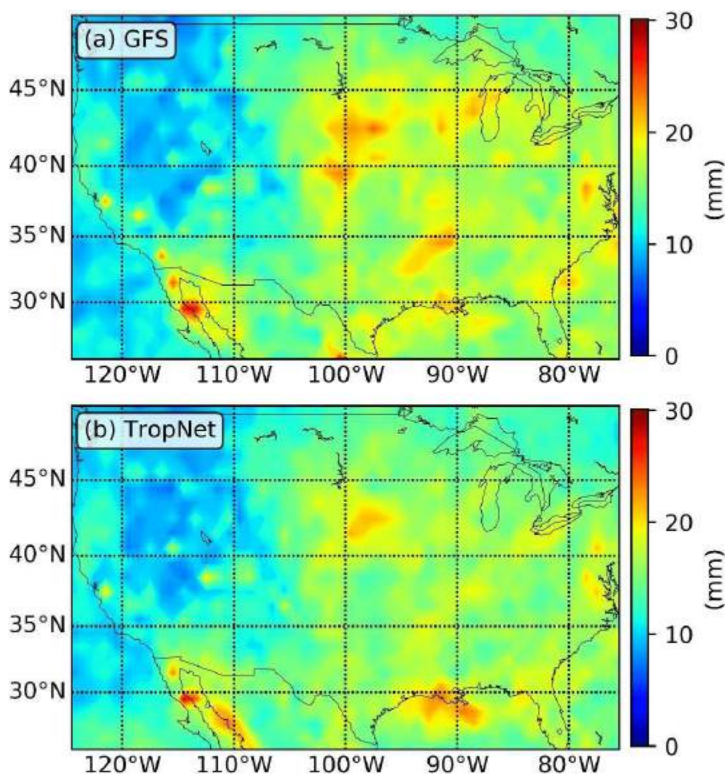


Figure 18: The RMS values of the ZWD differences between the GFS, TropNet, and VMF3 between 25° N–50° N and 75° W–125° W for DOY 182–212 of 2019.

Applications of GNSS tropospheric products in NWP and nowcasting

GNSS has become a mature observing technique for data assimilation applications, especially in Numerical Weather Prediction (NWP) models. Studies have been carried out in recent years, including the applying of GNSS PWV in assimilation-forecast cycle, using the zenith wet de- lays to track the properties of hurricanes and explore their spatial and temporal distributions, assimilating GNSS ZTDs with different temporal resolutions on severe convective weather now-casting based on the weather research and forecasting (WRF) model, as well as the inves- tigations on the ground-based GNSS for climate research (Guerova et al., 2022; Ikuta et al., 2022; Pacione et al., 2021; Johnston et al. 2022; Hintz et al., 2019; Zhang et al., 2023; Zus et al., 2019).

Accurately describing the water vapour distribution over the sea in a forecast model's initial conditions should improve the prediction accuracy of heavy rainfall events. Thus, the shipborne precipitable water vapour (PWV) observed by GNSS onboard ships is assimilated to show its impact on a heavy rainfall event in July 2020 (Ikuta et al., 2022). The study obtained the GNSS observations during a continuous water vapor observation campaign conducted at sea, one of the few in the world. The study applied the shipborne PWV, on the upwind side of the heavy rainfall, to the four-dimensional variational data assimilation method and conducted assimila- tion-forecast cycles. Although the shipborne PWV is a point observation, it can be assimilated as observation data covering space and time because the ships conducting the GNSS observa- tion sailed around Japan.

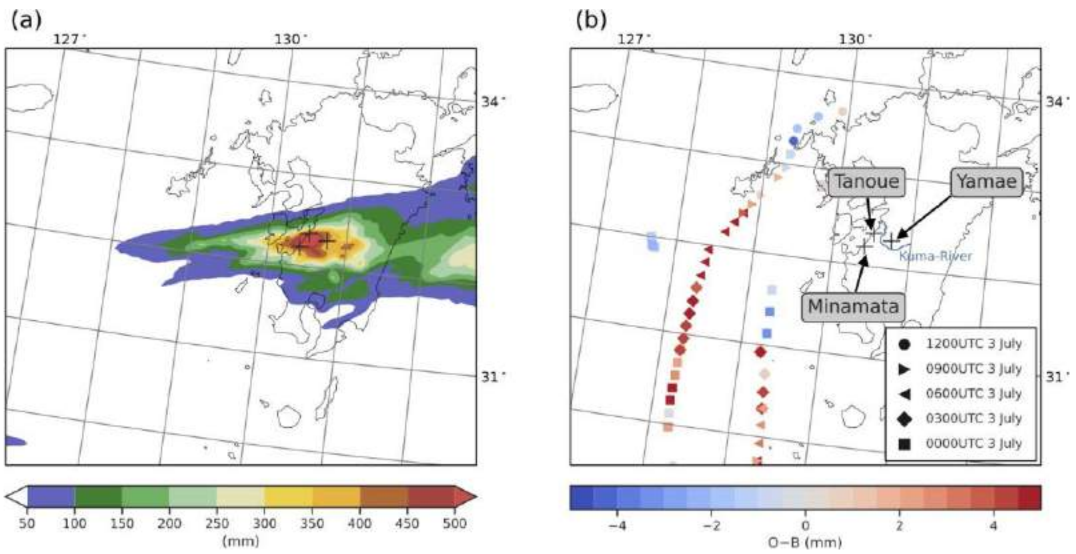


Figure 19: (a) 12-hr accumulated precipitation of R/A on July 4, 2020, at 0000 UTC. (b) O−B of ship- borne PWV. Red/blue indicates that the observation is wet/dry compared with the background. The marker type indicates the date and time of the initial condition

In addition, in the assimilation-forecast cycle, the effect of assimilation spread widely over the forecast area. Although the ship's motion affects the shipborne observations. The study found that the impact on PWV assimilation is negligible for practical use. For the temporal thinning of the data assimilation slot for the shipborne PWV, an interval of 30 min is more effective than an interval of 1 hr. As a result of assimilating this shipborne PWV on the upwind side of the disastrous heavy rainfall of July 2020, the forecast accuracy of rainfall, especially rainfall amount, was improved. The study also found that statistical improvements could be obtained from the water vapor profiles and wind velocity field in the lower atmosphere. The study demonstrates that the assimilation of shipborne PWV observations can improve the prediction accuracy of heavy rainfall events.

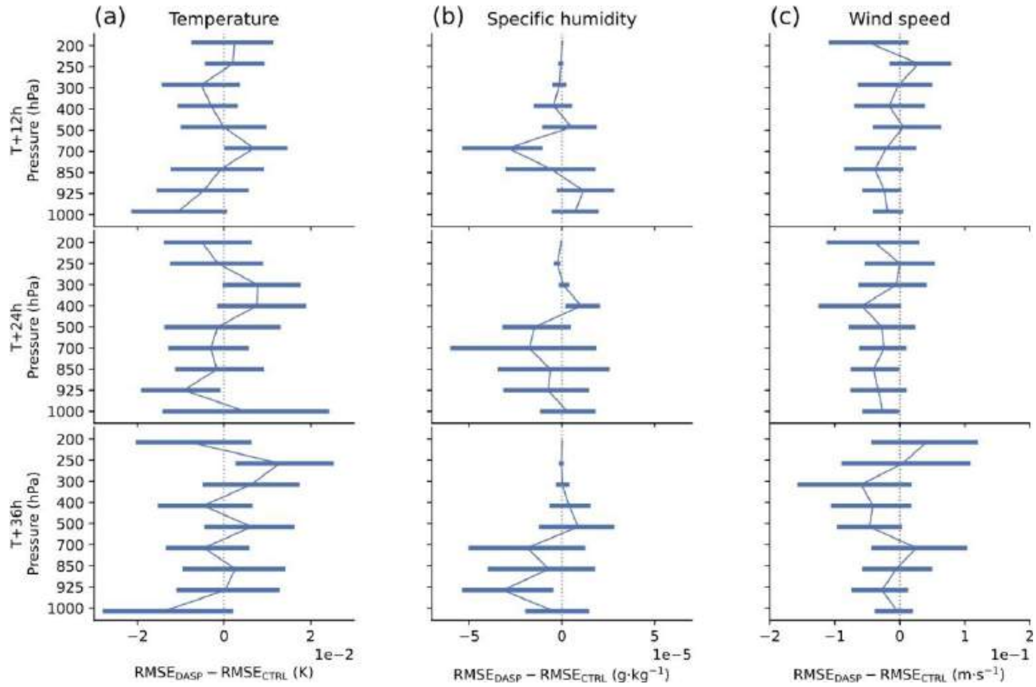


Figure 20. Differences in RMSE against radiosonde observations between DASP and CTRL.The lead times are (a)temperature,(b) specific humidity and (c) wind speed in T+12 hr (upper row), T+24 hr (middle row) and T+36 hr (lower row). Error bars are 95% confidence intervals calculated using the bootstrap method.

Hurricanes are some of the most potent hydrometeorological hazards and can cause severe dam- age to the coastal regions they strike. A study has reconstructed integrated water vapor (IWV) using the zenith wet delays to track the properties of hurricanes and explore their spatial and temporal distributions estimated from 922 GPS stations (Ejigu et al., 2021). The results show that a surge in GPS-derived IWV occurred at least six hours prior to the landfall of two major hurricanes (Harvey and Irma) that struck the Gulf and East Coasts of the USA in 2017.

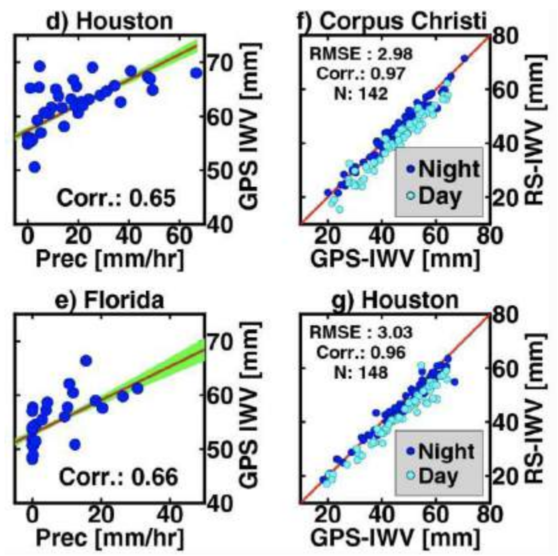


Figure 21: GPS-derived IWV measured during Hurricanes Harvey and Irma. The panels d and e show scatter plots presenting the regression between TRMM-derived precipitation and GPS-IWV. The red line denotes the estimated linear regression, and the light green shaded re- gion denotes the 95% confidence interval. The regression was carried out with a three-hour resolution over different periods (August 25– 31, 2017 for Hurricane Harvey over Houston and September 6–12, 2017 for Hurricane Irma over Florida). The panel f shows the radio-sonde station at Corpus Christi (CRP) and GPS station TXCC. Panel g shows the radiosonde station at Lake Charles (LCH) in Houston and GPS station LAC1. The red line denotes the estimated linear regression. The number of data samples (N), Pearson correlation, slope, intercept, and root-mean-square error is given in the legends.

This study observed enhanced IWV, in particular, for the two hurricanes' landfall locations. The observed variations exhibit a correlation with the precipitation value constructed from GPM/IMERG satellite mission coinciding with hurricane storm front passage. This study used GPS-IWV data as inputs for spaghetti line plots for our path predictions, helping us predict the paths of Hurricanes Harvey and Irma. Hence, a directly estimable zenith wet delay sourced from GPS that has not been previously reported can serve as an additional resource for improv- ing the monitoring of hurricane paths.

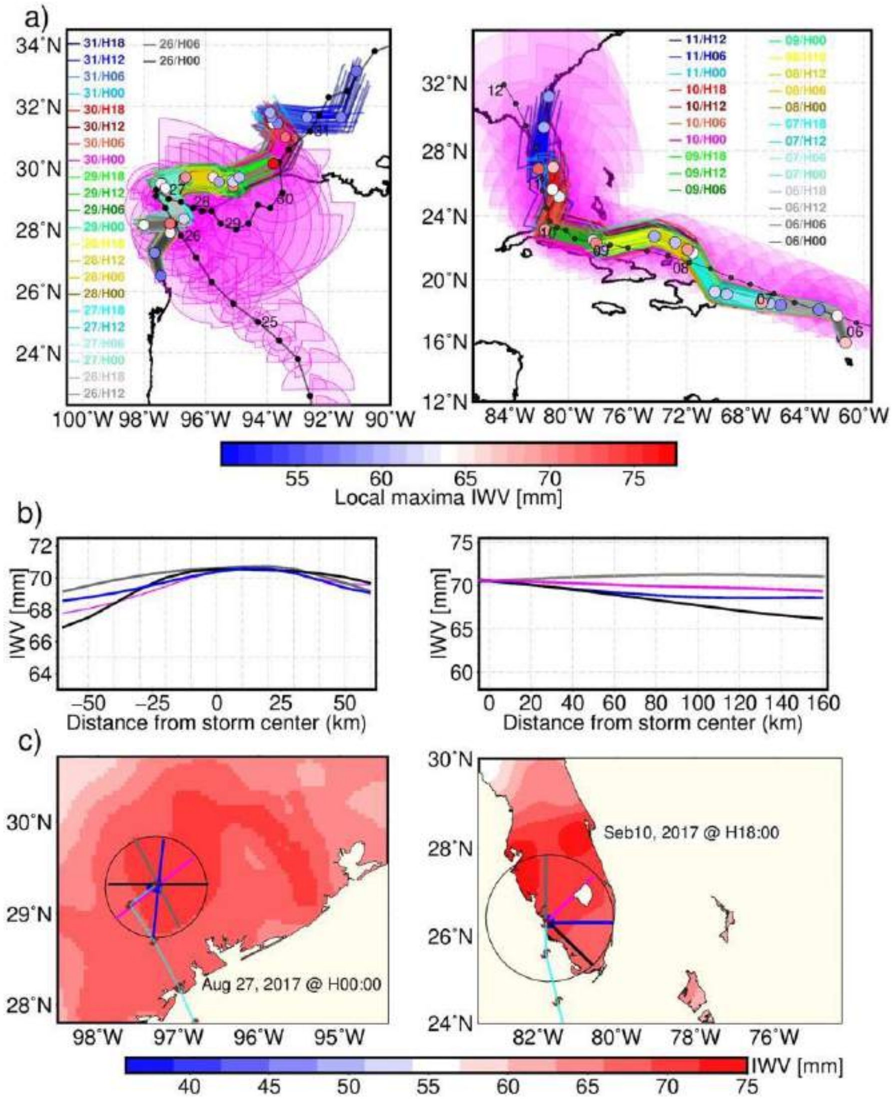


Figure 22: Spaghetti line plots derived from our GPS-estimated IWV levels. The top panels show spa- ghetti line plots (blue lines) transecting the GPS-IWV maxima for Hurricanes Harvey (left) and Irma (right). Coloured circles show the GPS-IWV maxima estimated for every six-hour interval. Light ma- genta polygons show the best tracks from the NHC model based on a post-storm analysis of all availa- ble data presented at six-hourly intervals. Mid panels show GPS-IWV crossing profiles along a straight line and sampled every 1 km over a grid for August 27, 2017 at 00 UTC (bottom left) and for September 10, 2017

In addition, the performance of assimilating GNSS ZTDs with different temporal resolutions on severe convective weather now-casting based on the weather research and forecasting (WRF) model was investigated. The GNSS ZTDs were processed with PPP method under the real-time mode based on the CORS network in Hubei Province, China and assimilated into a rapid update cycle (RUC) system. Figure 8 shows the comparison of four experiments with the observed precipitation in the inner domain at 03:00 UTC on 22 Aril 2018. In the control experiment (referred to CTR), the SYNOP and AIREP observations from NCEP Research Data Archive (RDA) were assimilated into the WRF model per every 3 hours, and the radiosonde observa- tions were assimilated at 00:00 UTC. In the other three ZTD assimilation experiments, the ad- ditional GNSS ZTD data were assimilated into the WRF model with 12 h, 6 h and 3 h cycles, respectively, hereafter referred to as ZTD-12h, ZTD-6h, and ZTD-3h. It can be seen that assim- ilating the GNSS ZTDs helps to remove the incorrect model precipitation, especially over the eastern part of Hubei province. When more ZTD data are assimilated into the model, the incor- rect precipitation decreases even more dramatically. The improvement is pretty remarkable for the ZTD-3h experiment, which may be attributed to more mesoscale information provided by the additional ZTD data.

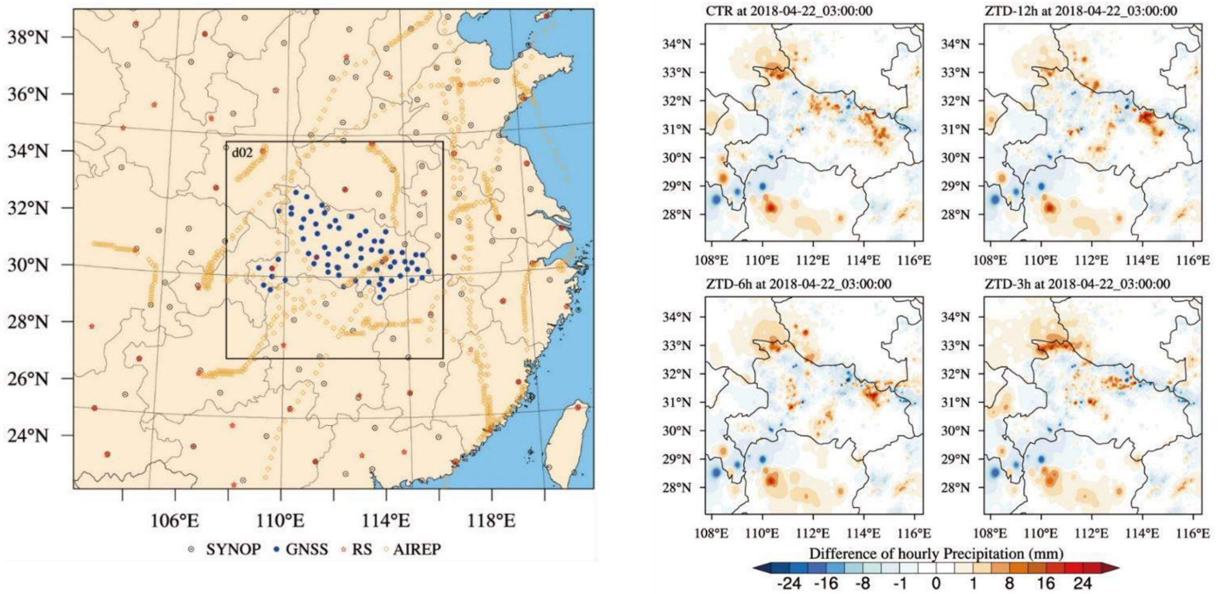


Figure 23: left: WRF domain configuration and stations distribution; right: Comparison of four experi- ments with the hourly precipitation observed by automatic stations at 03:00 UTC on 22 April 2018.
The CTR is experiment without assimilation of GNSS ZTD, and the other three experiments describe the assimilation of ZTD-12h, ZTD-6h, and ZTD-3h, respectively.

Working Group meetings and outreach

The working group members have participated in several workshops related to GNSS meteor- ology such as the Programme of the GNSS Meteorology Workshop held in Poland in 2019 and the International Workshop on Improving GNSS and SAR Tropospheric Products for Meteor- ology held in Luxembourg in 2020. One of the big gatherings was the EGU General Assembly 2021 (19th-30th April 2021) which took place in an online format, where the session “Atmos- pheric and Environmental Monitoring with Space-Geodetic Techniques” was held. Most of the members of IAG WG 4.3.5 submitted contributions to this session and it turned out to be a successful experiment of an online meeting. An online Joint splinter Meeting of IAG Sub-Com- mission 4.3 “Atmosphere Remote Sensing” was held on 26th April 2021. Another next expect- ing and exciting event was the IAG Scientific Assembly 2021, which was held in Beijing on

June 28-July 2, 2021, and organized as a hybrid meeting. The IAG 2nd Commission 4 Sympo- sium brought the group members together to discuss some general and urgent issues, which was held in Potsdam on September 5-8, 2022. The next exciting event will be the 28th IUGG Gen- eral Assembly on 11-20 July 2023 in Berlin, where the session "Remote Sensing and Modelling of the Atmosphere" will be fully discussed. Furthermore, each working group will report the results achieved in the past years, the current working topics, as well as the future research plan.

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WG 4.3.6 Sensing small-scale structures in the lower atmosphere with tomographic principles

Chair: *Gregor Moeller (Switzerland)*
Vice-Chairs: *Zohreh Adavi (Austria) / Chi Ao (USA)*

Members

Patricia A. Rosell (Argentina)
Natalia Hanna (Austria)
Kefei Zhang (Australia)
Hugues Brenot (Belgium)
Eric Pottiaux (Belgium)
Wenyuan Zhang (China)
Andreas Schenk (Germany)
Bettina Kamm (Germany)
Chaiyaporn Kitpracha (Germany)
Karina Wilgan (Germany)
Riccardo Biondi (Italy)
Estera Trzcina (Poland)
Witold Rohm (Poland)
Andre Garcia Sa (Portugal)
Endrit Shehaj (Switzerland)
George Hajj (USA)
Kuo-Nung (Eric) Wang (USA)

Activities and publications during the period 2019-2023

WG 4.3.6 was formed in 2019 with the intention to bring together researchers and professionals working on tomography-based concepts for sensing the neutral atmosphere with space-geodetic and complementary observation techniques - sensitive to the water vapour distribution in the lower atmosphere. While geodetic GNSS networks are nowadays the backbone for troposphere tomography studies, further local densifications, more flexible tomography models as well as advanced processing strategies are necessary to achieve very fine spatial and temporal resolu- tion.

In an initial survey, the collective interests of the working group members have been inquired. In the virtual kick-off meeting, which took place on the 17th of January 2020, the results of the survey have been discussed and a priority list has been drafted, which served as orientation and defined the objectives of the working group for the period 2019 - 2023.

Priority list for the period 2019-2023:

1. Sensor fusion based on tomographic principles including a benchmark campaign for algorithm testing and validation;
2. Working on dynamical tomography models - adaptable to varying input data (continuous-time image reconstruction, trade-off between model resolution and variance size);
3. Advanced ray-tracing algorithms for the reconstruction of atmospheric signal paths for ground-based and space-based (e.g. radio occultation) observations;
4. Evaluating approaches for the densification of existing dual-frequency geodetic networks;
5. Standards and formats for data exchange.

Furthermore, it has become evident that more emphasis should be given to practical and science applications of tomography – including the assimilation of tomographic products into numerical weather prediction models. Within the period 2019-2023, the following achievements can be reported.

Benchmark campaign

For algorithm testing and validation, the IAG working group has set up a benchmark dataset covering the storm system leading to the **Central European floods in summer 2021**.
Period: July 2021 (with July 12-15 as the core period of heavy precipitation)

The study area covers the five countries France, Germany, Belgium, Luxembourg and the Netherlands and ranges from 48.5° - 51.5° in latitude, and 4° - 10° in longitude, see Figure 1

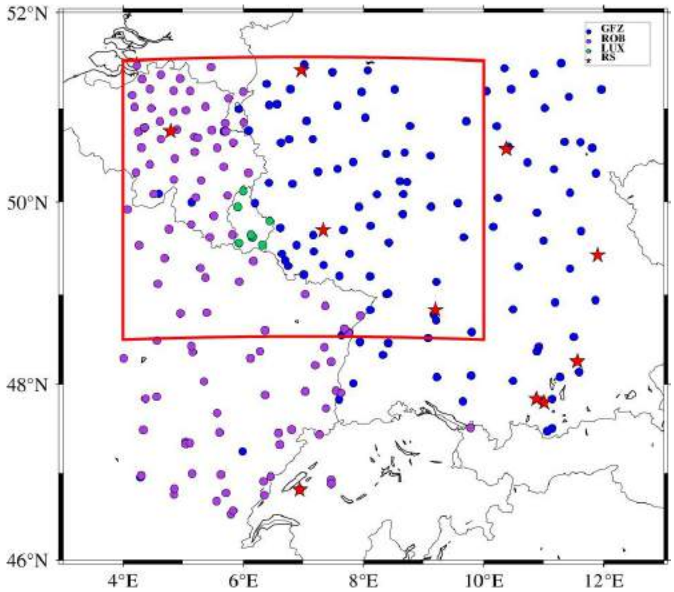


Figure 1: Study area for the IAG benchmark campaign. The purple, blue and green dots indicate the locations of the GNSS sites and the red stars are the locations of the radiosonde (RS) stations.

The proposed dataset includes near real- time multi-GNSS tropospheric estimates from 143 GNSS stations processed by two analysis centers: the German Re- search Centre for Geosciences (GFZ) and the Royal Observatory of Belgium (ROB). To enhance the dataset, additional data sources were incorporated, including radiosonde profiles from NOAA/ESRL data- base and ICON (Icosahedral Nonhydrostatic) forecast data from the German Meteorological Service (DWD). Colleagues from the Belgian Institute for Space Aeronomy (BIRA) converted the numerical weather model data into netcdf-format and tomography a priori files. The result- ing benchmark dataset serves as a reference point for algorithm development and validation in subsequent studies.

Tomographic fusion strategies

In terms of intra-technique combination, colleagues from Technische Universität Berlin (TUB), German Research Centre for Geosciences (GFZ) and the German Meteorological Service (DWD) were working on a **multi-GNSS solution** for the estimation of high-quality GNSS slant wet delays, the basic input data for ground-based GNSS tomography. Therefore, three multi- GNSS solutions have been calculated: GPS-only, GPS/GLONASS and GPS/GLONASS/ Galileo based on the dense German network SAPOS (around 300 stations). The slant total delays (STDs) have been calculated every 2.5 minutes and served as an input to reconstruct total and wet refractivity fields using tomography methodologies developed at BIRA (Brenot et al., 2020). In total, four tomographic solutions were generated, each employing different constrain- ing options and time resolutions, and utilizing either GPS-only or multi-GNSS estimates as input, alongside different processing strategies.

Figure 2 shows the results of the individual solutions for July 13, 2021, 00:30 UTC, exemplarily for a fixed altitude of 2.5 km.

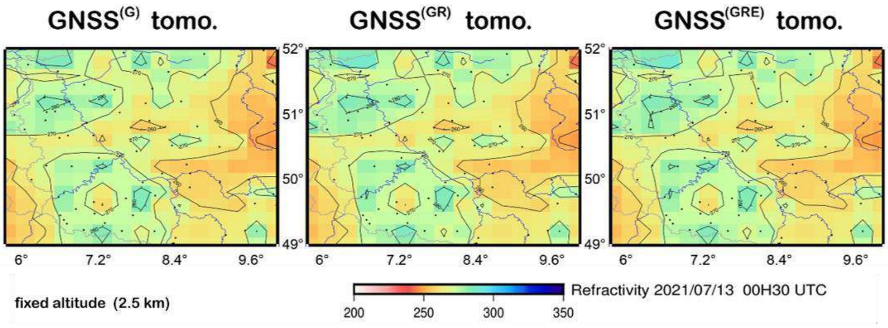


Figure 2: Tomography retrievals as obtained for July 13, 2021, 00:30 UTC from three individual so- lutions using GPS (G), GPS/GLONASS (GR) or GPS/GLONASS/Galileo (GRE) derived STDs as input. Source: Wilgan et al. (2023)

The tomography retrievals tended to produce wetter conditions compared to the reference data, which was, however, in line with the previous findings. During the phase of the initiation of deep convection on July 13, 2021, tomography retrievals show high values of total refractivity north-eastwards of the Grand Duchy of Luxembourg, which is not seen by ICON-D2 numerical weather prediction model and thus, could be substantial information to be considered in an assimilation system (Figure 3).

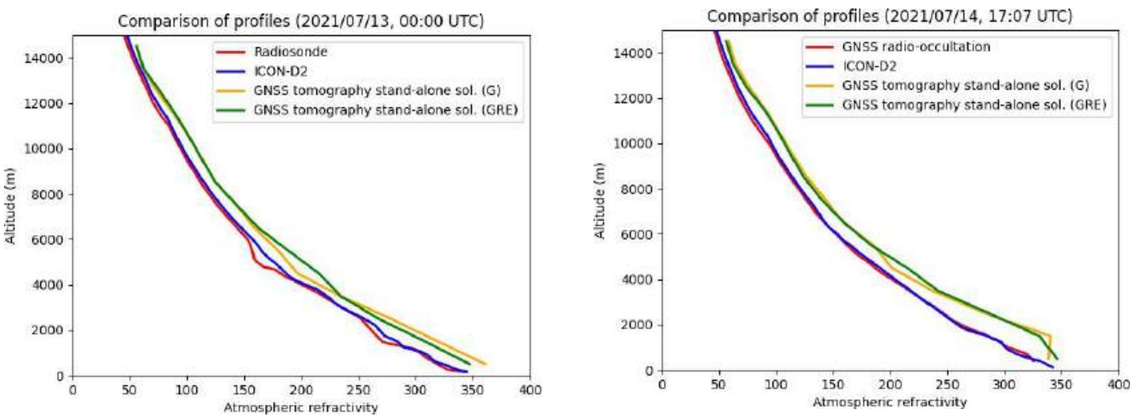


Figure 3: Validation of the multi-GNSS tomography solutions with external observations from radio- sondes and ICON-D2 numercial weather model data. Source: Wilgan et al. (2023)

In terms of inter-technique combination, Adavi and Weber (2020) investigated the **combination of GNSS with wet refractivity maps** obtained **from** the 16 bands **GOES** (Advanced Baseline Imager onboard the Geostationary Operational Environmental Satellite) mission. For this purpose, two different schemes have been defined to assess the impact of GOES data on the tomography solution: 1) GOES-16 as a constraint, and 2) ERA-5 as a constraint. For the tomography test case, a 3D tomographic model was defined over a regional area covered by the Continuously Operating Reference Station (CORS) Network in North America. Radiosonde measurements in the area of interest (RS72426) were used to validate the accuracy of the esti- mated 3D wet refractivity images, see Figure 4.

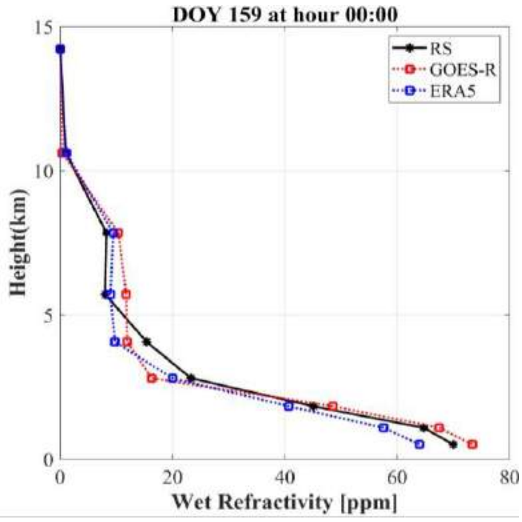


Figure 4. The comparison of reconstructed tomography profiles from GEOS-16 and ERA5 with RS72426 profiles at midnight for DoY 159.

Another interesting **combination of GNSS with infrared sensors** has been studied by Zhang et al. (2021a) and Zhang et al. (2021b). In the study conducted by Zhang et al. (2021a), high- resolution maps of precipitable water vapor (PWV) obtained from MODIS were utilized. This data demonstrated promising potential for supplementing the single GNSS acquisition geome- try by retrieving positive cone-shaped slant water vapor (SWV) observations. Tomographic experiments conducted in the study revealed that the introduction of infrared (IR) sensor obser- vations into the tomography model significantly improved the acquisition geometry, as illustrated in Figure 5.

Furthermore, the combined solution exhibited a noteworthy decrease in both the mean root- mean-square error (RMSE) and bias of the water vapor profiles compared to the results obtained from GNSS-only approaches. These improvements underscore the substantial poten- tial of using tomographic principles to combine GNSS with IR products in order to achieve a more accurate and reliable 4D distribution of atmospheric water vapor. In the study by Zhang et al. (2021b), the developed approach was extended to incorporate retrievals of precipitable water vapor from infrared radiometers on board remote sensing (RS) satellites. It is concluded that the rapid advancement of multi-source RS sensors offers significant opportunities for re- constructing SWV for tropospheric tomography.

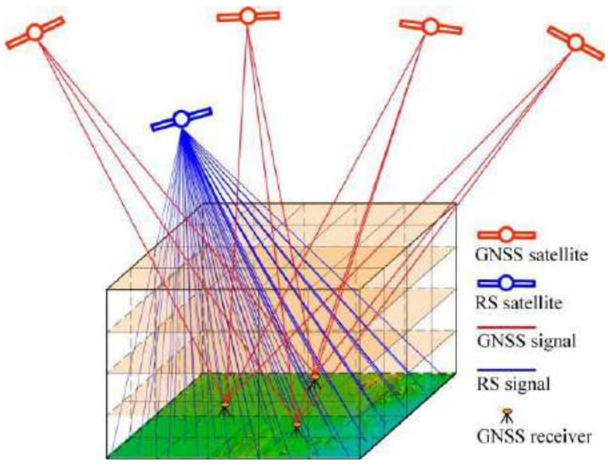


Figure 5: 3D observation geometry of GNSS and Remote Sensing (RS) measurements. Red and blue lines represent the transmission path of GNSS and RS signals, respectively. Source: Zhang et al. (2021b).

Shehaj et al. (2020) introduced an alternative approach for integrating GNSS and InSAR trop- ospheric delays using a least-squares collocation approach. A specialized model was developed to account for the relative slant delays derived from InSAR. The study demonstrated that the software was capable of efficiently processing large volumes of InSAR data. However, it was noted that careful consideration should be given to the weighting of the data, as the combined results often exhibited closer agreement with the InSAR differential delays. In addition, a sim- ulation study reveals the impact of SAR scene size and pixel resolution on achieving a satisfac- tory agreement between the InSAR/GNSS product and the reference NWM data.

Figure 6 presents time series plots illustrating the variations in GNSS, InSAR, and their combination.

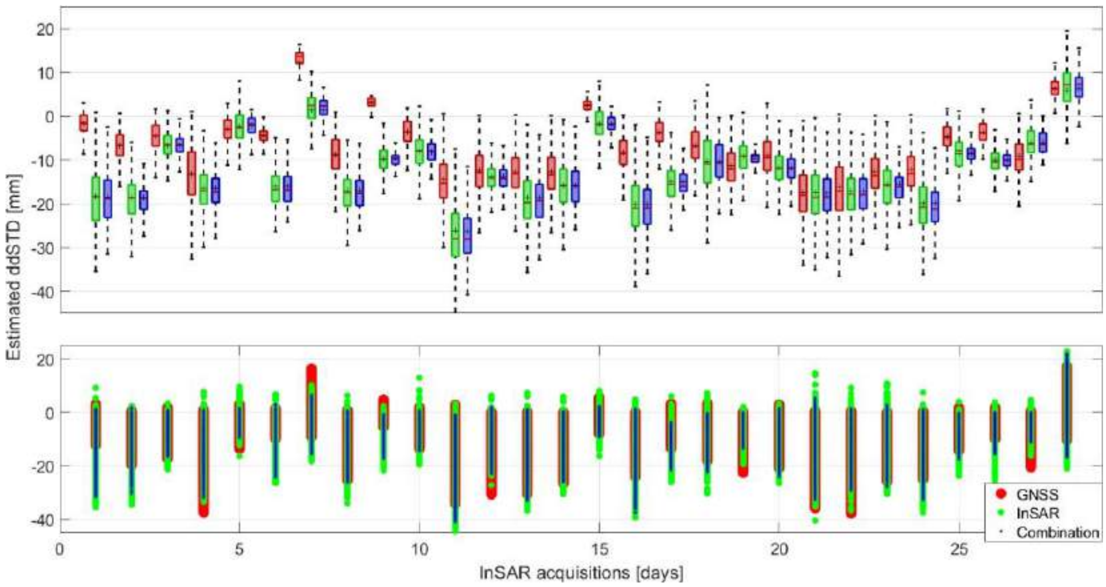


Figure 6:: Estimated ddSTDs time series using GNSS, InSAR and their combination. The top part is a quantile plot where the whisker corresponds to 99.3% coverage assuming a normal distribution ('+' and '-' in the box represent the mean and the median respectively). The bottom portion directly dis- plays the ddSTDs.

Researchers from Wroclaw University of Environmental Life Sciences (UPWr), University of Wroclaw (UoW), ETH Zürich (ETH), and Spire Global conducted a study focusing on the **com- bination of ground-based GNSS** (both geodetic and low-cost) **with space-based GNSS**, also known as the radio occultation technique. This approach aims to address two major limitations of GNSS tomography. Firstly, the typical inter-station distances of 30-50 km result in a similar horizontal resolution of the tomography model. Secondly, the ill-posedness of the solution is caused by a lack of observations traversing the troposphere horizontally. To overcome these limitations, we utilized a high density of low-cost receivers, spaced at distances of 3-5 km. Additionally, we incorporated radio occultation (RO) observations, which involve limb sound- ing and traversing the troposphere horizontally. By implementing these measures into a classi- cal tomography approach, both limitations were effectively overcome, making this technology suitable for high-density weather predictions.

Most recently, Shehaj (2023) proposed an **alternative method** for deriving refractivity fields from the combination of ground-based GNSS and GNSS-RO data. This combination utilizes collocation techniques and incorporates GNSS ground-based zenith total delays (ZTDs) and GNSS-RO refractivities. The study places significant emphasis on optimizing the relative noise levels between GNSS ZTDs and RO refractivities, as well as determining appropriate correla- tion lengths for the stochastic model. The primary improvement observed in the study was found in the higher layers of the atmosphere, particularly above 3 km, with notable enhance- ments in terms of bias. *Figure* (left) demonstrates that tomography-derived refractivities (shown in blue) are less biased in comparison to collocation-derived refractivities (shown in red), as a result of constraints on the a priori model. In Figure 7 (right), the average values for each tomographic height are subtracted. It is evident that collocation techniques are capable of estimating spatial variations within a single tomographic height more effectively (at least on a comparable level) compared to the classical tomography approach.

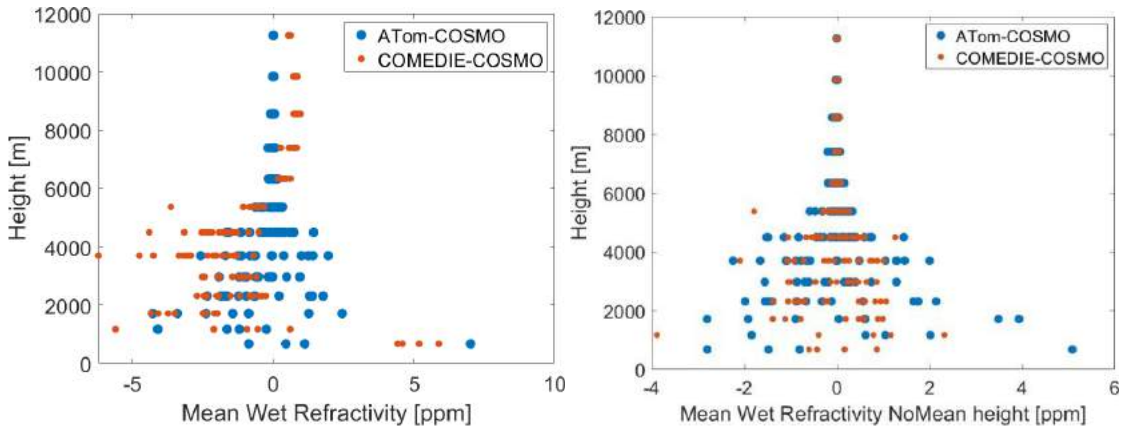


Figure 7: Tomography and collocation differences to numerical weather model data (COSMO-1) de- rived refractivities, as a function of height, averaged over a two-week period. Left: averaged total re- fractivity differences. Right: averaged refractivity differences after removal of the mean refractivity for each height.

Hanna and Weber (2023) conducted a study on the integration of ground- and space-based GNSS observations. In this study, the tomographic observation system in the ATom GNSS software was extended with the space-based wet refractivity profiles (wetPrf, level 2 data), ap- plying two different space-based observation weighting strategies: 1) Average formal errors

(CS1), 2) Average percentile wet refractivity uncertainties from wetPrf compared to the RS data. The obtained 3D wet refractivity field was compared to the a priori data (ERA5), the GNSS ground-based only solution, and in-situ measurements at Royal Netherlands Meteoro- logical Institute (KNMI) weather stations (Figure 8). Compared to the weather site data, the differences between the combined and ground-based only solutions reach 1 ppm (Figure 8, panel D), with the largest differences for stations located in the vicinity of voxels traversed by the RO profile.

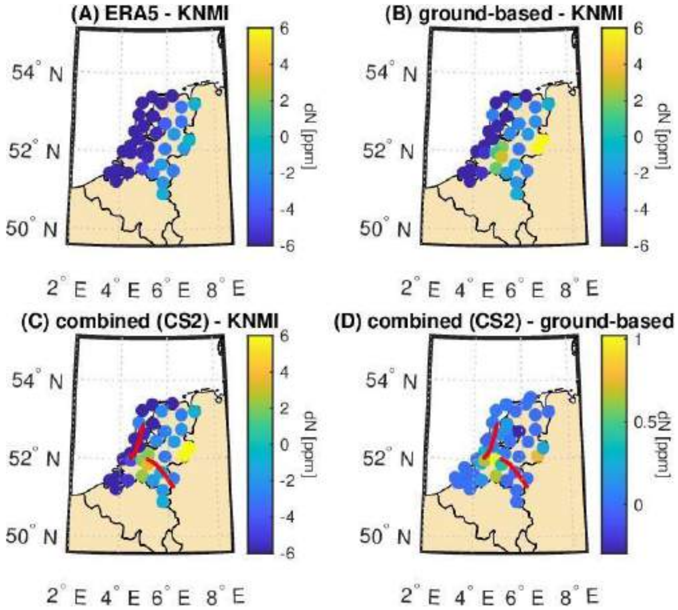


Figure 8:: Wet refractivity differences between the a priori data (ERA 5 ground based tomographic so- lution, combined tomographic solution (CS2) and reference Nw values for KNMI stations at the sta- tion height. Red lines indicate the location of RO profiles.

Dynamical tomography models

In the study of Zhang et al. (2021a) a methodology based on a node tomography model was developed to solve the geometry defect in water vapor tomography. For validation, the node- based model was used for the combination of GNSS and MODIS data; a schematic view of the parametrization process is shown in Figure 9.

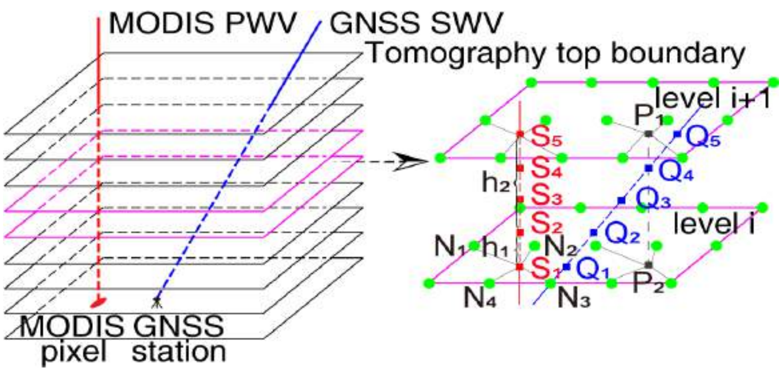


Figure 9: Schematic of the parameterization process for the GNSS and MODIS signals by using the node tomography model. The blue and red lines denote the GNSS and MODIS rays, respectively. Right: Partial enlarged drawing of the i-th layer. Source: Zhang et al. (2021a)

Trzcina et al. (2023) demonstrated that the GNSS tomography equation system could be solved on the irregular grid with **nodes distribution related directly to the density of intersections** between trajectories of GNSS signals; see *Figure* for a more detailed overview about the processing steps. The method applied to a high-density low-cost network (16 receivers with a mean distance of 3 km) yield an improvement in the refractivity field solution of 0.5-2.0 ppm in the bottom 0.5-2.0 km of the model, comparing to the standard rectangular tomography grid.

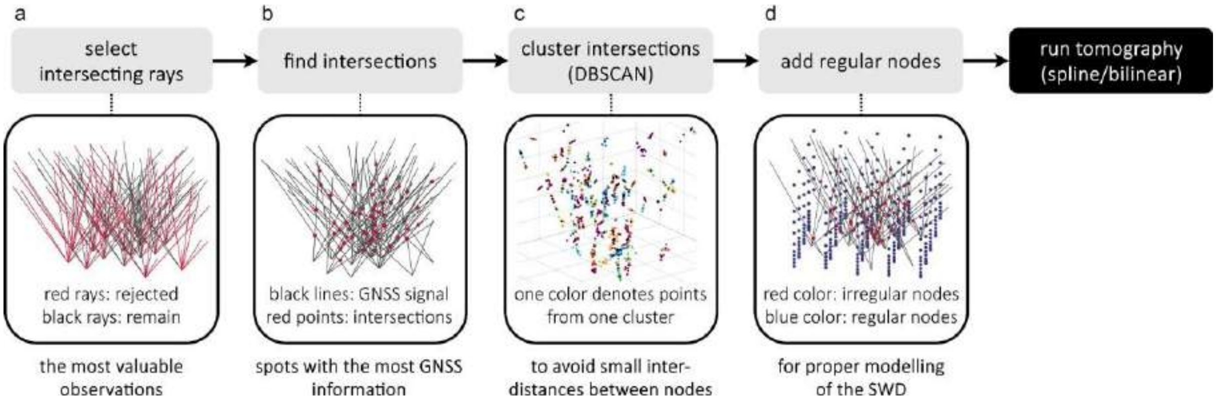


Figure 10: Steps applied to the signal – base grid calculation (Trzcina et al., 2023)

Since tomography is often recognized as a discrete, ill-posed problem, minor fluctuations in measurements can cause drastically unstable parameter solutions. To ensure a stable and unique tomography solution, it is essential to implement a regularization method during the inversion process. According to Adavi and Weber (2022), a regularized solution can be achieved using the Total Variation (TV) method. TV is a nonlinear technique that does not require an initial field, is tolerant of noise, and preserves discontinuities in the model well. It is capable of recon- structing the wet refractivity field in a shorter time span without an initial field. With an em- phasis on near-real-time applications, the TV method was applied to six tomography windows over a period of 10 minutes to 60 minutes. Evaluation of the results revealed that the accuracy of the field retrieved using the Landweber method was generally superior to that of the TV technique during midnight. TV's performance for retrieving wet refractivity was found to be equivalent to Landweber's at noon, especially when the span exceeded 40 minutes, see Figure

11. Due to this, the reconstruction of the tomographic model using the TV method is beneficial when a reliable initial field is unavailable, even in cases of short tomography windows, as long as the condition number of the design matrix is not excessively large and the amount of water vapour in the troposphere is high. However, it is worth noting that a short tomography window may not always be feasible due to varying daily weather conditions.

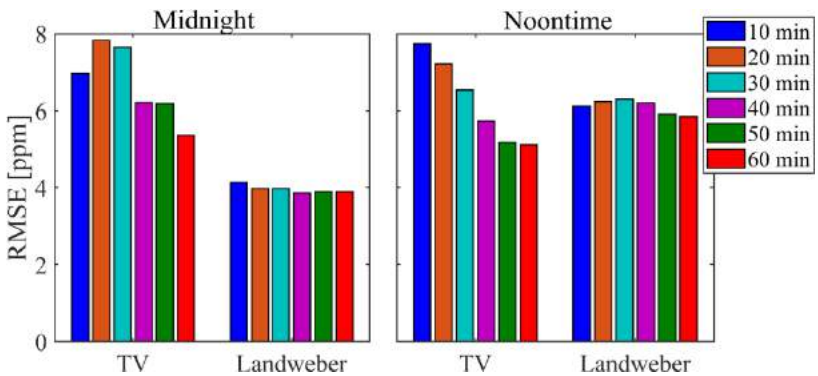


Figure 11: Mean absolute error (MAE) of the reconstructed wet refractivity field, employing total variation (TV) and Landweber's regularization method, within the height range of 2 to 6 km during midnight.

Despite these achievements, the real-time or near-real-time GNSS tomography still remains a challenging task due to the accuracy of (near)-real-time GNSS tropospheric parameters and due to computational load. For this purpose, a tomographic system SEGAL GNSS Water Vapour Reconstruction Image Software (SWART) was developed and tested. The new method makes use of parallelized algebraic reconstruction techniques (ARTs) and supersedes other implemen- tations in terms of speed by at least 50% for small networks. For SWART, the computation time grows linearly with the number of observations, see Figure 12.

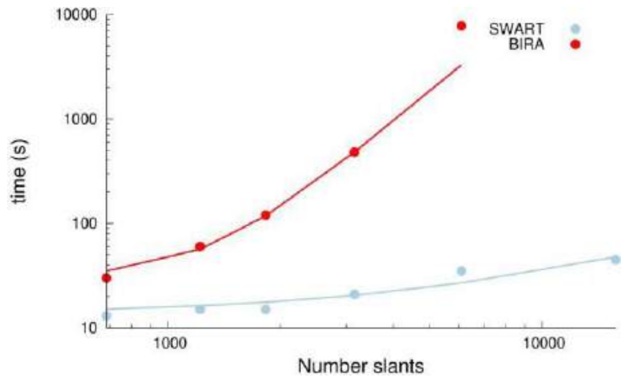


Figure 12: Processing time behavior from BIRA and SWART tomography model. The dots present the observed computation time. The solid lines present the fitted cubic (red) and linear (blue) function.

As a result, the new method makes possible to estimate the water vapor for larger GNSS net- works and can be used for near-real-time weather predictions. To show its potential, data from 26 stations in Poland were analyzed using data from a period of 56 days. Good agreement in the estimated water vapor between SWART and radiosondes solutions was obtained (Figure 13), with a mean RMS of 1.5 g/m³ for the lower layers and an overall improvement of 5% until the layer 6750 m when compared with the atmospheric model (WRF).

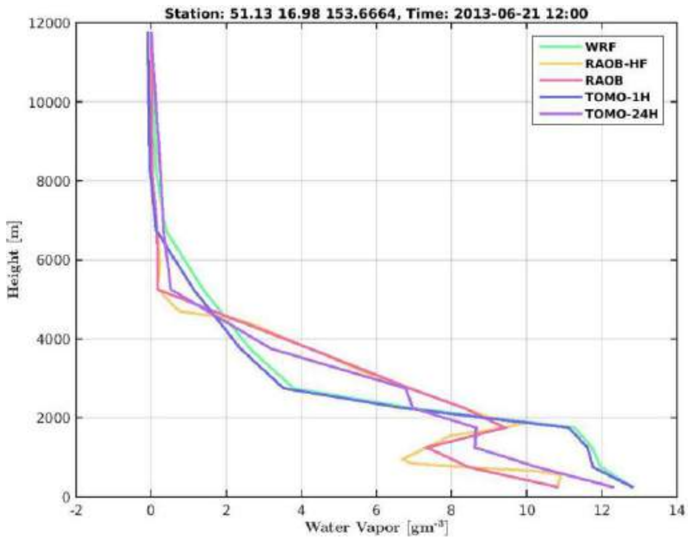


Figure 13: Comparison of the GNSS tomographic retrievals on the 21st of June 2013, 12h00 UTC with WRF initialization every hour (TOMO_1H: blue line) and with WRF initialization each 24h (TOMO_24H: violet line). RAOB=radiosonde (red line), RAOB-HF = radiosonde high-frequency (or- ange line), TOMO=GNSS derived tomography solution and WRF = numerical weather research and forecasting model.

For assessment of the quality of the tomography derived refractivity fields, colleagues from TU Wien and Wroclaw University of Environmental Life Sciences proposed the concept of spread values as a mathematical tool to provide a quality measure without the need to use reference observations to calculate statistical measures like RMSE and Bias. Therefore, two different data sets of real and simulated observations have been used to investigate the information content of the proposed indicators: Bakus-Gilbert (BGH) and Michelini (Michi). Therefore, two different schemes were defined to estimate the a priori covariance matrix of unknown' parameters with low (LC) and high (TC) weighting. Figure 14 shows the results for 10 days, in which a signifi- cant correlation between quality indicator and standard deviation of the differences between tomography and radiosonde derived wet refractivity (0.69 for synthetic and 0.55 for real obser- vations) is obtained. The correlation is also significant for bias, ranging from 0.71 for synthetic to -0.53 for real data.

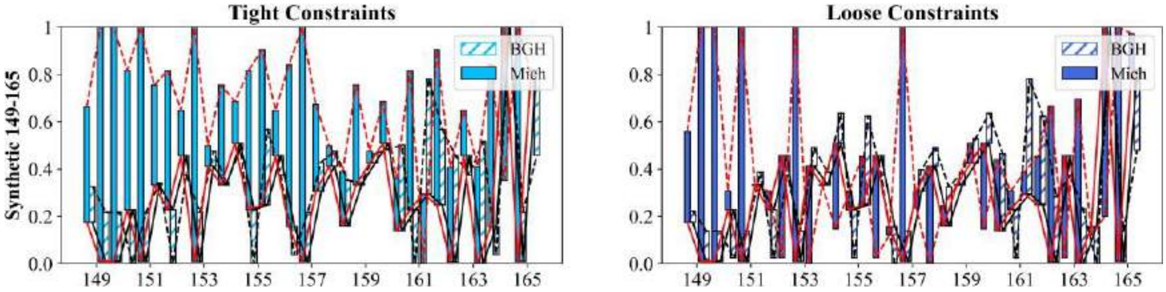


Figure 14: Time series of differences between spread values and standard deviation of the differences between tomography and RS10771 radiosonde data. Left column shows tight constraints, whereas the right column shows loose constraints. Moreover, dashed and solid lines demonstrate spread values and standard deviation, respectively.

Densification of existing geodetic networks

For a detailed impact study, a high-density GNSS network with 16 low-cost GNSS stations was temporarily established in Wrocław, Poland for 1 month - March 2021 (Marut et al., 2022). The mean distance is 3 km and the results of post-processing and real-time processing agrees within

1.0 and 1.5 kg/m^2, respectively, with radiometric observations. Moreover, the city-scale varia- bility of temporal and spatial distribution of water vapour content was measured reaching up to 5 kg/m^2.

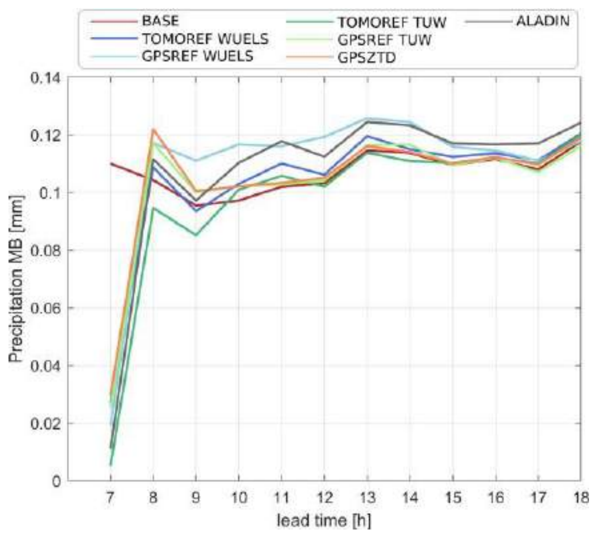
Adavi and Weber (2019) analyzed the impact of different constraints on the accuracy of the reconstructed refractivity field. For this purpose, three different schemes have been defined to reduce the elements of the model null space to the trivial ones. In the first scheme, minimum horizontal and vertical constraints were added to the system of observation equations. Then, five real GNSS stations have been left out and replaced by data of two additional virtual refer- ence station (VRS) sites to focus on the accuracy of the reconstructed field using the VRS sta- tions concept in a sparse GNSS network. In the third schemes, constraints have been applied to the tomography model in the sparse GNSS network in order to evaluate the accuracy of esti- mated parameters by the previous schemes. According to the obtained results, the RMSE of the reconstructed refractivity field in the dense GNSS network with respect to the radiosonde pro- file was about 2.80 ppm for the selected period of interest. For the sparse GNSS network, the average RMSE for schemes with VRS stations and applied constraints was about 3.02 ppm and

3.27 ppm, respectively. Consequently, the quality of the reconstructed refractivity profiles in scheme 1 was generally better than in the other two schemes. Besides, according to these results applying VRS stations in the sparse GNSS network can lead to a better solution in comparison to just applying vertical and horizontal constraints. Thus, it can be concluded that the refractiv- ity field can be reconstructed with acceptable accuracy from VRS stations if one of the follow- ing conditions is fulfilled: 1) the distance between GNSS stations are larger than the horizontal resolution, 2) topography is rough, 3) some GNSS station are not working for a short period of time.

Applying VRS stations in dense GNSS networks is not recommended as it might increase the inconsistency between the reconstructed field and the reference solution. However, it might be a good opportunity for the densification of sparse geodetic GNSS networks, such as the SIGAS- CON (Continuously Operating Geocentric Reference System for South America) covering the Pan-American region. This network is conformed of more than 450 operational stations, a num- ber that increases every year thanks to the local densification of each member country. Since 2014, the CIMA Analysis Center (Centro de Ingeniería, Mendoza, Argentina) implemented a strategy to combine the tropospheric parameters using Bernese GNSS Software v.5.2 (Calori et al, 2025, Mackern et al. 2020). The ZTDs obtained from the combination are considered final SIRGAS products and are published weekly on the SIRGAS website (https:// sir- gas.ipgh.org/en/ products/tropospheric-delays/). Although the SIGAS network has not been uti- lized for GNSS tomographic studies yet, we are optimistic about the future prospects. The in- troduction of cost-effective, high-quality equipment, coupled with innovative concepts for net- work densification, will undoubtedly contribute to achieving this goal.

Tomography assimilation

The first studies on assimilation of the GNSS tomography data into the numerical weather pre- diction model were performed by means of the AROME radiosonde observation operator (Moeller, 2016) and the GPSREF operator provided with the Weather Research and Forecasting (WRF) Data Assimilation (DA) system (Hanna et al., 2019; Trzcina and Rohm, 2019). The GPSREF operator requires total refractivity observations, which were calculated as a sum of tomographic wet refractivities and hydrostatic refractivities derived from ALADIN-CZ model.



The validation against radiosondes shows an improvement in the weather forecasting of rel- ative humidity (bias, standard deviation) and temperature (standard deviation) during heavy precipitation events.

Figure 2: Mean bias (MB) of the precipitation for the WRF simulations in the forecast lead time of 6–18hr, validated against radar observations.

A more recent study was focused on the direct assimilation of GNSS tomography-derived 3D fields of wet refractivity into the WRF model (Trzcina et al., 2020). To allow for a direct assimilation of wet refractivity fields, the **TOMOREF observation operator** was built. The new tool was tested based on wet refractivity fields derived during a very intense precipitation event. The results were validated using radiosonde observations, synoptic data, ERA5 reanalysis, and radar data. In the performed experiment, a small positive impact of the GNSS tomography data assimilation on the forecast of relative humidity (RH) was noticed (an improvement of root- mean-square error up to 0.5%). Moreover, within 1 hour after assimilation, the GNSS data re- duced the bias of precipitation up to 0.1 mm, see Figure 15. Additionally, the assimilation of GNSS tomography data had more influence on the WRF model than the Zenith Total Delay (ZTD) observations, which confirms the potential of the GNSS tomography data for weather forecasting.

Tomography projects

In terms of tomography applications, the working group has initiated or is involved in a series of national and international research projects (excerpt).

- **3D integrated sensing of troposphere using ground and space-based GNSS observa- tion:** This project, led by Wroclaw University of Environmental and Life Sciences (UPWr), aims on the use of the inverse Radon transform on dense space-based and ground-based GNSS observations for providing integrated 3D models of troposphere that will improve precipitation and humidity forecasts.
- **Water vapor fields by space-born geodetic sensing, tomographic fusion, and atmos- pheric modeling:** By using GNSS and InSAR based techniques in combination with high resolution regional atmospheric weather models and geostatistical data merging techniques, the research project, led by the Geodetic Institute of KIT (GIK), was aiming on the devel- opment and evaluation of new approaches to derive improved spatio-temporal estimates of the atmospheric water vapor distribution. In particular, tomographic-based approaches for the evaluation of geodetic and remote sensing data were further developed to improve the vertical and horizontal resolution of the investigated atmospheric state variables.
- **SINOPTICA** is a H2020 EU-project (collaboration of CIMA, DLR, AustroControl, GReD, UniBar and UniPd) which focuses on improving the prediction of extreme weather events (key objective to eliminate unexpected scenarios that compromise aviation safety). This project combines remote sensing derived, GNSS-derived and in situ weather stations vari- ables, in an automated assimilation system of a numerical weather model.
- **ALARM** is a H2020 EU-project (collaboration of UC3M, DLR, SATAVIA, Unipd, and BIRA). The overall objective of ALARM (*multi-h**A**zard monitoring and ear**L**y w**AR**ning syste**M***) is to develop a prototype global multi-hazard monitoring and early warning system for all these hazards (https://alarm-project.eu). Within the framework of these 2 projects (SINOPTICA and ALARM), Hugues Brenot (BIRA) and Riccardo Biondi (UniPd) will conduct a test of tomography applications with the objective of implementing early warning of the initiation of deep convection. Vertical extension from tomography and precursor of 3D structures will be looked at using the algorithmic development of Brenot et al. (2020).

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WG 4.3.7 Geodetic GNSS-R

Chair: *Sajad Tabibi (Luxembourg)*
Vice-Chair: *Felipe Geremia-Nievinski (Brazil)*

Members

Dave Purnell (Canada), Chung-Yen Kuo (Taiwan), Clara Chew (USA), Estel Cardellach (Spain), Jens Wickert (Germany), Jihye Park (USA), Joerg Reinking (Germany), Karen Boni- face (Italy), Kegen Yu (China), Kristine Larson (USA), Manuel Martín-Neira (ESA), Maximil- ian Semmling (Germany), Nikolaos Antonoglou (Germany), Ole Roggenbuck (Germany), Rashmi Shah (USA), Rüdiger Haas (Sweden), Simon Williams (UK), Thomas Hobiger (Ger- many), Wei Liu (China)

Activities and publications during the period 2019-2023

In early 2020, it was developed an inventory of GNSS-R stations with focus on sea level appli- cations (Figure 1), which was communicated to the entire IAG working group. The inventory is also available online for long-term archival at Zenodo.org (https://doi.org/10.5281/ze- nodo.3660521). It has been updated a few times since the initial release and it is intended to continue to be updated yearly.

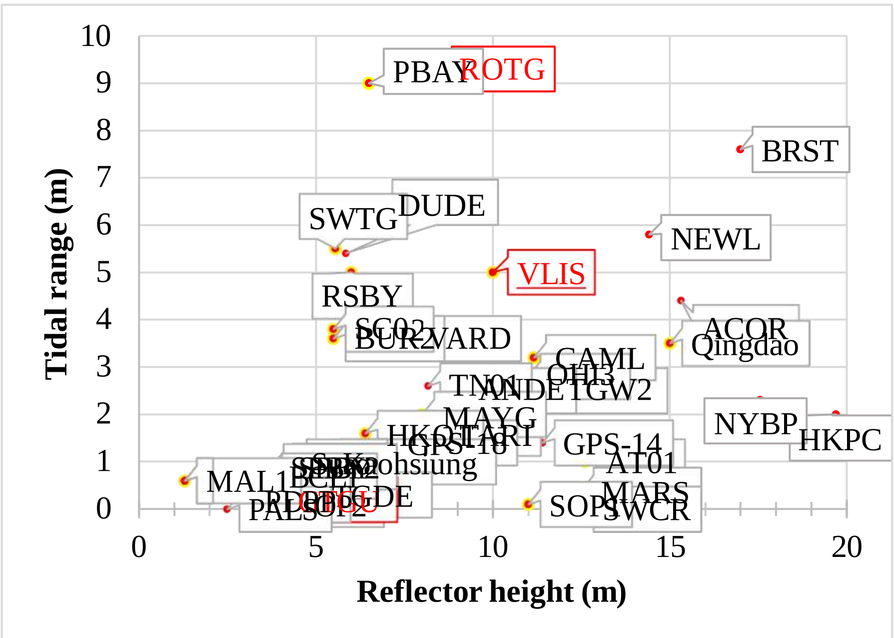

Figure 1: Inventory of GNSS-R stations with a focus on the ocean as the target and SNR as the obserable. The three GNSS stations used for the first and second intercomparisons are highlighted in red.

In July 2020, the Journal of Geodesy published a manuscript titled "SNR-based GNSS reflec- tometry for coastal sea-level altimetry: results from the first IAG inter-comparison campaign" reporting the findings from the first GNSS-R intercomparison campaign.

We established liaisons with the Inter-Commission Committee on Marine Geodesy (ICCM) and the chair became a member of the "Ocean tide, sea level changing, and vertical datum" Joint Study Groups (JSG 5.2).

In mid-July 2020, we launched the second demonstration campaign on GNSS-R for sea level monitoring using GNSS stations with large tidal amplitudes and greater reflector heights com- pared to the first inter-comparison campaign, would help to better characterize the quality of geodetic GNSS-R sea level products. To achieve this, we shared 1-Hz GNSS data collected for a 1-year period at station ROTG (Roscoff, France) with ~ 9 m of tidal ranges and at station VLIS (Vlissingen, Netherlands) with ~ 5 m of tidal ranges for the first nine months of 2020 with the entire IAG working group in early October 2020 (Figure 2).

We also provided the recommended processing settings to interested groups to ensure observa- tion conditions were consistent across all solutions (Table 1). The goal was to prevent differ- ences in processing settings from affecting the performance of GNSS-R sea levels, which could otherwise be a consequence of the choice of satellite visibility mask and elevation angle range per altimetric retrieval. The azimuthal and elevation angle masks were defined to ensure SNR reflections from the sea surface were obtained, avoiding obstructions such as piers, land, etc.

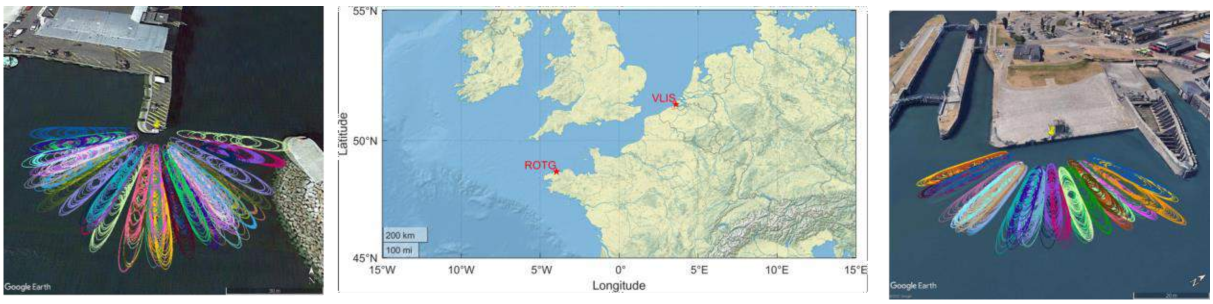

Figure 2: Location of the ROTG and VLIS GNSS stations (middle panel). Occurrences of first Fresnel zones (FFZ) at ROTG station (left), and (right) Occurrences of FFZs at VLIS. Each ellipse in color de- picts the FFZ for each GPS satellite. The location of the GNSS stations are shown as yellow pins.

Table 1: GNSS-R site descriptions; azimuthal masks are in clockwise order; RH: reflector height; TG: tide gauge.

	VLIS (The Nether- lands)	ROTG (France)
Lat., Long. (deg)	51.44286, 3.59734	48.71844, -3.966566
Receiver	LEICA GR50	TPS GB-1000
Antenna	LEIAR25.R4	TPSPG_A1+GP
Mean RH (m)	10	8.5
Tidal range (m)	5	9
Azimuth interval (deg.)	30-180	30-300
Sampling rate (Hz)	1	1
Distance to TG (m)	2	2

Five groups submitted their solutions for the inter-comparison campaign, using two different GNSS signals: GPS-L1-C/A only; or combined GPS-L1-C/A and GLONASS-R1-C/A., Three groups withdrew their submissions. Currently, the GNSS-R solutions have been compared with TG records. A manuscript is in preparation for submission reporting on this second intercom- parison campaign.

In April 2021, the WG 4.3.7 Geodetic GNSS-R was presented in the Joint splinter meeting of the IAG Sub-Commission 4.3, which the chair attended remotely. The goal of the second inter- comparison campaign on GNSS-R for sea level was presented to the other IAG WGs. In July 2021, a presentation titled "Status of the IAG Working Group 4.3.7 on Geodetic GNSS-R IAG 2021" was given at the IAG 2021 assembly held from June 28 to July 2021 in Beijing, China. The chair presented the status of the working group remotely. Later in the IAG 2021 assembly, the chair and the vicechair organized a breakout session on geodetic GNSS-R, which several members attended remotely. Other researchers working on GNSS-R also attended the session, where different aspects of geodetic GNSS-R were discussed. The session focused on how GNSS stations could be encouraged to be used for dual applications, PNT and GNSS-R, sim- ultaneously. Furthermore, new advancements and future research on geodetic GNSS-R were discussed in the GNSS-R breakout session.

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Sub-commission 4.4: GNSS Integrity and Quality Control

Chair: Pawel Wielgosz (Poland)
Vice Chair: Jianghui Geng (China)

Overview

The SC 4.4 is composed of three Working Groups (WG) and one Joint Study group (JSG). Moreover, members of SC 4.4 also participated in several other JSGs. After a good start to research activities in 2019 and early 2020, the Corona pandemic definitely slowed the activities in 2020 and 2021. However, the recent period shows another wave of progress.

The main topics studied within this SC are quality control and integrity monitoring of precise GNSS positioning (RTK, PPP, PPP-RTK), development of novel algorithms and processing methods for data collected with mass-market (low-cost) GNSS receivers and smartphones equipped with GNSS chipsets, assessment and validation of IGS products and open-source scientific software (in particular quality assessment of IGS RTS products), and finally analysis of GNSS interference and spoofing. Important progress has been achieved in each of these topics, with a high number of research papers published by the members of SC 4.4. The SC members were also involved in editing several special issues related to the SC topics.

Our interim results were presented at the 2nd IAG Commission 4 Symposium (September 5th to 8th, 2022, Potsdam, Germany). Besides, the members of SC 4.4 routinely presented their results at the European Geosciences Union (EGU) General Assemblies, where SC 4.4 organizes a dedicated session "High-precision GNSS: methods, open problems, and geoscience applications", which always attracts a high number of presentations. The presented results show that GNSS Integrity and Quality Control is still a hot research topic with many open scientific problems.

On the next pages, the WGs and JWG of the SC 4.4 provide an overview of their work within the last four years, i.e. the reporting period 2019 to 2023.

Working Groups of Sub-commission 4.4: GNSS Integrity and Quality Control

WG 4.4.1: Quality Control and Integrity Monitoring of Precise Positioning

Chair: Ahmed El-Mowafy (Australia)
Vice Chair: Christian Tiberius (Netherlands)

Members

- Kan Wang, University of the Chinese Academy of Science
- Mathieu Jöerger, Virginia Polytechnic Institute and State University, USA
- Juan Blanch, Stanford University, USA
- Safoora Zaminpardaz, RMIT, Australia
- Amir Khodabandeh, University of Melbourne, Australia
- Yang Gao, The University of Calgary, Canada
- Chris Rizos, University of New South Wales, Australia
- Michaela-Simona Circiu, The German Aerospace Centre (DLR), Germany
- Eugene Bang, The German Aerospace Centre (DLR), Germany
- Krzysztof Nowel, University Warmia and Mazuray in Olsztyn, Poland
- Nobuaki Kubo, Tokyo University of Marine Sciences and Technology, Japan

Activities and publications during the period 2019-2023

The study group addresses quality control and integrity monitoring (IM) for precise GNSS positioning using techniques such Precis Point Positioning (PPP), Real-Time Kinematic (RTK), Network RTK, and PPP-RTK. For a real-time user, integrity and performance-based monitoring is essential for protection from faults, either in the system, the signals, augmentation systems, or that caused by jamming or spoofing. It is also vital to alert the user in case that the system cannot reach the target performance.

The Group had online meetings to discuss critical aspects in Integrity Monitoring of Precise Positioning for land applications and its differences from IM in aviation, with the following activities:

- Design rigorous statistical testing regimes and quality control frameworks for integrity monitoring of RTK, PPP and PPP-RTK positioning methods.
- Development of improved fault detection and identification (exclusion), bounding of Gaussian and non-Gaussian errors, with improved computational efficiency suitable for recursive processing, with a focus on real-time applications.
- Identified threat models of multiple alternative fault hypotheses and carried out error characterization for a range of applications, and environments using the underlying precise positioning methods.
- Several applications were considered, with a particular focus on driverless (autonomous) vehicles and transportation in general.

Over the past four years, the group members have contributed in numerous journal and conference publications that address quality control and integrity monitoring, and produce two special Issues "Positioning and Navigation in the journal Remote Sensing (Q1) (ed. by A. El-Mowafy, A. Khodabandeh, K. Wang).

The following section summarizes some of the research being carried out, including the research questions, approaches and key findings.

Summary of the research carried out

Positioning with decimetre to sub-metre accuracy is a fundamental capability for self-driving, and other automated applications. Global Navigation Satellite System (GNSS) Precise Point Positioning (PPP) is an attractive positioning approach for ITS due to its relatively low-cost and flexibility. However, GNSS PPP is vulnerable to several effects, especially those caused by the challenging urban environments, where the ITS technology is most likely needed. To meet the high integrity requirements of ITS applications, it is necessary to carefully analyse potential faults and failures of PPP and to study relevant integrity monitoring methods. In one contribution, an overview of vulnerabilities of GNSS PPP is presented to identify the faults that need to be monitored when developing PPP integrity monitoring methods. These vulnerabilities are categorised into different groups according to their impact and error sources to assist integrity fault analysis, which is demonstrated with Failure Modes and Effects Analysis (FMEA) and Fault Tree Analysis (FTA) methods. The main vulnerabilities are discussed in detail, along with their causes, characteristics, impact on users, and related mitigation methods. In addition, research on integrity monitoring methods used for accounting for the threats and faults in PPP for ITS applications is briefly reviewed. Both system-level (network-end) and user-level (user-end) integrity monitoring approaches for PPP are briefly discussed, focusing on their development and the challenges in urban scenarios. Some open issues, on which further efforts should focus, are also identified.

In one study, a detailed threat model is developed for real-time kinematic (RTK) positioning application of short baselines. The model distinguishes between ambiguity-float and -fixed scenarios, and considers the influences of phase and code multipath as well as between-receiver atmospheric residuals. With the float ambiguities temporally constrained, the bias contribution that propagates with time-updated ambiguities was studied analytically for the horizontal protection level (HPL) in IM. Based on real data from both static and kinematic experiments, HPL was computed along the direction of the semi-major axis of the horizontal error ellipse. In ambiguity-float and -fixed cases, the HPL was mostly several meters and decimetres, respectively. It was found that time-propagated biases play a dominant role in the ambiguity-float HPL, and among them, phase and code multipath had in general the largest contributions. For ambiguity-fixed case, the phase multipath was found to play a dominant role in the HPL. This shows the importance of considering the biases in the RTK IM for both the ambiguity-float and -fixed scenarios. Given a horizontal alert limit (HAL) of 5 m, the availabilities of ambiguity-float solutions were low, i.e., below 50% for the static roof tests and below 5% for the kinematic road tests. For the ambiguity-fixed scenario, with HAL at 0.5 m, integrity availability was nearly 100% for the static roof tests and above 85% for the kinematic road tests.

Bounding satellites' nominal measurement errors to calculate the protection level (PL) of the position error is a salient step of integrity monitoring of positioning autonomous vehicles (AVs). In another contribution, we considered applying the network RTK approach as a possible technique for precise positioning of AVs. A measurement weighting matrix formed from the overbounding standard deviation (STD) and considers the correlation among differenced observations was developed to achieve conservative PLs. Two approaches were designed to estimate the overbounding parameters and compute the correlation coefficients using one full year of different satellites measurements from multiple GNSS. The Two-Step Gaussian Bounding method is used to calculate the overbounding parameters. The overbounding mean and STD of both code and phase observation errors for both approaches were in the range of 0.0003-1.369 m and 0.007-2.497 m, respectively. While the first approach provides a tight overbounding results, the second is more conservative.

In one study, as the traditional advanced receiver autonomous integrity monitoring (ARAIM) method is designed for (smoothed) pseudorange-based positioning, the complexity of multi-frequency multi-constellation PPPRTK using carrier phase measurements has not been given sufficient consideration. The study proposes an IM scheme for multi-frequency multi-constellation uncombined PPP-RTK applying the ARAIM theory, with a new comprehensive threat model to accommodate not only pseudorange measurements, but also carrier phase measurements, and other fault events arising from the network corrections that support PPP-RTK. Characteristics of different types of faults are analyzed with the aid of numerical experiments. In addition, the impact of ambiguity-fixed solutions on PPP-RTK integrity performance is investigated. Case studies were conducted, including static and real-kinematic positioning experiments. The experiments have demonstrated that fast convergence in accuracy and the position error bounds, or protection levels, with a given integrity risk, in horizontal position components of PPP-RTK could be achieved. For the open sky environments on a highway, the protection levels estimated by PPP-RTK solutions have the potential to meet the alert limit requirement for road transportation using ambiguity-fixed PPP-RTK positioning under the assumption that the risks of wrong ambiguity fixing are very small and can be ignored.

Positioning integrity monitoring (IM) methods such as solution separation apply multiple filters, which necessitates the use of computationally efficient algorithms in real-time applications. Therefore, in another contribution, a new approach that significantly improves the computation time of the measurement-update of Kalman Filter is presented where only one matrix inversion is applied for all filters with measurement subsets. The fault detection and identification (FDI) method and computation of the protection levels (PL) are discussed. The computational improvement comes on the expense of a small increase in the PL. Test results for Precise Point Positioning with float-ambiguities in an open-sky and suburban environment demonstrate the reduced computation time using the proposed approach compared to the traditional method with 23-42% improvement. Availability of integrity monitoring for PPP, i.e. when PL is less than a selected alert limit of 1.625m, ranged between 92% and 99%, depending on the allowable integrity risk, tested at 10-5 and 10-6, and the observation environment.

To ensure high availability for road transport users for in-lane positioning, a sub-meter horizontal protection level (HPL) is expected, which normally requires a much higher horizontal positioning precision of, e.g., a few centimeters. Precise point positioning-real-time kinematic (PPP-RTK) is thus another suitable positioning method that could achieve high accuracy without long convergence time and strong dependency on nearby infrastructure. Therefore, another contribution of the group proposes an IM strategy for multi-constellation PPP-RTK positioning. It analytically studies the form of the variance-covariance (V-C) matrix of ionosphere interpolation errors for both accuracy and integrity purposes, which considers the processing noise, the ionosphere activities and the network scale. In addition, this contribution analyzes the impacts of diverse factors on the size and convergence of the HPLs, including the user multipath environment, the ionosphere activity, the network scale and the horizontal probability of misleading information (PMI). It is found that the user multipath environment generally has the largest influence on the size of the converged HPLs, while the ionosphere interpolation and the multipath environments have joint impacts on the convergence of the HPL. Making use of 1 Hz data of Global Positioning System (GPS)/Galileo/Beidou Navigation Satellite System (BDS) signals on L1 and L5 frequencies, for small- to mid-scaled networks, under nominal multipath environments and for a horizontal PMI down to , the ambiguity-float HPLs can converge to 1.5 m within or around 50 epochs under quiet to medium ionosphere activities. Under nominal multipath conditions for small- to mid-scaled networks, with the partial ambiguity resolution enabled, the HPLs can converge to 0.3 m within 10 epochs even under active ionosphere activities.

When considering BeiDou navigation satellite system (BDS), it is foreseeable that the with global coverage system (BDS-3) and the BDS (regional) system (BDS-2) will coexist in the next decade. Care should be taken to minimize the adverse impact of the receiver-related biases, including inter-system biases (ISBs), differential code biases (DCB), and differential phase biases (DPB) on the positioning, navigation, and timing (PNT) provided by GNSS. Therefore, it is important to ascertain the intrinsic characteristics of receiver-related biases, especially in the context of the combination of BDS-3 and BDS-2, which have some differences in their signal level. In one study, we present a method that enables time-wise retrieval of between-receiver ISBs, DCB, and DPB from multi-frequency multi-GNSS observations. With this method, the time-wise estimates of the receiver-related biases between BDS-3 and BDS-2 are determined using all five frequencies available in different receiver pairs. Three major findings are suggested based on our test results. First, code ISBs are significant on the two overlapping frequencies B1II and B2b/B2I between BDS-3 and BDS-2 for a baseline with non-identical receiver pairs, which disrupts the compatibility of the two constellations. Second, epoch-wise DCB estimates of the same type in BDS-3 and BDS-2 can show noticeable differences. Thus, it is unreasonable to treat them as one constellation in PNT applications. Third, the DPB of BDS-3 and BDS-2 may have significant short-term variations, which can be attributed to, on the one hand, receivers composing baselines, and on the other hand, frequencies.

To assess the impact statistical model selection has on confidence levels of parameter estimators in linear(ized) GNSS models. In the processing of observational data, parameter estimation and statistical testing are often combined. A testing procedure is usually exercised to select the most likely observational model among the hypothesized ones, which is then followed by the estimation of the identified model parameters. The resulting estimator will inherit the uncertainties involved in both estimation and testing which need to be properly taken into account when computing the corresponding confidence level. The approach that is usually followed in practice to determine the confidence level is to compute the probability of the estimator lying in a region around its true value conditioned on the identified hypothesis. Therefore, use is made of the estimator's distribution under the identified hypothesis without regard to the conditioning process that led to the decision of accepting this hypothesis. Therefore, in one contribution, it is shown that for a proper computation of the confidence level in combined estimation-testing procedures, the associated probability should be conditioned not only on the identified hypothesis, but also on the testing outcome that led to the decision of accepting this hypothesis. Therefore, use need to be made of the conditional distribution of the estimator. A numerical analysis of confidence levels is provided with and without accounting for conditioning on testing decision using a number of examples in the context of GNSS single point positioning. It is demonstrated that the customary practice which makes use of unconditional distributions to evaluate the confidence level, may give a too optimistic description of the estimator's quality.

In another article, two fault detection and Exclusion (FDE) approaches are discussed. The first is its application in the observation domain using Chi-square test in Kalman filter processing. The second approach discusses FDE testing in the positioning domain using the solution separation (SS) method, where new FDE forms are presented that are tailored for ITS. In the first form the FDE test is parameterized along the direction of motion of the vehicle and in the cross direction, which are relevant to applications that require lane identification and collision alert. A combined test is next established. Another form of the test is presented considering the maximum possible positioning error, and finally a direction-independent test. A new test that can be implemented in the urban environment is presented, which takes into account multipath effects that could disrupt the zero-mean normal-distribution assumption of the positioning errors. Additionally, a test is presented to check that the position error resulting from the remaining measurements lies within acceptable limits. The proposed methods are demonstrated through a kinematic test run in various environments that may be experienced in ITS.

One can also see that in challenging environments, such as in urban areas, a single navigation system is often difficult to fulfil the precise positioning requirements. Therefore, integrating different navigation systems becomes intrinsic. This integration may include GNSS, the Inertial Navigation Systems (INS), the odometers and the Light Detection and Ranging (LiDAR) sensors. Developing innovative Integrity Monitoring (IM) techniques for the integrated vehicular navigation systems requires knowledge of many aspects including the structure, positioning methodology and the different errors affecting the positioning solution of each individual system and that of the integrated system. Moreover, knowledge is needed of the current mitigation techniques of these errors, possible Fault Detection and Exclusion (FDE) algorithms that can be implemented, and current algorithms for computation of Protection Levels (PLs) that can bind the positioning errors with a specific risk. Therefore, in one paper we have an overview and discussion of these aspects.

In another contribution, a method is presented for prediction of GNSS positioning integrity for ITS journey planning. This information, in addition to other route information, such as distance and time, can be utilized to choose the safest and economical route. We propose to combine the Advanced Receiver Autonomous Integrity Monitoring (ARAIM) technique, tailored for ITS, with 3D city models. Positioning is performed by GNSS Real-Time Kinematic (RTK) method, which can provide the accuracy required for ITS. Demonstration of the proposed approach is performed through a kinematic test in an urban area in Tokyo. The comparison between the prediction method and the actual observations show that the prediction method estimates close satellite geometry and PLs. The method produced PLs that bounds the actual position errors all the time and they were less than the pre-set alert limit.

In one study, a detailed threat model is developed for real-time kinematic (RTK) positioning application of short baselines. The model distinguishes between ambiguity-float and -fixed scenarios, and considers the influences of phase and code multipath as well as between-receiver atmospheric residuals. With the float ambiguities temporally constrained, the bias contribution that propagates with time-updated ambiguities was studied analytically for the horizontal protection level (HPL) in IM. Based on real data from both static and kinematic experiments, HPL was computed along the direction of the semi-major axis of the horizontal error ellipse. In ambiguity-float and -fixed cases, the HPL was mostly several meters and decimetres, respectively. It was found that time-propagated biases play a dominant role in the ambiguity-float HPL, and among them, phase and code multipath had in general the largest contributions. For ambiguity-fixed case, the phase multipath was found to play a dominant role in the HPL. This shows the importance of considering the biases in the RTK IM for both the ambiguity-float and -fixed scenarios. Given a horizontal alert limit (HAL) of 5 m, the availabilities of ambiguity-float solutions were low, i.e., below 50% for the static roof tests and below 5% for the kinematic road tests. For the ambiguity-fixed scenario, with HAL at 0.5 m, integrity availability was nearly 100% for the static roof tests and above 85% for the kinematic road tests.

It is known that for the short-baseline real-time relative kinematic positioning, such as in RTK, the spatially correlated errors, such as the orbital errors and the atmospheric delays are significantly reduced. However, the remaining atmospheric residuals and the multipath that are not considered in the observation model could directly bias the positioning results. Therefore, in one contribution, these biases are analysed with the focus put on the multipath effects in different measurement environments. A new observation weighting model considering both the elevation angle and the signal-to-noise ratios is developed and their impacts on the positional results are investigated. The coefficients of the proposed weighting model are determined for the open-sky and the suburban scenarios with the positional benefits maximised. Next, the overbounding excess-mass cumulative distribution functions (EMCs) are searched on the between-receiver level for the weighted phase and code observations in these two scenarios. Based on the mean and standard deviations of these EMCs, horizontal protection levels (HPLs) are computed for the ambiguity-fixed solutions of real experiments. The HPLs are compared with the horizontal positioning errors (HPEs) and the horizontal ALs (HALs). Using the sequential exclusion algorithm developed for the ambiguity resolution, the full ambiguity resolution can be achieved in around 100% and 95% of the time for the open-sky and the suburban scenarios, respectively. The corresponding HPLs of the ambiguity-fixed solutions are at the sub-dm to dm-level for both scenarios, and all the valid ambiguity-fixed HPLs are below a HAL of 0.5 m. For the suburban scenario with more complicated multipath environments, the HPLs increase by considering extra biases to account for multipath under a certain elevation threshold. In complicated multipath environments, when this elevation threshold is set to 30 degrees, the availability of the ambiguity-fixed solutions could decrease to below 50% for applications requiring HAL as low as 0.1 m.

Spoofing can seriously threaten the use of the Global Positioning System (GPS) in critical applications such as positioning and navigation of autonomous vehicles. Research into spoofing generation will contribute to assessment of the threat of possible spoofing attacks and help in the development of anti-spoofing methods. However, the recent commercial off-the-shelf (COTS) spoofing generators are expensive and the technology implementation is complicated. To address the above problem and promote the GPS safety-critical applications, a spoofing generator using a vector tracking-based software-defined receiver is proposed in this contribution. The spoofing generator aims to modify the raw signals by cancelling the actual signal component and adding the spoofing signal component. The connections between the spreading code and carrier, and the states of the victim receiver are established through vector tracking. The actual signal can be predicted effectively, and the spoofing signal will be generated with the spoofing trajectory at the same time. The experimental test results show that the spoofing attack signal can effectively mislead the victim receiver to the designed trajectory. Neither the tracking channels nor the positioning observations have abnormal changes during this processing period. The recent anti-spoofing methods cannot detect this internal spoofing easily. The proposed spoofing generator can cover all open-sky satellites with a high quality of concealment. With the superiority of programmability and diversity, it is believed that the proposed method based on an open source software-defined receiver has a great value for anti-spoofing research of different GNSS signals.

Selected publications

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WG 4.4.3: Reliability of low-cost & Android GNSS in navigation and geosciences

Chair: Jacek Paziewski (University of Warmia and Mazury in Olsztyn, Poland)
Vice-Chair: Robert Odolinski (University of Otago, New Zealand)

Members

- Vassilis Gikas (NTUA Greece)
- Xiaopeng Gong (Wuhan University, China)
- Martin Hakansson (Royal Institute of Technology Stockholm, Sweden)
- Amir Khodabandeh (Melbourne University, Australia)
- Guangcai Li (Wuhan University, China)
- Augusto Mazzoni (University of Rome La Sapienza, Italy)
- Dimitrios Psychas (Fugro, The Netherlands)
- Eugenio Realini (Geomatics Research & Development s.r.l. (GReD), Italy)
- Umberto Robustelli (Parthenope University of Naples, Italy)
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Main activities during the period 2019-2023

Recent advances in GNSS hardware inspired the scientific community to put a spotlight on the mass-market GNSS receivers and smartphones equipped with GNSS chipsets and the development of novel processing methods as a potential complement to the high-grade GNSS receivers in geoscience studies. Working Group 4.4.3 addressed and investigated issues related to applying a low-cost receiver and smartphone GNSS observations to navigation, positioning, and selected geoscience applications. The main objectives of current activities were:

- Analysis of multi-constellation observations tracked by recent Android smartphones;
- Feasibility study on integer ambiguity fixing with phase observations collected by smartphones;
- Assessment of SPP, DGNSS, PPP, and RTK positioning with Android smartphones;
- Development of algorithms and methods for integer ambiguity resolution on smart handheld devices.
- Application of low-cost GNSS receivers to troposphere sounding and precise positioning;
- Outline perspectives for positioning and applications with smartphone GNSS observations.

Over the reported period, the group members have contributed to publications and conference presentations that address this research area. The following section summarizes the selected studies carried out.

1. Characterization of smartphone GNSS observations

In a joint study by WG 4.4.3 members, the authors assessed the quality of multi-constellation GNSS observations of selected Android smartphones, namely Huawei P30, Huawei P20, and Huawei P Smart, as well as Xiaomi Mi 8 and Xiaomi Mi 9 (Paziewski et al. 2021). We investigated the properties of phase ambiguities to anticipate the feasibility of precise positioning with integer ambiguity fixing. The results revealed a significant drop in smartphone carrier-to-noise density ratio (C/N0) concerning geodetic receivers and discernible differences among constellations and frequency bands. We also showed that the higher the satellite's elevation, the larger the discrepancy in C/N0 between the geodetic receivers and smartphones. We depicted that an elevation dependence of the signal strength is not always the case for smartphones. We discovered that smartphone code pseudoranges are noisier by about one order of magnitude compared to the geodetic receivers. The code signals on L5 and E5a outperform those on L1 and E1, respectively. It was shown that smartphone phase observations are contaminated by the effects that can destroy the integer property and time-constancy of the ambiguities. The long-term drifts of GPS L5, Galileo E1, E5a, and BDS B1 phase observations of Huawei P30 were detected. The investigations also revealed competitive phase noise characteristics for the Xiaomi Mi 8 when compared to the geodetic receivers. At the same time, we showed a poor phase signal quality for the Huawei P30 smartphones related to the unexpected long-term drifts of the phase signals.

2. Performance assessment of multi-GNSS smartphone positioning

In (Paziewski et al., 2019), the authors showed the poor quality of the smartphone GNSS phase data. The analyses revealed that discontinuities, a gradual accumulation of errors, and the duty cycling effect affect smartphone GNSS phase measurements. These phenomena prevent correct ambiguity resolution and consequently impede the application of smartphone phase measurement to high-precision positioning techniques. Such smartphone data limitations have spurred an effort by the scientific community to handle them. In WG 4.4.3 joint paper by Paziewski et al. (2020) and Robustelli et al. (2021), the single point positioning (SPP) performance of three recent multi-frequency and multi-constellation smartphones, namely Xiaomi Mi 8, Xiaomi Mi 9, and Huawei P30 pro was evaluated. The analysis of the GNSS observation quality implied that the commonly employed elevation-dependent function is not optimal for smartphone GNSS observation weighting and suggested an application of the C/N0-dependent one. Regarding smartphone code signals on L5 and E5a frequency bands, it was found that they are characterized by noticeably lower noise than E1 and L1 ones. The SPP results confirmed an improvement in the performance when the weights are a function of the C/N0-rather than those dependent on the satellite elevation and that a smartphone positioning with E5a code observations significantly outperforms that with E1 signals. The results also showed important differences in the positioning performance between the smartphones.

3. Outline perspectives for positioning and applications with smartphone GNSS observations

The activities of the 4.4.3 Working Group members were also related to the analysis of the state-of-art and anticipation of the future progress in smartphone GNSS positioning and applications. The papers by Paziewski (2020) and Iakovidis et al. (2022) offer a review of the most recent advances in smartphone GNSS positioning and applications, identify challenges, and outline possible future developments. Notwithstanding the tremendous progress of low-cost GNSS devices and smartphones, we still recognize several limitations that deter their application to the most demanding areas of science and technology. The smartphone GNSS antennas suffer from a low and inhomogeneous pattern of gain, high susceptibility to multipath, lack of phase center models, and a linear polarization that does not prevent the acquisition of the non-line-of-sight left-hand circularly polarized signals. Moreover, users have to handle highly noisy smartphone observations, the presence of unaligned chipset initial phase biases, and other biases that destroy the integer and time-constant properties of carrier-phase ambiguities. However, continuous progress in hardware, algorithms, and applications is thought to be maintained in the future. With this development, the presumption of low performance commonly related to low-cost receivers and smartphones may not hold true since such receivers may reach a performance level close to high-grade receivers shortly.

4. Low-cost multi-GNSS data processing

The scope of another study by the members of WG 4.4.3 is on applying Best Integer Equivariant (BIE) estimation to low-cost GNSS data processing. Odolinski and Teunissen (2020a) analyzed the normal distribution-based BIE estimation for low-cost single-frequency multi-constellation Real Time Kinematics (RTK) positioning. This study was supplemented by (Odolinski and Teunissen 2020b), where the authors investigated the corresponding BIE performance for low-cost dual-frequency long baseline multi-GNSS RTK positioning. With the conducted experiment, the authors proved that the BIE estimator outperforms the Integer Least Squares estimator and the float solutions regarding positioning accuracy. Finally in (Odolinski and Teunissen 2022), the authors analyzed the BIE estimators using multi-constellation GNSS observations and compared them to their least-squares and integer least-squares contenders.

Next, Hohensinn et al. (2022) assessed the quality of a piece of low-cost GNSS equipment for real-time PPP and high-rate dynamic monitoring applications, such as strong-motion seismology. The authors proved that, with low-cost GNSS receivers, reaching a positioning precision of one centimeter is feasible. Thus these devices may densify existing GNSS monitoring networks, as needed for strong-motion seismology and earthquake-early-warning.

Finally, Paziewski (2022) assessed the current performance of single-frequency PPP with low-cost receivers. The author demonstrated the most prominent constraint of such receivers and antennas, which is multipath, and showed the benefit of applying a phase-code ionosphere-free linear combination to low-cost receiver GNSS data processing. Moreover, a great advantage of geodetic antennas over low-cost ones was revealed.

5. Troposphere sounding with smartphones and low-cost GNSS receivers

WG members conducted extensive studies on applying the smartphone and low-cost GNSS observations to troposphere sounding.

First, Stepniak and Paziewski (2022) assessed the quality of tropospheric estimates obtained from low-cost equipment. The results showed that tropospheric parameters derived from low-cost receiver data could achieve high precision and reliability, only slightly lower than that of high-grade receivers. The accuracy of low-cost receiver tropospheric estimates can be better when a surveying-grade antenna is employed than the low-cost receiver + a patch antenna. A strong correspondence between GNSS-derived tropospheric parameters and these of the global climate and weather – ERA5 reanalysis was also revealed. Such outcomes proved that low-cost equipment might contribute to atmospheric studies by taking advantage of their low cost and thus ease of GNSS permanent network densification, increasing the spatial resolution of the soundings.

Next, Stauffer et al. (2023) investigated the capability of using smartphone GNSS data to estimate tropospheric delays. With the experiment, the authors demonstrated that high-precision ZTDs could be successfully determined from smartphone GNSS observations and thus may contribute to numerical weather prediction models.

Finally, Aichinger-Rosenberger et al. (2023) introduced the deployment of MPG-NET - a multi-purpose GNSS station network in the Swiss Alps based on low-cost GNSS equipment. The ZTDs and volumetric soil moisture content were validated against benchmark data from numerical weather models and in-situ sensors and showed a good agreement.

6. Precise positioning and applications with smartphone GNSS observations

Comprehensive assessment of smartphone GNSS observations paved the way toward precise positioning with such observations (Paziewski et al. 2019). In the joint paper of WG 4.4.3 by Paziewski et al. (2021), the authors showed the coordinate precision level that may be reached in a relative mode for the baseline built of a pair of homogenous smartphones. The precision of coordinates obtained in an ambiguity-float solution and the improvement one can gain from integer ambiguity fixing were analyzed. It was proved that getting a precise solution at the cm-level in a smartphone-to-smartphone relative positioning mode with fixed ambiguities is feasible. These outcomes move us towards a precise collaborative positioning with smartphones.

Next, Li and Geng (2022) characterized the channel-dependent biases for the Android GLONASS G1, BDS B1I, Galileo E5a, and QZSS L1 carrier phase observations, which destroy the integer property of GNSS ambiguities and consequently result in varying GLONASS inter-frequency bias (IFB) rates. The authors proposed the on-the-fly phase biases correction method to solve such unwanted effects. The method allows reliability verification by resolving only the bias-free ambiguities and estimating the phase bias corrections on-the-fly by gain filtering.

In the following study by Geng et al. (2023), the WG members proposed a robust RTK scheme with sliding window-based Factor Graph Optimization to address the issue of numerous outliers present in Android smartphone GNSS observations. The developed algorithms take advantage of the GNSS carrier-phase sliding window marginalization, model the carrier-phase ambiguity as a random constant, and integrate multiple robust estimation strategies. With such enhancement, it was possible to reach a decimeter-level positioning accuracy.

Finally, Li et al. (2023) employed smartphone GNSS observations for velocimetry in high-precision vibration monitoring. Handling anomalous clock variations of smartphones was necessary to reach such an objective. With the developed processing schemes, the authors reached a few mm/s velocities using inexpensive smartphones or their embedded GNSS chipsets. Consequently, a concept of a low-cost smartphone-based monitoring system was demonstrated.

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Meeting and communications during the period 2019-2023

1. The communications of the WG 4.4.3 took place during European Geoscience Union General Assemblies that were held in April 2020, 2021 (online), and 2022 and 2023 in Vienna, Austria onsite. The chair of WG 4.4.3 conveyed a dedicated session "High-precision GNSS: methods, open problems and Geoscience applications".

The WG members were involved in editing special issues related to the objectives of the WG.

2. A Special Issue "*Precise Positioning with Smartphones"* in Sensors (ed. Y. Gao, J. Paziewski, M. Fu, A. Mazzoni).
3. A Special Issue "*Feature Papers in Navigation and Positioning"* in Sensors (ed. Y. Gao, J. Paziewski, M. Fu, A. Mazzoni).
4. A Special Issue "*Multi-GNSS Precise Positioning and Applications"* in Sensors (ed. R. Odolinski and A. Khodabandeh).
5. A Special Issue "*Recent Advances in Ubiquitous Positioning Systems for Mobility Applications*" in Measurement Science and Technology (ed. by J. Paziewski, A. Kealy, V. Gikas and J. Geng).
6. A Special Issue "*High-Precision GNSS: Methods, Open Problems and Geoscience Applications—Part II*" in Remote Sensing (ed. X. Li, J. Paziewski, M. Crespi).

JSG 4.4.4: Assessment and validation of IGS products and open-source scientific software

Chair: Yidong Lou (China)

Members

- Berkay Bahadur (Hacettepe University, Turkey)
- Deimos Ibáñez (Technical University of Catalonia, Spain)
- Feng Zhou (Shandong University of Science and Technology, China)
- Haojun Li (Tongji University, China)
- Weixing Zhang (Wuhan University, China)
- Xiaolei Dai (Wuhan University, China)
- Xiaopeng Gong (Wuhan University, China)

Activities and publications during the period 2019-2023

1. **Performance assessment of products from IGS RTS**

Since mid-2008, the Real-Time Working Group (RTWG) of the International GNSS Service (IGS) has provided continuous BDS/GNSS orbit and clock products. There are 3 RTS ACs (Real-Time Service analysis centers) in China, i.e., CAS (Chinese Academy of Sciences), SHA (Shanghai Observatory) and WHU (Wuhan University), that are providing RT orbit and clock for BDS, GPS, GLONASS and Galileo in SSR format. Comparisons among different IGS RTS centers showed that CNES (Centre National D'Etudes Spatiales) and WHU (GNSS Research Center of Wuhan University) provides the most complete products with the best quality, with one-dimensional BDS orbit precision of MEO better than 10 cm, and clock precision better than 0.35 ns.

2. **Assessment of the positioning performance and tropospheric delay retrieval with precise point positioning using products from different analysis centers**

The performance of precise point positioning (PPP) strongly depends on the quality of satellite orbit and clock products. To give a full evaluation of PPP performance with the various publicly available precise satellite orbit and clock products, members in our group comprehensively investigates the positioning performance as well as tropospheric delay retrieval of GPS-, GLONASS-, and Galileo-only PPP with the precise products from eight International GNSS Service (IGS) (i.e., cod, emr, esa, gfz, grg, igs, jpl, and mit) and five multi-GNSS experiment (MGEX) analysis centers (ACs) (i.e., com, gbm, grm, jax, and wum) based on the observations of 90 MGEX tracking stations in a 1-month period (April 2019). The positioning performance in terms of convergence time and positioning accuracy is assessed by coordinate-static and coordinate-kinematic PPP modes, while the tropospheric delay estimation in terms of accuracy is evaluated by coordinate-fixed PPP mode. For GPS-and GLONASS-only PPP with different AC products, the positioning performances are comparable with each other except that with emr, jpl, mit, and jax products. Overall, the positioning performance with cod and com products provided by CODE ranks the first. For Galileo-only PPP, the grm product performs the best. For ZTD estimation, the accuracy derived from GPS-, GLONASS-, and Galileo-only solutions agrees well and the differences in accuracy among different AC products can be negligible.

3. **Galileo-based precise point positioning with different MGEX products**

Considering the remarkable progress of the Galileo constellation in recent years, members from our group evaluated the performance of dual- and single-frequency Galileo-based Precise Point Positioning (PPP) and its contribution to GPS and Galileo integration with different precise products generated by four analysis centers (ACs) within the context of the Multi-GNSS Experiment (MGEX) of the International GNSS Service (IGS). The daily observation dataset collected at ten IGS stations over one month was processed in both static and kinematic modes for Galileo-only, GPS-only and GPS/Galileo

PPP scenarios. For dual-frequency PPP, the results demonstrate that while the Galileo-only solutions are highly comparable with GPS-only PPP for the static mode, the mean 3D positioning errors for Galileo-only processes are approximately 1-cm higher than those obtained from GPS-only solutions for all agencies. The analysis to evaluate the influence of Galileo satellites with highly eccentric orbits, namely E14 and E18, on the dual-frequency Galileo-only PPP performance indicates that including or excluding these satellites has an insignificant effect on the results. For single-frequency PPP, which is dependent on the GRAPHIC combination, Galileo-only PPP performs significantly better, approximately 40%, than GPS-only solutions in the static mode, whereas the kinematic Galileo-only and GPS-only PPP solutions are quite close for all agencies except for WHU. Also, the RMS of observation residuals for Galileo in single-frequency PPP was quite lower than that of GPS, which reveals that the observation quality of Galileo code measurements is better than GPS ones. Among the ACs, Galileo-based PPP solutions applying CODE products provided slightly better results than GFZ and CNES/CLS in general, while the processes using WHU products resulted in worse performance both in positioning accuracy and convergence time. Moreover, the integration of Galileo with GPS enhances PPP performance significantly in both static and kinematic modes.

4. **Comparative analysis of MGEX products for post-processing multi-GNSS PPP**

In recent years, the precise products generated by the International GNSS Service (IGS) as a part of the Multi-GNSS Experiment (MGEX) project have been increasingly used for multi-GNSS applications. Nowadays, six IGS Analysis Centers (ACs) have been providing GNSS products with different features. However, there is still neither a combined solution nor a standard accuracy definition for MGEX products, unlike the standard IGS products. For the GNSS techniques that are directly dependent on precise products, such as Precise Point Positioning (PPP), the quality of these products is a very crucial point in positioning performance. Members from this group have investigated the impact of MGEX products provided by different IGS ACs on post-processing PPP performance in terms of accuracy, availability, and consistency. An experimental test was performed including all possible multi-GNSS combinations of GPS, GLONASS, Galileo, and BeiDou. 24-hour observation datasets collected at ten IGS stations during the 1-month period of May 1–31 were processed with twelve PPP modes using all available precise products. As a first step, an analysis of product availability was carried out for the related MGEX precise products within the test period to be able to assess the impact of the availability on the test results. PPPH software was used to perform the test and the results were statistically assessed as regards positioning error, RMS error and convergence time. The results indicate that the PPP performance may considerably differ depending on the precise products utilized in the PPP process. For the test period, PPP solutions utilizing the precise products generated by GFZ (GeoForschungsZentrum Potsdam) and WU (Wuhan University) agencies have relatively better positioning performance for nearly all processing modes compared to other solutions. The quality and availability of precise products are significant factors which lay behind better PPP performance. On the other hand, while the integration of two or more systems significantly strength the PPP performance, GPS is still the dominant system for PPP and the solutions that do not include GPS constellation have very poor performance. The results also show that MGEX products have different impacts on the PPP performance as varying with the constellation involved in PPP solution and the geographical location of the station.

5. **Performance assessment of BDS-3 B2b PPP Service for different platforms**

The China BeiDou global navigation satellite system (BDS-3) has started to provide free and open precise positioning service to users in China and surrounding areas since Jul 2020 on the GEO B2b signal.

The assessment of BDS-3 PPP-B2b products and the PPP performance over a period of near five months from Jul 26, 2020 to Dec 19, 2020 was carried out by members from this group. Taking the GBM products as reference, the average signal-in-space ranging error (SISRE) of the disseminated orbit and clock products is approximately 82.3 cm (RMS) and 3.9 cm (STD) for BDS-3 satellites, and about 135.8 cm (RMS) and 7.5 cm (STD) for GPS. The average positioning error RMS at six permanent stations in China is about 2.1 (1.8) and 2.6 (2.1) cm in the horizontal and vertical component respectively for BDS-only (BDS+GPS) static PPP. In the kinematic PPP mode, the average positioning error (95%) at the same six stations is about 21.5 (15.2) and 33.4 (30.3) cm in the horizontal and vertical component respectively for BDS-only (BDS+GPS). In addition, two vehicle-based kinematic PPP tests show average position error (95%) of about 23.5 (18.6) and 48.8 (37.1) cm in horizontal and vertical respectively for BDS-only (BDS+GPS) PPP. The assessment results are overall in accordance with the official claim of centimeter-level in static mode and decimeter-level in kinematic mode from BDS-3 PPP service.

Futhermore, a general evaluation of a real-time PPP performance exploiting the PPP-B2b corrections in various user scenarios represented with a static station, a car, an offshore vessel and an aircraft. We found that errors of the PPP-B2b corrections are less stable and higher approximately by a factor of two for GPS compared to BDS-3 medium earth orbit (MEO) satellites. An average convergence time of 28.5 and 12.9 min can be achieved with a standalone BDS-3 and BDS-3 + GPS solution for an ordinary speed vehicle in real time when using the PPP-B2b corrections. For a high-kinematic airborne platform, the convergence time is much longer, reaching 48.9 min. The 95% positioning errors after convergence are less than 20 and 35 cm in horizontal and vertical directions for all the experiments. We conclude that the PPP-B2b service offered by the BDS-3 is prospective for real-time kinematic positioning applications.

6. EGNOS for maritime assessment

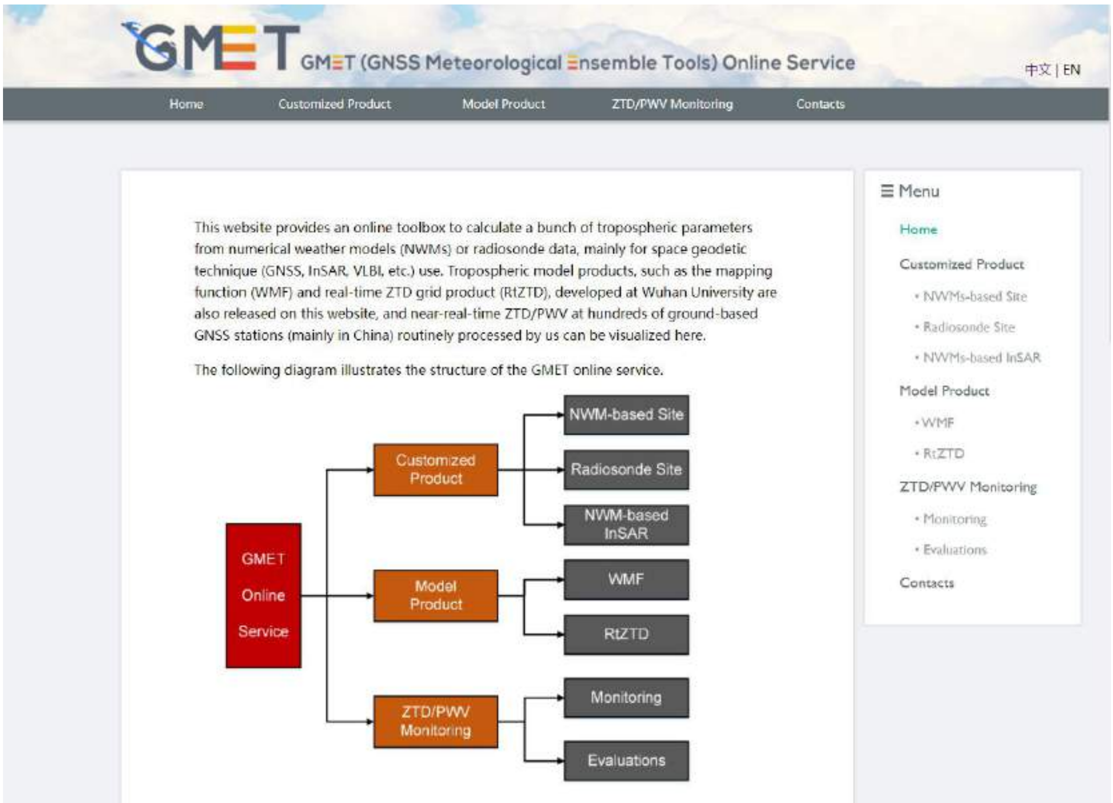
SBAS systems are currently used for aviation, but it is being studied its applicability for maritime purposes. The availability and continuity requirements for maritime differ from aviation, specially the continuity, which has a window size of 15 minutes and the method for computing the continuity differs from aviation. It has been assessed if EGNOS can meet the maritime requirements in the ECAC area, as well as the two methods for computing the continuity (aviation and maritime) have been compared to check which of them provides the best results (with and without DOP mask)

7. Improved stochastic models for multi-GNSS PPP applications

Although the emergence of new satellite systems offers considerable opportunities, the integration of Global Navigation Satellite System (GNSS) multi-constellation entails more complicated approaches, especially for stochastic modeling. This study proposes a filtering approach that combines robust Kalman filtering and variance component estimation to specify the weights of multi-GNSS observations in single-frequency positioning. In this approach, robust Kalman filter resists the impact of unexpected outliers by introducing the equivalent covariance matrix, while multi-GNSS observation variances are determined adaptively in each epoch by using variance component estimation. The study demonstrated that the proposed filtering approach determines the variances of multi-GNSS observations more rigorously as a result of the assessment of the observation residuals. The results also showed that the positioning accuracy of single-frequency multi-GNSS positioning that depends on the conventional weighting approaches is improved by 18.5% on average with the employment of the proposed filtering approach and its improvement ratio can exceed 30% in some stations.

8. Activities of group members on open-source scientific software

Prof. Yidong Lou and his team have recently launched the GMET online service (beta version) for GNSS meteorological research at http://gmet.users.sgg.whu.edu.cn/. This service provides an online toolbox to calculate a bunch of tropospheric parameters from numerical weather models (NWMs) or radiosonde data, mainly for space geodetic technique (GNSS, InSAR, VLBI, etc.) use.



Dr. Berkay Bahadur has developed real-time PPP software, namely PPPH-RT, by extending his previous open-source multi-GNSS PPP analysis software (PPPH). PPPH-RT is capable of performing real-time PPP processes including GPS, GLONASS, Galileo, BDS-2, and BDS-3 satellites. This software enables users to conduct real-time single-frequency PPP solutions as well as dual-frequency PPP solutions. Also, PPPH-RT has some advanced options for determining observation weights in real-time PPP processes, such as the variance component estimation method. It is planned to make PPPH-RT publicly available in the near future.

Mr. Deimos Ibáñez has published gLAB versions up to 5.5.1. In these updates it was addede the NeQuick-G model. He has also been working in the update for muti-constellation (GPS, Galileo, GLONASS, GEO, BDS2/3, QZSS and IRNSS) and multi-frequency (all frequencies in RINEX) in SPP and PPP along with the SBAS DFMC support. This version is foreseen to be published on 2023. He has also been working on integrating Fast-PPP processing in gLAB. All of this work in within his PhD thesis, which will be presented in 2023.

Dr. Feng Zhou has finished the GAMP II - GOOD (Gnss Observations and prOducts Downloader) toolkit, and made it available for global GNSS users on GitHub (https://github.com/zhouforme0318/GAMPII-GOOD). The current version is 1.8, and version 1.9 is still developing, which will be released on the same GitHub webpage soon. He dedicated to create a more powerful GNSS data downloading tool, which can allow every GNSSer to completely get rid of the trouble in GNSS data and product downloading.

Dr. Bahadur has completed a new version of PPPH, namely PPPH-SF, which enables the single-frequency Precise Point Positioning. PPPH-SF can process the multi-constellation data, i.e. GPS, GLONASS, Galileo, and BDS, and also provides several processing options, from different SF-PPP models to several filtering options. On the other hand, he has recently focused on the development of the real-time version of PPPH software, which is capable of processing single- and dual-frequency PPP models in real-time using the ultra-rapid and IGS-RTS products. It is planned that the software will be shared with the GNSS users when its latest and stable version is completed.

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WG 4.4.5: GNSS Interference and Spoofing

Chair: Harshad Sathaye (USA)
Vice Chair: Sriramya Bhamidipati (University of Illinois Urbana-Champaign, USA)

Members

- Aanjhan Ranganathan (Northeastern University, USA)
- Andriy Konovaltsev (DLR, Germany)
- Chengjun Guo (University of Electronic Science and Technology, China)
- Christina Popper (NYU Abu Dhabi, UAE)
- Fabian Rothmaier (Stanford University, USA)
- James T. Curran (USA)
- Jason Gross (West Virginia University, USA)
- Joon Wayn Cheong (University of New South Wales, Australia)
- Kai Jansen (Ruhr-Universität Bochum, Germany)
- Mathieu Joerger (Virginia Tech, USA)
- Pau Closas (Northeastern University, USA)
- Samer Khanafseh (Illinois Institute of Technology, USA)
- Shinan Liu (University of Chicago, USA)

Main activities and achievements during the period 2019-2023

1. Working Group Virtual Meetings & Seminars

The working group participated in a series of virtual meetings and seminars during the past year in light of the travel restrictions imposed by the pandemic. A brief summary of the virtual sessions organized as part of this working group is as follows:

- *June 2020*: On leveraging crowd-sourced ADS-B data to detect and localize GNSS spoofing attacks by Dr. Kai Jansen.
- *July 2020*: On spoofing GNSS/INS-based location tracking systems by Dr. Aanjhan Ranganathan.
- *November 2020*: On spoofing detection with direction-of-arrival measurements from a dual-polarized antenna by Fabian Rothmaier.
- *April 2021*: On reliable, low-cost spoofing detection with smartphone devices by Shinan Liu.

These meetings were 60—90 minutes in duration and attended by 10—12 members across different time zones. The invited speaker talks were followed by extensive discussion and feedback.

2. Working Group Activities & Initiatives

The working group has undertaken a few initiatives to support the research activities being performed by the group members.

- Acquired access to historical ADS-B database from adsbexchange.com to support research on detection and localization of GNSS spoofing attacks in-the-wild.
- Initiated work on development of a global GNSS interference situational-awareness map with crowd-sourced reporting of interference events along with associated evidence, data recordings, etc.

3. GNSS Spoofing Detection with ADS-B data

Over the past year, members of the working group have investigated the utility of ADS-B Out data for detection of GNSS interference activity. These efforts have followed two lines of research. On the one hand, Jansen et al. (2021) have developed a non-invasive crowd-sourced trust evaluation system to detect GNSS and ADS-B spoofing attacks on air-traffic surveillance. Taking advantage of the redundancy of geographically distributed ADS-B receivers, they have implemented verification tests to pursue security by wireless witnessing with the goal of protecting otherwise unsecured GNSS and ADS-B systems. The proposed system is shown to be effective in detecting both GNSS and ADS-B spoofing on real-world aircraft ADS-B data.

In contrast to the crowd-sourced security proposal above, Kujur et al. (2020a) have pursued a different line of investigation for on-board GNSS spoofing detection with the aid of an inertial navigation system (INS). They imagine a scenario where the spoofer tracks the ADS-B Out positions of the aircraft to execute a covert GNSS spoofing attack. In response, they propose a method to intentionally perturb the reported ADS-B positions such that a spoofed trajectory generated using these ADS-B data will be detectable by cross-examination against an INS. Furthermore, they analytically quantify the magnitude of ADS-B modulation that will be sufficient for spoofing detection.

4. First Results from Three Years of Interference Monitoring from Low-Earth Orbit

As massive low-earth orbit (LEO) broadband constellations are taking shape, the use of these satellites as probes for global GNSS interference monitoring has surfaced as an exciting new possibility. Observation of terrestrial GNSS interference from LEO is a uniquely effective technique for characterizing the scope, strength, and structure of interference and for estimating transmitter locations. Such details are useful for situational awareness and interference deterrence. Murrian et al. (To appear, 2021) have presented the results of a three-year study of global interference, with emphasis on a particularly powerful interference source active in Syria since 2017. Via Doppler positioning using a GPS receiver on the International Space Station (ISS), an estimate of the interference source's location is obtained whose horizontal errors are less than 1 km with 99% confidence. Such an accurate localization of a GNSS interference source from LEO is without precedent in the open literature.

Figure 1. Estimated transmitter location overlaid on formal-error 95% and 99% horizontal error ellipses. The location is coincident with an airbase on the coast of Syria. The semi-major axis of the 95% ellipse is 220 meters.

5. Optimal Hypothesis Tests for GNSS Spoofing Detection

Several GNSS spoofing detection methods have been developed in the GNSS literature over the last 15 years. Over the last year, individual research from a member of the working group has made two notable contributions towards *optimal* combinations of such statistics to maximize the sensitivity of the detection tests. In the first contribution, Rothmaier et al. (2021a) have developed the most sensitive, broadly applicable implementation of an optimal direction of arrival based spoofing detector that provides up to 10x reduction in missed detections compared to the open literature with guaranteed false alert probability, and is robust against a scenario where only a subset of the satellites is being spoofed. In the second contribution, Rothmaier et al. (To appear, 2021b) have created a general statistical inference framework for optimal detection using an arbitrary number of metrics that could have been formulated based on a broad variety of spoofing detection techniques developed in the literature thus far. They have identified that an optimal hypothesis test based on a combination of received signal power, correlation function distortion, and pseudorange residuals is both low-cost and extremely powerful.

Selected publications:

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Inter-Commission Committee on Theory (ICCT)

http://icct.kma.zcu.cz

President: Pavel Novák (Czech Republic)
Vice President: Mattia Crespi (Italy)

Structure

Joint Study Group T.23:	Spherical and spheroidal integral formulas of the potential theory for transforming classical and new gravitational observables
Joint Study Group T.24:	Integration and co-location of space geodetic observations and parameters
Joint Study Group T.25:	Combining geodetic and geophysical information for probing Earth's inner structure and its dynamics
Joint Study Group T.26:	Geoid/quasi-geoid modelling for realization of the geopotential height datum
Joint Study Group T.27:	Coupling processes between magnetosphere, thermosphere and ionosphere
Joint Study Group T.28:	Forward gravity field modelling of known mass distributions
Joint Study Group T.29:	Machine learning in geodesy
Joint Study Group T.30:	Dynamic modelling of deformation, rotation and gravity field variations
Joint Study Group T.31:	Multi-GNSS theory and algorithms
Joint Study Group T.32:	High-rate GNSS for geoscience and mobility
Joint Study Group T.33:	Time series analysis in geodesy and geodynamics
Joint Study Group T.34:	High resolution harmonic analysis and synthesis of potential fields
Joint Study Group T.35:	Advanced numerical methods in physical geodesy
Joint Study Group T.36:	Dense troposphere and ionosphere sounding
Joint Study Group T.37:	Theory and methods related to combination of high-resolution topographic/bathymetric models in geodesy

Overview

Terms of Reference

The Inter-Commission Committee on Theory (ICCT) was formally approved and established after the IUGG XXI Assembly in Sapporo, 2003, to succeed the former IAG Section IV on General Theory and Methodology and, more importantly, to interact actively and directly with other IAG entities, namely commissions, services and the Global Geodetic Observing System (GGOS). In accordance with the IAG by-laws, the first two 4-year periods were reviewed in 2011. IAG approved the continuation of ICCT at the IUGG XXIII Assembly in Melbourne, 2011. At the IUGG XXIV Assembly in Prague, 2015, ICCT became a permanent entity within the IAG structure.

The main objectives of the ICCT are:
- to be the international focal point of theoretical geodesy,
- to encourage and initiate activities to further geodetic theory,
- and to monitor research developments in geodetic modelling.

ICCT's Steering Committee 2019-2023

President	*Pavel Novák* (Czechia)
Vice-President	*Mattia Crespi* (Italy)
Past-President	*Nico Sneeuw* (Germany)
Commission 1	*Christopher Kotsakis* (Greece)
Commission 2	*Mirko Reguzzoni* (Italy)
Commission 3	*Janusz Bogusz* (Poland)
Commission 4	*Allison Kealy* (Australia)
GGOS	*Michael Schmidt* (Germany)
IGFS	*Riccardo Barzaghi* (Italy)
IERS	*Jürgen Müller* (Germany)
IAG	*Bofeng Li* (China)
IAG	*Marcelo Santos* (Canada)

During the 2019-2023 period, the ICCT Steering Committee did not meet physically due to travel restrictions imposed by the COVID-19 pandemic. ICCT-related business was discussed at several on-line meetings of the IAG's Executive Committee which could be considered as substitution of the ICCT Steering Committee meetings as their memberships largely overlap. The ICCT President informed members of the IAG Executive Committee about the structure of the ICCT, activities of its joint study groups and about the X. Hotine-Marussi Symposium on Mathematical Geodesy organized by ICCT in 2022. The ICCT Steering Committee was involved in planning and organizing the X. Hotine-Marussi Symposium.

ICCT Website

The ICCT website *http://icct.kma.zcu.cz* for the entire period of 2019-2023 was hosted at the web server of the Department of Geomatics, University of West Bohemia in Pilsen, Czechia. The website was powered by the MediaWiki Engine similar to that used for Wikipedia. Due to this setup, the content of the ICCT Website could easily be edited by authorized personnel (members of the ICCT Steering Committee and Chairs of the Study Groups). Thus, the website could be used by for fast and easy communication of ideas among the members of the Study Groups. This website was established in 2007; thus, it had served the ICCT for the period of 16 years (2007-2023).

X. Hotine-Marussi Symposium

The highlight of ICCT activities within the four-year period between two consecutive IUGG General Assemblies is the organization of the Hotine-Marussi Symposium on Mathematical Geodesy. Since the inception of ICCT, the already existing series of the Hotine-Marussi Symposia had fallen under the responsibility of ICCT. Previous ICCT-organized symposia include VI. (2006, Wuhan), VII. (2009, Rome), VIII (2013, Rome) and IX. (Rome, 2018) symposia. The venue of the last three Hotine-Marussi Symposia was the Faculty of Engineering of the Sapienza University of Rome.

The jubilee X. Hotine-Marussi Symposium on Mathematical Geodesy was held from 13 to 17 June 2022. In total, it was already the 18th Symposium on Mathematical Geodesy organized since 1959. The symposium, organized at the Politecnico di Milano, was attended by 60 participants, see Fig. 1, who contributed 80 papers (62 oral presentations and 18 posters) focused on recent developments in geodetic theory.

Figure 1: *Participants of X Hotine-Marussi Symposium, 15 June 2022, Politecnico di Milano*.

The scientific program of the symposium was organized in 10 regular sessions thematically modelled according to the topics of the ICCT study groups and convened by their chairs:

1. Advanced numerical methods in geodesy (R. Čunderlík, Z. Minarechová)
2. Theory of geodetic reference frames and Earth's rotation (Z. Altamimi)
3. Theory of multi-GNSS parameter estimation (A. Khodabandeh)
4. Multi-sensor and time series data analysis (A. Klos, K. Sośnica,)
5. Theory of global gravity field modelling (M. Reguzzoni, M. Šprlák)
6. Probing Earth's inner structure using geodetic methods (D. Sampietro, R. Tenzer)
7. Theoretical aspects of heights and height systems (R. Barzaghi)
8. Estimation theory and stochastic modelling (P. Teunissen)
9. Geodetic methods in Earth system science (M. Crespi, N. Sneeuw)
10. Theory of local gravity field modelling (H. Abd-Elmotaal, J. Huang)

Additionally, a special session was held on 15 June 2022. Its program consisted of 5 invited talks focused on the two basic concepts of physical geodesy – geoid and quasigeoid:

- Sansò F, Barzaghi R, Reguzzoni M: Molodensky's and Helmert's theories – two equivalent geodetic approaches to the determination of the gravity potential
- Sideris MG, Sansò F: The equivalence of the linearized original and 'Helmertised' geodetic boundary value problems of Stokes and Molodensky
- Sjöberg LE: Geoid or quasigeoid? – a short comparison
- Kingdon R, Vaníček P, Santos M, Sheng M, Foroughi I: The quasigeoid: why Molodensky heights fail
- Huang J, Wang Y: Numerical aspects of local and regional geoid and quasi-geoid determination

As an important outcome of the debate on the geoid and quasigeoid was a motion proposed to the Assembly of the X. Hotine-Marussi Symposium which recommended the quasigeoid should not be used as a reference surface for geodetic heights in scientific as well as engineering applications. The Assembly recommended discussing this proposal with leading experts in the field and possibly proposing a resolution to the IAG Assembly 2023.

The symposium was organized as a classic meeting with on-site participation; however, due to pandemic restrictions, a limited number of presentations were provided using online tools. Although the number of participants did not match the numbers of previous Hotine-Marussi symposia, the meeting was attended by numerous geodesists, both young and senior ones, who greatly contributed to its success. The X. Hotine-Marussi Symposium was also a success thanks to the efforts and organizational skills of the local organizing committee chaired by Riccardo Barzaghi (Politecnico di Milano).

Further Meetings

The Hotine-Marussi Symposium is not the only scientific meeting with the visible presence of the ICCT. Session dedicated to recent general developments in geodetic theory were organized by ICCT-related personnel at EGU General Assemblies 2020-2023 in Vienna. Other sessions on particular topics of theoretical geodesy related to joint study groups' activities are usually included in scientific programs of other IAG meetings (meetings of the IAG commissions, GGOS or meetings of the IAG services). However, the pandemic situation in 2020-2022 significantly influenced organization of many scientific meetings (they were either cancelled or postponed, only some were organized in the on-line mode).

Summary on Activities of Joint Study Groups

The activities of the ICCT are related namely to research activities carried out by members of its joint study groups. Their midterm reports specify main research areas under investigation, achieved results and outputs (namely publications and presentations). Based on the content of the submitted reports, it can be concluded that the joint study groups have been active, although the level of co-operation and/or interaction between its members is not necessarily the same for all the joint study groups. Some of the study groups extended its memberships.

Most importantly, JSG's chairmen delivered their report in time which confirms the main idea behind the current ICCT structure: involving young enthusiastic researchers as new study group chairmen who actively cooperate internationally at research topics which matter to current geodesy. Based on to-date activities of the groups, they had remained operational for the entire period 2019-2023.

Joint Study Group T.23: Spherical and spheroidal integral formulas of the potential theory for transforming classical and new gravitational observables

***Chair**: Michal Šprlák (Czechia)*

Members

Sten Claessens (Australia)
Mehdi Eshagh (Sweden)
Ismael Foroughi (Canada)
Peter Holota (Czechia)
Juraj Janák (Slovakia)
Otakar Nesvadba (Czechia)
Pavel Novák (Czechia)
Vegard Ophaug (Norway)
Martin Pitoňák (Czechia)
Michael Sheng (Canada)
Natthachet Tangdamrongsub (USA)
Robert Tenzer (Hong Kong)

1. Activities of the group

Members of JSG T.23 primarily focused on cooperation and published their research findings in the international journals on geodesy, geophysics, and planetary sciences (e.g., Earth-Science Reviews, Geophysical Journal International, Icarus, Journal of Geodesy, Planetary and Space Science, or Surveys in Geophysics). This effort has resulted in 29 peer-reviewed articles that suggests an active collaboration and actual research area.

The list of selected peer-reviewed publications is provided below. The research articles addressed four (out of seven) objectives of JSG T.23:

Objective 1: *Study noise propagation through spherical and spheroidal integral transforms*: Ophaug and Gerlach (2020) investigated error propagation in regional geoid determination using spherical splines, least-squares collocation, and Stokes's formula. Foroughi et al. (2023a,b) studied data requirements and the effect of the topographical density variations for determination of the sub-centimetre geoid.

Objective 2: *Propose efficient numerical algorithms for precise evaluation of spherical and spheroidal integral transformations*: Goli et al. (2019b) studied the effect of the noise, spatial distribution, and interpolation of ground gravity data on uncertainties of estimated geoidal heights. Precise and efficient numerical procedures were developed and applied for regional geoid determination by the one-step integration method (Goli et al. 2019a), Stokes-Helmert method (Foroughi et al. 2019), and KTH approach (Varga et al. 2021). Wang et al. (2021) provided a systematic summary of the main results for the Colorado geoid computation experiment. Šprlák and Han (2021) evaluated spherical harmonic series inside the minimum Brillouin sphere by GRAIL and LOLA satellite data.

Objective 3: *Complete the family of spheroidal integral transforms among various types of gravitational gradients and to derive corresponding integral kernel functions*: Novák et al. (2019) reviewed spherical integral formulas transforming the volumetric density to higher-order gravitational gradients up to the third order. Novák et al. (2021) systematically discussed mathematical models based on the spherical integral formulas for geoid determination from gradient data. Šprlák et al. (2020a) employed Newton's integral in the spectral domain to solve direct and inverse problems for the Moon. Šprlák et al. (2020b) derived spherical integral estimators relating the line-of-sight gravitational acceleration to an arbitrary order radial derivative of the gravitational potential and performed regional inversion with synthetic and realistic GRAIL observations.

Spheroidal integral transformations, which are particularly important for the gravitational field modelling of oblate or prolate planetary bodies, were presented in four contributions. Ghobadi-Far et al. (2019) formulated a rigorous spheroidal approach for the surface mass estimation. Holota and Nesvadba (2019a,b) discussed Neumann's problem formulated for the exterior of an oblate ellipsoid of revolution. Šprlák et al. (2020c) developed a rigorous spheroidal forward modelling technique.

Objective 4: *Investigate optimal combination techniques of various gravitational gradients for gravitational field modelling at all scales*: Pitoňák et al. (2019, 2020a,b, 2023) proposed functional models for optimal combination of distinct gravitational field quantities by spectral weighting and least-squares.

Three other objectives, i.e., 1) *Formulate and solve spheroidal gradiometric and spheroidal curvature boundary-value problems*, 2) *Develop mathematical expressions for calculating the distant-zone effects for spherical and spheroidal integral transformations*, and 3) *Study mathematical properties of differential operators in spheroidal coordinates* which relate various functionals of the gravitational potential, have partially been investigated and several related publications are in preparation.

In addition, numerous research contributions reached beyond the specified objectives of JSG T.23 as the theoretical apparatus of integral transformations may be used for numerous applications, e.g., in geophysics. Chen and Tenzer (2020) formulated Parker-Oldenburg's method for the estimation of the density interface depth in the spherical approximation. Vajda et al. (2020) presented a comprehensive view of the origin, significance, and implications of topographic effects in gravimetry. Sheng et al. (2019) introduced and validated a global laterally varying topographical density model for the Earth. Rathnayake et al. (2020) analysed interpretational properties of Bouguer gravity maps and Rathnayake et al. (2021) compared different gravimetric methods for a Moho modelling in the Indian Ocean. Tenzer et al. (2020) investigated geoid-to-quasigeoid separation due to the laterally variable density distribution. Eshagh et al. (2020) developed a mathematical model for describing the stress propagation from the sub-lithosphere through the lithosphere and used GRACE products to demonstrate applicability of this model. Ji et al. (2023) employed gravitational curvatures to detect point dislocation and to observe a more detailed information on slip fault parameters.

Members of JSG T.23 actively presented their research findings at major international conferences (e.g., the 27th IUGG General Assembly, IAG 2021 – the Scientific Assembly of the International Association of Geodesy, X Hotine-Marussi Symposium, or the annual meetings organized by EGU and AGU). A list of selected oral and poster presentations is provided below.

Except for the scientific activities, members of JSG T.23 were members of scientific or organising committees of international conferences. P. Holota and O. Nesvadba organised the session G1.1 called "Recent Developments in Geodetic Theory", which is regularly held at EGU General Assembly. P. Novák organised the session titled "ICCT Geodetic Theory" at the IAG 2021 – Scientific Assembly of the International Association of Geodesy in Beijing, China, in 2021. P. Novák and M. Šprlák participated at the organisation of the X Hotine-Marussi Symposium in Milan, Italy, in 2022.

2. Achievements and results

Cooperation among the members of JSG T.23 resulted in several notable achievements: 1) Foroughi et al. (2019) employed the UNB geoid determination approach and determined a sub-centimetre geoid model in the Auvergne test area. 2) Ghobadi-Far et al. (2019) derived a one-to-one relationship between ellipsoidal spectra of surface mass and gravitational potential for the spheroidal geometry. This mathematical relationship allows accurate determination of surface mass from time-variable gravitational field models. 3) The review papers by Novák et al. (2019), Vajda et al. (2020), Novák et al. (2021), Šprlák and Han (2021), and Foroughi et al. (2023) were published in the prestigious journal Earth-Science Reviews (impact factor 12.413 in 2020). 4) Sheng et al. (2019) compiled the first laterally varying topographical density model for the Earth with associated error estimates. 5) Šprlák et al. (2020b) estimated a global laterally varying crustal density model for the Moon. This lunar density model was parametrised by spherical harmonics and is available at ICGEM webpage. 6) Šprlák et al. (2020c) computed the first spheroidal gravitational field models generated by the crustal masses of the Moon and the dwarf planet 1 Ceres.

3. Interactions with the IAG Commissions and GGOS

Members of JSG T.23 collaborated with researchers from JSG T.26 "Geoid/quasi-geoid modelling for realization of the geopotential height datum" and JWG 2.2.2 "Error assessment of the 1 cm geoid experiment" of Commission 2.

4. Publications

Selected peer-reviewed publications

Chen W, Tenzer R (2020) Reformulation of Parker-Oldenburg's method for Earth's spherical approximation. *Geophysical Journal International* 222(2): 1046-1073

Eshagh M, Fatolazadeh F, Tenzer R (2020) Lithospheric stress, strain and displacement changes from GRACE-FO time-variable gravity: case study for Sar-e-Pol Zahab Earthquake 2018. *Geophysical Journal International* 223(1): 379-397

Foroughi I, Vaníček P, Kingdon RW, Goli M, Sheng M, Afrasteh Y, Novák P, Santos MC (2019) Sub-centimetre geoid. *Journal of Geodesy* 93(6): 849-868

Foroughi I, Goli M, Pagiatakis S, Ferguson S, Novák P (2023a) Data requirements for determination of the sub-centimetre geoid. *Earth-Science Reviews* 239: 104326

Foroughi I, Goli M, Pagiatakis S, Ferguson S, Vaníček P, Santos M, Sheng M (2023b) The uncertainties of the topographical density variations in view of a sub-centimetre geoid. In: *International Association of Geodesy Symposia*, Springer, Berlin, Heidelberg, Germany.

Ghobadi-Far K, Šprlák M, Han S-C (2019) Determination of ellipsoidal surface mass change from GRACE time-variable gravity data. *Geophysical Journal International* 219(1): 248-259

Goli M, Foroughi I, Novák P (2019a) Application of the one-step integration method for determination of the regional gravimetric geoid. *Journal of Geodesy* 93(9): 1631-1644

Goli M, Foroughi I, Novák P (2019b) The effect of the noise, spatial distribution, and interpolation of ground gravity data on uncertainties of estimated geoidal heights. *Studia Geophysica et Geodaetica* 63(1): 35-54

Holota P, Nesvadba O (2019a) Galerkin's matrix for Neumann's problem in the exterior of an oblate ellipsoid of revolution: Gravity potential approximation by buried masses. *Studia Geophysica et Geodaetica* 63(1): 1-34

Holota P, Nesvadba O (2019b) Green's function method extended by successive approximations and applied to Earth's gravity field recovery. In: Novák P, Crespi M, Sneeuw N, Sansò F (eds) IX Hotine-Marussi Symposium on Mathematical Geodesy. *International Association of Geodesy Symposia*, 151: 33-39, Springer, Cham.

Ji Y, Tenzer R, Tang H, Sun W (2023) Coseismic gravitational curvatures changes in a spherical symmetric Earth model. *Physics of the Earth and Planetary Interiors* 338: 107013

Novák P, Pitoňák M, Šprlák M, Tenzer R (2019) Higher-order gravitational gradients for geoscientific applications. *Earth-Science Reviews* 198: 102937

Novák P, Šprlák M, Pitoňák M (2021) On determination of the geoid from measured gradients of the Earth's gravity field potential. *Earth-Science Reviews* 221: 103773

Ophaug V, Gerlach C (2020) Error propagation in regional geoid computation using spherical splines, least-squares collocation and Stokes's formula. *Journal of Geodesy* 94(12): 120

Pitoňák M, Novák P, Šprlák M, Tenzer R (2019) On combining the directional solutions of the gravitational curvature boundary-value problem. In: Novák P, Crespi M, Sneeuw N, Sansò F (eds) IX Hotine-Marussi Symposium on Mathematical Geodesy. *International Association of Geodesy Symposia* 151: 41-47, Springer, Cham.

Pitoňák M, Šprlák M, Ophaugh V, Omang OCD, Novák P (2023) Validation of space-wise GOCE gravitational gradient grids using the spectral combination method and GNSS/levelling data. *Surveys in Geophysics* 44: 739-782

Pitoňák M, Novák P, Eshagh M, Tenzer R, Šprlák M (2020a) Downward continuation of gravitational field quantities to an irregular surface by spectral weighting. *Journal of Geodesy* 94(7): 62

Pitoňák M, Šprlák M, Novák P, Tenzer R (2020b) Validation of GOCE-based gravitational gradients grids by spectral combination method. International Seminar – Satellite Methods in Geodesy and Cadastre, January 30, Technical University, Brno, Czechia, pp. 28-36.

Rathnayake S, Tenzer R, Novák P, Pitoňák M (2020) Effect of the lateral topographic density distribution on interpretational properties of Bouguer gravity maps. *Geophysical Journal International* 220(2): 892-909

Rathnayake S, Tenzer R, Chen W, Eshagh M, Pitoňák M (2021) Comparison of different gravimetric methods for a Moho modelling under oceans and marginal seas – A case study for the Indian Ocean. *Surveys in Geophysics* 42(4): 839-897

Sheng MB, Shaw C, Vaníček P, Kingdon RW, Santos M, Foroughi I (2019) Formulation and validation of a global laterally varying topographical density model. *Tectonophysics* 762: 45-60

Šprlák M, Han S-C, Featherstone W (2020a) Crustal density and global gravitational field estimation of the Moon from GRAIL and LOLA satellite data. *Planetary and Space Science* 192: 105032

Šprlák M, Han S-C, Featherstone W (2020b) Integral inversion of GRAIL inter-satellite gravitational accelerations for regional recovery of the lunar gravitational field. *Advances in Space Research* 65(1): 630-649

Šprlák M, Han S-C, Featherstone W (2020c) Spheroidal forward modelling of the gravitational fields of 1 Ceres and the Moon. *Icarus* 335: 113412

Šprlák M, Han S-C (2021) On the use of spherical harmonic series inside the minimum Brillouin sphere: theoretical review and evaluation by GRAIL and LOLA satellite data. *Earth-Science Reviews* 222: 103739

Tenzer R, Chen W, Rathnayake S, Pitoňák M (2020) The effect of anomalous global lateral topographic density on the geoid-to-quasigeoid separation. *Journal of Geodesy* 95(1): 12

Vajda P, Foroughi I, Vaníček P, Kingdon R, Santos M, Sheng M, Goli M (2020) Topographic gravimetric effects in earth sciences: Review of origin, significance, and implications. *Earth-Science Reviews* 211: 103428

Varga M, Pitoňák M, Novák P, Bašić T (2021) Contribution of GRAV-D airborne gravity to improvement of regional gravimetric geoid modelling in Colorado, USA. *Journal of Geodesy* 95(5): 53

Wang YM, Sánchez L, Ågren J, Huang J, Forsberg R, Abd-Elmotaal HA, Ahlgren K, Barzaghi R, Bašić T, Carrion D, Claessens S, Erol B, Erol S, Filmer M, Grigoriadis VN, Isik MS, Jiang T, Koç Ö, Krcmaric J, Li X, Liu Q, Matsuo K, Natsiopoulos DA, Novák P, Pail R, Pitoňák M, Schmidt M, Varga M, Vergos GS, Véronneau M, Willberg M, Zingerle P (2021) Colorado geoid computation experiment: overview and summary. *Journal of Geodesy* 95(12): 127

Selected oral and poster presentations

Belinger J, Trnka P, Šprlák M, Pitoňák M, Novák P (2023) Implementation and testing of the software library for calculating far zone effects of the spherical integral transformations. XXVII Czech-Slovak-Polish Geodetic Days. May 25-27, Sobotín, Czechia.

Foroughi I, Pagiatakis S, Goli M, Ferguson S (2022) Accuracy requirements of the gravity measurements for sub-centimetre geoid. European Geosciences Union General Assembly, May 23-27, Vienna, Austria.

Ghobadi-Far K, Han S-C, Šprlák M, Papanikolaou T, Loomis B (2019) On the along-track data analysis of GRACE and GRACE Follow-On KBR and LRI data. GRACE Follow-On Science Team Meeting, October 8-10, Pasadena, California, USA.

Ghobadi-Far K, Šprlák M, Han S-C (2019) Comparison of spherical and ellipsoidal cryospheric mass change estimated from GRACE time-variable gravity data. Global Isostatic Adjustment Training School, August 26-30, Gävle, Sweden.

Ghobadi-Far K, Šprlák M, Han S-C (2019) Conversion of GRACE time-variable gravity data into surface mass change on the ellipsoid. GRACE Follow-On Science Team Meeting, October 8-10, Pasadena, California, USA.

Holota P (2019) Divergence of gradient and the solution domain in gravity field studies. Presented at the Wissenschaftliches "Kolloquium Ein und ein halbes Jahrhundert internationale Zusammenarbeit der Geodäten und Geophysiker" organized by the Leibniz-Sozietät der Disenchanted zu Berlin e.V. in cooperation with the Helmholtz-Zendrum Potsdam – GFZ, 15 February, Potsdam, Germany.

Holota P, Nesvadba O (2019) Integral representation and Green's function method in gravity field studies. 27th IUGG General Assembly, July 8-18, Montreal, Canada.

Holota P, Nesvadba O (2019) On the construction of Green's function when combining terrestrial data and global models for Earth's gravity field recovery. European Geosciences Union General Assembly, April 7-12, Vienna, Austria.

Holota P, Nesvadba O (2019) Using the Green's function method for solution domains with a complicated boundary in Earth's gravity field studies. European Geosciences Union General Assembly, April 7-12, Vienna, Austria.

Holota P, Nesvadba O (2020) Differential geometry and curvatures of equipotential surfaces in the realization of the World Height System. European Geosciences Union General Assembly, May 4-8, online.

Holota P, Nesvadba O (2020) Laplacian structure, solution domain geometry and successive approximations in gravity field studies. European Geosciences Union General Assembly, May 4-8, online.

Holota P, Nesvadba O (2021) Laplacian structure mirroring surface topography in determining the gravity potential by successive approximations. European Geosciences Union General Assembly, April 19-30, online.

Holota P, Nesvadba O (2021) Tensor calculus and functional analysis in the iteration solution of the geodetic boundary value problem. IAG 2021 - Scientific Assembly of the International Association of Geodesy, June 28 – July 2, Beijing, China.

Holota P, Nesvadba O (2022) Structure of the Laplace operator, geometry of the Earth's surface and successive approximations in the solution of the geodetic boundary value problem. European Geosciences Union General Assembly, May 23-27, Vienna, Austria.

Holota P, Nesvadba O (2022) General curvilinear coordinates, Laplace's operator with topography dependent coefficients and analysis of the iteration solution of the GBVP. 10th Hotine-Marussi Symposium, June 13-17, Milan, Italy.

Holota P (2022) Divergence of gradient and the solution domain in gravity field studies. Joint Conference, October 12-13, Plzeň, Czechia.

Novák P, Pitoňák M, Šprlák M, Tenzer R (2019) Higher-order gradients of the gravitational potential: theory and applications. AGU Fall Meeting, December 9-13, San Francisco, USA.

Ophaug V, Gerlach C (2019) Error propagation in regional geoid computation using spherical splines, least-squares collocation, and Stokes's formula. 27th IUGG General Assembly, July 8-18, Montreal, Canada.

Pitoňák M, Tenzer R, Šprlák M, Novák P (2019) On formal accuracy of global gravitational models of telluric planets and Moon. 27th IUGG General Assembly, July 8-18, Montreal, Canada.

Pitoňák M, Šprlák M, Novák P, Tenzer R (2020) An overview on the spectral combination of integral transformations. European Geosciences Union General Assembly, May 4-8, online.

Pitoňák M, Šprlák M, Novák P, Tenzer R (2020) Validation of GOCE-based gravitational gradients grids by spectral combination method. International Seminar – Satellite Methods in Geodesy and Cadastre, January 30, Brno, Czechia.

Pitoňák M, Šprlák M, Ophaug V, Omang OCD, Novák P (2021) Validation of calibrated GOCE gravity gradients GRD_SPW_2 by least-squares spectral weighting. European Geosciences Union General Assembly, April 19-30, online.

Pitoňák M, Varga M, Šprlák M (2021) The omission error modelling of global gravity field models using different digital terrain models. IAG 2021 – Scientific Assembly of the International Association of Geodesy, June 28 – July 2, Beijing, China.

Pitoňák M, Šprlák M, Ophaug V, Omang OCD, Novák P (2021) A quality assessment of the official GOCE Level 2 GRD SPW 2 products over Norway, Czechia, and Slovakia. IAG 2021 – Scientific Assembly of the International Association of Geodesy, June 28 – July 2, Beijing, China.

Pitoňák M, Šprlák M, Novák P (2022) Combination of integral transforms by spectral weighting – an overview. European Geosciences Union General Assembly, May 23-27, Vienna, Austria.

Pitoňák M, Šprlák M, Novák P (2022) Estimation of height anomalies from derivatives of the gravitational potential using a spectral combination method. 10th Hotine-Marussi Symposium, June 13-17, Milan, Italy.

Pitoňák M, Šprlák M, Ophaug V, Omang OCD, Novák P (2022) Validation of the official GOCE Level 2 product GRD SPW 2 using the spectral combination method and GNSS/Levelling data over Czechia/Slovakia and Norway. Gravity, Geoid and Height Systems, September 12-14, Austin, Texas, USA.

Pitoňák M, Šprlák M, Ophaug V, Omang OCD, Novák P (2022) Validating grids of gravitational gradients by height anomalies in Norway, Czechia, and Slovakia. Joint Conference, October 12-13, Plzeň, Czechia.

Pitoňák M, Šprlák M, Varga M (2022) Gravity disturbance modelling using XGM2019 and global terrain models. Tatry 2022 – Global Geodesy and Geoinformatics, November 24-25, Štrbské pleso, Slovakia.

Pitoňák M, Šprlák M, Ophaug V, Omang OCD, Novák P (2023) Validation of satellite gravitational gradients grids by spectral combination method and GNSS/Levelling data over Norway, Czechia, and Slovakia. International Seminar – Satellite Methods in Geodesy and Cadastre, February 1, Brno, Czechia.

Pitoňák M, Šprlák M, Novák P (2023) Regional gravitational field modelling by the spectral combination of satellite higher-order radial derivatives of the gravitational potential and a global geopotential model. European Geosciences Union General Assembly, April 24-27, Vienna, Austria.

Šprlák M, Han S-C, Featherstone WE (2019) High-resolution gravitational field of the Moon from GRAIL inter-satellite tracking and LOLA topography data. 19th Australian Space Research Conference, September 30 – October 2, Adelaide, Australia.

Šprlák M, Ghobadi-Far K, Han S-C (2020) Determination of surface mass from GRACE and GRACE-FO. International Seminar – Satellite Methods in Geodesy and Cadastre, January 30, Technical University, Brno, Czechia.

Šprlák M, Han S-C, Featherstone WE (2021) Crustal density and forward global gravitational field model on the Moon determined from GRAIL and LOLA satellite data. IAG 2021 – Scientific Assembly of the International Association of Geodesy, June 28 – July 2, Beijing, China.

Šprlák M, Han S-C, Featherstone WE, Novák P, Pitoňák M (2022) Crustal density and global gravitational field estimation on the Moon from GRAIL and LOLA satellite data. International Seminar – Satellite Methods in Geodesy and Cadastre, February 3, Brno, Czechia.

Šprlák M, Han S-C, Featherstone WE, Novák P, Pitoňák M (2022) Crustal density and global gravitational field models on the Moon from GRAIL and LOLA satellite data. XXVI Polish-Czech-Slovak Geodetic Days. June 2-4, Lodz, Poland.

Šprlák M, Han S-C, Novák P, Pitoňák M (2022) GRAIL and LOLA satellite data resolve the long-lasting convergence/divergence problem for the analytical downward continuation of the external spherical harmonic series. X Hotine-Marussi Symposium, June 13-17, Rome, Italy.

Šprlák M, Han S-C, Novák P, Pitoňák M (2022) GRAIL and LOLA satellite data resolve the long-lasting convergence/divergence problem for the analytical downward continuation of the

external spherical harmonic expansions. COSPAR 2022 – 44th Scientific Assembly, July 16-24, Athens, Greece.

Šprlák M, Ghobadi-Far K, Han S-C, Pitoňák M, Novák P (2022) Determination of surface mass from GRACE and GRACE-FO satellite missions. Tatry 2022 – Global Geodesy and Geoinformatics, November 24-25, Štrbské pleso, Slovakia.

Šprlák M, Han S-C, Pitoňák M, Novák P (2023) GRAIL and LOLA satellite data resolve the long-lasting convergence/divergence problem for the analytical downward continuation of the external spherical harmonic expansions. International Seminar – Satellite Methods in Geodesy and Cadastre, February 1, Brno, Czechia.

Šprlák M, Han S-C, Pitoňák M, Novák P (2023) Evaluation of external spherical harmonic series inside the minimum Brillouin sphere: examples for the lunar gravitational field. European Geosciences Union General Assembly, April 23-28, Vienna, Austria.

Trnka P, Belinger J, Šprlák M, Pitoňák M, Novák P (2023) Far zone effects for integral transformations: theory and implementation. International Seminar – Satellite Methods in Geodesy and Cadastre, February 1, Brno, Czechia.

Joint Study Group T.24: Integration and co-location of space geodetic observations and parameters

***Chair**: Krzysztof Sośnica (Poland)*

Members

Tzu-Pang Tseng (Australia)
Daniela Thaller (Germany)
Radosław Zajdel (Poland)
Grzegorz Bury (Poland)
Erik Schnoemann (Germany)
Florian Dilssner (Germany)
Dariusz Strugarek (Poland)
Mathis Blossfeld (Germany)
Julian Zeitlhöfler (Germany)
Mateusz Drożdżewski (Poland)
Toshimichi Otsubo (Japan)
Susanne Glaser (Germany)
Janina Boisits (Austria)
Urs Hugentobler (Germany)
Hongjuan Yu (China)
Joanna Najder (Poland)
Tomasz Kur (Poland)

1. Activities of the group

In the framework of JSG T.24 activities, the following topics were examined:

- Co-location of microwave Global Navigation Satellite System (GNSS) and Satellite Laser Ranging (SLR) observations onboard Galileo and GLONASS satellites for improving the quality of precise GNSS orbits and future reference frame realizations based on space ties (e.g., Bury et al. 2021a, 2021b, 2022).
- Analysis of geocenter coordinates derived from SLR observations to LAGEOS, GPS, GLONASS, and Galileo observations, as well as DORIS and GRACE data (Kosek et al. 2020; Zajdel et al. 2021; Yu et al. 2021a, 2021b).
- Integration of GPS, GLONASS, and Galileo data to derive daily and sub-daily Earth rotation parameters: polar motion and length-of-day excess with an analysis of system-specific systematic errors emerging from satellite orbit modelling (Zajdel et al. 2020, 2021).
- Integration of SLR observations to various Low Earth Orbiters (LEO) with precise GPS-based orbits, such as Sentinel-3A/B, SWARM, GRACE, TanDEM-X, with geodetic LAGEOS and LARES satellites and Galileo data to derive SLR station coordinates, geocenter motion, and Earth rotation parameters (Strugarek et al. 2019, 2021a), see Fig. 1.
- Realization of SLR reference frames based on integrated observations to active LEO and passive LAGEOS satellites in different approaches of the network realization: constrained approach and unconstrained SLR-PPP approach (Strugarek et al. 2019, 2021b).
- Analysis of SLR-derived low-degree gravity field coefficients including the Earth's oblateness term with a comparison to geophysical models and climate-driven constituents (Yu et al. 2021a).
- Improving the consistency and identification of systematic effects between Galileo, GPS, GLONASS, and BeiDou solutions (Hadaś et al. 2019; Kaźmierski et al. 2020; Sośnica et al. 2020; Zajdel et al. 2019a, 2022a, 2022b).

- Analysis of the impact of general relativistic effects on GNSS and LAGEOS orbits with assessing the order of magnitude for orbital perturbations caused by the Schwarzschild, Lense-Thirring, and de Sitter effects (Sośnica et al. 2021, 2022).
- Investigation of the best reference frame constraining approaches: no-net-translation and no-net-rotation and the network effects for GPS, GLONASS, and Galileo combined solutions, as well as SLR-based LAGEOS solutions (Zajdel et al. 2019a, 2019b).
- Precise orbit determination and validation of the combination methodology of the GNSS satellite orbits for, e.g., IGS repro3 and future ITRF realizations, based on SLR-to-GNSS data and intensive ILRS campaigns (Bury et al. 2019, 2020; Sośnica et al. 2020; Zajdel et al., 2022b).
- Improving a consistency between SLR and other space geodetic techniques by modelling and properly handling tropospheric delays with horizontal gradients (Drożdżewski et al. 2019, 2021; Strugarek et al., 2022; Boisits et al 2020).
- Simulation studies for Galileo inter-satellite links using different orbit configurations and considering range biases (Kur et al., 2021; Kur and Kalarus 2021; Kur and Liwosz 2022).
- Simulation studies for future geodetic satellite missions tracked by SLR (spherical satellites) with the assessment of their contribution to deriving Earth rotation parameters, gravity field, and reference frame realization.
- Improving orbit predictions for geodetic and navigation satellites (Nowak et al. 2023; Najder and Sośnica 2021).
- Simulation studies for the future ESA GENESIS mission with the goal of the co-location VLBI, GNSS, SLR, and DORIS in space (Delva et al. 2023).

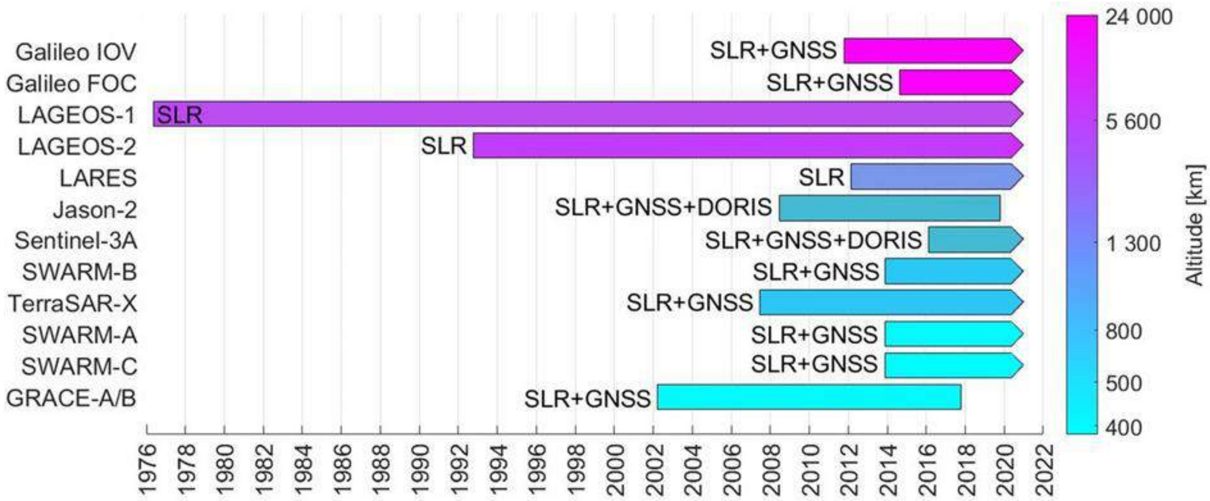

Figure 1: *Selected satellite missions allowing for the co-location in space combined by Strugarek et al. (2021a).*

2. Achievements and results

The achievements of the IAG study group concern three main aspects:

- Development of the methodology for the integration of space geodetic techniques onboard GNSS satellites, especially GNSS and SLR, for future terrestrial frame realizations with the co-location in space.
- Identification and modelling of systematic effects in geodetic observations and parameters.
- Determination of global geodetic parameters, such as geocenter motion, the Earth's oblateness term, and Earth's rotation parameters based on multi-technique and multi-constellation solutions based on real and simulated data.

The results were discussed during the meetings, disseminated during workshops and scientific conferences, and finally published in a few peer-reviewed papers (see Publications). The activities included the organization and co-chairing of a dedicated session of the IAG Scientific Assembly 2021 “Terrestrial and space geodetic ties for multi-technique combinations” with 17 abstracts in the session; the session “Multi-sensor and time series data analysis” during the X Hotine-Marussi Symposium 2022 with 7 abstracts; and the session “Space geodetic measurement techniques” during the Reference Frames for Applications in Geosciences (REFAG 2022) Symposium with 23 abstracts and presentations.

2.1. Combination of SLR and GNSS data and co-location in space

The precise orbit determination of Galileo has greatly been improved due to the release of satellite metadata, which provides important information, such as the size and surface properties of satellite components, modified yaw-steering law, laser retroreflector offsets, and calibrated antenna offsets and variations. Using this information, Bury et al. (2019) developed a box-wing model for Galileo IOV and FOC satellites, which improves the orbits by reducing the number of empirical orbit parameters and excluding twice-per-revolution and quadruple terms proposed by Arnold et al. (2015) in the new Empirical CODE orbit model (ECOM). This model is especially effective during eclipsing periods, decreasing the standard deviation of SLR residuals from 37 to 25 mm compared to the extended empirical ECOM model. In addition, Bury et al. (2019, 2020) evaluated the impact of non-gravitational force modelling on Galileo satellites, including direct solar radiation pressure, albedo, Earth infrared radiation, and navigation antenna thrust. They found that the published Galileo metadata can account for about 97 % of the total non-gravitational perturbing forces, while the remaining portion must be absorbed by empirically estimated orbit parameters.

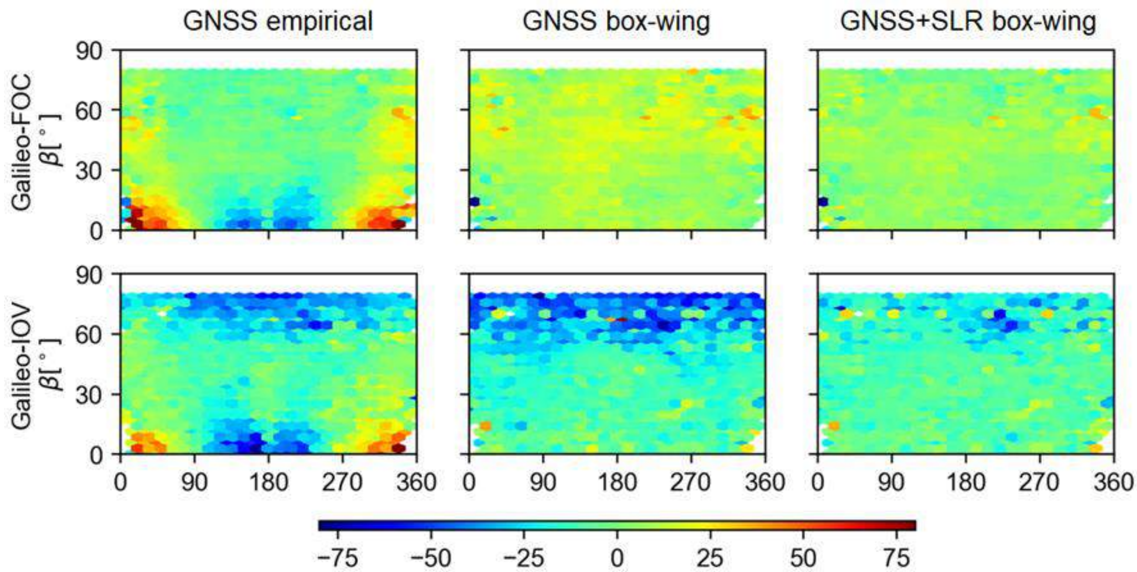

Figure 2: *Galileo orbit modelling and reducing systematic patterns – SLR residuals to Galileo orbits for the GNSS-based empirical orbit solution (left), GNSS-based box-wing orbit model solution with estimating five ECOM parameters (middle), and the combination of GNSS and SLR data with the box-wing model and estimating five ECOM parameters (right). All values are in millimeters. After Bury et al. (2021b) and Sośnica et al. (2023).*

Integrating SLR and GNSS data can lead to further improvements in orbit determination (see Fig. 2). Bury et al. (2021b) demonstrated that combining SLR and GNSS data can improve the orbits during periods when the Sun is almost perpendicular to the orbital plane, which can cause issues in orbit modelling due to large correlations between orbit parameters. However, it is important to properly weigh the SLR and GNSS observations because assuming that they are of the same quality can introduce spurious effects in determined orbits. For example, Bury et al. (2021b) down-weighted the SLR observations by a factor of four for Galileo, and Bury et al. (2022) used satellite-dependent weighting for GLONASS with even further reduced weights to obtain high-quality combined orbits. The proper combination of SLR and GNSS observations allows for space ties onboard GNSS that are independent of the local ties and errors included in the local tie measurements (Bury et al. 2021a). Co-location in space introduces new opportunities for future terrestrial reference frame realizations.

2.2. Orbital and aliasing signals in GNSS time series

The time series of geodetic parameters often have erroneous signals that can be attributed to various factors. These include (1) orbital resonances that occur due to the interaction between satellite revolution period and Earth rotation, (2) aliasing that results from sub-daily background models and parameter sampling, and (3) draconic errors due to issues with orbit modelling. GNSS-based Earth rotation parameters, sub-daily polar motion, geocenter coordinates, station coordinates derived from Precise Point Positioning (PPP), and tropospheric parameters have all been found to be affected by these errors, see Fig. 3.

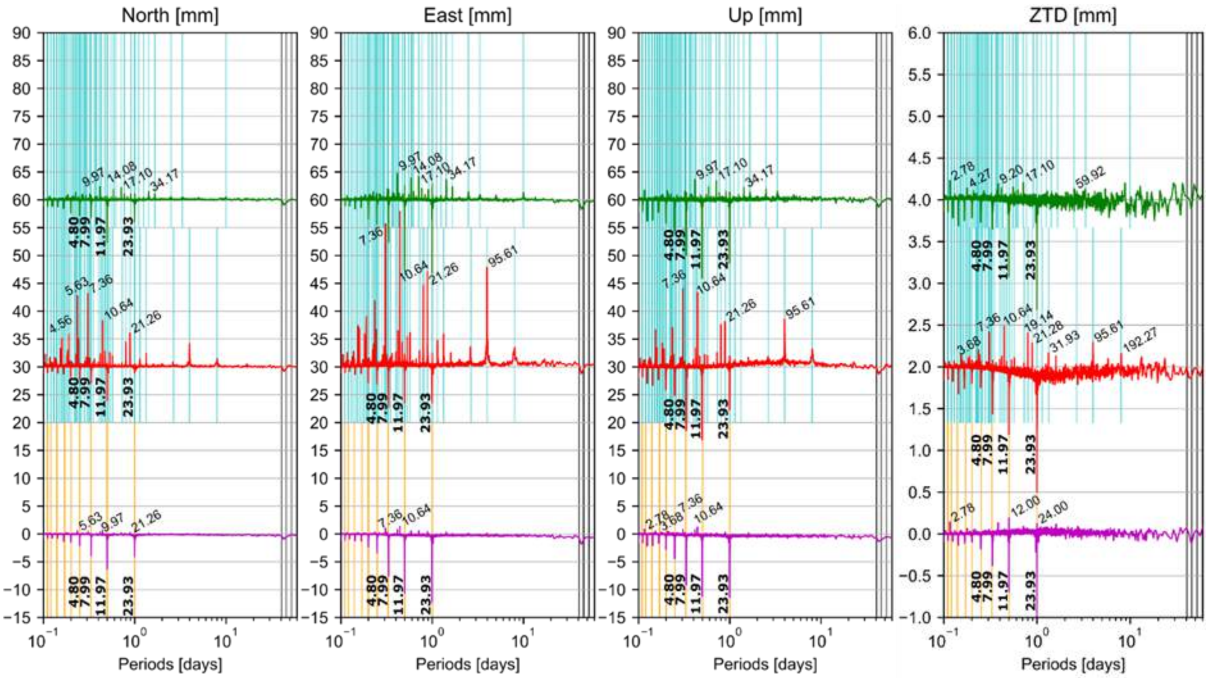

Figure 3: *Stacked differential periodograms of station coordinates for the North, East, and Up components, and zenith total delays (ZTD) corrections. Top: the difference between Galileo and GPS, middle: the difference between GLONASS and GPS, bottom: the difference between multi-GNSS and GPS. Positive values denote that the signals have larger amplitudes in system-specific solutions than in GPS-only solutions, whereas negative values denote a reduction of the signals that occurred in GPS-only solutions. Blue lines denote orbital signals for Galileo and GLONASS, whereas orange lines denote the harmonics of the sidereal day (orbital signals for GPS). Labels are in hours. After: Zajdel et al. (2022a) and Sośnica et al. (2023).*

To address these issues, Zajdel et al. (2022a) suggested multi-satellite combinations to mitigate orbital resonances. This method involves using satellites with different revolution periods to avoid the correlation between global geodetic parameter estimation intervals with satellite ground track repeatability. Improved background models can help to mitigate aliasing issues caused by high-frequency phenomena. Better sub-daily Earth rotation models based on geophysical ocean tide models or empirical models can also enhance the quality of derived geodetic parameters. Improved orbit modelling, such as using satellite macro-models with a minimum number of empirical orbit parameters, can reduce draconic errors. However, GLONASS has been found to provide lower-quality station coordinates and its contribution had to be down-weighted to avoid degrading multi-GNSS PPP solutions (Zajdel et al., 2022a).

Additionally, using different GNSS may result in inter-system biases which require proper handling for multi-GNSS time transfer and receiver clock modelling (Mikoś et al., 2023a, 2023b).

2.3. Tropospheric effects in SLR data

The accuracy of SLR results is often limited by errors in modelling the troposphere delay, which is corrected using meteorological data collected at SLR stations (Boisits et al. 2020). However, this method assumes symmetry in the atmosphere and can lead to systematic errors. To improve SLR solutions, Drożdżewski et al. (2019) proposed using numerical weather models to account for the asymmetry of the atmosphere, which improved the horizontal gradients and mapping functions used in SLR solutions. However, direct meteorological data still provided more accurate zenith delays. By using a hybrid approach with both direct meteorological data and numerical models, the pole coordinates were improved by 20 µas and became more consistent with results from other space geodetic techniques, e.g., GNSS.

To further improve SLR solutions, tropospheric biases have been proposed for estimation (Drożdżewski and Sośnica, 2021). This improves the repeatability of SLR station coordinates, changes the geocenter mean offset at the millimeter level, and substantially reduces SLR residuals to LEO satellites (Strugarek et al., 2022). Tropospheric biases are elevation-dependent and thus better suited to account for systematic errors in SLR data than range biases, which are independent of elevation angle. Therefore, estimating tropospheric biases is beneficial for SLR solutions, while estimating range biases may result in biased SLR-based parameters, especially the height component of station coordinates and the global scale (Drożdżewski and Sośnica, 2021). Some SLR stations may also be affected by barometer biases, leading to tropospheric biases, which can be mitigated through estimation (Strugarek et al., 2022).

2.4. General relativity effects acting on GNSS orbits

The validation of general relativity effects such as the Schwarzschild, Lense-Thirring, and De Sitter effects requires high-quality orbits. Sośnica et al. (2021) have developed theoretical formulas for changes in Keplerian parameters and satellite revolution periods due to these effects. The authors calculated the magnitude of periodical and secular perturbations for GNSS, LAGEOS, LARES, and geostationary orbits. The Lense-Thirring and De Sitter impact the secular rates of the ascending node, whereas the Schwarzschild effect results in measurable variations of the semi-major axis and eccentricity. Accumulating long-term GNSS solutions can further improve the confirmation of general relativistic effects.

Sośnica et al. (2022) used GPS, GLONASS, and Galileo orbits to investigate the impact of the Schwarzschild effect on the semi-major axis and eccentricity of GNSS orbits. The authors found that the Galileo satellites in eccentric orbits demonstrated a strong agreement with the theoretically derived values. Specifically, the change of the satellite semi-major axis was +28.3 and −7.8 mm when eccentric Galileo satellites were in their perigees and apogees, respectively. The mean observed semi-major offset of the full GPS, GLONASS, and Galileo constellation was −17.41 mm, resulting in a relative error versus the expected value from the theory of 0.36% (Sośnica et al., 2022). Consequently, GNSS satellites with enhanced orbit modelling significantly contribute to the understanding of fundamental physics.

3. Interactions with the IAG Commissions and GGOS

Cooperation with GGOS Committee on Performance Simulations and Architectural Trade-Offs (PLATO) has been established in terms of the conducting simulation studies for future geodetic satellites, which possibly will complement the existing LAGEOS-LARES satellite constellation. The impact of the proposed spherical geodetic satellites at different heights and inclination angles has been assessed from the perspective of gravity field parameters, Earth rotation parameters, geocenter motion, and SLR station coordinates (Najder et al. 2023).

In November 2022, ESA decided to fund a satellite mission dedicated to the co-location in space of VLBI, GNSS, SLR, and DORIS onboard one satellite – GENESIS-1 (Delva et al. 2023). GENESIS will be the first ESA mission with its major goal related to improving geodetic products and future terrestrial reference frame realization by co-location in space. Dedicated simulation studies have been conducted to assess the GPS and Galileo visibility at the GENESIS heights as well as the contribution of GENESIS to deriving global geodetic parameters in the framework of cooperation with ESA GNSS Science Advisory Committee (GSAC).

The International GNSS Service (IGS) Analysis Centre Coordinator (ACC), in the framework of IGS experimental Multi-GNSS Orbit Combination, provided the initial orbit products based on new combination procedures in the framework of the preparation of combined obits for ITRF2020. ITRF2020 is the very first reference frame realization that includes the Galileo system. In the framework of the JSG T.24 activities, several tests have been conducted to check the Galileo applicability to realize terrestrial reference frames, determination, and quality assessment of Galileo-based global geodetic parameters and inconsistencies between SLR and GNSS. Moreover, the procedures for the orbit combination were tested using SLR observations to Galileo, GLONASS, BeiDou, and QZSS together with IGS ACC (Sośnica et al. 2020; Zajdel et al. 2023), confirming the superior quality of combined Galileo orbits for IGS contribution to ITRF2020, which is of fundamental interest of IAG Commission 1. A series of intensive GNSS tracking campaigns were launched by the International Laser Ranging Service (ILRS). The ILRS data were employed for the GNSS orbit validation and SLR-GNSS co-location in space and to improve GGOS products. The quality of orbit predictions for ILRS has been assessed with the aim of improving the ILRS station performance (Najder and Sośnica 2021; Nowak et al., 2023). The topics related to identifying the systematic effects and biases in SLR data caused by tropospheric effects and improving the consistency of SLR and GNSS tropospheric products and quality of orbit predictions were studied in the framework of the cooperation with IAG JSG "Intra- and Inter-Technique Atmospheric Ties".

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Joint Study Group T.25: Combining geodetic and geophysical information for probing Earth's inner structure and its dynamics

Chair: *Robert Tenzer (Hong Kong)*

Members

Lars Sjöberg (Sweden)
Mohammad Bagherbandi (Sweden)
Carla Braitenberg (Italy)
Mirko Reguzzoni (Italy)
Aleksej Baranov (Russia)
Franck Ghomsi (Cameroon)
Róbert Čunderlík (Slovakia)
Wenjin Chen (China)

1. Activities of the group

The seismic tomography is primarily used to provide images of the Earth's inner structure based on the analysis of seismic waves due to earthquakes and (controlled) explosions. Until now, however, large parts of the world are not yet covered by seismic data. To address this problem, gravity data together with topographic, bathymetric, and lithospheric density structure models (in regions where seismic data are absent) or jointly with seismic data have been used to interpret the Earth's inner structure.

Our study group focus on studies of the lithospheric structure in different parts of the world, including the Indian Ocean, Antarctica, Africa, and Fennoscandia, and parts of the African continent. We also completed the study of a Moho geometry beneath the whole African continent based on the analysis of available seismic data. Moreover, we updated the Antarctic seismic crustal and sediment models. Selected results of activities are presented in Section 2.

Members of our study group participated with other researchers on the determination of the effective elastic thickness of the lithosphere and the lithospheric stresses (Eshagh et al., 2020; Gido et al., 2019a). We also developed and improved methods and numerical approaches to solve gravimetric forward and inverse problems in physical geodesy and geophysics.

2. Achievements and results

During the working period (2019-2023) our study group delivered several results, covering various topics in gravimetric and seismic geophysics that are summarized next. Some studies focus on development and improvement of theoretical models and numerical procedures, while most projects have been related to applications of existing numerical techniques to study and interpret the lithospheric structure, delineate major geological units as well as better understand a tectonic configuration. We also tested different methods for a gravimetric inverse modelling to estimate a Moho depth under the oceanic crust.

2.1 Theoretical and methodological studies

Chen and Tenzer (2020) modified the Parker-Oldenburg's method for the Earth's spherical approximation and developed the relevant software package. Ji et al. (2023) combined the co-seismic displacement theory with expressions describing the third-order derivatives of the gravity potential (i.e., the components of the gravity curvature). Numerical demonstration revealed that the components of the gravity curvature determined from time-variable GRACE gravity solutions could better detect co-seismic deformations associated with large earthquakes (2011, Tohoku earthquake, 9.1 Mw). Rathnayake et al. (2021) applied and compared performance of different numerical methods for a Moho depth determination under the oceanic crust from gravity data. Their comparative study was carried out for the Indian Ocean. Gido et al. (2019a) applied a gravimetric method to determine horizontal stress field due to flow in the mantle in Fennoscandia. Chuvaev et al. (2020) inspected the possibility of using cloud technologies to model the mantle convection pattern.

2.2 Interpretational and numerical studies

The study group made a significant effort to better understand the geological and tectonic configuration of various regions in West and Central Africa by using gravity, seismic, and aeromagnetic data (Pham et al., 2023; Ghomsi et al., 2021; 2022a; 2022b; 2022c; 2022d; Apeh et al., 2022). Delvaux et al. (2021) investigated the stratigraphy and subsurface structure in the Congo Basin by using seismic reflection, refraction and well data, and Kaban et al. (2021) estimated the sediment thickness in the Congo Basin.

Rathnayake et al. (2020) investigated the effect of the lateral topographic density distribution on interpretational properties of Bouguer gravity maps. Tadiello and Braitenberg (2021) used gravity data to model the alpine lithosphere affected by magmatism based on seismic tomography. Sjöberg and Bagherbandi (2020) investigated the upper mantle density and surface gravity changes in Fennoscandia by using the GRACE monthly solutions.

Our study group dedicated several studies to a Moho modeling and an estimation of the Moho uncertainties. Sjöberg and Abrehdary (2021) estimated, for instance, the uncertainty of CRUST1.0 Moho depth and density contrast. Reguzzoni et al. (2020) investigated the gravimetric contribution to the Moho estimates in the presence of vertical density variations. The Moho depth estimates for various regions were accied out by Abrehdary and Sjöberg (2020; 2021a; 2021b). Baranov (2021a; 2021b) and Baranov and Morelli (2023) updated the estimates of the sediment and crustal thickness in Antarctica, and Baranov et al. (2023b) compiled a new seismic model of the crustal thickness for Africa.

Lobkovsky et al. (2022; 2023a; 2023b; 2023c) and Gido et al. (2019b) investigated various phenomena associated with the climate change. Shebalin and Baranov (2020) and Baranov et al. (2019) investigated the effect of aftershock on ocean tide.

The lithospheric stress, strain, and displacement changes due to the Sar-e-Pol Zahab Earthquake in 2018 were investigated by Eshagh et al. (2020). Bobrov et al. (2022) studied the evolution of stress fields during the supercontinent cycle, and Baranov et al. (2023) studied the evolution of lateral tectono-physical stresses in the spherical shell convection with an immobile supercontinent. Baranov et al. (2023a) developed a global geodynamic model of the Earth, and Bobrov and Baranov (2019) carried out the study of thermo-chemical mantle convection with drifting deformable continents.

2.3 Brief summary of selected numerical studies with major results

Ghomsi et al. (2021) investigated Cameroon's geological structure by applying the gravity separation and using seismic crustal models. The regional and residual gravity anomalies obtained after applying the spectral analysis were found to be consistent with a regional tectonic configuration, highlighting structural faults, such as the Kribi-Campo Fault, the geophysical over-thrust zone between the Adamawa Plateau and the Congo Craton (Fig. 1). They applied different forward gravity modelling techniques and compared their performance my means of realistically identify known geological and tectonic units. Their results demonstrated that the forward modelling based on incorporating available geological and geophysical information improved the interpretational quality of residual and regional gravity maps for the study area. The residual gravity anomalies highlighted (Fig. 2) main sedimentary basins, the Cenozoic volcanism, Cretaceous rift system of the Benue Trough and old cratonic units (the Congo Craton, the Saharan Metacraton and the metacratonized Adamawa Plateau).

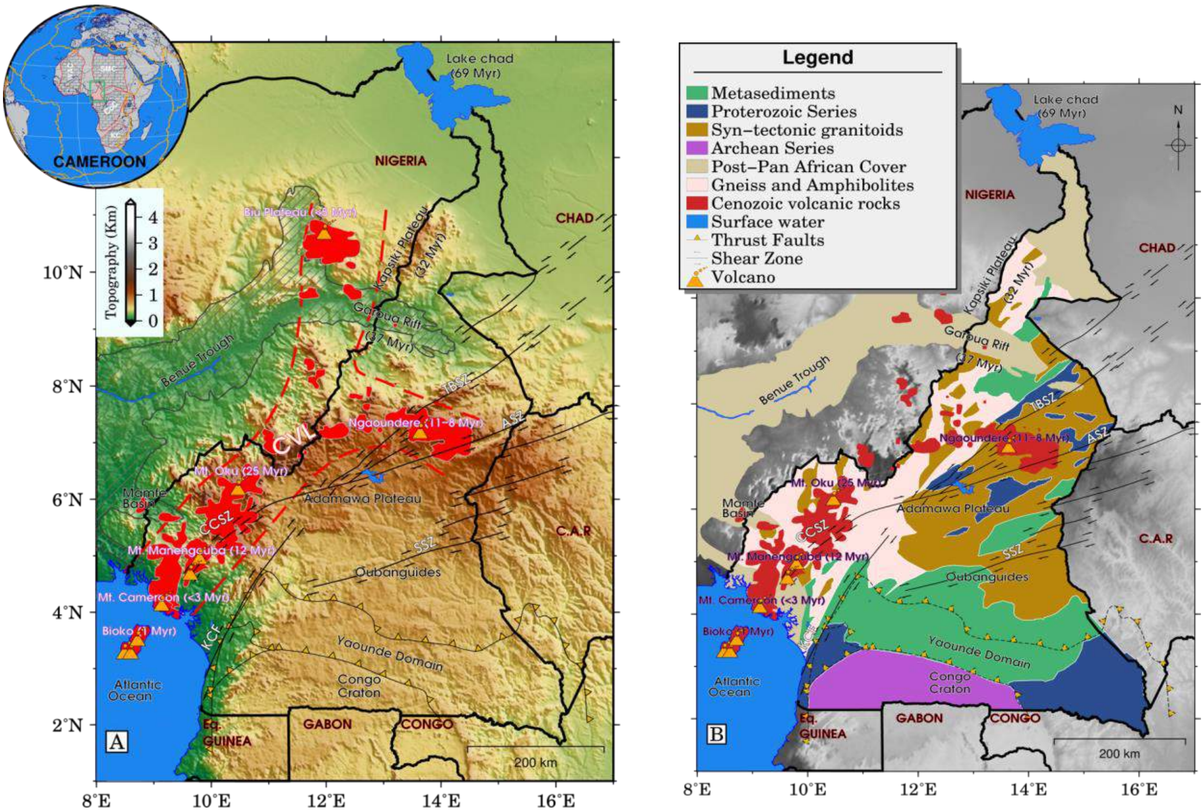

Figure 1: *Regional maps of (a) topography, and (b) geological structure of Cameroon.*

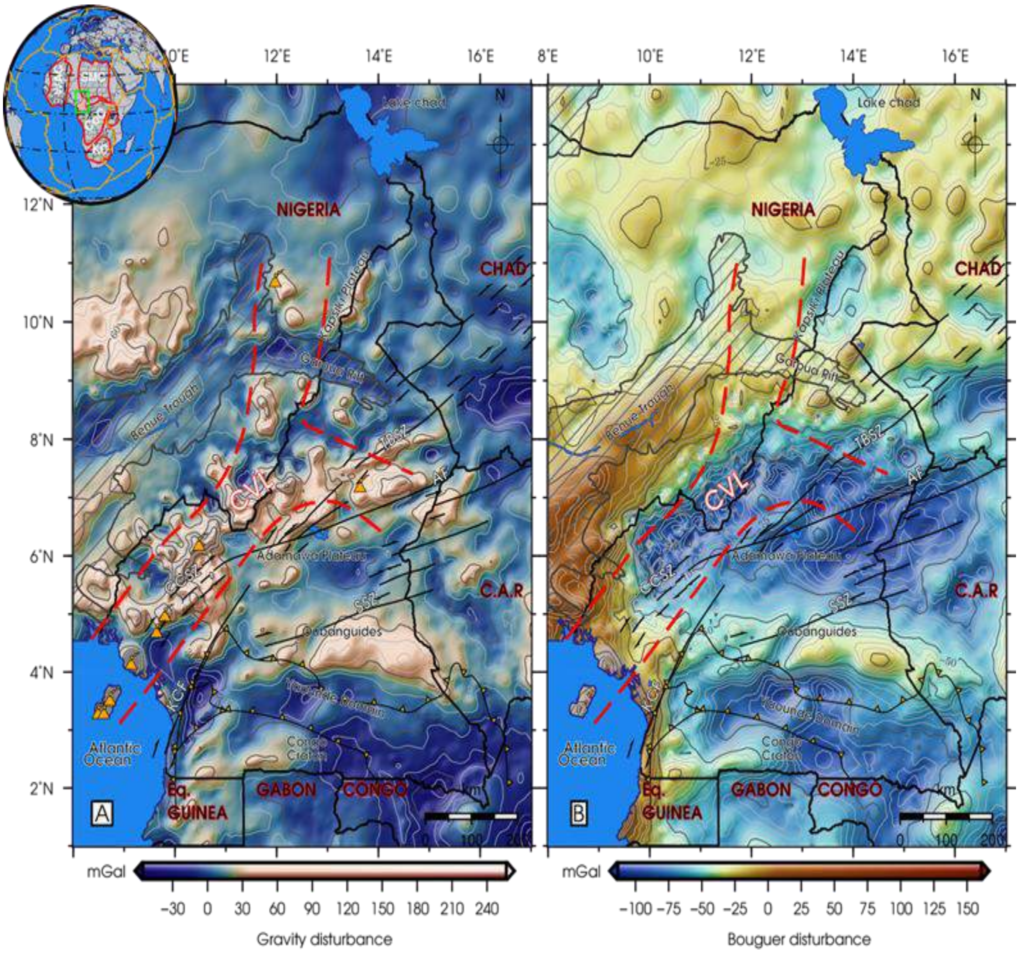

Figure 2: *Maps of: (a) the free-air gravity anomalies and (b) the Bouguer gravity anomalies.*

Abrehdary and Sjöberg (2021b) combined seismic and gravity data within Antarctica to estimate the Moho density contrast. According to their result, The Moho density contrast varies from 81 kg/m^3 in the Pacific Antarctic Ocean ridge to 579 kg/m^3 in the central continent with a general mean value of 403 kg/m^3. A Moho depth and density contrast model for ocean areas by using gravimetric-altimetry data was published by Abrehdary and Sjöberg (2020) with depths varying from 7.3 to 53 km (in Gulf of Bothnia) and density contrasts varying between 20 kg/ m^3 (north of Iceland) and 570 kg/m^3 (in the Baltic Sea). Abrehdary and Sjöberg (2021a) presented a new Moho depth model for Fennoscandia. Sjöberg and Abrehdary (2021) estimated the uncertainty of the crustal depth model CRUST1.0 from several other models, yielding standard error variations of 3.2-6 and 2-5 km for continental and oceanic crusts, respectively.

Baranov et al. (2021a) updated the seismic crustal model for Antarctica. They found large differences between East and West Antarctica, see Fig. 3. In East Antarctica, a high P-wave velocity (v_P >7 km/s) layer in the lower crust is absent. The P-wave velocity in the lower crust changes from 6.1 km/s beneath the Lambert Rift to 6.9 km/s beneath the Wilkes Basin. In West Antarctica, a thick mafic lower crust is characterized by large P-wave velocities, ranging from 7.0 km/s under the Ross Sea to 7.3 km/s under the Byrd Basin. In contrast, velocities in the lower crust beneath the Transantarctic and Ellsworth-Whitmore Mountains are ~6.8 km/s. The P-wave velocities in the upper crust in East Antarctica is within the range 5.5-6.4 km/s. The upper crust of West Antarctica is characterized by the P-wave velocities 5.6-6.3 km/s. The P-wave velocities in the middle crust vary within 5.9-6.6 km/s in East Antarctica and within 6.3-6.5 km/s in West Antarctica. A low-velocity layer (5.8-5.9 km/s) is detected at depth of ~20-25 km beneath the Princes Elizabeth Land.

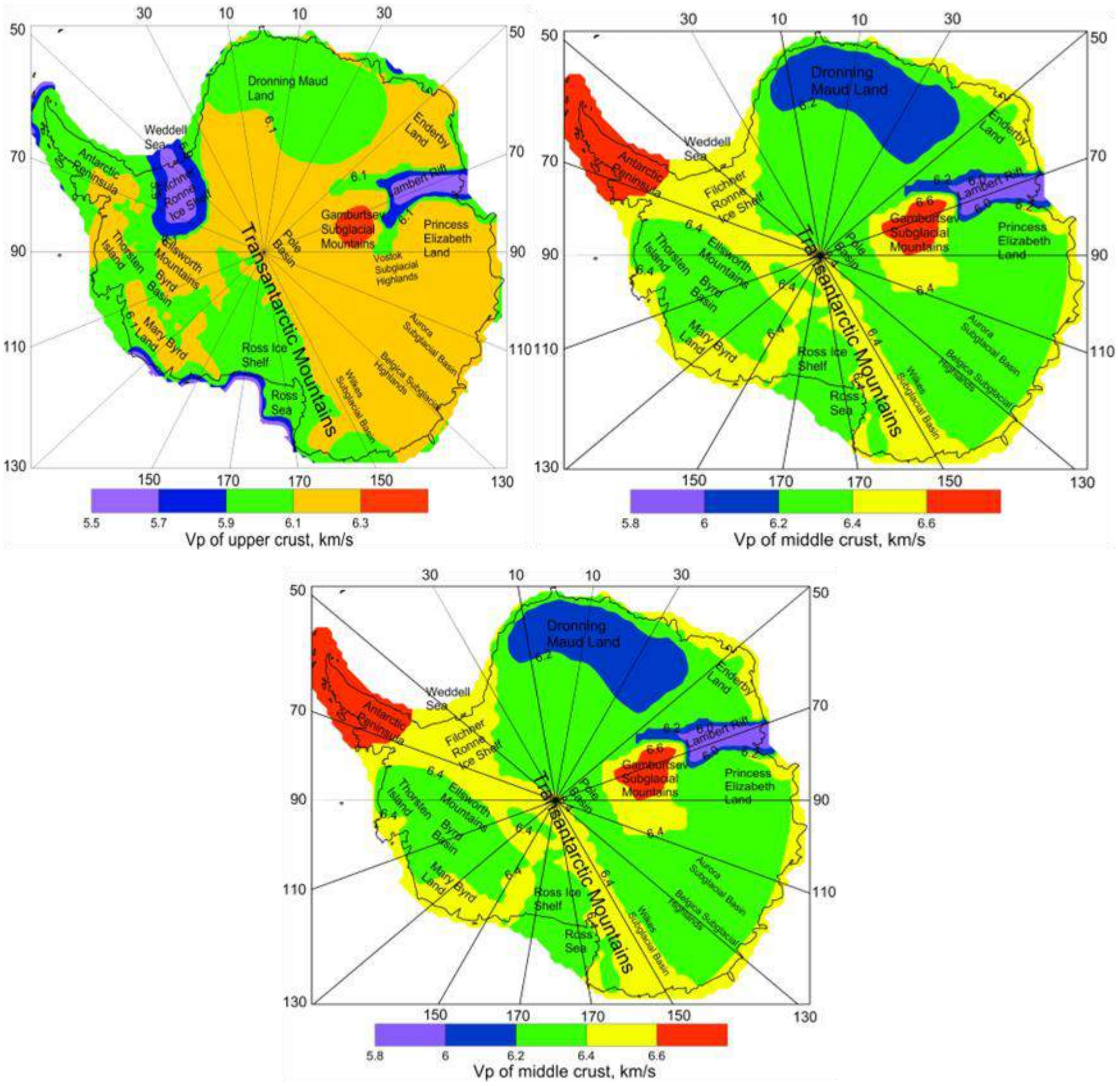

Figure 3: *P-wave velocities in the upper, middle, and lower crust. Black lines represent seismic profiles.*

Rathnayake et al. (2020) investigated the effect of lateral topographic density on interpretational properties of the Bouguer gravity maps. Their result show that the anomalous topographic density distribution modifies the Bouguer gravity pattern in some parts of the world. Even if this effect is globally mostly within ±25 mGal, large values are detected in Himalaya, Tibet, central Andes, and along the East African Rift System. They also demonstrated that errors in the Bouguer gravity data attributed to topographic density uncertainties are mostly less than ±15 mGal, but in mountainous regions could reach large values exceedingly even ±50 mGal.

Gido et al. (2019a) investigated sub-lithosphere horizontal stresses in the mantle and its secular rate, due to the dominating deformation of the crust in Fennoscandia e.g., by the ongoing mantle convection and Glacial Isostatic Adjustment (GIA) by using gravimetric method. According to Sjöberg (1983) the gravity field change in Fennoscandia reflects some geodynamical phenomena like the GIA and mantle convection. However, this gravity signal is likely mixed with other effects like plate tectonics, etc. Therefore, they used certain spherical harmonic degrees of the disturbing potential to filter the gravity signals related to the lower mantle and core masses. Bowin (2000) model shows that the spherical harmonic degrees between 5 and 40 belong to about 100 to 1600 km depth, where the asthenosphere and the mantle are located. Therefore, they used this harmonic window (i.e., the degrees 5 to

40) to determine the horizontal stress. Generally, there are different geodynamical phenomena those can be the reasons for the current horizontal stress in the study region such as the mantle convection, horizontal and vertical land motions due to plate tectonics, and the GIA, which makes it very complicated to separate and distinguish gravity signals attributed to individual phenomena. To prove the outcomes of Bowin's model, they performed a correlation analysis by using a land uplift model. Their result revealed that the spherical harmonic degrees between 5 to 40 have the highest correlation (0.87) between land uplift and the obtained horizontal stress, which support the use of degrees 5 to 40 to determine the horizontal stress in this study. The main outcome of their study is demonstrated in Fig. 4. The secular rate of the sub-crustal horizontal stress obtained from GRACE monthly solutions is plotted in Fig. 4a. As seen, the GNSS stations outside the uplift dome experience more horizontal stress changes than the stations inside the dome. Generally, for regions where the geoid goes up, mass increases, and it probably also reflects mass transport from lower layers of the Earth (i.e., sub-crustal mass transportation) and erosion phenomena. The likely reason that the stress changes more in the periphery region is that the thinner lithosphere produces higher stress change, which is due to less flexure of the lithosphere and erosion. Furthermore, Fig. 1c shows that there is significant correlation between the secular rate of the stress and seismic activities in Fennoscandia.

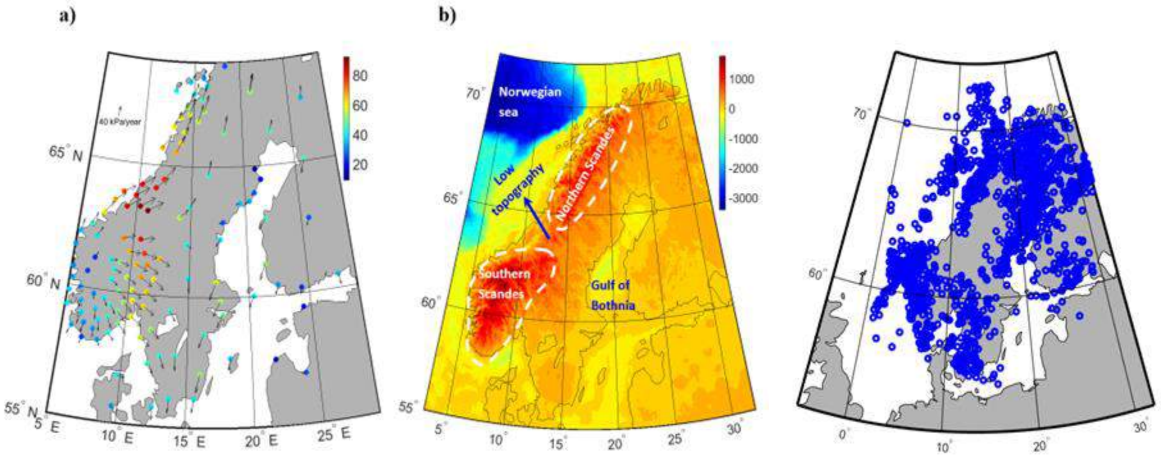

Figure 4: *a) Secular rate of sub-crustal horizontal stress due to mantle convection (tectonics). Secular rates of the horizontal stress are shown as colour circles (kPa/year) and direction of the horizontal stress changes with black arrows (mm/year), b) topography/bathymetry of Fennoscandia using DTM2006 (Pavlis et al. 2007) up to degree and order 2160 (metre), and c) shows seismic activity for 10 years (2007-2017) using FENTEC (Finnish Institute of Seismology, University of Helsinki).*

Sjöberg and Bagherbandi (2020) used the GRACE monthly solutions over the period 2003-2016 to estimate the upper mantle density (with a mean value of 3402.5 kg/m^3) and a surface gravity change of -0.172 μGal/mm of uplift in Fennoscandia.

Gido et al. (2019b) studied permafrost thawing and its associated gravity changes in terms of ground water storage (GWS) changes, and organic material changes have been studied by using the GRACE solutions and additional satellite and ground-based observations in the northern high-latitude regions. The estimation of permafrost changes in this region requires combining information from various sources, particularly by using the gravity field change, surface temperature change, and GIA. The most significant factor for careful monitoring of this phenomena is its possible contribution for releasing an additional enormous amount of greenhouse gases emitted to the atmosphere, most importantly the carbon dioxide (CO_2) and the methane that are currently stored in the frozen ground. Hence, studying thawing permafrost is very important, not only from a perspective of localized geo-hazard such as erosion, damage to buildings and infrastructure but also with respect to its possible global impact due to greenhouse gas emissions.

Bagherbandi and Gido (submitted) studied the relationship between the isostatic balance and seismicity, and probable main reasons of geodynamics processes, e.g., seismic activities, by analysing the isostatic state in the study area covering parts of Northeast Africa and Arabian Peninsula by using a combined Moho model. Moreover, they estimated the sub-crustal stress and its relationship with seismicity by using the gravimetric method introduced in Gido et al. (2019a). The most important phenomenon that occurs in this region is the East African continental rifting (Fig. 5), mainly caused by the horizontal extensional forces in the lithosphere. Moreover, there is several active volcanoes. The movement of the African plates, i.e., Nubian and Somali, can lead potentially to the formation of new plate boundaries in the study area, which is the reason for such seismic activities in the form of earthquakes and volcanism. The so often-called "African Superswell" phenomena, i.e., the raise up of the mantle plume and consequently causes the rift, can also result in land uplift and volcanism (Fig. 6). The main goal of their study was to better understand how isostasy and Moho parameters (depth and density contrast) explain the rift valley configuration.

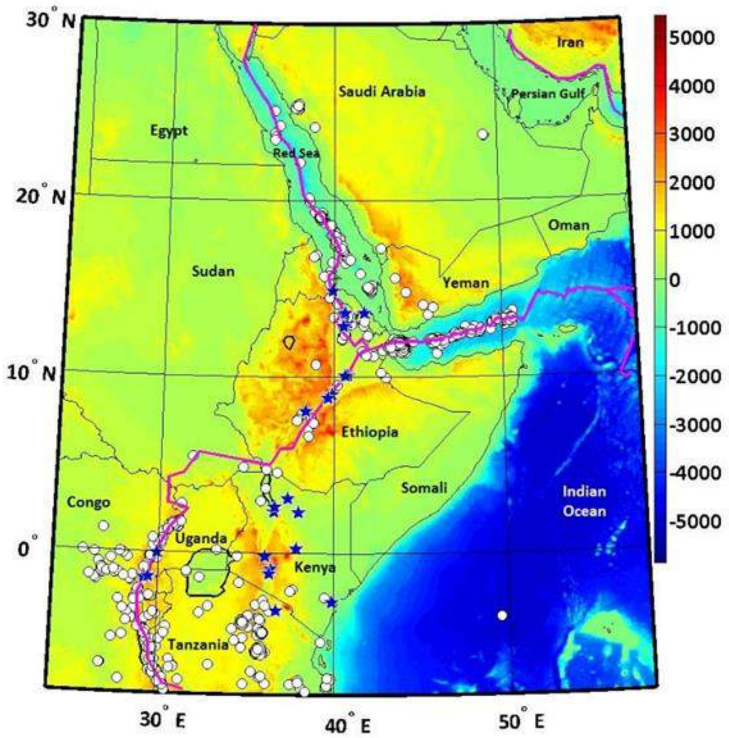

Figure 5: *General map of the study area showing ETOPO1 digital elevation model, main plate tectonic boundaries (solid magenta), volcanic areas (blue stars), and earthquakes larger than 4 Richter magnitude scale between 2008-2018 (white colour circles).*

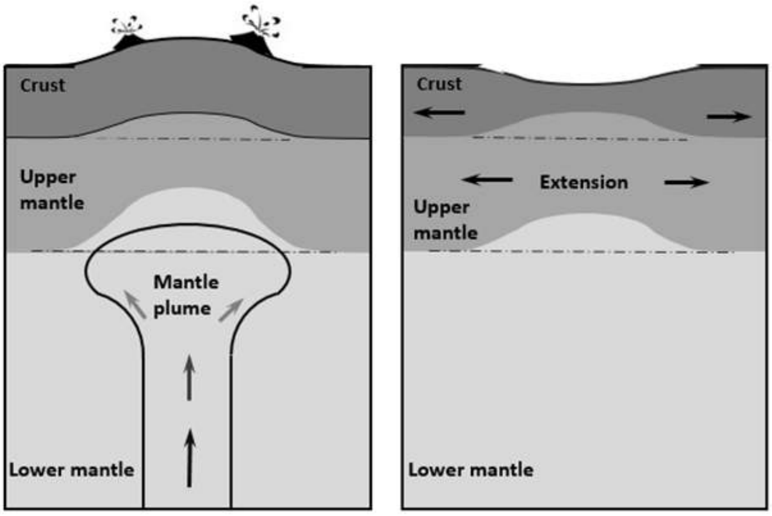

Figure 6*:* *Schematic of: (**a**) a mantle plume (active rifting), and (**b**) an extension-related rift (passive rifting, right) in the African rift region (revised after Merle 2011).*

Kaban et al. (2021) investigated the sediment structure in the Congo Basin. They presented a map of sediment thickness for the whole basin based on the inversion of the decompensated gravity anomalies. Contrary to the conventional Bouguer or isostatic gravity anomalies, the effect of the isostatic compensation of sediments is reduced in the decompensated anomalies, which provides a possibility to recover the full effect of low-density sediments. The calculated decompensated correction reaches ±70 mGal and exceeds the amplitude of isostatic anomalies, especially at the long wavelengths. The final decompensated anomalies are negative over the whole basin and their pattern closely mimics a tectonic configuration. By inverting these anomalies with the predefined density-depth relationship, they obtained the sedimentary thickness map for the whole Congo Basin. According to their results, the maximum basement depth exceeding 10 km is found in the Lokoro Basin and basins in the South. In the Lomami Basin, thickness of sediments reaches about 6.5 km. They also detected a new deep basin adjacent to the Lokonia High (on the SW side) that they proposed to name as the Salonga Basin.

Tadiello and Braitenberg (2021) used gravity data to create a 3D lithosphere density model based on a high-resolution seismic tomography model. Their results demonstrated a highly complex density distribution in good agreement with the different geological domains of the Alpine area represented by the European Plate, the Adriatic Plate, and the Tyrrhenian Basin. The Adriatic-derived terrains (Southalpine and Austroalpine) of the Alps are typically denser (2850 kg/m^{-3}, whilst the Alpine zone, composed of terrains of European provenance (Helvetic and Tauern Window), presents lower density values (2750 kg/m^{-3}). They also try to explain the existence of a well-known positive gravity anomaly located south of Dolomites. Based on the modelled density, they suggested that the anomaly is related to two different sources; the first involves the middle crust below the gravity anomaly and is represented by localized mushroom-shaped bodies interpreted as magmatic intrusions, while a second wider density anomaly affects the lower crust of the southern Alpine realm and could correspond to a mafic and ultramafic magmatic underplating (gabbro and related cumulates) developed during Palaeozoic extension.

Delvaux et al. (2021) reconstructed the stratigraphy and tectonic evolution of the Congo Basin by using all available and geological seismic data (reflection and refraction seismic, borehole, and field data). They interpreted almost 2600 km of seismic reflection profiles and well log data located inside the central area of the basin (the “Cuvette Centrale”). Their results indicate that the depth to the basement varies quite significantly, defining a series of structural highs and depocenters that developed throughout the history of the basin. The major controlling factors for the development of the Congo Basin are, besides the deep geodynamic processes, the inherited heterogeneity of the pre-Neoproterozoic basement, the tectonic evolution of Rodinia, Gondwana, and Pangea amalgamation and breakup, and environmental conditions influenced by the drifting through the South Pole towards its present-day equatorial position and global climatic fluctuations between icehouse and greenhouse conditions.

Bobrov and Baranov (2019) and Bobrov et al. (2022) built 2D mantle models of thermos-chemical convection with non-Newtonian rheology and phase transitions, in the presence of floating deformable continents and oceanic crust. All the stages of super-continent cycle were studied: assembly, evolution of supercontinent, its breakup and divergence of continents. The results demonstrated certain irregularities of supercontinent cycle. Typical shear stresses in the mantle are less than 30 MPa; in the subduction zones and on the continent borders they are 100–250 MPa. Before the breakup, maximum shear stress generated in the supercontinent can reach 200 MPa.

Baranov et al. (2019) and Shebalin and Baranov (2020) revealed the connection between ocean tides and seismicity. A total of 16 sequences of M ≥6 aftershocks of Kamchatka and 15 sequences of M ≥6 aftershocks of New Zealand and background seismicity were examined. The heights of the ocean tides at various locations were modelled by using FES 2004. An increase in aftershock rate was observed by more than two times at high water after main M≥6 shocks in Kamchatka. For New Zealand, they also observed an increase in aftershock rate at high water after thrust type main shocks with M ≥6. After normal-faulting, main shocks have the tendency of the rate increasing at low water. For the aftershocks of the strike slip, main shocks have a less evident impact of the ocean tides on their rate. This suggests two main mechanisms of the impact of ocean tides on seismicity rate, an increase in pore pressure at high water, or a decrease in normal stress at low water, both resulting in a decrease of the effective friction in the fault zone.

Chuvaev et al. (2020) and Baranov et al. (2023a) investigated the spherical mantle convection based on the SMEAN2 seismic tomography model. Results demonstrated the structure of mantle flows in modern Earth, see Fig. 7. Under continents, with exception of East Africa, Southeast and East Asia, and West Antarctica, there are downward mantle flows and negative temperature anomalies. The descending mantle flow under Eurasia and the ascending flow under the Arctic push North Eurasia to the south is causing stresses in the crust and orogenic processes within Eurasia. Another powerful downward mantle flow occurs between North and South America along the Caribbean subduction zone. Ancient cratons are characterized by cold regions in the mantle beneath them. Under East Africa, there is a positive temperature anomaly and an upward mantle flow, responsible for a formation of the East African Rift System. A similar anomaly was also identified in the Baikal rift zone. A global ascending mantle flows are formed under the Pacific Ocean and South Africa. For Antarctica, an explanation was obtained for the existence of the West Antarctic Rift System, which contains one of the largest and least known volcanic provinces on Earth, which is consistent with the measured increased surface heat flow and modern volcanism here. The increased heat flow and volcanoes in this region are causing instability and accelerating the flow of glaciers from the West Antarctic Ice Sheet into the ocean, which could lead to a significant rise in global sea level.

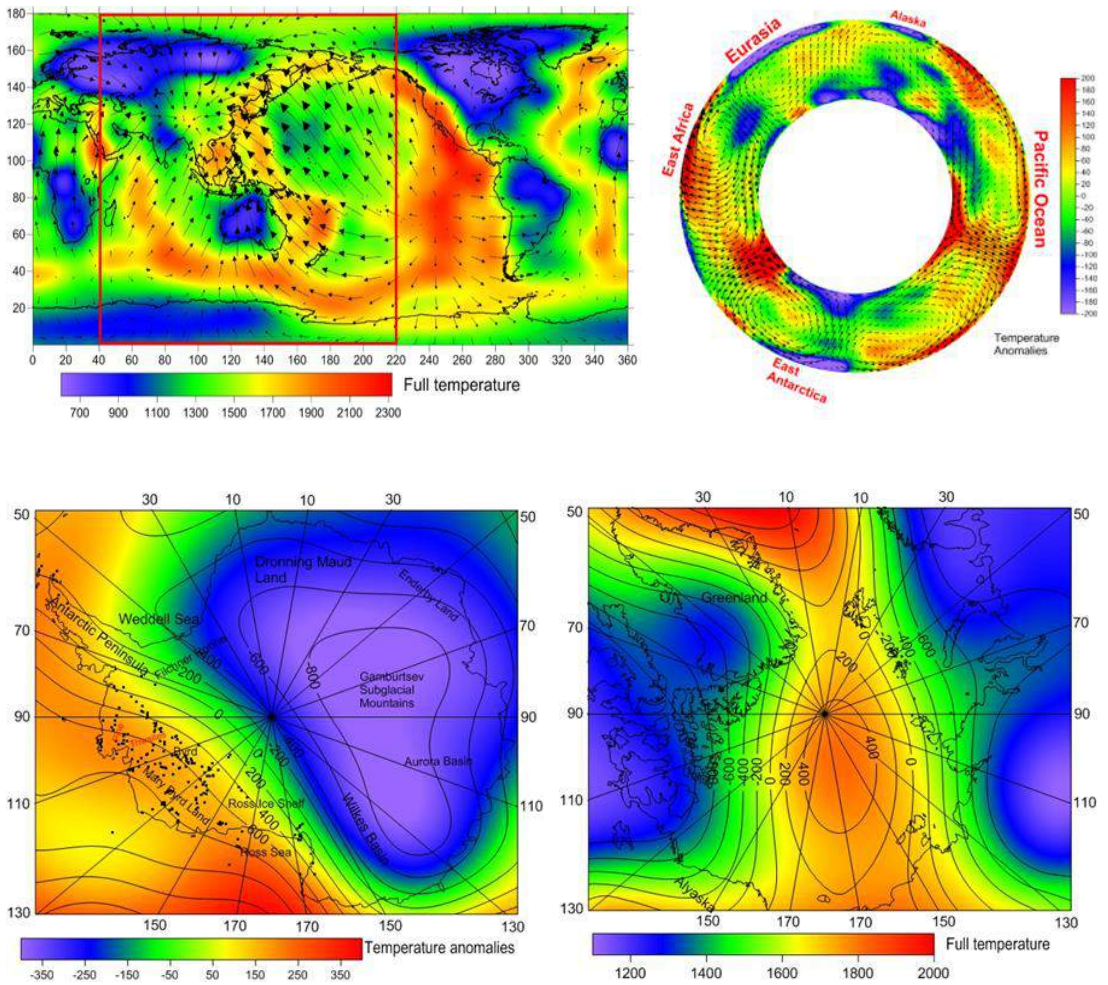

Figure 7: *Global mantle model: **a**) Full mantle temperature and the flow velocities at 100 km depth. The contours of the continents are shown in black. The red line is the cross section of the Earth at the longitude of 40 degrees east and 220 degrees east, respectively; **b**) Mantle temperature variations and flow velocity distributions in the section of the Earth at the longitude of 40 degrees east and 220 degrees east, respectively. **c**) Mantle temperature variations for the Antarctic region at a depth of 100 km. Black outlines show dynamic topography in meters, black dots show volcanoes. **d**) Full mantle temperature for the Arctic region at a depth of 100 km. Black outlines show dynamic topography in meters.*

Baranov et al. (2021b) and Baranov and Morelli (2023) built a new three-layer sediment model for Antarctica based on seismic, relief (BEDMACHINE), radar, gravity, and magnetic data. Their results revealed significant sediment accumulations in Antarctica with several types of sedimentary basins: parts of the Beacon Supergroup and more recent rifting basins (Fig. 8). West Antarctica has wide sedimentary basins: the Ross Basin (thickness 1-6 km), the Filchner-Ronne Basin (2-12 km) with continuations into East Antarctica, the Bentley Subglacial Trench and the Byrd Basin (2-4 km). The deepest Filchner-Ronne Basin has a complex structure with multi-layered sediments. East Antarctica is characterized by vast sedimentary basins such as the Pensacola-Pole (1-2 km), Coats Land (1-3 km), Dronning Maud Land (1-2 km), Vostok (2-7 km), Aurora (1-3 km), Astrolabe (2-4 km), Adventure (2-4 km), and Wilkes (1-3 km) Basins, along with narrow deep rifts filled by sediments: JutulStraumen (1-2 km), Lambert (2-8 km), Scott, Denman, Vanderford and Totten (1-2 km) rifts. An average thickness of sediments for the whole continent is about 0.77 km. The new model, ANTASed, represents significant improvement over CRUST1.0 for Antarctica and revealed new sedimentary basins. Differences between ANTASed and CRUST 1.0 reach +12/-3 km. Dronning Maud Land, Bentley, and Byrd Basins belong to the Beacon

Supergroup, while more complex and thicker Ross, Lambert and Filchner-Ronne Basins contain sediments from Beacon Supergroup in the middle or lower layer, respectively. Other sedimentary basins with more moderate velocities possibly belong to the East Antarctic Rift System which formed later during Gondwana breakup.

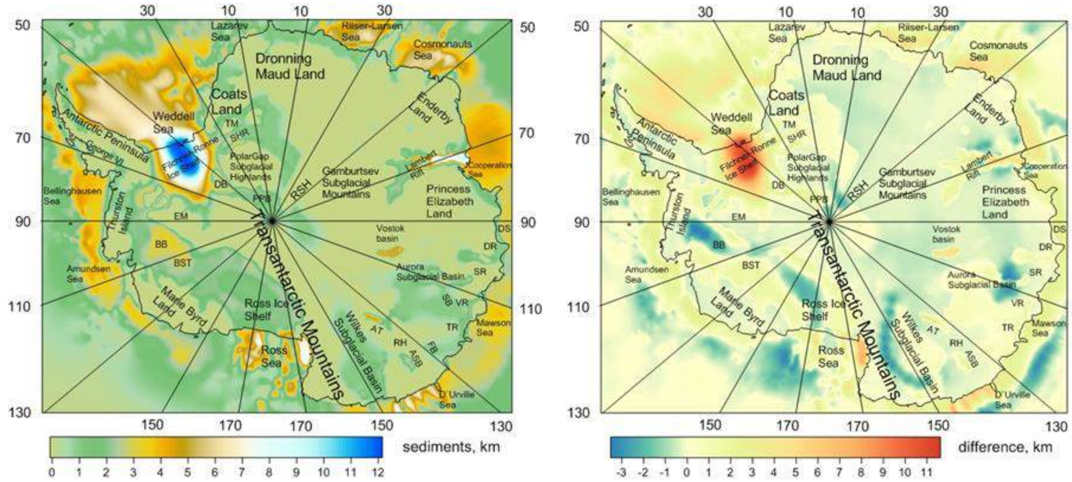

Figure 8: ***a****) Map of sediment thickness for Antarctica and surroundings (ANTASed), and* ***b****) difference between ANTASed and the CRUST1.0 model (Laske et al., 2013).*

Lobkovsky et al. (2022, 2023a, 2023b, 2023c) revealed a connection between rapid climate warning and ice shelf collapse in Antarctica with geodynamical processes and strong earthquakes in subduction zones. A correlation was observed between changes in the level of Earth's seismic activity and increments of the atmospheric methane concentration over the past 40 years. Trigger mechanisms are proposed for methane emissions, and glacier collapse in Polar Regions. These mechanisms are due to deformation waves caused by large earthquakes in subduction zones, located near the Polar Regions: the Aleutian and Kuril-Kamchatka subduction zones, closest to the Arctic, and the Antarctica–Chilean and Kermadec–Macquarie subduction zones. Disturbances of the lithosphere are transmitted over the distances of 2000–4000 km and more at a speed of about 100 km/year. Additional stresses associated with them come to the Arctic and Antarctica several decades after the occurrence of large earthquakes. In the Arctic zone, additional stresses affect the low-permeability structure of gas bearing sedimentary strata causing increased methane emission and climate warming. In West Antarctica deformation waves could trigger the acceleration and intensive collapse of West Antarctic glaciers, which is being observed since 1970s. These waves are also capable of activating dormant volcanoes located under the sheet glaciers of West Antarctica, leading to increase in heat flux, melting of ice at the glaciers' base and their accelerated sliding towards the ocean, as happens with the Thwaites Glacier.

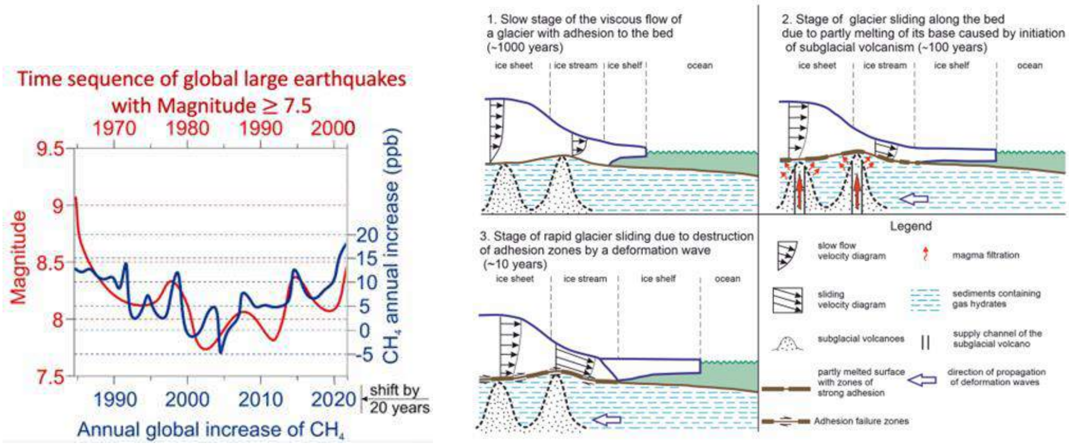

Figure 9*:* ***a****) Correlation between changes in the Earth's seismic activity and variations in the atmospheric methane concentration. Blue line shows the envelope curve for the change in the average annual increments of methane concentration during 1984–2022. Red line corresponds to variation in the Earth's seismic activity level during 1964–2002; and* ***b****) Different modes of ice sheet movement in West Antarctica.*

Baranov et al. (2023c) investigated the evolution of horizontal stress fields after implementing a supercontinent into a spherical mantle model with phase transitions, the temperature- and pressure-dependent rheology, while assuming that the mantle is heated from the base and from within. The supercontinent covered one third of Earth`s surface and it is modelled as a non-deformable, highly viscous immobile lid with respect to the ambient mantle and it is abruptly imposed on well-developed mantle convection. After implementation of the supercontinent, the mantle flow is re-arranged and a group of upwelling mantle plumes is formed under the supercontinent and their hot heads increase in size due to the heat-insulating effect of the supercontinent, while quasi-linear subduction zones increase in the oceanic region. As a result, the average temperature of the area under the supercontinent rises over time and becomes higher than the average temperature of the suboceanic area, where cold descending mantle flows intensify. Formed under the supercontinent, mantle plumes dramatically change the stress pattern in the super-continental area producing tensional stresses in the supercontinent and over-lithostatic compressive horizontal stresses in the subcontinent mantle. Tensile over-lithostatic horizontal stresses inside the supercontinent are about (25-50) MPa, whereas beneath a supercontinent we recognize the over-lithostatic compressive horizontal stresses in the subcontinent mantle of about (20-60) MPa.

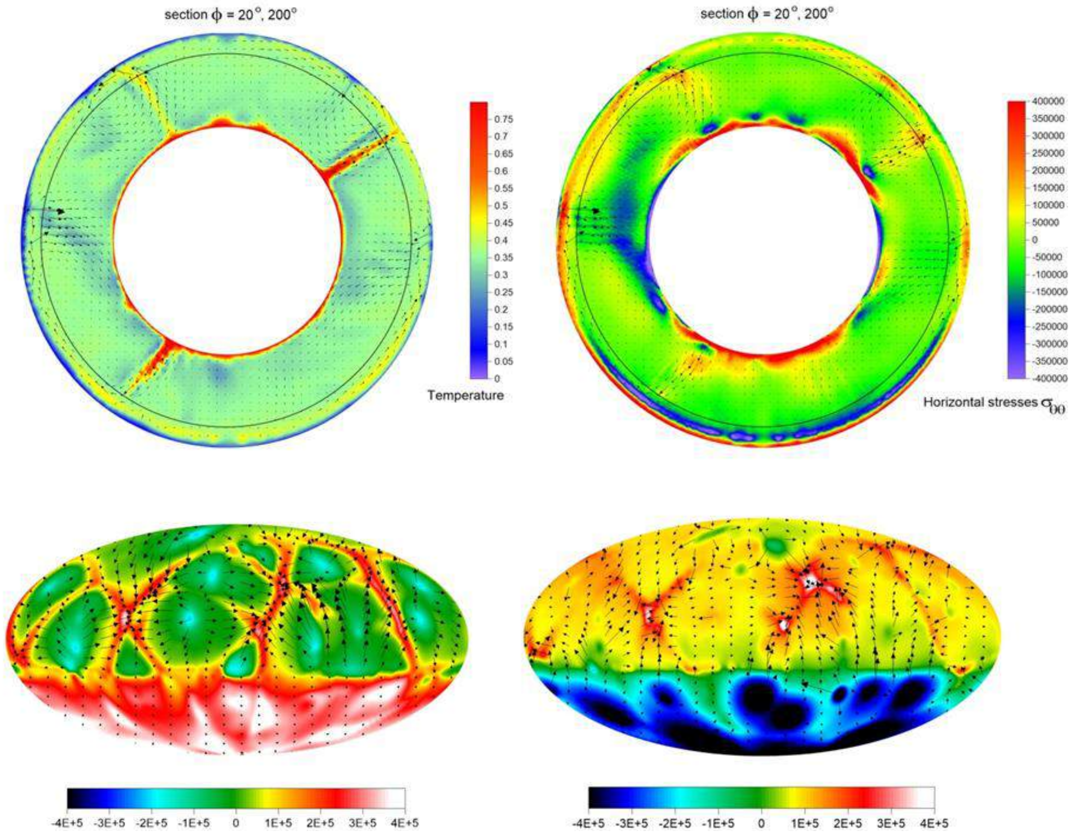

Figure 10*: Mantle model, continent thickness is 200 km the stage t = 160 Ma. From top to bottom: (**a**) section φ =20^o and 200^o the spatial distribution of the dimensionless temperature, the flow velocities are shown by the black arrows; (**b**) section φ =20^o and 200^o the field of the dimensionless normal horizontal stress $\sigma_{\theta\theta}$ with flow velocities. (**c**) section on depth of 100 km, the field of the dimensionless normal horizontal stress $\sigma_{\theta\theta}$; (**d**) section on depth of 300 km, the field of the dimensionless normal horizontal stress $\sigma_{\theta\theta}$.*

Baranov et al. (2023b) developed a new Moho model for Africa based on seismic, relief, and other geophysical data. The result revealed considerable Moho depth variations, with values ranging from 14-20 km for the Afar Triple Junction and Turkana Lake to 46 km beneath the Rif Mountains, parts of the Ethiopian Plateaus, and the Namaqua-Natal Belt. A localized Moho deepening (~44 km) was found beneath the western and eastern blocks of the Congo Craton, the central part of Victoria Lake, the Rehoboth Province, the eastern part of the Kaapvaal Craton, and the Irumide Belt. A shallow Moho depth is detected beneath wide areas in North, Central, and East Africa, particularly along the North Africa coast (24-30 km), the Mauritanian Belt (26-30 km), the West and Central African Rift System (30-32 km), the Benue Trough (24-28 km) and beneath the Rwenzori Mountains (26-30 km) and the southern part of Somali Plate (22-26 km).

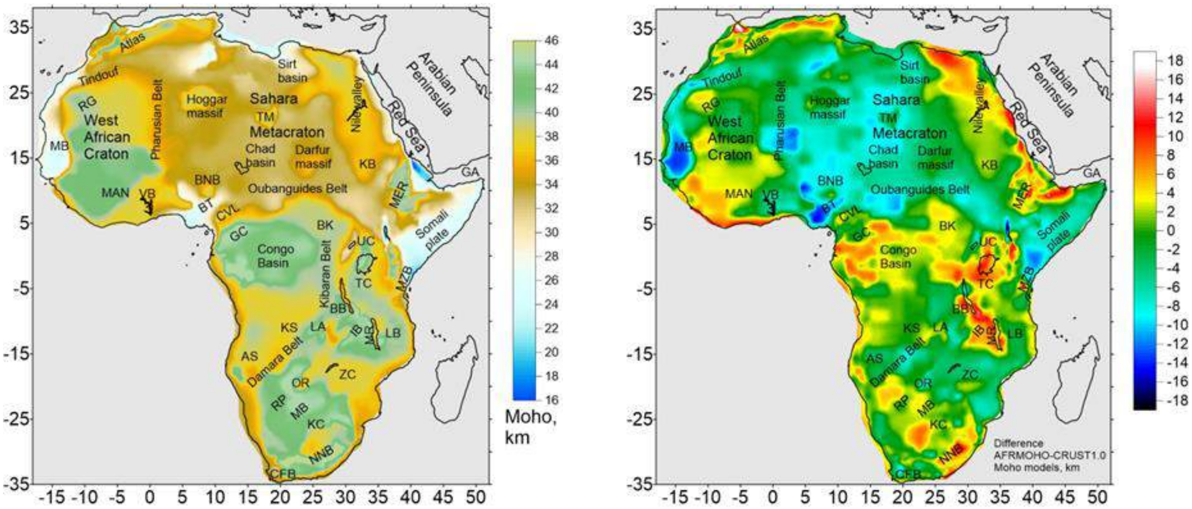

Figure 11*:* ***a****) The AFRAMOHO African Moho mode, and.* ***b****) The Moho depth differences between the AFRAMOHO and CRUST 1.0 models.*

Dashtbazi et al. (2023) studied a high-resolution global Moho model by combining gravimetric and seismic data and applying spectral combination methods. They combined seismic and isostatic models by using the Butterworth filter to compile the Moho depth model globally on a 1°×1° grid. They assessed the performance of the Butterworth and spectral combination techniques for the isostatic-seismic Moho depth modelling on a global scale. In addition, they investigated a possibility of developing a global Moho depth model with a high resolution based on the principle that the gravity information could be used to interpolate the Moho geometry in regions where seismic data coverage is sparse, irregular, or otherwise insufficient. Despite the idea of using gravity data to interpolate a detailed Moho pattern between irregularly or sparsely distributed seismic stations and profiles is not new, until now it has been applied exclusively only in local, regional, and (some) continental-scale studies. Dashtbazi et al. (2023) applied it globally and assessed the performance of two techniques by comparing their results with the high-quality seismic Moho depth estimates in the United States and Eurasia as well as in some other parts of the world characterized by a complex tectonic configuration (i.e., the Makran subduction zone).

The high-resolution Moho depth obtained by applying the Butterworth filter varies between 75 and 3.5 km, with a mean of 26.5 km and a standard deviation of 12.5 km. The corresponding continental and oceanic mean Moho depths are 37.2 and 15.8 km, respectively. For the spectral combination method, the Moho depth variations are between 75.6 and 4.5 km, with a mean of 24.7 km and a standard deviation of 11.0 km. The corresponding continental and oceanic mean Moho depths are 37.3 and 18.7 km, respectively. The presented results in Fig. 12 are satisfactory and close to the regional Moho depth models that we used for the validation. The newly developed high-resolution Moho models could be used, for instance, to study subduction zones, where the geometry and physical characteristics (such as a crust-mantle density contrast) of the Moho interface vary significantly even on a local scale.

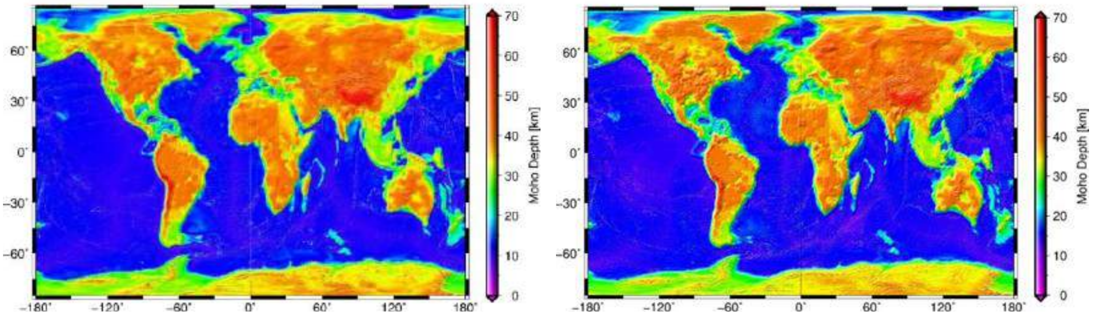

Figure 12: Global Moho depth models: (Left) the HRCM model obtained by applying the Butterworth filter (with the resolution of 5'×5'), and (Right) the HRCM model obtained by using the spectral combination method (with the resolution of 5'×5').

For validation, some regional Moho models were used to assess the accuracy of the obtained high-resolution Moho solutions. The test areas are Eurasia, Europe, Fennoscandia, Makran (in Iran), and the US. The Moho models are provided by Stolk et al. (2013), Grad et al. (2009), Luosto (1997), Abdollahi et al. (2018), and Zhang et al. (2020), respectively. Table 1 summarizes statistics of the Moho depth differences between both results and validation models. The comparison shows that the RMS of Moho depth differences varies between 1.7 and 4.7 km when using the Butterworth filter and between 0.41 and 4.1 km when employing the spectral combination. One can note that both HRCM solutions were resampled from a 5'×5' to 1°×1° grid to become compatible with other models used for the validation. It is important to note that there are some substantial differences in Europe between the Eurasian Moho model (Stolk et al., 2013) and the European Plate Moho model (Grad et al., 2009). These differences are due to applying different methods and partially also due to some differences between seismic datasets used to compile these two models. We, therefore, used both models in our comparison.

Table 1. *Statistics of the Moho depth differences between the high-resolution Moho models and the continental and regional Moho depth models. Unit: km.*

Method	Statistics	Eurasia	Europe	Fennoscandia	Makran	US
Butterworth	Max	37.8	20.7	8.6	19.5	39.8
	Mean	0.8	1.1	-1.2	-2.4	-1.1
	Min	-23.1	-27.6	-15.6	-46.6	-13.4
	RMS	2.9	1.7	2.8	4.7	1.9
Spectral Combination	Max	38.1	15.6	12.8	14.2	39.5
	Mean	-0.7	-1.1	-0.1	-1.01	-2.0
	Min	-20.8	-19.1	-14.1	-46.6	-13.0
	RMS	2.4	0.4	2.9	4.1	2.1

Bagherbandi et al. (2022) inferred the Earth's mantle viscosity from the geoid anomaly and vertical land motions due to the Earth's mass redistribution deglaciation in Greenland. The viscoelastic responses of the Earth's crust (on time scales of a few thousand years) due to deglaciation are important observables to estimate mantle viscosity. They used a correlation analysis approach to find the best harmonic window of the geoid (i.e., geoid anomaly that shows the remaining uplift to isostatic equilibrium) so that the truncated geoid reveals maximum correlation with the land uplift rates beneath the Greenland lithosphere. However, the GIA-related gravity field has been mixed with other gravitational signals that can be removed using the proposed approach in this study. They calculated a combined land uplift rate using the land uplift rate obtained from GNET (Khan et al., 2016), GIA models (ICE-6G (VM5a) model provided by Peltier et al., 2013 and Caron et al., 2018), and the GRACE data in Greenland. We know that the uncertainty is also significantly large in the glaciated regions.

Hence, they integrated these data because the uncertainties, patterns and rates of the land uplift models are different in Greenland. The combined uplift rate at the GNET sites is shown in Fig. 13. In addition, a comparison of the Kalman filtering results and the uplift rates obtained from GRACE, GPS and the GIA model are shown in Fig. 14. As seen, the forward and backward Kalman filtering methods provide the same results because the uncertainties of the initial values are low. The uncertainty of the estimated uplift rates is presented in Fig. 15. Using the Kalman filtering approach, the obtained uplift rate error varies 0.48 to 0.07 mm/year with a mean value of 0.20 and a standard deviation of 0.10 mm/year. The large errors can be observed in the stations experiencing extreme decreasing ice mass loss (e.g., SRMP, RINK, KAGA, KBUG, HEL2, and KUAQ stations).

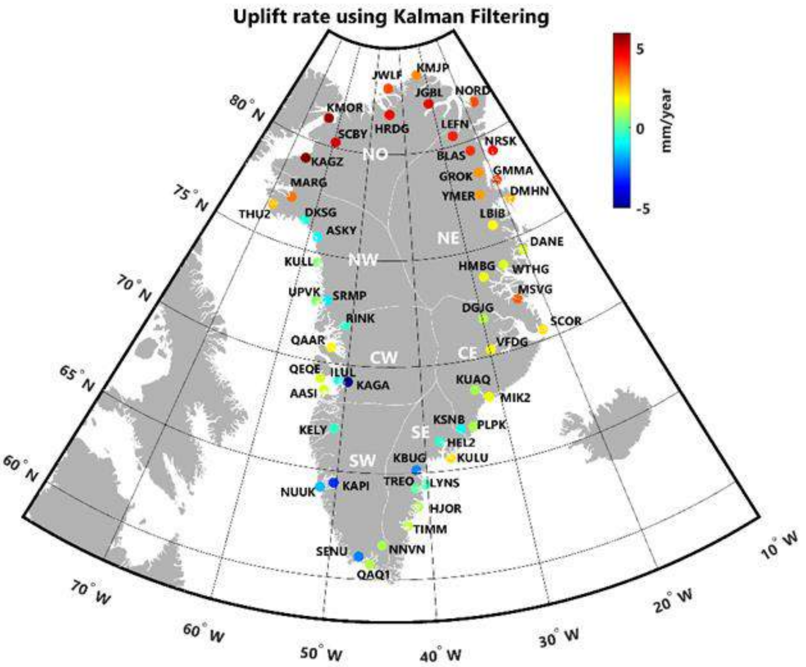

Figure 13: *Estimated combined uplift rates at the GNET sites using Kalman filtering (mm/year).*

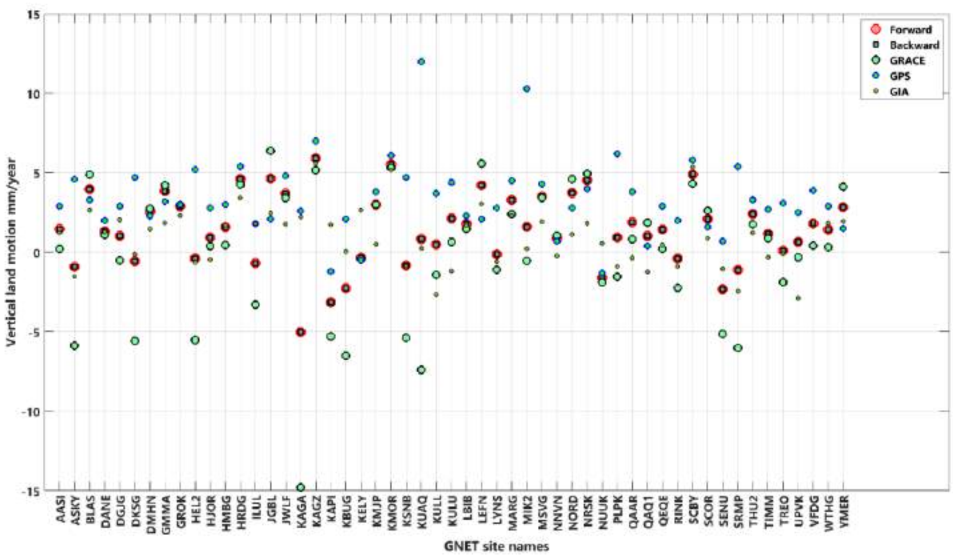

Figure 14*: Comparison of the estimated uplift rates at the GNET sites using the Kalman filtering forward and backward approaches, uplift rates from GRACE, GPS and GIA model (Caron et al., 2018). Unit: mm/year.*

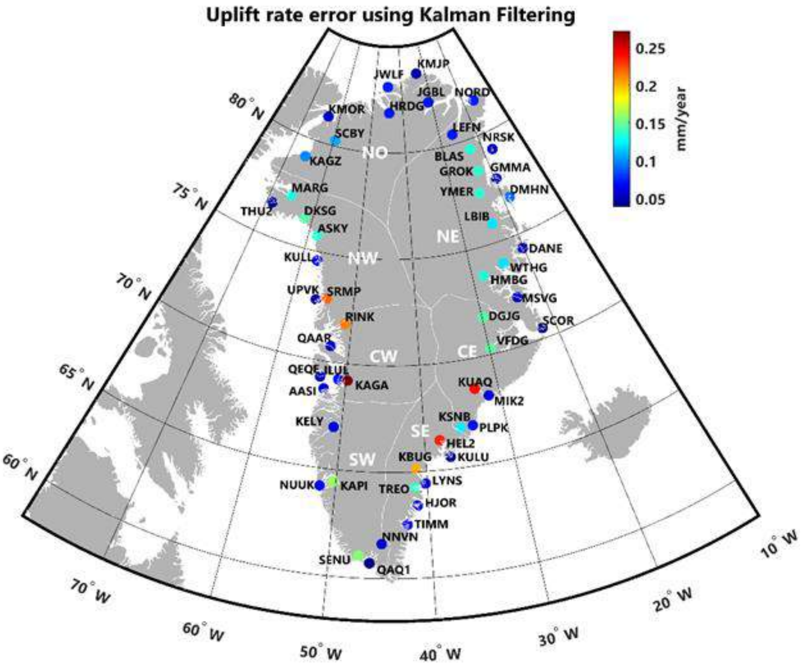

Figure 15*: Uncertainties of the estimated uplift rates at the GNET sites using the Kalman filtering approach. Unit: mm/year.*

Table 2 shows the mean value of mantle viscosities associated with different harmonic windows and different land uplift models, called Scenario 1 to 5 in the table. The viscosities vary between 1.3×10^{21} and 1.9×10^{22} Pa s depending on the land uplift model used for viscosity determination. It also shows the harmonic window and maximum correlation between the geoid signals and the utilized land uplift models. We observe lower correlation coefficients compared to other regions between the geoid and land uplift rates (e.g., Laurentia and Fennoscandia). One reason can be (probably) experiencing a decreasing mass loss with time in Greenland and the employed elastic correction for the land uplift models obtained from GPS, GRACE, and combined model.

Table 2. *Mantle viscosity obtained using different scenarios.*

Scenarios	**Data**	**Harmonic window**	**Correlation coefficient**	**Viscosity** (Unit: Pa s)	**Uncertainty** (Unit: Pa s)
Scenario 1	EGM2008 ICE-6G (VM5a)	$10 \le n \le 39$	0.65	1.9×10^{22}	-----
Scenario 2	EGM2008 Caron et al. 2018	$11 \le n \le 26$	0.68	9.2×10^{21}	1.2×10^{17}
Scenario 3	EGM2008 GNET uplift rate	$18 \le n \le 25$	0.40	1.3×10^{21}	2.6×10^{16}
Scenario 4	EGM2008 GRACE GIA uplift rate	$11 \le n \le 26$	0.68	5.1×10^{21}	1.2×10^{17}
Scenario 5	EGM2008 Combined GIA uplift rate	$11 \le n \le 26$	0.68	7.8×10^{21}	1.4×10^{17}

3. Interactions with the IAG Commissions and GGOS

IAG2021 Session 2a.6: Gravity Inversion for Solid Earth (joint with 2b.5 of the ICCT) organized in the framework of Commission 2, Convener: Mirko Reguzzoni (Italy), co-conveners: Robert Tenzer (ICCT, Hong Kong, China), Srinivas Bettadpur (S2b. USA), and Wenke Sun (China).

4. Publications

Abrehdary M, Sjöberg LE (2020) Estimating a combined Moho model for marine areas via satellite altimetric – gravity and seismic crustal models. *Studia Geophysica et Geodaetica* 64: 1-25

Abrehdary M, Sjöberg LE (2021a) A new Moho depth model for Fennoscandia with special correction for the Glacial isostatic effect. *Pure and Applied Geophysics* 178: 877-888

Abrehdary M, Sjöberg L E (2021b) A Moho density contrast model in Antarctica determined by satellite gravimetry and seismic data. *Geophysical Journal International* 225: 1952-1962

Apeh OI, Tenzer R, Ghomsi KFE, Rathnayake S (2022) Bouguer and mantle gravity maps of Nigeria. *Geocarto Int* 37(27): 16342–16369

Bagherbandi M, Amin H, Wang L, Shirazian M (2022) Mantle viscosity derived from geoid and different land uplift data in Greenland. *Journal of Geophysical Research – Solid Earth* 127(8): 10.1029/2021jb023351

Baranov A, Baranov S, Shebalin P (2019) A Quantitative estimate of the effects of sea tides on aftershock activity: Kamchatka. *Journal of Volcano Seismology* 13(1): 56-69

Baranov A, Tenzer R, Morelli A (2021a) Updated Antarctic crustal model. *Gondwana Research* 89: 1-18

Baranov A, Morelli A, Chuvaev A (2021b) ANTASed – An updated sediment model for Antarctica. *Frontiers of Earth Science* 9: 722699

Baranov A, Morelli A (2023) The structure of sedimentary basins of Antarctica and a new three-layer sediment model. *Tectonophysics* 846: 299-313

Baranov A, Lobkovsky L, Bobrov A (2023a) Global geodynamic model of the Earth and its application for Antarctica. *Earth Sciences* (accepted)

Baranov A, Tenzer R, Ghomsi F (2023b) A new Moho map of the African continent from seismic, topographic, and tectonic data. *Gondwana Research* (under revision).

Baranov A, Bobrov A, Tenzer R, Chuvaev A (2023 submitted) Evolution of lateral tectonophysical stresses in the spherical shell convection with an immobile supercontinent. *Tectonophysics* (http://dx.doi.org/10.2139/ssrn.4251364)

Bobrov A, Baranov A (2019) Thermochemical Mantle Convection with Drifting Deformable Continents: Main Features of Supercontinent Cycle. *Pure and Applied Geophysics* 176(8): 3545-3565

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Chen W, Tenzer R (2020) Reformulation of Parker-Oldenburg's method for Earth's spherical approximation. *Geophysical Journal International* 222(2): 1046-1073

Chuvaev A, Baranov A, Bobrov A (2020) Numerical modeling of mantle convection in the Earth using cloud technologies. *Comput Technol* 25(2): 103-117

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Delvaux D, Maddaloni F, Tesauro M, Braitenberg C (2021) The Congo Basin: Stratigraphy and subsurface structure defined by regional seismic reflection, refraction and well data. *Global Planet Chang* 198:103407

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Gido NAA, Bagherbandi M, Sjöberg LE (2019a) A gravimetric method to determine horizontal stress field due to flow in the mantle in Fennoscandia. *Geosci J* 23: 377-389

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Ji Y, Tenzer R, Tang H, Sun W (2023) Coseismic gravitational curvatures changes in a spherical symmetric Earth model. *Phys Earth Planet Inter* 338: 107013

Kaban MK, Delvaux D, Maddaloni F, Tesauro M, Braitenberg C, Petrunin AG, El Khrepy S (2021) Thickness of sediments in the Congo basin based on the analysis of decompensative gravity anomalies. *J Afric Earth Sci* 179: 104201

Lobkovsky LI, Baranov AA, Ramazanov MM, Vladimirova IS, Gabsatarov YV, Semiletov IP, Alekseev DA (2022) Trigger mechanisms of gas hydrate decomposition, methane emissions, and glacier breakups in polar regions as a result of tectonic wave deformation. *Geosciences* 12: 372

Lobkovsky LI, Baranov AA, Vladimirova IS, Gabsatarov YV (2023a) Possible seismogenic-trigger mechanism of activation of glacier destruction, methane emission, and climate warming in Antarctica. *Oceanology* 63(1): 131-140

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DA (2023b) Possible seismogenic-trigger mechanism of methane emission, glacier destruction and climate warming in the Arctic and Antarctic. *Izvestiya, Physics of the Solid Earth* 3: 364-376

Lobkovsky LI, Baranov AA, Ramazanov MM, Vladimirova IS, Gabsatarov YV, Alekseev DA, Semiletov I (2023c) Large earthquakes in subduction zones around the Polar Regions as a possible reason of rapid climate warming in the Arctic and glacier's collapse in West Antarctica. *Geosciences* (accepted).

Pham LT, Ghomsi FEK, Vu TV, Steffen R, Tenzer R (2023) Delineating structural features of North Cameroon using the EIGEN6C4 high-resolution global gravitational model. *Phys Chem Earth* 129: 103341

Rathnayake S, Tenzer R, Novák P, Pitoňák M (2020) Effect of the lateral topographic density distribution on interpretational properties of Bouguer gravity maps. *Geophysical Journal International* 220(2): 892-909

Reguzzoni M, Sampietro D, Rossi L (2020). The gravimetric contribution to the Moho estimation in the presence of vertical density variations. *Rendiconti Lincei Scienze Fisiche e Naturali* 31: 69-81

Shebalin P, Baranov A (2020) Aftershock rate changes at different ocean tide heights. *Front Earth Sci* 8; doi:10.3389/feart.2020.559624

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Rathnayake S, Tenzer R, Chen W, Eshagh M (2021) Comparison of different methods for a Moho modeling under oceans and marginal seas: A case study for the Indian Ocean. *Surv Geophys* 42(4): 839-897

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The published software:

The software for the gravimetric forward and inverse modelling by using modified the Parker-Oldenburg's method for the Earth's spherical approximation (Chen and Tenzer 2020) is available at: https://academic.oup.com/gji/article/222/2/1046/5824632 (supplementary data).

Joint Study Group T.26: Geoid/quasi-geoid modelling for realization of the geopotential height datum

Chair: *Jianliang Huang (Canada)*

Members

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Jonas Ågren (Sweden)
Riccardo Barzaghi (Italy)
Heiner Denker (Germany)
Bihter Erol (Turkey)
Christian Gerlach (Germany)
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Laura Sanchez (Germany)
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Marc Véronneau (Canada)
Yanming Wang (USA)
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1. Activities of the group

For the period of 2019-2023, the JSG has made remarkable achievements towards its objectives despite the COVID-19 pandemic:

- Contributed to the strategy for the realization of the International Height Reference System (IHRS), (Sánchez et al. 2021), and the Colorado geoid computation experiment (Wang et al. 2021).
- Improved the data combination methods for the geoid modelling (Erol et al. 2020a; Liang et al. 2020a 2020b; Işık et al. 2021; Varga et al. 2021; Grigoriadis et al. 2021). These methods include spherical harmonic modelling, LSC and the least-squared kernel modification. LSC was the most used method for the combination of airborne and terrestrial gravity data.
- Investigated impact of denser terrestrial datasets on geoid modelling (Erol et al. 2020b).
- Characterized, stabilized and performed the downward continuation of high-altitude airborne GRAV-D gravity data (Li et al. 2021; Grigoriadis et al. 2021; Varga et al. 2021). LSC, RLC and RBF methods showed stable and reliable DC results.
- Developed a novel regional RTM approach reducing approximation errors by the classical RTM technique due to the harmonic correction and the spectral inconsistence (Bucha et al. 2019).
- Advanced error estimation of the three commonly used geoid modelling techniques, i.e., Stokes's integration, least-squares collocation and modelling using radial basis functions (Ophaug and Gerlach 2020).
- Identified the data requirement for dynamic geoid/quasi-geoid modelling using GRACE models, GIA models, GLDAS, and RACMO2.3 in Canada (Huang et al. 2019).

2. Achievements and results

Combining multiple types of gravity data

Erol et al. (2020a) investigated the role of the global geopotential model selection in accuracy of regional geoid model determination using a least-squares modification of Stokes's integral with additive corrections method. In the content of this research article, the progress in geopotential model accuracies and thus the regional geoid models with data contribution of GOCE satellite mission was emphasized. In conclusion, the improvement in regional geoid model accuracies depending on the appropriate selection of the global geopotential model and its optimal expansion degree was figured out through the numerical test results. This paper also depicts methodological documentation of geopotential model selection in regional geoid modelling studies.

Liang et al. (2020a) proposed a new method for regionally improving GGMs with GNSS /levelling data. First, the GNSS/levelling data is converted to disturbing potential data with inverse Bruns's formula. Then the systematic errors in disturbing potential data are removed with a 3-parameter correction surface. Afterwards, the disturbing potential data on the Earth's surface are downward continued to the surface of an inner sphere with inverse Poisson's integral equation. At last, the final Regionally Improved Geopotential Model (RIGM) could be recovered from the disturbing potential data using least-squares method. Four RIGM models for Qingdao (QD) in China are determined based on four different sets of GNSS/levelling data points to validate the capability of the method. The STD of height anomaly errors of RIGM-QDs is nearly 25% on average smaller than EGM2008 on checkpoints, see Table 1.

Table 1: *Statistics of the height anomaly errors of RIGM-QD models and EGM2008 on the 12 checkpoints in centimetres.*

Model	Min	Max	Mean	STD
RIGM-QD-1	2.10	32.80	18.33	7.99
EGM2008[1]	-9.00	27.70	17.07	11.05
RIGM-QD-2	6.40	34.10	18.21	7.62
EGM2008[2]	-8.20	28.00	18.01	9.91
RIGM-QD-3	7.10	27.00	19.01	6.20
EGM2008[3]	-10.00	32.90	19.74	9.10
RIGM-QD-4	11.60	32.60	21.04	6.812
EGM2008[4]	4.70	31.90	20.48	8.67

Based on the least-squares formulas of the ellipsoidal harmonic analysis and coefficient transformation (EHA-CT) method, Liang et al. (2020b) developed a new model SGG-UGM-2 up to the degree 2190 and order 2159 by combining the observations of GOCE, the normal equation of GRACE, marine gravity data derived from satellite altimetry data, and EGM2008-derived continental gravity data. The GPS/levelling data in mainland China and the USA is used to validate SGG-UGM-2 together with other models, such as EIGEN-6C4, GECO, EGM2008 and SGG-UGM-1 (the predecessor of SGG-UGM-2). Compared to other models, the model SGG-UGM-2 shows a promising performance in the GPS/levelling validation. All GOCE-related models have similar performances both in the USA and China, and better performances than that of EGM2008 in mainland China. Due to the contribution of GRACE data and the new marine gravity anomalies, SGG-UGM-2 is slightly better than SGG-UGM-1 both in mainland China and USA, see Tables 2 and 3.

Table 2: *Statistics of comparison with GPS/levelling data in the USA (6169 points) in metres.*

Model	Max	Min	Mean	STD	RMS
EGM2008	0.360	-1.396	-0.511	0.284	0.584
SGG-UGM1	0.317	-1.407	-0.511	0.280	0.583
SGG-UGM2	0.386	-1.394	-0.511	0.277	0.578
GECO	0.313	-1.391	-0.513	0.281	0.585
EIGEN-6C4	0.397	-1.392	-0.512	0.282	0.585

Table 3: *Statistics of comparison with GPS/levelling data in mainland China (649 points) in metres.*

Model	Max	Min	Mean	STD	RMS
EGM2008	1.729	-1.535	0.239	0.240	0.339
SGG-UGM1	0.744	-0.618	0.246	0.162	0.294
SGG-UGM2	0.744	-0.603	0.246	0.161	0.292
GECO	1.165	-0.847	0.244	0.180	0.303
EIGEN-6C4	0.729	-0.698	0.243	0.157	0.289

Işık et al. (2021) provides the investigation results that it was conducted in the 1-cm geoid experiment of the International Association of Geodesy Joint Working Group (IAG JWG) 2.2.2. In the content of the study, the least-squares modification of Stokes’s and Hotine’s integral formulas were applied with the terrestrial-only, airborne-only and combined gravity datasets in U.S. Colorado area, and the significant contribution of the airborne gravity measurements at the mountainous part of the study area was clarified. In the investigation results, it was reported the Hotine integral formula provided slightly improved geoid model accuracy in comparison with the Stokes integral formula. The article also includes a comprehensive comparison of the issued geoid model solutions with the solutions, which were submitted by the contributed institutions to the IAG JWG 2.2.2. Shortly saying this study aims to make a contribution to the applied research regarding the clarifying the methodology differences and data contribution in local geoid modeling.

Varga et al. (2021) performed the spectral analysis of surface and airborne gravity anomaly grids across the mountainous area in Colorado, USA, which provided insights into specific wavelength bands in which airborne gravity data contributed and improved the power spectrum. It is shown that airborne gravity anomalies were significantly more powerful in the bandwidth of 200–1400 compared to only terrestrial gravity anomalies and combined gravity anomalies. The airborne gravity power decreased beyond the SH degree 1400, where parts of the medium- and high-frequency spectrum caused by the topographic gravity signal were not detected by the airborne gravity or were filtered out during data preprocessing.

Grigoriadis et al. (2021) applied LSC for combination of the airborne and terrestrial data for the Colorado 1-cm geoid experiment. The covariance model employed in the gridding procedure was the one of the residual surface gravity data. This model properly also fits the empirical covariance of the downward continued values (R2 = 0.93), as it is, since these values have been obtained by LSC using this model covariance. When being compared to the GPS/levelling data along the GSVS17 line, the combined quasi-geoid models reach an accuracy of 2.4 cm and 2.8 cm for the FFT and LSC based methods, respectively. The airborne only solution shows the same level of accuracy as the one from terrestrial data.

Identification of data requirements and gaps

In many regions in the world, the metadata of the terrestrial gravity observations, which are used in geoid modeling studies, are either incomplete or not well known. In some countries, terrestrial gravity measurements are not dense enough for the high accuracy geoid model calculation. Erol et al. (2020b) combine the terrestrial gravity datasets obtained by two different institutions in Turkey to calculate the local geoid model with higher accuracy by using combined gravity datasets in a denser grid. Within the scope of the research, the geoid model accuracies obtained by using the data before and after combining were compared. The least-squares collocation approach, where the stochastic information of the terrestrial datasets is employed, was applied in the calculation of the experimental local geoid models in the study area.

Downward continuation of high-altitude airborne gravity data

Li et al. (2021) characterized the ill-posedness of the downward continuation problem (DCP) by comparing six DC methods, which are spherical harmonic analysis (SHA) (NGS), LSC (DTU Space), Poisson and ADC (NRCan), RBF (DU Delft), and RLSC (TUM) using both simulated data and real data. The data were downward continued to both surface points and to the reference ellipsoid surface. The surface points are directly evaluated with the observed gravity data on the topography. The results show the LSC, RLSC and regularized RBF methods can effectively stabilize the DCP.

Grigoriadis et al. (2021) applied LSC for downward continuation of GRAV-D data for the Colorado 1-cm geoid experiment. The covariance function model employed in these LSC computations was the one of the reduced terrestrial free-air gravity anomaly residuals. Given the point-wise downward continued gravity anomaly residuals, a consistency check with the surface gravity anomaly residuals was performed. The mean and the standard deviation of the differences are 1.96 mGal and 5.42 mGal, respectively, while the minimum value is -30.44 mGal and the maximum value is 42.45 mGal. Varga et al. (2021) also applied LSC for the downward continuation of GRAV-D data over the same experiment region.

Modelling of topographic effects

The classical RTM technique is subject to approximation errors due to the harmonic correction and the spectral inconsistence. Bucha et al. (2019) have proposed and successfully applied a novel regional RTM approach that combines spatial- and spectral-domain gravity forward modelling techniques. This approach can be considered as a regional modification of the baseline global RTM solution of Hirt et al. (2019). The newly introduced regional feature avoids the global spatial-domain Newtonian integration (Hirt et al. 2019), which is too demanding computationally. A validation over two mountainous areas, Switzerland and Slovakia, reveals that this technique is at least comparable with two other common RTM variants (RMS agreement up to 0.1 mGal).

Estimation of data and geoid/quasi-geoid model errors

During the 2015-2017 period of ICCT's JSG on Regional Geoid/-Quasigeoid Modelling, Ophaug and Gerlach (2017) conducted a synthetic study on the equivalence of three commonly used geoid modelling techniques, namely Stokes integration, Least-Squares Collocation and modelling using radial basis functions. The methods were found to agree numerically on the millimeter level. In a follow-up study Ophaug and Gerlach (2020) investigated the agreement of formal error measures derived from the three methods. Comparing empirical and formal errors, it was found that the formal errors are realistic if the methods are tuned with respect to spectral band limitation and adaption of the covariance function. However, direct comparison of the error measures must also consider that integration and estimation methods not necessarily give identical results, because integration techniques may not take the signal properties into account, possibly leading to too optimistic results. Another important finding was that standard methods, like the L-curve method or generalized cross validation failed to provide an optimal regularization parameter – something that can only be investigated in a simulation scenario. Further investigations are necessary on how to use these findings in real-case scenarios.

Dynamic geoid/quasi-geoid modelling

CGVD2013 represents a modern vertical datum in Canada as it is compatible with today's positioning technique through Global Navigation Satellite System (GNSS). It was realized by the Canadian Gravimetric Geoid of 2013, an equipotential surface representing the best fit of mean sea level (MSL) for the North American region. Even though this geoid model is associated to an epoch (2011.0), NRCan currently considers the geoid model as static, i.e., the geoid heights do not change in time. However, the real-time geoid varies with time in response to mass redistributions associated with various processes in the Earth system. These processes include atmospheric, oceanic and hydrological circulations, glacial accumulation/ loss, glacial isostatic adjustment (GIA), solid earth and ocean tides, earthquakes and volcanic eruption, and other mass variations inside the Earth. Observations from space and ground-based sensors are required to study these processes. To connect CGVD2013 to its defined equipotential surface in time, temporal change of the geoid needs to be determined from the observations and resulting models of these processes. Huang et al. (2019) aimed to define the data requirement for determining the geoid change greater than 1 cm and its corresponding spatial scale over a time scale of 10 years. The study primarily focuses on temporal geoid changes due to GIA, glacial/ice melt, and terrestrial water storage variations, which are three dominant processes in Canada. It has used two GIA models (ICE-5G and ICE-6G models), and GPS-absolute-gravity derived gravity changes, the ice mass balance model of RACMO2.3, and GLDAS prediction to quantify spatial scales and amplitudes of the changes, and monthly GRACE models from three processing centers (CSR, GFZ, JPL) to determine the suitability of GRACE and GRACE FO for monitoring the geoid changes. Main conclusions are:

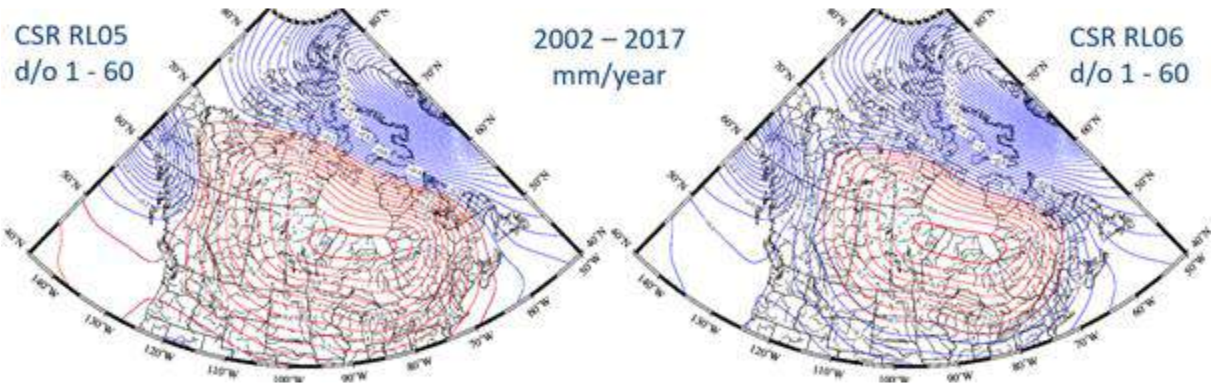

Figure 1: *Dynamic geoid models derived from the monthly GRACE models. Degree-1 coefficient series are from JPL RL05 (Swenson et al. 2008) and RL06 (Sun et al. 2016), and C20 coefficient series from CSR RL05 and RL06 (Cheng et al. 2013; Cheng and Ries 2017).*

- Significant difference is shown between dynamic geoid models derived from RL05's and RL06's monthly GRACE models as shown in Fig. 1 and is found largely due to degree-1 terms, to a less extent degree-2 terms.
- Geoid change components above degree/order 60 are dominated by glacial melt effect.
- ITSG Grace2018s and GOCO06s's time-variable models captured small scale of geoid change signal over mountain glaciers in western North America.

The geoid and quasi-geoid models for South America

For the last two years, Ana Cristina de Matos has collaborated in scientific projects with prof. Denizar Blitzkow at the University of São Paulo (USP) and the Center of Studies of Geodesy (CENEGEO), see, e.g., Hernandez et al. 2019, as:

- updating, analyzing the gravimetric database belonging to USP in order to compute the geoid and quasegeoid models for South America;
- teaching geoid computation at the Instituto Geografico Militar in Ecuador in July 2019;
- computing the Colorado geoid model;
- computing the quasi-geoid model for São Paulo State;
- contributing to the altimetric reference at the Funil Hydroelectric Plant;
- computing the geopotential number and potential for the absolute stations in São Paulo State and IHRF stations in Brazil;
- collaborating in the analysis of the absolute gravimetric network that was established in Costa Rica;
- evaluating the geoid model GEOID2015 and GPS/levelling in Colombia.

3. Interactions with the IAG Commissions and GGOS

- The JSG actively supports the implementation of the International Height Reference Frame (IHRF) under GOGOS Focus Area: Unified Height System in collaboration with IGFS, ISG, IAG SC 2.2, in particular, JWG 2.2.1: Error assessment of the 1-cm geoid experiment.
- Ana Cristina de Matos coordinates geoid models for the SIRGAS-GTIII (Vertical datum) and member of Joint Working Group on Implementation of the International Height Reference Frame (IHRF).

4. Publications

Selected peer-reviewed publications

Bucha B, Hirt C, Yang M et al. (2019) Residual terrain modelling (RTM) in terms of the cap-modified spectral technique: RTM from a new perspective. *Journal of Geodesy* 93: 2089-2108, https://doi.org/10.1007/s00190-019-01303-4

Erol B, Işık MS, Erol S (2020a) An assessment of the GOCE high-level processing facility (HPF) released global geopotential models with regional test results in Turkey. *Remote Sensing* 12(3): 586

Erol B, Işık MS, Erol, S (2020b). Assessment of gridded gravity anomalies for precise geoid modeling in turkey. *Journal of Surveying Engineering* 146(3): 05020005.

Guimarães GN, Blitzkow D, Matos ACOC, Castro Junior CAC, Inoue MEB (2020) 30 Anos De Medições Gravimétricas Absolutas No Brasil. *Revista Brasileira De Cartografia* 72(1): 159-76, https://doi.org/10.14393/rbcv72n1-50229

Grigoriadis VN, Vergos GS, Barzaghi R et al. (2021) Collocation and FFT-based geoid estimation within the Colorado 1 cm geoid experiment. *Journal of Geodesy* 95: 52, https://doi.org/10.1007/s00190-021-01507-7.

Hirt, C, Bucha B, Yang M et al. (2019) A numerical study of residual terrain modelling (RTM) techniques and the harmonic correction using ultra-high-degree spectral gravity modelling. *Journal of Geodesy* 93: 1469-1486, https://doi.org/10.1007/s00190-019-01261-x.

Işık MS, Erol B, Erol S, Sakil FF (2021) High-resolution geoid modeling using least squares modification of Stokes and Hotine formulas in Colorado. *Journal of Geodesy* 95(5): 1-19

Liang W, Pail R, Xu X, Li J (2020a) A new method of improving global geopotential models regionally using gnss/leveling data. *Geophysical Journal Intetnational* 221: 542-549, https://doi.org/10.1093/gji/ggaa047.

Wei L, Li J, Xu X, Zhang S, Zhao Y (2020b) A high-resolution Earth's gravity field model SGG-UGM-2 from GOCE, GRACE, satellite altimetry and EGM2008. *Engineering* 6: 860-878, https://doi.org/10.1016/j.eng.2020.05.008

Ophaug V Gerlach C (2020) Error propagation in regional geoid computation using spherical splines, least-squares collocation, and Stokes's formula. *Journal of Geodesy* 94: 120, doi: 10.1007/s00190-020-01443-y.

Sánchez L, Ågren J, Huang J et al. (2021) Strategy for the realization of the International Height Reference System (IHRS). *Journal of Geodesy* 95: 33, https://doi.org/10.1007/s00190-021-01481-0.

Silva VC, Blitzkow D, Almeida FGV, Matos ACOC, Bjorkstrom IM (2020) Atualização da Estrutura Gravimétrica do Estado de São Paulo: Vínculo ao Sistema Gravimétrico de Referência. Anuário do Instituto de Geociências 43: 212-226, https://doi.org/10.11137/2020_3_215_226.

Varga M, Pitoňák M, Novák P, Bašić T (2021) Contribution of GRAV-D airborne gravity to improvement of regional gravimetric geoid modelling in Colorado, USA. *Journal of Geodesy* 95: 53, https://doi.org/10.1007/s00190-021-01494-9.

Wang Y, Sánchez L, Ågren J, Huang J, Forsberg R, Abd-Elmotaal H, Ahlgren K, Barzaghi R, Bašic T, Carrion D, Claessens S, Erol B, Erol S, Filmer M, Grigoriadis VN, Isik MS, Jiang T, Koc O, Li X, Ahlgren K, Krcmaric J, Liu Q, Matsuo K, Natsiopoulos DA, Novák P, Pail R, PitoňákM, Schmidt M, Varga M, Vergos GS, Véronneau M, Willberg M, Zingerle P (2021) Colorado geoid computation experiment – overview and summary. *Journal of Geodesy*.

Presentations

Blitzkow D, Matos ACOC (2019) Colorado geoid model from Helmert anomaly. 27th IUGG General Assembly, Québec, Canada, July 8-18, 2019. https://www.czechin.org/cmPortalV15/CM_W3_Searchable/iugg19/normal#!abstractdetails/0000737270

Guimarães GN, Blitzkow D, Matos ACOC, Mendonça L (2019) First efforts for the IHRF establishment in Brazil by least squares collocation and numerical integration. https://www.czech-in.org/cmPortalV15/CM_W3_Searchable/iugg19/normal#!abstractdetails/0000737100

Guimarães GN, Blitzkow D, Matos ACOC (2019) An analysis of the use of least squares collocation and the numerical integration to compute the disturbing potential at IHRF stations in Brazil. SIRGAS2019, Rio de Janeiro, Brazil, Nov 11-14, 2019, http://www.sirgas.org/fileadmin/docs/Boletines/Bol24/89_Guaimaraes_et_al_2019_LSC_IHRF_Brazil.pdf

Guimarães GN, Blitzkow D, Matos ACOC, Castro Junior CAC, Inoue MEB (2019) 30 years of absolute gravity measurements in South America. Symposium SIRGAS2019, Rio de Janeiro, Brazil, Nov 11-14, 2019, http://www.sirgas.org/fileadmin/docs/Boletines/Bol24/45_Guaimaraes_et_al_2019_Absolute_gravimetry_SouthAmerica.pdf

Hernandez JN, Blitzkow D, Matos ACOC, Mora F (2019) Evaluación del modelo geoidal GEOID2015 en Colombia, 2019. SIRGAS2019, Rio de Janeiro, Brazil, Nov 11-14, 2019, http://www.sirgas.org/fileadmin/docs/Boletines/Bol24/83_Hernandez_et_al_2019_Evaluacion_GEOI2015_Colombia.pdf

Huang J, Véronneau M, Pavlic G, Crowley JW (2019) Data requirement for determining temporal change of the Canadian Geodetic Vertical Datum of 2013 (CGVD2013) and IHRF, AGU 100 Fall Meeting, 9-13 December 2019

Li X, Huang J, Willberg M, Pail R, Slobbe C, Klees R, Forsberg R, Hwang C, Hilla S (2021) On downward continuing airborne gravity data for local geoid modeling. EGU General Assembly, 19-30 April 2021, EGU21-2706, https://doi.org/10.5194/egusphere-egu21-2706, 2021

Lucke OH, Salvatierra JP, Leon JG, Fernandez AV, Blitzkow D, Bjorkstrom I, Silva VC, Matos ACOC (2019). Absolute gravity network in Costa Rica. 27th IUGG General Assembly, Québec, Canada, July 8-18, 2019, https://www.czech-in.org/cmPortalV15/CM_W3_Searchable/iugg19/normal#!abstractdetails/0000737560

Pacino MC, Blitzkow D, Matos ACOC (2019) Geoid modelling in South America, 2019. Symposium SIRGAS2019, Rio de Janeiro, Brazil, Nov 11-14, 2019, http://www.sirgas.org/fileadmin/docs/Boletines/Bol24/46_Pacino_et_al_Geoid_modelling_SouthAmerica.pdf

Sanchez L, Ågren J, Huang J, Wang YM, Mäkinen J, Denker H, Ihde J, Abd-Elmotaa H, Ahlgren K, Amos M, Barzaghi R, Bašić T, Blitzkow D, Carrion D, Claessens S, Erol B, Filmerm M, Forsberg R, Grigoriadis VN, Serkan Işık M, Jiang T, Li X, Liu Q, Matos ACOC, Matsuo K, Novák P, Pail R, Pitoňák M, Roman D, Schmitd M, Sideris M, Varga M, Vergos G, Véronneau M, Willberg M, Zhang C, Zingerle P (2019) Advances in the realization of the International Height Reference System. Symposium SIRGAS2019, Rio de Janeiro, Brazil, Nov 11-14, 2019, http://www.sirgas.org/fileadmin/docs/Boletines/Bol24/42_Sanchez_et_al_2019_IHRS_IHRF_advances.pdf

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Joint Study Group T.27: Coupling processes between magnetosphere, thermosphere, and ionosphere

***Chair**: Andres Calabia (China)*

Members

Christine Amory-Mazaudier (France)
Astrid Maute (USA)
Yury Yasyukevich (Russia)
Gang Lu (USA)
Anoruo Chukwuma (Nigeria)
Oluwaseyi Emmanuel Jimoh (Nigeria)
Munawar Shah (Pakistan), Vice-Chair
Binod Adhikari (Nepal), Research Coordinator
Piyush M. Mehta (USA)
LiangLiang Yuan (Germany)
Naomi Maruyama (USA)
Toyese Tunde Ayorinde (Brazil)
Charles Owolabi (Nigeria)
Emmanuel Abiodun Ariyibi (Nigeria)
Olawale S. Bolaji (Australia)
Ayomide Olabode (Nigeria)

1. Activities of the group

The Joint Study Group, "Coupling Processes Between Magnetosphere, Thermosphere, and Ionosphere," has been active from 2019-2023. The group has worked towards achieving the following goals:

- Creating a structured group of active members who can contribute as advisors or skilled participants to the planned activities in the JSG1/JSG-T.27 Terms of Reference of "The Geodesists Handbook 2020" (Poutanen and Rózsa, 2020), and as listed in the "IAG-FA-GSWR-JSG1 2019 Initial Report" (Calabia et al., 2020b).
- Creating a common platform to improve communication within the group, JSG1/JSG-T.27 started a website-forum with information on the coupled processes within the MTI.
- Enhancing international cooperation with developing countries by sharing knowledge and research tools, co-supervising theses, and helping to improve manuscripts.
- Enhancing and achieving successful interaction and cooperation along with the Joint Working Groups of the IAG GGOS FA GSWR and other IAG Commissions.
- Elaborating and submitting scientific manuscripts co-authored by the group members.
- Creating data and model products that are freely available for the scientific community.
- Elaborating and submitting project proposals to national and international calls.

In summary, this joint study group has made significant progress towards understanding the coupling processes between magnetosphere, thermosphere, and ionosphere, and contributed to the scientific community through cooperation, communication, and open access to data and models.

2. Achievements and results

- Calabia et al. (2023): Editor‘s Research Topic that focus on the latest advancements in algorithms, methodologies, and techniques for characterizing the upper atmosphere in the context of geodetic space weather research and applications.

- Calabia et al. (2022) describes a study that investigated the effects of a multiphase geomagnetic storm on the low-latitude ionosphere in February 2014. The study used data from space weather indices, magnetometers, TEC data from ground stations, and ionospheric models.
- In Calabia et al. (2021), the low-latitude ionosphere responses and coupling mechanisms to the February 2014 multiphase geomagnetic storm are investigated from space weather indices, magnetometer and TEC data from ground stations, and ionospheric models.
- Shah et al. (2021) investigates GNSS vTEC, magnetic field data, geomagnetic indices, global ionospheric maps, thermospheric mass density, and [O/N2] ratio measurements under strong ionospheric and upper-atmospheric disturbances.
- Maruyama (2020) provides an overview of recent advances in the study of Earth's ionosphere during magnetic storms and substorms, with a focus on electrodynamics and its consequences over the past 14 years. The chapter emphasizes the importance of studying the magnetosphere, ionosphere, and thermosphere as a whole system, and highlights the value of combining ground-based and space-based observations from magnetospheric missions.
- In Heelis and Maute (2020), the challenge to Understand the MTI System is addressed to advance in geodetic observations of plasma and mass density compositions and velocities, as well as the dynamics of energetic particles and field-aligned currents from magnetospheric energy inputs.
- In Calabia and Jin (2020b), Total Electron Content (TEC) and Thermospheric Mass Density (TMD) observables show a very similar response to solar flux. The annual cycle of TEC is approximately one order of magnitude larger. A hemispheric asymmetry is shown in TMD, with higher values in the southern hemisphere. The asymmetry is not visible in TEC.
- In Petadella et al. (2018), the uncertainties in physics-based models are investigated by perturbing high-latitude electric potential and auroral energy flux. Specification of high-latitude electric fields is an important source of uncertainty when modelling the ionosphere response to geomagnetic storms.
- In Calabia and Jin (2019), a seasonal dependence in amplitude of TMD variability due to magnetospheric forcing is shown only in the southern high latitude.
- In Lu et al. (2020), comparisons between physics-based models and TEC observations show storm phenomena driven by ionospheric convection, aurora precipitation, and SubAurora Plasma Stream field.
- In Zhang et al. (2020), the TMD cooling due to only NO show is not sufficient to explain the observed variability.
- In Zhu et al. (2019), physics-based model simulations show Joule heating is 27% globally enhanced by the small-scale and mesoscale electric field variation, but particle precipitation reduce this enhancement in 5% globally, and up to 18% locally.
- In Forbes et al. (2020), physics-based model simulations show the tide contributions to S0 TMD response at 325 km consists of planetary wave fluctuations of order ±4%, roughly equivalent to the day-to-day variability associated with low-level geomagnetic activity. The short periods TMD variability (< 9 days) correlates with temperature changes (hydrostatic origin). Over longer periods TMD is also controlled by composition and mean molecular mass.

3. Interactions with the IAG Commissions and GGOS

Iteraction with JWG1 – Electron density modelling: Akala et al. (2020), Amaechi et al. (2020a,b, 2021a,b), Astafyeva et al. (2022), Calabia and Jin (2020b), Dung et al. (2021, 2022), Idosa et al. (2023), Jin et al (2021), Licata et al. (2021), Lu et al (2020), Migoya-Orué et al. (2021), Oluwaseyi et al. (2022), Pandit et al. (2023), Pham et al (2022), Pedatella et al. (2018), Shahzad et al. (2021), Yasyukevich et al (2020b), Yasyukevich et al (2020a), Younas et al. (2022, 2021), Zhukov et al (2021).

Interaction with JWG2 – Improvement of thermosphere models: Yuan et al (2019), Calabia et al. (2019, 2020a), Licata et al. (2021), Forbes et al. (2018), Poudel et al. (2022), Yuan et al. (2021a).

Interaction with JWG3 – Space Weather Events: Baral et al (2019), Calabia et al (2021c, 2023), Calabia and Jin (2019), Dahal et al (2022), Didier et al. (2021), Lejosne et al. (2021, 2022), Maruyama et al (2020, 2023), Mendes et al (2022), Mishra et al. (2022), Obana et al. (2021), Sapkota et al. (2022), Shah et al (2022), Syrovatskiy et al. (2019), Tulegenov et al. (2022).

Interaction with FA – Geohazards: Shah et al (2020a,b, 2021), Adil et al. (2021a,b,c), Ahmed et al (2021), Hafeez et al. (2021), Mehdi et al. (2021, Satti.et al. (2022), Tariq et al (2021).

Interaction with Commission 4 – Positioning and Applications: Demyanov et al. (2021a,b), Gao et al. (2021), Hou et al. (2022), Ndao et al (2021), Su et al. (2021), Yasyukevich et al (2021, 2022, 2020a,b), Yuanet al. (2021b).

Interaction with Commission 4.3 – Atmospheric Remote Sensing: Amory-Mazaudier et al. (2019, 2021, 2022), Calabia and Jin (2021a,b), Gautam et al (2022), Malaspina et al. (2022), Vankadara et al (2022), Tang et al. (2020), Vasiliev et al. (2021), Yuan et al. (2019), Zhang et al (2019), Zhu et al. (2018, 2019).

4. Outlook

- Working effectively within the group members to increase communication.
- Advancement of MTI science in developing countries by organizing workshops, etc.
- Elaboration and submission of scientific manuscripts co-authored by the group members.
- Elaboration of data and model products freely available for the scientific community.
- Keep the Website-Forum active and updated.
- Improvement and submission of projects to request funds for publications fees, etc.
- Elaboration of proposal for International Workshop on MTI Coupling (IWMTIC2021): Prospects, Challenges, and Opportunities. Kathmandu, Nepal.

5. Publications

Selected peer-reviewed publications

Adil MA, Senturk A, Shah M, Naqvi NA, Saqib M, Abbasi AR (2021a) Atmospheric and ionospheric disturbances associated with M>6.0 earthquakes in the East Asian regions: a case study from Taiwan. *Journal of Asian Earth Sciences* 220: 104918, https://doi.org/10.1016/j.jseaes.2021.104918

Adil MA, Abbas A, Ehsan M, Shah M, Naqvi NA (2021b) Investigation of ionospheric and atmospheric anomalies associated with three Mw > 6.5 EQs in New Zealand. *Journal of Geodynamics* 145: 101841, https://doi.org/10.1016/j.jog.2021.101841

Adil MA, Erman S, Entu RK, Pulinets SA, Amory-Mazaudier C (2021c) A lithosphere-atmosphere-ionosphere coupling phenomenon observed before 2020 M7.7 Jamaica Earthquake. *Pure and Applied Geophysics*, https://doi.org/10.1007/s00024-021-02867-z

Ahmed J, Shah M, Awai M, Jin S, Zafar WA, Ahmed N, Amin A, Shah M, Ali I (2021) seismo-ionospheric anomalies before the 2019 Mirpur earthquake from ionosonde measurements. Advances in Space Sciences. https://doi.org/10.1016/j.asr.2021.07.030

Akala AO, Oyeyemi EO, Amaechi PO, Radicella SM, Nava B, Amory-Mazaudier C (2020) Longitudinal responses of the equatorial/low latitude ionosphere over the oceanic regions to geomagnetic storms of May and September 2017. *Journal of Geophysical Research*: Space Physics, 125: e2020JA027963, https:// doi.org/10.1029/2020JA027963

Amaechi PA, Oyeyemi EO, Akala AO, Amory-Mazaudier C (2020a) Geomagnetic activity control of irregularities occurrences over the crests of the African EIA. *Earth and Space Science* 7: e2020EA001183, https://doi.org/10.1029/2020EA001183

Amaechi PA, Oyeyemi EO, Akala AO, Falayi EO, Kaab M, Benkhaldoun Z, Amory-Mazaudier C (2020b) Quiet-time ionospheric irregularities over the African Equatorial Ionization Anomaly (EIA) region. *Radio Science* 55: e2020RS007077, https://doi.org/ 10.1029/2020RS007077

Amaechi PO, Oyeyemi EO, Akala AO, Messanga HE, Panda SK, Seemala GL, Oyedokun JO, Fleury R, Amory-Mazaudier C (2021a) Ground-based GNSS and C/NOFS observations of ionospheric irregularities over Africa: a case study of the 2013 St. Patrick's Day geomagnetic storm. *Space Weather*, doi:10.1029/2020SW00263

Amaechi, PO, Oyeyemi EO, Akala AO, Kaab M, Younas W, Benkhaldoun Z, Khan M, Amory Mazaudier C (2021b) Comparison of ionospheric anomalies over African equatorial/low-latitude region with IRI-2016 model predictions during the maximum phase of solar cycle 24. *ASR*, https://doi.org/10.1016/j.asr.2021.03.040

Amory-Mazaudier C, Fleury R, Masson F, Gadimova S, Anas E (2019) Training on GNSS and space weather in Africa in the framework of a North-South scientific network GIRGEA. *Sun and Geosphere* 14(1): 71-79

Amory-Mazaudier C, Radicella S, Doherty P, Gadimova S, Fleury R, Nava B, Anas E, Petitdidier M, Migoya-Orué Y, Alazo K, Shiokawa K (2021) Development of research capacities in space weather: A successful international cooperation. *J. Space Weather Space Clim.* 11: 28, Published by EDP Sciences, https://doi.org/10.1051/swsc/2021006

Amory-Mazaudier C (2022) Magnetic signatures of large-scale electric currents in the Earth's environment at middle and low latitudes. *Atmosphere* 13: 1699, https://doi.org/10.3390/ atmos13101699

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Baral, R, Adhikari B, Calabia A, Shah M, Mishra RK, Silwal A, Bohara S, Manandhar R, del Peral R, Rodriguez MD (2022) Spectral features of Forbush Decrease during geomagnetic storms. *J. Atmos. Solar Terrest. Phys* 242: 105981, doi:10.1016/j.jastp.2022.105981

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Calabia A, Jin SG (2021a) Upper-atmosphere mass density variations from CASSIOPE precise orbits. *Space Weather* 19: e2020SW002645. doi:10.1029/2020SW002645.

Calabia A, Jin SG (2021b) Thermospheric mass density disturbances due to magnetospheric forcing from 2014-2020 CASSIOPE precise orbits. *J. Geophys. Res. Space Phys*. 126, doi:10.1029/2021JA029540.

Calabia A, Anoruo C, Munawar S, Amory-Mazaudier C, Yasyukevich Y, Owolabi C, Jin SG (2021c) Low-latitude ionospheric responses and coupling to the February 2014 multiphase geomagnetic storm from GNSS, magnetometers, and space weather data. *Atmosphere* 13: 518, doi:10.3390/atmos13040518

Calabia A, Jin SG (2020a) Upper atmospheric characterization from neutral and electron density observations. *International Association of Geodesy Symposia*, IAGS-D-19-00063R2, doi:10.1007/1345_2020_123

Calabia A, Jin SG (2020b) New modes and mechanisms of long-term ionospheric TEC variations from Global Ionosphere Maps. *J. Geophys. Res. – Space Phys*. 125(6), doi:10.1029/2019JA027703

Calabia A, Tang G, Jin SG (2020a) Assessment of new thermospheric mass density model using NRLMSISE-00 model, GRACE, Swarm-C, and APOD observations. *J. Atmos. Solar Terrest. Phys*. 199: 105207, doi:10.1016/j.jastp.2020.105207

Calabia A, Jin SG (2019) Solar-flux and asymmetric dependencies of GRACE-derived thermospheric neutral density disturbances due to geomagnetic and solar wind forcing. *Ann. Geophys*. 37(5): 989-1003, doi:10.5194/angeo-37-989-2019

Dahal S, Adhikari B, Khadka AK, Silwal A, Gupta SK, Chapagain NP (2022) Ionospheric signatures during G2, G3 and G4 storms in mid-latitude. *Radio Science* 57(5): 1-22

Demyanov VV, Yasyukevich YV (2021a) Space weather: risk factors for Global Navigation Satellite Systems, *Solar-Terrestrial Physics* 7(2): 28-47, doi:10.12737/stp-72202104.

Demyanov V, Danilchuk E, Yasyukevich Y, Sergeeva M (2021b) Experimental estimation of deviation frequency within the spectrum of scintillations of the carrier phase of GNSS signals. *Remote Sensing* 13(24): 5017, doi:10.3390/rs13245017.

Demyanov V, Danilchuk E, Sergeeva M, Yasyukevich Y (2023) An increase of GNSS data time rate and analysis of the carrier phase spectrum. *Remote Sens*ing 5(15): 792, doi: 10.3390/rs15030792.

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Vasiliev A, Yasyukevich Y, Garashchenko A, Edemskiy I, Vesnin A, Sidorov D (2021) Computer Vision for GNSS-based Detection of the Auroral Oval Boundary. *International Journal of Artificial Intelligence* 19(N2): 132-151

Vesnin, A, Yasyukevich Y, Perevalova N, Şentürk E (2023) Ionospheric response to the 6 February 2023 Turkey–Syria Earthquake. *Remote Sensing* 15: 2336, doi:10.3390/rs15092336

Yasyukevich Y et al. (2019) Ionosphere modeling and monitoring using GPS and GLONASS techniques. Invited talk at the 10th China satellite navigation conference. Beijing, China.

Yasyukevich Y, Astafyeva E, Oinats A, Vesnin A, Yasyukevich A, Vasiliev A, Garashchenko A, Sidorov D (2021) Multi-instrumental View of the Auroral Oval. PIERS proceedings: 210620161850. doi:10.1109/PIERS55526.2022.9792594.

Yasyukevich YV, Syrovatskii SV, Padokhin AM, Frolov VL, Vesnin AM, Zatolokin DA, Kurbatov GA, Zagretdinov RV, Pershin AV, Yasyukevich AS (2021) GPS positioning accuracy during the 2016 September and 2010 August campaigns at the SURA heater. XXXIVth General Assembly and Scientific Symposium of the International Union of Radio Science, pp. 1-3, doi:10.23919/URSIGASS51995.2021.9560199.

Yayukevich Y, Yasyukevich AS, Zatolokin DA (2021) Assessing the performance of models for ionospheric correction for single-frequency GNSS positioning. PIERS Proceedings, 210620155135.

Yasyukevich YV, Zatolokin DA, Yasyukevich AS, Vesnin AM, Nava B, Li Z, Wang N (2021) Ionosphere modeling in TEC and positioning error domain. AGU Fall Meeting, Abstract ID SA44B-09.

Yasyukevich Y and GNSS monitoring group (2021) Space weather and global navigation satellite systems. Modern navigation technologies and their applications for smartphones and wearables. HUAWEI.

Yasyukevich YV, Zatolokin D, Padokhin A, Wang N, Nava B, Li Z, Yuan Y, Yasyukevich A, Chen C, Vesnin A (2023) Klobuchar, NeQuickG, BDGIM, GLONASS, IRI-2016, IRI-2012, IRI-Plas, NeQuick2, and GEMTEC ionospheric models: a comparison in total electron content and positioning domains. *Sensors* 23: 4773, doi:10.3390/s23104773

Conference Services

Calabia A: Member of Scientific Committee. X Hotine-Marussi Symposium 2022, Politecnico di Milano, Milan, Italy, 13-17 June 2022.

Calabia A: Forum Panelist: Meet the Scientists & Careers in Space. Seventh International Conference on Aerospace Science Engineering 2021 (ICASE2021), December 14-16, 2021, Islamabad, Pakistan.

Calabia A: Panel Discussion Panelist: Space Weather and GNSS. ICASE2021

Calabia A: Keynote Speaker. ICASE2021

Shah M: Organize and Chair sessions related to JSG1 activities, November 2021, international conference on aerospace science & engineering (ICASE), Islamabad, Pakistan.

Shah M: Co-convener session in EGU-2021 with Juergen Mueller and Sergei Kopeikin on PNT solutions in Space Geodetic Techniques.

Yasyukevich Y: Member of Scientific Committee and of Organizing Committee. Baikal young scientists' international school on fundamental physics "physical processes in outer and Near-Earth space" and XVII Young Scientists' Conference "Interaction of fields and radiation with matter". September 5-10, 2022. Irkutsk, Russia.

Editorial Services

Calabia A, Gang Lu G, Olawale S, Bolaji OS became Guest Editors of Special Issue "*Advances on upper-atmosphere characterization for geodetic space weather research and applications*", in Frontiers in Astronomy and Space Sciences, Frontiers.

Calabia A: Editorial Board Member, Journal of Geodesy and Geoinformation Science.

Calabia A: Review Editor, Frontiers in Astronomy and Space Sciences.

Adhikari B: Editor in Chief, Journal of Nepal Physical Society (2019-2022).

Anoruo C: Editorial team member, Journal of International Physics Students (JIAPS).

Shah M Editor in Chief, NASIJ journal Editor (since 2017).

Yasyukevich Y: Associate Editor, Advances in Space Research (since 2022).

Yasyukevich Y: Guest Editor, GPS solutions (since 2021).

Other Services in Scientific Community

Calabia A, Adhikari B became members of Study Group *'Low-Latitude Ionospheric Research Working Group'* of the Asia Oceania Geosciences Society (AOGS). 2022–now.

Calabia A became Council member and Regional Representative at *Young Earth System Scientists (YESS),* 2022-2023.

Anoruo C, Associate members of the *World Climate Research Program, Explaining and Predicting Earth System Change* (EPESC).

Yasyukevich Y, Scientific secretary of dissertation council at ISTP SB RAS, since 2023.

Internal Reports

Calabia A, Shah M, Adhikari B, Amory-Mazaudier C, Maute A, Lu G, … Yasyukevich Y (2021). IAG-FA-GSWR-JSG1 2020 Mid-term Report PPT. Zenodo. http://doi.org/10.5281/zenodo.4767575

Calabia A, Shah M, Adhikari B, Amory-Mazaudier C, Maute A, Lu G, … Yasyukevich Y (2020). IAG-FA-GSWR-JSG1 2019 Initial Report, doi:10.13140/RG.2.2.17845.19687

Awards and Honors

Amory-Mazaudier C, *Vikram Sarabhai Isro-Cospar Joint Medal*, Indian Space Research Organisation (ISRO), Committee on Space Research (COSPAR), Ceremony of Awards COSPAR 44th Athens July 18, 2022.

Projects and Contracts

Calabia A (2022) *Characterization of Plasma Depletions and Effects on Geodetic Applications* (PI), 1,000€, PITHIA-NRF EU Horizon 2020 Research and Innovation Programme Grant Agreement Trans-National Access, at Ebro Observatory, Spain.

Calabia A (2021) *Variability, impacts, and applications of cosmic ray and radiation belt particles*, 2,350€, Giner de los Ríos Grant, University of Alcalá, Madrid, Spain.

Yuan L (since 2021) Co-I, EGNOS Next SBAS-PPP, ESA.

Yuan L (since 2021) Co-I, *MEDUSE Data assimilation project*, DLR.

Shah M (2021-2022) Post Doc, KMITL, Prince of Chumphon Campus, Thailand.

Shah M (since 2022) Co-PI, Space Education and GNSS lab, National Center for GIS and Space Application, Institute of Space Science, Pakistan

Shah M (since 2022) Consultant, Agriculture field assessment in Northern Pakistan using GPS and GIS, partners Helvetas Swiss International.

Maruyama N (2022) *GDC AETHER instrument proposal selected for the NASA GDC mission*. It measures the electron density and temperature of the ionosphere(~400km) for the GDC mission. https://lasp.colorado.edu/home/2022/04/27/lasp-instrument-selected-for-the-next-nasa-living-with-a-star-mission/

Yasyukevich Y (2017-2022) PI, Machine learning driven tool for near-Earth space research: recording, processing, and analysing the data deduced from global navigation satellite systems, Russian Science Foundation.

Yasyukevich Y (2023-2025) PI, Development of methods for monitoring and forecasting the state of the ionosphere and the quality of high-precision navigation using intelligent data analysis, Russian Science Foundation.

Website & Forum

- https://ggos.org/about/org/fa/geodetic-space-weather-research/groups/jsg1-coupling-processes/
- https://www.researchgate.net/project/IAG-JSG1-Coupling-processes-between-magnetosphere-thermosphere-and-ionosphere-MTI

Data & Software Products

Calabia A, Jin SG (2021) CASSIOPE GNSS-based thermospheric mass densities from 325 to 425 km at intervals of 25 km. Zenodo, https://zenodo.org/record/5079186

Calabia A, Jin SG (2019) Supporting Information for "Solar-cycle, seasonal, and asymmetric dependencies of thermospheric mass density disturbances due to magnetospheric forcing". Zenodo, http://doi.org/10.5281/zenodo.3234582

Calabia A, Jin SG (2019) Supporting Information for "New modes and mechanisms of long-term ionospheric TEC variations from Global Ionosphere Maps". Zenodo, http://doi.org/ 10.5281/zenodo.3563463

Calabia A, Jin SG (2020) Supporting Information for "Short-term ionospheric TEC variations from Global Ionosphere Maps" [Data set]. Zenodo, http://doi.org/10.5281/zenodo.4280436

Yasyukevich Y (2022) SIMuRG: System for Ionosphere Monitoring and Research from GNSS, https://simurg.iszf.irk.ru

Joint Study Group T.28: Forward gravity field modelling of known mass distributions

Chair: *Dimitrios Tsoulis (Greece)*

Members

Carla Braitenberg (Italy)
Christian Gerlach (Germany)
Ropesh Goyal (India)
Olivier Jamet (France)
Michael Kuhn (Australia)
Pavel Novák (Czech Republic)
Konstantinos Patlakis (Greece)
Daniele Sampietro (Italy)
Matej Varga (Croatia)
Jérôme Verdun (France)

1. Activities of the group

Over the previous four years the activities of the study group concentrated on two major objectives: (a) the performance of analytical and numerical computations of terrain effects over dense Digital Elevation Models and (b) the investigation of alternative and more stable computational strategies for the potential harmonic coefficients of a polyhedral source.

2. Achievements and results

The main achievements and results can be briefly outlined as follows:

- Development of a modified spatial-spectral combined methodology for efficient computation of local planar terrain corrections (TC) with demonstrated convergence (Goyal et al. 2020a).
- The spatial-spectral combination method has been utilized to calculate 1”x1” and 3”x3” local planar TC maps over India and adjacent regions using SRTM1” DSM and MERIT 3” DEM, respectively. These are the first high-resolution TC maps that i) are constructed in a region having varied topography consisting of the Himalayas, the Gangetic plain, the Thar desert, the Deccan plateaus, and various Hill ranges and ii) have guaranteed convergence of < 1μGal. However, with some more testing we found that the stripe effects that are present in the SRTM 1” DSM are propagated to the computed TC values. Considerations on the corresponding TC error grid are on the way.

  A 0.02˚x0.02˚ grid of TC constructed by block-averaging the 3”x3” TC map from MERIT DEM has been utilized for the computation of the first gravimetric geoid model for India (Goyal et al., 2020b; 2021c). The TC computed using our strategy has already been utilized in the geoid/quasigeoid computation over Colorado (Claessens and Filmer, 2020) and Auvergne (Goyal et al., 2021b), respectively. The original and block-averaged TC grids are shown in Figures 1 and 2, respectively. The scatter plot of block-averaged TC wrt to heights and the corresponding histogram are shown in Figure 3.

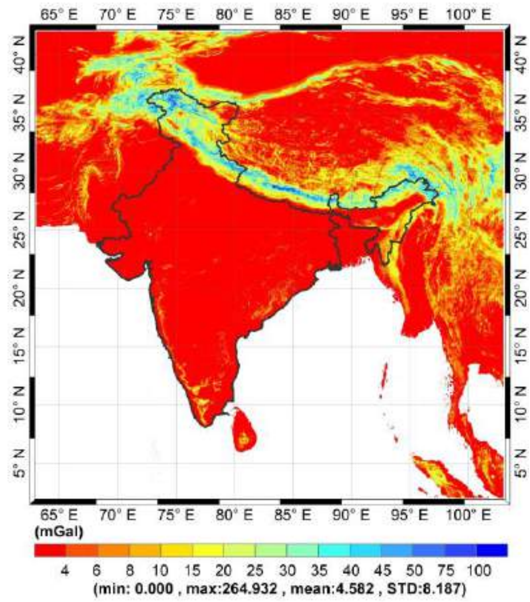

Figure 1: *3" TC from MERIT 3" DEM.*

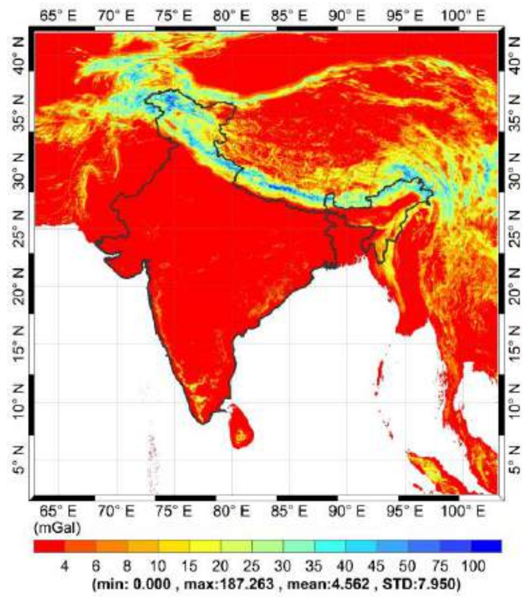

Figure 2: *Block-averaged TC from MERIT 3" DEM.*

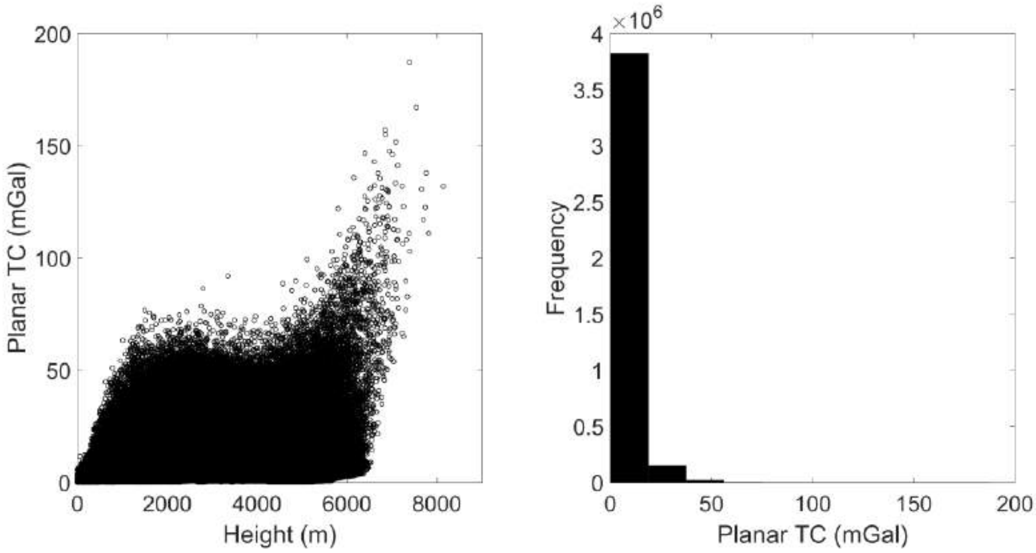

Figure 3: *Scatter plot of block-averaged TC wrt heights and the corresponding histogram.*

Larger values of TC are obtained in the regions with high peaks and rapidly undulating terrain. In the plateau regions where we have high elevation but lesser undulating terrain, TC have smaller values. TC vary considerably (~1mGal to 50 mGal) for the areas having greater heights (~2000 m to 6500 m). Thus, TC vary noticeably in the regions with the undulating terrain compared to the regions only having higher elevations.

- The application of FFTs in these computations provided input for further investigations. With some random tests in extremely plain areas, i.e., regions with no emerging condition of divergence, FFTs are providing unexpected results. Moreover, on further derivations of TC errors up to higher order binomial expansion it is observed that the FFT based TC errors are divergent. Thus, the stability of FFT in different topographical features should be examined.
- Another important observation is the substantial difference in TC for various regions (especially mountainous regions) computed with different DEMs/DSMs. This is due to the horizontal shifts among various freely available global DEMs/DSMs. Moreover, the freely

available DSM/DEM are not in agreement at various topographical features, especially in the undulating mountainous hills (cf. Goyal et al. 2021a). Therefore, a study on the minimization of geolocation errors and their effect on terrain effects will be undertaken.

- Explicit introduction of 'dynamic' or 'floating' integration radius may be introduced in the computation of topographical/terrain effects involving numerical integration with cascading grid. It may be possible that researchers might be already using the floating integration radius as it is required to avoid the effects from overlapping or missing DEM elements, especially at the transition zones. This has been followed to compute the topographical effect in the gravimetric geoid model of India using the UNB method. A numerical test will be undertaken to quantify this effect.
- A novel approach for the computation of the spherical harmonic coefficients induced by a constant density polyhedral source has been presented. Unlike previous computational algorithms the coefficients emerge directly from the evaluation of the corresponding line integrals. The derived algorithm is also numerically much more stable with respect to its predecessors, with stable computed coefficients up to degree 360 (Jamet and Tsoulis 2020), see Fig. 4.

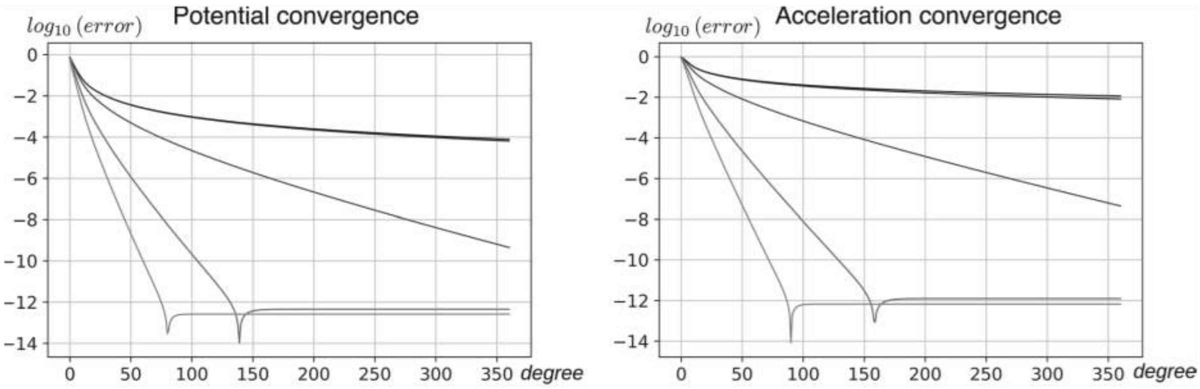

Figure 4: *Convergence rate in line integral coefficient algorithm (Jamet and Tsoulis 2020).*

- The spherical harmonic expansion of topography and the implied gravity signal has been considered in terms of its convergence behavior especially for very high degrees (Bucha and Kuhn 2020). Numerical considerations and technical definitions regarding these expansions, such as the definition of the integration cap, were investigated in the frame of Residual Terrain Modelling computations and spectral forward gravity modelling (Bucha et al. 2019a-d, Hirt et al. 2019a).
- A global computation of terrain corrections has been conducted using SRTM terrain information at a 3'' spatial resolution. The obtained computational volume was tackled by a combination of spatial and spectral techniques in a parallel computing environment (Hirt et al. 2019b).
- The line integral approach for the analytical computation of the potential, first and second order derivatives of a generally shaped polyhedral source has been revisited with emphasis on its geometrical interpretation and computational aspects, see Fig. 5. All algorithmic details of the specific formulation are documented, thus providing useful insights for similar methodologies that are also based on the common approach of gradually breaking down a three-dimensional Newtonian integral into a set of lower dimension integrals by applying the divergence theorem of Gauss (Tsoulis and Gavriilidou 2021).

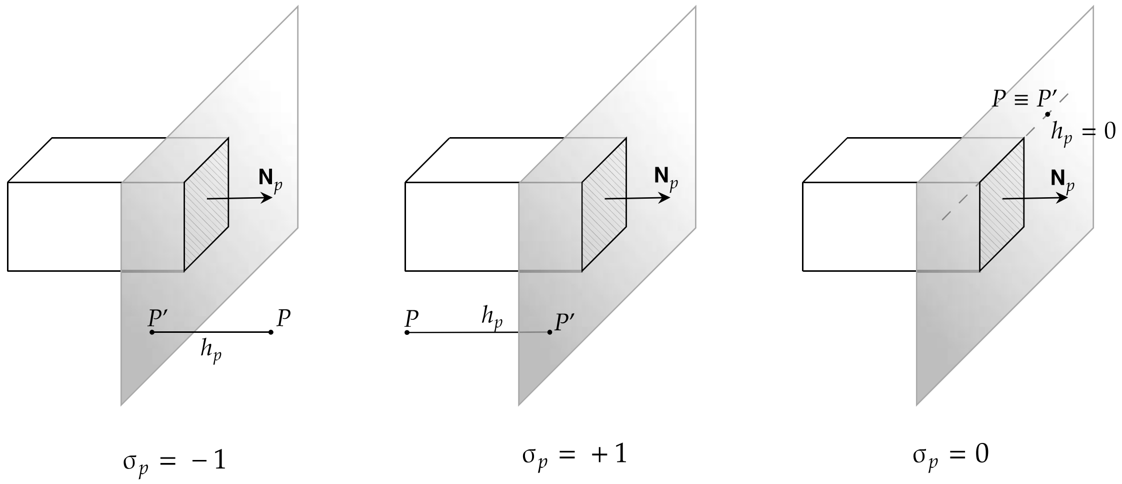

Figure 5: *Relative positions of computation point with respect to a polyhedral face and numerical values of parameter σ_P (Tsoulis and Gavriilidou 2021).*

3. Interactions with the IAG Commissions and GGOS

- Gravity and geoid in the Asia-Pacific: Sub-Commission 2.4e.

4. Overall assessment and outlook

The mathematical formulation and practical evaluation of the gravity signal of finite mass distributions is an interdisciplinary activity with a wide range of application areas. It is an active research topic, substantial for gravity field modeling and interpretation with direct links to other disciplines, such as geophysics and astronomy.

5. Publications

Bucha B, Hirt C, Yang M, Kuhn M, Rexer M (2019a) Residual terrain modelling (RTM) in terms of the cap-modified spectral technique: RTM from a new perspective. *Journal of Geodesy* 93(10): 2089-2108

Bucha B, Hirt C, Kuhn M (2019b) Cap integration in spectral gravity forward modelling up to the full gravity tensor. *Journal of Geodesy* 93(9): 1707-1737

Bucha B, Hirt C, Kuhn M (2019c) Divergence-free spherical harmonic gravity field modelling based on the Runge-Krarup theorem: a case study for the Moon. *Journal of Geodesy* 93(4): 489-513

Bucha B, Hirt C, Kuhn M (2019d) Cap integration in spectral gravity forward modelling: near- and far-zone gravity effects via Molodensky's truncation coefficients. *Journal of Geodesy* 93(1): 65-83

Bucha B, Kuhn M (2020) A numerical study on the integration radius separating convergent and divergent spherical harmonic series of topography-implied gravity. *Journal of Geodesy* 94(12): 112

Claessens SJ, Filmer MS (2020) Towards an International Height Reference System: insights from the Colorado geoid experiment using AUSGeoid computation methods. *Journal of Geodesy* 94(52), doi:10.1007/s00190-020-01379-3

Goyal R, Featherstone WE, Tsoulis D, Dikshit O (2020a) Efficient spatial-spectral computation of local planar gravimetric terrain corrections from high-resolution digital elevation models. *Geophysical Journal International* 221(3): 1820-1831

Goyal R, Featherstone WE, Claessens SJ, Dikshit O, Balasubramanian N (2020b) Indian gravimetric geoid model: data, methods and a preliminary test using Curtin University's approach. In: First Asia-Pacific geoid workshop for IAG Sub-Commission 2.4e.

Goyal R, Featherstone WE, Dikshit O, Nagarajan B (2021a) Comparison and validation of satellite-derived digital elevation/surface models over India. *Journal of Indian Society of Remote Sensing* 49: 971-986, doi:10.1007/s12524-020-01273-7.

Goyal R, Ågren J, Featherstone WE, Sjöberg LE, Dikshit O, Balasubramania N (2021b) Empirical comparison between stochastic and deterministic modifiers over the French Auvergne geoid computation testbed. *Survey Review*, doi:10.1080/00396265.2021.1871821.

Goyal R, Featherstone WE, Claessens SJ, Dikshit O, Balasubramanian N (2021c) Indian gravimetric geoid modelling using Curtin University's approach. *Terrestrial, Atmospheric and Oceanic Sciences*, under-review.

Hirt C, Yang M, Bucha B, Kuhn M (2019a) A numerical study of residual terrain modelling (RTM) techniques and the harmonic correction using ultra-high-degree spectral gravity modelling. *Journal of Geodesy* 93(9): 1469-1486

Hirt C, Yang M, Kuhn M, Bucha B, Kurzman A, Pail R (2019b) SRTM2gravity: An ultra-high resolution global model of gravimetric terrain corrections. *Geophysical Research Letters* 46(9): 4618-4627

Jamet O, Tsoulis D (2020) A line integral approach for the computation of the potential harmonic coefficients of a constant density polyhedron. *Journal of Geodesy* 94(3): 30

Tsoulis D, Gavriilidou G (2021) A computational review of the line integral analytical formulation of the polyhedral gravity signal. *Geophysical Prospecting* 69(8-9): 1745-1760

Joint Study Group T.29: Machine learning in geodesy

***Chair**: Benedikt Soja (Switzerland)*

Members

Kyriakos Balidakis (Germany)
Clayton Brengman (USA)
Jingyi Chen (USA)
Maria Kaselimi (Greece)
Ryan McGranaghan (USA)
Randa Natras (Germany)
Bertrand Rouet-Leduc (USA)
Simone Scardapane (Italy)
Ashutosh Tiwari (India)

1. Activities of the group

Since the establishment of the JSG T.29 "Machine learning in geodesy" (from here on, simply "JSG"), two meetings have been organized to coordinate the activities of the JSG and promote cooperation and interactions of the group members. In the context of the JSG, several activities – as envisioned in the Terms of Reference – have been pursued as highlighted below.

Scientific session organization

A new series of sessions at the European Geosciences Union (EGU) General Assemblies has been established by members of the JSG. The sessions focus on the very topic of the JSG, i.e., machine learning in geodesy. Since their first inception at the virtual EGU 2021 conference, the sessions have attracted enough abstracts to fill oral slots in the EGU Geodesy Division program. Concretely, the following sessions were convened by JSG members:

- vEGU21: G1.4 "Data science and machine learning in geodesy"
- EGU22: G1.3 "Data science and machine learning in geodesy"
- EGU23: G1.3 "New developments in mathematical methods in geodesy, with a focus on machine learning"

The sessions attracted a wide variety of topics related to the application of machine learning in geodesy, featuring several types of data, methods, and applications. In terms of geodetic observation techniques, most of the presentations focused on GNSS, followed by InSAR and satellite gravimetry. Concerning the type of machine learning algorithm, most authors utilized some form of deep artificial neural networks, although tree-based ensemble algorithms were also popular choices. The sessions were well attended and among the most popular sessions in the program of the EGU Geodesy Division.

Editorial activities

A Special Issue in the Journal *Remote Sensing* was organized by members of the JSG. The title of the Special Issue was "Data Science and Machine Learning for Geodetic Earth Observation" and submissions were accepted from mid-2021 to February 2023. Eight papers were published as part of the Special Issue. The papers covered the application of machine learning to the prediction of Earth rotation, tropospheric and ionospheric parameters, among other topics.

A new Special Issue in the Journal *Remote Sensing* was organized in early 2023 by members of the JSG. The title is "Signal Processing and Machine Learning for Space Geodesy Applications", and it can be considered a follow-up activity to the successful Special Issue mentioned above. The submission of manuscripts is possible until the end of 2023.

Website:

A website with a description of the JSG and its activities was created and has since been maintained https://space.igp.ethz.ch/services/services-to-iag/icct-study-group.html. It includes general information on the JSG, such as the Terms of Reference and member list, as well as a description of the activities of the JSG.

Repository:

A major objective of the JSG was the establishment of a platform to share code examples concerning the application of machine learning in geodesy. This would allow interested geodesists with no or just little expertise in machine learning to find examples to get started. On the other hand, also experienced users can benefit from the code, for example concerning specific implementation details.

For this purpose, a public *github* repository has been created by the JSG:
https://github.com/ICCT-ML-in-geodesy

So far, it features working machine learning examples for:
- Earth orientation parameter prediction,
- Ionospheric vertical total electron content prediction,
- CyGNSS-based windspeed retrieval.

Each example is based on a Jupyter Notebook, which is useful for education purposes as it facilitates the interaction with the code and visualization of the results. In addition to the code, the required data is included in the repository. An additional example concerning InSAR-based pixel selection is in development.

2. Achievements and results

The members have been actively researching topics related to the JSG. Related publications and presentations are listed in the last section of this report. Publications can be grouped into:
- Time series modeling and prediction. While mostly based on GNSS data, very different types of parameters are investigated, including station positions, tropospheric and ionospheric parameters as well as Earth orientation (e.g., Gou et al. 2023, Halbheer 2021, Kaselimi et al. 2020ff, Natras et al. 2020ff, Kiani et al. 2021ff, Ruttner et al. 2022).
- InSAR-related investigations, mostly utilizing deep convolutional neural networks (Meganadh et al. 2021, Srivastava et al. 2022, Tiwari et al. 2020ff).
- Gravity field and mass change modeling, primarily to increase the spatial or temporal resolution (Agarwal et al. 2023, Uz et al. 2022f)
- Other topics include the use of artificial intelligence and machine learning for improved VLBI scheduling (Schartner et al. 2021a,b, Wicki 2021), Earthquake classification (Crocetti et al. 2021), seismology (Pan et al. 2020, Shujian 2021, Wu et al. 2022f), wind detection based on GNSS (Aichinger-Rosenberger et al. 2022), high-resolution refractivity field modeling (Shehaj et al. 2023), and remote-sensing-related topics (Marsocci et al. 2023a,b).

A variety of machine learning algorithms were utilized, from decision tree ensembles (random forest, boosting trees, etc.) to artificial neural networks (convolutional, recurrent, graph, transformers, etc.). The investigation of uncertainties (e.g., Natras et al. 2022, Kiani and Soja 2022) is becoming increasingly important. This is also an important principle related to ethical use of artificial intelligence and machine learning as identified in Shelley et al. (2023), a comprehensive report co-authored by Ryan McGranaghan, a member of the JSG.

3. Interactions with the IAG Commissions and GGOS

The JSG is affiliated with IAG Commissions 2, 3, 4, as well as GGOS. Additional engagements by the JSG with other entities are mentioned as well.

GGOS Focus Area on Geodetic Space Weather Research

It has been identified that several members of the JSG work on the topics related to the ionosphere and space weather (M. Kaselimi, R. McGranaghan, and R. Natras). Machine learning has become an important tool for the prediction of ionospheric parameters, typically utilizing not only geodetic measurements, but also solar data as features. This fits well to the scope of the GGOS Focus Area about the relationships between ionosphere/thermosphere and space weather. B. Soja, chair of the ICCT JSG, is vice-chair of the JWG "Improved understanding of space weather events and their monitoring by satellite missions". Synergies between these groups are fostered.

IAG Working Group 4.3.2 Ionosphere Prediction

In a collaboration between members of the JSG and IAG Working Group 4.3.2. "Ionosphere Prediction", predictions of global ionospheric maps (GIMs) have been investigated. The contributions from the JSG (concretely, ETH Zurich) were based on deep learning (convLSTM). In a hindcast experiment, the 1-hour and 1-day forecasts provided by the different institutions were compared with each other for both quiet days in terms of ionospheric activity as well as storm days. More details on the comparison are provided in the report of the IAG WG 4.3.2 as part of the IAG Travaux 2023.

IERS Second Earth Orientation Parameter Prediction Comparison Campaign (2^{nd} EOP PCC)

The chair of the JSG was involved in the committee for the organization of the Second EOP PCC and represented the interests of the JSG in this context. The goal of the EOP PCC was to compare operational EOP prediction products provided by various institutions. The first EOP PCC finished more than ten years ago and was considered a success. A repetition was important due to the significant changes in data quality and availability as well as the new developments in prediction algorithms since then.

Several institutions participated in the 2^{nd} EOP PCC, including ETH Zurich as a member of the JSG. Overall, there was an increase in popularity of machine learning/deep learning for EOP prediction. The 2^{nd} EOP PCC was completed at the end of 2022 and the results are currently under investigation.

ITU-T Focus Group on Artificial Intelligence for Natural Disaster Management

The chair of the JSG has been involved in the ITU-T Focus Group on "Artificial Intelligence for Natural Disaster Management" (FG-AI4NDM), in particular the Topic Group on "AI for Tsunami data monitoring" that heavily relies on GNSS data. Synergies in this context have been identified, as studies related to the detection of earthquakes and tsunamis with machine learning are in progress in different groups, including those of JSG members.

GGOS Focus Area on Artificial Intelligence for Geodesy (AI4G)

On May 12, 2023, the GGOS Coordinating Board accepted the proposal to establish a new GGOS Focus Area on Artificial Intelligence for Geodesy (AI4G). In general, it will utilize methods from the field of Artificial Intelligence (AI), including machine learning techniques, to improve geodetic observations and products. This new GGOS Focus Area will be chaired by Benedikt Soja together with his vice-chair Maria Kaselimi, both members of the JSG. The activities of the JSG have thus commenced in the successful establishment of this new GGOS component, which anchors the topic of machine learning in geodesy at a higher level within the structure of IAG. While the GGOS Focus Area can be seen as a follow-up activity to a certain degree, the focus of the GGOS Focus Area AI4G is on the actual improvement of geodetic data and products, whereas this JSG addresses the theoretical and methodological aspects. Within the GGOS Focus Area AI4G, there will be three Joint Study Groups with close relations to other IAG components:

- AI for GNSS Remote Sensing
- AI for Gravity Field and Mass Change
- AI for Earth Orientation Parameter Prediction

4. Publications

Agarwal V, Akyilmaz O, Shum CK, Feng W, Yang T-Y, Forootan E, Syed TH, Haritashya UK, Uz M (2023) Machine learning based downscaling of GRACE-estimated groundwater in Central Valley, California. *Science of the Total Environment* 865: 161138, doi:https://doi.org/10.1016/j.scitotenv.2022.161138.

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Joint Study Group T.30: Dynamic modeling of deformation, rotation and gravity field variations

Chair: *Y. Tanaka (Japan)*

Members

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Guangyu Fu (China)
Anthony Mémin (France)
Volker Klemann (Germany)
Zdeněk Martinec (Ireland)
Daniele Melini (Italy)
Giorgio Spada (Italy)
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Taco Broerse (Netherlands)
Riccardo Riva (Netherlands)
Wouter van der Wal (Netherlands)
Craig Miller (New Zealand)
Peter Vajda (Slovakia)
José Fernández (Spain)
Pablo J. González (Spain)
Cheinway Hwang (Taiwan)
Hom Nath Gharti (USA)
Jeanne Sauber (USA)

1. Activities of the group

The goal of the joint study group is to promote dynamic modeling of geophysical phenomena with various spatio-temporal scales that are observed with geodetic methods, through collaboration among members and sharing of knowledge on various approaches. Below is a categorization of modeling targets and approaches that members are working on. For further details, refer to the references listed in "Publications". Note that results are excerpted due to space limitations, reflecting Chair's choices.

Earthquake and subduction processes

- Co and postseismic deformation of 1-D layered spherical models (Liu et al., 2019-2021) and effects of curvature, gravity, and compressibility on them (Chen et al., 2020; Liu et al., 2023)
- Coseismic deformation of 3-D spherical models (Tanaka et al., 2019; 2022)
- Earthquake-induced gravity perturbations, seismic wave propagation and magnetic anomaly for a heterogeneous earth model (Gharti, 2019; Gharti and Tromp, 2019; Eaton et al., 2022)
- Topographic effects and material heterogeneities on displacement field (Langer et al., 2019)
- Tearing of the lithosphere at the lateral end of a subduction zone (Broerse et al., 2022)
- Effects of mantle flow on postseismic faster landward motion (D'Acquisto et al., 2023)
- Viscoelastic structure constrained from postseismic satellite gravity field change (Sauber et al., 2021) and rapid analysis of postseismic deformation using laser ranging data (Han et al., 2022)
- Sea level rise escalated by postseismic relaxation (Han et al., 2019)

Volcano

- Caldera formation model based on gravity and magnetic inversion (Miller et al., 2020; 2022)
- Geological insights of summit area of Mt. Etna from microgravimetry (Pánisová et al., 2023)
- Correlation between the tsunami and the acoustic-gravity waves triggered by the 2022 Tonga eruption (Omira et al., 2022)
- First thermal-and-topographic satellite data analysis for estimating lava effusion rates and volume (Plank et al., 2023)
- Mechanisms of volcanic activities revealed from geodetic, geophysical and petrological observations (Wallace et al., 2020; Rodriguez-Molina et al., 2021; Fernández et al., 2021; 2022)
- Review on Ruapehu and Tongariro stratovolcanoes in New Zealand (Leonard et al., 2021)

Inversion and data analysis method

- Inference of complex fault slip pattern based on a crack model derived from laboratory experiments (Jian et al., 2022)
- Bayesian approach to identify the mechanism of postseismic deformation (Nijholt et al., 2021)
- Treatment of the deformation–induced topographic effect in interpretation of spatiotemporal gravity change (Vajda et al., 2019; 2020a; 2020b; 2021)
- Nonlinear inversion of gravity changes and surface deformation to determine 3D bodies embedded into elastic/poroelastic medium (Camacho and Fernández, 2019; Camacho et al., 2020)
- Advanced InSAR and GNSS analysis for ground motion monitoring (Jiang and González, 2020; Lazecký et al., 2020a; 2020b; Sparacino et al., 2020; Weiss et al., 2020; Fonseca et al., 2021; Escayo et al., 2020; 2022; Huang et al., 2022; Kos et al., 2023; Zhang et al., 2023), integration of InSAR, SAR and GNSS data (Simons et al., 2022) and inference of ice mass loss from InSAR data (Erfan Jazi et al., 2022).
- Argument on the design of bootstrap methods (Trottini et al., 2021)
- Aerial photogrammetry method using unmanned aerial vehicle (Arévalo-Verjel et al., 2022)

Glacial Isostatic Adjustment

- Physical analysis of the GIA pattern based on sea level equation (Spada and Melini, 2019a)
- Sensitivity analysis using different models including lateral heterogeneity (Melini and Spada, 2019; Bagge et al., 2021; Simon et al., 2022; van Calcar et al., 2022; Irie and Okuno, 2023)
- Present-day global GIA model based on gravity field data (Sun and Riva, 2020)
- Seismicity affected by present-day GIA in Alaska (Rollins et al., 2021; Sauber et al., 2021; 2022)
- Regional analysis and constraints on compositional and rheological structures (Pappa et al., 2019; Reusen et al.; 2020; Rovira-Navarro et al., 2020; Spada G, Melini, 2021)
- Reviews on ArCS project and GIA including its modeling (Goto-Azuma et al., 2021; van der Wal et al., 2022)
- Data assimilation of paleo sea-level data to constrain GIA models (Schachtschneider et al., 2022)

Atmosphere, ocean and terrestrial water

- Nontidal atmospheric, oceanic and hydrological loading in vertical motion (Mémin et al., 2020a)
- Impacts of Megalake Chad on paleo-shorelines (Mémin et al., 2020b)
- Multivariate data assimilation for improved groundwater storage estimates (Tangdamrongsub et al., 2020; Yin et al., 2020; Khaki et al., 2023)
- Land subsidence due to seasonal hydrological loading in Taiwan (Yang et al., 2020)
- Seasonal change in seismicity correlated with terrestrial water storage (She et al., 2022)
- Groundwater flow model in a volcanic/land subsidence area for gravimetry (Chen et al., 2021; 2023; Lien et al., 2022)

Tides and related phenomena

- Effects of lateral heterogeneity and anelasticity in earth structure on ocean tide loading (Huang et al., 2021; 2022)
- Tidal modulation of seismicity during a volcanic unrest (Miguelsanz et al., 2021)
- Poroelastic model to explain tidal triggering of tectonic tremors (Sakamoto and Tanaka, 2022)
- Decadal variations in seismicity and slip history reproduced with a fault slip model driven by tides and non-tidal ocean loading (Tanaka et al., 2022)

Earth rotation and global structure/deformation

- Effects of earthquakes (Xu and Chao, 2019) and electromagnetic core-mantle coupling (Kuang et al., 2019) on polar motion
- The 6-year LOD fluctuation and its mechanism (Chen et al., 2019; Chao and Yu, 2020; Chao et al., 2020; Shih and Chao, 2020).
- Global thermochemical model of the lithosphere and underlying upper mantle constrained by seismic, geodetic, surface elevation and heat flow data (Fullea et al., 2021)
- Geocenter motion and gravitational field inverted from GPS and GRACE (Razeghi et al., 2019)
- Earth's free oscillation excited by the 2004 Sumatra earthquake revealed from GRACE KBR data (Ghobadi-Far et al., 2019)

Other Celestial bodies

- Tidal deformation of Moon (Briaud et al., 2023; Hu et al., 2023) and Venus (Saliby et al., 2023)
- Tidal response of porous media and its application to Enceladus (Rovira-Navarro et al., 2022)

2. Achievements and results

The results obtained over the past four years could be characterized as follows:

- Multidisciplinary data use including thermal, magnetic, geochemical, and geological observations.
- Modeling and observability of lateral heterogeneous viscoelastic structures
- Several new physical concepts in modeling subduction zone processes and tides
- Applications of global deformation theory to other celestial bodies
- Promotion of related fields brought about by software release (see below)
- Mutual validation between different theories by the members (Klemann et al., 2022)
- We created a website to share our results: https://onl.tw/J9p5ive (contents still in

preparation, URL may be subject to change).

Software

- Strain analysis method that can deal with large deformation (Broerse et al., 2021, https://doi.org/10.5281/zenodo.4529475)
- Determination of 3D density structures from gravity anomaly data (GROWTH-dg) (Camacho et al., 2021a; 2021b; Bódi et al., 2023; Vadja et al., 2023)
- Surface glacier ice flow from Sentinel-2 optical image data (Nagy et al., 2019, https://www.nve.no/hydrology/glaciers/copernicus-glacier-service/glacier-velocity/)
- GIA simulation (SELEN version 4.0) (Spada and Melini, 2019b)
- Earthquake-induced gravity perturbations (Gharti et al., 2019, geodynamics.org)
- Viscoelastic Love numbers for general planetary models: ALMA^3 (Melini et al., 2022)
- Advection-diffusion-reaction equations in 3D heterogeneous models using the spectral-element method (SPECFEM3D, Gharti et al., 2022)

3. Interactions with the IAG Commissions and GGOS

The modeling by the members covers a wide range of subjects, and each member has been working in collaboration with the related IAG components and GGOS. Here are a few examples of session and workshop organized by the members:

- Interpretation of volcanic surface deformation using a 3D multi-source approach. EGU General Assembly 2021, Fernandez J et al.
- GIA workshop, see https://www.scar.org/scar-news/serce-news/gia-workshop-2019, lecturer in a GIA summer school, see https://polenet.org/2019-glacial-isostatic-adjustment-gia-training-school.
- First/Second Asia Pacific Geoid workshop for IAG-SC2.4e, 2020/2022, Huang C et al.

4. Publications

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Joint Study Group T.31: Multi-GNSS theory and algorithms

***Chair**: Amir Khodabandeh (Australia)*

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Bofeng Li (China)
Jacek Paziewski (Poland)
Robert Odolinski (New Zealand)
Baocheng Zhang (China)
Ali Reza Amiri-Simkooei (Iran)
Dimitrios Psychas (The Netherlands)
Gabriele Giorgi (Germany)

1. Activities of the group

While the planned group's activities were delayed due to the pandemic in the first period of 2019-2020, the group has achieved their main objectives during the second period of 2021-2023. A number of the group members could meet and discuss their collaborative research topics in two proceedings: 1) the IUGG General Assembly (Montreal, 2019), and 2) the Hotine-Marussi Symposium (Milan, 2022).

2. Achievements and results

Some of the multi-GNSS research outcomes of the group members are listed below:

- A new Frequency Division Multiple Access (FDMA) GLONASS model: Teunissen and Khodabandeh (2019) and Hou et al. (2020) studied and applied the new GLONASS FDMA ambiguity resolution model, as developed by Teunissen (2019), for short- and long-baseline data. This FDMA model is also applicable to low-cost GNSS receivers able to track FDMA GLONASS signals, such as the ublox ZED-F9P receivers, as explicitly demonstrated in Teunissen and Khodabandeh (2019). Zaminpardaz et al. (2021) performed a Code Division Multiple Access (CDMA) and FDMA combination of GLONASS-only satellites for real-time kinematic (RTK) positioning, and analyzed its performance using the future GLONASS constellation.
- Next Generation GNSS constellations: Giorgi et al. (2019) reviewed recent progress in optical frequency references and optical communication systems and discussed their utilizations in global satellite navigation systems and satellite geodesy. The study concerned a *revised* GNSS architecture, discussing a novel architecture which enables a more clear-cut separation between the space and time domains—which hinders current satellite navigation and geodesy applications—with a strong impact on orbit determination and time dissemination capabilities.
- E1/E5b rovers receiving E1/E5a RTK corrections: Sleewaegen and De Wilde (2019) presented a patent-pending technique addressing the situation where an E1/E5b rover receives RTK corrections of E1/E5a signals. Accordingly, the rover can recreate the missing E5b corrections by modifying his RTK-based observation equations, thus achieving RTK positioning without significant loss of positioning accuracy.
- Best Integer Equivariant Estimation applied to mass-market multi-GNSS receivers: Odolinski and Teunissen (2020a) analyzed the normal distribution-based BIE estimation for low-cost single-frequency (SF) multi-GNSS RTK positioning. Odolinski and Teunissen (2020b) analyzed subsequently also the corresponding BIE performance for

low-cost dual-frequency (DF) long baseline multi-GNSS RTK positioning. It was shown that the BIE estimator outperforms ILS and the float solutions in terms of their positioning mean squared errors (MSEs).

- Role of multi-GNSS integration on the phase-only ambiguity resolution performance: Khodabandeh et al. (2021) studied the role played by the multi-GNSS integration in improving the ambiguity resolution performance of a dual-epoch phase-only model. It was shown that multi-GNSS integration makes near real-time centimetre-level phase-only positioning possible. The applicability of the presented phase-only model has the potential to be extended for LEO-based positioning applications through communication signals that are *not* necessarily accompanied by pseudo-range measurements.
- LEO enhanced Global Navigation Satellite System (LeGNSS): Ge et al. (2020) studied several aspects of LEO constellations in terms of number of LEO orbital planes, number of LEO satellites, and the selection of orbital inclinations to find out a suitable LEO constellation for LeGNSS. It was shown that the combination of several LEO constellations with different inclinations can lead to a more uniform distribution of the number of visible LEO satellites along the latitude for global fast convergent PPP.
- Smartphone positioning: Paziewski et al. (2021) assessed the quality of multi-GNSS observations of recent Android smartphones. It was shown that show that the higher the elevation of the satellite, the larger discrepancy in C/N0 between the geodetic receivers and smartphones. Through positioning experiments, it was demonstrated that it is feasible to obtain a precise cm-level solution of a smartphone to smartphone relative positioning with fixed integer ambiguities.
- Bias-bounded Estimation of AmbiguiTy (BEAT): In the literature, it is often argued that pseudo-range (code) measurements must accompany their carrier phase counterparts in order to realize single-epoch (instantaneous) positioning. This seems to be a bottleneck for opportunistic navigation applications in which fast positioning is required using measurable codeless interferometric signals. To address this research gap, Khodabandeh (2022) developed a new integer estimation method by extending the existing theory of integer estimation to "bias-bounded mixed-integer models". This extension accommodates the presence of bounded real-valued parameters in mixed-integer models through incorporating prior knowledge of a set, in which the parameters reside, into the estimation process. This new codeless estimation method, BEAT, can be employed for the processing of phase measurements that are dedicated to ranging and navigation techniques, including those using the carrier phase signals of recent mega-constellation LEO satellites. Figure 1 illustrates, for a simple two-dimensional example, how the BEAT pull-in regions are formed to incorporate potential non-zero biases in carrier phase float ambiguity solutions, increasing the chance of correctly resolving the solutions to their integers, thereby improving the bias-affected success-rate of the method of Integer Least-Squares (ILS).

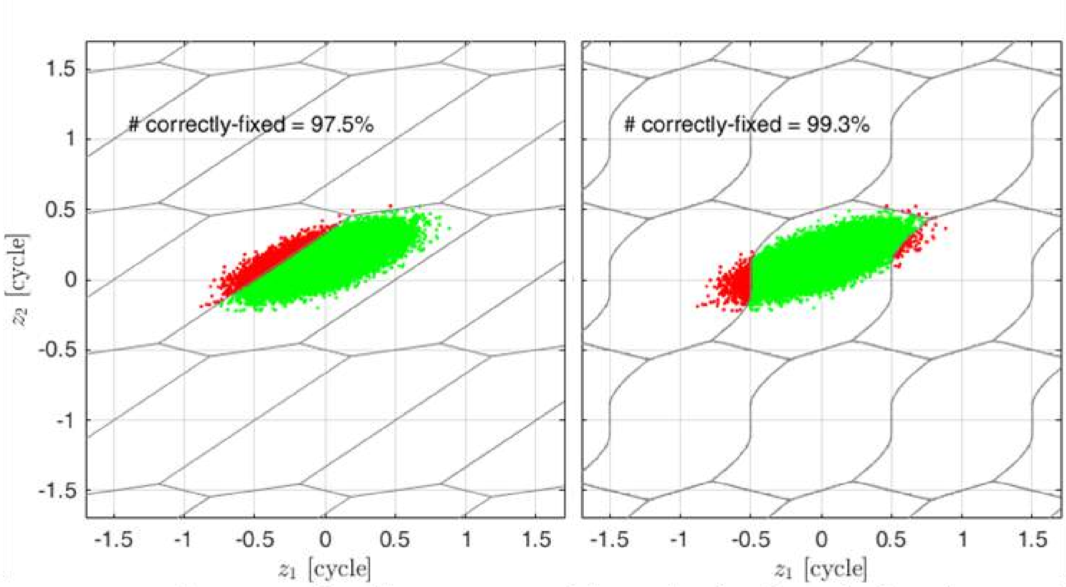

Figure 1: *Two-dimensional pull-in regions of the methods of ILS (left) and BEAT (right) shown in grey lines. 100,000 normally-distributed float ambiguity solutions (green and red dots), with a non-integer bias of size 0.14 cyles in their second component (z2), are simulated. By incorportating non-zero bias-bounds, the number of correctly-fixed solutions (green dots) increases, that is, the bias-affected success-rate of ILS (97.5%) increases to its BEAT counterpart (99.3%).*

3. Interactions with the IAG Commissions and GGOS

The IUGG General Assembly was held in Montreal, Canada in July 2019, while the Hotine-Marussi Symposium was held in Milan, Italy in June 2022. In these two events, a number of the group members met and discussed potential research topics. There are also common research interests with WG 4.2.2: "Ambiguity resolution for low-cost GNSS positioning".

4. Publications

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Joint Study Group T.32: High-rate GNSS for geoscience and mobility

Chair: *Mattia Crespi (Italy)*

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Sebastian Riquelme (Chile)
Giorgio Savastano (Luxembourg)
Peiliang Xu (Japan)

1. Activities of the group

In the framework of JSG T.32 activities the following topics were investigated, in agreement with the original plans and goals:

- high-rate GNSS for real-time and post-processing earthquake seismology and ionosphere seismology,
- high-rate GNSS for real-time estimation of ground-motions induced by natural causes and anthropogenic activities (special attention to mining),
- high-rate GNSS for structural health monitoring (SHM),
- high-rate GNSS as a resource for improving seismological networks and tsunami early warning services,
- high-rate GNSS and other sensors integration for kinematic parameters estimation and vehicle trajectory determination,
- high accuracy static and kinematic positioning with Android multi-frequency and multi-GNSS smartphones (EU GSA Task Force).

2. Achievements and results

The activities of the group members developed both within the group and in cooperation with other Colleagues/research groups, mainly following the foreseen plans. The main topics which have been focused are listed hereafter:

- comprehensive inventory of the available and applied methodologies for high-rate GNSS,
- real-time earthquake seismology: earthquake magnitude estimation from peak ground displacements (PGDs),
- real-time tomography: earthquake magnitude estimation from peak ground displacements (PGDs),
- the first initialization of GNSS rotational seismology demonstrated to be feasible,
- high-rate GNSS as a resource for improving seismological networks and tsunami early warning services (GGOS Geohazards Focus Area GATEW Working Group) – cooperation with JSGs T.29 and T.36,
- real-time estimation of ground-motions induced by natural causes and anthropogenic activities (special attention to mining - EU H2020 GATHERS project),
- high accuracy static and kinematic positioning with Android multi-frequency and multi-GNSS smartphones (EU GSA Task Force),
- estimation and comparison of velocity and acceleration from very high-rate GNSS and from current velocimeters and accelerometers,
- improved methods for high accuracy displacements detection with multi-frequency and multi-GNSS receivers,
- accuracy and reliability achievable with PPP kinematic positioning and monitoring based on real-time data stream service,
- integration approaches of multi-GNSS and multi-frequencies low-cost receivers and other sensors,
- improvement of earthquake magnitude estimation from peak ground displacements (PGDs).

3. Interactions with the IAG Commissions and GGOS

The interactions with other IAG components were mainly related to the following topics of shared interest:

- Commission 1 – accuracy and reliability of PPP kinematic positioning based on real-time data stream service.
- Commission 3 (SC 3.5: Seismogeodesy (joint with IASPEI)) – GNSS seismology.
- Commission 4 (SC 4.1: Emerging Positioning Technologies and GNSS Augmentations) – high accuracy static and kinematic positioning with Android multi-frequency and multi-GNSS smartphones
- GGOS (Geohazards Focus Area) – high-rate GNSS as a resource for improving seismological networks and tsunami early warning services.

4. Publications

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Joint Study Group T.33: Time series in geodesy and geodynamics

Chair: *Anna Kłos (Poland)*

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1. Activities of the group

Main activity of the group is a co-organization of the PICO sessions "Mathematical methods for the analysis of potential field data and geodetic time series" at the European Geosciences Union General Assemblies in Vienna, Austria in 2020, 2021, 2022 and 2023. Due to pandemic, meetings in 2020 and 2021 were held on-line, but the session has still been a great success, due to several presentations submitted and the interest shown by the geodetic community. In 2023, the session was combined with a session on machine learning and held as a regular oral and poster session.

2. Achievements and results

Members of the group were very active in the past four years. Below is a list of major results they obtained:

The problem of discrete Fourier analysis of complex valued function observations at equidistant or non-equidistant time moments using the standard set of complex harmonics and least squares method is studied. Observation model considered includes correlated complex valued random errors with zero mean value and finite variance. Uniqueness and finite sample properties of the observed function Fourier coefficients estimators obtained by the least squares method are examined and compared with those of the standard Discrete Fourier Transform (Popiński 2020).

The study of Keleş et al. (2021) aims to fill the 11-months of gap between GRACE and GRACE-FO missions where there are no observations. GRACE-like monthly terrestrial water storage anomalies (TWSA) for this 11-months period using data driven, state of the art deep machine learning algorithms/models were produced. The time series of the observed GRACE/GRACE-FO derived TWSA have been used along with series of hydro-meteorological observations to retrieve spatio-temporal interconnections/relationships between the two by adjusting the deep neural network parameters through advanced machine learning algorithms.

Global seismic tomography has been compared using the varimax Principal Component Analysis (PCA). It was found that such rotated version of the PCA which compresses the large amount of information is a useful tool for the quantitative comparison and interpretation of tomography models (De Viron et al. 2021).

The capability of time-series clustering to retrieve such features on real time-lapse ERT datasets considering three aspects: (1) the comparison between three clustering algorithms k-means, hierarchical agglomerative clustering (HAC), and Gaussian Mixture Model (GMM), including the question of the optimal choice of cluster number and the identification of resistivity series whose classification is uncertain, (2) the effect of adding a spatial constraint in clustering, and (3) the robustness of the approaches to various representations of resistivity values and the number of time-steps involved in the clustering (Delforge et al. 2021).

A parsimonious data-driven model, EDM-Simplex, with two objectives: forecasting recession and characterizing its nonlinear behaviour was proposed. The new model through a global sensitivity analysis applied to three distinctive hydrograph series from a heterogeneous karstic catchment was evaluated (Delforge et al. 2020).

The weighted wavelet transform was used to study naked-eye observations series of sunspots from 200 BC to 1918 AD from historical documents. The results show the Suess/de Vries cycle with a period from 195- to 235-year existing in the discontinuous sunspot series. Meanwhile, the cycle signal changes with time (Lihua Ma and Vaquero 2020).

With wavelet analysis, possible connection between average temperature series in the contiguous United States during the period from January 1895 to July 2018 and solar activity was investigated. The results show modulation action from solar activity plays an important role in the oscillation of the contiguous United States average temperature, especially on decade time scales (Lihua Ma 2021a).

The Lomb-Scargle periodogram was used to study long-term slowdown trend, periodic and irregular fluctuations in the LOD series in the past 4000 years. The significant quasi-1500 years cycle signal was found. Furthermore, with weighted wavelet Z-transform, time-varying characteristics of the cycle in the LOD change were obtained (Lihua Ma 2021b).

The Lomb-Scarle periodogram was also employed by Klos et al. (2021b) to provide a comprehensive assessment of noise present in daily GPS height time series after seasonal signals were subtracted by using conventional harmonic function approach and GRACE-assimilating hydrological model. Analysis was also supported by Maximum Likelihood Estimation (MLE) approach. They concluded that the GRACE-assimilated model output removes the effect of high-frequency hydrological deformations, producing less correlated residuals of GPS height time series.

Hydrology-induced interannual displacements derived from GRACE (Gravity Recovery and Climate Experiment) observations and hydrological models were studied by Lenczuk et al. (2020). Authors used Singular Spectrum Analysis (SSA) to model the interannual variations of displacements in eastern European river basins. They noted a large interannual displacements observed by GRACE between 2004 and 2009, but mismodelled by both GLDAS (Global Land Data Assimilation System) and WGHM (Water GAP Global Hydrological Model) hydrological models.

Richter et al. (2021) addressed a problem of a gap between two consecutive GRACE missions, namely GRACE and GRACE Follow-On, which is 11 months long. They filled the gap by combining low-resolution gravity field models derived from European Space

Agency's Swarm satellites with the dominating spatial modes of mass variability obtained from GRACE by using Empirical Orthogonal Function (EOF) analysis. In this way, they reduced noise present in Swarm gravity fields and obtained sufficient gravity changes for a few global basins.

Delforge et al. (2022) employed the monthly global ocean bottom pressure (OBP) from GRACE(-FO) mass concentration solutions and analyzed the global patterns of interannual and intraseasonal mass variations. They removed trends and seasonal signals from the OBP time series. Then, spatiotemporal patterns were identified using rotated PCA. The authors identified 23 modes and discussed them with regards to sea-level anomalies, wind stress curl, and major climate indices.

GPS (Global Positioning System) tropospheric products were used for the first time to monitor and predict hurricane tracks by Eijgu et al. (2021). Authors employed GPS-derived integrated water vapour (IWV) derived for stations situated at the east coast of North America and constructed spaghetti plot lines during hurricane season with two major hurricanes Harvey and Irma, both occurred in 2017.

Yuan et al. (2021) analyzed the trends of IWV over Europe and discussed them in terms of climate change. They employed GPS-observed IWV time series and values modelled within the newly released fifth generation European Centre for Medium-Range Weather Forecasts (ECMWF) atmospheric reanalysis (ERA5) for the period 1994–2019. They demonstrated that autoregressive moving average ARMA(1,1) noise model is preferred to describe the stochastic properties of both GPS-observed and ERA5-derived IWV time series rather than the commonly assumed white noise (WN) or first-order autoregressive AR(1) noise for about 68% of time series. Results have strong implications for climate-related analyses, since the errors of climate-related trends are computed assuming a proper noise model.

Klos et al. (2023) provided a comprehensive assessment of stochastic properties of Zenith Total Delay (ZTD) time series over Europe. They employed four different GNSS solutions provided by the EPN analysis centers, which differed in terms of processing strategy. They proved that trends and seasonal components of ZTD time series are consistent between the solutions, but changes in the processing influence the stochastic properties of these time series.

Klos et al. (2021a) provided a comprehensive assessment of sensitivity of GPS displacements for non-tidal environmental loadings for stations in Eurasia. They examined various frequency bands from the lowest frequencies, i.e., 2 days, up to long-term trends, by retrieving them using wavelet decomposition. They concluded that non-tidal atmospheric loading is a main contributor to GPS displacements in the highest frequencies, while hydrological loading contributes to seasonal band only.

Gobron et al. (2021) analyzed the impact of aperiodic variations present in the predictions of displacements from non-tidal atmospheric and oceanic loading on the stochastic properties of GPS displacements. They examined the repeatability of displacement residuals, the power-spectrum of displacement residuals, the estimated time-correlation properties, the corresponding velocity uncertainties, and the spatial correlation of the residuals. They showed that correcting the GPS displacements by both loading models may reduce velocity uncertainties at high latitudes by 70 %.

Gobron et al. (2022) analyzed the impact of offsets on the low-frequency stochastic properties of geodetic time series. They demonstrated that part of the impact of offsets on the stochastic properties of the time series is due to estimation bias of the MLE method. This has a dramatic effect on the uncertainties of deterministic parameters, such as velocity.

Lenczuk et al. (2023) examined the sensitivity of GPS displacements to changes in groundwater masses. They used the probabilistic PCA to examine the spatio-temporal variations of displacements from 98 GPS stations located in 9 regions of the world recognized as those where changes in groundwater masses are the most significant and compared them with GRACE-derived and model-predicted changes. They found that GPS observed displacements arising from groundwater mass changes capture most of the wet and dry periods reflected by the Standardized Precipitation Evapotranspiration Index (SPEI). Also, a prominent 6-year cycle was detected in those time series and fits nicely into an ongoing discussion about Earth-system-related signal.

The atmospheric surface pressure time series of Madras, Darwin, and Tahiti together with non-tidal length-of-day (LODR) variations and axial component of atmospheric angular momentum (AAM) were analyzed by wavelet transform as well as the combination of the Fourier transform band pass filter with the Hilbert transform (FTBPF+HT) to detect interannual and intra-seasonal oscillations in them. Variable characteristics of annual and semi-annual oscillations in the atmospheric surface pressure variations, LODR and AAM were found (Lihua Ma et al. 2021).

The integrated Length-of-Day (LoD) values from GNSS were compared against UT1-UTC values from VLBI. Special focus was put on the numerical integration itself, as well as on the calibration of the biases which are inherent in the LoD series from GNSS (Mikschi et al. 2019).

The common geocenter signal in the the geocenter coordinates based on four independent techniques: Doppler Orbitography and Radiopositioning Integrated by Satellite (DORIS), Global Navigation Satellite System (GNSS), Gravity Recovery and Climate Experiment with the ocean bottom pressure model, and Satellite Laser Ranging, was found using the wavelet-based semblance filtering (WBSF) method. Variable amplitudes and phases of the annual and semi-annual oscillations in the geocenter coordinates of these techniques by the combination of the Fourier Transform Band Pass Filter (FTBPF) with the Hilbert Transform (FTBPF+HT) and to compare their mean values with those obtained by other authors (Kosek et al. 2020).

Similar amplitude variations of 3–4-year oscillations caused by ENSO were found in LOD, axial component of atmospheric angular momentum, global mean surface temperature, southern oscillation index, Nino3.4 index and global mean see level based on the tide gauge and satellite altimetry data using FTBPF+HT (Kosek 2020).

At Jet Propulsion Laboratory (JPL) a time series approach to determining ITRF-like combined reference frames using sequential estimation was developed. The main concepts underlying the determination of terrestrial reference frames (TRFs) through a recursive algorithm based on Kalman Filtering and Rauch-Tung-Striebel (RTS) smoothing which is currently adopted to compute sub-secular frame products (JTRFs) were reviewed. Comparisons of JTRF solutions to standard products such as the International Terrestrial Reference Frame (ITRF) suggest high-level consistency in a long-term sense with time derivatives of the Helmert transformation parameters connecting the two TRFs below 0.18 mm/yr (Abbondanza et al, 2020).

Van Camp et al. (2022) proposed a new quantitative approach to search for mantle plumes in global seismic tomography models. The method is based on the naive Bayesian clustering analysis and coupled with varimax principal component analysis. They found that their new approach greatly reduces the errors of detection of different seismic velocities, comparing to arbitrary assumptions.

3. Interactions with the IAG Commissions and GGOS

There are several interactions with other IAG components. The papers of Lenczuk et al. (2020) and Keleş et al. (2021) are relevant to the goals/tasks of IAG Commission 2 (Gravity Field) as well as those of GGOS where monitoring and prediction of extreme weather events and consequent hazards (floods/droughts) are crucial. Research activities of Lihua Ma (2021a, b) as well as Lihua Ma and Vaquero (2020) involve Earth rotation and geodynamics (IAG Comissions 3), space reference frame (IAG Comissions 1) and positioning and application (IAG Comissions 4 and GGOS). Research activities of Eijgu et al. (2021), Klos et al. (2021a,b), Richter et al. (2021) and Kosek (2020) closely inherent with the objectives of ICCC (Inter-Commission Committee on Geodesy for Climate Research). Dr. Anna Klos was the convener of the session G3.2 "Observing geophysical signals in the Climate and Earth System through Geodesy" at the EGU 2020, 2021, 2022 and 2023 and the session "Geodesy for Climate Research" held during the AGU in 2020, 2021 and 2022.

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Joint Study Group T.34: High resolution harmonic analysis and synthesis of potential fields

Chair: *Sten Claessens (Australia)*

Members

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Toshio Fukushima (Japan)
Ropesh Goyal (India)
Christian Hirt (Germany)
Elmas Sinem Ince (Germany)
Norbert Kühtreiber (Austria)
Kurt Seitz (Germany)
Michal Šprlák (Czechia)
Philipp Zingerle (Germany)

1. Activities of the group

Research by members of the group has provided new insights into high-resolution harmonic analysis and synthesis of potential fields over the period 2019-2023.

New methods have been developed for the computation of high-resolution harmonic potential models using ellipsoidal geometry. A major component of any high-resolution harmonic model is forward gravity modelling to generate a topographic gravity model. Ince et al. (2020) derive a mass layer concept that makes use of a sequence of thin ellipsoidal shells. Ince et al. (2022) show the impact of the shell thickness on the model accuracy and computation time. Their model agrees with older models up to d/o 2190 at the sub-mm level in the high-frequency components of the gravity field (n>180). Abd-Elmotaal and Kühtreiber (2021) derive a direct technique suitable for computation of the topographic or topographic-isostatic potential for a certain data-window as well as globally, which also shows a good agreement to earlier models. Šprlák et al. (2020a) derive a novel, explicit, and efficient method for spectral forward modelling in the spheroidal domain and apply this to the Moon and 1 Ceres. Šprlák et al. (2020b) also study spectral forward gravity modelling using lateral and spatial 3D density variations and show the significance of density variations for modelling of the topographic gravity field of the Moon.

The combination of different data sources requires special attention in the creation of a high-resolution global gravity model. Ince et al. (2020) combine a topographic gravity model with a satellite-only or combined model using a weighted combination of the harmonic coefficients in a dedicated degree transition range. Zingerle et al. (2019a, 2021b) describe different strategies for the combination of topographic gravity and satellite gravity data and Zingerle et al. (2021a) present a method for the smooth integration of terrestrial and airborne gravity observations into high-resolution global models. Their method relies on a combination of terrestrial data grids with a satellite-only model on the normal equation level, thus far up to degree and order 5400.

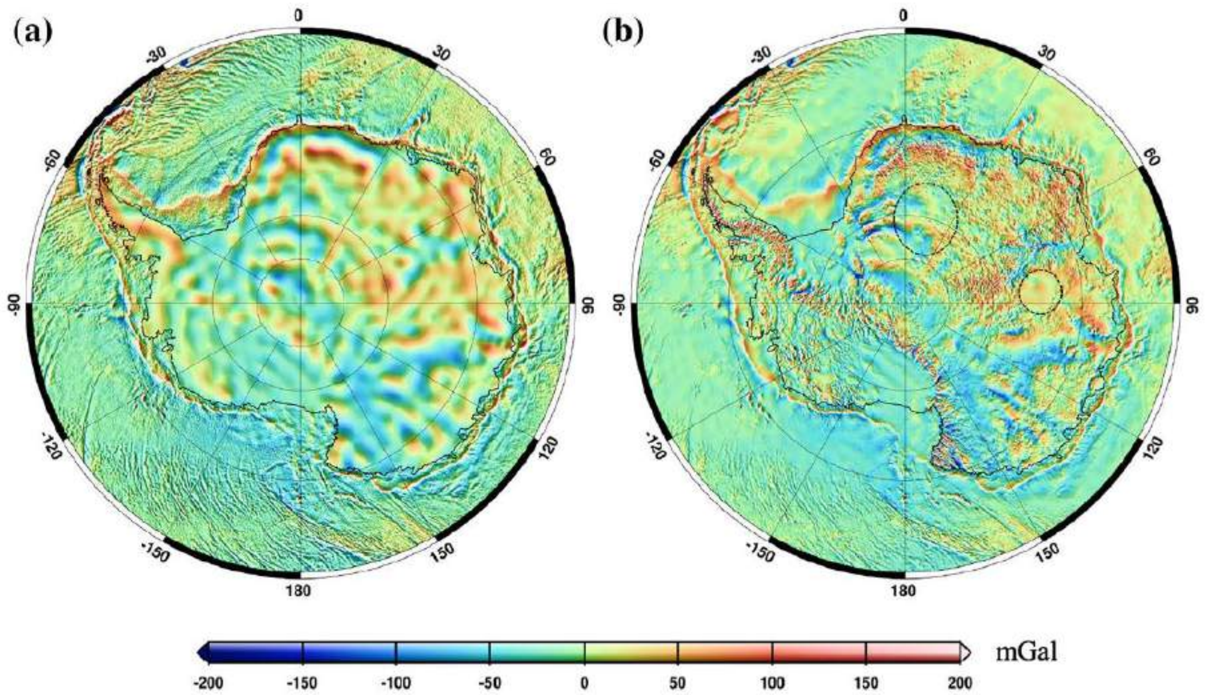

Figure 1: *Spherically approximated gravity anomalies synthesised from a) EIGEN-6C4 and b) GOCE-DIR6 combined with forward-modelled topography, showing the enhancement due to the contribution of the forward model over Antarctica (Ince et al. 2020).*

High-resolution residual terrain modelling (RTM) also has an application in the development of combined global gravity models. Hirt et al. (2019) apply spectral forward modelling to investigate RTM approximation errors including the harmonic correction problem. Bucha et al. (2019a, 2019b) presented a method for the spectral forward modelling of data within a spherical cap that can be used to mitigate the spectral filter problem. Bucha et al. (2019c) provided a new perspective on RTM, showing that both these problems are caused by filtering in the topography domain and can be avoided by filtering in the gravity domain.

Possible divergence of spherical and spheroidal harmonic series near the Earth's surface is an ongoing challenge, but recent studies on the Moon and other celestial bodies have provided interesting insights. Šprlák et al. (2020a) quantify divergence of both spherical and spheroidal series on the Moon and 1 Ceres. Šprlák and Han (2021) review the use of spherical harmonic series inside the Brillouin sphere and derive analytical downward continuation errors for the gravitational potential and its first- and second-order derivatives. They show through numerical analysis with GRAIL and LOLA satellite data that models of the lunar gravitational field based on external spherical harmonics do not correspond to the true field inside the Brillouin sphere, and that analytically downward continued fields tend to diverge at high frequencies. These findings were further expanded upon in Šprlák et al. (2022, 2023).

Bucha et al. (2019d) and Bucha and Kuhn (2020) also study the divergence effect on the Moon. They show that a Runge-Krarup type harmonic series can be created that does not diverge near the surface like a harmonic series derived by spectral forward modelling, and that harmonic series derived only from far-zone topography do not significantly diverge. Bucha and Sansò (2021) further study the divergence effect for the irregularly shaped asteroid Bennu, revealing conceptual differences between spherical harmonic coefficients from satellite data and from surface gravity data. Error bounds for the gravitational potential obtained from spherical harmonic series to ultra-high degree and order are derived by Bucha et al. (2021), who applied it to estimate the upper bound of errors in terrain corrections on Earth.

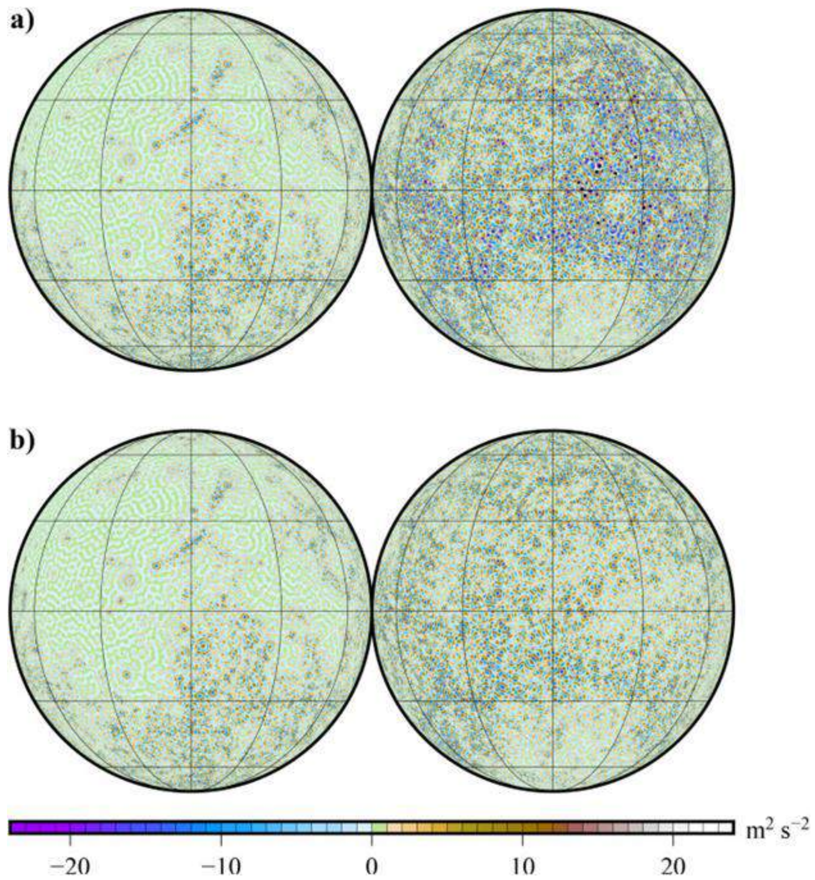

Figure 2: *Gravitational potential of the Moon (left: near side, right: far side) synthesised inside the Brillouin sphere ($r = 1738$ km) from (a) external and (b) internal spherical harmonic series, showing that the analytical continuation of the external harmonic series into the crustal masses on the far side fails (Šprlák and Han 2021).*

Validation of high-resolution harmonic analysis methods for topographic gravity modelling is routinely performed through comparison with gravity forward modelling in the spatial domain. This has proved very successful in spherical approximation but is still a challenge for modelling of the ellipsoidal topographic potential (Claessens and Kuhn 2019). Members of the group have also worked on forward gravity modelling in the spatial domain, which can be of use for these validations among other applications (e.g., Fukushima 2020a, 2020b; Goyal et al. 2020a; Marotta et al. 2019; Yang et al. 2019, 2020). Seitz et al. (2023) derive formulas for the external gravitational potential of a homogeneous ellipsoidal shell that can be used for testing of forward modelling algorithms in the ellipsoidal domain.

Spherical harmonic synthesis was considered by Goyal et al. (2020b) and Bucha (2022b). The latter derived a new method to compute area-mean potential values from a spherical harmonic expansion on irregular surfaces.

2. Achievements and results

Apart from the many theoretical advances described in the previous section, research by members of the group has also resulted in the generation of several high-resolution gravity models. Many of these are published by the International Centre for Earth Gravity Models (ICGEM; Ince et al. 2019; Förste et al. 2020) and are freely available to the wider scientific community.

A highlight is the creation of XGM2019e (Zingerle et al. 2019b, 2020a), the first static global gravity model (GGM) beyond degree and order 2190 listed by ICGEM. This model is complete to spheroidal harmonic degree and order 5400, and available as a spherical harmonic model to degree and order 5540. It has been used extensively since its publication for many different applications and has been found to significantly outperform other GGMs in many parts of the world (e.g., Pham et al. 2023).

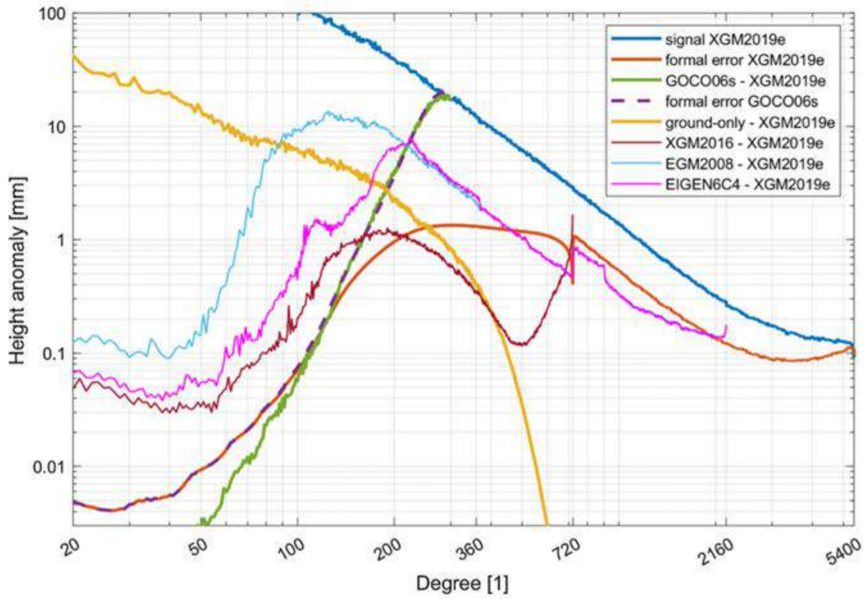

Figure 3: *XGM2019e degree signals and errors in terms of height anomalies and the degree signal differences with other models (Zingerle et al. 2020a).*

Another high-resolution global model published in this time is the topographic gravity model ROLI_EllApprox_SphN_3660 to degree and order 3660 (Abrykosov et al. 2019; Ince et al. 2020). A further extension of this model to degree and order 5495 (ROLI_EllApprox_SphN_5494) was presented in Ince et al. (2022), and a model up to degree and order 10,800 is currently pursued under the GRAV4GEO project (GRAVitational field modelling of Earth's topography For GEOdetic and GEOphysical applications; Ince et al. 2023). This model will be computed from high-resolution laterally varying density and elevation models using an optimal shell thickness of a few metres.

High-resolution topographic gravity models for the Moon have been published by Bucha et al. (2019d) and Šprlák et al. (2020a) and for 1 Ceres by Šprlák et al. (2020a), and these are also listed by ICGEM. Finally, a new C library for ultra-high degree spherical harmonic analysis and synthesis (to degree ~20,000 and higher) has been developed by Bucha (2022a).

3. Interactions with the IAG Commissions and GGOS

Two conference sessions related to the topic of this study group have been organised in interaction with IAG Commission 2. At the IAG Scientific Assembly, Beijing, China, June/July 2021, a session was held in Symposium 2a organised jointly by IAG Commission 2 and ICCT: 2a.7 Topography and bathymetry gravity modelling (conveners: R. Forsberg, S. Claessens and B. Ke). At the IUGG General Assembly, Berlin, Germany, July 2023, a joint session was held in collaboration between IAG and IAGA: JG02 Theory and methods of potential fields (conveners: D. Tsoulis, S. Claessens and M. Fedi).

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Joint Study Group T.35: Advanced numerical methods in physical geodesy

Chair: *R. Čunderlík (Slovakia)*

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1. Activities of the group

Activities of JSG-T.35 have been focused on further development of the advanced numerical methods used in physical geodesy, mainly for high-resolution gravity field modelling in spatial domain. To obtain numerical solutions of the geodetic boundary value problems (BVPs) directly on the Earth's surface, the oblique derivative problem has to be treated. For this purpose, there have been developed numerical approaches based on the finite volume method (FVM) (Droniou et al. 2019) and finite element method (FEM) (Macák et al. 2020, Minarechová et al. 2021, Macák et al. 2023a, 2023b) that have been applied for high-resolution local gravity field modelling (Čunderlík et al. 2020, Minarechová et al. 2021, Čunderlík et al. 2023).

In the case of boundary integral methods like the boundary element method (BEM) or method of fundamental solution (MFS), we have focused on an elimination of far zones interactions using the Hierarchical matrices, namely the Adaptive Cross Approximation (ACA) algorithm (Bejdák 2021). It has efficiently reduced numerical complexity of the BEM or MFS approaches while allowing more detailed global modelling. For the FVM approaches, the domain decomposition (DD) methods based on the Additive Schwarz Method have been implemented in order to reduce large memory requirements (Macák et al. 2021).

An innovative approach to solve the complex BVPs for determining the gravitational fields of asteroids or comets has been developed. It is based on a concept of the computational fluid dynamics (CFD) techniques that are used to derive the FVM numerical scheme for solving the complex BVPs of such irregularly shaped bodies (Yin and Sneeuw 2019, 2021).

Activities of JSG-T.35 and their results were presented at various geodetic conferences like EGU or the X Hotine-Marusi Symposium and have been published in several papers listed below. The members of JSG-T.35 organized a session "Advanced numerical methods in geodesy" within the X Hotine-Marusi Symposium in Milan, June 2022.

2. Achievements and results

In the case of FVM, the oblique derivative boundary condition (BC) has been treated in the way that its tangential component is considered as an advection along the Earth's topography regularized by a carefully designed surface diffusion term. For this approach, the theoretical rates of convergence have been illustrated by several numerical tests (Droniou et al. 2019). Later, this approach has been applied for local gravity field modelling in Slovakia using terrestrial gravimetric measurements (Čunderlík et al. 2020).

In the case of FEM, two different approaches have been developed. In the first one, the oblique derivative BC is considered as an average value on the bottom side of finite elements (Macák et al. 2020). In the second one, the oblique derivative is incorporated directly into the computational nodes using two tangential vectors for each node (Minarechová et al. 2021). This has led to more stable and the second order accurate numerical scheme which has been afterwards applied for local quasigeoid modelling in Slovakia (Minarechová et al. 2021) and in the Hong Kong territories (Čunderlík et al. 2023).

The FEM or FVM approaches require a discretization of the whole 3D computational domain. To avoid a discretization of the 3D semi-infinite domain outside the Earth, an artificial upper boundary has been usually considered where the numerical solutions have been fixed to satellite-only GGMs by the Ditichlet BC (Droniou et al. 2019, Macák et al. 2020, Minarechová et al. 2021). Consequently, a condition of the regularity at infinity has been abandoned. To overcome this drawback, the FEM with mapped infinite elements has been developed and implemented (Macák et al. 2023a). Such infinite elements are formed by "stretching" the finite elements in radial direction to reproduce an effect of the far field boundary on an infinite domain.

The FEM approach has been also applied to solve the nonlinear geodetic BVP. It is based on an iterative approach that determines directions of the gravity vectors together with values of the disturbing potential. In the first iteration, the oblique derivative BVP is solved. The next iterations update values of the geopotential and directions of the gravity vectors (Macák et al. 2023b).

Reducing of numerical complexity of the BEM or MFS approaches using the Hierarchical matrices has shown that the ACA algorithm is able to save almost 99 % of memory requirements in the case of a detailed discretization of the Earths' surface (Bejdák 2021). Such an elimination of far zones interactions is highly effective and enables us to use BEM or MFS for high-resolution global gravity filed modelling in spatial domain.

For the FEM or FVM approaches, the DD methods can be used to reduce large memory requirements. An implementation of the overlapping DD methods for the FVM approach based on the Additive Schwarz Method has demonstrated how to optimize large-scale parallel computations. It has resulted in a reduction of memory requirements by the factor 4.5 while reaching a significant speed-up of the computation time (Macák et al. 2021).

By reformulating the gravitational field in terms of a potential flow, a concept from fluid dynamics, the gravitational vector field is mapped onto a potential-flow vector field. In this way, the complex BVP has been made amenable to the off-the-shelf CFD techniques (Yin and Sneeuw 2019). The methodology has been successfully demonstrated on the comet 67P/Churyumov–Gerasimenko, geometrically a notoriously difficult body, known for its irregular double-lobed shape. Here the Laplacian property of the potential flow's velocity field is proved mathematically. From both theoretical and practical points of view, the proposed numerical method can overcome the divergence problem and, hence, has a good potential for solving the complex BVPs (Yin and Sneeuw 2021).

3. Interactions with the IAG Commissions and GGOS

Majority of activities of JSG-T.35 are focused on high-resolution global or local gravity field modelling in spatial domain, so they directly interact with *Commission 2* of IAG. The obtained gravity field models can also contribute to the process of establishing and realization of the IHRS, and thus can interact with objectives of *GGOS*.

4. Publications

The achieved results have been published in several papers (see below) and they were presented at major geodetic conferences like the EGU General Assemblies in Vienna 2020-2023 within the session "Recent Developments in Geodetic Theory".

Droniou J, Medľa M, Mikula K (2019) Design and analysis of finite volume methods for elliptic equations with oblique derivatives; application to Earth gravity field modelling. *Journal of Computational Physics* 398: 108876, doi:10.1016/j.jcp.2019.108876

Yin Z, Sneeuw N (2019) Modeling the gravitational field by Using CFD techniques. In: *IAG Symposia Series* 151, https://doi.org/10.1007/1345_2019_72

Čunderlík R, Medľa M, Mikula K (2020) Local quasigeoid modelling in Slovakia using the finite volume method on the discretized Earth's topography. *Contributions to Geophysics and Geodesy* 50 (3): 287-302

Macák M, Minarechová Z, Čunderlík R, Mikula K (2020) The finite element method as a tool to solve the oblique derivative boundary value problem in geodesy. *Tatra Mountains Mathematical Publications* 75 (1): 63-80

Bejdák M (2021) Boundary methods for gravity field modeling using the Hierarchical matrices. Diploma thesis. Slovak University of Technology in Bratislava (in Slovak).

Macák M, Čunderlík R, Minarechová Z, Mikula K (2021) Computational optimization in solving the geodetic boundary value problems. *Discrete & Continuous Dynamical Systems – S* 14 (3): 987-999, doi:10.3934/dcdss.2020381

Minarechová Z, Macák M, Čunderlík R, Mikula K (2021) On the finite element method for solving the oblique derivative boundary value problems and its application in local gravity field modelling. *Journal of Geodesy* 95: 70

Yin Z, Sneeuw N (2021) Modeling the gravitational field by using CFD techniques. *Journal of Geodesy* 95 (6): 1-22

Čunderlík R, Tenzer R, Macák M, Zahorec P, Papčo J, Nsiah AA (2023) A detailed quasigeoid model of the Hong Kong territories computed by applying a finite-element method of solving the oblique derivative boundary-value problem. *Journal of Geodetic Science* 13(1): 20220153, https://doi.org/10.1515/jogs-2022-0153

Macák M, Minarechová Z, Tomek L, Čunderlík R, Mikula K (2023a) Solving the fixed gravimetric boundary value problem by the finite element method using mapped infinite elements. *Computational Geosciences* (accepted in May 2023).

Macák M, Minarechová Z, Čunderlík R, Mikula K (2023b) A local gravity field modelling in mountainous areas by solving the nonlinear satellite-fixed geodetic boundary value problem. *Acta Geodaetica et Geophysica* (submitted in April 2023).

Joint Study Group T.36: Dense troposphere and ionosphere sounding

***Chair**: Giorgio Savastano (Luxembourg)*

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1. Activities of the group

This report presents the activities and achievements of the Joint Study Group T.36 during the period of July 2019 to June 2023. The report is divided into two main research areas: troposphere and ionosphere sounding, and a third operational topic focusing on enhancing the data infrastructure for handling large datasets. Due to the global COVID-19 pandemic, the study group faced limitations in holding meetings and convening conference sessions during the 2019-2021 period.

Troposphere sounding

The study group primarily focused on analysing the impact of GNSS (Global Navigation Satellite System) and InSAR (Interferometric Synthetic Aperture Radar) technologies in meteorology and weather forecasting. Ground based GNSS and InSAR were used as complementary tools to obtain tropospheric delay data to study of water vapor variations and their relationship with weather forecasts and – to some extent – with climate analyses. To this end, tests conducted on data provided by both geodetic and mass-market GNSS receivers have contributed to improved data processing, leading to a more accurate comparison with products from different atmosphere measurement techniques, as well as to a better understanding of the atmospheric water vapor behaviour in relation with various types of rain events. The impact of using GNSS- and InSAR-derived tropospheric delay information to produce/improve rain forecasts was studied in terms of both physics-based numerical weather prediction models and machine learning-based neural networks.

Ionosphere sounding

The study group focused on several key topics within ionosphere sounding:

- Classification of perturbations in the lower ionosphere, such as sporadic E layers and TIDs (Traveling Ionospheric Disturbances), using GNSS radio occultation (RO) observations from Spire's constellation of CubeSats. The group achieved high vertical resolution (better than 100 m) in extracting sTEC (slant total electron content) information from high-rate (50 Hz) GNSS-RO profiles.

- Development of Total Variometric Approach (TVA) methodology to contribute to the understanding of the physics and detectability of tsunami genesis by real-time GNSS ionospheric monitoring and to support tsunami warning systems.
- Investigation of methods to densify GNSS information using ionospheric observations from dual-frequency smartphones, geostationary satellites, and ship-based GNSS receivers.
- Application of machine learning algorithms to the detection of tsunami induced ionospheric perturbations.
- Investigation on the possible ionospheric signature induced by Mt. Etna eruptions.
- Analysis of the ionospheric response of the 15 January 2022 Hunga Tonga volcanic eruption.

Some of the ongoing activities are:
- Development of an innovative methodology to estimate the correct altitude of the ionospheric perturbation detection.
- Analysis of the complex ionospheric response after the 2023 Türkiye- Syria earthquake (Ravanelli et al., 2023b).

Enhancement of current data infrastructure for extremely large datasets

In response to the increasing volume of atmospheric remote sensing datasets, which often comprise multi-dimensional arrays of numerical data, such as sTEC point measurements scattered irregularly in latitude, longitude, altitude, and time dimensions, we recognized the need to improve our data infrastructure. Traditionally, analysts would download datasets to personal laptops or workstations and conduct all analysis locally. However, with the continuous advancements in sensor technology and computer power, the size of our datasets has grown exponentially, rendering this workflow impractical and inefficient for multi-terabyte and petabyte-scale datasets.

To address these challenges, a significant portion of our efforts focused on enhancing our current data infrastructure to accommodate extremely large datasets and facilitate effective exploratory data analysis. By leveraging cutting-edge technologies, we aimed to optimize data handling and enable efficient processing of massive volumes of information. This infrastructure enhancement allowed us to overcome the limitations of traditional workflows and embrace a more scalable and resource-efficient approach.

2. Achievements and results

The activities conducted by the study group resulted in significant achievements:

Troposphere sounding

The definition of an effective method for processing data from single-frequency receivers (Mascitelli et al. 2019a) and their integration with data from geodetic receivers for meteorological purposes has led to the prosecution of tests aimed at assimilating GNSS data into numerical weather prediction models (Mascitelli et al. 2020, Mascitelli et al. 2019b, Lagasio et al. 2019a, b) and their subsequent use for neural networks (Sangiorgio et al. 2019a, b, Chkeir et al. 2023, Biondi et al. 2022). The validation of products obtained using different techniques has provided a definition of the level of quality of the derived values (Mascitelli et al. 2019c, Tiberia et al. 2021, D’Adderio et al. 2020, Meroni et al. 2020, Pierdicca et al. 2020, Manzoni et al. 2020, Tagliaferro et al. 2019, Coletta et al. 2021, Mascitelli et al. 2022) and the contribution of GNSS-derived data to climatological studies has shown the potential of the technique for long-term studies as well (Ssenyunzi et al. 2019, 2020).

Ionosphere sounding

The definition of a new methodology to automatically classify perturbations in the lower ionosphere using GNSS radio occultation observations collected using Spire's constellation of CubeSats (Savastano et al. 2020, 2022). Presently, Spire processes over 15k GNSS-RO profiles each day, with the expectation of further growth due to new satellite launches and an increased duty cycle of the existing fleet. A description of the measurement system can be found (Angling et al., 2021). Space-based GNSS-RO sTEC measurements are collected in an atmospheric limb sounding geometry where the GNSS receiver (Rx) is on an LEO satellite (Savastano et al., 2022). As the LEO satellite moves in its orbit, the GNSS satellite (Tx) is seen to rise above or set below the horizon. The ray path from the Tx to Rx is quasi horizontal and can be characterized by the height of its tangent point. Thus, at each time epoch, the sTEC measurement made along each ray path can be associated with the tangent height in order to construct an sTEC profile.

The definition of the Total Variometric Approach methodology for real-time tsunami genesis estimation (Ravanelli et al. 2021), to the integration of ionospheric observations coming dual-frequency smartphones, geostationary satellites and ship-based GNSS receivers (Ravanelli et al. 2020, Savastano et al. 2019a, Savastano et al. 2019b, Fortunato et al. 2019, Rolland et al. 2021) into the VARION algorithm and to the validation of inverse modelling to reproduce ionospheric perturbation from GNSS ground motion data (Meng et al., 2019; Meng et al., 2022).

The development of numerical models to rapidly retrieve the main characteristics of the driver source (tsunami waveform or seismic deformation) from the ionospheric perturbation (Rolland et al. 2021, Zedek et al. 2021, Mikesell et al. 2019).

Application of machine learning algorithms to the detection of ionospheric perturbations generated by tsunamis were studied. In detail, Convolutional Neural Networks (CNNs) were used to detect tsunami-related gravity waves in the ionosphere (Constantinou et al., 2021; Liu et al., 2021). Furthermore, ship-based GNSS ionospheric observations were employed for the detection of tsunamis through deep learning algorithms (Xie et al., 2022).

Study on the eventual ionospheric response induced by Mt. Etna with the VARION algorithm in order to better study the coupling between volcanic eruptions and the ionosphere (Ravanelli et al., 2022; Ferrara et al., 2023).

Investigation onto the ionospheric response of the 15 January 2022 Tonga volcanic eruption. Astafyeva et al., 2022a-b detected at least five large explosions between 4 and 5UT and estimated the onset time to be 04:05:54UT from GNSS-TEC data. Ravanelli et al., 2023a carried out a joint study of oceanic and ionospheric response in New Caledonia-New Zealand and Chile-Argentina to the Tonga eruption, showing that near-surface propagating Lamb wave caused a small tsunami in the ocean (air-sea wave) and unusually strong disturbances in the ionosphere, while inversely, the eruption-generated tsunami showed significant wave heights in the ocean and much smaller response in the ionosphere.

Data infrastructure for extremely large datasets

The implementation of a DataCube infrastructure by indexing data into grids of target resolutions, see the EASE grids at https://nsidc.org/ease/ease-grid-projection-gt. We have employed Xarray and Dask technology, enabling lazy data loading and analysis within Jupyter notebooks. The group has extensively utilized the Zarr format for storage on the cloud, specifically AWS S3 buckets.

3. Publications

Angling MJ, Nogués-Correig O, Nguyen V, Vetra-Carvalho S, Bocquet F-X, et al. (2021) Sensing the ionosphere with the Spire radio occultation constellation. *J. Space Weather Space Clim. 11: 56*, doi:10.1051/swsc/2021040.

Astafyeva E, Maletckii B, Mikesell TD, Munaibari E, Ravanelli M, Coïsson P, Manta F, Rolland L (2022a) The 15 January 2022 Hunga Tonga eruption history as inferred from ionospheric observations. *Geophysical Research Letters* 49(10): e2022GL098827

Astafyeva E, Maletckii B, Ravanelli M, Rolland L, Mikesell D, Coisson P, Manta F, Munaibari E, Lognonne P (2022b) How the 15 January 2022 Hunga Tonga- Hunga Ha'pai volcano eruption shook the ionosphere. 3rd URSI Atlantic and Asia Pacific Radio Science Meeting.

Biondi R, Chkeir S, Anesiadou A, Mascitelli A, Realini E, Nisi L, Cimarelli C (2022) Multivariate multi-step convection nowcasting with deep neural networks: The Novara case study. In IGARSS 2022-2022 IEEE International Geoscience and Remote Sensing Symposium, pp. 6598-6601.

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Lasota E, Steiner AK, Kirchengast G, Biondi R (2020) Tropical cyclones vertical structure from GNSS radio occultation: an archive covering the period 2001-2018. *Earth System Science Data* 12(4): 2679-2693

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Joint Study Group T.37: Theory and methods related to the combination of high-resolution topographic/bathymetric models in geodesy

***Chair**: Daniela Carrion (Italy)*

Members

Riccardo Barzaghi (Italy)
Mattia Crespi (Italy)
Vassilios Grigoriadis (Greece)
Karsten Jacobsen (Germany)
Kevin Kelly (US)
Michael Kuhn (Australia)
Rajinder Nagi (US)
Dan Palcu (Brazil)
Cornelis Slobbe (Netherlands)

1. Activities of the group

The activities of the Study Group focused on the exploration of critical transitions from land to sea and to the impact of the DTM/DBM choice for local geoid computation, comparing different datasets. In particular, the assessments raised from ongoing computation activities for the GEOMED2 project, for the geoid of Cameroun computation as well as for the preliminary activities for the computation of the new release of the official Italian geoid. These activities involved subgroups of the commission membership.

The land-sea height transition has been explored, where data come from different sources of information and with different resolutions for land and sea respectively. The following terrain and bathymetry models have been considered.

On land:

- SRTM, 3’’ resolution, accuracy: +/- 8 m RMSE (https://www2.jpl.nasa.gov/srtm/);
- AW3D30 (ALOS Global Digital Surface Model), 30m resolution, +/- 5 m RMSE (https://www.eorc.jaxa.jp/ALOS/en/dataset/aw3d30/aw3d30_e.htm);
- EU DEM, by Copernicus land sevice, 25m resolution, +/- 7 m RMSE, derived from ASTER GDEM, SRTM and russian topomap series (https://land.copernicus.eu/imagery-in-situ/eu-dem/eu-dem-v1.1).
- MERIT DEM: 3’’ resolution, +/- 12 m RMSE (http://hydro.iis.u-tokyo.ac.jp/~yamadai/MERIT_DEM/index.html)

On the sea:

- Bathymetry used for Italian computation which includes NOAA dataset (original resolution of 5’) and local maps from IIM (*Istituto Idrografico della Marina*, Italian Hydrographic Institute of the Navy) close to the coast, interpolated at 3’’ resolution, the accuracy of the combined product is variable in space due to the different origins of data;
- SRTM15+ V1 and V2, which integrates global SRTM on land and available bathymetric data, the original resolution is 15’’, the accuracy varies due to different origins of the data (https://portal.opentopography.org/datasetMetadata?otCollectionID=OT.122019.4326.1);
- EMODnet bathymetry, 2021 release (https://emodnet.ec.europa.eu/en), the spatial resolution is 1/16’, the accuracy varies due to the different origins of the source data.

When displayed, different combinations of DTM/DBM show differences, particularly when the gradient of height is computed. In Figure 1 it is possible to see that the gradient shows sharp boundaries, a sort of squared pattern due to the data sources and to the different resolutions, these differences appear also close to the coastline.

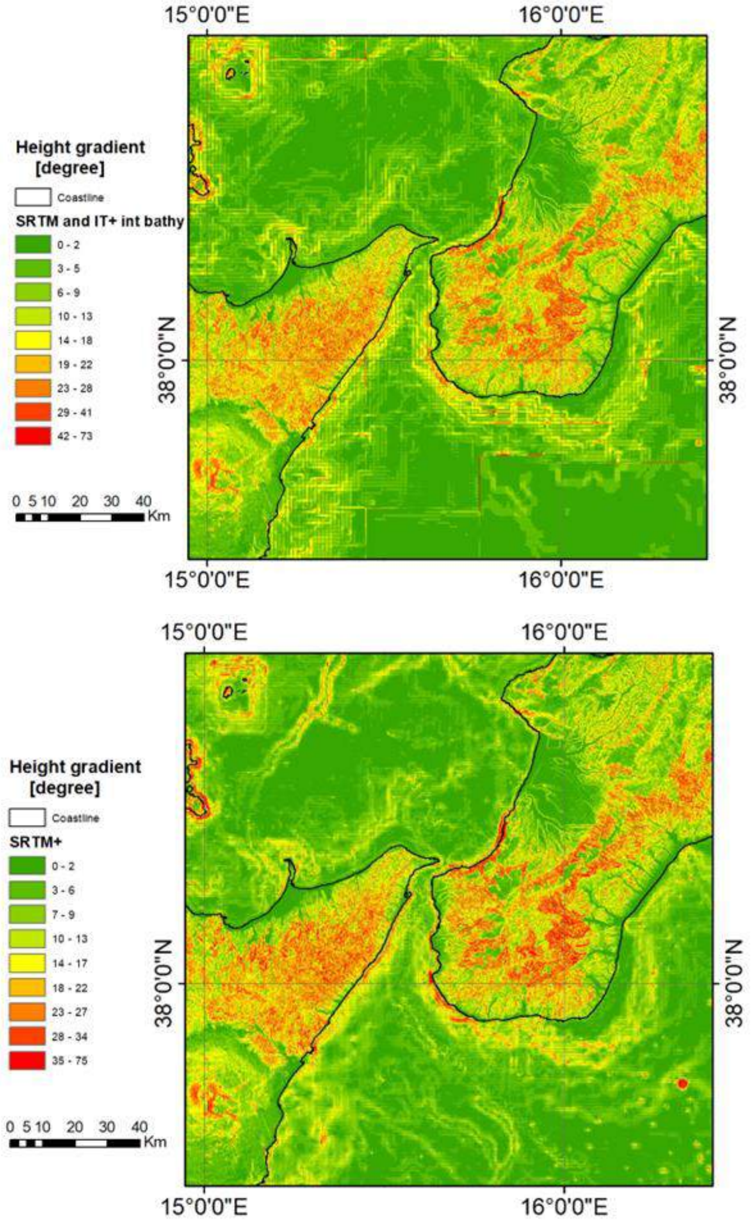


Figure 1: *Height gradients in Southern Italy, around the Strait of Messina for the height model used for Italian geoid computation (top) and for SRTM+ (bottom).*

Tests have been performed on the study area to verify criticalities in the height transition from land to sea. In particular, the impact has been verified with respect to the geoid modelling computation and, more in general, the geodetic functionals, exploiting the remove-compute-restore technique. In particular, the pre-computation tests of the new release of the official Italian geoid model have been performed. Italy has very long coastlines and the accuracy of the knowledge of the land-sea transition can affect the geoid computation accuracy, indeed, before the computation of the last official release of the official Italian geoid it was verified that the DBM information is crucial to improve the accuracy of the local geoid computation.

In 2022 the X Hotine-Marussi Symposium was held in Milan and part of the commission members were there as well members of the organizing and scientific committees. During the

Symposium, a presentation was given with the title “The impact of DTM/DBM land-sea transition for geoid computation: a test case in southern Italy”.

2. Achievements and results

The test area selected is in southern Italy, around the Strait of Messina (see Figure 2). This is an interesting area because it has steep heights close to the coastline and deep sea, with steep transition. It is a volcanic area, with active volcanoes and it corresponds to the boundaries between the Eurasian and the African tectonic plates. The Italian test site allows for the comparison between different combinations of the DTMs and DBMs considered, which have been listed in the first section. The height values have been compared to the reference heights of the gravity points available in the database used for the computation of the Italian geoid. The statistics of the differences are shown in Table 1. The values show variations among the datasets that are consistent with the declared RMSE of the DTM datasets and that, despite the different resolutions of considered products, are not very large.

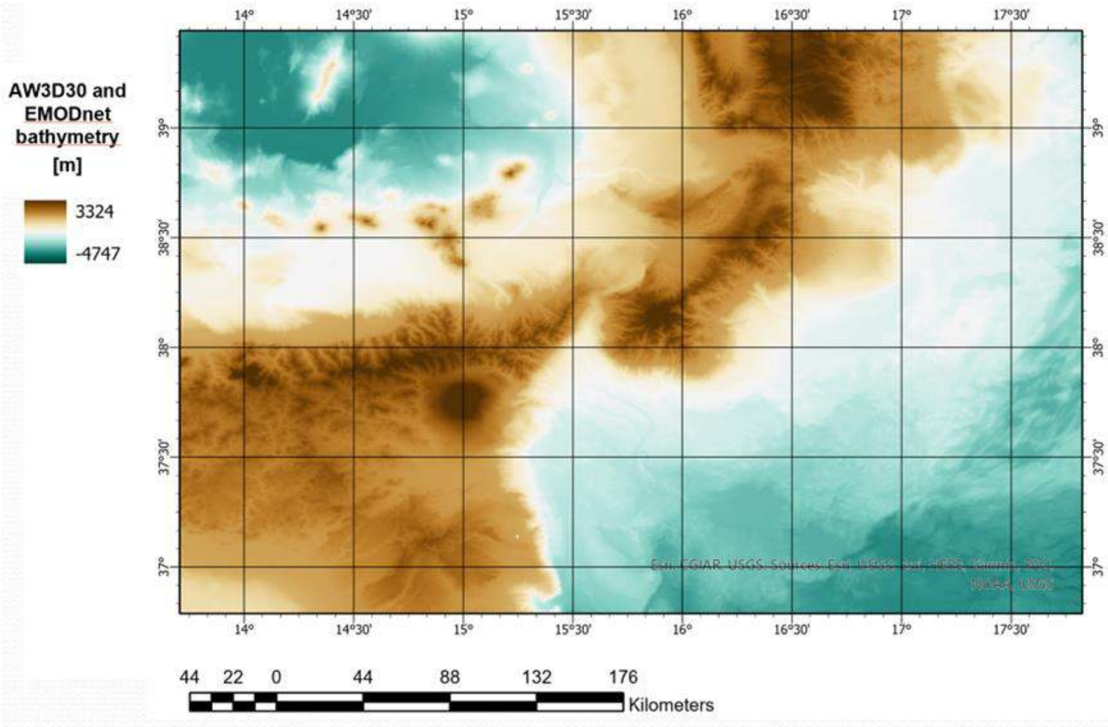


Figure 2: *AW3D30 and EMODnet bathymetry [m] in Southern Italy, around the Strait of Messina.*

Table 1: *Statistics of the differences between the measured heights of the GPS/levelling points over the area of interest and the considered DTMs*

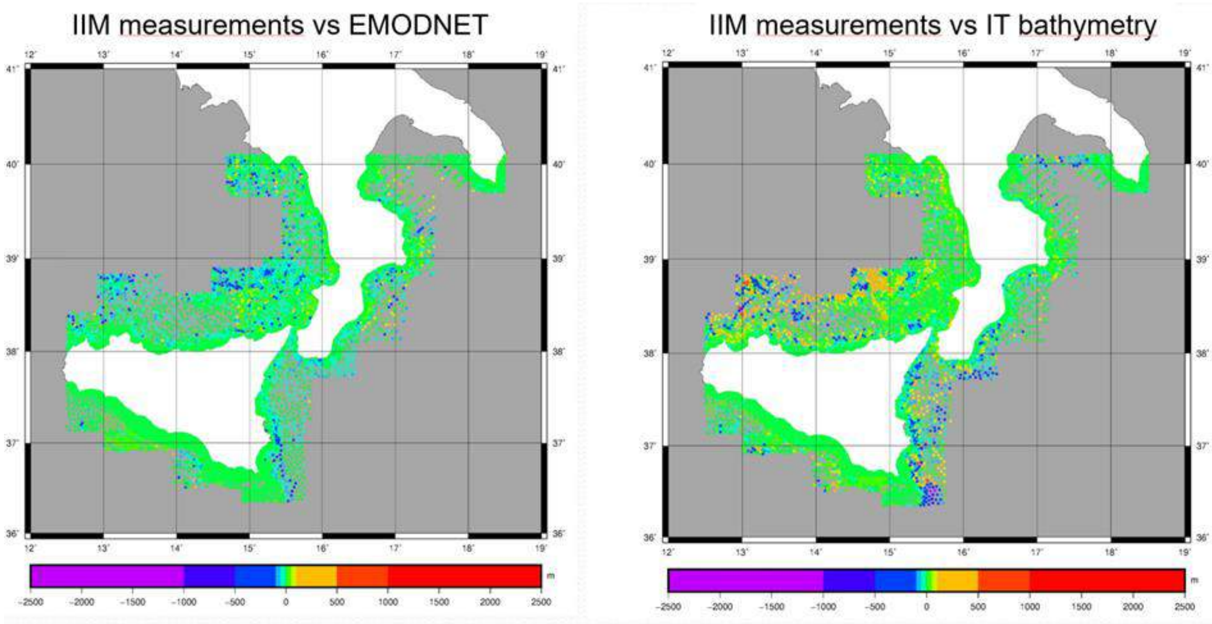
	SRTM	SRTM15+ V1	AW3D30	EU DEM	MERIT
#	59	59	59	59	59
Average [m]	-1.39	0.00	-0.22	-1.40	1.2
StDev [m]	6.04	4.35	5.32	5.59	4.5
Min [m]	-33.98	-10.29	-17.29	-18.29	-7.1
Max [m]	8.52	13.60	26.26	7.99	20.2
RMS [m]	6.20	4.35	5.32	5.76	4.66

The bathymetry values of the considered products have been compared with the reference measures provided by the IIM. It was possible to compare the values of 12630 points in the area of interest. The statistics of the differences are available in Table 2.

Table 2: Statistics of the differences between the reference echo-soundings provided by IIM and the bathymetry of the considered products in the area of interest.

	IT_bathymetry	SRTM15+	EMODNET
#	12630	12630	12630
Mean [m]	-0.389	-4.845	-9.182
StDev [m]	64.244	40.009	43.583
Min [m]	-1080.000	-886.000	-2174.500
Max [m]	879.000	518.000	417.000
RMS [m]	64.245	40.301	44.540

The differences can reach very high peaks, of thousands of meters, however, the average is between 0 and 10 meters, the standard deviation is of the same order of magnitude for all products, ranging between 40 m and 64 m. The RMS for the three products is like the standard deviation. The largest standard deviation is for the Italian bathymetry, the best performance is provided by the SRTM15+, which has smaller peaks and, consequently smaller standard deviation. The differences between the reference data and the products are mapped in Figure 3. The differences are smaller closer to the coastlines, as it could be expected, which is the most surveyed and least deep area. The differences are larger for the Italian bathymetry product, which shows the worst performance.



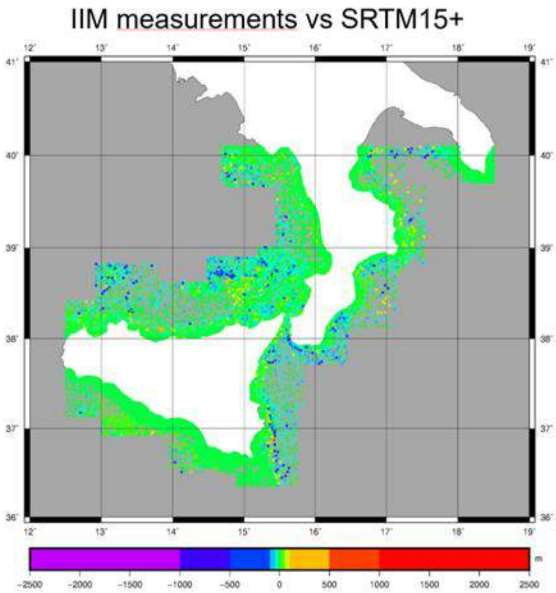


Figure 3: *Maps of the differences between the reference echo-sounding points provided by the IIM and the considered DBMs.*

A profile has been drawn, see Fig. 4, to show the transition between land and sea for the considered products along the Messina strait. On land, the differences are very small. Below the sea level the differences between the products are more significant. Three IIM measurements are shown on the map, confirming the worst performance of the Italian bathymetry. Among the products, the best option seems to be the SRTM15+, which shows the smallest peaks and the smallest RMS with respect to the reference data. In addition, SRTM15+ has been produced taking care of the transition between DTM and DBM.

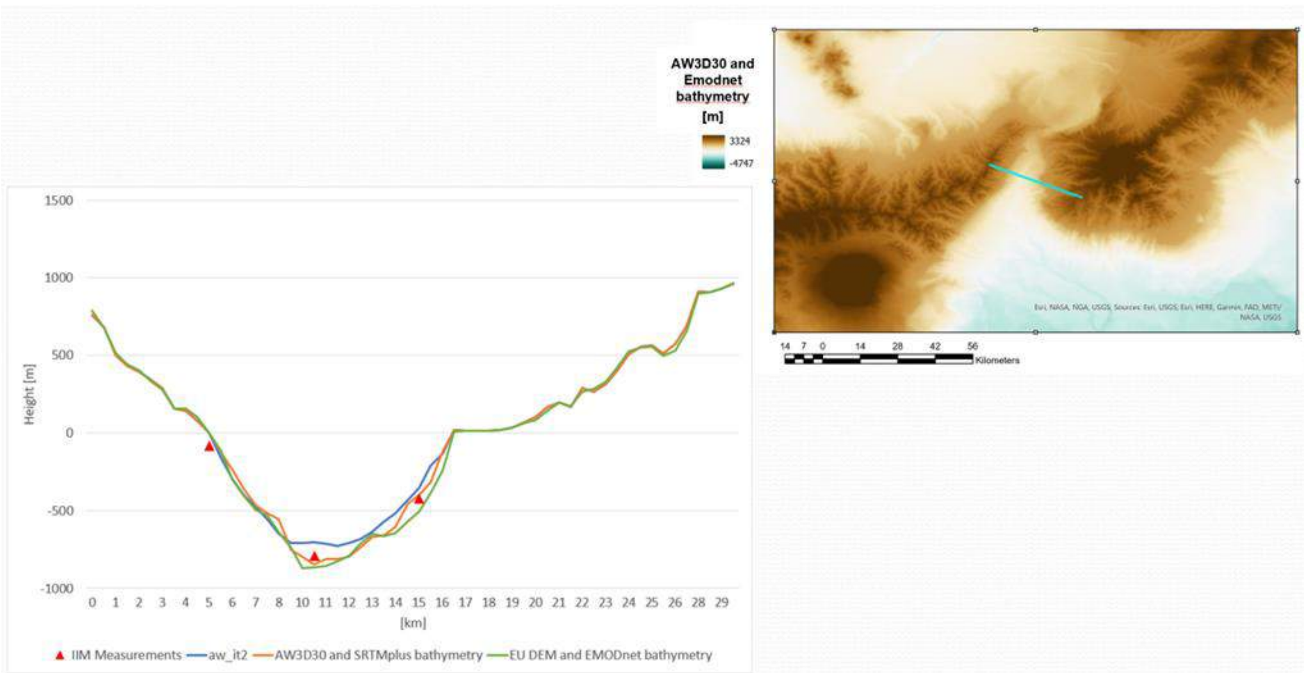


Figure 4: *Comparison over a profile along the Messina strait.*

The considered models of land heights and bathymetries have been combined, and the available combinations of DTMs and DBMs have been used to compute local quasi geoids over the area of interest. The obtained combinations have been first compared with each other, showing significant differences in the bathymetry (Figures 5 and 6).

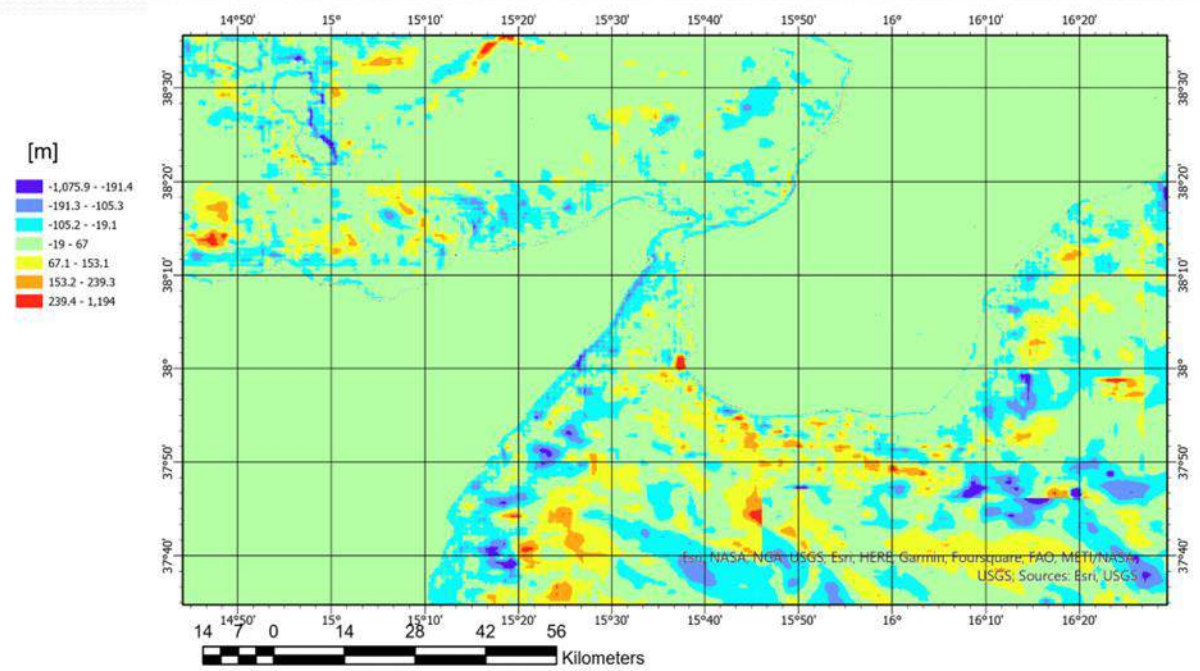


Figure 5: *Difference between SRTM15+ v1 and SRTM_Italian_NOAA bathymetry.*

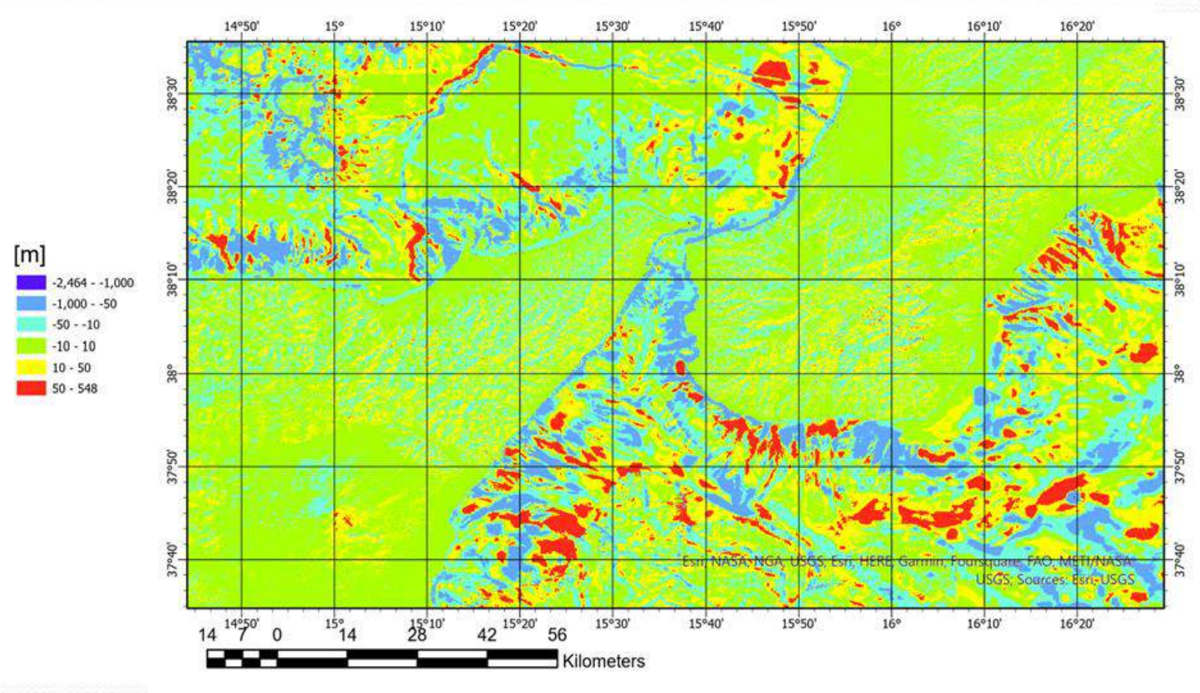


Figure 6: *Difference between SRTM15+ v1 and AW3D30_EMODnet bathymetry.*

The remove-compute-restore technique has been applied, considering the Italian database of gravity data (see Figure 7), which has been recently filtered applying outlier rejection. Figure 7 shows the available GPS/levelling points as well in area of interest, which have been used to check the results of the geoid computations with the different datasets.

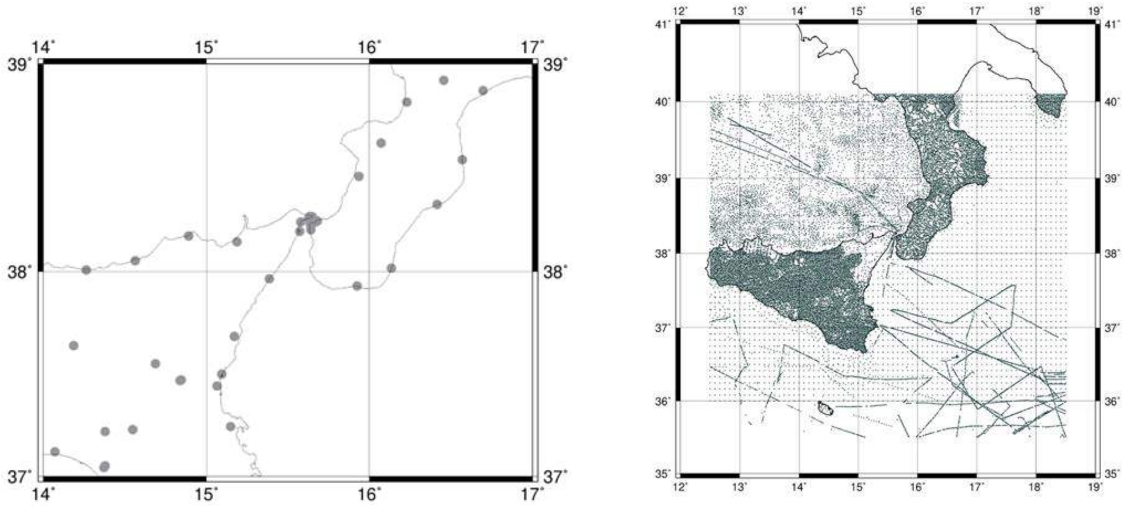


Figure 7: *Left: GPS/Levelling points over the area of interest in southern Italy; right: gravity data over the area of interest.*

The gravity residuals have been obtained by removing the low frequency component using the XGM2019e global gravity model up to D/O 1000, then, the RTC has been computed with the GRAVSOFT package to remove the high frequency component. The undulation has been computed from the gravity residuals using the fast collocation, Fig. 8 shows the covariance function that has been modelled.

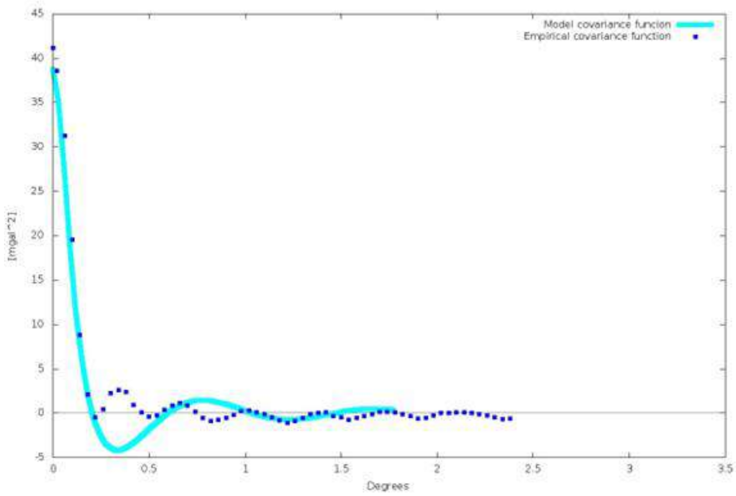


Figure 8: *The empirical and model covariance function used for the fast collocation.*

The undulation model and RTC components have been added to the undulation residuals to obtain the height anomalies. Examples of differences among the obtained local estimates are shown in Fig. 9. On land the differences cannot be noted, over sea differences are visible and they are of the order of magnitude of few centimeters.

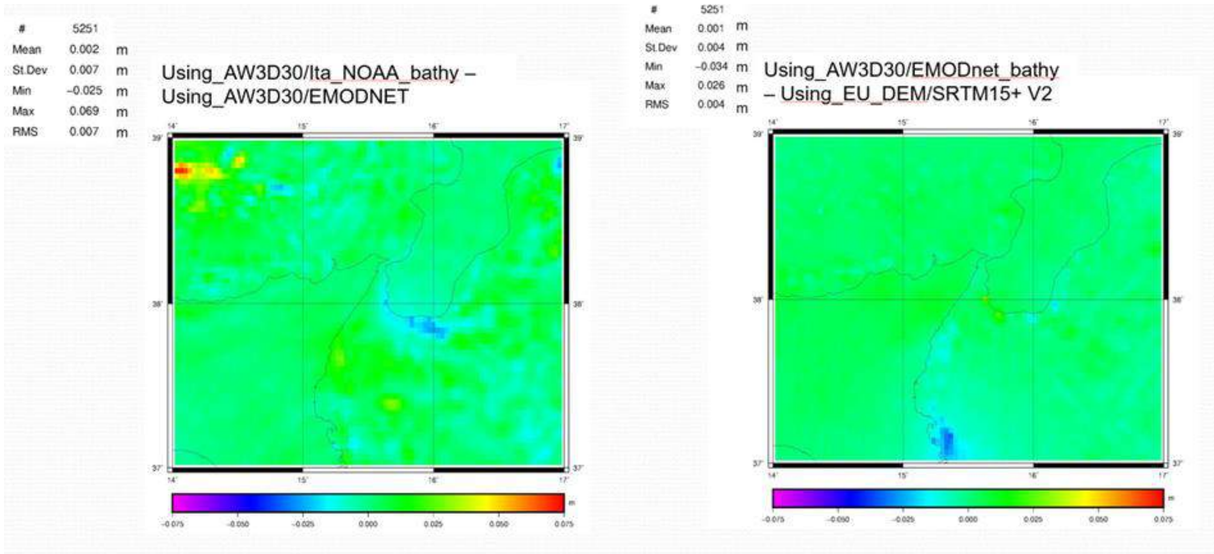
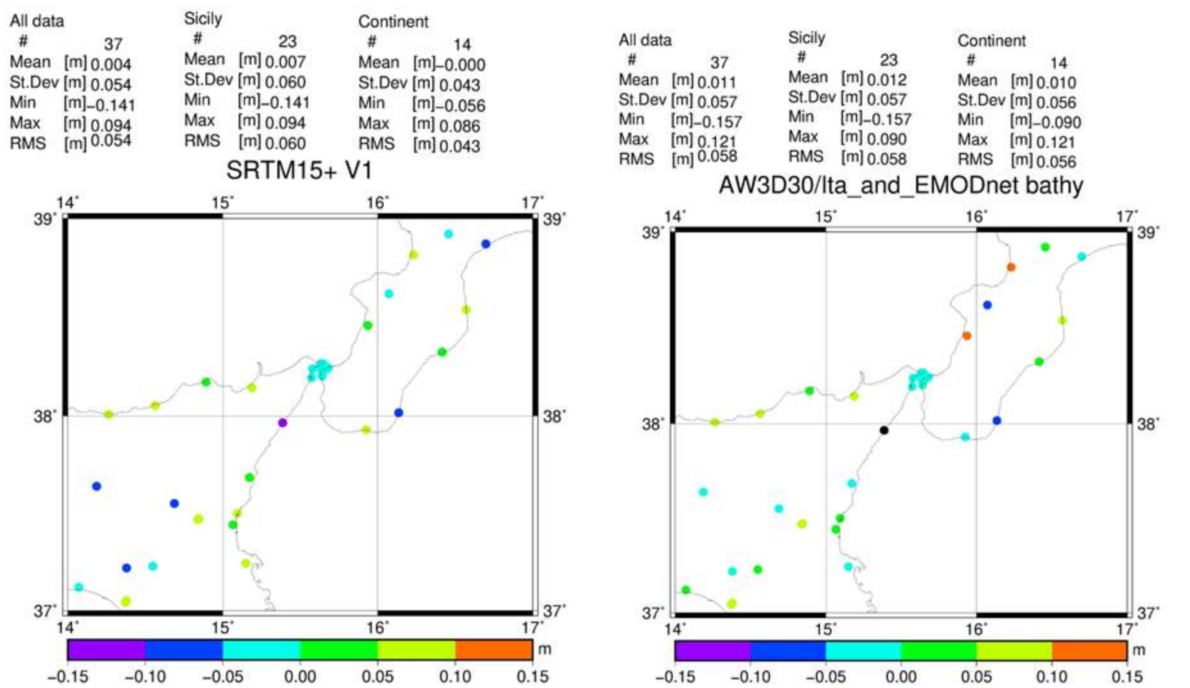


Figure 9: *Difference of height anomalies computed with different combinations of DTM/DBM.*

The local geoids obtained with the different combinations of DTMs and DBMs have been compared with the GPS/levelling points, see Fig. 7, available in the area of interest (after removing bias and tilt). Sicily island and continental Italy refer to different tide gauges, thus, the GPS/levelling points should be considered separately. Due to the limited extension of the area of interest, the comparison between the GPS/lev and the computed quasi geoids has been performed for points falling on Sicily only, falling on continentals Italy only, but also all points in the area of interest have been considered together. Some of the statistics on the GPS/lev points for the combinations are shown in Figure 10. The variations for all considered products are comparable, within few centimeters, within the accuracy of the last computed Italian geoid, which was around 5 cm.



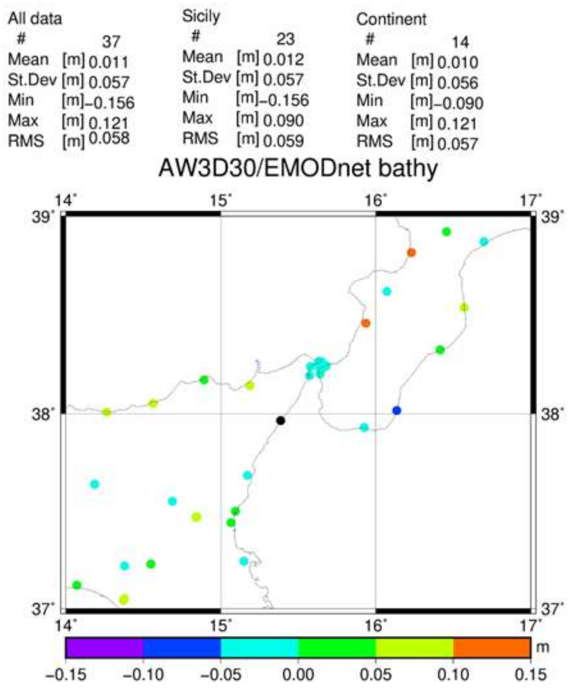


Figure 10: *Statistics of the local quasi-geoids obtained with the considered different combinations pf DTMs/DBMs with respect to the GPS/levelling after removing bias and tilt.*

These differences could be significant if accuracy required for the local geoid is around 1 cm, as it was the aim of the recent Colorado experiment. In this respect, also possible impacts of the different tide systems for high accuracy geoid determination should be taken into account.

Another experiment was conducted, in the same context, by Grigoriadis et al. (2023), who validated in two test areas some of the most used models, i.e., ASTER GDEM; AW3D30 DSM; Copernicus DEM; EU-DEM; GEBCO 2020; NASADEM HGT; SRTM15+ and SRTM Global, using GNSS; spirit levelling; and gravity measurements. The validation was performed along two traverses of 14.5 and 12.0 km each in Northern and Central Greece, respectively. Since these models are based on geoid heights obtained from Global Geopotential Models (GMs), the influence of GMs was also investigated. Moreover, comparisons were made between GEBCO 2020, SRTM15+, and the Greek Seas DTM, with depths derived from in situ coastal measurements in six different areas in Northern Greece. From the analysis, it was concluded that the heights obtained from the Copernicus DEM provide the best overall results in terms of mean value and standard deviation while also showing consistent results in the two test areas. Similarly, the Greek Seas DTM showed better consistency with the measured depths in the coastal test areas. The comparison with in-situ depths depicted also that the transition from sea to land in coastal areas still requires in-situ measurements to be incorporated in models in order for the latter to be safe and reliable.

3. Interactions with the IAG Commissions and GGOS

The commission interacted with IGFS and the OGC working group on the discussion about developing a standardized Gridded Geodetic data eXchange Format (GGXF).

The definition of a standard for grid data sharing is essential, considering the variety of available formats, which are very similar one to the other and that with lack of metadata could lead to misinterpretations. It is evident that the choice of such a standard is strongly related to the use of DTM/DBM-models. JSG T.37 focuses on assessing the impact of terrain and bathymetric models on geoid estimation, with respect to accuracy and resolution. These models are almost always provided in gridded form, often with little or incomplete metadata that can hinder reliable analysis with them or combination of them, the latter essential for the JSG T.37 work. This is especially important when the datasets differ significantly in their method of capture and processing such as exists for land DEM and marine bathymetric datasets. Accurate and comprehensive metadata is essential for the data to be treated correctly in geodetic analyses. The current Open Geospatial Consortium (OGC; Home - Open Geospatial Consortium (ogc.org)) Gridded Geodetic data eXchange Format (GGXF; OGC Requests Public Comment on a Standardized Deformation Model and a Geodetic Data Grid Exchange Format - Open Geospatial Consortium) standard can mitigate this deficiency. Moreover, such gridded models are often interpolated for model phenomena at off-grid locations. GGXF is designed to be a single file format that may be used for a wide range of geodetic applications requiring interpolation of regularly gridded data. GGXF can cope with multiple levels of data resolution in a single file, supports multiple data values at grid nodes, and provides a header that furnishes comprehensive metadata information for file interpretation and application. These features and more engender GGXF with superior capability for both geodetic analysis as well as data dissemination and exchange in a standardized format that lends itself well to automated processing strategies.

Activities are ongoing, in interaction with International Height Reference System JWG GGOS 0.1.3, as the consistency of DTM/DBM with the tide gauges, which are positioned along the coast, is essential.

4. Publications

Grigoriadis VN, Vassilios DA, Dimitrios AN (2023) Validation of recent DSM/DEM/DBMs in test areas in Greece using spirit leveling, GNSS, gravity and echo sounding measurements. *ISPRS International Journal of Geo-Information* 12(3): 99, https://doi.org/10.3390/ijgi12030099

Toro JF, Carrion D, Rossi L, Reguzzoni M (2022) The open database of regional models of the International Service for the Geoid. *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences* – ISPRS Archives, 43(B5-2022): 29-35, https://doi.org/10.5194/isprs-Archives-XLIII-B5-2022-29-2022

Grigoriadis VN, Vergos GS, Barzaghi R, Carrion D, Koç Ö (2021) Collocation and FFT-based geoid estimation within the Colorado 1 cm geoid experiment. *Journal of Geodesy* 95(5): 52, https://doi.org/10.1007/s00190-021-01507-7

Reguzzoni M, Carrion D, De Gaetani C, Barzaghi R, Sansó F (2021) Open access to regional geoid models: The International Service for the Geoid, Earth System Science Data 13(4): 1653-1666, https://doi.org/10.5194/essd-13-1653-2021

Barzaghi R, Carrion D, Kamguia J, Kande L, Yap L, Betti B (2021) Estimating gravity field and quasi-geoid in Cameroon (CGM20). *Journal of African Earth Sciences* 184: 104377, https://doi.org/10.1016/j.jafrearsci.2021.104377

Wang YM, Sanchez L, Agren J, Huang J, Forsberg R, Abd-Elmotaal HA, Ahlgren K, Barzaghi R, Basic T, Carrion D, Claessens S, Erol B, Erol S, Filmer M, Grigoriadis VN, Isik MS, Jiang T, Koc O, Krcmaric J, Li X, Liu Q, Matsuo K, Natsiopoulos DA, Novák P, Pail R, Pitonak M, Schmidt M, Varga M, Vergos GS, Veronneau M, Willberg M, Zingerle P (2021) Colorado geoid computation experiment: overview and summary. *Journal of Geodesy* 95(12): 127

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Acknowledgements

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Inter-Commission Committee on Geodesy for Climate Research (ICCC)

https://iccc.iag-aig.org/

President: Annette Eicker (Germany)
Vice President: Carmen Boening (USA)

Structure

Joint Working Group C.1:	Climate Signatures in Earth Orientation Parameters
Joint Working Group C.2:	Quality control methods for climate applications of geodetic tropospheric parameters
Joint Working Group C.3:	Geodesy for the Cryosphere: advancing the use of geodetic data in polar climate modelling
Joint Working Group C.4:	Sea level and vertical land motion
Joint Working Group C.5:	Understanding the monsoon phenomenon from a geodetic perspective
Joint Working Group C.6:	Numerical Simulations for Recovering Climate-Related Mass Transport Signals
Joint Working Group C.7:	Satellite geodetic data assimilation for climate research
Joint Working Group C.8:	Methodology of comparing/validating climate simulations with geodetic data

Overview

The new Inter-Commission Committee on "Geodesy for Climate Research" (ICCC) was officially established during the IUGG General Assembly in Montreal (July 2019) to enhance the use of geodetic observations for climate studies. The aim is to enable a systematic and comprehensive approach among the various geodetic communities, but also to establish and foster links to climate science.

ICCC Steering Committee (2019-2023):

President:	Annette Eicker (Germany)
Vice-President:	Carmen Boening (USA)
Representative of Comm.1:	Christopher Kotsakis (Greece)
Representative of Comm.2:	Wei Feng (China)
Representative of Comm.3:	Michael Schindelegger (Germany)
Representative of Comm.4:	Anna Klos (Poland)
Representative of GGOS:	Mayra Oyola (USA)
Representative of IAMAS:	Vincent Humphrey (USA)
Member at Large:	Felipe Nievinski (Brazil)

The following specific goals were identified for the ICCC:

- to deepen the understanding of the potential (and limitations) of geodetic measurements for the observation, analysis and identification of climate signals.
- to advance the development of geodetic observing systems, analysis techniques and data products regarding their sensitivity to and impact on Essential Climate Variables.

- to advance the improvement of numerical climate models, climate monitoring systems, and climate reanalysis efforts through incorporating geodetic observations.
- to stimulate scientific exchange and collaboration between the geodetic and the climate science communities.
- to make geodetic variables more user-friendly by sharing them publicly and explaining their usefulness.

Outreach and communication:

An important focus in the starting phase of the ICCC was the set-up of **outreach activities** to enhance the visibility of the ICCC:

- The new ICCC website (https://iccc.iag-aig.org/) was established within the framework of the IAG web pages.
- An ICCC Twitter account (@IAG_climate) was set up and has actively started tweeting (949 followers & 202 tweets as of June 2023).
- An overview article was published in GIM International and in the IAG Newsletter.
- An ICCC representative (A. Eicker) has become member of the IUGG Union Commission on Climatic and Environmental Change (CCEC).
- Emails were sent to contact persons at various climate organizations (IAMAS, WCRP/GEWEX, GCOS,…) to connect the ICCC with the climate science community.

Fig. 1: ICCC Twitter account

Furthermore, facilitating efficient **communication** means has been considered an important basis for starting a successful cooperation. Therefore, both an internal mailing list was set up for everyone actively involved in the ICCC and an open mailing list has been established to which everyone interested in the ICCC can subscribe. To enable more rapid communication, e.g., during the workshop planning phase, an ICCC workspace was established on the chat platform Slack and later switched to Zulip. Additionally, personal communication was achieved during regular video conferences, such as the ICCC Kick-Off meeting (May 2020) and various meetings of the workshop planning team over the months leading up to the first workshop. Since then, communications among the team have continued and led to several additional ICCC-organized events including a second workshop in 2023 and the start of a seminar series on 'Geodesy for Climate Research'.

1. ICCC Workshop

The first ICCC event involving the larger climate and geodetic communities was the successful implementation of the first ICCC workshop as the beginning of a regular ICCC workshop series. It took place on March 29-30, 2021 as an online event and was planned as a mixture of live sessions (held on Zoom) and additional online content to be viewed and discussed at any time to accommodate time zone conflicts. All presentations (orals and posters) were be available for download before the beginning of the workshop to allow asynchronous viewing. The live sessions were held in 2x2h blocks each day, one in the morning (CEST) and one in the late afternoon to enable participation from all time zones. The live meetings consisted of invited overview lectures and short 12-minutes oral presentations. Additionally, two poster sessions were carried out in which each presenter had the opportunity to discuss the poster and to show additional content in their own Zoom breakout room. The chat platform Slack was applied to enable communication between all workshop participants and to discuss the science presentations and posters. No financial budget was anticipated for the workshop. As only free tools (or tools freely available to the organizers) were used, it was possible to offer the workshop free of charge to all participants. This resulted in more than 400 registered participants from over 50 countries and a strong participation of between 100-160 people in each live session. More than half of both participants and speakers identified themselves as early career researchers. In addition to individual scientific presentations, overarching discussions were encouraged on topics such as possible geodetic contributions to observing Essential Climate Variables and on best ways to increase visibility of geodesy in in the public and in neighboring disciplines. The outcome of these discussions will be a good starting point for future ICCC activities.

CEST (UTC+2)	Monday (29.03.21)	Tuesday (30.03.21)	Wednesday (31.03.21)
« Morning » block (2 hours)			
8:00	Welcome	Session 04 : Cryosphere	Keynote : Sea level & cryo
8:15	Keynote : ECVs		Session 07 : Sea level
8:30	Session 01 : Hydrology and data processing (Hydrology I)		
8:45			
9:00			
9:15		Session 05 : Poster breakout II	
9:30			
9:45	Discussion		Discussion
« Afternoon » block (2 hours)			
17 :00	Keynote : Climate models	Keynote : Troposphere	Session 08 : Hydrology II
17 :15	Session 02 : Climate model evaluation	Session 06 : Atmosphere	
17 :30			
17 :45			
18 :00			
18 :15	Session 03 : Poster breakout I		
18 :30			
18 :45		Discussion	
			Closing and next steps

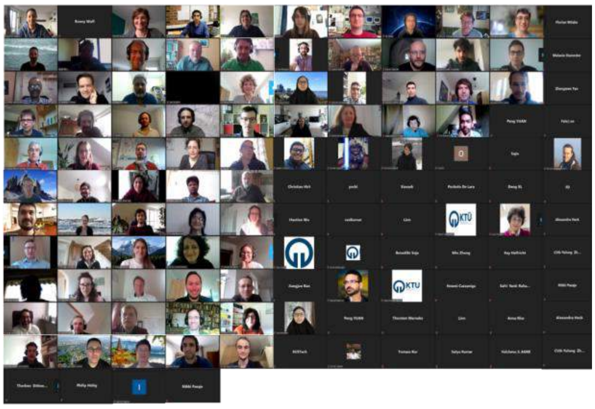

Fig. 2: 1. ICCC Workshop: Program and participants

2. ICCC Workshop

After the success of the first workshop, the ICCC organized a second workshop on March 28-29, 2023. Similar to 2021, the workshop was held online and consisted of 4 oral and one poster session displaying in total 47 presentations. Topics ranged from general data processing techniques to discipline specific presentations on using geodetic methods and observations for climate research. The workshop received great resonance in the climate and geodetic communities with 290 total registered participants across the world. Slight modification to the format were made as workshop-related discussion were moved from Slack to the free platform Zulip to provide easier access and sessions were grouped by timezone-specific presentation preferences rather than topical themes to allow for more flexibility for the speaker and audience. Overall, ~80 researchers participated in each session and contributed to a fruitful discussion to further connect geodesy and climate research.

CEST (UTC+2)	Tuesday (28.03.2023)	Wednesday (29.03.23)
08:00 – 10:00	**Session 1:** Welcome Ocean Altimetry Misc	**Session 4:** Ice mass balance Hydrology GRACE
15:00 – 15:40	**Session 2:** GNSS	**Session 5:** GNSS Hydrology Atmosphere Misc
15:40 – 17:00	**Session 3:** Posters	

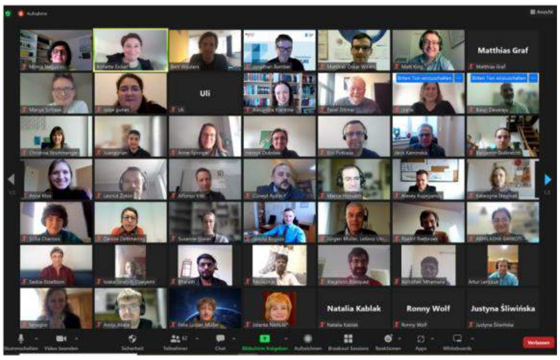

Fig. 3: 2. ICCC Workshop: Program and participants

‘Geodesy for Climate Research’ Seminar Series

To ensure continued exchange between the geodetic and climate community, a seminar series was started in 2022. Adam Scaife of the UK MetOffice gave the first invited talk on ‘Initialised climate prediction and length of day fluctuations’ on June 7, 2022.A total number of 144 participants registered for the event from a range of different disciplines. Second talk in the series was by Jonathan Bamber of the University of Bristol, Technical University Munich entitled ‘The emergence of satellite geodesy as a game changing tool in climate science’ on November 17, 2022 with 241 registrations. After the positive reception of the first couple of talks that invigorated the discussion among climate and geodetic science communities, it is planned to continue the series with talks at a biennial frequency.

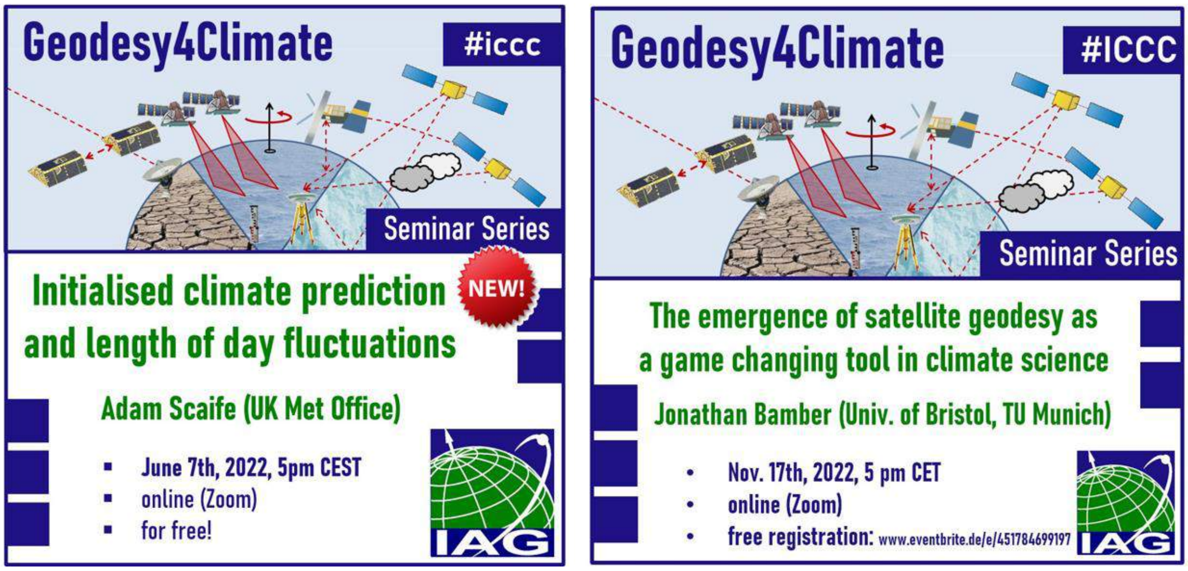

Fig. 4: Announcement of ICCC Seminar talks.

Scientific sessions

To further promote ICCC activities, dedicated sessions have been proposed and carried out under the umbrella of the ICCC at major international conferences (e.g., EGU 2020, 2021, 2022, & 2023, IAG Scientific Assembly 2021, AGU 2020 & 2021 & 2022). A highlight at the end of the first 4-year period of the ICCC represents the IAG-led Joint Symposium “Geodesy for Climate Research” organized together with four other IUGG associations (IAHS, IAMAS, IACS, IAPSO) to be held with 6 oral sessions at the 2023 IUGG General Assembly. Additionally, various JWGs have organized specific sessions on their JWG topics.

Joint Working Group C.1: Climate Signatures in Earth Orientation Parameters

Chair: *Jolanta Nastula (Poland)*
Vice-Chair: *Henryk Dobslaw (Germany)*

Members

- *Christian Bizouard (France)*
- *Sigrid Boehm (Austria)*
- *Aleksander Brzezinski (Poland)*
- *Benjamin Fong Chao (Taiwan)*
- *Yavor Chapanov (Bulgaria)*
- *Jianli Chen (USA)*
- *Alexandre Couhert (France)*
- *Robert Dill (Germany)*
- *Alberto Escapa (Spain)*
- *José Manuel Ferrandiz (Spain)*
- *Laura Fernandez (Argentina)*
- *Franziska Goettl (Germany)*
- *Richard Gross (USA)*
- *Robert Heinkelmann (Germany)*
- *Sébastien Lambert (France)*
- *Vladimir Pashkevich (Russia)*
- *Elena Podladchikova (Belgium)*
- *Cyril Ron (Czech Republic)*
- *David Salstein (USA)*
- *Michael Schindelegger (Germany)*
- *Nikolay Sidorenkov (Russia)*
- *Leonid Zotov (Russia)*

Activities and publications during the period 2019-2023

During the reporting period, Working Group C.1 has organized ten virtual meetings on the following topics: 1. *EOP and Climate* (May 6th, 2020), 2. *Polar Motion from CMIP6 models* (June 11th, 2020), 3. *Pole Tide Signatures in GRACE Data* (August 28th, 2020), 4. *EOP Prediction* (November 12th, 2020), 5. *Atmospheric and Oceanic Excitation Functions* (January 14th, 2021), 6. *Consistent Combination of EOP and Geophysical Excitation Functions* (March 18th, 2021), 7. *Gravimetric Polar Motion Estimates* (June 17th, 2021), 8. *Madden-Julian Oscillation and Climate Fingerprints in EOP* (September 23rd, 2012), 9. *Current Capabilities for EOP Prediction* (Nov 25th, 2021), and 10. *EOP and Climate Change from CMIP6* (January 19th, 2023). All meetings were held online via zoom/webex and have attracted between 25 and 45 members of the working group and other interested scientists. JWG C.1 also contributed actively to the organization of the two Workshops of the ICCC via participation in the Organizing Committee, by chairing a Session, and by contributing several oral presentations and posters.

To further expedite the scientific work, a new website (https://syrte.obspm.fr/~bizouard/ipercc/index.html) provides structured access to data sets and literature that is relevant to the work of JWG C.1. A number of scientific publications have been already completed on topics like terrestrial water storage contributions to observed EOP (Sliwinska et al., 2020), the accurate representation of the effects of the oceanic pole tide in EOP and satellite gravimetry (Chen et al., 2021), and on the ability of numerical oceans to accurately simulate high-frequency ocean mass transports (Schindelegger et al., 2021). Other relevant publications include the long-range predictability of extratropical climate and LoD changes (Scaife et al., 2022) as well as the utilization of ocean reanalyses for EOP research (Börger et al., 2023). It is expected that international collaboration expedited by the Joint Working Group C.1 will lead to further scientific publications in the near future.

The topic of the fourth meeting of the JWG C.1, *EOP Prediction*, has met with particularly high interest by the scientific community. In total five talks from scientists representing different international research centers active in the field of EOP prediction have been presented. Following the discussion, it has been decided to rigorously compare the accuracy of present-day methods and algorithms applied in EOP prediction by means of a dedicated international comparison campaign. This campaign will be organized under the auspices of the IERS within a newly established working group (https://www.iers.org/WGEOPPCC2), but cooperation with JWG C.1 on this topic will be maintained also in the future.

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JWG C.2: Quality control methods for climate applications of geodetic tropospheric parameters

Chair: Rosa Pacione (Italy)
Vice-Chair: Marcelo Santos (Canada)

Affiliation: Commission 4, IGS, IVS

Members

- *Kyriakos Balidakis (Germany)*
- *Sharyl Byram (USA)*
- *Galina Dick (Germany)*
- *Gunnar Elgered (Sweden)*
- *Olalekan Isioye (South Africa)*
- *Jonathan Jones (UK)*
- *Michal Kačmařík (Czech Republic)*
- *Anna Klos (Poland)*
- *Haroldo Marques (Brazil)*
- *Thalia Nikolaidou (Canada)*
- *Tong Ning (Sweden)*
- *Mayra Oyola (USA)*
- *Eric Pottiaux (Belgium)*
- *Paul Rebischung (France)*
- *Roeland Van Malderen (Belgium)*
- *Yibin Yao (China)*

Activities and publications during the period 2019-2023

The original scientific questions JWG C.2 procures to address were: (a) are there advantages of combining ZTD estimates over not combining them? Is there any ‘loss of information’ in performing combinations? (b) Would there be difference in trends derived from them? If so, how much implication for feeding information to climate? (c) Can we trust in a combined ZTD as we trust any combined products (e.g., orbits, clock, site coordinates) (d) What the best combination strategy can be done (not necessarily to combined exactly the same way as other products)? (e) Under what criteria can we use spectral analysis to demonstrate that a ‘good’ combined product has the same properties of the contributing solutions? (f) What metrics should be used to ascertain that the optimal set of ZTD estimates, gradients and their trends, are provided to the climate community?

A choice was made since the inception of JWG C.2 to base our investigation on the, at the time, still to be released REPRO3, more specifically, their tropospheric estimates. We acknowledge the huge and careful effort by the IGS Analysis Centres to generate REPRO3, an effort which demanded a large amount of time, which overlapped with most of the term of the JWG C.2. Therefore, activities of JWG C.2 can be divided into two segments, one before and another after the release of REPRO3.

Before the release of REPRO3, activities were constrained to discussions on various virtual meetings involving the members of the JWG C.2, due to COVID-19 restrictions. One such meeting had the participation of a few invited guests from the climate community. Their participation helped to clarify a few points as well as to open important insights from their perspective, to understand their needs, as well as provide our perspective into what kind of tropospheric products could be generated. One concern that still lingers over space geodetic derived parameters for climate, such as ground GNSS, is its still short period. GNSS is barely reaching the 30-year climate normal cycle. Nonetheless, during the discussions, we were told that the climate modellers may find wealth in GNSS derived tropospheric parameters for periods shorter than 30 years. If the concern is primarily with improving the representation of processes and models, a data set that provides with something new, with something that is not provided from elsewhere, allowing to investigate and improve a particular physical process in the model, is where lies the benefit. It may be better spatial gradients in the water vapour field or better high frequency variability. If such things can be isolated, there lies a great contribution. Therefore, a few years of high-quality data might be as important as a full 30-years data.

With the release of REPRO3, a taskforce started to handle a subset of 39 stations, as shown in Figure C2.1, selected due to their long-term GNSS time series. They are distributed around the world to cover different climatic regimes. Some stations are relatively close to provide some extra level of comparison. Not all Analysis Centres provide ZTD, they do not use the same processing strategies and their output follow a different rate. Six ZTD solutions were used (each Analysis Centre is represented by its three-letter code, followed by their own output rate): COD, 1h; ESA, 1h; GFZ, 1h; GRG, 2h; JPL, 100s; TUG 5m. Besides REPRO3 ZTD estimates, we also used ERA-5 extracted ZTD, serving as a trustful independent reference, as well as for the homogenization of the ZTD time series (Klos et al., 2022).

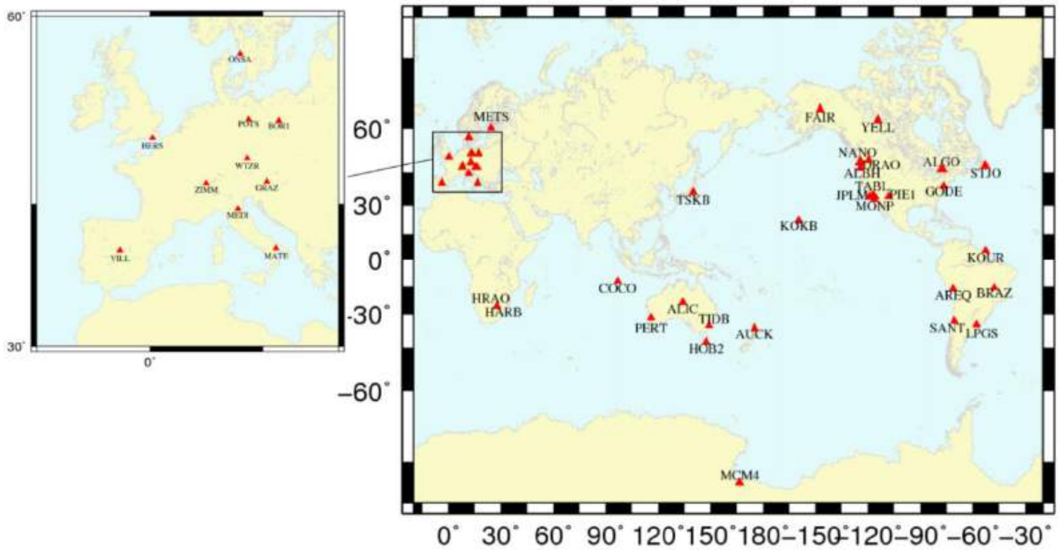

Fig C2.1: Geographical distribution of the selected stations

Following the homogenization, daily mean values are produced. The reduction to daily mean values is an attempt to accommodate the differences in strategies that each Analysis Centre use. The daily mean values are computed using a simple weighted average using the ZTD standard deviation in the process. When available, the PPP-generated IGS final ZTD product in REPRO3 will go through the same process.

The next step in the methodology calls for the combination among the six averaged homogenized ZTD time series. This process is done as a simple weighted mean, as the daily mean input values are considered outlier-free. The combination becomes both a separate time series for analysis and a testbed for quality control of each one of the Analysis Centres.

The trends are then estimated from the six averaged homogenized ZTD time series and the combined solution using robust estimation. The same input is to be used in an analysis in frequency domain.

As an illustration, results for station ALBH are shown. Figure C.2 displays the homogenized daily mean ZTD time series of all six Analysis Centers and their combination. Colors are indicated on the label. This figure indicates that there are data gaps in the original time series, which are reflected in the final homogenized daily means. The importance of this fact will be made clear in the sequence.

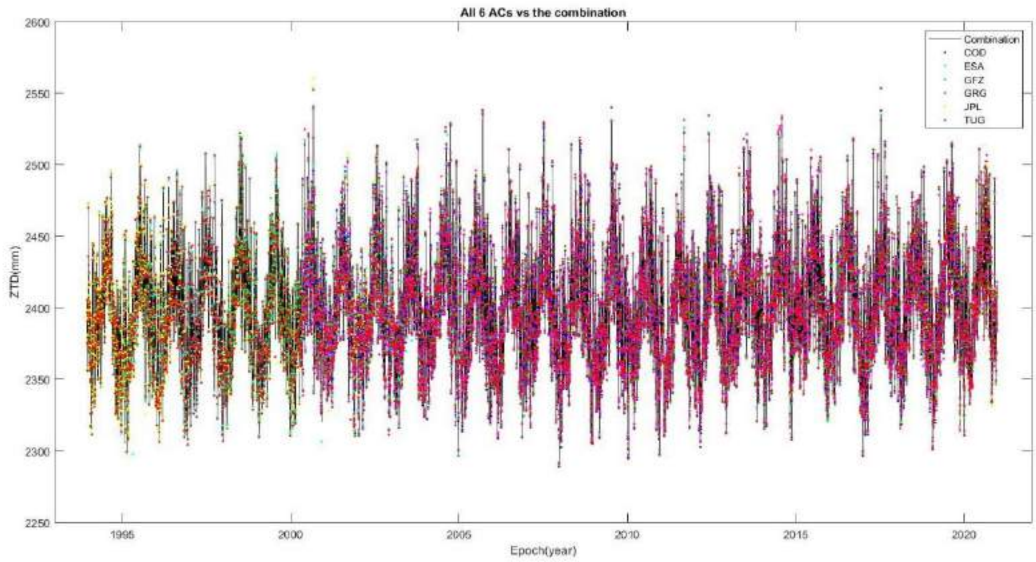

Fig C2.2 Homogenized daily mean ZTD times series of all six Analysis Centres and their combination. Colours: combination (black continuous line), COD (navy blue dot), ESA (sky blue dot), GFZ (green dot), GRC (pink dot), JPL (yellow dot) and TUG (red dot)

Table C2.1 summarizes trends as derived from the homogenized daily mean ZTD time series from each of the six Analysis Centers, and that of the combination. The table shows the trends (mm/decade), the annual amplitudes (mm), the annual phases (degrees), as well as the number of points involved in each solution. The last column indicates that the number of points are different, as the data collected at this particular station ended up being used differently by each Analysis Center. This difference may be the explanation of the large variation seen among the solutions based on different Analysis Centers. The inter-Analysis Center scatter is 1.25 mm/decade for the trends, 0.73 mm for the annual amplitudes and 1.99 degrees for the annual phase.

Table C2.2 is like Table C2.1 with a major difference. The trends were computed only using the common epochs between all Analysis Centers, which caused the ZTD time series from ESA and JPL to be disregarded. The inter-Analysis Center scatter decreased to 0.47 mm/decade for the trends, to 0.11 mm for the annual amplitudes, and to 0.29 degrees for the annual phase.

A simple look at the statistics shows us that the trend using TUG is slightly away from the mean at 1-sigma, whereas amplitude and phase from GRG are negligibly above the mean at 1-sigma. The reason for that was not established, perhaps some kind of jump that was not detected during the homogenization or such a difference could indicate that those parameters should not be used. Such an analysis lies within the discussion on establishing metrics to determine if a trend can be trusted or not.

Table C2.1 – Trend, amplitude, and phase of original ZTD time series

	Trend [mm/decade]	Amplitude [mm]	Phase [°]	Number of points
Combination	3.28	31.99	54.82	9849
COD	3.06	31.43	54.15	7170
ESA	6.43	33.39	55.14	3270
GFZ	2.95	31.78	54.46	9061
GRG	4.03	31.68	53.25	7478
JPL	5.05	32.91	59.42	1337
TUG	4.10	31.80	54.62	9837

Table C2.2 – Trend, amplitude, and phase of the synchronized ZTD time series

	Trend [mm/decade]	Amplitude [mm]	Phase [°]	Number of points
Combination	3.18	31.44	54.03	7079
COD	3.19	31.48	54.09	7079
GFZ	3.00	31.35	54.06	7079
GRG	3.63	31.58	53.40	7079
TUG	4.16	31.30	53.80	7079

The delays in availability of the desired input data, has prevented the completion of the whole analysis by the time this report is being submitted. Besides, many new questions have appeared, and they could require additional investigation time.

To finalize this report, be registered other activities worth mentioning, the participation and presentation of orals during the EGU general assemblies (2020, 2021, 2022 and 2023), the first and second ICC Workshop (2021 and 2023), and in the IAG Scientific Assembly 2021.

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JWG C.3: Geodesy for the Cryosphere: advancing the use of geodetic data in polar climate modelling

Chair: *Bert Wouters (Netherlands)*
Vice-Chair: *Ingo Sasgen (Germany)*

Members

- *Mike Bevis (USA)*
- *Matthias Braun (Germany)*
- *William Colgan (Denmark)*
- *Christoph Dahle (Germany)*
- *Olga Engels (Germany)*
- *Xavier Fettweis (Belgium)*
- *Dana Floricioiu (Germany)*
- *Heiko Goelzer (Denmarl)*
- *Natalya Gomez (USA)*
- *Martin Horwath (Germany)*
- *Michalea King (USA)*
- *Kristine Larson (USA)*
- *Jan Lenaerts (USA)*
- *Lin Liu (Hong Kong)*
- *Malcolm McMillan (UK)*
- *Brice Noël (Netherlands)*
- *Masashi Niwano (Japan)*
- *Louise Sandberg Sørensen (Denmark)*
- *Mirko Scheinert (Germany)*
- *Nicole Schlegel (USA)*
- *David Wiese (USA)*

Activities and publications during the period 2019-2023

The activities of this Joint Working Group were focused on creating awareness of the importance of bridging the currently existing gap between the geodetic and modelling communities, and on establishing ties to relevant to relevant ongoing international activities and communities.

A large number of members from both communities were involved in the Ice Sheet Mass Balance Intercomparison Exercise (IMBIE) which aims to come to reconciled estimates of ice sheet mass loss based on geodetic and model-based mass balance data. Results were published Shepherd et al. (2020) and Otosaka (2023). A similar activity was initiated for mountain glaciers within the Regional Assessments of Glacier Mass Change (RAGMAC; Zemp et al., 2020) initiative, which aims to bring together the research community that is assessing regional glacier mass change. The ultimate goals is to establish a new consensus estimate of global glacier mass changes and related uncertainties, which can be used for model calibration and initialization. Within the GrSMBMIP an intercomparison was carried out between state-of-the-art ice sheet models and geodetic data, again with the involvement of JWG members. Our members are also well represented in the recently launched Horizon 2020 PROTECT initiative, which aims to assess and project changes in the land-based cryosphere, with fully quantified uncertainties, in order to produce robust global, regional and local projections of SLR on a range of timescale. Furthermore, members have continued their contribution to ESA Climate Change Initiatives, which strives to provide easy accessible and interpretable satellite observations to a wide range of researchers. We are also involved in the INStabilities & Thresholds in ANTarctica (INSTANT) initiative of the Scientific Committee on Antarctic Research (SCAR), which aims to quantify the Antarctic ice sheet contribution to past and future global sea-level change, from improved understanding of climate, ocean and solid Earth interactions and feedbacks with the land ice, from a modelling and observational perspective.

In terms of outreach, team members were involved the successful ICCC 2021 and 2023 workshops, either as co-organizer or presenters. This workshop was also promoted by a team member in the newsletter of the European Climate Research Alliance ECRA. We were also well represented at the European Polar Science Week 2020, where members presented their, hosted sessions and round table discussions involving researchers from both the geodetic and modelling community. At EGU 2020 and 2021, and IUGG 2023, a session on Geodesy for Climate Research was organized, which included a number of presentations tied to our JWG.

With respect to future geodetic observables, group members contributed to NASA and ESA working groups in preparation of future gravimetry and altimetry missions.

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JWG C.4: Regional Sea level and vertical land motion

Chair: *Roelof Rietbroek (Netherlands)*
Vice-Chair: *Riccardo Riva (Netherlands)*

Members

- *Alvaro Santamaria (U. Toulouse III, France), GPS vertical land motion*
- *Sönke Dangendorf (U. Siegen, Germany), tide gauges*
- *Adrian Borsa (Scripps, USA), VLM.*
- *Aimée Slangen (NIOZ, NL), projections/models*
- *Ropesh Goyal (Kanpur/Curtin), Geoid modelling, India*
- *Guy Woppelmann (U. La Rochelle, France), TG & VLM*
- *Giorgio Spada (U. Urbino, Italy), TG and GIA*
- *Erik Ivins (JPL, USA), sea level & solid earth*
- *Marta Marcos (UBI, Spain), TG & oceanography*
- *Thomas Frederikse (JPL, USA), sea level & VLM*
- *Don Chambers (USF, USA), oceanography & GRACE*
- *Francisco Calafat (NOC, UK), oceanography*
- *Karen Simon (TU Delft, NL), GIA*

Activities and publications during the period 2019-2023

Despite the covid19 pandemic, there have been several online meetings with the joint working group, or a selection thereof, over the period 2019-2023. Partially these involved bringing together ideas of how to showcase and translate the scientific challenges of regional sea level and vertical land motion to a non-geodetic audience. The joint working group has discussed ideas for setting up materials, and which may potentially be hosted on the IAG website in the future.

Several of the members have represented the joint working group and participated in the organization of the ICCC workshop which was successfully held online in March 2021 and March 2023 They additionally contributed a keynote lecture (in collaboration with the cryosphere working group) and scientific content, and a live twitter feed targeting the general public through the @iag_climate account. A summerschool hosted at the TU Delft in the summer of 2022 and organized by Riccardo Riva have further exposed the themes of the working group.

Furthermore, during the online assemblies of AGU2020, AGU2021, AGU2022, AGU2023 and EGU2021, EGU2022, EGU2023 joint working group members have served as conveners in sessions which were closely aligned with the ICCC goals and explicitly mentioned the ICCC and its goals in the session description.

The group members have been actively publishing scientific works which cover the goals of the joint working groups, of which a selection is listed below.

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Joint Working Group C.5: Understanding the monsoon phenomenon from a geodetic perspective

Chair: *Balaji Devaraju (India)*
Vice-Chair: *Matthias Weigelt (Germany)*

Members

- *Alexander Braun (Canada)*
- *Alka Singh (India)*
- *Bramha Dutt Vishwakarma (UK, India (since 2021))*
- *Chandrakanta Ojha (India)*
- *Karim Douch (Germany)*
- *Mohammad A. Sharifi (Iran)*
- *Nabila Putri (Indonesia)*
- *Nico Sneeuw (Germany)*
- *Peng Yuan (Germany)*
- *Qiang Chen (Luxembourg)*
- *Shivam Tripathi (India)*
- *Subimal Ghosh (India)*
- *Susanna Werth (USA)*
- *Vagner Ferreira (China)*
- *Zhizhou Liu (Hong Kong, China)*

Activities and publications during the period 2019-2023

Monsoon is a large-scale atmospheric phenomenon that brings precipitation to a major section of the global population. It sustains agriculture and replenishes the water resources. In the recent decades, geodetic sensors have enabled a greater understanding of earth system processes, especially that of hydrology. In this context, the joint working group is invested in understanding the monsoon phenomenon from a geodetic perspective, and thereby improve the process understanding of monsoon, and contribute towards its monitoring and modelling. It is to be noted here that the monsoon phenomenon has not been studied widely in the geodetic literature, and to a large extent the geodetic sensors have not been used in monsoon studies. Thus, the main objective of the joint working group is to promote the use of geodetic sensors in monsoon research, and thereby demonstrate their respective abilities.

The first step in demonstrating the abilities of geodetic sensors is to choose the physical variables measured by the geodetic sensors that are more sensitive to the monsoon phenomenon, and thereby identify the signature – timing, intensity and spatial distribution. The geodetic sensors that are considered in the joint working group are satellite altimetry (radar and lidar), satellite gravimetry, GNSS and InSAR. In the first internal workshop of the joint working group, several variables like precipitable water vapour, total water storage change, vertical crustal motion due to hydrological loading, steric sea-level, wind speed and wind direction, which can all be measured by the geodetic sensors have been identified as sensitive to the monsoon phenomenon. Currently, the monsoon signatures of these variables are being investigated. To this end the joint working group is preparing a white paper on the role of geodesy in monsoon research in which all the above-mentioned issues are discussed in detail.

The joint working group is active in organizing internal workshops, contributing sessions in conferences and disseminating information through social media. As a kickstart event an internal workshop was conducted to understand the strengths of the working group members and the processes involved in the monsoon phenomenon. The joint working group contributed to the 1st ICCC workshop "Geodesy for Climate Research" both in terms of science as well as its organization. In the upcoming 18th Annual Meeting of the Asia-Oceania Geosciences Society 2021, the joint working group is conducting a session on *Data-driven approaches for studying the monsoon phenomenon*, which will have eleven contributions (eight oral and three poster presentations). In addition, our group has also applied for a dedicated session in the upcoming American Geophysical Union Fall Meeting 2021. Further activities, especially, more internal workshops and special issue publications will be planned in the second and final phase of the joint working group.

The group conducted a session in the 18th Annual Meeting of the Asia-Oceania Geosciences Society 2021, titled *Data-driven approaches for studying the monsoon phenomenon*. It received 11 contributions. A similar session was conducted in the American Geophysical Union Fall Meeting 2021, titled *Understanding the Monsoon phenomenon through geodetic and other earth observation data.* The session received 5 contributions. The use of GRACE total water storage, GNSS and InSAR observed precipitable water vapour estimates in monsoon research were depicted by many of these studies. The working group is finalizing the white paper that was indicated earlier. The main focus of the white paper has been on collating the information on the sensors and their data characteristics that will enable monsoon studies.

Summary and Outlook

The joint working group explored the role of geodetic sensors and their observations for studying the monsoon phenomenon. As such monsoon is a complex phenomenon, especially the Asian Summer Monsoon whose process understanding is still elusive. The current methods and models in monsoon studies focus on the wind data and the thermodynamic aspects of the phenomenon. However, geodetic sensors provide information on the geometric and mass aspects of the monsoon phenomenon, which is unprecendented.

Three variables from geodetic sensors have shown promise in monsoon studies – total water storage (GRACE and GRACE-FO), GNSS position time-series, and precipitable water vapour from InSAR data. GNSS Radio Occultation provides vertical profiles of temperature and pressure, and this data has been unexplored in terms of monsoon studies. Given the nascent nature of this research further effort is required in turning the promising studies to operational activities, and to determine the required standards for incorporating geodetic data in models predicting the monsoon.

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Ghosh, S (2021) Understanding processes of Human-Natural hydroclimatic system in the Indian Monsoon region. AGU Fall Meeting 2021, December 13-17, 2021, New Orleans and Online.

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Srivastava, S and Devaraju, B (2021). Signatures of the Indian Monsoon Dynamics in daily GRACE data. AGU Fall Meeting 2021, December 13-17, 2021, New Orleans and Online

Srivastava, S, Ghoshal, R and Devaraju, B (2021). Use of GRACE Data for Understanding the Indian-monsoon. 18th AOGS Annual Meeting, August 1-7, 2021, Online

Werth, S, Shirzaei, M and Ojha, C (2021). Predicting and Validating Integrated Water Vapor from SAR Interferometric Analysis of Sentinel-1 Data over Kerala, India. AGU Fall Meeting 2021, December 13-17, 2021, New Orleans and Online.

Werth, S, Shirzaei, M, Ojha, C and Sherpa, S (2021). InSAR Based Water Vapor Mapping During Monsoon Related Flood Events. 18th AOGS Annual Meeting, August 1-7, 2021, Online

Yuan, P and Kutterer, H (2021). Spatiotemporal Variations of Integrated Water Vapor over China Sensed by Ground-based GPS and Atmospheric Reanalyses 18th AOGS Annual Meeting, August 1-7, 2021, Online

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JWG C.6: Numerical Simulations for Recovering Climate-Related Mass Transport Signals

Chair: *Roland Pail (Germany)*
Vice-Chair: *Wei Feng (China)*

Members

- *Roland Pail (Germany)*
- *Wei Feng (China)*
- *Henryk Dobslaw (Germany)*
- *Laurent Longuevergne (France)*
- *Vincent Humphrey (US)*
- *Benoit Meyssignac (France)*
- *Lijing Cheng (China)*
- *Qiang Chen (Luxembourg)*
- *Sonia Seneviratne (Switzerland)*
- *Martin Horwath (Dresden)*
- *Bert Wouters (Netherlands)*
- *Erik Ivins (US)*
- *Marius Schlaak (Germany)*

Activities and publications during the period 2019-2023

The main objective of this working group is to set-up and run long-term numerical simulation studies to evaluate the feasibility to derive climate-related signals by current (GRACE, GRACE-Follow On) and future gravity field missions.

In a first step, a 100-year time series of continental hydrology was generated. For this, land water storage related variables from a variety of climate models taking part in the Coupled Model Inter-comparison Project Phase 6 (CMIP6) was compared and assessed against each other (Jensen et al. 2019, 2020). Finally, a specific model run was selected that closely matches both GRACE observations, and a multi-model median.

In parallel, numerical simulation software was adapted to be capable of dealing with very long time series of up to one century, and the parameter model was extended to directly parameterize linear (and optionally quadratic) trends and annual signals (Schlaak et al. 2021). In the course of several test runs, the covariance structure and thus the arising correlation among the parameter groups was analyzed in detail. Additionally, a study was performed to evaluate the long-term behavior of various errors and their impact on single- and double-pair gravity solutions. Further work included extended parameterization schemes of climate-related long-term changes in global to regional mass transport (Schlaak et al. 2022).

Significant contributions regarding the applicability of gravity field missions for climate model validation were provided to the joint ESA/NASA Mission Requirement Document of MAGIC (Mass-change And Geoscience International Constellation) and the corresponding mission advisory group, leading eventually to the decision at ESA' Ministerial Conference 2022 on the further mission implementation of MAGIC (https://www.esa.int/Applications/Observing_the_Earth/FutureEO/It_s_a_kind_of_MAGIC). It could be demonstrated, that climate change impacts on the global water cycle such as its intensification will be markedly better be observed by a MAGIC double pair mission than by a GRACE-like mission. While, according to our simulations, a GRACE-like mission can only detect the projected changes of the annual amplitude of continental water storage in 36% of the land area after 30 years of observation, MAGIC-like missions would be able to identify such changes in 64% of the land area (Figure C6.1). Similarly, the projected 30-years phase change of water storage can be detected by the single-pair scenario in 30% of the land area while a significant increase of this portion (56% of land area) can be achieved with the MAGIC constellation.

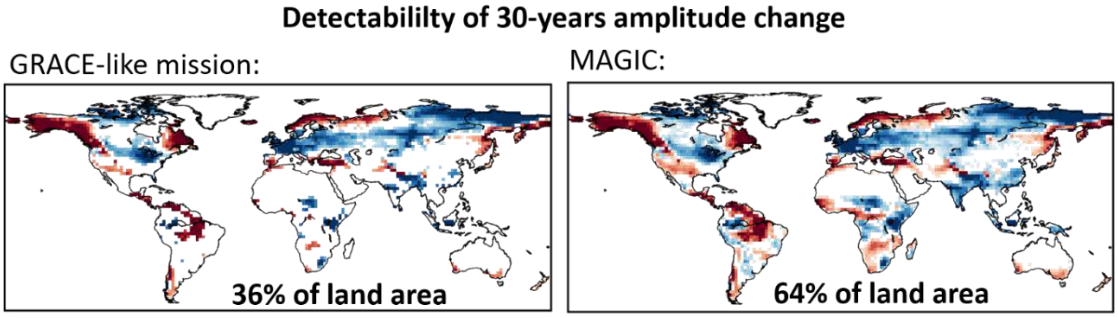

Figure C6.1: *Detectability of the projected climate-change induced annual amplitude change of terrestrial water storage after 30 years of satellite gravimetry observations: coloured pixels denote where projected amplitude change exceeds the magnitude of the GRACE or MAGIC accuracy.*

One of the main prerequisites to compare simulation results of various contributing groups is to inter-compare the performance of the different numerical mission simulators first. Therefore, an inter-comparison exercise of numerical simulators and simulation results among four Chinese groups and the simulator at Technical University of Munich was performed (Pail et al. 2019). Figure C6.2 shows resulting coefficient differences in terms of equivalent water height (EWH) degree RMS curves. This case study is based on a 9-day Bender double-pair constellation and temporal gravity field signals of atmosphere, ocean, hydrology, ice and solid Earth (AOHIS), and assuming realistic instrument and background model errors. The results demonstrate that very similar and thus comparable results could be achieved.

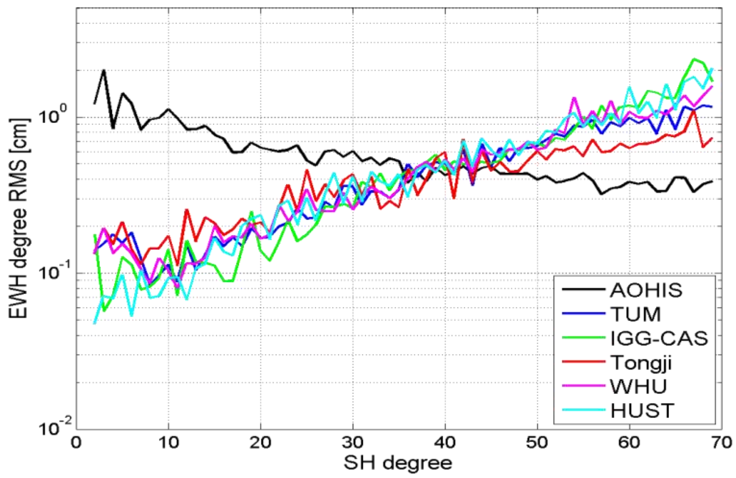

Figure C6.2*: Degree (error) RMS of estimated time-variable coefficients from the true signal (black) of five groups, based on a Bender double-pair constellation with 9 days repeat period.*

The JWG C.6 also contributed to the preparation and realization of the two ICCC Workshops, that were held on 29-31 March 2021, and 28-29 March 2023. Working group members also actively contributed with several presentation there, and also other international conferences such as EGU, AGU and the IAG General Assembly.

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JWG C.7: Satellite geodetic data assimilation for climate research

Chair: Mehdi Khaki (Australia)

Members

- *Hamid Moradkhani (The University of Alabama)*
- *John T. Reager (NASA Jet Propulsion Laboratory)*
- *Harrie-Jan Hendricks Franssen (Institute of Bio- and Geosciences Agrosphere, IBG-3)*
- *Gabrielle J. M. De Lannoy (Katholieke Universiteit Leuven)*
- *Benjamin Zaitchik (Johns Hopkins University)*
- *Natthachet Tangdamrongsub (university of Maryland)*
- *Luca Brocca (National Research Council)*
- *Christian Massari (National Research Council)*
- *Ibrahim Hoteit (King Abdullah University)*
- *Jan Saynisch (GFZ German Research Centre for Geosciences)*
- *Ashkan Shokri (Monash University and Hydrologist at Bureau of Meteorology)*
- *Yoshihide Wada (International Institute for Applied Systems Analysis, IIASA)*
- *Joseph Awange (Curtin University)*
- *Jayaluxmi Indu (Indian Institute of Technology Bombay)*

Activities and publications during the period 2019-2023

The working group has been established in late 2019. Soon after contacting the potential members, multiple activities have been arranged. These are summarized below.

Website and sharing materials

As proposed in the working group's initial objectives, a website was created to introduce members and their activities, as well as provide a platform for sharing relevant materials. The website (www.satellite-da.com) has been constantly updated to cover the latest news and upcoming events. It is decided in the latest meeting by the group members that more parts should be invested in educational objectives. This has been done in 2022 and all group members have been contributing to offer documents/videos in this line.

Meetings

Proposed and agreed upon by the members, frequent meetings have been held. This has been as virtual meetings starting with activity updates followed by free discussions and scientific presentations by members. Individual meetings and conversations have also been held between the members about the relevant topics. Junior members of the involved research institutes have been engaged in discussions as suggested by the members.

Session contributions

The working group has been involved with three session organizations. The first one was the 2021 Australian Earth Sciences Convention (AESC), February 2021 Tasmania (Australia). The conference aim was to showcase current trends and advances in earth science, including the latest findings on the deep structure and composition of our planet, our diverse crust and surface environments, developments in the energy and resources sectors and critically, the essential role that geoscience plays in our sustainable future. The second event was ICCC Workshop "Geodesy for Climate Research" March 29-30, 2021. The working group represents two sessions in the event; Session 1 (Hydrology I) and Session 8 (Hydro II). An internal workshop on satellite data assimilation for land surface hydrology has also been held in Newcastle 2022 and members have been invited to contribute. This has been focusing on interested undergraduate students.

Publications

Several relevant research efforts have been published by the group members for the period of 2019-2023, which are summarized below.

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JWG C.8: Methodology of comparing/validating climate simulations with geodetic data

Chair: *Jürgen Kusche (Germany)*

Members

- *Felix Landerer (USA)*
- *Vincent Humphrey (USA, Switzerland)*
- *Ben Marzeion (Germany)*
- *Petra Friederichs (Germany)*
- *Henryk Dobslaw (Germany)*
- *Anna Klos (Poland)*
- *Laura Jensen (Germany)*
- *Anne Springer (Germany)*

Activities and publications during the period 2019-2023

The group members have participated in, and co-organized several activities related to the group's ToR including the ICCC workshops, the ISSI Workshop on Challenges in Understanding the Global Water Energy Cycle and its Changes in Response to Greenhouse Gas Emissions, the WCRP Earth Energy Imbalance Assessment Workshop 2023, the Hamburg SPP1889 Sea level conference 2023, various workshops of the newly established CRC1502 ("Regional Climate Change: Disentangling the Role of Land Use and Water Management") and the IMBIE activities; while the group as a whole has not been too active - this is to blame on the chairman's involvement in several other "challenges" (some related to climate science).

In Hakuba et al. (2021) the authors assessed the sea-level budget and its implications on Earth's energy imbalance EEI over 2005–2019 (space geodesy suggests an EEI of 0.94 ± 0.24 Wm^{-2}, with multiple approaches suggesting that heat uptake is increasing most markedly in recent years). This data has also been submitted to the GEWEX EEI Assessment.

Frederikse et al. (2021) estimate 20th-century sea-level changes in the South Atlantic Ocean from tide-gauge data and a new paleo proxy - 20th-century sea-level rise in the South Atlantic might have been above the global mean, but uncertainties remain large. Estimates of contemporary mass redistribution and sterodynamic effects support this above-average trend. Datasets (incl GRD fingerprints) are available at https://doi.org/10.5281/zenodo.4542572. Frederikse et al. (2020), using improved measurements and models better representing changes in land-based ice, water storage on land and ocean thermal expansion, reveal that these sources are the main causes of observed sea level rise and that no additional unknown processes are required to close the sea level budget. The new data reconciles recorded sea level rise measurements with these contributing processes all the way back to 1900. The resulting global and basin-scale reconstructions, the time series of global and basin sea-level changes and its contributors, grids with local sea-level and solid-Earth deformation due to contemporary GRD effects.

Uncertainties in glacial isostatic adjustment models are considered as one of the biggest challenges in the sea level budget when present-day ice mass is derived from space gravimetry. Willen et al. (2022) evaluated the feasibility of a global inversion for spatially resolved glacial isostatic adjustment and ice sheet mass changes through simulations, and Stolzenberger et al

(2022) compare signatures of Greenland melting in the North Atlantic simulated with the FESOM ocean model to data from Argo floats, satellite observations, and ocean reanalyses.

In Gerdener et al. (2023), a new global land water storage (GLWS) data set is produced by assimilating gridded GRACE and GRACE-FO-derived total water storage anomalies (TWSA) into the WaterGAP global hydrological model, using the Parallel Data Assimilation Framework. Total water storage as well as groundwater, soil moisture or surface water storage anomalies from this data set may serve as benchmark data for climate model evaluations, although the timeseries is still short. Data are available on PANGAEA. Following a very different concept, Li et al. (2021) had generated a multi-decadal reconstruction of global total water storage changes using methods complementing those from Humphrey and Gudmundsson (2019); still the same caveats are appropriate here.

Li et al. (2023) identified the large-scale concentrically propagating disturbances of upper thermosphere density induced by the 2022 Tonga volcanic eruption, potentially related to gravity waves and Lamb waves, in GRACE and Swarm-C accelerometer data. The idea here is that the derived wave speeds of 200–450 m/s may be eventually used for testing numerical models of high-atmosphere circulation and wave propagation.

Hamlington et al. (2020) provide an overview of the current state of understanding of the processes that cause regional sea-level change is provided. Areas where the lack of understanding or gaps in knowledge inhibit the ability to assess future sea-level change are discussed. The role of the expanded sea-level observation network in improving our understanding of sea-level change is highlighted. Landerer et al. (2020) describe how GRACE-FO is extending the 15-year GRACE record of global monthly mass change at an equivalent precision and spatiotemporal sampling. Since its launch in 2018, GRACE-FO has observed large water storage and ice mass changes driven by interannual climate anomalies. GRACE-FO's instrument/flight system performance has largely improved over GRACE. The novel laser ranging instrument works successfully.

Humphrey et al (2023) published a general introduction for hydrologists and climate scientists on using GRACE data. It does attempt to provide recommendations/caveats for comparing model simulations against GRACE data: In terms of data sets, the long-term reconstruction of total water storage anomalies provided by Humphrey and Gudmundsson (2019) may be considered as benchmark, although the authors caution that this is not entirely suited to evaluating climate simulations, or maybe only for some limited aspects like inter-annual variability or extremes.

Klos et al. (2019) introduced a new model of vertical land movements to describe GPS displacements of permanent stations from earthquake-affected areas. This model included, in addition to trend and seasonal components, post-seismic decay functions and offsets at the time of the earthquake. The model allows for a much more reliable estimate of absolute sea level from tide-gauge observations compared to absolute values provided from altimetric observations. In determining absolute level trends, they considered the impact of climate variability resulting from the Pacific Decadal Oscillation (PDO) and the North Pacific Gyre Oscillation (NPGO) on sea level change. They found that although absolute sea level records derived from altimetric observations and tide-gauge observations are well correlated with PDO and NPGO indices at the noise level (after removing trends and seasonal signatures), absolute sea level trends are affected below the 1-sigma significance level. Van Malderen et al. (2020) focused on the detection of breaks that affect the determination of climate trends and low-frequency variability provided from tropospheric series obtained in the processing of GNSS observations. Therefore, several break detection methods have been evaluated on benchmarked daily and monthly simulated time series (Klos et al., 2020). They found that most methods underestimate the number of breaks and have a significant number of their false detections.

Yuan et al. (2021) examined the statistical significance of the trends of integrated water vapor (IWV) derived from the tropospheric time series derived from the GNSS processing and from the newly released fifth generation European Centre for Medium-Range Weather Forecasts (ECMWF) atmospheric reanalysis (ERA5) for climate change analysis in continental Europe. They demonstrated that autoregressive moving average ARMA(1,1) noise model is preferred rather than the commonly assumed white noise (WN) or first-order autoregressive AR(1) for the European IWV time series. They found that improper noise model may lead to underestimation of trend uncertainty. Lenczuk et al. (2023) examined the sensitivity of GPS technique to record the groundwater storage changes which are classified as Essential Climate Variables (ECV). They selected permanent stations situated in 9 different regions of the world, where changes in groundwater are the most significant. They used GPS displacements from which total water storage compartments other than groundwater were removed using the WaterGAP model (WGHM). The same procedure was applied to GRACE-derived displacements. They noted that spatial-temporal patterns are very consistent between GPS-WGHM and GRACE-WGHM differences, with significant signatures observed during periods of intense natural and/or human-induced changes in groundwater masses. They showed that GRACE-WGHM and GPS-WGHM differences capture most of the wet and dry periods reflected by the Standardised Precipitation Evapotranspiration Index (SPEI).

In addition to these contributions, the group had agreed to produce a white paper on the methodology of validating climate simulations with geodetic data (working title) which is meant to address the following questions: "What is meant by 'validating climate simulations'? What different purposes exist? How is it conventionally done in climate science (e.g. which variables, how do we deal with ensembles)? What metrics are/should be used for validation? What is required from geodetic data sets (we consider TWS, water vapor, sea level and ocean mass) from climate model validation perspective? How are long geodetic data sets conventionally constructed, for what purpose, and what are the problems in using them for climate model validation? What new methods of constructing/reconstructing long and dense data sets are being considered? What recommendations should be formulated for the climate community and the geodesy community" this has unfortunately not yet come into fruition but it will be continued.

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Inter-Commission Committee on Marine Geodesy (ICCM)

2021-2023 part will be added soon

President: Yuanxi Yang (China)
Vice President: Heidrun Kopp (Germany)

Structure

Joint Study Group 5.1: Seafloor Geodesy
Joint Study Group 5.2: Ocean tide and vertical datum
Joint Study Group 5.3: Ocean remote sensing and topography survey
Joint Study Group 5.4: Marine positioning and undersea navigation
Joint Study Group 5.5: Ocean disaster monitoring

Overview

This report presents the activities of the entities of ICCM for the reporting period 2019-2021. As shown above, till now ICCM has proposed 5 Joint Study Groups (JSG).

Terms of reference

The Inter-Commission Committee on Marine Geodesy (ICCM) was first proposed by the Chinese National Committee to the IAG Executive Committee (EC) in Kobe, Japan in 2017 and then passed at the Sixth/Seven Meetings of the IAG EC, 2018. The Inter-Commission Committee on Marine Geodesy (ICCM) was formally approved and established following the IUGG General Assembly in Montreal, Canada, 2019.
The main objectives of the ICCM are:

- to shorten the gaps between theory and applications in marine geodesy, and to encourage transdisciplinary integration of the contemporary geodetic sensors, including marine geophysical sensors, oceanic sonar and physical oceanography instrumentation;
- to improve the global realization of the International Terrestrial Reference Frame (ITRF) by connecting the seafloor geodetic network component with the ITRF, and to improve current marine geodetic models by including the space, surface and subsurface geodetic observations;
- to encourage development of marine geodetic methodology, especially for the fusion methods of multi-marine geodetic observations;
- to promote international collaborations in regional marine geodetic surveys, and to develop and establish international conventions for marine geodetic data processing, the seafloor reference frame, and other standards.

ICCM's Steering Committee 2019-2023

President	Yuanxi Yang (China)
Vice President	Heidrun Kopp (Germany)
Commission 1	Chris Danezis (Cyprus)
Commission 2	Xiaoli Deng (Australia)
Commission 3	Cezary Specht (Poland)
Commission 4	Ana Paula Camargo Larocca (Brazil)
IERS	Henryk Dobslaw (Germany)
	Ruediger Haas (Sweden)
GGOS	Marie-Françoise Lalancette-Lequentrec (France)
	Yusuke Yokota (Japan)

According to the last IAG EC meeting minutes, ICCM have finalized the above steering committee.

Summary on activities

Preparing the ToR of each subgroup

The member list has gradually been extended, e.g., the new added Prof. Laurent Testut's from LIENSs Laboratory at La Rochelle University, France, and Prof. Bofeng Li from the Tongji university. With regard to the currently received participants, we have reduced six groups previously planned to be five groups. Three subgroup ToRs have been completed and the left two groups needs to be further discussed and enclosed. A Tencent virtual meeting was held in June 7, 2021 for discussing the preparation plan and for preparing the midterm report of ICCM.

Launched a special issue on Seafloor Geodesy and Acoustic Positioning, the international journal the Marine Geodesy

During March to April, we made arrangements with the Marine Geodesy to publish a series of special issue according to the ICCM missions. In April 9 2021, we have launched one special issue on Seafloor Geodesy and Acoustic Positioning. Till now, we have received five papers, and now the special issue is still open for submitting papers. The submitted manuscripts should describe methods, techniques, models and algorithms in seafloor geodesy and acoustic positioning. Results related to seafloor geodetic data processing and sonar propagation error reduction are encouraged. Topics may include, but not limited to: 1) Acoustic positioning and navigation model of high precision; 2) Surface and subsurface geodetic network processing method; 3) Acoustic ray error processing and efficient ray tracing algorithm; 4) Strategies for the seafloor geodetic station maintenance; Models and algorithm for seafloor geodesy; Subsea multi-sensor navigation.

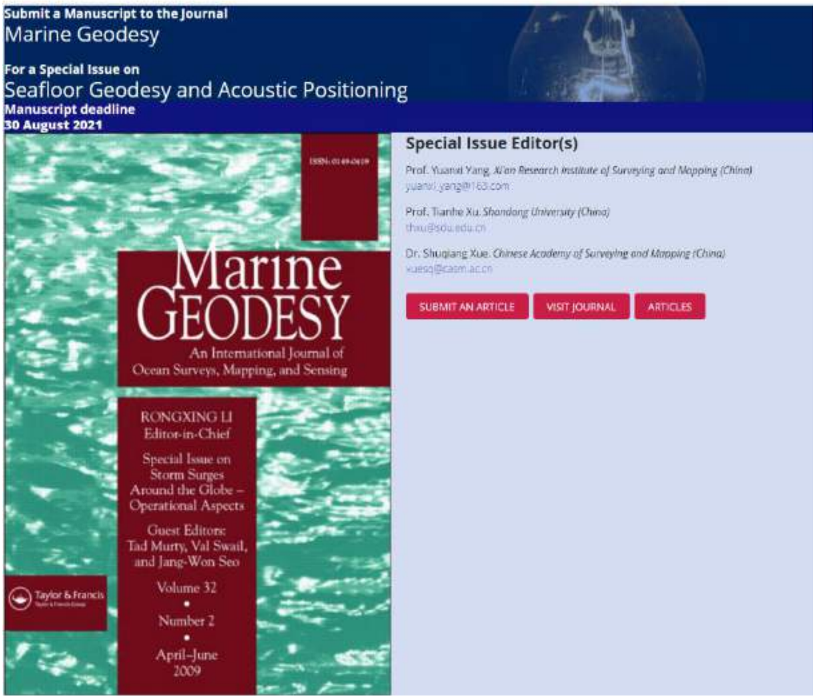


Figure 1. Call for paper web access

(**https://think.taylorandfrancis.com/special_issues/seafloor-geodesy-acoustic-positioning**)

Technology Seminars and symposiums

Marine geodetic datum and under water navigation technology symposium was held in Beijing, June 2,2019 for reporting the new progresses in the marine geodesy and undersea navigation. Seafloor geodesy seminar was held in Beijing during Nov. 11-12 for discussing the key techniques of the seafloor geodesy and the new progresses on the geodetic positioning. During March 23-24 2021, a seminar on the marine positioning, navigation and timing (PNT) was held in Jinan, China, and there are more than 30 scholars participating this seminar.

A marine geodesy and undersea navigation symposium will be held from July 17 to 18, 2021 during the 4th CONGRESS OF CHINA GEODESY AND GEOPHYSICS (CCGG). CCGG is an academic conference to report the latest progress and achievements in theory, technology and application of geodesy and geophysics in China, and to promote interdisciplinary, integrated and interdisciplinary researches.

Summary on activities of study groups

The activities of the ICCM are related namely to research activities carried out by members of its joint sub groups. Their midterm reports specify main research areas under investigation, achieved results and outputs (mainly from their publications). Based on the content of the submitted reports, it can be concluded that the joint study groups have been active, although the preparation progress is is not necessarily the same for all the joint study groups. The activities are gradually covering some of ICCM objectives, such as the development of marine geodetic methodology, especially for the fusion methods of multi-marine geodetic observations, a deep-sea network trial for test the realization of a local seafloor geodetic frame to remedy the International Terrestrial Reference Frame (ITRF) coverage.

Great achievements have been made in developing new models for the marine positioning and undersea navigation, including solving the problems of ocean gross error control, systematic error correction or parameterization, temporal and spatial correlation error processing, precision evaluation and precision calibration. The second activity is development of GNSS-Acoustic (GNSS/A) observation systems which are capable of real-time and long-term monitoring of seafloor crustal deformation. As currently implemented, the GNSS/A measurements are performed using vessels, which restricts temporal resolution and real-time detection of crustal deformation. The next objective is, therefore, to achieve continuous and real-time measurements of GNSS/A using other sea-surface platform rather than vessels. Only one study group have not technical report as this group is ongoing to prepare the ToR. We cannot get contact with the chair of JSG 5.5 to collect the mid-term report, but we only received a report from one member of this group.

Joint Study Group 5.1: Seafloor geodesy

Chair: Pierre Sakic (Germany) [TBD]

Members

Ian Church (Canada)
Valérie Ballu (France)
Shuqiang Xue (China)

Activities and publications during the period 2019-2021

The ToR of JSG5.1 was draft and the objectives are as follows: 1) To shorten the theoretical gaps between the seafloor geodetic frame and Terrestrial Reference Frame (ITRF), and to develop the standards and conventions for GNSS-A data processing; 2) To encourage development of seafloor geodetic methodology and models for high precision positioning, especially for the fusion methods of multi seafloor geodetic observations; 3) To investigate the ocean environment influence on the positioning and to develop ocean environment influence estimation and inversion tools; 4) To monitor deformation on the seafloor and to better understanding tectonic processes and assess related ocean hazards; 5) To promote international collaborations in regional seafloor geodesy.

The activities of JSG5.4 in the period 2020-2021 included in particular:

1. Performed GNSS-acoustic sailing line optimization and the China south sea trial;
2. Proposed resilient functional model and stochastic model for seafloor geodetic positioning;
3. Launched a special issue on Seafloor Geodesy and Acoustic Positioning, the international journal of Marine Geodesy
4. Investigated the ocean environment influence on the positioning;
5. Developed multi-observation least-squares inversion for GNSS-Acoustic seafloor positioning, and acoustic ray tracing tools of high-efficient.

GNSS-acoustic sailing line optimization and the China south sea trial

Bi-symmetrical positioning configuration for seafloor geodesy was proposed where both sailing line and seafloor geodetic network have symmetrical structures. Under the observability condition, generally three seafloor acoustic beacons can be used to determine the three-dimensional position of the submarine vehicle, and the regular triangle configuration should be the optimal configuration. If further considering the time synchronization requirement, we need at least four necessary geodetic stations and one backup station to form the simplest network, then the regular pentagon is the optimal configuration, as shown in Figure 2. As to submarine PNT applications in special regions, the seafloor geodetic network can be realized by extending or densifying the above-mentioned basic configurations. When the regular polygon network cannot be laid due to the limitation of the seafloor topography and sediment conditions, we can minimize the geometric dilution of precision (GDOP) at the network center, and the optimization criterion can be expressed as $\min \mathrm{GDOP} ⍰ \min \sqrt{\mathrm{tr}(A^T \mathrm{A})^{-1}}$ where A is the design matrix of the underwater positioning and navigation model. It is definite that the mean GDOP of the regional coverage can be used as the network optimization criterion, which might be more suitable for underwater PNT applications.

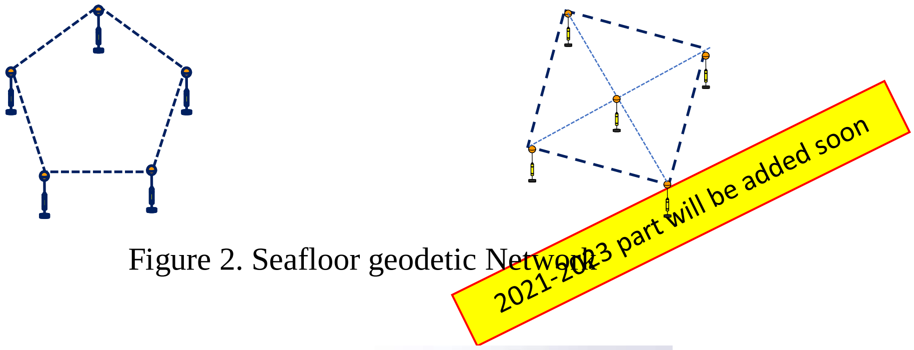


Figure 2. Seafloor geodetic Network

Figure 3. Seafloor geodetic station

Applying the above-mentioned seafloor geodetic shelter development strategy, seafloor geodetic location selection criterion and geodetic network layout strategy, we conducted a deep-sea experiment in a sea areas of 3000 m depth in July, 2019. Fig.1 illustrates the seafloor geodetic network and the surface ship tracking lines, where the five seafloor stations adopt the configuration as shown in Figure 4, and the radius of each circle tracking line is about 0.5 times the seawater depth. In addition, a circle tracking line with the radius of 1.5 times the seawater depth and a series of cross lines are laid for locating the station. Based on the developed seafloor geodetic shelter and sufficient verification in the shallow sea experiment, a long-term seafloor geodetic station in the deep-sea area of 3000 m depth was established for the first time, and the preliminary positioning result shows that the internal precision of this station is better than 5 cm.

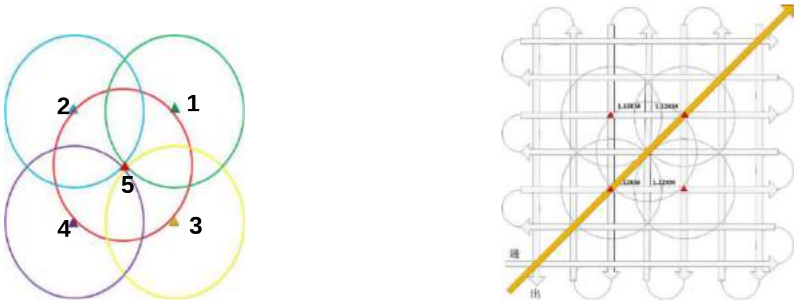


Figure 4. Surface GNSS/acoustic tracking line

Proposed resilient functional model and stochastic model for seafloor geodetic positioning

The Sound velocity error is an important error source of underwater positioning, which mainly includes the uncertainty of sound velocity measurement and the sound velocity error caused by the temporal-spatial variation of the sound speed field. We establish a resilient model to compensate various systematic errors. A simple resilient observational model with range bias and time bias parameters is established, and the resilient observational model with periodic error terms for compensating the sound speed systematic errors of the acoustic ranges are also proposed, and the square root of variance of the coordinate component is better than 0.4 cm and the root mean square errors (RMSE) of the one-way slant range residuals are better than 11 cm.

Based on the constant gradient sound ray tracking model, we derive a mathematical model for the sound ray disturbance analysis about the incident angle, sound velocity gradient and water depth. The results show that, for the same water depth and sound velocity error, the greater the incident angle is, the greater the impact of incident angle perturbation on the sound ray, and the greater the impact of sound ray bending will be. Figure 5 shows that RMS of ranging error is inversely proportional to the elevation angle.

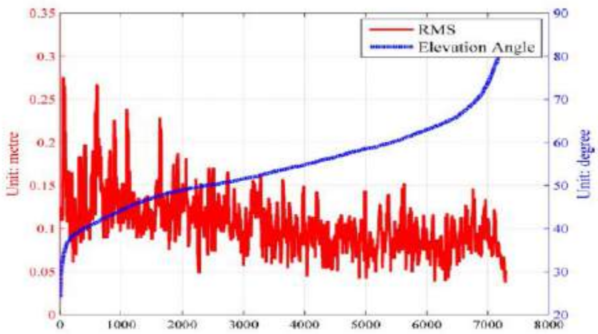


Figure 5. Relationship between ranging error RMS and elevation angle

Establish four stochastic models based on the sound ray incidence angle. The results show that the established incidence angle stochastic models have advantages over the equal weight model, especially that the positioning result of using the segmental cosine model is the best. Moreover, according to the derived function response relation between incident angle disturbance and acoustic ray disturbance, a piecewise exponential function stochastic model of underwater positioning based on incident angle correlation is established. The positioning results of the piecewise-exponential weight function random model are compared with the equal weight model.

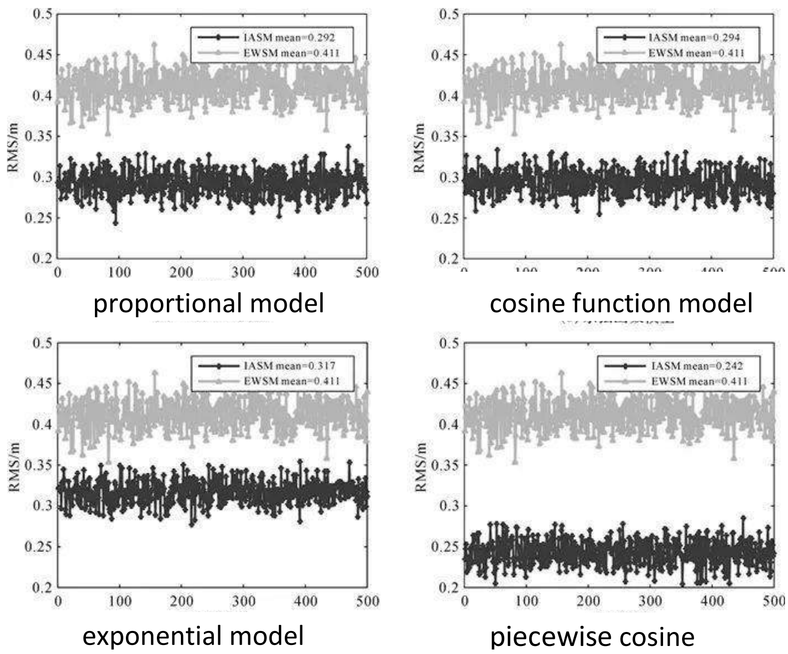


Figure 6. Potential stochastic models

Proposed relationship between the epoch-differential solution and non-differential solution and realize a fast algorithm for seafloor geodetic epoch-differential positioning

Differential approaches have been widely used in geodetic positioning. Seafloor geodetic positioning using the shipborne GNSS/acoustic (GNSS-A) technique is unlike GNSS positioning having synchronous satellite observations, and therefore the epoch-differential approach was proposed to reduce the influence of spatial-temporal systematic errors on the seafloor geodetic positioning. We discuss systematic error sources in the undersea acoustic positioning, and establish conversion formulae between the epoch-differential and non-differential solution. It shows that: (1) the non-differential solution can be converted into the epoch-differential solution requiring only a few of calculations, and this attributes to perform the eigenvalue decomposition upon the differential equivalent weight matrix proposed; (2) the equivalence between the epoch-differential and the non-differential solution is that, the sum of direction-cosines of the observations is zero, i.e., GNSS-A tracking line should be exactly symmetrical in the whole three-dimensional space around the seafloor geodetic station, but this is obviously unrealistic to form a symmetrical geometry in the height direction; (3) For observations with the same elevation angle, the epoch-differential model becomes rank-deficient along the height direction.

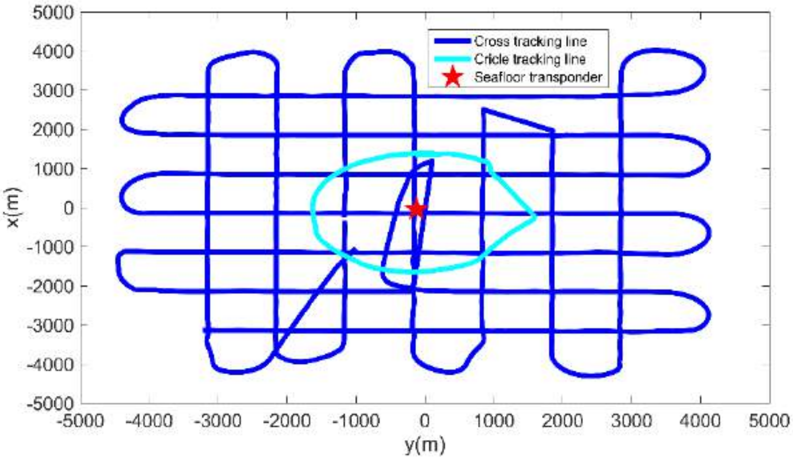


Figure 7. Surface GNSS-A tracking lines

The proposed results have been verified in the China Sea 3000 depth trial as shown in Figure 4. It shows that, the strict differential model regarding the correlations among differential observations can produce a more precise positioning result which more precisely reflects the actual precision level along the height direction. This indicates that, the epoch-differential model ensures the horizontal positioning, but removes some positioning information in the height direction which might be unreliable.

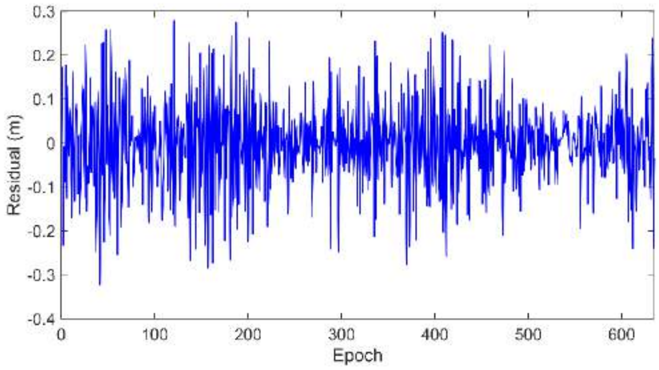
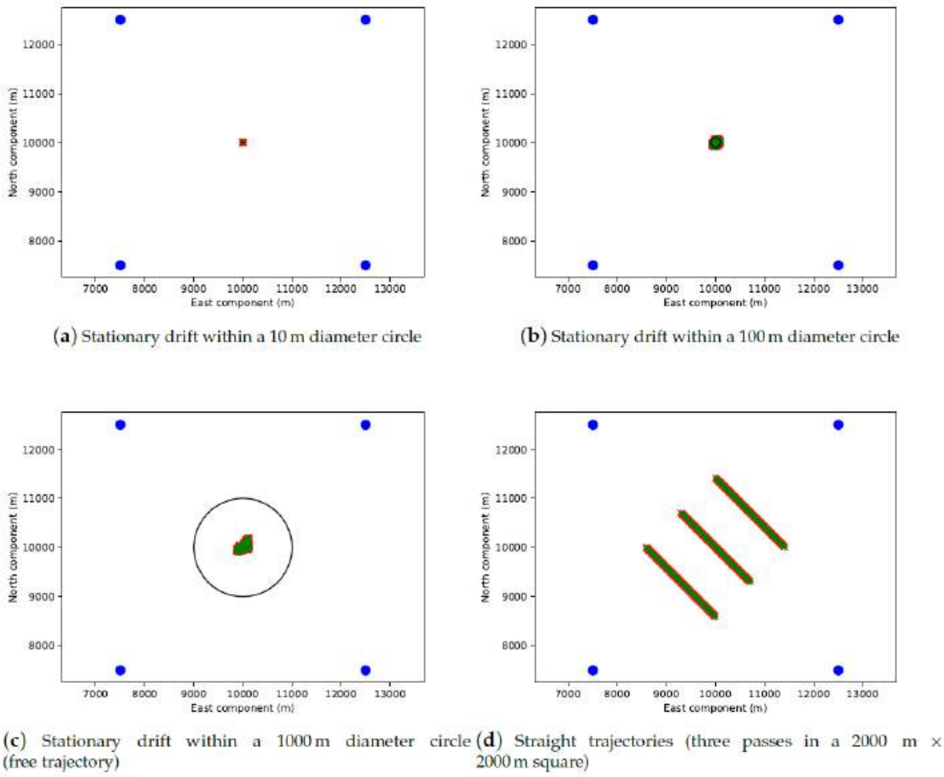


Figure 8. Residuals of differential observations

As shown by Figure 8, the differential model can produce a stationary residual sequential that can be utilized to facilitate the outlier detection. The deep-sea acoustic positioning trial uses a medium-frequency about 8Hz sonar system and the nominal precision of the acoustic ranging is better than 0.15m, which is indirectly confirmed by the residual sequential deviation.

Developed multi-observation least-squares inversion for GNSS-Acoustic seafloor positioning and high-efficient acoustic ray tracing positioning algorithm.

<u>Multi-observation least-squares inversion for GNSS-Acoustic seafloor positioning</u>. Monitoring deformation on the seafloor is a major challenge for modern geodesy; it is a key to better understanding tectonic processes and assess related hazards. The extension of the geodetic networks offshore can be achieved by combining satellite positioning (GNSS) of a surface platform with acoustic ranging to seafloor transponders. This approach is called GNSS-Acoustic (GNSS-A). A least-squares inversion method to get the absolute position of a seafloor transponder array was proposed. This method also considered the baseline lengths and the relative depth-differences between different pairs of them.



(**a**) Stationary drift within a 10 m diameter circle

(**b**) Stationary drift within a 100 m diameter circle

(**c**) Stationary drift within a 1000 m diameter circle (free trajectory)

(**d**) Straight trajectories (three passes in a 2000 m × 2000 m square)

Figure 9. Trajectories design for test the proposed results

High-efficient acoustic ray tracing positioning algorithm. The computational efficiency of seafloor geodetic positioning based on the ray tracing is mainly limited to a great amount of calculation of ray inverse problem. We propose two kinds of p-order secant methods to improve the efficiency of traditional method, and the proposed methods can be regarded as a generalization of the traditional secant method from two points to p points for rapidly solving the inverse problem. In the proposed methods, the calculation information in previous iterations is utilized to fit a polynomial model to speed up the algorithm convergence. In the first-kind method, the inverse problem is calculated by solving a polynomial equation approximating the function mapping from the emission angle to the radial distance of the ray. In the second-kind method, the inverse problem is however directly solved by approximating the function mapping from the radial distance to the emission angle. As the first-kind method needs to solve a p-order polynomial equation, the practicability of this method is limited to the complexity of solving the high-order equation, while the second-kind method can directly approximate the solution of the inverse problem, which is more practical and flexible.

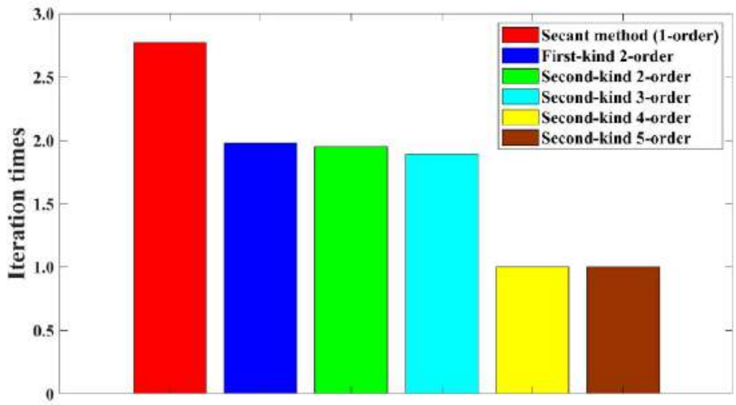


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Figure 10. The computational efficiency comparison

The proposed methods have been verified in deep-sea trial. It shows that, the proposed methods can precisely produce the solution of the acoustic ray inverse problem within one iteration, and the computational efficiency of proposed method is about 6 times faster than that of the traditional method as shown in Figure 10.

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Joint Study Group 5.2: Ocean tide and vertical datum

Chair: Ole Baltazar Andersen (Denmark)

Members
- *Xiaoli Deng (Australia)*
- *Felipe Nievinski (Brazil)*
- *Sajad Tabibi (Luxembourg)*
- *Testut Laurent (France)*

Activities and publications during the period 2019-2021

The activities of JSG5.4 is ongoing to prepare the ToR and the objectives.

Joint Study Group 5.3: Ocean remote sensing and topography survey

Chair: Bofeng Li (China)
Co-Chair: Rongxing (Ron) Li, Fanlin Yang (China)

Members

- *Samuel F. Greenaway, NOAA*
- *Brian R. Calder, U. of New Hampshire*
- *Ian William Church, U. of New Brunswick*
- *Chung-Yen Kuo, Taiwan*

Activities of the group

Due to the pandemic, the planned group's activities have been delayed. However, during the period of 2021-2023, the group aims to establish continuous online meetings to discuss and address research challenges on the topic of ocean remote sensing and topography survey and to hopefully achieve the main objectives of this study group.

Achievements and results

Some of the ocean remote sensing and topography survey research outcomes of the group members are listed below:
- A Simplified calibration method for multibeam footprint displacements due to non-concentric arrays: when the offset between the transmitter and the receiver in the multibeam is large, neglecting the offset will introduce depth errors into the multibeam footprints. To solve the issues, Yang et al. (2020) drew on the advantages of both the virtual concentric cone algorithm (VCCA) and the NCCA, and proposed a simplified method. By using two separately intersecting triangles, the analytical expression of the footprint coordinates can be directly developed, which avoids calculating the complex hyperbolic equations. Consequently, the proposed calibration method is relatively simple with less computational complexity, which has significance in improving the efficiency of data processing.
- An automatic sidelobe effect suppression method for multibeam water column images: Yang et al (2019) proposed an adaptive soft threshold denoising algorithm for the water column images (WCI). The WCI data are divided into background areas and target-noise mixing areas by analyzing the mathematical features of all angle sequences; thus, the target, noise, and sidelobe artefacts are separated using adjustable threshold parameters and by suppressing noise and sidelobe artefacts to obtain a clearer image. Lastly, the measured data

are used for verification. The results indicate that the algorithm has a certain reference value for sidelobe suppression of multibeam WCI.

- Construction of multibeam automatic seabed sediment classification system: Cui and Yang et al. (2019; 2021a; 2021b) summarized the latest progress and technical architecture of the current acoustic seabed sediment classification technology, and compared and discussed the application effects of classic classification methods in large-scale multibeam data. On this basis, a feature optimization method based on fuzzy ranking and a deep learning classification method based on DBN are proposed, which overcomes the problem of high-dimensional acoustic feature optimization, and further improves the efficiency and stability of the seabed sediment classification modeling.

- Propagated Uncertainty Models for the airborne LiDAR bathymetry (ALB) and noises removal for ALB: Yang et al studied the various uncertainty sources for an ALB measurement and proposed a uncertainty model that considering ten different effects from four aspects: the device aspect (laser pointing deflection, trajectory uncertainty, and boresight/lever arm offset), environmental aspect (atmospheric limitation, refraction on the sea surface, refraction in water, scattering in water, and water level fluctuation), target aspect (irregular bottom), and other aspect (accuracy of coordinate transformation model). In addition, Yang et al (2020) also proposed a bidirectional cloth simulation filtering (BCSF) method to avoid current filtering algorithms' limitations, such as cannot identify negative anomalies or avoid over-filtering of the data.
- Registration and merging for seabed points cloud from ALB and multibeam echo sounder (MBES): To reduce the effects of point density and data gaps on the performance of registration method, Yang et al. (2021) proposed a registration algorithm based on Point-to-TIN model for airborne LiDAR bathymetry (ALB) and multibeam echo sounder (MBES) point clouds. The method was tested using the dataset around Yuanzhi Island in the South China Sea. The results indicate that the proposed method performs well for the registration of ALB and MBES datasets, with advantages in accuracy and robustness.

Interactions with the IAG Commissions

The Scientific Assembly of the International Association of Geodesy (IAG) is going to be held in Beijing, China on June 28–July 2, 2021, and a number of the group members had submitted papers concerning the research topics, such as multibeam data processing, et al.

Publications

Bu, X., Yang, F., Ma, Y., Wu, D., Zhang K., Xu. F., (2020). “Simplified calibration method for multibeam footprint displacements due to non-concentric arrays”. Ocean Engineering, 197.

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Joint Study Group 5.4: Marine positioning and undersea navigation

Chair: Keiichi Tadokoro (Japan)

Members

- *Pierre Sakic (Germany)*
- *Stéphane Calmant (France)*
- *Tianhe Xu (China)*

Activities and publications during the period 2019-2021

The activities of JSG5.4 were firstly concentrated on precise data processing method of marine geodetic observation. Considering the complex ocean observation environment and the application of navigation and positioning, it is necessary to systematically solve the problems of ocean gross error control, systematic error correction or parameterization, temporal and spatial correlation error processing, precision evaluation and precision calibration. The research of the above methods can provide technical support for marine geodetic datum positioning and marine acoustic navigation. The second activity is development of GNSS-Acoustic (GNSS/A) observation systems which are capable of real-time and long-term monitoring of seafloor crustal deformation. As currently implemented, the GNSS/A measurements are performed using vessels, which restricts temporal resolution and real-time detection of crustal deformation. The next objective is, therefore, to achieve continuous and real-time measurements of GNSS/A using other sea-surface platform rather than vessels.
The activities of JSG5.4 in the period 2020-2021 included in particular:

1. A systematic error compensation model of observation model combined with KF based on the random walk model is proposed to eliminate the influence of systematic error for marine acoustic navigation and positioning.
2. An inversion method of ocean sound speed space-time field based on neural network algorithm is developed and applied to ocean topographic survey to improve its sounding accuracy.
3. Development and operation test of the measurement systems of GNSS/A installed on an Unmanned Surface Vehicle (USV) and a moored buoy.

Marine acoustic navigation and positioning method based on systematic error compensation and adaptive robust Kalman filtering

In order to better explore the marine geography and physical environment, the construction and maintenance technology of marine geodetic datum need to be solved and improved. The data processing method of marine precise observation plays an important role in the construction of marine geodetic datum.

The accuracy of underwater acoustic positioning is greatly influenced by both systematic error and gross error. Aiming to the above problem, a robust zero-difference Kalman filter based on the random walk model and the equivalent gain matrix is proposed (Wang et al., 2020). The proposed algorithm is verified by the simulation experiment and a real one for underwater acoustic positioning. Figure 11 shows the calculation results of robust zero-difference Kalman filter (R-KF). The result proves that the R-KF can estimate the systematic errors by the random walk process, and provide robust solutions by using the equivalent gain matrix, which has higher precision and stability for underwater acoustic positioning.

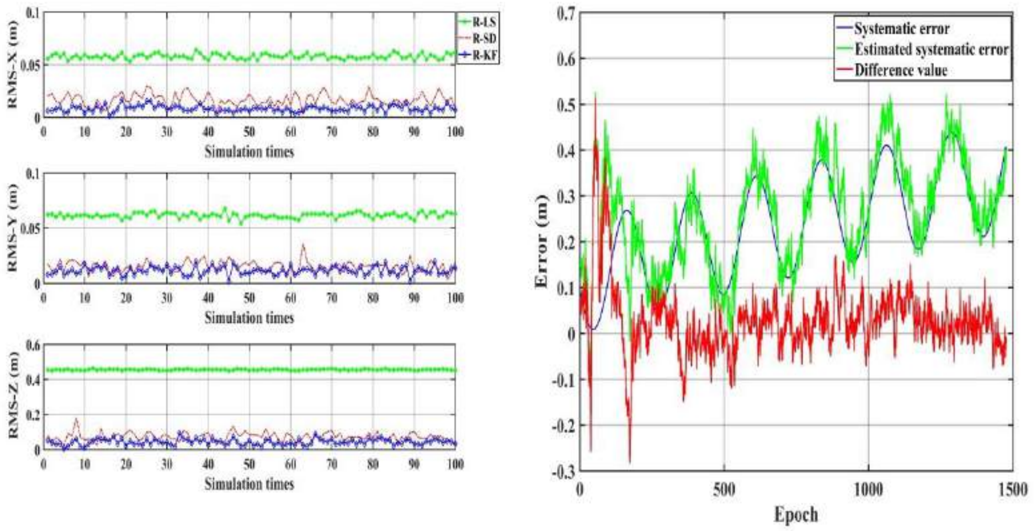


Figure 11. The calculation results of different algorithms (left) and the estimated results of systematic error (right)

In order to further verify the effectiveness of the R-KF algorithm, the acoustic positioning data of single transponder is used. From Table 1, compared with the robust least square (R-LS) and the robust single-difference (R-SD), the RMS of the validated residuals of the R-KF is greatly reduced from 1.63 m and 1.81 m to 0.85 m respectively, which proves the higher precision of R-KF.

Table 1. The residuals statistics of different algorithms

Method	RMS (m)	Max (m)	Min (m)
LS	1.73	2.16	0.99
SD	1.91	2.59	1.39
KF	1.24	2.12	0.51
R-LS	1.63	2.17	0.92
R-SD	1.81	2.55	1.26
R-KF	0.85	1.69	0.04

Autonomous underwater vehicle (AUV) acoustic navigation is challenged by unknown system noise and gross errors in the acoustic observations caused by the complex marine environment. Since the classical unscented Kalman filter (UKF) algorithm cannot control the dynamic model biases and resist the influence of gross errors, an adaptive robust UKF based on the Sage-Husa filter and the robust estimation technique is proposed for AUV acoustic navigation (Wang et al., 2020). The effectiveness of the algorithm is verified by the simulated long baseline positioning experiment of the AUV. Figure 12 shows that the adaptive robust UKF can estimate system noise using the Sage-Husa filter and achieve robust estimation with the equivalent gain matrix. Therefore, the robust UKF performs as the best algorithm in terms of positioning accuracy and reliability.

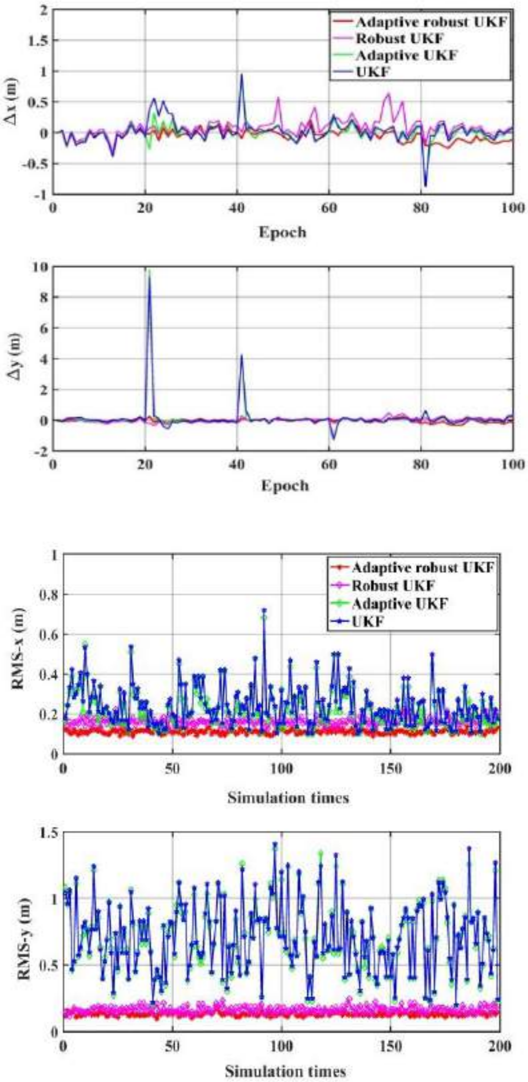


Figure 12. The difference between the true value (left) and the calculation value and the statistical RMS-x and RMS-y of 200 simulations (right).

Inversion method of ocean sound speed space-time field

Sound speed error is the main error source of marine acoustic navigation and positioning. In order to correct the influence of sound speed error, the key point is to obtain the real-time ocean sound velocity profile.

Aiming at the high-precision construction of sound speed field (SSF) in the complex marine environment, a sound speed field model based on back propagation neural network (BPNN) by considering the correlation of learning samples is proposed (Wang et al., 2020). The proposed algorithm is validated by the global Argo data as well as compared with the spatial interpolation and the empirical orthogonal function (EOF) algorithm. Figure 13 shows that present the construction results of sound velocity profile in the two selected positions. From the results, we can see that the sound speed by four algorithms differs little from the true values due to the small variation of sound speed in the deep-sea isotherm. In the main thermocline and the seasonal thermocline, the performance of spatial interpolation method is poor because of the obvious change of sound speed with depth. The EOF algorithm can improve the accuracy of sound speed construction through the orthogonal function compared to the spatial interpolation method. The BPNN algorithm can fully use the measured environmental parameters to construct the real sound speed field, and the construction accuracy is significantly improved especially in the region where the sound speed changes greatly.

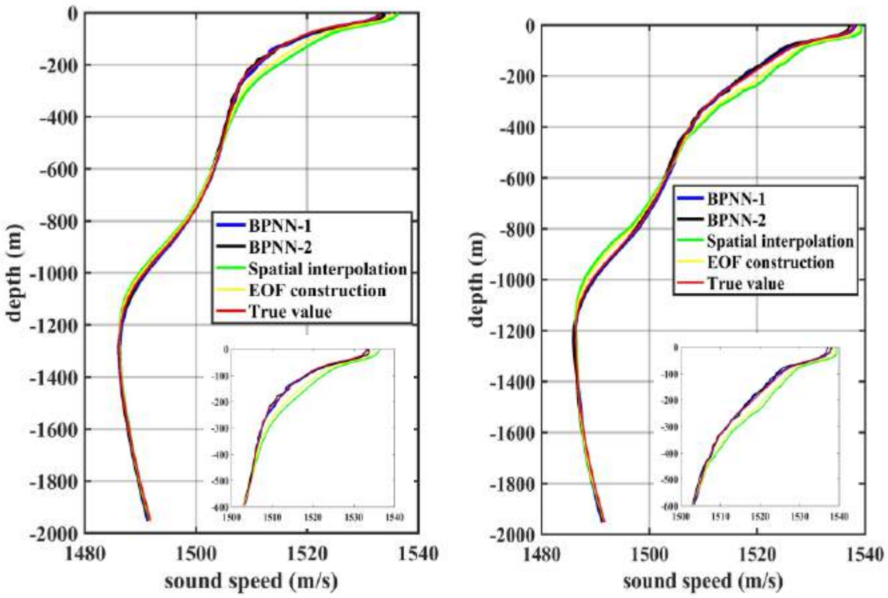


Figure 13 The comparison of SSPs for different algorithm

As a marine environmental parameter, sound velocity has an important impact on sound propagation in the ocean. In the same sea area, the sound velocity profile (SVP) changes dynamically due to the influence of marine environment, season change and other factors. To accurately obtain the SVP of seawater in time and to improve the underwater positioning accuracy for marine research and development, a method of SVP inversion and prediction based on radial basis function (RBF) neural network is proposed (Yu et al., 2020). The proposed SVP prediction method is verified with the Argo data of At-lantic Ocean from 2004 to 2018. In the Figure 14, V_0 is the actual SVP of the sea area, V_1 is the monthly average SVP, V_2 is the SVP predicted by the BP neural network, V_3 is the SVP predicted by the RBF neural network, V_4, V_5, and V_6 represent the difference between V_1 and V_0, the difference between V_2 and V_0, and the difference between V_3 and V_0 respectively. As shown in Figure 14, the prediction accuracy based on the BPNN and RBFNN respectively are significantly better than that of the average sound velocity method. Especially in shallow water, the accuracy of the SVPs predicted is greatly improved by involving the sea surface temperature and salinity in the construction of the prediction models.

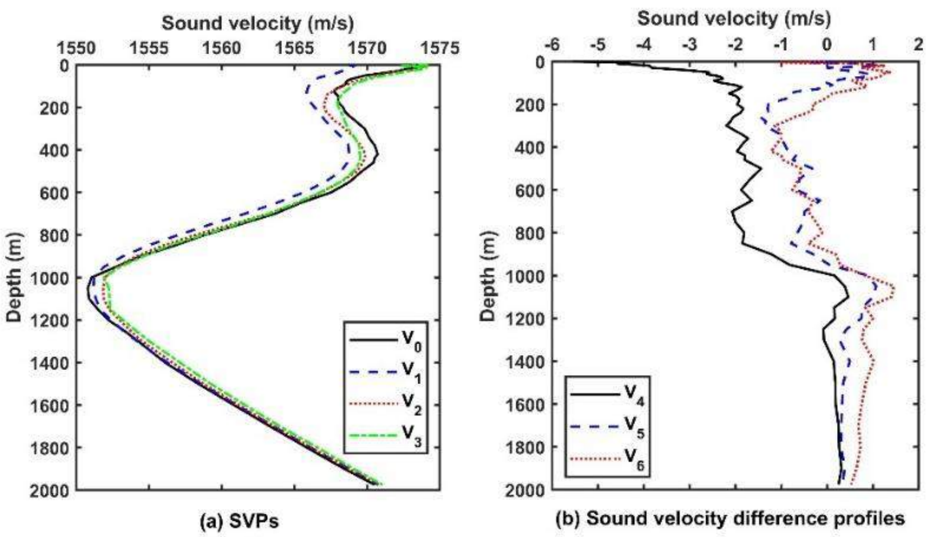
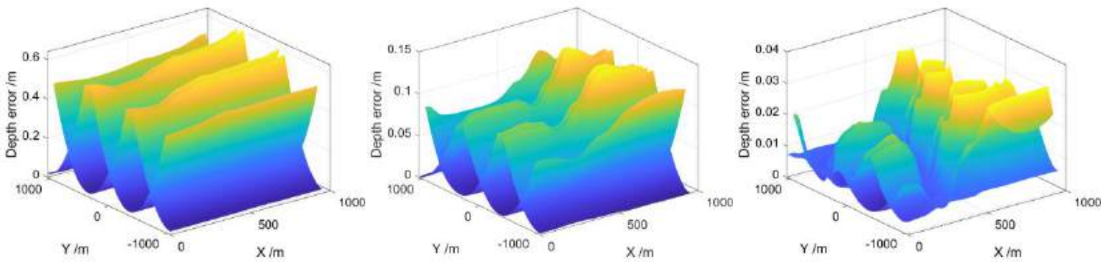


Figure 14 Sound velocity profile prediction results in May 2018

Based on the sound velocity profile inversion method, a method for correcting underwater topography distortion is proposed (Liu et al., 2021). The method can reduce the representative error of sound velocity profile to improve the precision of sounding. The proposed algorithm is verified by three types of experiments based on measured SVPs. As shown in Table 2, compared with these sounding errors calculated by Method-1 (Max 0.6397; Mean 0.2000; RMS 0.2577; MRE 0.4300) and Method-2 (Max 0.1448; Mean 0.0211; RMS 0.0223; MRE 0.0890), these of Method-3 are smaller (Max 0.0325; Mean 0.0325; RMS 0.0325; MRE 0.0180). The RMS values of sounding errors of Method-3 are 54.79% and 91.39% lower than Method-2 and Method-1, respectively. According to Figure 15, among these methods, the sounding error calculated by Method-3 is the smallest in UUT. The above results can improve that the proposed method has a high precision for the multi-beam sounding. Meanwhile, the distortion of underwater topography can be efficiently corrected by the proposed method.

Table 2 Various sounding errors calculated by the three methods in UUT(Max, Min and Mean represent the maximum sounding error, the minimum sounding error and the mean sounding error, respectively, and the unit is m)

Method	Max	Min	Mean	MRE	RMS
Method-1	0.6397	0.0183	0.2000	0.4300	0.2577
Method-2	0.1448	1.5E-07	0.0363	0.0890	0.0491
Method-3	0.0324	2.2E-07	0.0211	0.0180	0.0222



(a) (b) (c)

Figure 15 Sounding errors calculated by three methods in UUT. (a) Method-1; (b) Method-2; (c) Method-3.

New system for continuous and real-time GNSS/A measurements using USV and moored buoy

A compact GNSS/Acoustic experimental instrument was developed and installed in an Unmanned Surface Vehicle (USV) with the length of 3 m (Sakic et al., 2021). The system was tested from July 23 to 25, 2019 in the shallow, 40 m, waters of the Bay of Brest, France. The test was performed with three different acquisition protocols: 1) the USV navigated for about 20–30 min along repeated circles with diameters of 10 m, 2) the USV remained stationary for 10–15 min just above each transponder, and 3) the USV remained stationary during 1 hour just above the barycenter of the three seafloor transponders. The test results show a repeatability of ~5 cm in the locations of the transponders. Post-processing of the GNSS data, instead of Real-Time Kinematic (RTK) positioning during the test, significantly improved the travel time residuals of acoustic signal. In addition, it was also considered supplementary Direction-of-Arrival observations (acoustic ray's reception angles) in the data processing (Sakic et al., 2021). These works were the preliminary tests related to the geodetic network of the FOCUS project, combining BOTDR optical fiber deformation monitoring and precise acoustic positioning off the coasts of Sicily (Gutcher et al., 2019). This is the first operational geophysics-oriented GNSS/A experience in Europe. In parallel, the European group engaged discussions regarding common exchange standards with the American community federated under the leadership of the UNAVCO (Sakic et al., 2020).

The Japanese group of JAMSTEC (Japan Agency for Marine-Earth Science and Technology) and Tohoku University developed a GNSS/Acoustic observation system mounted on another USV, Wave Glider (Iinuma et al., 2021). The acquired data are transmitted to land via satellite communication. The equipment has already been used for the GNSS/A observations at Japan Trench, and it efficiently retrieve data at several seafloor transponders.

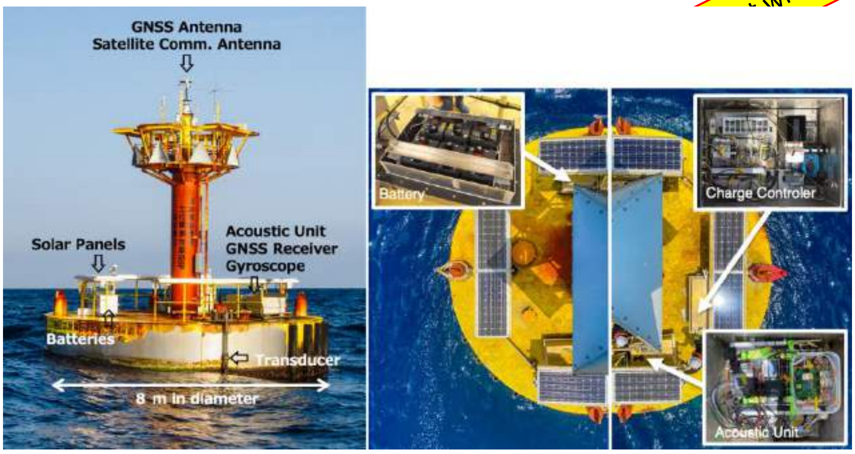


Figure 6. GNSS/A measurement system mounted on the moored buoy. (Left) Side view and (Right) top view.

Tadokoro et al. (2020) reported observation system for GNSS/A technique mounted on a moored buoy of 8-m diameter located at more than 30 km from the Japanese coast (Figure 6). The long-term operation test was performed for almost three years, from March 28, 2018 to January 15, 2021. The continuous acoustic ranging between the buoy and the three seafloor transponders was succeeded for 6 and 10 months in 2019 and 2020-2021, respectively (Figure 7) which was interrupted due to poor power supply during the winter season before it was improved in 2020. The total number of acoustic ranging was 257,413 times. The data of the acoustic ranging, the GNSS positioning employed the PPP-AR technique, and the gyroscope were transmitted to the land base station via a commercial satellite communication network. Because some troubles have happened on the modem and the cable of the satellite communication, only 69 % of acoustic ranging data were received at the land base station. The seafloor position, the barycenter position of seafloor transponder array, was estimated with the method of Kinugasa et al. (2020) for the period between August 18, 2020 and January 15, 2021. The present test site is under the strong ocean current, and it was expected that the sound speed structure under the sea had noticeable amount and temporal variation of horizontal gradient. The method used here estimates the horizontal gradient of sound speed structure and its temporal change as well as the seafloor position using the acoustic travel-time data for 28 days employed the B-spline function. The positioning result are shown in Figure 8. The RMS error of the seafloor position was about 3 cm.

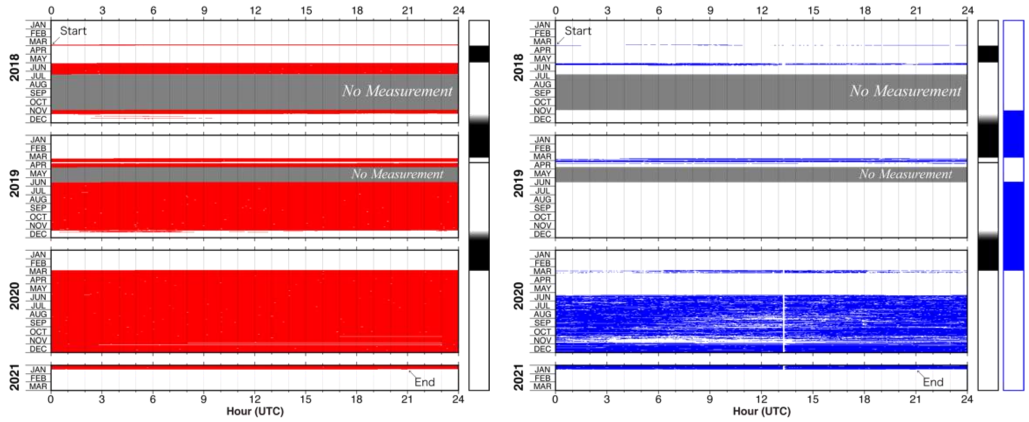


Figure 7. Result of three-years operation test. Red and blue bars show periods of (left) acoustic ranging and (right) data transmission to the ground base station. Periods of no power supply and of no connected satellite modem are indicated by vertical black and blue bars, respectively.

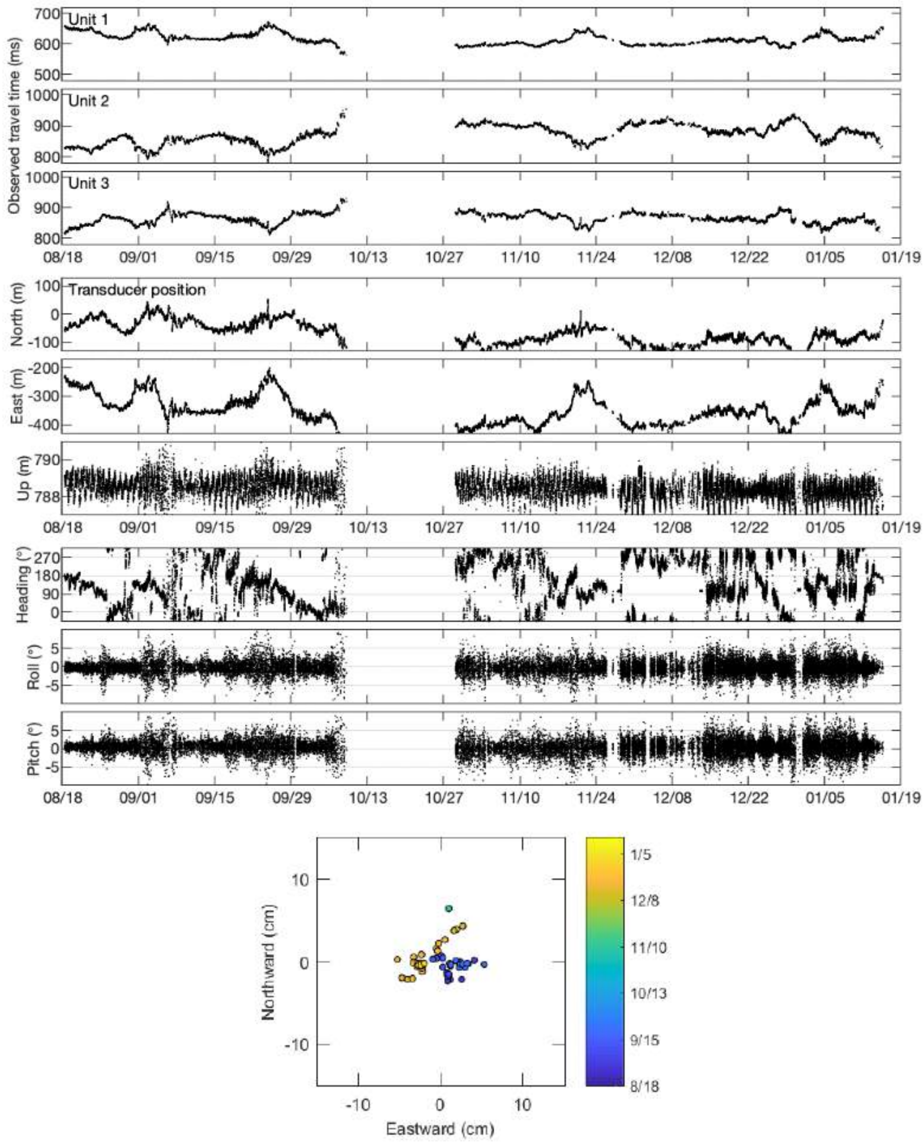


Figure 8. (a) Acoustic travel time for the three seafloor transponders, (b) Transducer position w.r.t. the local coordinate whose origin is 32.48662°N and 133.20850°E, (c) attitude of the buoy, and (d) 28-days averaged barycenter position of seafloor transponder array.

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Joint Study Group 5.5: Ocean disaster monitoring

Chair: Morelia Urlaub (Germany)

Members

Lifeng Bao (China)

Activities and publications during the period 2019-2021

The activities of JSG5.4 were to investigate the relevant literatures to propose the ToR and the Objectives. The investigations of JSG5.4 in the period 2019-2021 included in particular: 1) Development of Earth Observations services for Monitoring Marine Hazards; 2) 2 influence studying of main ocean disaster (storm surge) for coastal areas; 3) Impact of ocean tidal changes for coastal flooding.

Development of Earth Observations services for Monitoring Marine Hazards

In the recent years, Earth observations (EO), and in particular satellite remote sensing, provide invaluable information: satellite-borne sensors allow an effective monitoring of the quasi-global ocean, with synoptic views of large areas, good spatial and temporal resolution, and sustained time-series covering several years to decades (Melet et al. 2020). Satellite observations offer great potential for a long-term, synoptic, and rather high-frequency monitoring of the Earth's surface, thanks to a variety of sensors. The use of EO to monitor coastal metocean conditions, coastland hydro-geo-morphological setting, and hazards has significantly developed with the increasing number of satellites with radar sensors.

Benveniste et al. (2020) provide a tour of satellite missions for ocean Hazards Monitoring, of relevant applications, as well as the downstream International Services such as the Copernicus Ocean and Land Monitoring Services. Earth observation (EO) satellite remote sensing provides global, repetitive and long-term observations with increasing resolution with every new generation of sensors. They permit the monitoring of small-scale signals like the ones impacting the coastal zone. The Earth observations (EO) product have many applications, including sea surface temperature, sea-level variations and trends, wave height, hurricane monitoring, storm surge monitoring, sediment transport and coastal Erosion. Significant wave height (SWH) was derived from the radar altimeter measurement. Figure 4 shows an example of satellite-derived climatology for the month of January estimated in the ESA GlobWave Project. The SWH implication for safeguarding ships in extreme weather. As an example, while Hurricane Florence was impacting.

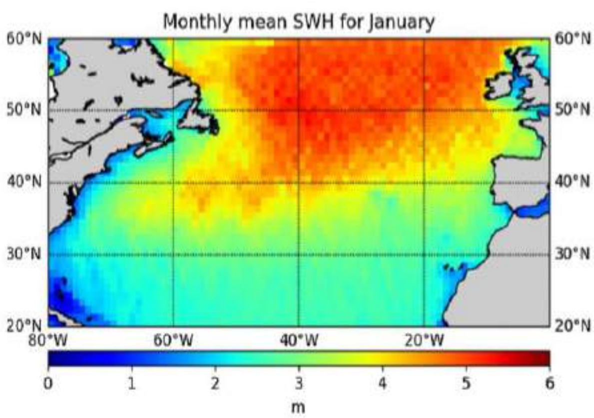

Figure 4 Significant wave height (SWH) as derived from the radar altimeter measurement for the month of January. Source: GlobWave, SatOC.

Influence studying of main ocean disaster (storm surge) for coastal areas

Storm surge is one of the most serious ocean disasters in the world. Risk assessment of storm surge disaster for coastal areas has important implications for planning economic development and reducing disaster losses (Marcos et al. 2019; Couasnon et al. 2020; Ganguli et al. 2020). Coastal flooding is caused by a combination of factors, among which storm surges and wind waves are of major relevance due to their potentially large contributions to coastal extreme sea levels and their widespread effects, severe storm episodes may lead to extreme storm surges, and at the same time, to heavy precipitation and high river runoff. Quantifying compound flood hazard under climate change poses a particular challenge in geodesy.

Based on global scale numerical simulations of these storm surges and wind waves, Marcos et al. (2019) investigated the relationship between extreme storm surges and waves along the world coastlines. they found that in more than half of the coastal regions, storm surges tend to be accompanied by large wind waves, thus increasing the potential coastal flooding. Hence, for a given level of probability, neglecting these dependencies leads to underestimating extreme coastal water levels. Translated in terms of return periods, this means that along 30% of global coastlines, extreme water levels expected at most once in a century without considering dependence between storm surges and waves become a 1 in 50 ‐ year event. The joint 50 ‐ year return levels for storm surges and wave height Hs are mapped in Figures 8a and 8b for coastal grid points where there is dependence between both extreme values. The median value in the ratio of increase along the coastal regions where there is dependence between surge and waves is 2.5 and maxima values reach a twentyfold increase (Figure 8).

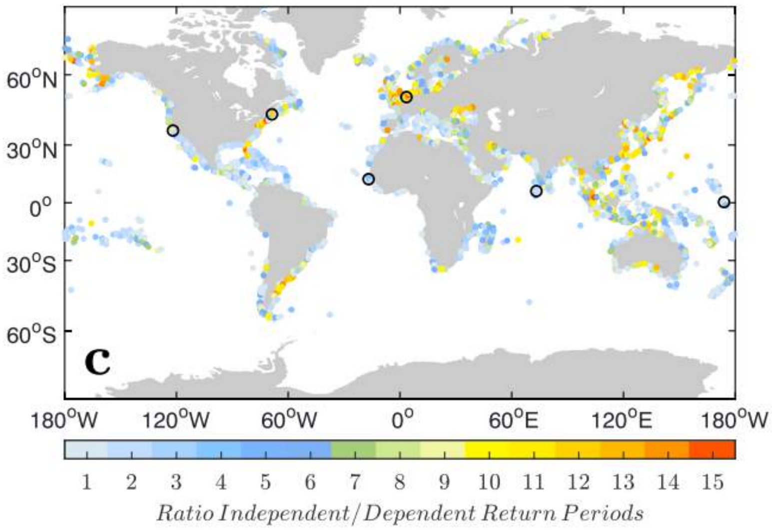

Figure 8. Ratio between the joint return period (50-year) and the independent return periods assuming independence, with selected grid points highlighted (Marcos et al. 2019).

Ganguli et al. (2020) combined projected storm surges and river floods with probabilistic, localized relative sea ‐ level rise scenarios to assess the future compound flood hazard over northwestern coastal Europe in the high (RCP8.5) emission scenario. They used high ‐ resolution, dynamically downscaled regional climate models to drive a storm surge model and a hydrological model, and analyze the joint occurrence of high coastal water levels and associated river peaks in a multivariate copula ‐ based approach. Their results suggest decreasing compound flood hazard over the majority of sites by 2050s (2040–2069) compared to the reference period (1985–2005), an increase in projected compound flood hazard is limited to around 34% of the sites. Further, they show the substantial role of sea ‐ level rise, a driver of compound floods, which has frequently been neglected.

Impact of ocean tidal changes for coastal flooding

Nuisance flooding (NF) is defined as minor, nondestructive flooding that causes substantial, accumulating socioeconomic impacts to coastal communities. While sea-level rise is the main driver for the observed increase in NF events (Li et al. 2021). Li et al. (2021) first show that secular changes in tides also contribute. An analysis of 40 tidal gauge records from U.S. coasts finds that, at 18 locations, NF increased due to tidal amplification, while decreases in tidal range suppressed NF at 11 locations. Estuaries show the largest changes in NF attributable to tide changes, and these can often be traced to anthropogenic alterations. Limited long-term measurements from estuaries suggest that the effects of evolving tides are more widespread than the locations considered here. The total number of NF days caused by tidal changes has increased at an exponential rate since 1950, adding ~27% to the total number of NF events observed in 2019 across locations with tidal amplification.

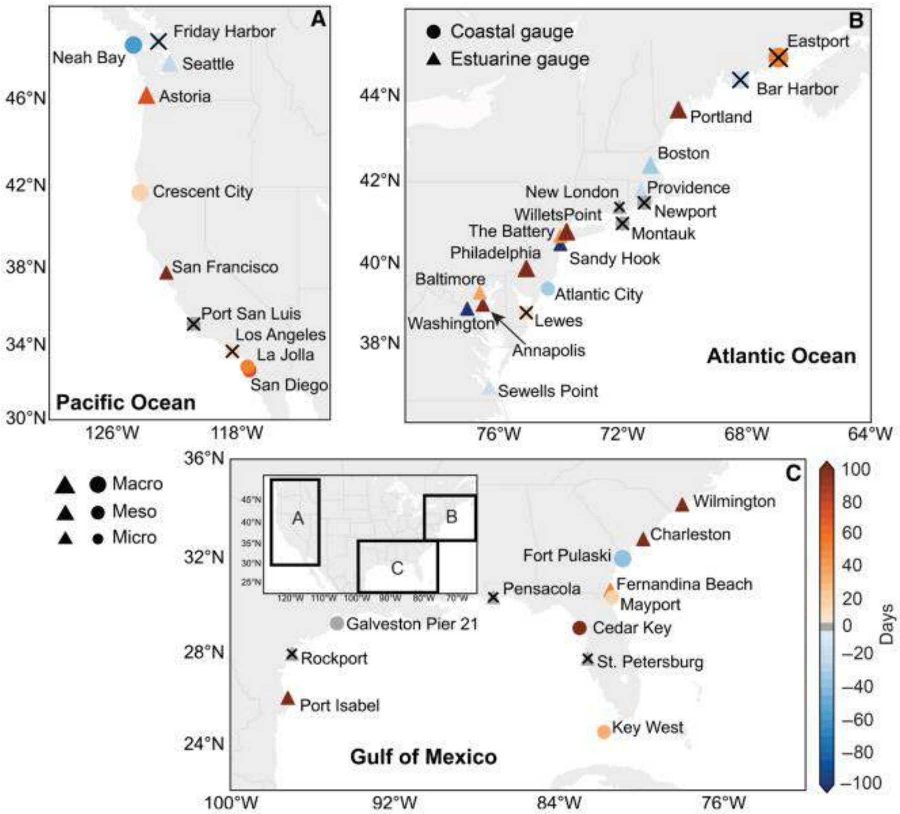

Figure 9 Effect of tidal changes on cumulative NF days at 40 tide gauge locations (Li et al. 2021).

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Project Novel Sensors and Quantum Technology for Geodesy (QuGe)

http://quge.iag-aig.org

President: **Jürgen Müller** (Germany)
Vice President: **Marcelo Santos** (Canada)

Structure

Working Group Q.1:	Quantum gravimetry in space and on ground
Working Group Q.2:	Laser interferometry for gravity field missions
Working Group Q.3:	Relativistic geodesy with clocks

QuGe's Steering Committee 2019-2023

President
Jürgen Müller, Germany
Vice-President
Marcelo Santos, Canada
Representatives of the four Commissions
IAG Comm. 1: *Erricos Pavlis*, USA
IAG Comm. 2: *Adrian Jäggi*, Switzerland
IAG Comm. 3: *Federica Migliaccio*, Italy
IAG Comm. 4: *Suelynn Choy*, Australia (since 2021 *Allison Kealy*, Australia)
Representatives of Services
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GGOS: *Ulrich Schreiber*, Germany
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Gabriel Guimarães, Brazil
WG Q.1
Franck Pereira, France
Michel van Camp, Belgium
WG Q.2
Michael Murböck, Germany (since 2021 *Samuel Francis*, USA)
Bob Spero, USA (since 2021 *Kirk McKenzie*, Australia)
WG Q.3
Gerard Petit, France (since 2022 *Pacôme Delva*, France)
Jakob Flury, Germany
Christian Lisdat, Germany

Mission of QuGe

In close collaboration between physics and geodesy, this IAG project exploits the high potential of quantum technology and novel measurement concepts for various innovative applications in geodesy. See also https://quge.iag-aig.org/

Overview and activities during the reporting period 2019 – 2023

The IAG project Novel Sensors and Quantum Technology for Geodesy (QuGe) explores the applications in geodesy of the most recent developments in quantum physics and novel measurement concepts, including prospects for enhancing satellite geodesy, terrestrial gravity sensing and reference systems. QuGe seeks to bring together researchers and engineers, whether from universities, government agencies, metrology institutes, or industry, dedicated to quantum gravimetry and new measurement methods, aiming to advance the frontiers in terms of development of models, techniques, and instruments. The project is built upon three pillars, reflected in its three working groups. The pillars are atom interferometry for gravimetry on ground and in space (quantum gravimetry), laser-interferometric ranging between test masses in space with nanometer accuracy, and frequency comparisons of highly precise optical clocks connected by optical links.

The work within QuGe was coordinated by means of four executive meetings which took place via WEBEX involving QuGe members as well as representatives from other IAG entities, when activities were planned and discussed. In the period between the meetings, work has been discussed in smaller groups or via email. Activities of QuGe have been presented as solicited talks at various meetings of Physics and Geodesy. We just mention COSPAR 2021, IAG SA 2021, Unified Analysis Workshop 2002, GGOS days 2022, AGU 2022, continued by IUGG GA 2023. The specific activities of the Working Groups are detailed below under each one of them. Other important activities were participation in scientific events, including the organization of dedicated sessions and symposia in many of them. We highlight the following events:

2021 IAG Scientific Assembly (hybrid format), 29 June – 2 July, in Beijing,

COSPAR 2021, 28 January – 4 February,

COSPAR 2022, 16 – 24 July, in Athens,

EGU general assembly 2020 (Sharing Geoscience Online), 4 – 8 May,

EGU general assembly 2021 (vEGU21 Gather online), 19 – 30 April,

EGU general assembly 2022, 3 – 8 April, in Vienna,

EGU general assembly 2023, 23 – 28 April, in Vienna.

Some of these events were virtual, the more recent ones in person.

We plan for a strong presence during the 28th IUGG General Assembly, in Berlin, with the organization of a joint symposium JG07 with IAVCEI, IASPEI and IAPSO on modern gravimetric techniques for geosciences. The large number of orals and posters in those past events emphasize the growing importance of the topic. We expect a similarly strong presence also of the audience at the IUGG GA.

An overview of the QuGe activities and their relevance for geodesy and beyond has been published for the wider geoscience community: Van Camp, M., Pereira dos Santos, F., Murböck, M., Petit, G., Müller, J. (2021): Lasers and Ultracold Atoms for a Changing Earth. EOS, 102, DOI: 10.1029/2021EO210673, EOS 103 (1), p. 32-37, 2022 (print version).

Intra-relations within IAG entities include participation in the GGOS Science Panel. Outreach activities involved a short note in the GIM magazine: "Van Camp, M., Pereira dos Santos, F., Müller, J. (2022): Lasers and cold atoms in space and on ground. GIM International, 4/2022." QuGe maintained its own website, at https://quge.iag-aig.org.

The importance of the topic demands the development of closer relations with national metrology institute and related industry, calling attention to needs and markets for new products.

The strong relevance of project QuGe and its success is underlined by the realization of major international research projects with strong and essential contribution by QuGe members. One example is the EU funded project CARIOQA led by CNES, France, where a quantum accelerometer mission shall be realized within the next 5 years. Another one is the preparation of next generation satellite missions beyond GRACE-FO (keyword MAGIC) in the next decade where double-pair missions will be realized by NASA and by ESA. Or, to enable and demonstrate relativistic geodesy with clocks, dedicated fibre networks are being extended in Europe and high-level clock comparisons are performed.

Finally, awarding the 2023 Vening Meinesz Medal of the EGU to QuGe president Jürgen Müller is to be mentioned, as one major reason for this prize was his activities in pushing the new fields related to quantum technology and applied relativity for geodesy.

The 2023 Vening Meinesz Medal of the EGU has been awarded to QuGe president Jürgen Müller (right). The past IAG president Harald Schuh (left) read the citation. [Photo copyright EGU]

Working Groups of QuGe

WG Q.1: Quantum gravimetry in space and on ground

Chair: *Franck Pereira dos Santos* (France)
Vice-Chair: *Michel van Camp* (Belgium up to May 2023)

Members

- *Olivier Carraz* (ESA)
- *Yuichi Imanishi* (Japan)
- *Jeffrey Kennedy* (USA)
- *Markus Krutzik* (Germany)
- *Marie-Françoise Lalancette* (France)
- *Thomas Lévèque* (France)
- *Federica Migliaccio* (Italy)
- *Roland Pail* (Germany)
- *Ernst Rasel* (Germany)
- *Alex Rülke* (Germany)
- *Steffen Schön* (Germany)
- *Shuqing Wu* (China)
- *Nan Yu* (USA)

Description

On ground, quantum sensors based on matter wave interferometry with cold atoms are very well suited for rapid and very precise gravity sensing. They can perform continuous absolute gravity measurements with sub-µGal stability. Mobile devices are developed for field campaigns and large-scale stationary devices for achieving extreme accuracy. While the former enable new strategies for local and regional gravity surveys, the latter will provide a new gravity standard in the future.

In space, the long-term stability and low noise level of quantum sensors will allow improving the spatial gravity field models in GOCE-type gradiometer missions. The determination of mass transport processes on Earth at low and medium degrees in GRACE-type missions will benefit from quantum accelerometers providing the measurement of the specific non-conservative forces. In addition, hybrid systems (i.e. a combination of electrostatic and atom-interferometric accelerometers) can cover a wider spectral range, which will greatly support navigation and inertial sensing on ground and in space.

The goal of this WG is to elaborate the major benefit and most promising applications of atom interferometry for gravimetry and inertial sensing in space and on ground.

Objectives

- Terrestrial quantum gravimeters and application scenarios (including airborne and marine instruments),
- (Hybrid) accelerometers for space missions and spacecraft navigation,
- Atom interferometric gradiometry,

- Elaboration of further applications / space demonstrator (e.g. pathfinder) like atmosphere research, relativity tests, etc.
- Elaboration of synergies between different science topics in a single mission (Earth observation and fundamental physics, navigation and space exploration, several scenarios for Earth observation, e.g. gravimetry, atmospheric research and magnetometry).

Meetings

Four meetings were organized. The kick-off meeting occurred on January the 26th of 2021, where members of the group introduced themselves and their activities. A follow-up meeting was organized in March to discuss the organization of the workshop planned on May 26-27. A third meeting took place on January the 11th of 2022, and the fourth one on June the 9th of 2022. At these meetings, general information was exchanged, and updates on activities at national levels were presented by members of the working group as well as the contribution of WG members to major research projects in these fields. We reviewed relevant conferences and the participation of our community. A review of companies involved in the development of quantum sensors was also realized. It was proposed to organize a meeting where these companies would be invited to present their activities, if they agree. Since then, contacts have been taken and several companies have expressed their interest in contributing. This meeting is now to be organized, probably in the next period of project QuGe.

Website

We have added content to the webpage dedicated to WG Q.1 on the QuGe website, with a list of selected publications, the list of the WG members, as well as illustrative pictures of quantum gravity sensors developed by the community.

Workshop

An online workshop took place on the 26th and 27th of May 2021. This (virtual) meeting covered a broad scope of quantum gravity sensing, from the development of the sensors and their characterization, to a large panel of present and future applications. It brought together instrument scientists from the quantum physics community and users from the geoscience community.

The program was the following:

<u>Wednesday, the 26th of May</u>

2:00 – 2:35	Bastian Leykauf	HU Berlin	Precision gravimetry with an atom interferometer
2:35 – 3:10	Jean Paul Montagner	IPGP	Prompt Earthquake Gravity Anomalies - Speed-of-light Seismology
3:10 – 3:45	Thomas Lévèque	CNES	Development of quantum sensors for space geodesy
3:45 – 4:20	Roland Pail	TUM	Impact of new measurement technologies for the monitoring of mass transport processes in the Earth system
4:20 – 4:55	Glyn Williams-Jones	SFU	Volcano gravimetry – insights from past successes and future opportunities

Thursday, the 27th of May

2:00 – 2:35	Yannick Bidel	ONERA	Airborne and marine quantum gravimetry
2:35 – 3:10	Andreas Güntner	GFZ	Applications of terrestrial gravimetry in hydrology
3:10 – 3:45	Qiang Lin	Zhejiang U. of Technology	Absolute gravity measurement for field applications based on quantum gravimeter
3:45 – 4:20	Alain Dassargues	U Liege	Land subsidence due to induced water pressure changes in aquifers and confining layers
4:20 – 4:55	Frédéric Domps	European Commission	Quantum Space Gravimetry at European Commission

We had 290 registrations, and an average attendance of about 150 persons. This success confirmed the great interest of the community.

Selected publications

Abend S., M. Gersemann, H. Ahlers, M. Sahelgozin, J. Matthias, N. Grove, H. Heine, N. Gaaloul, W. Herr, C. Schubert, W. Ertmer, E.M. Rasel, M. Gebbe, H. Müntinga, C. Lämmerzahl, L. Timmen, J. Müller (2019): Atom-chip–based quantum gravimetry with BECs. Proceedings of the International School of Physics "Enrico Fermi", IOS press e-book: Foundations of Quantum Theory, vol. 197, p. 393-397, Doi:10.3254/978-1-61499-937-9-393

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B. Canuel, S. Abend, P. Amaro-Seoane, F Badaracco, Q. Beaufils, A. Bertoldi, K. Bongs, P. Bouyer, C. Braxmaier, W. Chaibi, N. Christensen, F. Fitzek, G. Flouris, N. Gaaloul, S. Gaffet, C. L. Garrido Alzar, R. Geiger, S. Guellati-Khelifa, K. Hammerer, J. Harms, J. Hinderer, J. Junca, S. Katsanevas, C. Klempt, C. Kozanitis, M. Krutzik, A. Landragin, I. Làzaro Roche, B. Leykauf, Y-H. Lien, S. Loriani, S. Merlet, M. Merzougui, M. Nofrarias, P. Papadakos, F. Pereira dos Santos, A. Peters, D. Plexousakis, M. Prevedelli, E. Rasel, Y. Rogister, S. Rosat, A. Roura, D. O. Sabulsky, V. Schkolnik, D. Schlippert, C. Schubert, L. Sidorenkov, J.-N. Siemes, C. F. Sopuerta, F. Sorrentino, C. Struckmann, G.M. Tino, G. Tsagkatakis, A. Viceré, W. von Klitzing, L. Woerner, X. Zou, "ELGAR - a European Laboratory for Gravitation and Atom-interferometric Research", Quantum and Classical Gravity 37, 225017 (2020)

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WG Q.2: Laser interferometry for gravity field missions

Chair: *Samuel Francis* (USA)
Vice-Chair: *Kirk McKenzie* (Australia)

Members

- *Michael Murböck* (Germany), Chair 2019-2022
- *Robert Spero* (USA), Vice-Chair 2019-2022
- *Vitali Müller* (Germany)
- *Gerhard Heinzel* (Germany)
- *Jürgen Kusche* (Germany)
- *Felix Landerer* (USA)
- *David Wiese* (USA)
- *Peter Bender* (USA)
- *Gilles Metris* (France)
- *Christophe Le Poncin-Lafitte* (France)
- *Shuanggen Jin* (China)
- *Christopher Woodruff* (USA)
- *Brent Ware* (USA)
- *Frank Flechtner* (Germany)
- *Markus Hauk* (Germany)
- *Thomas Papanikolaou* (Denmark)
- *Andrew Wade* (Australia)
- *Emily Rose Rees* (Australia)
- *Clément Courde* (France)
- *Julien Chabé* (France)
- *Julie Rolla* (USA)

Description

GRACE has excellently demonstrated the great potential of inter-satellite tracking to determine time-variable gravitational signals which are related to mass transport processes in the Earth system. Examples are ice mass loss in Greenland and Antarctica, ground water loss in Asia, droughts in USA, quantification of the global water cycle, mass contribution to sea level rise, mass variation due to land uplift in North America and Scandinavia, or mass changes related to earthquakes. To increase the resolution and to extend the time series, GRACE-FO was launched in May 2018 also carrying a Laser Ranging Interferometer (LRI) as technology demonstrator which is able to approach an accuracy of tens of nm for inter-satellite ranging.

Optical sensing of the motion of test masses in the gravitational field with nanometer accuracy and beyond can be realized in various measurement concepts such as for ranging between satellites like in GRACE-FO or future swarms of satellites. Further concepts apply LRI for sensing single test-mass motion (accelerometry) or multiple test-mass constellations within one satellite (GOCE-type gradiometry). The overall goal of this WG is to study optical sensing for inter-satellite tracking, accelerometry and gradiometry, and its applications for next generation gravity field missions.

Activities

The first year was covered by organizing that WG, to collect the members, to fill the website and to develop (in sub-groups) the further strategy of the collaborations. WG leadership was changed in early 2022.

The GRACE Follow-On Laser Ranging Interferometer (LRI) continues to operate in-orbit with performance well below requirements. No signs of optical contamination or degradation have been seen after 5 years of operation and there have been few unplanned interruptions to tracking. Gravity fields derived from LRI are consistent with those derived from primary microwave instrument, while offering improved performance at high frequencies.

The laser ranging interferometer will be the primary instrument on the NASA/ DLR Mass Change mission. Work on the Mass Change laser ranging interferometer has started and is in Phase A for NASA. Research at the Australian National University is investigating a scale factor unit for the Mass Change LRI which will provide a way to measure the absolute frequency of the optical cavity.

The Mass Change and Geosciences International Constellation (MAGIC) is a NASA/ESA constellation concept with two orbital gravimeters operating simultaneously. With the NASA/ DLR Mass Change mission and ESA's Next Generation Gravity Mission (NGGM), both using laser interferometers to measure variations in inter-satellite separation, gravity fields with improved spatial and temporal resolution will be possible. In such double-pair constellations, also the negative effect of the insufficient quality of the background models (i.e. high frequency mass changes in the atmosphere and oceans) on the gravity field solutions will be reduced.

Looking further ahead, the WG chairs are currently planning a workshop that will cover the future of inter-satellite laser ranging, covering topics including:

- GRACE-FO Laser Ranging Interferometer data processing and applications,
- Measures to reduce limitations related to background modelling, sensors and constellations,
- Working on a "Road-map" paper for future of inter-satellite laser ranging.

Selected Publications

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WG Q.3: Relativistic Geodesy with Clocks

Chair: *Gerard Petit* (France) / *Jakob Flury* (Germany, since 2022)
Vice-Chair: *Jakob Flury* (Germany) / *Pacôme Delva* (France, since 2022)
Consultant from Physics: *Christian Lisdat* (Germany)

Members

- *Claude Boucher* (France)
- *Davide Calonico* (Italy)
- *Pascale Defraigne* (Belgium)
- *Pacôme Delva* (France)
- *Ropesh Goyal* (India)
- *Gesine Grosche* (Germany)
- *Hua Guan* (China)
- *Chris Hughes* (UK)
- *Sergei Kopeikin* (USA)
- *Jürgen Kusche* (Germany)
- *Claus Lämmerzahl* (Germany)
- *Marie-Françoise Lequentrec* (France)
- *Guillaume Lion* (France)
- *Andrew Ludlow* (USA)
- *Helen Margolis* (UK)
- *Elena Mazurova* (Russia)
- *Nathan Newbury* (USA)
- *Bijunath Patla* (USA)
- *Nikos Pavlis* (USA)
- *Paul-Eric Pottie* (France)
- *Ulrich Schreiber* (Germany)
- *Wen Bin Shen* (China)
- *Simon Stellmer* (Germany)
- *Yoshiyuki Tanaka* (Japan)
- *Pieter Visser* (Netherlands)

Description

Optical clocks are sensitive to the gravity potential in which they are operated. The comparison of two clocks will reveal a frequency offset from the value expected from side-by-side comparisons that can directly be related to the potential difference between both clocks. The best optical clocks now reach resolutions of 0.1 m^2/s^2, transportable ones about 0.5 m^2/s^2. They can be achieved already after few hours of averaging.

The WG aims at evaluating how this technique can be used to generate unified and long-term stable height networks and reference systems. This includes the discussion about the feasibility to realize a datum by reference to a, e.g., space-borne clock with ideally negligible gravitational interference. Future clock networks might also be used as ground-truth for mass-change monitoring of space missions or even to bridge gaps in satellite observations.

Other aspects to be addressed are the application of observed time-variable signals in de-aliasing of satellite observations. In cooperation with WG Q.1 and WG Q.2, sensor fusion concepts are discussed to utilize the different spatial integration characteristics of clocks and the other gravity sensors to disentangle local and extended signal sources.

In summary, the goals of this WG are using clocks measurements for determining differences of physical heights and gravity potential for various geodetic applications.

Activities

During the year 2020, the membership was consolidated.

After some delay to adapt to the COVID crisis, the kick-off meeting was held virtually on December 21, 2020. It included several presentations by Jürgen Müller (The IAG project QuGe), Gérard Petit (Activities at the BIPM and CCTF related to this WG), Jakob Flury (Related IAG activities, IHRS), Yoshiyuki Tanaka (Progress about chronometric levelling in Japan), Claus Lämmerzahl (Last activities in relativistic modelling) and Chris Hughes (Global hydrodynamic levelling).

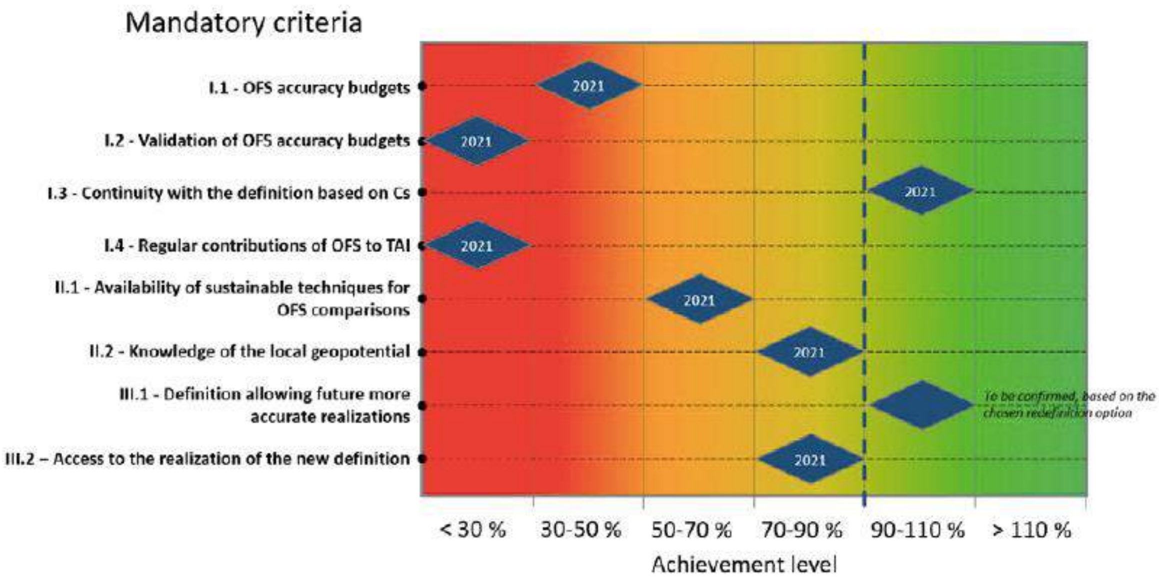
An in-person workshop of WG Q.3 was planned but could not be held due to the ongoing pandemic situation. In February 2022, Gerard Petit decided to resign as chair of the WG in the context of his retirement. After consultation, the WG unanimously supported the proposal of Jakob Flury as chair and Pacôme Delva as co-chair in March 2022. The proposal was accepted by the IAG Executive Board.

The second online meeting of WG Q.3 was held on October 25, 2022. The meeting included presentations by Jakob Flury (Current and upcoming activities), Jürgen Müller (Simulation study on chronometric leveling), Pacôme Delva (Report on TOFU, ROYMAGE, and REFIMEVE projects), Christian Lisdat (Upcoming optical clock campaign in Europe), Biju Patla (Uncertainties of geopotential models) as well as slides provided by Rupesh Goyal (Geoid modeling).

The third WG Q.3 meeting was held as an online meeting on June 8, 2023. The meeting included presentations by Andrew Ludlow (NIST transportable Yb lattice clock), Paul-Eric Pottie (ROYMAGE and REFIMEVE+ projects), Yoshiyuki Tanaka (Chronometric leveling activities in Japan), Wen Bin Shen (Test of gravitational redshift based on the China Space Station), Miltiadis Chatzinikos (Model development for the study of temporal networks of optical-atomic clocks), Biju Patla (Relativistic geodesy with constant redshift surfaces), Asha Vincent (Terrestrial clock networks and applications in geodesy) and Akbar Shabanloui (Determination of temporal variations of Earth‘s gravity field with optical clocks onboard LEO satellites).

The presentations and the minutes of the meetings are made available at https://quge.iag-aig.org/quge-meetings.

Several members of the working group are involved in the work of the Consultative Committee for Time and Frequency (CCTF). The 22nd CCTF meeting was held in October 2020 and March 2021, and the 23rd meeting was held in June/July 2022 (see https://www.bipm.org/en/committees/cc/cctf/meetings). CCTF has established a Task Force and is carrying out a redefinition campaign. Mandatory and auxiliary criteria for the redefinition have been agreed on, and progress related to these criteria is being monitored by CCTF.



Fulfilment levels of mandatory criteria for the redefinition of the second based on optical frequency standards, from CCTF (2022)

The work of the Task Force has considerable intersection with the activities of WG Q.3, concerning the techniques and campaigns for remote optical clock comparisons, and concerning the determination of the relativistic frequency shift to a level equivalent to 10^{-18} in relative frequency.

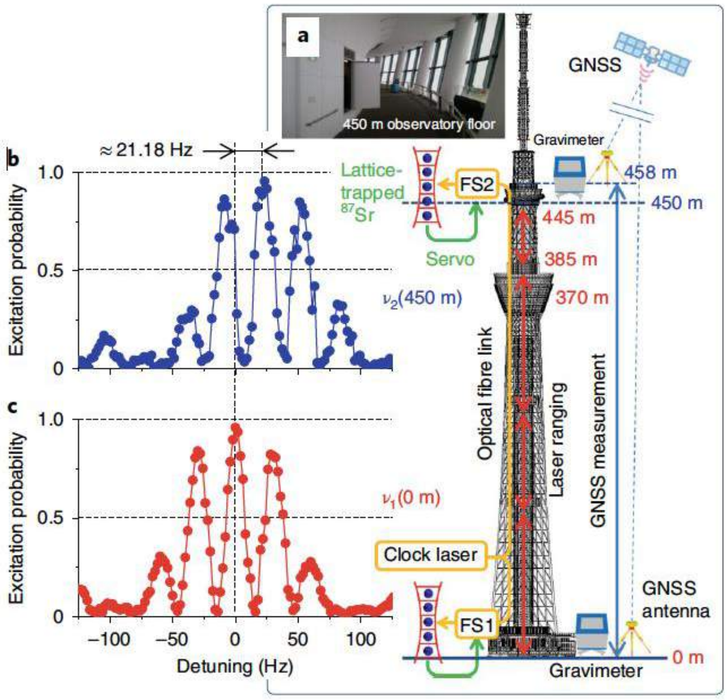
Jakob Flury contributed a description of optical atomic clocks to the Observations section of the ggos.org webpages.

Conferences: Topics of WG Q.3 were presented, e.g., in special sessions on modern concepts for gravimetric Earth observation that were included in the EGU General Assemblies in 2021, 2022, and 2023, and related sessions at COSPAR 2021 and 2022, IAG SA 2021, UAW 2023, GGOS Days 2022, etc. WG Q.3 topics and results will be presented at the IUGG 2023 General assembly in Berlin in various symposia such as JG07 and G02 (Jakob Flury, solicited talk).

Relativistic geodesy with clocks and related work by WG3 group members was featured in an article "Einstein Says: It's 309.7-Meter O'Clock" in AGU's journal EOS in October 2019.

Remote frequency comparison measurement campaigns

A campaign highlight during the reporting period was the relativistic height measurement of the Tokyo Skytree broadcasting tower using two transportable cryogenic ^{87}Sr optical lattice clocks by the group of H. Katori at RIKEN / University of Tokyo. Gravitational redshift measurements between clocks at the base of the tower and at a height of 450 m above the base were carried out during several days in April / May 2019. The relativistic result agreed within 5 cm with classical measurements of the height difference using GNSS observations and laser ranging, demonstrating the feasibility of centimeter-level chronometric leveling under rather harsh conditions (Takamoto et al. 2020).



Tokyo Skytree experiment setup and frequency comparison result, from Takamoto et al. (2020), doi:10.1038/s41566-020-0619-8

One of the Tokyo transportable Sr clocks participated in frequency comparison measurements in Europe in spring 2023. The measurement results of this campaign are currently being evaluated. A remote frequency comparison campaign between Tokyo and the Mizusawa National Astronomical Observatory of Japan is planned for 2023.

In France, the REFIMEVE network allowing remote frequency comparisons has been extended. A third cross-border fiber link between Paris and Torino via the underground laboratory of Modane (LSM) has established the connection to the Italian Quantum Backbone network (Clivati et al. 2022).

A 2220 km phase-stabilized fiber link has been successfully demonstrated between PTB (Germany) and NPL (United Kingdom), via Paris (Schioppo et al. 2022).

Determination of the gravity potential with clocks

Simulation studies of the impact of future optical atomic clock networks on the unification of height systems have been carried out, e.g., by Wu et al. (2019).

Selected Publications

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Global Geodetic Observing System

https://www.ggos.org

President: Basara Miyahara (Japan)
Vice President: Laura Sánchez (Germany)

As the observing system of the IAG, the Global Geodetic Observing System (GGOS) facilitates a unique and essential combination of roles focused on advocacy, integration, and external relations with affine Earth science disciplines and general stakeholders. The IAG charged GGOS to provide the observations needed to monitor, map, and understand changes in the Earth's shape, rotation, and mass distribution, to provide the global geodetic frame of reference for the measurement and consistent interpretation of key global change processes and for many other scientific and societal applications, and to benefit science and society by providing the foundation upon which advances in Earth and planetary system science and applications are built. To accomplish its mission, GGOS develops and maintains working relationships with the other IAG components and a variety of external groups and organizations.

GGOS Structure

The structure of GGOS is shown in Figure 1. The decision-making bodies are the Consortium and the Coordinating Board. The GGOS Executive Committee is responsible for the day-to-day activities necessary to carry out the mandate given by the decision-making bodies. Permanent Standing Committees and limited-term Working Groups are the thematic working bodies of GGOS and are distributed over two Bureaus, the Science Panel, and the Focus Areas. The GGOS Coordinating Office serves as the Secretariat of GGOS and carries out the administrative work as directed by the decision-making bodies and the Executive Committee. The work of the Coordinating Office includes communications, outreach, external relations and the maintenance and enhancement of the GGOS website and social media presence.

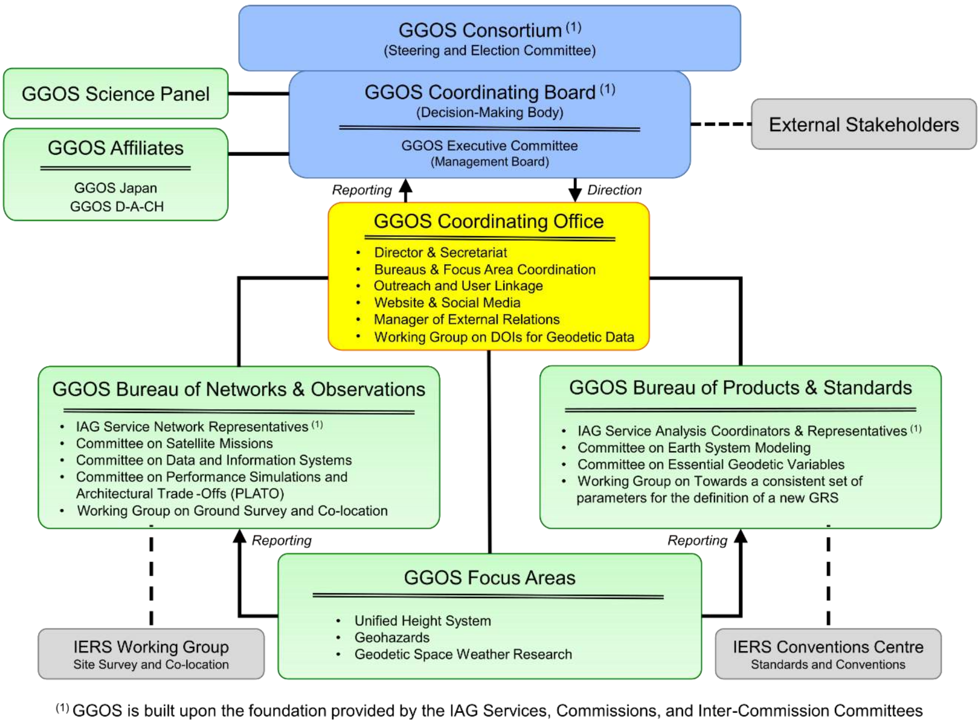


Figure 1. Organization chart of GGOS.

Overview

GGOS renewed its structure in 2019 including the election of new President and Vice President and the restructuring of the GGOS Consortium and GGOS Coordinating Board. A Working Group on "DOIs for Geodetic Data Sets" was established within the GGOS Coordinating Office. The Working Group on "ITRS Standards for ISO TC 211" completed its work and was dissolved with successful contribution to ISO 19161-1. The Working Group on "Establishment of the Global Geodetic Reference Frame (GGRF)" was renewed and renamed to Working Group on "Towards a consistent set of parameters for the definition of a new GRS" and continues to work on the challenge to define a new Geodetic Reference System (GRS). The GGOS Focus Area "Sea Level Change" was terminated in 2019.

The GGOS Bureau of Products and Standards (BPS) published a 2nd updated version of the BPS inventory in the Geodesist's Handbook 2020 to compile and refine a registry of standards and conventions used for the generation of IAG products.

The GGOS Focus Area “Unified Height System” defined a strategy for the implementation of the International Height Reference Frame (IHRF) and is currently working in the first computation of the IHRF. The IHRF operational coordination center will be launched in the coming year under the responsibility of the International Gravity Field Service (IGFS) and this Focus Area will be terminated at the IUGG2023 General Assembly. The Focus Area “Geohazards” played a central role in the development of the initiative “GNSS enhancement to tsunami early warning systems (GTEWS)” and presently is supporting the creation of the GTEWS Consortium within the Community Activity “Geodesy for the Sendai Framework” of the Group on Earth Observations (GEO). This Focus Area has started to work in Oceania and established GTEWS Oceania as practical implementation of the system in the region. The Focus Area “Geodetic Space Weather Research” identified four central challenges and established four dedicated working groups. In addition to these three Focus Areas, a new Focus Area “Artificial Intelligence (AI) for Geodesy” has been established in May 2023 and will mainly work on three study areas: GNSS remote sensing, gravity field and mass changes, and Earth orientation parameter prediction.

As a mechanism to increase participation in GGOS, the second of two GGOS Affiliates was established in 2021. GGOS D-A-CH is a regional affiliate group of the German-speaking countries: D (Germany), A (Austria) and CH (Switzerland). GGOS D-A-CH is the result of a strong cooperation between the national geodetic commissions of these countries and was developed on the basis of the strategic white paper “Geodesy 2030” (Müller, Pail et al., 2019, https://doi.org/10.12902/zfv-0243-2018). Its founding chair is Hansjörg Kutterer of the Karlsruhe Institute of Technology, a former GGOS President. GGOS D-A-CH has formulated its Terms of Reference with a clear focus on strategic topics in GGOS-related science. A next GGOS Affiliate is planned to be established by Spanish and Portuguese colleagues: GGOS Iberoatlantic. It aims to enhance participation in GGOS from counties around the Atlantic, including African and South American countries. GGOS Iberoatlantic has been officially adopted by the Spanish Geodetic Commission and is currently under discussion by Portuguese colleagues.

Web and Social Media Presence

One of the main focus of GGOS during the period 2019-2023 was devoted to outreach and communication. GGOS completely renewed its website (https://www.ggos.org). The new website highlights the dual roles of GGOS: one as an organization to foster collaboration within the IAG and among stakeholders, and the other as the IAG's geodetic observing system, supporting science and society as a fundamental infrastructure for monitoring the Earth. In the new website, the IAG Services are brought to the forefront to make them more visible and to provide easier access to their Internet portals. The new GGOS site also provides detailed descriptions and data registries of geodetic observations and products. These web components present the role and importance of geodesy, its observing techniques and products to non-geodesists with plain text and brief explanations, as well as eye-catching visual aids. This information is complemented by links to background articles on geodesy that can help non-geodesists to understand what geodesy is and why geodesy it is important to science and society.

Another new fundamental tool is the repository of key documents in the GGOS Cloud (https://cloud.ggos.org), which enables us to share the GGOS related materials such as Terms of Reference, reports, papers and presentations and ensures their long-term availability. Recently, GGOS has started to develop the GGOS-Portal. The GGOS-Portal aims to serve as a comprehensive search and access point for geodetic data and products (one-stop shop) by combining easy-to-understand descriptions of products and observation techniques with complete source descriptions and detailed metadata. To this end, GGOS conducted a survey the geodetic and affine communities from March to April 2023 to gauge the opinions of geodetic data users on data availability and visibility and to identify requirements for a comprehensive and user-friendly GGOS Portal. The results are being analyzed and will be utilized for the design of the Portal.

External relations and Digital Object Identifiers

GGOS also continued to strengthen and expand its external relations and stakeholder engagement. Continued participation in GEO included the establishment of a Geodesy Advocacy Community Activity within GEO entitled "Geodesy for the Sendai Framework", as well as continued and diverse participation in the GEO Programme Board. GGOS also continues to strongly support the actions and initiatives of the UN GGIM Subcommittee on Geodesy, and has extended this support to the UN Global Geodetic Centre of Excellence newly established on March 29, 2023 in the UN Campus in Bonn, Germany.

In addition to external advocacy, GGOS routinely looks inward to identify the best ways to cite and track the impact of the geodetic data, products, and other resources provided by the IAG and its Services. At the 2019 Unified Analysis Workshop, Digital Object Identifiers (DOIs) were discussed as a unique and unambiguous identifier for data as well as publications. DOIs are already widely used by publishers, and their implementation for data sets is expected to be beneficial for both users and data providers. The Working Group on DOIs is chaired by Kirsten Elger of GFZ Potsdam and is composed of more than 20 colleagues, mainly from IAG Services. The WG analyzed use cases and best practices in geodesy and other scientific fields, and has been compiling recommendations directed to establish parameters and procedures for properly assigning DOIs to GNSS data, as the first example. Once the best procedure is identified, it will be extended to the other geodetic data sets.

Towards a new GGOS Strategic Plan

The current GGOS Strategic Plan was released in 2014. Given the advances in Geodesy and recent developments within the IAG, it became necessary to revise and update the GGOS Strategic Plan to meet new demands from the global geodetic community. With this purpose, GGOS conducted a Strategy Plan Survey between July 11 and Sep 30, 2022. This survey consisted of six closed questions (multiple choice of pre-given answers) and seven SWOT (Strengths, Weaknesses, Opportunities, Threats) questions. Seventy colleagues from 32 countries answered the GGOS survey. 71% of them are involved in IAG and 34% involved in the UN-GGIM's Subcommittee of Geodesy (SCoG). The outcomes of the survey were discussed at the GGOS Strategic Plan Workshop held in Munich, Germany in November 2022. From these discussions, four strategic goals and 16 objectives were identified as the core elements of the new GGOS Strategic Plan. This plan will be released after the IUGG2023 General Assembly after approval and endorsement by the GGOS Coordinating Board and consultation with the IAG Executive Committee, respectively.

Another key recommendation arising from the Strategic Plan survey is to merge the GGOS Consortium (steering and electoral committee) and the GGOS Coordinating Board (decision-making body) into one body as:

1) The functions of both bodies can be performed by only one body,
2) The involvement of all IAG components in the GGOS activities should be more visible, and
3) Having only one governing body would make decision-making within GGOS more efficient.

Accordingly, the GGOS Coordinating Board members were asked to vote for, against or abstain on the proposal to merge the current GGOS Coordinating Board and the GGOS Consortium into a single managing body called "GGOS Governing Board". This proposal was approved by 89% of the members. As following step, the proposal was presented to the IAG Executive Committee, whose members endorsed the decision of the GGOS Coordinating Board. Currently, the GGOS Executive Committee is aligning the GGOS Terms of Reference with the new Strategic Plan and governing body. Once the GGOS Coordinating Board and the IAG Executive Committee have approved the new GGOS Terms of Reference, both the new Strategic Plan and the new structure will come into effect.

Consortium

The GGOS Consortium acts as the large steering committee and collective voice of GGOS and is comprised of one representative from each GGOS Affiliate and up to two representatives from each IAG Service, Commission, and Inter-Commission Committee. According to the GGOS Terms of Reference, the Consortium membership is revised and renewed if necessary every four years, coinciding with the IUGG General Assemblies. The members of the GGOS Consortium for the term 2019–2023 are listed in Table 1.

The President of GGOS is the chair of the GGOS Consortium. The GGOS Consortium meets annually. The meetings corresponding to the 2019–2023 term were held as follows:

1. GGOS Days 2019, Rio de Janeiro, Brazil, 12-14 November 2019
2. GGOS Days 2020, held virtually via Video Conference, 5-7 October 2020
3. GGOS Days 2021, held virtually via Video Conference, 11-13 October 2021
4. GGOS Days 2022, Munich, Germany, 14-15 November 2022

Table 1. Members of the GGOS Consortium (term 2019–2023)

Organization	Name	Title
GGOS	Basara Miyahara	Chair
GGOS Affiliate: GGOS Japan	Yusuke Yokota	Designated GGOS Representative
GGOS Affiliate: GGOS D-A-CH	Markus Rothacher	Designated GGOS Representative (2021-2023)
IAG Service Representatives		
International Gravimetric Bureau (BGI)	Sylvain Bonvalot	Director
	Sean Bruinsma	Designated GGOS Representative
International Centre for Global Earth Models (ICGEM)	E. Sinem Ince	Designated GGOS Representative
International DORIS Service (IDS)	Laurent Soudarin	Director, Central Bureau
	Frank Lemoine	Chair, Governing Board
International Earth Rotation and Reference Systems Service (IERS)	Daniela Thaller	Director, Central Bureau
	Robert Heinkelmann	Analysis Coordinator
International Service for Geoid (ISG)	Urs Marti	Designated GGOS Representative
	Jianliang Huang	Designated GGOS Representative
International Gravity Field Service (IGFS)	Riccardo Barzaghi	Chair
	Georgios Vergos	Director, Central Bureau
International GNSS Service (IGS)	Nicholas Brown	Designated GGOS Representative
	Arturo Villiger	Designated GGOS Representative
The International Laser Ranging Service (ILRS)	Toshimichi Otsubo	Chair, Governing Board
	Erricos Pavlis	Chair, Analysis Working Group
International VLBI Service for Geodesy and Astrometry (IVS)	Axel Nothnagel	Chair, Directing Board
	Dirk Behrend	Director, Coordinating Center
Permanent Service for Mean Seal Level (PSMSL)	Elizabeth Bradshaw	Director
	Andy Matthews	Designated GGOS Representative
International Geodynamics and Earth Tides Service (IGETS)	Christoph Foerste	Designated GGOS Representative
	Hartmut Wziontek	Designated GGOS Representative
International Digital Elevation Model Service (IDEMS)	Kevin M. Kelly	Director
	Christian Hirt	Designated GGOS Representative
IAG Commissions Representatives		
Commission 1: Reference Frames	Christopher Kotsakis	President
	Tonie van Dam	Designated GGOS Representative
Commission 2: Gravity Field	Adrian Jäggi	President
	Mirko Reguzzoni	Vice President
Commission 3: Earth Rotation and Geodynamics	Janusz Bogusz	President
	Chengli Huang	Vice President
Commission 4: Positioning and Applications	Paweł Wielgosz	President
	Michael Schmidt	Vice President
IAG Inter Commission Committee (ICC) Representatives		
ICC on Theory (ICCT)	Pavel Novák	President
	Dimitrious Tsoulis	Designated GGOS Representative
ICC on Climate Research (ICCC)	Anette Eicker	President
	Carmen Boening	Vice President
ICC on Marine Research (ICCM)	Yuanxi YANG	President
	Heidrun Kopp	Designated GGOS Representative

Coordinating Board

The Coordinating Board is the decision-making body of GGOS. The members of the GGOS Coordinating Board in the term 2019–2023 are listed in Table 2.

The President of GGOS chairs the Coordinating Board. The Coordinating Board meets twice-per-year, usually during the GGOS Days and around the EGU. In the 2019-2023 term, following meetings were held:

1. GGOS Days 2019, Rio de Janeiro, Brazil, 12-14 November 2019
2. GGOS CB Meeting, held virtually via Video Conference, 8 May 2020
3. GGOS Days 2020, held virtually via Video Conference, 5-7 October 2020
4. GGOS CB Meeting, held virtually via Video Conference, 7 May 2021
5. GGOS Days 2021, held virtually via Video Conference, 11-13 October 2021
6. GGOS CB Meeting, held virtually via Video Conference, 16 May 2022
7. GGOS Days 2022, Munich, Germany, 14-15 November 2022
8. GGOS CB Meeting, Vienna, Austria, 22 April 2023

Table 2. Members of the GGOS Coordinating Board (term 2019–2023)

Position	Voting	Name
Chair	Yes	Basara Miyahara
Vice Chair	Yes	Laura Sánchez
Chair, Science Panel	Yes	Kosuke Heki
Director, Coordinating Office	Yes	Martin Sehnal
Manager, External Relations	Yes	Allison Craddock
Director, Bureau of Networks & Observations	Yes	Mike Pearlman
Director, Bureau of Products & Standards	Yes	Detlef Angermann
Representative, GGOS Affiliates	Yes	Toshimichi Otsubo
	Yes	Hansjörg Kutterer (2021-2023)
Representative, IAG President	Yes	Zuheir Altamimi
Representative, IAG Services	Yes	Riccardo Barzaghi
	Yes	Daniela Thaller
	Yes	Sean Bruinsma
	Yes	Robert Heinkelmann
Representative, IAG Commissions and ICC	Yes	Tonie Van Dam
	Yes	Adrian Jäggi
Member-at-Large	Yes	Maria Cristina Pacino (2019-2021) Claudia Tocho (2021-2023)
	Yes	Nicholas Brown
	Yes	Ludwig Combrinck
GGOS Focus Area (FA) Leads		
FA Unified Height System	No	Laura Sánchez
FA Geohazards	No	John LaBrecque
FA Geodetic Space Weather Research	No	Michael Schmidt
FA Artificial Intelligence for Geodesy	No	Benedikt Soja (May-July 2023)
GGOS Committee Chairs		
Committee on Satellite and Space Missions	No	Roland Pail
Committee on Data and Information Systems	No	Martin Sehnal (2019) Nicholas Brown (2020-2023)

Committee on Contribution to Earth System Modelling	No	Maik Thomas
Committee on PLATO (IAG WG)	No	Daniela Thaller
Committee on Essential Geodetic Variables	No	Richard Gross
GGOS Working Group Chairs		
JWG: Ground Survey and Co-Location	No	Ryan Hippenstiel
JWG: Definition of a new GRS	No	Urs Marti
WG: DOIs for Geodetic Data Sets	No	Kirsten Elger
Others		
Manager, GGOS Web and Social Media	No	Martin Sehnal
Immediate Past Chair of GGOS	No	Richard Gross

Executive Committee

The GGOS Executive Committee serves under the direction of the Coordinating Board to accomplish the day-to-day business of GGOS. The members and guest observers of the Executive Committee during 2019–2023 are listed in Table 3. The President of GGOS is the Chair of the Executive Committee. The Executive Committee holds monthly conference calls and meets face-to-face or virtual during the meetings of the Coordinating Board (see above).

Table 3. Members of the GGOS Executive Committee (term 2019–2023)

Position	Status	Name
Chair	Member	Basara Miyahara
Vice Chair	Member	Laura Sánchez
Director, Coordinating Office	Member	Martin Sehnal
Manager, External Relations	Member	Allison Craddock
Director, Bureau of Networks & Observations	Member	Mike Pearlman
Director, Bureau of Products & Standards	Member	Detlef Angermann
Representative, IAG Services	Member	Riccardo Barzaghi
Representative, IAG Commissions	Member	Adrian Jäggi
Immediate Past Chair of GGOS	Guest	Richard Gross
Chair, Science Panel	Guest	Kosuke Heki
Representative, IAG President	Guest	Zuheir Altamimi

GGOS Coordinating Office

Director: *Martin Sehnal (Austria)*
Manager of External Relations: *Allison Craddock (USA)*
Chair of WG on DOIs: *Kirsten Elger (Germany)*

Working Group (WG) affiliated with GGOS Coordinating Office:

- GGOS Working Group on "DOIs for Geodetic Data Sets"

Purpose and Scope

The GGOS Coordinating Office (CO) serves as a centralized administrative and organisational entity and interacts with the GGOS Bureaus and Focus Areas for organisational matters. The CO performs the day-to-day activities and generates reports in support of the various components of GGOS especially the GGOS Executive Committee and the GGOS Coordinating Board. The CO ensures information flow, maintains and archives documentation and in its long-term coordination role ensures consistency and continuity in the contributions of the GGOS components. The CO implements and operates the GGOS website and outreach.

The Manager of External Relations connects GGOS with external organisations.

The Director of the CO and the Manager of External Relations are both ex-officio members of the GGOS Coordinating Board and the GGOS Executive Committee.

Activities and Actions

New Director of GGOS Coordinating Office

The director of the GGOS Coordinating Office changed in September 2019. Helmut Titz (BEV, Austria) stepped down due to health issues and Martin Sehnal (BEV, Austria) followed him interimistically and was finally approved by the BEV (Federal Office of Metrology and Surveying, Austria) as the new director of GGOS CO in July 2020.

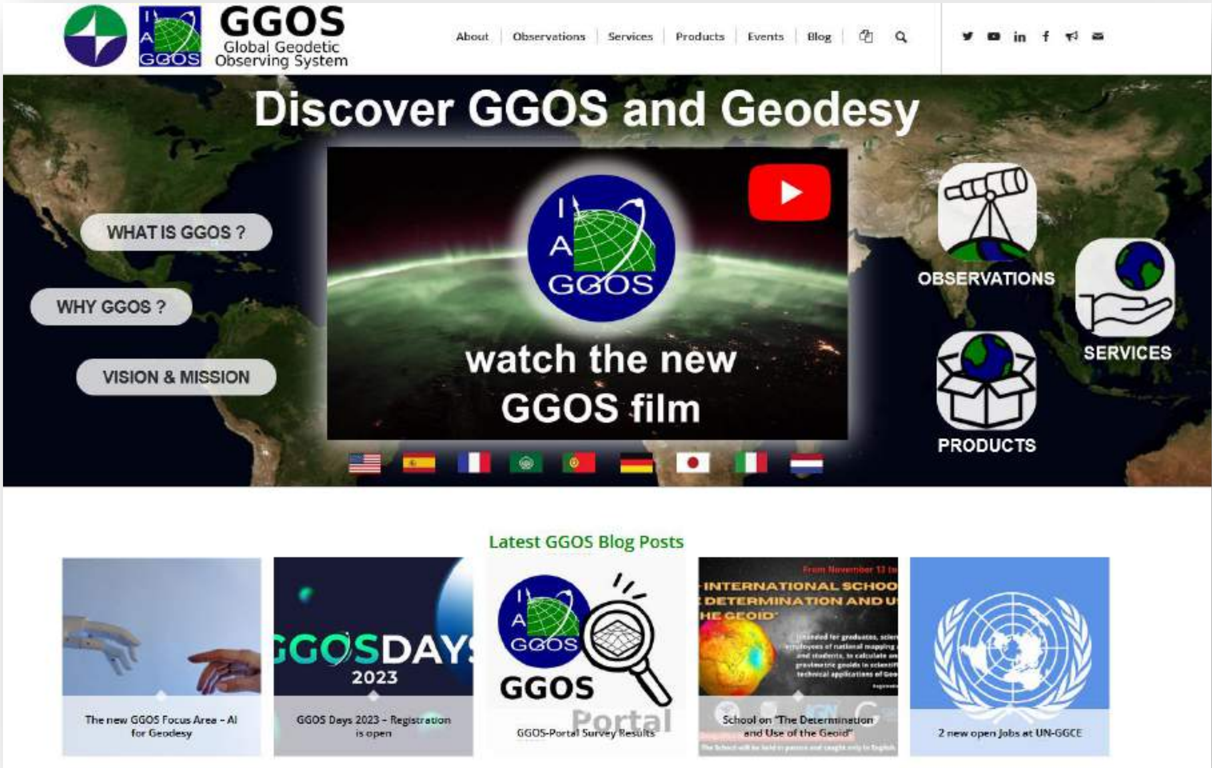
Day-to-day activities and organisational matters

- Communicate with all entities of GGOS by sending and answering on emails
- Organizing GGOS Executive Committee teleconferences
- Creating posters, brochures, logos, images and templates
- Collecting/Distributing reports
- Meeting preparation

New GGOS website – https://ggos.org

One major goal of GGOS is to communicate and advocate the benefits of Geodesy to scientists, user communities, policy makers, funding organizations and society. To reach this goal, it is essential to establish a strong online presence. The GGOS website serves as a source of information about GGOS, geodetic data, products, and services, as well as other non-technical resources for the IAG community.

After the transition of the GGOS CO from ASI (Agenzia Spaziale Italiana, Italy) to BKG (Bundesamt für Kartographie und Geodäsie, Germany) in 2015, it was transitioned again to BEV (Federal Office of Metrology and Surveying, Austria) in 2016. BEV installed a completely



new server system and launched a new designed GGOS website in 2017. In 2019 the GGOS Executive Committee decided to refresh and further develop it again to optimize the usability.

The new GGOS website (see image), which was published in December 2020, now emphasizes more on the "Observing System" than on the "GGOS organization" itself. Therefore, the website was enhanced to provide an extensive information platform to bring the IAG observations, products and services in the focus and to attract users from other disciplines. Visually attractive graphics navigate users to easy understandable introductions about geodetic products or observation techniques. Observation and product descriptions are complemented with a huge selection of web links containing scientific descriptions and data repositories provided by the IAG Services and additional data sources.

From 2019 to 2021, the GGOS Coordinating Office worked intensively together with all GGOS components and other important persons of the geodetic scientific community, to establish and launch this new information platform. Furthermore, the contributions of the IAG Services and other providers of geodetic products are gratefully acknowledged. The new GGOS website contributes to make geodesy more visible and to promote IAG and GGOS at global and multidisciplinary levels.

*New GGOS Cloud – https://*cloud.ggos.org

A first version of the GGOS Cloud service was installed in September 2017 and was based on the OwnCloud software. But due to several organizational and technical issues it was switched off. Together with the new GGOS Website, the GGOS Cloud was new developed and was published again in 2020. It is now based on the worldwide often used, regularly updated and free software Nextcloud. GGOS Cloud is fully integrated in the GGOS Website and is used as a file hosting platform for public files. Additionally, it is used to share files within the GGOS community.

*GGOS Blog & GGOS Newsletter – https://*blog.ggos.org

A blog was set up on the GGOS website, where users can find latest news and events of GGOS as well as short introductions into Geodesy and GGOS. Interested persons can subscribe to the GGOS mailing list to receive this news via the GGOS Newsletter https://ggos.org/newsletter/.

GGOS Videos

In 2021 the idea was born to produce a short film about GGOS and Geodesy in General. It was produced within the GGOS Coordinating Office by the BEV (Federal Office of Metrology and Surveing of Austria) to explain the applications and importance of Geodesy to non-geodesists. The English version was published together with the Spanish, German and Japanese versions in February 2022. Now there are 12 language versions, created with the great help of volunteer geodesists who translated the text into their native language and made the sound recordings. This "Discover GGOS and Geodesy" film is available on YouTube: https://youtu.be/Jwqz097N2IY.

Due to the great success of the GGOS film by more than 11.000 views, the GGOS Coordinating will produce more short videos about geodetic observation techniques and products. All videos are available at the GGOS YouTube Channel www.youtube.com/@iag-ggos.

GGOS social media presence (Twitter, LinkedIn, YouTube, Facebook)

Nowadays it is very important for an organization to be active at Social Media to reach out to more people. The GGOS CO started with GGOS first Social Media presence in 2016 by setting up a Twitter account to be present in the social media and to speed up dissemination of GGOS-related information to the customers. In order to extend the audience, the GGOS CO set up further Social Media channels of GGOS at LinkedIn, YouTube and Facebook in 2021 (see table).

Platform	Set Up	Follower (May 2023)	Link
Twitter	2016	1133	twitter.com/IAG_GGOS
LinkedIn	May 2021	782	linkedin.com/company/iag-ggos
YouTube	June 2021	410	youtube.com/@iag-ggos
Facebook	Dec. 2021	38	facebook.com/iagGGOS

GGOS Portal – A unique access point for geodetic data

The services of the International Association of Geodesy (IAG) provide very important and valuable geodetic data, information, and data products that are increasingly relevant for Earth system research, including monitoring of global change phenomena and a wide range of diverse applications such as satellite navigation, surveying, mapping, engineering, geospatial information systems, and so on.

Currently, it is difficult for many people to obtain an overview of all available geodetic products and data. The GGOS CO aims to fill this gap by developing the GGOS-Portal (ggos.org/portal), which will serve as a unique search and access point (one-stop shop) for geodetic data and products. Data and products will be described by rich metadata and remain physically located at their originating data centers of each contributing IAG service and other data providers. With this future platform, GGOS will contribute to increase the visibility of geodetic data for scientific research and to make other disciplines and the society aware of geodesy and its beneficial products.

To get an overview of the current availability of data products and their metadata, GGOS conducted a survey within the geodetic and geoscience community. This survey also inquired the opinions of geodetic data users on data availability and visibility, as well as desired requirements for a comprehensive and user-friendly GGOS-Portal.

Organized Conferences & Meetings

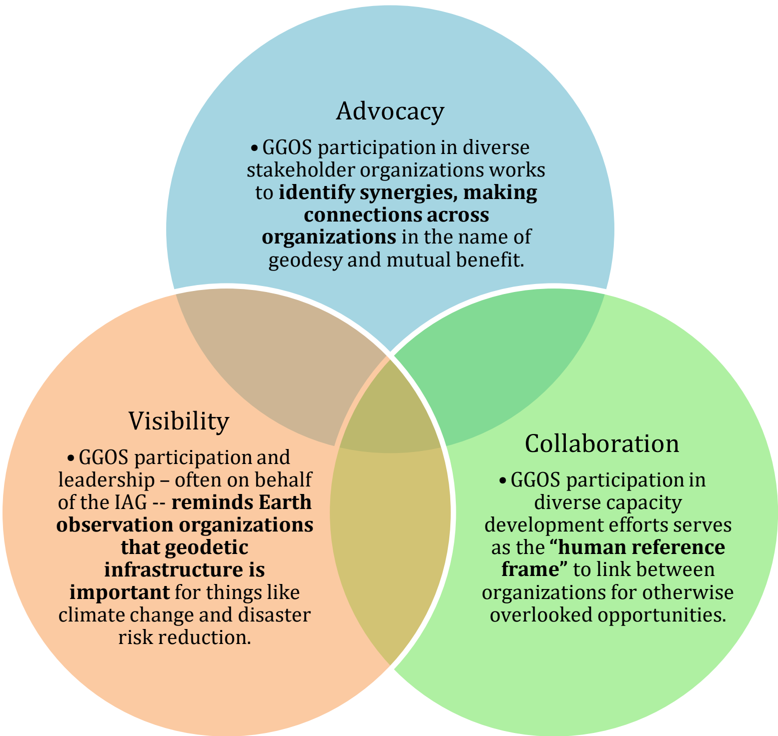
- Unified Analysis Workshop (UAW) – together with IERS
    - 2019 in Paris, France
    - 2022 in Thessaloniki, Greece
- GGOS Coordinating Board (CB) meetings (virtual: 2020, 2021, 2022, hybrid: 2023)
- GGOS Days 2019, Rio de Janeiro, Brasilia
- GGOS Days 2020 & 2021, virtual conference
- GGOS Days 2022, Munich, Germany

Conference attendance

- European Geosciences Union (EGU) (2020, 2021, 2022, 2023)
- American Geophysical Union (AGU) (2019, 2020, 2021, 2022)
- IAG Scientific Assembly 2021, virtual
- IUGG General Assembly 2023, Berlin, Germany

GGOS External Relations

To ensure geodesy is a visible, valued, and sustainable worldwide asset, GGOS external relations efforts within the GGOS Coordinating Office work toward proactive engagement with the broader Earth observations community. This is done by advocating for interoperable, discoverable, and openly available geospatial data, promoting infrastructure development, identifying tangible geodetic contributions to UN SDG and Sendai Framework targets and indicators, as well as working with external partners in capacity building and development initiatives.



Group on Earth Observations (GEO)

GROUP ON EARTH OBSERVATIONS

GGOS represents the IAG in the Group on Earth Observations (GEO), where it has represented the interests of the geodetic community by promoting visibility of geodesy within the broader Earth Observations community. IAG(GGOS) was first nominated as a member organization of the GEO Programme Board during 2018-2020. This representation on the GEO Programme Board was renewed for the 2020-2024 period, IAG(GGOS) continues to have a voice in steering the activities of GEO. In addition to participating on the Programme Board, IAG(GGOS) is also one of three participating organizations to serve on the GEO Executive Committee (2021-present). Richard Gross and Allison Craddock have served as the GGOS-appointed IAG representatives to the GEO Work Programme since 2018.

In the last four years, GGOS has ensured representation of the IAG and geodesy in the following GEO efforts:

- Subgroup on Sustainable Earth Observations, which works in tandem with the GEOSS In-Situ Earth Observation Resources foundational task to assess the current Foundational Tasks focusing on both GEOSS Satellite and In-Situ Earth Observation Resources, and to evaluate strengths and weaknesses of observing systems for GEO's activities over the past decade, and to clarify the challenges in coordination of in-situ observations as well as in integrating in-situ and satellite observations toward coordinated observation systems in the future to implement GEOSS.
- Subgroup on the Sendai Framework, later re-convened as the Working Group on Disaster Risk Reduction. This group supports GEO's strategic engagement priority area on the Sendai Framework for Disaster Risk Reduction, in the realm of championing and supporting the development of policy objectives that add value, drive efficiencies, and promote the uptake of Earth observations in alignment with Sendai and other disaster risk reduction initiatives. This is particularly relevant to supporting the GGOS Geohazards Focus Area and its Global Navigation Satellite System to Enhance Tsunami Early Warning Systems (GTEWS).
- Capacity Development Working Group. IAG(GGOS) served as one of three co-chairs of the GEO Capacity Development Working Group, whose tasks included organizing virtual capacity development seminars, developing the GEO Statement on Open Knowledge. IAG also served in drafting and administering capacity development components of the over-arching "Mapping the Engagement of the 2020-2022 GEO Work Programme in Climate Action, Disaster Risk Reduction, and Capacity Development."
- Climate Change Working Group. IAG(GGOS) is a member of GEO's Climate Change Working Group that was established to develop and implement a strategy to advance the use of Earth observations for climate change adaptation and mitigation. The role of IAG(GGOS) in the Working Group is to ensure that geodetic observations are appropriately included in the strategy.
- Subgroup on Equality, Diversity, and Inclusion. IAG(GGOS) was a co-author of the GEO Statement on Equality, Diversity, and Inclusion (EDI).The GEO five-pillar EDI framework outlines a vision that equality, diversity, and inclusion are considered in every aspect of GEO, answering the mandate of the GEO mission to "*unlock the power of Earth observations by facilitating their accessibility and application to global decision making within and across many different domains."*
- Review Team for Digital Earth Africa proposal. IAG(GGOS) chaired the review team for the Digital Earth Africa proposal, reporting the process, criteria for a GEO Initiative, and the review team's assessment of the implementation plan against said criteria. This review ultimately led to Digital Earth Africa's accession as a GEO Initiative.

Participation at the Programme Board level ensures that IAG and GGOS efforts in alignment with GEO's global priorities (supporting the UN SDGs, Sendai Framework, as well as the Paris Agreement on Climate Change) are well supported and complimentary to other related work – as well as preventing unnecessary redundancy of work. Geodetic observations have a clear role in helping to reduce the risk of disasters, as well as contribute to disaster preparedness with better mitigation and response. Earth observations also play a major role in monitoring progress toward, and achieving, the SDGs.

GGOS also plays a leadership role in a GEO Pilot Initiative within the GEO Work Programme, which is described below.

Group on Earth Observations: Geodesy for the Sendai Framework Pilot Initiative

GGOS has led the establishment and administration of the first geodesy-centric component of the GEO Work Programme, initially as a Community Activity in the 2020-2022 GEO Work Programme, and extended as a Pilot Initiative in the 2022-204 GEO Work Programme. The overall objective of this group is to promote visibility for Geodetic observations and their role in helping to reduce the risk of disasters, as well as contribute to disaster preparedness with better mitigation and response.

Key goals of the Geodesy for the Sendai Framework Pilot Initiative include:

- Ministerial-level political support and funding for GNSS-enhanced tsunami early warning systems in the Circum-Pacific Belt (Pacific Ring of Fire) and Caribbean basin.
- Ministerial-level political support and funding for geodetic capacity building for disaster risk reduction and resilience.

Work led by GGOS on behalf of this group included:

- GGOS-Geohazards Working Group contributed content for the 2019 UN Global Assessment Report on Disaster Risk Reduction (GAR19)
- GGOS-IGS joint contribution to the 2022 UN Global Assessment Report on Disaster Risk Reduction (GAR22)
- Supporting geodetic development and capacity building for disaster risk reduction and resilience; identifying existing resources and stakeholder communities, and making connections
- Identifying geodetic elements of targets and indicators of the Sendai Framework for Disaster Risk Reduction
- Facilitating opportunity for other GEO efforts to interact with the international geodesy community
- Promoting integration of gedesy-enabled applications with UN Sustainable Development Goals and UN-GGIM World Bank Integrated Geospatial Information Framework

Joint collaborations with ITU, WMO, and UNEP supporting Artificial Intelligence for Geodetic Enhancements to Tsunami Monitoring and Detection.

GGOS also worked to identify and support innovations through participation in the Group on Earth Observations as well as joint initiative of the International Telecommunications Union (ITU), World Meteorological Organization (WMO), and UN Environment Programme (UNEP). The GEO Geodesy for the Sendai Framework Community Activity (later Pilot Initiative), represented by GEO participating organizations IAG and IUGG, led a new tsunami early warning collaboration with the recently established ITU Focus Group, organized jointly with WMO and UNEP to enhance the management of natural disasters, such as tsunami, by demonstrating the value of Earth Observations, namely GNSS data and infrastructure, in applications utilizing artificial intelligence (AI) and machine learning (ML).

The Topic Group "AI for Geodetic Enhancements to Tsunami Monitoring and Detection" has been set up this year under ITU Focus Group on Artificial Intelligence for Natural Disaster Management (FG-AI4NDM). The topic group has worked on several deliverables, such as technical use-case reports with the relevant best practices in two uses of GNSS data: seismic/displacement observations, as well as ionospheric observations. Use cases will include descriptions of existing cutting-edge systems, such as: 1) Japanese real-time tsunami inundation forecast service that provides warning/forecast and estimated damage report to the Prime Minister's Office, and 2) NASA Jet Propulsion Laboratory's GNSS-based Upper Atmospheric Real-time Disaster Information and Alert Network (GUARDIAN system). The group will also contribute to a future ITU Recommendation on the topic of AI for disaster management.

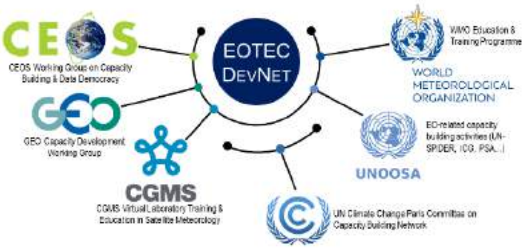
This new cooperation among the multiple international organizations aims to help lay the groundwork for the development and implementation of AI and ML applications expanding the use of geodetic Earth observations in places such as Small Island Developing States, which suffer from increasing tsunami threats in addition to other climate change impacts such as sea level rise.

Committee on Earth Observation Satellites (CEOS)

The Committee on Earth Observation Satellites

GGOS is an Associate Member of CEOS and regularly participates in its Plenary meetings, giving presentations and discussing the fundamental importance of the global geodetic reference frame to Earth observations. GGOS has participated in CEOS Plenaries, discussing what GGOS might need from participation in CEOS as an Agency/Partner Update. This is an opportunity for GGOS to speak about its plans and strategies in relation to CEOS, as well as the benefits and expectations of CEOS from the GGOS perspective.

GGOS also participates in the CEOS Working Group on Disasters, which supports the efforts of Disaster Risk Management authorities in protecting lives and safeguarding property by means of satellite-based Earth observations and science-based analyses. GGOS participation in this working group supports geodetic contributions to the group's objective to foster increased use of Earth observations in support of Disaster Risk Management and raise the awareness of politicians, decision-makers, and major stakeholders of the benefits of using geodetic Earth observations in all phases of Disaster Risk Management.



GGOS also participated in the initial establishment of the CEOS-led "EOTEC DevNet," a network of networks created to improve coordination and enhancement of Earth Observation asset and training providers in support of key global sustainable development outcomes. This is currently a deliverable in the CEOS 2021-2023 Work Plan. The goals of this effort include:

- **Improving coordination and cooperation among capacity building providers and users in order to meet existing needs and fill gaps**
- Fostering information sharing and exchange on capacity building resources
- Promoting effective assessment of capacity development needs at regional and national levels

GGOS also participated in the (now disbanded) CEOS Ad Hoc Team on the Sustainable Development Goals (AHT SDG), which worked toward highlighting the potential role for Earth observations in supporting the global indicator framework of the United Nations Sustainable Development Goals.

UN GGIM Subcommittee on Geodesy

GGOS supports and, as needed, represents the IAG at the United Nations Committee of Experts on Global Geospatial Information Management (UN GGIM), as well as the meetings of the Sub-Committee on Geodesy (SCoG), to provide stability and long-term planning for the Global Geodetic Reference Frame (GGRF). GGOS supports IAG participation in major SCoG activities, including the following efforts to:

- provide an intergovernmental forum, with equitable international representation, for communication and cooperation on issues relating to **the maintenance and enhancement of a Global Geodetic Reference Frame (GGRF);**
- develop a roadmap for a **collaborative global geodetic observation network and the associated infrastructure**, with sustainable funding and investment, as well as strategic partnerships between mapping, space and other interested agencies;
- encourage **open sharing of geodetic data and information** that contribute to regional and global reference frames;
- advocate for guidelines and standards to **advance the interchangeability and interoperability** of geodetic systems and data; and
- **address various technical, institutional and policy issues** related to the implementation of a GGRF.

Numerous GGOS Consortium members were active in the UN GGIM SCoG on behalf of the IAG in the last four years, including Harald Schuh, Mike Pearlman, Detlef Angermann, Zuheir Altamimi, Laura Sanchez, and Martin Sehnal in key support and participation roles.

GGOS Consortium members also participate on behalf of their member state (country) and in consultation with GGOS External Relations, including: Richard Gross(USA), SCoG Working Group on Governance, and Allison Craddock (USA), SCoG Working Group on Communications and Outreach, Working Group on Education, Training and Capacity Building

GGOS has also served as a strong supporter of the recently-established United Nations Global Geodetic Centre of Excellence (UN-GGCE) with its goal to assist Member States and geodetic organizations to coordinate and collaborate to sustain, enhance, access and utilize an accurate, accessible and sustainable GGRF to support science, society and global development.

Future Connections

As GGOS connections with the SDGs and Sendai Framework mature, more opportunities to support these initiatives will become available. GGOS External Relations will pursue the most relevant and impactful avenues to ensure that GGOS support of IAG enables the greatest use of geodetic data in support of these United Nations initiatives and beyond.

GGOS Working Group Digital Object Identifiers (DOIs) for Geodetic Data Sets

WG Kickoff: December 2019

Members

Chair: Kirsten Elger (GFZ, Germany), Detlef Angermann (TU Munich, Germany), Yehuda Bock (UCDC, US), Sylvain Bonvalot (GET, France), Markus Bradke (GFZ, Germany), Elisabeth Bradshaw (NOC, UK), Carine Bruyninx (ROB, Belgium), Daniela Carrion (Politecnico Milan, Italy), Glenda Coetzer (SARAO, South Africa), Pierre Fridez (CODE/ AIUB, Switzerland), Elmas Sinem Ince (GFZ, Germany), Philippe Lamothe (Geodetic Survey Canada), Vicente Navarro (ESA), Carey Noll (CDDIS/NASA, US until 2021), Mirko Reguzzoni (Politecnico Milan, Italy), Jim Riley (UNAVCO, US), Dan Roman (NGS, US), Laurent Soudarin (CLS, France), Daniela Thaller (BKG, Germany), Yusuke Yokota (GGOS Japan)

Associated Members

Godfred Amponsah (NGS, US), Sandra Blevins (CDDIS/NASA, US), Roelf Botha (SARAO, South Africa), Francine Coloma (NOAA CORS, US), Allison Craddock (JPL/NASA, US), Michael Craymer (Canadian Geodetic Networks, Canada), Theresa Damiani (NOAA CORS, US), Patrick Michael (CDDIS/NASA, US), Basara Miyahara (GGOS, Japan), Mike Pearlman (Harvard Smithsonian – Center for Astrophysics, US), Nacho Romero (ESA), Christian Schwatke (TU Munich, Germany), Martin Sehnal (GGOS, BEV, Austria), Lori Tyahla (CDDIS/NASA, US)

Motivation and purpose

Data publications with digital object identifiers (DOI) are best practice for FAIR sharing data. Originally developed with the purpose of providing permanent access to (static) datasets described in scholarly literature, DOI today are more and more assigned to dynamic data too. These DOIs are providing a citable and traceable reference of various types of sources (data, software, samples, equipment) and means of rewarding the originators and institutions. As a result of international groups, like the Coalition on Publishing Data in the Earth, Space and Environmental Sciences (COPDESS[1]) and the Enabling FAIR Data project[2], data with assigned DOIs are fully citable in scholarly literature and many journals require the data underlying a publication to be publicly available. Initial metrics for data citation allows data providers to demonstrate the value of the data collected by institutes and individual scientists.
This is especially relevant for geodesy, because geodesy researchers are often much more involved in operational aspects and data provision than researchers in other fields might be. Therefore, compared to other scientific disciplines, geodesy researchers appear to be producing less ‘countable scientific’ output. Consequently, geodesy data and equipment require a structured and well-documented mechanism which will enable citability, scientific recognition and reward that can be provided by assigning DOI to data and data products.

[1] https://copdess.org
[2] https://copdess.org/enabling-fair-data-project/

While this is easy for static data, like for global of regional gravitational models or GNSS campaign data, most geodetic data are large (mainly due to the large number of files with high temporal resolution), dynamic (real time data acquisition and provision), and highly granular. Geodetic services of the International Association for Geodesy (IAG) are international key player for geodetic data provision and distribution and their operating institutions and funding agencies increasingly require the provision of tangible data use and access statistics. Credit through citation was a major reason for the Global Geodetic Observing System (GGOS) to establish a 'Working Group on Digital Object Identifiers (DOIs) for Geodetic Data Sets'[3] (GGOS DOI WG) in October 2019. This Working Group is designated to establish best practices and advocate for the consistent implementation of DOIs across all IAG Services and in the greater geodetic community.

Objectives

The main objectives and activities of this working group are

(1) To identify what the community needs from consistent usage of DOIs for data to being able to discover, permanently cite and access data, and acknowledge the data providers;
(2) develop recommendations for DOI minting strategies for different geodetic data types and granularity across IAG Services (static, dynamic, observational data, data products, combination products, networks);
(3) to develop recommendations for a consistent method for data citation across all IAG Services, to support data providers, and to provide quantitative support detailing the use of geodetic datasets and other resources;
(4) to develop recommendations for connecting metadata standards for data discovery (e.g. DataCite, ISO19115) with community metadata standards (e.g. GeodesyML, Sitelogs).

Activities and Actions

- Physical kickoff meeting during AGU2019, 3-5 video conferences per year.
- Regular presentations of the group's activities during national and international conferences and workshops (AGU, EGU, GGOS Days, IAG GA, IVS GM, UAW, etc., see also the publications section below)
- Creation of a Zenodo Community where presentations and documents are collected and published with DOI[4]
- Collection of data products and already existing and planned DOI activities for IAG services and geodetic data centers (living document).
- Outside the box: exploration of DOI minting and citation practices from other communities in the Earth sciences for potential adoption for geodetic data sets: e.g. network DOIs, persistent identifier for instruments, DOI citation recommendations for data compilations and hierarchical data products.
- Introduction to different persistent identifiers (PID) and agreement on their importance for making data findable, accessible, interoperable and reusable (FAIR, Wilkinson et al., 2016). PIDs allow, e.g., to uniquely identify published data, scholarly literature and code (via DOIs), persons (via ORCID), institutions and funding agencies (via ROR – the registry of research organizations) via machine-actionable links that should be included in the metadata. PIDs within machine-actionable metadata (e.g. DataCite, GeodesyML)

[3] https://ggos.org/about/org/co/dois-geodetic-data-sets/
[4] https://zenodo.org/communities/ggos-doi-wg/

are key elements for connecting data with articles, software and other research outcome as well as to institutions, funding agencies, researchers, and instruments.

- Discussions on the objects, DOIs are assigned to, i.e. data products vs. data files or continuous time series from individual stations and development of recommendations for metadata properties.

Outcomes

- Support for the development of a **DOI Service for the International Service for the International Service for the Geoid (IGS)** in collaboration with GFZ Data Services (start July 2020). As part of this collaboration, regional geoid models are successively assigned with DOI and collected in the dedicated 'IGS datacenter' of the catalogue of GFZ Data Services[5] with direct links to ISG's Geoid Repository[6] Recently also official models (e.g. Slovenia, Costa Rica, Austria) provided by federal agencies, have been assigned with DOI. This is a clear sign that DOI are increasingly attractive beyond the academics.
- **DOIs for data products or data files?** One of the first recommendation of the GGOS DOI WG is that DOIs for product 'types' (e.g. Precise Science Orbits, IAG final products) or observational networks (e.g., GNSS networks) are preferred to DOIs for individual data files. These DOIs for growing time series mainly serve for citation purposes and not for identifying individual data streams (similar to DOIs for seismic networks, e.g. Evans et al. 2015).
- **DOIs for rapid or ultra-rapid products?** These are existing for different geodetic techniques and are outdated very soon (precisely within days or few weeks when the next better product is available). However, they are occasionally used in research articles (and could be cited if assigned with a DOI). Due to the requirement that DOI-referenced data have to be available persistently, the group agrees to support DOIs for rapid and ultra-rapid products only if the data are archived for the long term by the datacenter. A datacenter that is not planning to archive rapid or ultra-rapid products should not assign DOIs to them (e.g. AIUB and GFZ have assigned DOIs to their rapid and ultra-rapid IGS products, while ESA is not using DOIs for these products, because of their 'rolling archive')
- Development of a **concept for assigning DOI to hierarchical products** and its implementation for the use case ICGEM/ COST-G (Combination Service for Time-variable Gravity Fields): monthly GRACE time series[7]: Individual monthly field solutions are produced by a number of International Analysis Centers and are later combined to the COST-G combination product which represents a „best fit model'. The connection between the original solutions and the combination product is done via the "related identifier" property of the DataCite Schema: the DOI metadata of the original solutions from the Analysis Center includes a reference (using the "related identifier" property) to the combination Product using the DataCite relation type „Is Part Of' (i.e., they have contributed to the COST-G combination product). The metadata of the combination product includes the citation of all original products from the Analysis

[5] https://dataservices.gfz-potsdam.de/portal/?fq=datacentre_facet:%22DOIDB.ISG%20-%20ISG%20International%20Service%20for%20the%20Geoid%22
[6] https://www.isgeoid.polimi.it/Geoid/geoid_rep.html
[7] Monthly GRACE series: https://doi.org/10.5880/ICGEM.COST-G.001, Monthly GRACE-FO series: https://doi.org/10.5880/ICGEM.COST-G.002)

Centers using the relation type „Is Derived From'. The adoption of this concept for ITRF2020 has been agreed by the IERS CB (May 2021) and in currently being implemented.

- **DOIs for GNSS data**: One task of the current project FAIR GNSS[8], funded by the Belgian Science Policy Office (BELSPO), is to apply the FAIR Principles (Wilkinson et al, 2016) to GNSS Data and to develop a DOI service for the European and Belgian GNSS data collections managed by the Royal Observatory Belgium. This was the opportunity begin with the development of metadata recommendations for the use case GNSS data. Moreover, GNSS data represents a good use case for geodetic data in general: DOIs for GNSS campaign data are examples for static products; IAG orbit and clock products are good examples for DOIs for dynamic data with new DOI versions only required when there are changes in the data processing routine; DOIs for GNSS networks are also already used (e.g. by UNAVCO, AIUB, GFZ, INGV), however: GNSS stations are not always organized as networks and some stations may be part of several networks. We have therefore accepted the necessity to assign DOI for the (ongoing) time series measured with one GNSS station. Tangible results of our discussions resulted in the:
- '**Metadata Recommendations for geodetic data: GNSS'**: a guide to recommended metadata properties and sub-properties relevant for GNSS data for DataCite and geodesyML schemas with examples on how to provide the information (e.g. separating first and last names, adding ORCID and ROR identifier whenever possible). This document is currently in discussion with the GGOS DOI WG and a first version expected to be released after IUGG2023. It includes a general introduction to DOIs and their application for geodetic data, followed by recommendations for the provision of specific metadata properties DataCite, GeodesyML metadata with examples. The document was developed for the GNSS use case, but already with a more general focus allowing an easily extension to apply for other geodetic datasets. Guiding principles for the recommendations were (1) maximum automatization: for metadata properties from GeodesyML/ Sitelogs mapped into DataCite metadata, (2) following the FAIR Principles and integration of PIDs in the metadata, (3) compliance with the General Data Protection Regulation (GDPR).
- **DOI assignment to GGOS Documents:** documents, like the GGOS Strategic Plan, GGOS implementation plan, IAG Travaux will be published with DOI from 2023 on (collaboration with GFZ).

Ongoing discussions and future plans

Ongoing discussions focus on the revision of the metadata recommendations and its extension to metadata s for other geodetic techniques. Our activities will further include recommendations of controlled vocabularies describing geodetic datasets (to be used in metadata for stations and data, ideally the same vocabularies to facilitate cross-references between stations, sensory, data and networks). These vocabularies should be registered via a vocabulary registration service (e.g. Research Vocabularies Australia[9]) and provided in machine-actionable format (RDF) following the SKOS[10] guidelines for the semantic web. Moreover, we will explore the potential implementation of the concept of the "Persistent Identification of Instruments Working

[8] https://fair-gnss.oma.be/
[9] https://ardc.edu.au/services/research-vocabularies-australia/
[10] https://www.w3.org/2004/02/skos/

Group[11]" of the Research Data Alliance (RDA[12]) for using PIDs for instruments and explore the required harmonization of DOI-related metadata from different data centers for similar products.

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GGOS Affiliate: GGOS Japan

Chair: Toshimichi Otsubo (Japan)
Secretary: Basara Miyahara (Japan)

This multi-institution entity was initially established as GGOS Working Group of Japan in 2013, later approved as GGOS Affiliate in 2017 and renamed as GGOS Japan in 2019. The purpose was to strengthen collaboration among Japan's geodetic stations and colleagues and to foster Japanese space geodetic activities internationally. It is reaching the 10-year anniversary in 2023.

In recent years, GGOS Japan has constantly hosted its own annual meetings for broad range of space geodetic research and activities where additional English-spoken sessions were recently arranged with the DACH (2022) and Iberoatlantic (2023) colleagues. It also organises smaller-size meetings on specific topics such as data DOI minting (2019) and co-location local tie (2020). It was remarkable that Japanese institutes were nicely collaborated to conduct local tie campaigns for the ITRF2020 project. A new aspect of GGOS Japan is to co-organise existing domestic meetings in the field of VLBI and SLR in 2020 where GGOS Japan core members are often given an opportunity of invited talks. GGOS Japan has updated the terms of reference in 2021 so that co-hosting or supporting related meetings can be accommodated as one of its roles. It should be noted that in accordance with the renewal of GGOS website the webpages of GGOS Japan were largely updated, utilizing the GGOS Cloud function. GGOS Japan has adopted its logo in 2022, often shown in the presentation slides, the leaflets and the stickers.

GGOS Japan is a loose organization of public sectors and university members. It does not have membership qualification, but its core members are selected. As of May 2023, they are:

Chair: Toshimichi Otsubo (Hitotsubashi University)
Secretary: Basara Miyahara (Geospatial Information Authority of Japan)
Outreach: Shinobu Kurihara (Geospatial Information Authority of Japan)
Data DOI WG Lead: Yusuke Yokota (University of Tokyo)
Technique Representatives:
- VLBI: Kensuke Kokado (Geospatial Information Authority of Japan)
- SLR: Yuto Nakamura (Japan Coast Guard)
- GNSS: Hiroshi Takiguchi (Japan Aerospace Exploration Agency)
- DORIS: Yuichi Aoyama (National Institute of Polar Research)
- Gravity: Koji Matsuo (Geospatial Information Authority of Japan)

These members have actively involved in session planning of annual JpGU meetings and annual Geodetic Society of Japan meetings, where "GGOS" is always seen as (a part of) a session name. Likewise, we should make every effort to utilize the "GGOS" keyword for budget hunting, aiming at future GGOS Core sites in Japan or Antarctica. Encouraging geodetic technology development is also in our scope - in addition to high precision and high operability, we are aware that we should significantly reduce costs per geodetic facility envisaging a denser global geodetic network in the future.

GGOS Affiliate: GGOS D-A-CH

Chair: Hansjörg Kutterer (Germany)

GGOS D-A-CH is the GGOS affiliate of the so-called D-A-CH region representing those countries in Central Europe with significant German-speaking populations: Germany (D), Austria (A), Switzerland (CH). GGOS D-A-CH is based on a joint initiative of the national geodetic commissions DGK, ÖGK and SGK in 2020. It was approved by GGOS CB on May 19, 2021, as the second regional GGOS affiliate after GGOS Japan.

GGOS D-A-CH was initiated by the members and guests of the Geodesy department of DGK and the respective members of ÖGK and SGK. There is a long-term and outstanding tradition of cooperation within these commissions both contributing to and benefitting from activities in mathematical, physical and space geodesy. GGOS D-A-CH was established as basis and forum for GGOS-related activities in the D-A-CH region and in particular as a stimulator and incubator for GGOS-related coordinated research. The publication "Geodesy 2023" by J. Müller and R. Pail (https://geodaesie.info/zfv/zfv-archiv/zfv-147-jahrgang/zfv-2022-4/geodesy-2030), with contributions from a multitude of scientists in the D-A-CH region, serves as scientific guideline. It addresses the grand challenges of Earth sciences and the respective contributions of Geodesy reflecting the scientific innovations and technological developments of the present decade and beyond.

GGOS D-A-CH comprises university members and members from the public sector. Qualification for membership is based on an expression of interest. As of June 2023, there are the following participations:

Coordination group: Johannes Böhm (Austria), Johannes Bouman (Germany), Susanne Glaser (Germany), Adrian Jäggi (Switzerland), Roland Pail (Germany), Markus Rothacher (Switzerland), Harald Schuh (Germany)

Group of member institutions:

- Universities: Technical University Berlin, University Bern, University Bonn, Technical University Dresden, Leibniz University Hannover, Karlsruhe Institute of Technology, Technical University Munich, University Stuttgart, Technical University Vienna, ETH Zurich
- Research institutions and national agencies: Federal Office of Metrology and Surveying (BEV, Austria), Federal Agency for Cartography and Geodesy (BKG, Germany), GFZ German Research Centre for Geosciences (GFZ, Germany)

Members of GGOS D-A-CH have actively been involved in the preparation of scientific meetings and conferences. In May 2022, a round-table discussion was organized under the umbrella of the German Research Foundation (DFG) in order to prepare a joint research proposal. Regular presentation and reporting is organized within the GGOS CB meetings, the annual GGOS Days and the annual gatherings of the national geodetic commission. In addition, regular meetings with GGOS Japan took place for mutual exchange. Finally, the IAG Symposium G06 "Monitoring and Understanding the Dynamic Earth with Geodetic Observations" within the 28th General Assembly of the IUGG in Berlin 2023 was co-organized and co-convened.

GGOS Science Panel

Chair: Kosuke Heki (Japan) Comm. 2

Members:
Original members in this term 2019-2023
- *M. Rothacher (Switzerland) Comm.1*
- *G. Blewitt (USA) Comm. 1*
- *T. Gruber (Germany) Comm. 2*
- *J. Chen (USA) Comm. 3*
- *J. Ferrandiz (Spain) Comm. 3*
- *J. Wickert (Germany) Comm. 4*
- *P. Wielgosz (Poland) Comm. 4*
- *Y. Tanaka (Japan) ICCT*
- *M. Crespi (Italy) ICCT*
- *M. Sideris (Canada) FA (UHS)*
- *P. Lognonne (France) FA (Geohazards)*
- *D. Chambers (USA) FA(Sea level)**
- *E. Forootan (UK/Germany) FA (Geod. Space Weather)*

Members representing new organizations added in 2021
- *J. Muller (Germany) QuGe*
- *M. Van Camp (Belgium) QuGe*
- *P. Sakic (Germany) ICCM*
- *K. Tadokoro (Japan) ICCM*
- *A. Klos (Poland) ICCC*
- *C. Blackwood (USA) ICCC*

*FA dissolved

Two new members from each of the three newly organized organizations within IAG have been added in 2021. This made the number of members of the GGOS Science Panel increase from 14 to 20.

Purpose and Scope

The GGOS Science Panel is a multi-disciplinary group of experts representing the geodetic and relevant geophysical communities that provides scientific advice to GGOS in order to help focus and prioritize its scientific goals. The Chair of the Science Panel is a member of the Coordinating Board and a permanent guest at meetings of the Executive Committee. This close working relationship between the Science Panel and the governance entities of GGOS ensures that the scientific expertise and advice required by GGOS is readily available.

Activities and Actions

The Science Panel provides scientific support to GGOS. During the 2019-2023 period, this support included participation in Consortium, Coordinating Board, and Executive Committee meetings and conference calls.

The Science Panel has been actively promoting the goals of GGOS by helping to organize GGOS sessions at major scientific conferences. During the 2019-2023 period, GGOS sessions have been organized at:

- 2019 American Geophysical Union Fall Meeting in San Francisco
- 2020 American Geophysical Union Fall Meeting (virtual conference)
- 2020 European Geosciences Union General Assembly (virtual conference)
- 2021 European Geosciences Union General Assembly (virtual conference)
- 2021 American Geophysical Union Fall Meeting (virtual conference)
- 2022 European Geosciences Union General Assembly (virtual conference)
- 2022 American Geophysical Union Fall Meeting (hybrid conference)
- 2023 European Geosciences Union General Assembly (hybrid conference)

Owing to the COVID19 pandemic, most international conferences from 2020 until 2022 spring were held as virtual (on-line) meetings. The 2022 December American Geophysical Union (AGU) and 2023 April European Geoscience Union (EGU) meetings were held as hybrid meetings. As a future session, the Science Panel proposed a GGOS session in the 2023 December AGU Fall Meeting (hybrid meeting in San Francisco). AGU and EGU intend to keep the meetings hybrid in future (2024-), but the on-site aspect will become major.

Starting in 2021, the Science Panel cooperated in the effort to renew the GGOS website, being led by the GGOS Coordinating Office and the GGOS Bureau of Products and Standards, specifically in reviewing the GGOS product page descriptions. The pages are now complete and are visited frequently by researchers.

Unified Analysis Workshops (UAW) are co-organized by GGOS and International Earth Rotation and Reference Systems Service (IERS). The 2022 Workshop was the 6th in a series of workshops that are held every two years for the purpose of discussing issues that are common to all the space-geodetic measurement techniques. Attendance at the Workshops are by invitation only with each IAG Service nominating 5-6 experts to attend and participate in the discussion. The 2022 Workshop was held as a hybrid meeting in Thessaloniki, Greece, 21-23 October. There, the discussion focused on the data analysis especially on ITRF2020.

Objectives and Planned Efforts for 2023-2027 and Beyond

During the next four years the Science Panel will continue to participate in Consortium, Coordinating Board, and Executive Committee meetings and conference calls. In addition, the Science Panel will continue to help organize GGOS sessions at conferences and symposia including:

- American Geophysical Union (AGU), Fall Meetings
- Asia Oceania Geosciences Society (AOGS), Annual Meetings (optional)
- European Geosciences Union (EGU), General Assemblies
- International Association of Geodesy, General and Scientific Assemblies*
  *GGOS sessions in IUGG/IAG are mainly organized by GGOS-EC members rather than the Science Panel

The Strategic Plan Workshop was held in Munich, Germany during 16-17 November 2022 following the GGOS Days. There, future roles expected for the Science Panel were briefly discussed.

With the GGOS Bureau of Products and Standards, the Science Panel will help conduct a Gap Analysis to identify the gap between the data and products provided by the IAG and the needs of the user community. As part of this analysis, a list of Essential Geodetic Variables (EGVs) will be compiled along with observational requirements on those variables. This list of EGVs and their observational requirements can then be used to determine requirements on derived products like the terrestrial reference frame. Activities related to EGV will continue in the committee on EGV established in 2019, which includes the whole Science Panel members.

GGOS Bureau of Networks and Observations

Prepared by Michael Pearlman, Erricos C. Pavlis, Frank Lemoine, Daniela Thaller, Benjamin Männel, Roland Pail, C.K. Shum, Nick Brown, Sandra Blevins, Ryan Hippenstiel

Membership

Standing Committees affiliated with this Bureau:

- **GGOS Standing Committee on Satellite Missions**
- **GGOS Standing Committee on Data and Information Systems**
- **GGOS Standing Committee on Performance Simulations and Architectural Trade-Offs (PLATO)**
- **IERS Working Group on Survey and Co-location**

Associated Members and Representatives:

- Director (Mike Pearlman/CfA USA)
- Secretary (Claudia Carabajal/SSAI NASA USA)
- Analysis Specialist (Erricos Pavlis/UMBC USA)
- IERS Representative (Ryan Hippenstiel/ NOAA USA)
- Representatives from each of the member Services:
  - IGS (Allison Craddock/JPL CalTech USA, Markus Bradke/ GFZ Germany
  - ILRS (Frank Lemoine /NASA USA, Clement Courde/OCA, France)
  - IDS (Jérôme Saunier/IGN France, Guilhem Moreaux, CLS France)
  - IVS (Hayo Hase/BKG Germany, Dirk Behrend/NASA USA)
  - IGFS (Riccardo Barzaghi/PM Italy, George Vergos/UT Greece)
  - PSMSL (Elizabeth Bradshaw/BODC UK, Lesley Rickards/ BODC UK)
- Representatives from each of the member Standing Committees:
  - PLATO (Daniela Thaller/BKG Germany, Benjamin Maennel/GFZ Germany)
  - Data and Information Systems (Nick Brown/GA Australia, Sandra Blevins/NASA/USA)
  - Satellite Missions (Roland Pail/TUM Germany, C.K. Shum/OSU USA)
  - IERS WG on Survey Ties and Co-location (Ryan Hippenstiel/ NOAA USA)

Purpose and Scope

- Advocate for new and increased network participation, encouraging formation of new partnerships to develop new sites and co-location sites
- Hold annual meetings of the Services and Standing Committees/Working Groups to share and discuss status plans, progress;
- Give talks and posters at public meetings to help familiarize the community with GGOS activities;
- Encourage integration of ground observation networks within the GGOS affiliated Network;
- Work with the UN GGIM and its affiliates to develop a plan for the implementation of the IAG geodetic network to satisfy the IAG requirement for the ITRF

Activities

- Participated and gave talks/posters on the BN&O and the ILRS at the AGU, EGU, IAG, JpGU-AGU, etc.

- The BN&O has been advocating for enhanced network infrastructure for Latin America, and participated and gave talks on the GGOS Bureau of Networks and Observations at;
    - IUGG meeting "Implementation of the Global Reference Frame (GGRF) in Latin America" in in Buenos Aires, September 16 - 20, 2019;
    - SIRGAS meeting in Rio de Janeiro, November 12 – 14, 2019;
    - Unified Analysis Workshop in Paris, October 2 – 4, 2019;
- Met with representative from existing and planned stations in Latin America to discuss strategies, station details, equipment, etc.
- Supported new and vulnerable stations and analysis centers with letters of support and documentation;
- New SLR and VGOS stations have recently become active and others are scheduled to become active over the next few years; we have been disappointed by the schedule delays in many stations so we are now taking a closer look at deployment schedules to try to figure out what is realistic and what kind performance we can reasonably expect; from that we can estimate the expected quality of our data products including the Reference Frame.
- Worked with the IGFS define the gravity field measurement configuration at GGOS network core and co-location sites; encourage the cooperation of the IGS and DORIS with PSMSL to enhance the geodetic link of the tide gauges to the reference frame;
- A Memorandum of Cooperation had been established with ROSCOSMOS and the ILRS to enhance cooperation and data diagnosis issues: this may provide a vehicle for broader cooperation; the Russians have been regular participants in ILRS activities, we believe that are desirous of formally joining the GGOS network; Unfortunately the current situation with Ukraine has put a significant hold on much of this activity;
- The GGOS "Site Requirements for GGOS Core Sites" document (with the IAG Services) should be updated to include the requirements for the gravity field with the guidance of the IGFS;

Outcomes and Future Plans

- Continue the tasks above;
- Bureau Call for Participation in the "Global Geodetic Core Network: Foundation for Monitoring the Earth System"; work with new potential groups interested in participating; discussions are underway with the Russian SLR network; they participate in ILRS and VLBI activities, but have yet to join the GGOS network; close with the Russians;
- Project network status 5 and 10 years ahead to anticipate data product quality especially the ITRF;
- Work with the IAG and the UN GGIM to develop a plan for the IAG Network to satisfy the ITRF requirements;
- The Standing Committees/Working Groups will each continue their tasks (see below)

Websites:

https://ggos.org/about/org/bureau/bno/

Presentations and Posters

Pearlman, et al., *Update on the Activities of the GGOS Bureau of Networks and Observation,* AGU Fall virtual meeting, December 14, 2018.
..
M. Pearlman, D. Behrend, A. Craddock, C. Noll, E. Pavlis, J. Saunier, A. Matthews, R. Barzaghi D. Thaller, B. Maennel, S. Bergstrand, J. Müller, "*GGOS: Current Activities and Plans of the Bureau of Net*works and Observations", Abstract No. EGU2019-6181, presented at the European Geosciences Union General Assembly, Vienna, Austria, April 07-12, 2019.

Pearlman et al., *Status and Plans for the GGOS Bureau of Networks and Observations*, IUGG Meeting, Montreal Convention Center, July 15, 2019.

Pearlman, M., *GGOS Bureau of Networks and Observations*, presented at the IUGG, Implementation of the Global Reference Frame (GGRF) in Latin America, Buenos Aires, Argentina, September 16 – 20, 2019.

Pearlman, M., C. Noll, and E. Pavlis, *GGOS Bureau of networks and Observations*, GGOS Days 2019, October 5 – 7, 2019.

Pearlman, M. and Noll, C., *GGOS Bureau of Networks and Observations*, GGOS Days 2019 Meeting, Rio de Janiero, Brazil, November 13 – 14, 2019.

Pearlman, M., et al., *Current Activities and Plans of the Bureau of Networks and Observations*" *(poster)*, AGU Fall virtual meeting, December 1 – 17, 2020.

Pearlman, M., et al., "*GGOS Bureau of Networks and Observations: Network Status and Related Activities"* (poster), IAG Symposium 2021 Beijing, China, June 28 – July 2, 2021.

Pearlman, M., et al., "*An Update on the GGOS Bureau of Networks and Observations*", EGU General Assembly, Vienna, Austria, May 23 – 27, 2022.

Presentations on the BN&O at each annual GGOS Coordinating Board meeting and GGOS Days Meeting.

GGOS Standing Committee on Performance Simulations & Architectural Trade-Offs (PLATO)

(Joint WG with IAG Commission 1)

Chair: Daniela Thaller (Germany)
Vice-Chair: Benjamin Männel (Germany)

Contributing Institutions (as of May 2023):
- AIUB, Switzerland: R. Dach, F. Andritsch (left AIUB)
- BKG, Germany: D. Thaller, H. Hellmers
- DGFI-TU Munich, Germany: M. Bloßfeld, A. Kehm
- ETH Zürich, Switzerland: M. Rothacher, B. Soja, M. Schartner, I. Herrera Pinzón (now at AIUB)
- GFZ/TU Berlin, Germany: B. Männel, S. Glaser
- IfE University Hannover, Germany: J. Müller, L. Biskupek
- IGN, France: D. Coulot, A. Pollet
- JPL, USA: R. Gross
- NASA GSFC/JCET, USA: E. Pavlis

- NMA, Norway: E. Mysen, G. Hjelle
- TU Vienna, Austria: J. Böhm, H. Wolf
- University Wrozlaw, Poland: K. Sosnica, J. Najder

Purpose and Scope

- Develop optimal methods of deploying next generation stations, and estimate the dependence of reference frame products on ground station architectures
- Estimate improvement in the reference frame products as co-located and core stations are added to the network
- Estimate the dependence of the reference frame products on the quality and number of the site ties, the space ties, and potential atmospheric ties
- Estimate the improvement in the reference frame products as other satellites are added, e.g., cannonball satellites, LEO, GNSS constellations
- Estimate the improvement in the reference frame products as co-locations in space are added, e.g., use co-locations on GNSS and LEO satellites, add special co-location satellites (GRASP, E-GRASP/Eratosthenes, NanoX, GENESIS, etc.)
- Estimate the improvement in the reference frame products as new observation types and concepts are added, e.g., inter-satellite links

Achievements during the reporting time span:

- Several projects related to simulation studies became funded and even extended to a second phase at various institutions (e.g., GFZ, DGFI-TUM, TU Vienna, University Wrozlaw, IfE Hannover)
- Several geodetic software packages have been augmented by the capability to carry out realistic simulation scenarios (e.g., VieVS, DOGS, Bernese, Geodyn, EPOS-OC)
- Simulations of optimal locations for an additional VGOS station were carried out, with special focus on its contribution to EOP determination (Schartner et al., 2020). A location in South America is most beneficial.
- Studies on integration of VGOS and S/X-legacy network for VLBI were carried out.
- Optimized scheduling methods for VGOS were investigated.
- Simulations and analysis of VLBI tracking data of Galileo satellites are carried out to assess the possibilities for improving dUT (Wolf et al. 2021).
- The benefit of using a local time transfer system for short VLBI baseline analysis was demonstrated.
- Studies for combined GNSS-Rapid and VLBI Intensives showed that improved ERPs with low latency can be derived (Hellmers et al., 2019).
- Studies on the quality of GNSS-based scale by adding LEOs to an integrated processing or by using Galileo data were carried out. A correction to the satellite antenna phase center offset (PCO) in nadir direction of approx. -200mm was found for GPS (Huang et al., 2021; Huang et al., 2022).
- Studies on the potential of SLR Short baseline observations (e.g. at Wettzell) for monitoring the terrestrial local ties were carried out in order to identify technique-specific systematic error sources.
- Studies on the impact of adding the LLR data in infra-red to reference frame products were carried out by IfE, Uni Hannover.
- Studies on future GNSS constellations were carried out (Glaser et al., 2020).
- Consistent estimation of TRF+CRF+EOP started along with the VLBI reprocessing activities related to ITRF2020 generation.
- Studies related to alternative parameterization of EOPs from 24-h VLBI sessions started, in order to be consistent with estimation intervals by the other space-geodetic techniques.
- PLATO members are involved in the GENESIS science team and supports the mission with realistic simulations and contributed to the GENESIS white paper (Delva et al., 2023)
- Presentations were given at IAG Assembly (July 2019), annual conferences of EGU and AGU as well as meetings of IAG Services.

Future Plans

- Improved analysis methods for reference frame products will be developed with the focus of including all existing data (especially to satellites not yet included in standard TRF products) and all available co-locations
- Simulations performed by PLATO members showed impressively the benefits of a dedicated satellite mission as co-location in space. Therefore, we recommend to strive by all means for a satellite mission dedicated to co-location in space. The acceptance of the GENESIS mission by ESA's ministerial conference in November 2022 was a first achievement in this context.
- A coordinated analysis campaign with exchanged simulated observations was re-started in May 2021 in order to get an estimate about the comparability of the simulation studies.
- Simulations of network projections will be carried out if new potential stations come up.

Publications

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- Delva, P., Altamimi, Z., Blazquez, A., Blossfeld, M., Böhm, J., Bonnefond, P., Boy, J.-P., Bruinsma, S., Bury, G., Chatzinikos, M., Couhert, A., Courde, C., Dach, R., Dehant, V., Dell'Agnello, S., Elgered, G., Enderle, W., Exertier, P., Glaser, S., Haas, R., Huang, W., Hugentobler, U., Jäggi, A., Karatekin, O., Lemoine, F. G., Le Poncin-Lafitte, C., Lunz, S., Männel, B., Mercier, F., Métivier, L., Meyssignac, B., Müller, J., Nothnagel, A., Perosanz, F., Rietbroek, R., Rothacher, M., Schuh, H., Sert, H., Sosnica, K., Testani, P., Ventura-Traveset, J., Wautelet, G., Zajdel, R. (2023): GENESIS: co-location of geodetic techniques in space. - Earth Planets and Space, 75, 5. https://doi.org/10.1186/s40623-022-01752-w
- Dill, R., H. Dobslaw, H. Hellmers, A. Kehm, M. Bloßfeld, M. Thomas, F. Seitz, D. Thaller, E. Schönemann, U. Hugentobler (2020): Evaluating Processing Choices for the Geodetic Estimation of Earth Orientation Parameters with Numerical Models of Global Geophysical Fluids. J Geophys Res Solid Earth 125(9):e2020JB02,002. https://doi.org/10.1029/2020JB020025
- Glaser S, König R, Neumayer K H, Balidakis K, Schuh H (2019) Future SLR station networks in the framework of simulated multi-technique terrestrial reference frames, Journal of Geodesy doi:10.1007/s00190-019-01256-8
- Glaser S, König R, Neumayer K H, Nilsson T, Heinkelmann R, Flechtner F, Schuh H (2019) On the impact of local ties on the datum realization of global terrestrial reference frames, Journal of Geodesy, doi:10.1007/s00190-018-1189-0
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- Glaser S, Michalak G, Männel B, König R, Neumayer K H, Schuh H (2020c) Future GNSS Infrastructure for Improved Geodetic Reference Frames, IEEE Xplore, doi: 10.23919/ENC48637.2020.9317460
- Hellmers, H., D. Thaller, M. Bloßfeld, A. Kehm, A. Girdiuk (2019): Combination of VLBI Intensive Sessions with GNSS for generating Low-latency Earth Rotation Parameters. Advances in Geosciences, 50:49-56. Doi: 10.519/adgeo-50-49-2019
- Huang W., Männel B., Brack A., Schuh H. (2021) Two methods to determine scale-independent GPS PCOs and GNSS-based terrestrial scale: comparison and cross-check. *GPS Solut* **25,** 4. https://doi.org/10.1007/s10291-020-01035-5
- Huang, W., Männel, B., Brack, A., Maorong, G., Schuh, H. (2022) Estimation of GPS transmitter antenna phase center offsets by integrating space-based GPS observations, Advances in Space Research, 69(7), https://doi.org/10.1016/j.asr.2022.01.004
- Kehm A., Bloßfeld M., König P., Seitz F. (2019): Future TRFs and GGOS – where to put the next SLR station? Advances in Geosciences, 50, 17–25, DOI 10.5194/adgeo-50-17-2019
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- Lengert, L., D. Thaller, C. Flohrer, H. Hellmers, A. Girdiuk (2022): On the improvement of combined EOP series by adding 24-hours VLBI to VLBI Intensive and GNSS data. In: Proceedings of the IAG Scientific Assembly 2021, Beijing / virtual. IAG Symposia Series
- Michalak G, Glaser S, Neumayer K H, König R (2021) Precise orbit and Earth parameter determination supported by LEO satellites, inter-satellite links and synchronized clocks of a future GNSS, Advances

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- Pinzón, I.H., Rothacher, M. (2020). Co-location of Space Geodetic Techniques: Studies on Intra-Technique Short Baselines. In: Freymueller, J.T., Sánchez, L. (eds) Beyond 100: The Next Century in Geodesy. International Association of Geodesy Symposia, vol 152. Springer, Cham. https://doi.org/10.1007/1345_2020_95

- Herrera Pinzón, I., Rothacher, M. and Riepl, S. Differencing strategies for SLR observations at the Wettzell observatory. *J Geod* **96**, 4 (2022). https://doi.org/10.1007/s00190-021-01588-4
- M. Schartner, J. Böhm, A. Nothnagel (2020): Optimal antenna locations of the VLBI Global Observing System for the estimation of Earth orientation parameters. Earth Planets and Space, 72 (2020), 87; S. 1 – 14
- Singh, V.V., Biskupek, L., Müller, J., Zhang, M. (2021): Impact of non-tidal station loading in LLR. Advances in Space Research DOI: 10.1016/j.asr.2021.03.018

GGOS Standing Committee on Satellite Missions (CSM)

Chair: Roland Pail (Germany)
Vice-Chair: C.K. Shum (USA)

Members

CSM has quite an open team of members, associate members and guests to work on the various CSM tasks and to provide material for the website, presentation material, and other documentation. CSM traditionally has about one meeting per year, although the pandemic has precluded and will likely prohibit in the near future any such meetings. Therefore, the main work is and will accomplished via email exchanges. Additional members will be added in the near future.

Purpose and Scope

The Committee on Satellite Missions (CSM) has been set-up as an international panel of experts, with consultants of national and international space agencies.

The purpose and scope of CSM is the information exchange with satellite missions as part of the GGOS space infrastructure, for a better ground-based network response to mission requirements and space-segment adequacy for the realization of the GGOS goals. New space missions shall be advocated and supported, if appropriate.

Satellite missions are a prerequisite for realizing a global reference for any kind of Earth observation. They are the key for monitoring change processes in the Earth system on a global scale with high temporal and spatial resolution. Therefore, beyond purely scientific objectives they meet a number of societal challenges, and they are an integral part of the GGOS infrastructure and essential to realize the GGOS goals. The role of CSM is to monitor the availability of satellite infrastructure, to propose and to advocate new missions or mission concepts, especially in case that a gap in the infrastructure is identified.

Activities

Improve coordination and information exchange with the missions for better ground-based network response to mission requirements and space-segment adequacy for the realization of GGOS goals, including:

- Advocate, coordinate, and exchange information with satellite missions as part of the GGOS space infrastructure, for a better ground-based network response to mission requirements and space-segment adequacy for the realization of the GGOS goals;
- Assess current and near-future satellite mission infrastructures and their relevance towards achieving GGOS 2020 goals;
- Support proposals for new mission concepts and advocate for needed missions;
- Interfacing and outreach with other components of the Bureau; especially with the ground networks component, the GGOS Performance Simulations and Architectural Trade Offs (PLATO) activities, as well as with the Bureau of Standards and Products.
- Advocate the realization of future gravity field missions: Future gravity satellite constellation MAGIC (double-pair mission). Decision on funding of polar pair (P1) by NASA/DLR; decision on Phase B of inclined pair (P2) at ESA Ministerial Conference in November 2022

Future Activities and Objectives

- Continue the planned activities, i.e., updating the two central lists, supporting future satellite missions, etc.;
- Work with the Coordinating Office to set up and maintain a Satellite Missions Committee section on the GGOS website;
- Evaluate the contribution of current and near-term satellite missions to the GGOS 2020 goals;
- Work with GGOS Executive Committee, Focus Areas, and data product development activities (e.g., ITRF) to advocate for new missions to support GGOS goals;

- Support the Executive Committee and the Science Committee in the GGOS Interface with space agencies;
- Finalize and publish (outreach) of Science and User Requirements Documents for future gravity field missions.
- Advocate and support national and international space agencies in their processes towards future gravity missions, by providing/exchange available technical information, and propose to support/participate in missions studies towards their realization;
- Communicate with Chinese IAG colleagues to seek advice and collaborations to advocate for possible availability of Chinese gravity mission data to the scientific community, Continue exchange with PLATO on joint interests and possible collaborations; set up a more formal procedure of collaboration; discuss needs and run simulations to study the impact of future satellite missions, identify gaps for fulfilling the GGOS goals, etc.;
- Investigate possible collaborations with commercial satellite companies, e.g., Spire Global, Inc., PlanetIQ, GeoOptics, with launched Cubesat constellations, on GGOS research and applications including GNSS occultation, and bistatic radar reflectometry.

Website

Website will be built or improved.

Publications and Presentations

Pail, R.; IUGG, Writing Team: Observing Mass Transport to Understand Global Change and Benefit Society: Science and User Needs, An international multi-disciplinary initiative for IUGG; in: Pail, R. (eds.) Deutsche Geodätische Kommission der Bayerischen Akademie der Wissenschaften, Reihe B, Vol. 2015, Heft 320, Verlag der Bayerischen Akademie der Wissenschaften in Kommission beim Verlag C.H. Beck.

Schlaak, M; Pail, R; Jensen, L; Eicker, A: Closed loop simulations on recoverability of climate trends in next generation gravity missions. Geophysical Journal International 232 (2), 2022, 1083-1098.

Zahzam, Nassim; Christophe, Bruno; Lebat, Vincent; Hardy, Emilie; Huynh, Phuong-Anh; Marquet, Noémie; Blanchard, Cédric; Bidel, Yannick; Bresson, Alexandre; Abrykosov, Petro; Gruber, Thomas; Pail, Roland; Daras, Ilias; Carraz, Olivier: Hybrid Electrostatic–Atomic Accelerometer for Future Space Gravity Missions. Remote Sensing 14 (14), 2022, 3273.

Purkhauser, Anna F.; Pail, Roland: Triple-Pair Constellation Configurations for Temporal Gravity Field Retrieval. Remote Sensing 12 (5), 2020.

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GGOS Standing Committee on Data and Information Systems

Chair: Nicholas Brown (GA Austria)
Vice-Chair: Sandra Blevins (NASA USA)

Purpose and Scope

The Committee on Data and Information had two GGOS objective areas:

- Development and implementation of a portal;
- Development and implementation of a metadata scheme

Near term Metadata activity (NASA CDDIS)

CDDIS continues to add new data and derived product collections and further populate collection-level metadata stored in the Earth Observation System Data and Information System (EOSDIS) Common Metadata Repository (CMR). CDDIS is an EOSDIS Distributed Active Archive Centers (DAACs) and thus utilizes the EOSDIS infrastructure to manage collection and granule level metadata describing CDDIS archive holdings; these metadata include 120 published DOIs representing DORIS, GNSS, and SLR data and derived product collections archived at the CDDIS archive. Since the AGU Fall Meeting 2019 the CDDIS actively participates in the GGOS DOI Working Group, sharing NASA Earth Science Data and Information System (ESDIS) DOI methods and best practices with the greater Geodesy community.

Longer-Term Metadata activity (Nick Brown/Geoscience Australia)

Development of a Geodesy Markup Language (GeodesyML), for the GNSS community; potential for expansion to the other space geodesy techniques and GGOS. The current study is identifying metadata standards and requirements, assessing critical gaps and the how these might be filled, what changes are needed in the current standards, and who are the key people who should work on it (more comprehensive scheme). The schema that would be used by its elements for standardized metadata communication, archiving, and retrieval. First applications would be the automated distribution of up-to-date station configuration and operational information, data archives and catalogues, and procedures and central bureau communication. One particular plan of great interest is a site metadata schema underway within the IGS Data Center Working Group. This work is being done in collaboration with the IGS, UNAVCO, SIO, CDDIS, and other GNSS data centers. The current activity is toward a means of exchange of IGS site log metadata utilizing machine-to-machine methods, such as XML and web services, but it is expected that this will be expanded to the other Services to help manage site related metadata and to other data related products and information. Schema for the metadata should follow international standards, like ISO 19xxx or DIF, but should be extendable for technique-specific information, which would then be accessible through the GGOS Portal.

This work has been put on hold due to the unavailability of Nicholas Brown and Sandra Blevins departure from CDDIS. Sandra Blevins has been replaced by Taylor Yates from NASA/CDDIS; Discussion has been initiated with the IGS on a possible path forward in Nick's activity.

Activities and Actions

Activities underway at CDDIS:

1. Complete collection level metadata related to CDDIS data and derived product holdings in the EOSDIS Common Metadata Repository (CMR)
2. Continue to re-ingest CDDIS data and derived product holdings in order to extract granule level metadata linked to these new collection level records

Activities underway in Geodesy Markup Language (GeodesyML) System

1. Review and document the metadata and standards requirements of precise positioning users in expected high use sectors (e.g. precision agriculture, intelligent transport, marine, location-based services etc.).

2. Assess and document the critical gaps in standards which restrict how Findable Accessible Interoperable and Reusable (FAIR) precise positioning data is for the expected high use sectors.
3. Record use cases of standards being applied well and the benefits it provides to users.
4. Review the "use cases" of geodetic data developed by Geoscience Australia and the IGS Data Center Working Group. (https://drive.google.com/drive/folders/1L792ImLktAiAbmhX9WZhvHrXB3BMD00G?usp=sharing) and document what work and time would be required to ensure these use cases can be met in international standards. This could be:
   - Identify which gaps can be filled by GeodesyML
   - Identify which components of GeodesyML would be better, handled by / integrated with, existing standards (such as TimeSeriesML, SensorML, Observations and Measurements) where possible.
   - Identify which components of already existing international geospatial infrastructure can be approached (such as the European Inspire initiative)
   - Advise on who we should engage with from the OGC/ISO community to facilitate a change to a standard to meet our requirements.
5. Work with Project Partners to develop and test other use cases (e.g. integration of geodetic data with geophysics data (e.g. tilt meters), Intelligent Transport Sector data, mobile applications). Then, document what work and time would be required to ensure these use cases can be met in international standards.
6. Provide advice on how to best engage with the right communities to learn from their experiences, test their tools and influence the development of required standards.

Future Activities and Objectives

1. Working with the IGS Infrastructure Committee, complete the development of the metadata system for GNSS (IAG) and then expand its role to the other IAG Services (IVS, ILRS, IDS, IGFS, etc.).

IERS Working Group on Site Survey and Co-location

JWG 1.2.2 : Methodology for surveying geodetic instrument reference points

Chair: Ryan Hippenstiel (USA)
Vice-chair : Sten Bergstrand (Sweden)

Members
• Zuheir Altamimi (IGN, France)
• Sten Bergstrand (BIPM, France)
• Steven Breidenbach (NOAA/NGS, USA)
• Benjamin Erickson (NOAA/NGS, USA)
• Cornelia Eschelbach (Frankfurt Univ. of Applied Sciences, Germany)
• Kendall Fancher (NOAA/NGS, USA)
• Charles Geoghegan (NOAA/NGS, USA)
• Dionne Hansen (LINZ, New Zealand)
• Ryan Hippenstiel (NOAA/NGS, USA)
• Christopher Holst (Technische Universität München, Germany)
• Michael Lösler (Frankfurt Univ. of Applied Sciences, Germany)
• Kevin Jordan (NOAA/NGS, USA)
• Saho Matsumoto (GSI, Japan)
• Jack McCubbine (GA, Australia)
• Damien Pesce (IGN, France)
• Anna Riddell (GA, Australia)
• Owen Smallfield (LINZ, New Zealand)
• Jerome Saunier (IGN, France)
• Elena Martínez Sánchez, (Observatorio de Yebes, Spain)
• Daniela Thaller, (BKG, Germany)
• Bart Thomas (GA, Australia)
• Agnes Weinhuber (Technische Universität München, Germany)

Correspondent Members
• Xavier Collilieux (IGN, France)
• Mike Pearlman (Harvard/GGOS, USA)
• Robert Heinkelmannm, (GFZ, Germany)

Overview

Areas of work of the Working Group on Site Survey and Co-location are standards and documentation (guidelines, survey reports, etc.), coordination (share know-how and join efforts between survey teams), research (investigate discrepancies between space geodesy and tie vectors, alignment of tie vectors into a global frame), and cooperation. Our group has a new set of terms and has received confirmation of new participants in the group. We would continue to encourage participation from any agency or community that is conducting research, improving protocols, or completing field surveys of local ties as sites with various space geodesy techniques present. Our group has continued to share improved protocols, technologies, and instrumentation to provide the most accurate tie measurements possible for all sites around the world. We reminded participants to share their contributions of local tie data for inclusion into ITRF2020 and many were submitted.

Activities and publications during the period 2019–2023

Improvements have been made to standardize report and data submissions of local tie surveys to provide consistency across all agencies. Survey data has recently been reported with new standards in place.

The group is continuing to explore methodologies to measure and quantify antenna deformation. Research and continued field tests using laser scanning and terrestrial inSAR have been discussed. In addition, a comparison of two approaches to quantifying deformation effects at Onsala will be undertaken. Members completed and documented work researching site-dependent GNSS antenna calibrations to account for systematic errors and biases. Personnel at Yebes are studying data collected from both a laser scanner and UAV, detailing differences in solutions at various temperatures and times of day.

Measurements were collected at the Zeppelin Observatory (Svalbard, Norway) and Hartebeesthoeck has been reprocessed (Muller et al., 2020). The latter was assisted by updating of local software to allow estimating VLBI and SLR references points from raw survey data into one single processing.

A tie survey at Yarragadee was completed in June of 2021, the results of which were developed into a presentation shared with working group members and participants of the Unified Analysis Workshop in 2022. In addition, Geoscience Australia (GA) recently completed a tie survey at Hobart with survey results and reporting forthcoming. GA continues to look at cooperation with universities to improve resources available and the efficiency of surveys.

Colleagues from Frankfurt Univ. of Applied Sciences, BKG and NLS submitted the results and further processing of tie surveys at Wettzell and Metsähovi for publication in the IAG 2021 conference proceedings.

IGN contributed local tie surveys at Malé, Crozet, Futuna, and Grasse, including new SAR reflectors and additional work processing with fully automated determination of the SLR telescope reference point at Côte d'Azur. This work (Barneoud, et al., 2023) was presented at REFAG2022. IGN also completed an updated of the COMP3D software which now includes full integration of axis determination and increased ability to input data. This software was used to process a 2021 survey of Ny-Ålesund (Brandal).

The US National Geodetic Survey conducted an IERS local site survey at the National Radio Astronomy Observatory in Maui (GNSS and SLR), the Table Mountain Geophysical Observatory in Colorado (new GNSS, gravity), Midway Naval Research Laboratory's OTF in Virginia (GNSS and SLR), and the International Earth Rotation and Reference Systems Service (IERS) Mauna Kea site (VLBA). Surveys were paused in the spring of 2020 due to the COVID pandemic and partially resumed in the fall of 2021. In addition, surveys investigating lines of sight and detailing the calibration piers for the SLR were performed at Goddard Geophysical and Astronomical Observatory (GGAO) in 2021 and 2022. A survey at KPGO - Kōke‘e Park Geophysical Observatory was completed in May of 2023 and the final results and report will be released soon.

NGS fully implemented the use of an absolute laser tracking system (Leica AT402) into all completed tie surveys, enhancing precision of terrestrial observations. Progress was made on technical memorandum documenting current NGS procedures which will be released when developments are complete.

NGS has developed deflection of vertical (DoV) measurement capabilities utilizing a robotic total station and camera, and will continue testing equipment for deployment on upcoming local tie surveys. It is being called the TSACS (Total Station Astrogeodetic Control System), and the procedures and specifications were shared with researchers from Frankfurt who built and tested a similar system.

Collaboration among the group members has increased with information sharing leading to software, hardware, processing, and field protocols improvements. As an example, GSI Japan and Land Information New Zealand held a recent workshop with positioning staff. Saho presented about a local tie survey at Ishioka. In addition, GSI also released a video detailing the Ishioka site which highlighting co-location work.

Within the joint project GeoMetre, members determined the reference point of an SLR telescope at Wettzell, the Satellite Observing System Wettzell (SOS-W), using applied close-range photogrammetry instead of a polar measurement system.

Close range photogrammetry was also used to investigate on the deformation behaviour of the receiving unit of the Onsala Twin Telescope (OTT-N), as well as the 20 m Radio Telescope Wettzell (RTW) and the Twin Telescope Wettzell (TTW-2) in joint measurement campaigns of Frankfurt Univ. of Applied Sciences and Bochum Univ. of Applied Sciences. The signal path variations of these radio telescopes were derived using the common approach as well as spatial ray tracing. The results were reported to the IVS. Since VGOS-antennas are designed for broadband reception, the impact of frequency-dependent illumination functions onto the obtained signal path variations was studied in detail.

There is also a general interest from all members about moving towards locating InSAR targets and including them in tie surveys when co-located with other techniques. Some field results were captured in Collilieux et. al. 2022 as listed below.

Overall, the group has been active in this period, increasing the vectors used from ITRF2014 to ITRF2020, and decreasing the number of vectors with a discrepancy of greater than 5 mm. (Altamimi, 2023).

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GGOS Bureau of Products and Standards

Director: Detlef Angermann (Germany)
Vice Director: Thomas Gruber (Germany)

Members

- *Michael Gerstl (Germany)*
- *Robert Heinkelmann (Germany)*
- *Urs Hugentobler (Germany)*
- *Laura Sánchez (Germany)*
- *Peter Steigenberger (Germany)*

GGOS entities associated to the BPS:

- *Committee "**Contributions to Earth System Modeling**", Chair: Maik Thomas (Germany)*
- *Committee "**Definition of Essential Geodetic Variables (EGV)**", Chair: Richard Gross (USA)*
- *Working Group "**Towards a consistent set of parameters for the definition of a new GRS**", Chair: Urs Marti (Switzerland)*

The Bureau of Products and Standards (BPS) is chaired and operated by the Technical University of Munich (TUM). The BPS staff members are Detlef Angermann, Thomas Gruber, Michael Gerstl, Urs Hugentobler and Laura Sánchez (all from TUM), as well as Robert Heinkelmann (GFZ German Research Centre for Geosciences Potsdam) and Peter Steigenberger (German Aerospace Centre (DLR), Oberpfaffenhofen). The Bureau comprises the staff members, the chairs of the associated GGOS components as well as representatives of the IAG Services and other entities involved in standards and geodetic products. The present status of the associated members as BPS representatives is summarized in Table **X.1**.

***Tab. X.1**: Representatives of IAG Services and other entities involved in standards and geodetic products (status: June 2023)*

R. Heinkelmann, Germany	International Earth Rotation and Reference Systems Service (IERS)	
N. Stamatakos, USA	International Earth Rotation and Reference Systems Service (IERS)	
U. Hugentobler, Germany	International GNSS Service (IGS)	geometry
E. Pavlis, USA	International Laser Ranging Service (ILRS)	
J. Gipson, USA	International VLBI Service for Geodesy and Astrometry (IVS)	
P. Štěpánek, Czech Republic	International DORIS Service (IDS)	
R. Barzaghi, Italy	International Gravity Field Service (IGFS)	
S. Bonvalot, France	Bureau Gravimétrique International (BGI)	
M. Reguzzoni, Italy	International Service for the Geoid (ISG)	gravity
E. S. Ince, Germany	International Center for Global Earth Models (ICGEM)	
K. M. Kelly, Germany	International Digital Elevation Model Service (IDEMS)	
H. Wzointek, Germany	International Geodynamics and Earth Tide Service (IGETS)	
J. Kusche, Germany	Representative of gravity community	
J. Ferrandiz, Spain	IAU Commission A3 Representative	
M. Craymer, USA	Chair of Control Body for ISO Geodetic Registry Network	
L. Hothem, USA	Vice-Chair of Control Body for ISO Geodetic Registry Network	other entities
S. Rózsa, Hungary	IAG Communication and Outreach Branch	
M. Sehnal, Austria	GGOS Coordinating Office	

Overview

The Bureau of Products and Standards (BPS) is a key component of IAG's Global Geodetic Observing System (GGOS). It supports GGOS in its goal to obtain consistent products describing the geometry, rotation and gravity field of the Earth as well as the temporal changes of these quantities in mm-accuracy. In order to fully benefit from the ongoing technological improvements of the geodetic observing systems, it is essential that the analysis of the precise observations is based on the definition and application of common standards and conventions. This is an important requirement for reliably monitoring global change phenomena (e.g., global sea level rise, ice melting, global water cycle) and for providing the metrological basis for an improved understanding of the Earth system. Figure **X.1** illustrates the integration of different observation types to determine consistent geodetic parameters as the basis for studies of the Earth system, the interactions among its sub-components and the connection to outer space.

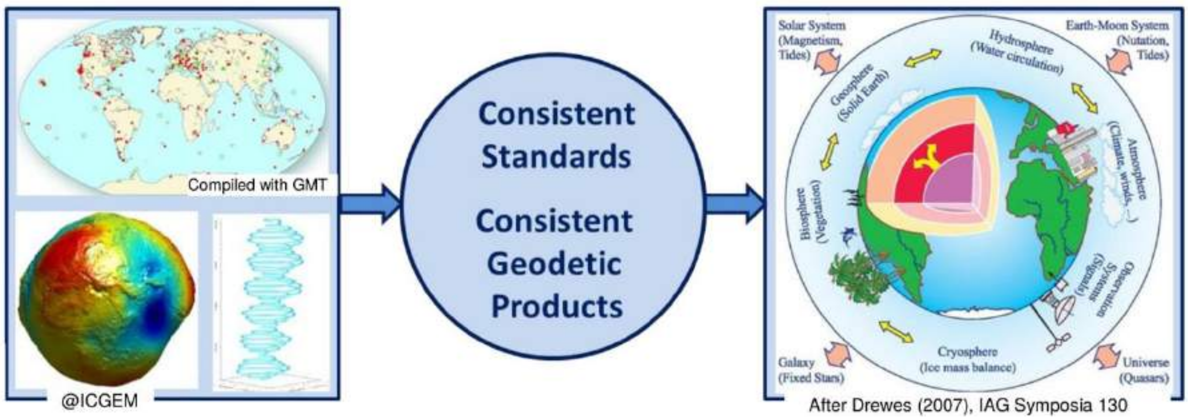

Fig. X.1: *The integration of the "three pillars" Earth's geometry, rotation and gravity field requires unified standards to obtain consistent geodetic products as the basis for Earth system research and for precisely quantifying global change phenomena.*

The mission of the BPS is:

- to serve as coordinating point for the homogenization of IAG standards and products;
- to keep track of the adopted geodetic standards and conventions across all components of the IAG;
- to motivate the development of new and integrated geodetic products, needed for Earth sciences and society;
- to describe and promote geodetic products (see GGOS website, www.ggos.org).

To accomplish these BPS tasks, a close interaction between the BPS and the IAG Services, the IERS Conventions Center and other entities involved in standards and conventions such as the IAU Commission A3 "Fundamental Standards", the International Organization for standardization (ISO/TC 211), the Committee on Data for Science and Technology (CODATA), the United Nation Global Geospatial Information Management (UN-GGIM) Subcommittee on Geodesy (SCoG) Working Group "Data Sharing and Development of Geodetic Standards", and the newly established UN Global Geodetic Centre of Excellence (UN-GGCE) has been established.

Objectives

The objectives of the BPS are divided into two major topics:

- **Standards**: A key objective is the compilation of an inventory regarding standards, constants, resolutions and conventions adopted by IAG and its components. This includes an assessment of the present status, the identification of gaps and shortcomings concerning geodetic standards and the generation of the IAG products, as well as the provision of recommendations. It is obvious that such an inventory needs to be regularly updated, since the IAG standards and products are continuously evolving. The BPS shall also propose the adoption of new standards where necessary and propagate standards and conventions to the wider scientific community promoting their use. In this context, the BPS recommends the development of a new Geodetic Reference System GRS20XX based on the best estimates of the major parameters related to a geocentric level ellipsoid.
- **Products**: The BPS shall take over a coordinating role regarding the homogenization of standards and geodetic products. The present status regarding IAG Service products shall be evaluated, including analysis and combination procedures, accuracy assessment with respect to GGOS requirements, documentation and metadata information for IAG products. The Bureau shall initiate steps to identify user needs and requirements for geodetic products and shall contribute to develop new and integrated products. The BPS shall also contribute to the development of the GGOS Portal (as central access point for geodetic products), to ensure interoperability with IAG Service data products and external portals (e.g., GEO, EOSDIS, EPOS, GFZ Data Services).

Activities

The BPS Implementation Plan 2020 – 2022 gives an overview and schedule of the BPS tasks (see Figure **X.2**). The activities of the BPS are divided into three main categories: Coordination activities, specific tasks of the BPS, and outreach activities. Currently, GGOS is developing a refined strategy and new implementation plans for its components for the term 2023 – 2026.

Updating of the BPS inventory

In 2019 and 2020, the second version of the inventory has been prepared for publication in the Geodesist’s Handbook 2020 (Angermann et al., 2020). In this updated version of the inventory the general structure of the original document published in the Geodesist’s Handbook 2016 is largely kept, whereas the contents of the individual sections has been updated to take into account the latest developments.

The updates in the field of standards and conventions comprise the newly released ISO standards by ISO/TC211 covering geographic information and geomatics, the activities of the GGRF Working Group “Data Sharing and Development of Geodetic Standards” within the UN-GGIM Subcommittee on Geodesy, the update of the IERS Conventions initiated by the IERS Conventions Center, and the recently adopted resolutions by IAG, IUGG and IAU that are relevant for geodetic standards and products. In the framework of the update of the IERS Conventions, the director of the BPS has been nominated as Chapter Expert for Chapter 1 “General definitions and numerical standards”.

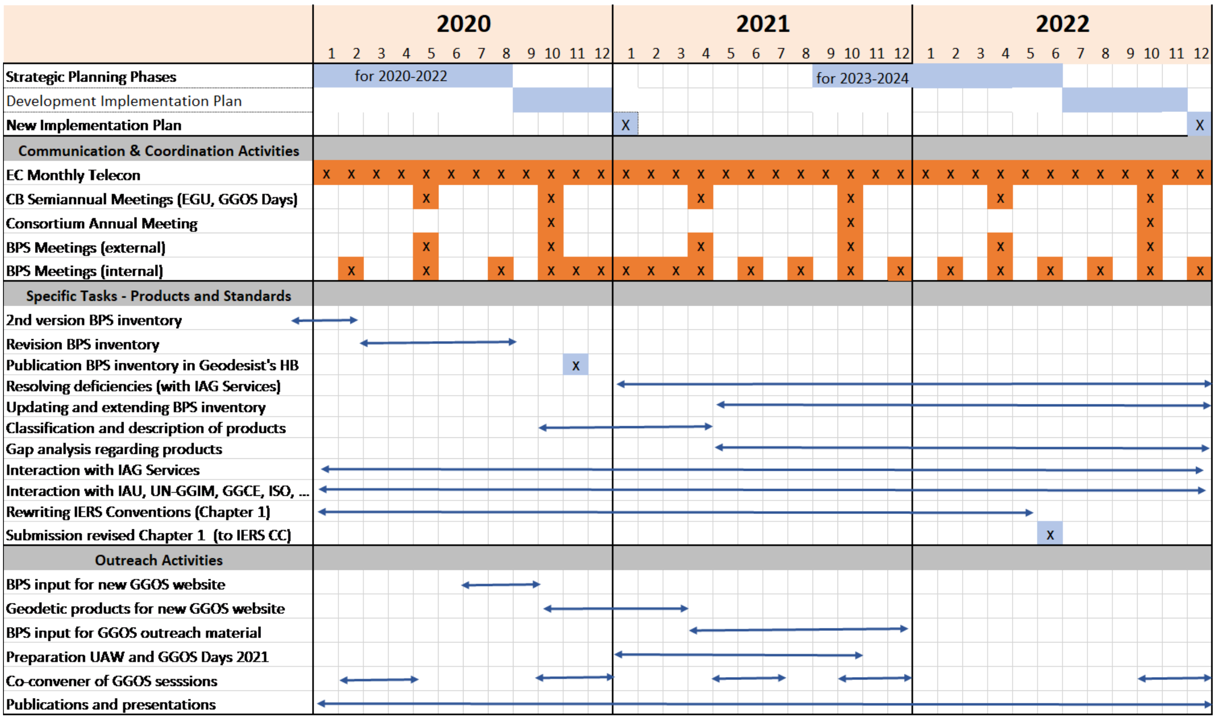

***Fig. X.2:** Overview and schedule of BPS activities. Please note that some changes regarding the schedule of meetings and workshops were necessary due to the pandemic situation.*

Product-based review of standards and conventions

The second version of the inventory also provides an update regarding IAG products, addressing the following major topics (see Angermann et al., 2020):

- Celestial reference systems and frames
- Terrestrial reference systems and frames
- Earth orientation parameters
- GNSS satellite orbits
- Gravity and geoid
- Height systems and their realizations

New versions of IERS products have been released for the celestial and terrestrial reference frame as well as for the EOP, namely ICRF3, ITRF2014 and EOP 14C04. Although a significant progress has been achieved compared to previous realizations, there are still some deficiencies and open problems that are addressed in this inventory. Recommendations are provided for each product to further improve their accuracy and consistency. Concerning GNSS satellite orbits, the modelling has been improved and some missing information has been provided by the satellite operators, but there are still some remaining deficiencies. A remarkable progress has been achieved in the field of gravity and geoid related data and products, including the development of a dedicated data and products portal based on online applications for the creation of metadata for gravity and geoid data. Also the latest developments and achievements in the field of height systems and their realizations are reported (for details see the Report of the GGOS Focus Area "Unified Height System").

Description and representation of geodetic products

In cooperation with the IAG Services, other data providers and contributing experts as well as the GGOS Coordinating Office and the members of the GGOS Science Panel, user-friendly product descriptions have been generated and implemented at the GGOS website (www.ggos.org).

The geodetic products are classified into two categories:

- **Geodetic themes**: Reference frames, geometry, Earth orientation, gravity field, positioning and applications.
- **Earth system components and space**: Outer and near space, atmosphere, hydrosphere, oceans, cryosphere, solid Earth.

Until now, about 23 product descriptions are displayed at the GGOS website. Table **X.2** provides a list of these product descriptions along with so-called "appetizer questions" for each particular product. With such an information portal, GGOS contributes to advertise data science products to other disciplines and to make geodesy more visible in the geoscientific community and beyond (Angermann et al., 2022a). The product descriptions have been reviewed by the members of the GGOS Science Panel, coordinated by its chair Kosuke Heki, and have been implemented at the GGOS website by Martin Sehnal, the Director of the GGOS Coordinating Office. All the above mentioned contributions are gratefully acknowledged by the BPS.

Table X.2: *List of product descriptions that are currently displayed at the GGOS website (www.ggos.org), including an "appetizer question" for each particular product.*

Reference Frames		
	Terrestrial reference frame	How can we provide a stable reference for measuring changes of our planet?
	Celestial reference frame	How can we link Earth and space?
	Gravity reference frame	How to refer gravity measurements at the Earth surface to a uniform reference?
	Height reference frame	What is a height above sea level?
Geometry		
Land surface	Station positions & variations	Why do we need precise positioning and navigation on Earth and in space?
	Digital elevation model	How can the Earth's surface be represented?
	Surface deformation models	Why is the Earth's surface in constant change?
Ocean surface and lakes	Sea surface heights	How can the height of oceans be observed?
	Ocean topography models	What are dynamic ocean topography models and why are they needed?
	Sea level change	How fast is the sea level rising?
	Tide gauge records	What is the best sea level reference along the coasts?
Ice surface	Ice sheets and glaciers - variations	How fast is the ice being lost in Greenland and Antarctica?
Gravity field		
	Global gravity field models	How and why does the Earth's gravity change with location?
	Gravity field temporal variations	Why is the gravity field variable?
	Regional / local geoid models	What is a geoid and why is it needed?
	Terrestrial gravity data	What is the purpose of measuring gravity on the Earth's surface?
	Ice sheets and glaciers - variations	How fast is the ice being lost in Greenland and Antarctica?
	Height systems	Why are height systems so important?
Earth Orientation		
	Earth orientation parameters	Why are days getting longer and Earth is wobbling?
Positioning and Applications		
Atmosphere	Atmospheric products	How can space geodetic techniques observe the atmosphere?
	Lower neutral atmosphere	How can geodesy contribute to weather prediction?
	Ionosphere	How does electron density affect positioning and navigation?
	Thermosphere	How does the atmosphere influence low-flying satellites?
GNSS products	GNSS satellite orbits and clocks	How positioning benefits from precise satellite orbits and clocks?

BPS contributions to the updating of the IERS conventions

In the framework of the Unified Analysis Workshop (Thessaloniki, Greece, October 21-23, 2022), a dedicated session on standards, conventions, and formats has been organized by the BPS and the IERS Conventions Center. In this session, an overview about the status of the IERS Conventions update was given, followed by presentations on particular topics such as numerical standards, nutation issues, high-frequency EOPs, relativistic effects, etc.

In this context, the focus of the BPS is on the updating of Chapter 1 of the IERS Conventions "General definitions and numerical standards". One issue was the treatment of the permanent tide in heights as specified in the definition of the International Height Reference System (IHRS), which prescribes the IHRF coordinates in the mean-tide system to support oceanographic and hydrographic modeling. Section 1.1 "Permanent Tide" of the IERS Conventions will be updated accordingly to refer to these IHRS developments. Furthermore, the present status concerning numerical standards (Section 1.2 of the IERS Conventions) has been addressed. Several updates have been proposed that will be incorporated to reflect the latest changes in the field of standards and conventions (Angermann et al., 2022b). As outcome of the Unified Analysis Workshop 2022, two recommendations on numerical standards have been endorsed:

- **REC-1**: The BPS recommends that the used numerical standards including time and tide systems must be clearly and consistently documented for all geodetic products (IAG/GGOS)
- **REC-2**: The BPS recommends that the necessity of a new Geodetic Reference System (GRS) should be further clarified (WG: Urs Marti)

GGOS Days 2022 and Strategic Plan Workshop 2022 in Munich

The GGOS Days 2022 (Nov. 15-16) and the Strategic Plan Workshop (Nov. 16-17) took place in the city center of Munich, hosted at the representative facilities of the Bavarian Academy of Sciences and Humanities (BAdW).


Fig. X.3: *On-site participants of the GGOS Days 2022.*

The GGOS Days 2022 were organized by the German Geodetic Commission (DGK), the Technical University of Munich (TUM) and GGOS. In total 111 interested people from many countries around the world participated in this hybrid conference, 33 of them in-person and 78 virtually. Further information is available at the GGOS website (https://ggos.org/event/ggos-days-2022/). This website also provides links to download the presentations, videos and photos of the conference.

Directly after the GGOS Days 2022, the GGOS Strategic Plan Workshop was convened at the same venue. About 20 invited IAG representatives participated in this workshop to discuss the future direction and goals of GGOS. Besides about 15 in-person participants, a few colleagues attended remotely. The discussions were based on the results of a community survey to develop a new strategy for GGOS.

Selected publications:

- Angermann D, Gruber T, Gerstl M, Heinkelmann R, Hugentobler U, Sánchez L, Steigenberger P: GGOS Bureau of Products and Standards: Inventory of standards and conventions used for the generation of IAG products. In: Drewes H, Kuglitsch F, Adám J, Rozsa S (Eds.) The Geodesist's Handbook 2020, Journal of Geodesy, https://doi.org/10.1007/s00190-020-01434-z, 2020.
- Angermann D., Gruber T., Gerstl M., Heinkelmann R., Hugentobler U., Sánchez L., Steigenberger P., Gross R., Heki K., Marti U., Schuh H., Sehnal M., Thomas M.: GGOS Bureau of Products and Standards: Description and promotion of geodetic products}. In: Freymueller J., Sánchez L. (Eds.), IAG Symposia, doi 10.1007/1345_2022_144, 2022a.
- Angermann D., Gruber T., Gerstl M., Heinkelmann R., Hugentobler U., Sánchez L., Steigenberger P.: GGOS of Products and Standards (BPS): BPS Activities on Standards}. Unified Analysis Workshop 2022, Thessaloniki, Greece, 10.5281/zenodo.7291721, 2022b.

GGOS Committee on Earth System Modeling

Chair: Maik Thomas (Germany)

Role

The GGOS Committee on "Earth System Modeling" tends to promote the development of physically consistent modular Earth system modeling tools that are simultaneously applicable to all geodetic parameter types (i.e., Earth rotation, gravity field and surface geometry) and observation techniques. Hereby, the committee contributes to:

- The interpretation of geodetic monitoring data and, thus, to a deeper understanding of processes responsible for the observed variations;
- The establishment of a link between the geodetic products delivered by GGOS and numerical process models;
- A consistent combination and integration of observed geodetic parameters derived from various monitoring systems and techniques;
- The utilization of geodetic products for the interdisciplinary scientific community.

Objectives

The long-term goal is the development of a physically consistent modular numerical Earth system model for homogeneous processing, interpretation and prediction of geodetic parameters with interfaces allowing the introduction of constraints provided by geodetic time series of global surface processes, rotation parameters and gravity variations. This ultimate goal implicates the following objectives:

- Development of Earth system model components considering interactions and relationships between surface deformation, Earth rotation and gravity field variations as well as interactions and physical fluxes between relevant compartments of the Earth system;
- Promotion of homogeneous processing of geodetic monitoring data (de-aliasing, reduction) by process modeling to improve analyses of geodetic parameter sets;
- Contributions to the interpretation of geodetic parameters derived from different observation techniques by developing strategies to separate underlying physical processes;
- Contributions to the integration of geodetic observations based on different techniques in order to promote validation and consistency tests of various geodetic products.

Activities

The activities of the committee mainly concentrated on systematic comparisons of different stand-alone and coupled model approaches as well as on the further development and evaluation of model interfaces for dynamical coupling and algorithms for data assimilation.

- Implementation of interfaces to geodetic monitoring data based on Kalman and particle filter approaches in order to constrain and improve stand-alone model approaches and to prove consistency of various geodetic monitoring products;

- Implementation and evaluation of various numerical approaches with different complexities for the consideration of self-attraction and loading in ocean general circulation models;
- Feasibility studies regarding the coupling of neural networks with traditional data assimilation techniques and application of the combined approach in stand-alone models. Application of neural networks for downscaling purposes.
- Discussion and estimation of consequences of upcoming hardware developments for CPU intensive model simulations (high-performance computing vs. exascale modeling).
- Feasibility studies for the provision of error and uncertainty estimates of model predictions of geodetic parameters (Earth rotation, gravity field, surface deformation) due to imperfect model physics, initialization, and external forcing.

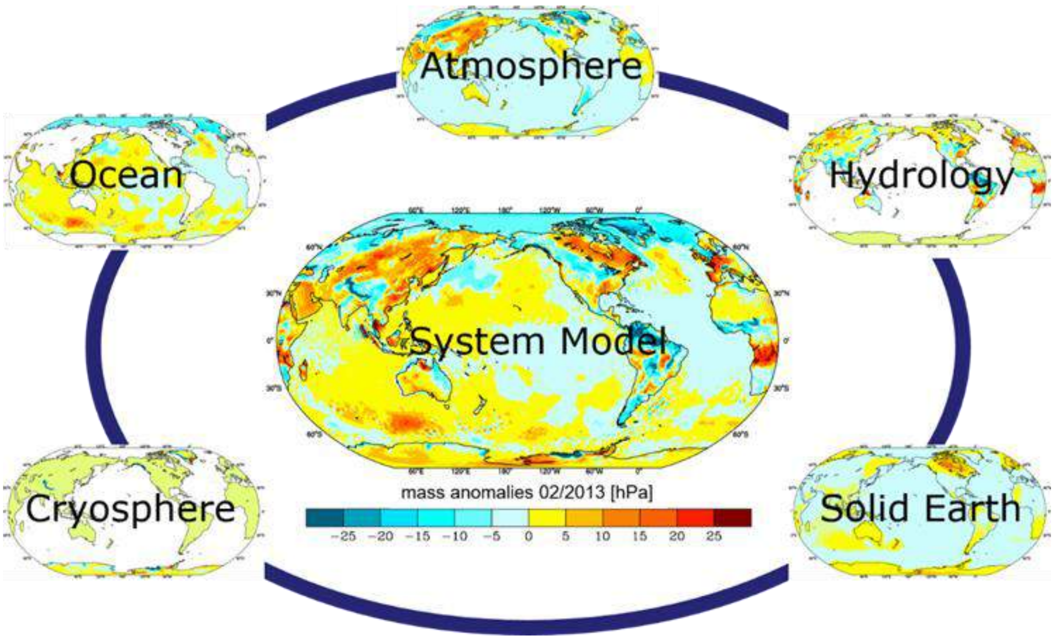

Fig. X.4: *Simulated mass anomalies in a modular system model approach.*

Selected publications:

- Bagge, M., Klemann, V., Steinberger, B., Latinovic, M., Thomas, M.: Glacial-isostatic adjustment models using geodynamically constrained 3D Earth structures. Geochemistry Geophysics Geosystems (G3), 22, 11, e2021GC009853, 2021.
- Boergens, E., Dobslaw, H., Dill, R., Thomas, M., Dahle, C., Flechtner, F.: Modelling spatial covariances for terrestrial water storage variations verified with synthetic GRACE-FO data. GEM - International Journal on Geomathematics, 11, 24, 2020.
- Huang, P., Sulzbach, R., Tanaka, Y., Klemann, V., Dobslaw, H., Martinec, Z., Thomas, M.: Anelasticity and lateral heterogeneities in Earth's upper mantle: impact on surface displacements, self-attraction and loading and ocean tide dynamics. Journal of Geophysical Research: Solid Earth, 126, 9, e2021JB022332, 2021.

- Irrgang, C., Dill, R., Boergens, E., Saynisch-Wagner, J., Thomas, M.: Self-validating deep learning for recovering terrestrial water storage from gravity and altimetry measurements. Geophysical Research Letters, 47, 17, e2020GL089258, 2020.
- Irrgang, C., Boers, N., Sonnewald, M., Barnes, E. A., Kadow, C., Staneva, J., Saynisch-Wagner, J.: Towards neural Earth system modelling by integrating artificial intelligence in Earth system science. Nature Machine Intelligence, 3, 667-674, 2021.
- Schachtschneider, R., Saynisch-Wagner, J., Klemann, V., Bagge, M., Thomas, M.: An approach for constraining mantle viscosities through assimilation of palaeo sea level data into a glacial isostatic adjustment model. Nonlinear Processes in Geophysics, 29, 1, 53-75, 2022.

Committee on Essential Geodetic Variables

Chair: Richard Gross (USA)

The GGOS BPS Committee on Essential Geodetic Variables was established in 2018 in order to define a list of Essential Geodetic Variables and to assign requirements to them. Essential Geodetic Variables (EGVs) are observed variables that are crucial (essential) to characterizing the geodetic properties of the Earth and that are key to sustainable geodetic observations. Examples of EGVs might be the positions of reference objects (ground stations, radio sources), Earth orientation parameters, ground- and space-based gravity measurements, etc. Once a list of EGVs has been determined, requirements can be assigned to them. Examples of requirements might be accuracy, spatial and temporal resolution, latency, etc. These requirements on the EGVs can then be used to assign requirements to EGV-dependent products like the terrestrial and celestial reference frames. The EGV requirements can also be used to derive requirements on the observing systems that are used to observe the EGVs. And the list of EGVs can serve as the basis for a gap analysis to identify observations needed to fully characterize the geodetic properties of the Earth. During GGOS Days 2017 it was agreed that a Committee within the GGOS Bureau of Products and Standards should be established in order to define the list of Essential Geodetic Variables and to assign requirements to them. This Committee was subsequently established in 2018 and consists of representatives of the IAG Services, Commissions, Inter-Commission Committees, and GGOS Focus Areas.

Tasks

The tasks of the Committee on Essential Geodetic Variables are to:

- Develop criteria for choosing from the set of all geodetic variables those that are considered essential
- Develop a scheme for classifying EGVs
- Within each class, define a list of EGVs
- Assign requirements to each EGV
- Document each EGV including its requirements, techniques by which it is observed, and point-of-contact for further information about the EGV
- Perform a gap analysis to identify potential new EGVs
- Define a list of geodetic products that depend on each EGV
- Assign requirements to the EGV-dependent products
- Hold workshops to engage the geodetic community in the process of defining EGVs, determining their dependent products, and assigning requirements to them

Activities

- A meeting of the Committee on Essential Geodetic Variables was held on 14 July 2019 in Montreal in conjunction with the 27th General Assembly of the IUGG. At the meeting, defining characteristics of essential geodetic variables were discussed.

Working Group "Towards a consistent set of parameters for the definition of a new GRS"

Chair: Urs Marti (Switzerland)

Members: Detlef Angermann (Germany), Richard Gross (USA), Ilya Oshchepkov (Russia), Christopher Kotsakis (Greece), Jonas Ågren (Sweden), Ulrich Meyer (Switzerland), Riccardo Barzaghi (Italy), Jaakko Mäkinen (Finland), Pavel Novak (Czech Republic), Laura Sánchez (Germany), Hartmut Wziontek (Germany), John Nolton (USA), Robert Heinkelmann (Germany), Sergei Kopeikin (USA), Erricos Pavlis (USA), ILRS

Objectives and Activities

The main task of this WG is to define a consistent set of parameters and formulas for the definition of a new conventional Global Reference System (GRS). This includes the geometry (size and shape of a reference ellipsoid), the gravity field (normal gravity field of this ellipsoid), physical heights, terrestrial time and Earth rotation.

This new definition becomes necessary because since the introduction of GRS80 (Moritz, 1980) the knowledge in Geodesy has improved a lot (e.g. GNSS, gravity space missions) and the use of the parameters became inaccurate and inconsistent over time. The problem of the permanent Earth Tide was not yet a topic at the epoch of the definition of GRS80. A new set of parameters was published by Groten in 2004 but was not widely introduced in Geodesy. Another source of parameters are the IERS conventions, which do not strictly apply GRS80.

The acceptance of the IAG Resolution No. 1 in 2015 which defines the potential at sea level (W_0) even increases the inconsistency in the geodetic parameters of the conventional GRS (in GRS80, W_0 is a derived quantity).

The new set of parameters is based on the four fundamental parameters: W_0 (Potential at Reference Level), J2 (dynamic form factor, "flattening"), GM (geocentric gravitational constant) and ω (angular velocity of the Earth). All these quantities are well observed and monitored by various geodetic space techniques. (This implies that the semi major axis of the ellipsoid will be a derived parameter).

Most of the defining parameters change with time. This includes seasonal variations and long-term trends. These changes are important and must be considered for the consistency with the ITRF (e.g. ellipsoidal heights). Nevertheless, in order to keep things simple for the user, this time variability will not be treated in the published definition of a new GRS. All quantities will be fixed to the epoch 2010.0. This is the epoch at which the W_0 of the IAG resolution No. 1 is defined.

All calculations will be done in the zero-tide system. Only at the very end, conversion formulas to mean tide and tide-free will be given for all quantities. In order to keep things simple, some very minor terms in this conversion will be neglected.

Results

A draft of the paper with the calculation of the parameters is available. It follows more or less the structure of the papers by Moritz (1980) and Groten (2004). However, it is not ready to be published to a broader community, since it has not been thoroughly discussed yet and is not in a state of general agreement of the WG members. Therefore, this WG should be continued in some form.

The calculation of a new set of parameters is one thing. The main problem will be to convince the users to adopt such a system as a new global reference. Many users don't see the necessity to replace GRS80, as they just see it as a conventional model for the conversion of geocentric coordinates or for the calculation of gravity anomalies. Main concerns are the danger of confusion and the necessity to update many software packages. This discussion has still to be lead and arguments for and against such a change are still evaluated.

Another question to be answered is the necessity to define a conventional global gravity field model. For many applications (e.g. global height system, reference for local geoid determination), the assignment of such a standard model has some advantages. For different application we would need a low-resolution satellite-only model and a high-resolution combined model.

The progress of the work has been presented in October 2022 at the Unified Analysis Workshop (UAW) in Thessaloniki by D. Angermann and regularly at the GGOS days.

Focus Area "Unified Height System"

Lead: Laura Sánchez (Germany)

With contributions from: *H.A. Abd-Elmotaal (Egypt), J. Ågren (Sweden), H. Denker (Germany), R. Forsberg (Denmark), A. Gómez (Argentina), V.N. Grigoriadis (Greece), T. Gruber (Germany), G. Guimarães (Brazil), J. Huang (Canada), T. Jiang (China), Q. Liu (Germany), J. Mäkinnen (Finland), U. Marti (Switzerland), K. Matsuo (Japan), P. Novák (Czech Republic), D. Smith (USA), M. Varga (Croatia), G. Vergos (Greece), M. Véronneau (Canada), Y. Wang (USA), K. Ahlgren (USA), R. Winefield (New Zealand), M. Amos (New Zealand), D. Avalos (Mexico), M. Bilker-Koivula (Finnland), D. Blitzkow (Brazil), S. Claessens (Australia), X. Collilieux (France), M. Filmer (Australia), A.C.O.C. Matos (Brazil), J. McCubbine (Australia), R. Pail (Germany), D. Roman (USA), H. Teitsson (Faroes), C. Tocho (Argentina), E. Antokoletz (Argentina), H. Wziontek (Germany).*

The GGOS Focus Area "Unified Height System" (GGOS-FA-UHS, formerly Theme 1) was established at the 2010 GGOS Planning Meeting (February 1 - 3, Miami, Florida, USA) to lead and coordinate the efforts required for the establishment of a global unified height system that serves as a basis for the standardisation of height systems worldwide. Starting point was the results delivered by the IAG Inter-Commission Project 1.2 Vertical Reference Frames (IAG-ICP1.2-VRF), which was operative from 2003 to 2011. During the 2011-2015 term, different discussions focussed on the best possible definition of a global unified vertical reference system resulted in the IAG resolution for the Definition and realisation of an International Height Reference System (IHRS) that was approved during the 2015 General Assembly of the International Union of Geodesy and Geophysics (IUGG) in Prague, Czech Republic. In the term 2015-2019, actions dedicated to investigate the best strategy for the realisation of the IHRS (i.e., the establishment of the International Height Reference Frame – IHRF) were undertaken. In particular, a preliminary station selection for the IHRF reference network was achieved and different computation procedures for the determination of potential values as IHRS coordinates were evaluated. For the present term, 2019-2023, the objectives of the GGOS-FA-UHS are (i) to compile detailed standards, conventions, and guidelines to support a consistent determination of the IHRF at global, regional and national levels; (ii) to coordinate with regional/national experts in gravity field modelling the computation of a first IHRF solution; and (iii) to design an operational infrastructure that ensures the long-term sustainability and reliability of the IHRS/IHRF. This infrastructure should operate under the responsibility of the International Gravity Field Service (IGFS).

Networking within the IAG

The implementation of a global reference system for physical heights as the IHRS is a big challenge and requires the support of a wide scientific community. Thus, the installation of the IHRS/IHRF is only possible within a global and structured organisation like the IAG. Presently, following entities are contributing to achieve the goals of the GGO-FA-UHS:

- GGOS-FA-UHS and IGFS working group *Implementation of the International Height Reference Frame (IHRF)*, chairs L Sánchez (Germany) and R Barzaghi (Italy).
- ICCT joint study group *Geoid/quasi-geoid modelling for realization of the geopotential height datum*, chairs: J Huang (Canada), YM Wang (USA).
- IAG SC 2.2: *Methodology for geoid and physical height systems*, chairs: G. Vergos (Greece), Rossen S. Grebenitcharsky (Saudi Arabia).
- IAG Commission 2.2 working group *Error assessment of the 1 cm geoid experiment*, chairs: T Jiang (China), V Grigoriadis (Greece).

- IAG Commission 2 joint working group *On the realization of the International Gravity Reference Frame*, chairs: H. Wziontek (Germany), S. Bonvalot (France)
- GGOS-BPS working group *Towards a consistent set of parameters for a new GRS*, chair U Martí (Switzerland)
- *International Gravity Field Service* – IGFS, chair: R, Barzaghi (Italy), vice-chair: G. Vergos (Greece).

Advances in the establishment of the IHRF

To move forwards in the realisation of the IHRS, we currently concentrate on four primary aspects: (1) specific standards and conventions that ensure consistency between the IHRS definition and the IHRF coordinates; (2) a global reference network for the IHRF; (3) the determination of IHRF coordinates at the reference stations; and (4) an operational infrastructure to guarantee a reliable and long-term sustainability of the IHRS/IHRF. (see a detailed discussion of these four aspects in Sánchez et al. 2021).

Standards and conventions for the IHRS/IHRF

The IHRS is a gravity potential-based reference system: the vertical coordinates are geopotential numbers [$C(P) = W_0 - W(P)$] referring to an equipotential surface of the Earth's gravity field realised by the IAG conventional value W_0 = 62 636 853.4 m^2s^{-2}. The spatial reference of the position P for the potential $W(P) = W(X)$ is given by the coordinates **X** referring to the ITRS/ITRF. Geopotential numbers are defined as the primary vertical coordinate as they can be converted to any type of physical heights (orthometric or normal heights). As the reference value W_0 is constant and conventionally adopted, the IHRS essentially materialises the combination of a geometric component given by the coordinate vector **X** in the ITRS/ITRF and a physical component given by the determination of potential values W at **X**. To be compatible with the ITRF, the accuracy of the IHRF geopotential numbers and their variation with time should be at least $\pm3\times10^{-2}$ m^2s^{-2} (equivalent to $\approx \pm3$ mm in height) and $\pm3\times10^{-3}$ $m^2s^{-2}a^{-1}$ ($\approx \pm0.3$ mm a^{-1}), respectively. However, for the moment, the goal is to reach $\pm1\times10^{-1}$ m^2s^{-2} (about 1 cm) in the static component.

The most pragmatic way to determine potential values W(P) would be to introduce the ITRF coordinates of any point into the harmonic expansion equation representing a global gravity model (GGM) of high degree (up to degree 2190 or higher). These models could provide potential values with accuracies of around ±0.2 m^2s^{-2} (equivalent to ±2 cm in height) in regions with flat and moderate terrains when dense and consistent gravity data are used in the computation of the GGM. If no regional gravity data are available to be included in the GGM, the best possible mean accuracy offered by these models would be around ±2.0 m^2s^{-2} (±0.2 m), or even worse (up to ±10 m^2s^{-2} or ±1 m) in regions with strong topography gradients. To increase this accuracy, the values W(P) could be determined from gravity field observables applying appropriate modelling strategies, which in general correspond to geoid or quasi-geoid computation methods. In the geoid/quasi-geoid computation, the primary functional to be determined is the disturbing potential $T = W - U$. If the disturbing potential T(P) is known, the determination of station potential values W(P) is straightforward. However, the determination of the disturbing potential relies not only on the available gravity data but also on the gravity field modelling approaches. This includes different methods for the handling of terrain effects, the filtering and combination of surface gravity data, the treatment of long-wavelength errors, the mathematical formulations to invert and to integrate gravity and terrain observations, etc. Since there are so many parameter choices when handling the gravity and terrain data, the obtained potential values inevitably vary from computation to computation. Thus, different groups can generate quite different results from the same input data, see Fig. 1. Nevertheless, to define only one standard procedure for the computation of potential values is unsuitable as different data availability and different data quality exist around the world, and additionally, regions with different characteristics require particular approaches (e.g. modification of kernel functions, size of integration caps, geophysical reductions like GIA, etc.). On the other hand, a centralised computation of the IHRF coordinates (like in the ITRF) also poses a problem due to the restricted accessibility to terrestrial gravity data.

In order to get as similar and compatible results as possible, we complied a set of basic standards covering general constants, reference ellipsoid, mass centre convention, zero-degree correction to realise the vertical datum defined by the conventional W_0 value, standardised formulas for the conversion of potential coordinates between different permanent tide systems, and a standardised procedure to recover potential values from existing regional/national geoid or quasi-geoid models. The latter is of particular importance as (1) the regional geoid/quasi-geoid models include surface gravity data sets that are not always available for the determination of GGM, (2) the regional models can assimilate new regional/local gravity surveys very quickly, and (3) national/regional experts on gravity field modelling have the best possible knowledge about the local conditions (topography, data distribution, geophysical corrections, validation data, etc.) to be considered in the computation of the geoid/quasi-geoid, or more precisely, in the determination of the disturbing potential T in their countries/regions.

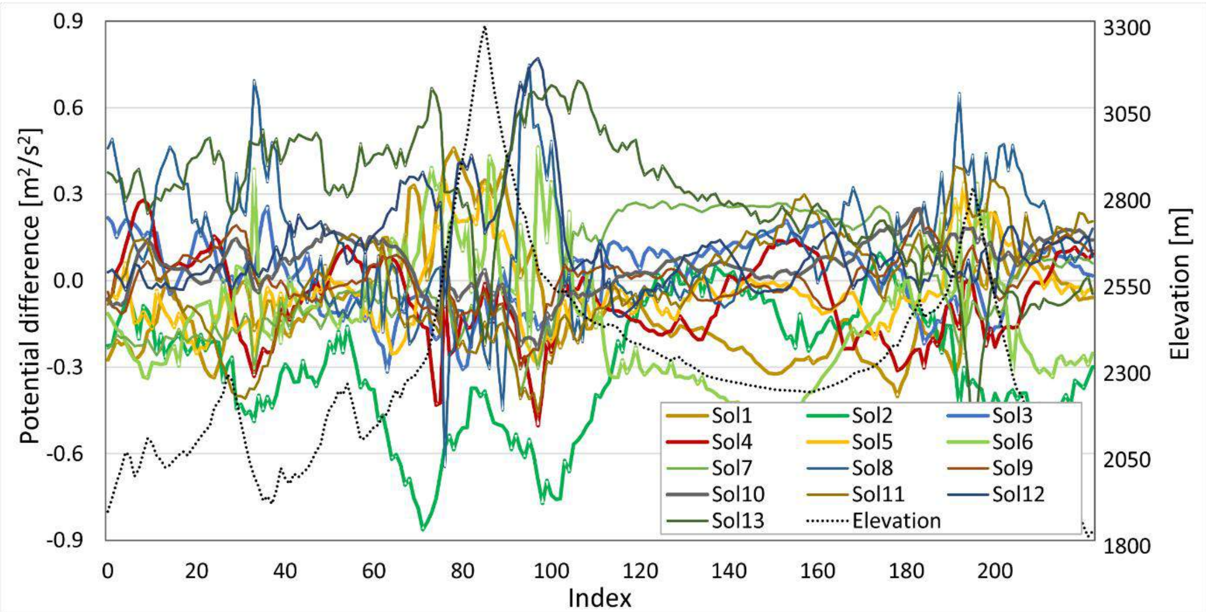

Fig. 1 Comparison of potential values obtained from different approaches using the same input gravity data: Standard deviation of the differences between C(P) from gravity field modelling and from levelling varies from 0.12 m2s-2 (~1.2 cm) to 0.78 m2s-2 (7.8 cm).

Global reference network of the IHRF

The main criteria for the selection of IHRF reference stations were defined as:

- GNSS continuously operating reference stations to detect reference frame deformations (with preference for stations belonging to the ITRF and the regional reference frames like SIRGAS, EPN, APREF, etc.);
- Co-location with fundamental geodetic observatories to ensure a consistent connection between geometric coordinates, potential and gravity values, and reference clocks;

- Co-location with reference stations of the International Gravity Reference Frame (IGRF) to integrate the gravity and physical height reference frames;
- Co-location with reference tide gauges and connection to the national levelling networks to facilitate the vertical datum unification;
- Availability of terrestrial gravity data around the IHRS reference stations as main requirement for high-resolution gravity field modelling (i.e., precise estimation of potential values).

Based on this criteria, a preliminary station selection for the IHRF was initiated in 2016. This selection was based on a global network with worldwide distribution, including a core network (to ensure sustainability and long-term stability of the reference frame) and regional/national densifications (to provide local accessibility to the global frame). The core network includes fundamental geodetic observatories, ITRF sites with more than two space geodetic techniques, IGRF reference stations and selected IGS reference stations to ensure a global coverage as homogeneous as possible. During 2017-2018, regional and national experts were asked to evaluate whether the preliminary selected sites are suitable to be included in the IHRF (availability of gravity data or possibilities to survey them); and to propose additional geodetic sites to improve the density and distribution of the IHRF stations in their regions/countries. After the feedback from the regional/national experts, the first approximation to the IHRF reference network was completed in 2019. This network comprises about 170 stations (Fig. 2) and currently, it is regularly refined in agreement with changes/updates of other geodetic reference frames (ITRF and IGRF and their densifications).

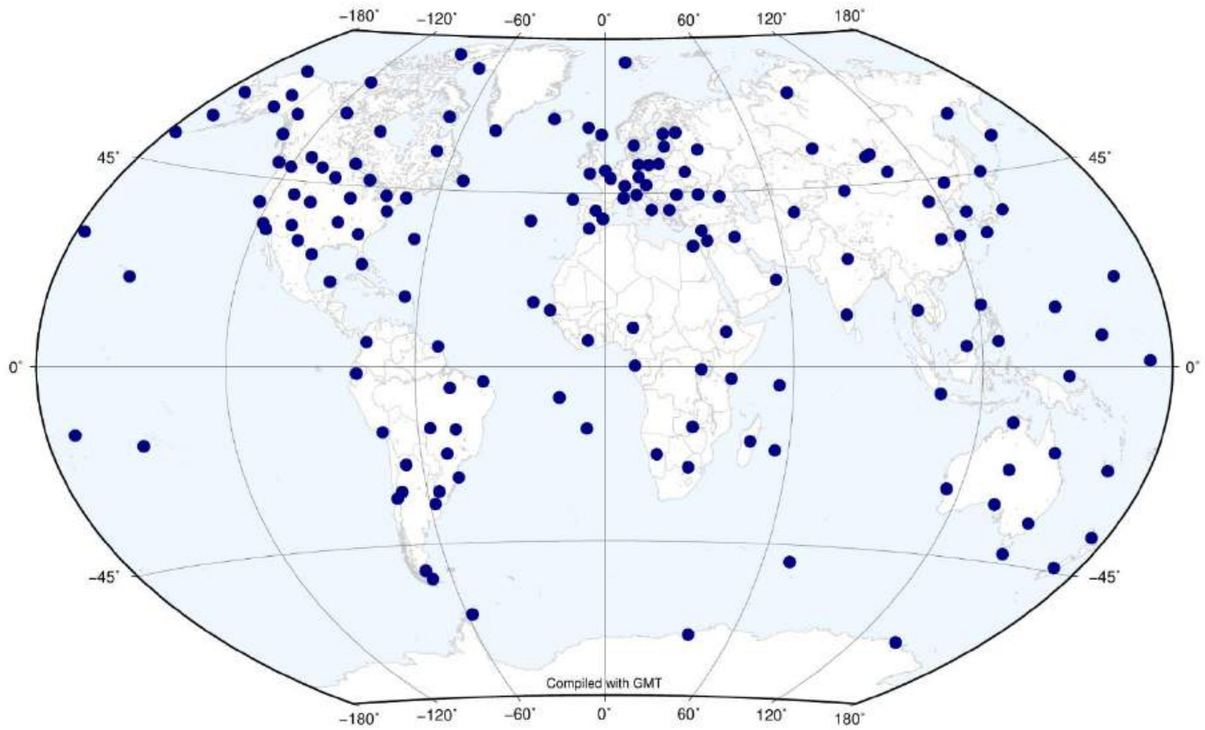

Fig. 2 IHRF core network (as of June 2023)

Determination of IHRF coordinates

A key activity in this regard was the evaluation of different methodologies for the determination of potential values as IHRS/IHRF reference coordinates within the so-called Colorado experiment. This experiment aimed at computing geoid, quasi-geoid and potential values using the same input data and the own methodologies of colleagues involved in the gravity field modelling. About 40 colleagues grouped in fourteen international computation groups contributed to this initiative. The Colorado experiment started at the IAG/IASPEI Scientific Assembly (Aug 2017, Kobe). First results were discussed at the GGHS2018 Symposium (Sep 2018, Copenhagen). A second computation was ready for the EGU2019 (Apr 2019, Vienna) and some refinements (third computation) were delivered in Jun 2019. The results were extensively discussed at the IUGG2019, Symposium G02: Static Gravity Field and Height Systems (July 2019, Montreal).

The input gravity and topographic data, the GNSS/levelling validation data, and the 14 geoid and quasi-geoid models produced within the Colorado experiment are available from the International Service for the Geoid (https://www.isgeoid.polimi.it/Projects/colorado_experiment.html) and can be used as a basis to evaluate any geoid computation method or software anywhere.

Based on the efforts of the previous term 2015-2019, in particular, the outcomes of the Colorado experiment, we classified the computation of potential values in three main scenarios:

a) Regions without (or with very few) surface gravity data,
   - The only option to determine potential values is the use of GGM of high resolution
   - Expected mean accuracy values around the ±4.0 m^2s^{-2} (±40.0 cm in terms of height) level or even worse in regions with strong topography gradients
   - It could be improved for instance to the ±1.0 m^2s^{-2} (±10.0 cm) level if new and better surface gravity data are included in the GGMs.
   - To avoid multiple potential values provided by different GGM-HRs at the same point, it is necessary to select one GGM-HR as reference model.
b) Regions with some surface gravity data, but with poor data coverage or unknown data quality,
   - The reliability of the existing (quasi-)geoid models is poor
   - Additional gravity surveys around the IHRF stations would help to increase the accuracy of the geopotential numbers computed at those specific stations.
c) Regions with good surface gravity data coverage and quality.
   - Potential values may be inferred from precise geoid/quasi-geoid regional models.

Using this classification, we started in the beginning of 2021 the computation of a first solution for the IHRF. As an initial action, a short description of the "step by step" to infer IHRF potential values from local/regional geoid/quasi-geoid models was prepared. It is based on the IHRS paper published by Sánchez et al. (2021) and was distributed to the members of the working group *Implementation of the International Height Reference Frame (IHRF)*, so that they can compute potential values at the IHRF stations located in their countries using their present/latest geoid/quasi-geoid models. This activity is supported by about 40 colleagues from Canada, Mexico, USA, Germany, Italy, Switzerland, Austria, Sweden, Finland, Australia, Japan, China, South America, Russia, and Africa. Complementary, the ISG and the IGFS are evaluating the quality and documentation of the different regional models available at the Geoid Repository of ISG in order to identify which models can be used to infer potential values. This action is useful for the IHRF computation in areas underrepresented in the working group.

Simultaneously, we are computing potential values for all the IHRF stations (Fig. 2) using GGM extended with topography-based synthetic gravity signals, reaching resolutions up to degree ~ 80000 … ~ 90000. As mentioned, this would be the only option available in those regions where no geoid/quasi-geoid models are available. At the end, we will have different potential values for the same points. The agreement of the different GGM and the models stored by ISG with the own computations performed by the colleagues of the working group will allow us to decide which GGM+topography models perform better. The results of these computations will be presented at the next IUGG2023 General Assembly in Berlin, Germany.

Special Issue of the Journal of Geodesy on "*Reference System in Physical Geodesy*"

Based on the advances for the establishment of the IHSR/IHRF and the International Terrestrial Gravity Reference System and Frame (ITGRS/ITGRF), a special issue on *Reference Systems in Physical Geodesy* of the Journal of Geodesy has been completed. With the 18 papers in this special issue, important issues related to the establishment of the IHRF and ITGRF as well as to the improvement of accurate geoid modelling and the long-term stability of absolute gravity observations have been addressed. We are grateful to all authors for the efforts. A large number of international colleagues served as reviewers for the manuscripts, a laborious and time-consuming task. We thank them all for their important and diligent work. Finally, we would like to thank the Editor-in-Chief, Jürgen Kusche, for his generous and indispensable support in the editorial process, from the development of the special issue to its final publication. The papers included in this special issue are (papers contributing to this report are marked in fett):

Antokoletz ED, Wziontek H, Tocho CN *et al.* (2020) Gravity reference at the Argentinean–German Geodetic Observatory (AGGO) by co-location of superconducting and absolute gravity measurements, J Geod 94, 81, https://doi.org/10.1007/s00190-020-01402-7.

Bilker-Koivula M, Mäkinen J, Ruotsalainen H, *et al.* (2021) Forty-three years of absolute gravity observations of the Fennoscandian postglacial rebound in Finland, J Geod 95, 24, https://doi.org/10.1007/s00190-020-01470-9.

Claessens SJ, Filmer MS (2020) **Towards an International Height Reference System: insights from the Colorado experiment using AUSGeoid computation methods**, J Geod 94, 52, https://doi.org/10.1007/s00190-020-01379-3.

Grigoriadis VN, Vergos GS, Barzaghi R et al (2021) **Collocation and FFT-based geoid estimation within the Colorado 1 cm geoid experiment**, J Geod 9, 52, https://doi.org/10.1007/s00190-021-01507-7.

Işık MS, Erol B, Erol S, Sakil FF (2021) **High-resolution geoid modeling using least squares modification of stokes and hotine formulas in Colorado**, J Geod 95, 49, https://doi.org/10.1007/s00190-021-01501-z.

Liu Q, Schmidt M, Sánchez L, Willberg M (2020) **Regional gravity field refinement for (quasi-) geoid determination based on spherical radial basis functions in Colorado**, J Geod 94, 10, https://doi.org/10.1007/s00190-020-01431-2.

Mäkinen J (2021) **The permanent tide and the International Height Reference Frame IHRF**, J Geod 95, 106, https://doi.org/10.1007/s00190-021-01541-5.

Oja T, Mäkinen J, Bilker-Koivula M, *et al.* (2021) Absolute gravity observations in Estonia from 1995 to 2017, J Geod 95, 131, https://doi.org/10.1007/s00190-021-01580-y.

Pálinkáš V, Wziontek H, Vaľko M, *et al.* (2021) Evaluation of comparisons of absolute gravimeters using correlated quantities: reprocessing and analyses of recent comparisons, J Geod 95, 21, https://doi.org/10.1007/s00190-020-01435-y.

Sánchez L, Ågren J, Huang J, Wang YM, Mäkinen J, Pail R, Barzaghi R, Vergos GS, Ahlgren K, Liu Q (2021) **Strategy for the realisation of the International Height Reference System (IHRS)**, J Geod, 95, 3, https://doi.org/10.1007/s00190-021-01481-0.

Scherneck HG, Rajner M, Engfeldt A (2020) Superconducting gravimeter and seismometer shedding light on FG5's offsets, trends and noise: what observations at Onsala Space Observatory can tell us, J Geod 94, 80, https://doi.org/10.1007/s00190-020-01409-0.

Schilling M, Wodey É, Timmen L. *et al.* (2020) Gravity field modelling for the Hannover 10 m atom interferometer, J Geod 94, 122, https://doi.org/10.1007/s00190-020-01451-y.

Van Westrum D, Ahlgren K, Hirt C, Guillaume S (2021) **A Geoid Slope Validation Survey (2017) in the rugged terrain of Colorado**, USA, J Geod 95, 9, https://doi.org/10.1007/s00190-020-01463-8.

Varga M, Pitoňák M, Novák P, Bašić T (2021) **Contribution of GRAV-D airborne gravity to improvement of regional gravimetric geoid modelling in Colorado**, USA, J Geod 95, 53, https://doi.org/10.1007/s00190-021-01494-9.

Wang YM, Li X, Ahlgren K, Krcmaric J (2020) **Colorado geoid modeling at the US National Geodetic Survey**, J Geod 94, 106, https://doi.org/10.1007/s00190-020-01429-w.

Wang YM, Sánchez L, Ågren J, Huang J, Forsberg R, Abd-Elmotaal HA, Barzaghi R, Bašić T, Carrion D, Claessens S, Erol B, Erol S, Filmer M, Grigoriadis VN, Isik MS, Jiang T, Koç Ö, Li X, Ahlgren K, Krcmaric J, Liu Q, Matsuo K, Natsiopoulos DA, Novák P, Pail R, Pitoňák M, Schmidt M, Varga M, Vergos GS, Véronneau M, Willberg M, Zingerle P (2021) **Colorado geoid computation experiment – Overview and summary**, J Geod, 95, 12, https://doi.org/10.1007/s00190-021-01567-9.

Willberg M, Zingerle P, Pail R (2020) **Integration of airborne gravimetry data filtering into residual least-squares collocation: example from the 1 cm geoid experiment**, J Geod 94, 75, https://doi.org/10.1007/s00190-020-01396-2.

Wziontek H, Bonvalot S, Falk R, Gabalda G, Mäkinen J, Pálinkáš V, Rülke A, Vitushkin L (2021) Status of the International Gravity Reference System and Frame, J Geod 95, 7, https://doi.org/10.1007/s00190-020-01438-9.

Operational infrastructure to ensure the long-term sustainability of the IHRS/IHRF

An IHRS/IHRF objective is to support the monitoring and analysis of Earth's system changes. The more accurate the IHRS/IHRF is, the more phenomena can be identified and modelled. Thus, the IHRS/IHRF must provide vertical coordinates and their changes with time as accurately as possible. As many global change phenomena occur at different scales, the global frame should be extended to regional and local levels to guarantee consistency in the observation, detection, and modelling of their effects. From this perspective, we are proposing the establishment of an operational infrastructure within the IGFS that takes care of

a) Maintenance of the IHRF reference network in accordance with the GGOS-BNO and the coordinators of the reference networks for the ITRF, IGRF and their regional densifications. This activity should be faced by the IHRF reference network coordination (see blue boxes in Fig. 3).
b) Maintenance of a catalogue with the conventions and standards needed for the IHRF. This should consider a harmonisation with the conventions and standards kept by the GGOS-BPO, the IERS Conventions (for the determination of the ITRF), and the standards applied in the IGRF and the global gravity field modelling. This task should be carried out by the IHRF conventions' coordination (see pink boxes in Fig. 3).
c) The national/regional agencies/entities contributing to the realisation of the IHRF in their regions may be declared as IHRF national/regional computation centres (dark blue box in Fig. 3). The input data would then be provided by existing IAG gravity field services and local data centres; e.g., GGM are provided by ICGEM and surface gravity data are provided by the Bureau Gravimétrique International (BGI) and

refined/complemented with gravity data available at local data centres. In a similar way, one can proceed with digital elevation models (see violet box in Fig. 3).

d) In an ideal data flow scheme, the national/regional IHRF computation centres would provide the IGFS with the following products (cyan box in Fig. 3): potential values at the IHRF reference stations; vertical datum unification parameters (to transform the existing local height systems to the IHRF); mean gravity anomalies or disturbances (without violating data confidentiality but contributing to the determination of improved GGMs); and regional geoid/quasi-geoid models of high resolution. The mean gravity anomalies (or disturbances) and the geoid/quasi-geoid models would be then managed by BGI and ISG. For the combination of the regional/national solutions, validation, storage, management, and servicing of potential values at IHRF stations and vertical datum parameters, the IGFS would have to establish a new element, which could be called IHRF product centre (see magenta boxes in Fig. 3).

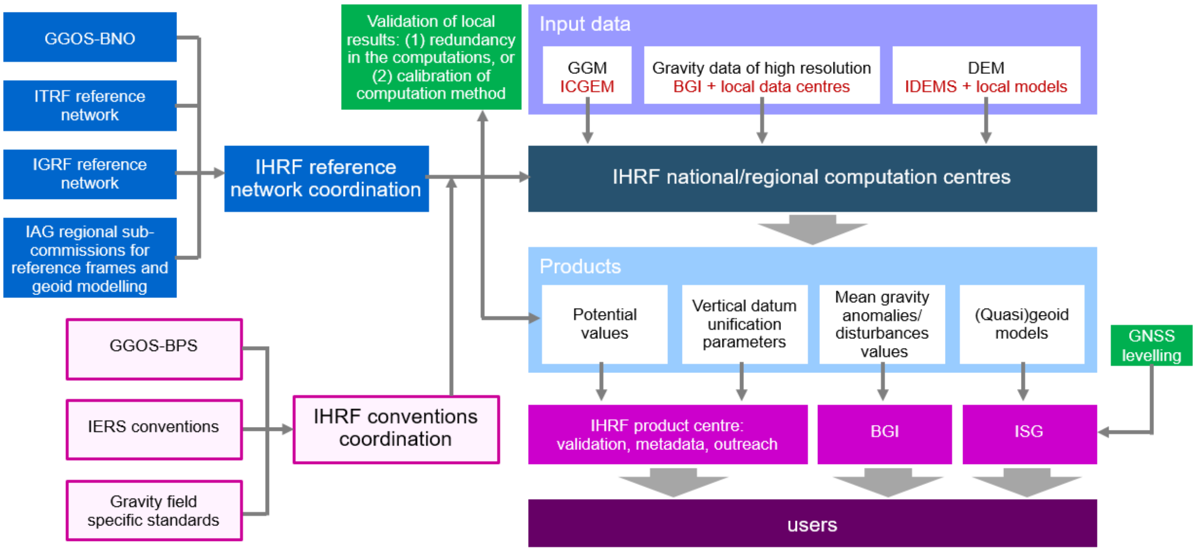

Fig. 3 Proposal for an IHRF operational infrastructure within the IGFS

The IHRF operational infrastructure within the IGFS will be managed by the *IHRF Coordination Centre*. Presently, we are preparing the terms of reference for this centre for approval by the IAG Executive Committee. With this centre established in the IGFS, we can declare the objectives of the GGOS-FA-UHS accomplished and this FA will be decommissioned at the IUGG2023 General Assembly.

GGOS Geohazards Focus Area

Focus Area Lead: John LaBrecque
Center for Space Research, U. Texas Austin
Austin, Texas
email: jlabrecq@mac.com

Activities, Actions, and Publications during 2019-2023:

Introduction: The concept of GNSS Tsunami Early Warning Systems (GTEWS) was borne of the societal suffering inflicted by the Great Indian Ocean Earthquake and Tsunami of Boxing Day 2004. We learned that the existing sparse regional IGS network of GPS receivers could have provided warning of the impending tsunami within 15 minutes of the initial fault zone rupture that produced the tsunami, many hours in advance of the seismological warning. GTEWS related research was further advanced by the Japanese GEONET realtime network measurements of the 2011 Tohoku Oki earthquake. Analysis of the GEONEt GNSS data demonstrated that an accurate tsunami prediction could be generated within 5 minutes of the initial fault rupture using the existing infrastructure. The GEONET data also demonstrated that ionospheric Total Electron Content measurements could also provide images of the development and propagation of the tsunami beginning within ten minutes of initial ocean uplift.

The 2019-2023 activities of GGOS Geohazards Focus Area (GGOS Geohazards) involve nearly a decade of continuous effort. Therefore, we will provide a brief recap of the integrated effort since 2015 to provide perspective on our efforts. GGOS Geohazards maintains a library containing relevant documents, presentations, newsletters, videos and other files of interest to the GATEW community at the following link https://www.dropbox.com/sh/fg20mtydg136vx6/AABNr2kSnMo429nCxEHhBDfoa?dl=0 .

Activities During 2015-2019: These significant demonstrations of GNSS based Tsunami Disaster Early Warning prompted the GGOS encourage the 2015 General Assembly adoption of Resolution #4 calling for the IUGG membership to support the development of a GNSS augmentation to Tsunami Warning Systems within the Indo-Pacific. On April, 2016 the GGOS issued its Call for Participation in the GNSS Augmentation for Tsunami Early Warning (GATEW) working group in support of Resolution #4. The GATEW working group now includes 18 institutions from 12 nations with substantial experience and roles in the development of geodetic applications to disaster risk reduction. The GGOS Geohazards collaborated with the Association of Pacific Rim Universities (APEC), NASA and the IUGG Commision on Geophysical Risk and Sustainability (GRC) to conduct the GTEWS 2017 workshop to explore the feasibility and utility of GTEWS.

Activities during 2019-2023: The GTEWS 2017 workshop report was published by the APRU in 2019 and subsequently UNDRR in 2020 as a contributing paper to its Global Assessment Report of 2019. The work shop report reviews the scientific and programmatic developments of GTEWS, endorses the development of an Indo-Pacific GTEWS and provides specific recommendations to insure a strong Indo-Pacific GTEWS program. The first recommendation was the formation of a "GNSS Shield Consortium" to apply the GTEWS 2017 recommendation for the establishment of an Indo-Pacific GTEWS program in support of the UNDRR Sendai Framework for Disaster Risk Reduction.

Scientific development of the GTEWS 2017 was significantly slowed by the COVID 19 pandemic that restricted international collaboration. Despite these restrictions the IGS, GRC and the GGOS/Geohazards FA worked with GEO to develop the Geodesy for Sendai framework to develop collaborations for the application of GNSS to goals of the Sendai Framework of the UNDRR. Geodesy4Sendai was codified in the GEO Work Programme of 2020-2022 and 2023 to 2O25. within the Geodesy for Sendai Framework. The GRC applied was granted $10K by the IUGG to support the organization of the GTEWS Coordinating Committee as recommended by the GTEWS 2017 workshop.

***Activities during* 2023:** The implementation of GTEWS continued as recommended by the IUGG Resolution #4 within the individual programs of Indian, Japanese, Chilean, and US agencies. Unfortunately, as noted by the GTEWS 2017 workshop report, a reticence persists among several Indo-Pacific nations to engage in the sharing of real time GNSS essential for the realization operation of an Indo-Pacific GTEWS. The GGOS Geohazards recognizes that GTEWS for the Indo-Pacific will require significant international collaboration between institutions and agencies. Our activities work to implement this important need for international collaboration.

The GGOS Geohazards. the IGS and the GRC have joined in support of the UN ICG Working Group task force on “Applications of GNSS for Disaster Risk Reduction” (Geodesy4DRR). The IGS published Stop 5 of the Tour de l’IGS that focussed upon GNSS Applications to the South Pacific Disaster Risk Reduction. Stop 5 included a report by the GRC/GGOS_Geohazards recommendation on the formulation of GTEWS_Oceania. The GTEWS_Oceania concept recognizes the need to develop a South Pacific real time GNSS network in support GTEWS as well as numerous other GNSS applications to environmental hazard risk reduction. The GRC and the GATEW working group members as well as the IGC Geodesy4DRR task force are engaging the member nations of the Oceania region in the formulation of GTEWS_Oceania. GTEWS_Oceania is holding monthly meetings to resolve a development plan for the GTEWS network.

Future Activities:

Following the GTEWS 2017 workshop report, the objective is to establish a governing council to determine data policy, identify resources, and establish a development plan to establish a GTEWS_Oceania network and analysis capability. It is too early to resolve the success of the GTEWS_Oceania Initiative but there is a growing participation by the nations of Oceania.

A draft Charter (Terms of Reference) is under review and implementation plans are being developed by a growing number of participating nations. The Oceania region has a significant number of GNSS receivers of varying quality and varying communications capability. Resources will be needed to upgrade these receiver stations and provide the regional broadband communications as well analysis systems. Discussions are underway to apply the $10K IUGG/GRC grant as a matching grant to further develop further resources for GTEWS_Oceania.

GGOS Focus Area 'Geodetic Space Weather Research'

Chair: Michael Schmidt (Germany)
Vice-Chair: Ehsan Forootan (Denmark)

Introduction

Space weather is a very up-to-date and interdisciplinary field of research. It describes physical processes in the near-Earth space mainly caused by the Sun's radiation of energy. The manifestations of space weather are multiple, e.g. variations of the Earth's magnetic field, variations of the upper atmosphere consisting of the compartments magnetosphere, ionosphere, plasmasphere, and thermosphere, also known as the MIPT system (due to coupling processes), as well as solar wind, i.e. the permanent emission of electrons and photons including the interplanetary magnetic field (IMF), i.e. the component of the solar magnetic field that is dragged out from the solar corona by the solar wind flow. The magnetosphere is the part of the near-Earth space, in which the total magnetic field is dominated by the Earth's magnetic field and not by the IMF. It is well-known that the pressure of the solar wind compresses the magnetic field on the day side of the Earth and stretches it into a long tail on the night side.

Activities

The GGOS Focus Area on Geodetic Space Weather Research (FA-GSWR) has been installed in 2017. At the FA-GSWR splinter meeting during the IUGG 2019 General Assembly in Montreal, it was decided to extend the scientific content of the FA-GSWR by the magnetosphere and the plasmasphere such that it now deals with the complete MIPT system and the mutual couplings. As shown in Fig. 1, the scientific structure of the FA-GSWR can be visualised now as a double tetrahedron.

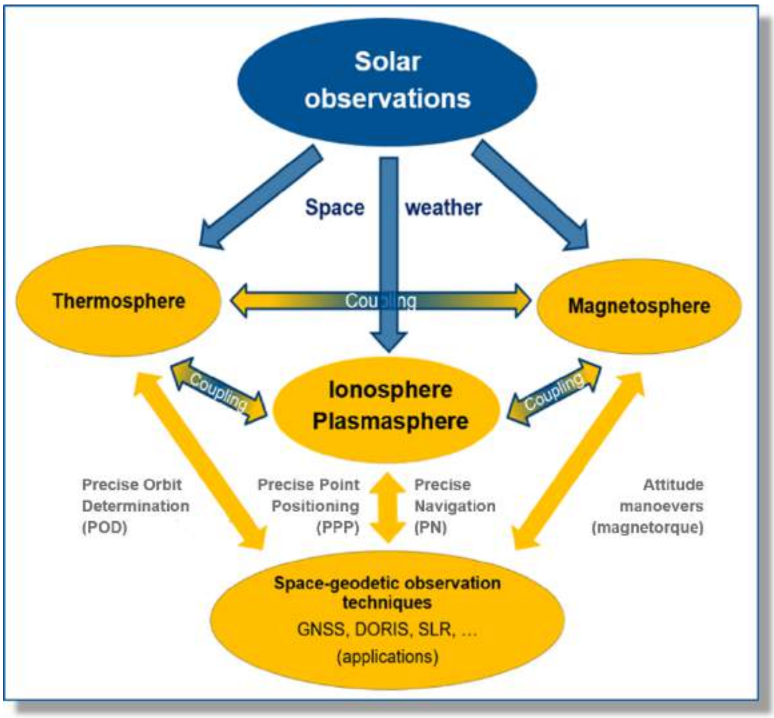

Fig. 1: Structure of the FA-GSWR including the plasmasphere and the magnetosphere: the yellow-coloured parts are related to geodetic applications such as Precise Orbit Determination (POD) and Precise Point Positioning (PPP); the blue-coloured parts are related to solar phenomena especially to space weather.

The most important task of the FA-GSWR is the development of a concept for the combined evaluation of measurements from solar and geodetic satellite missions, as well as magnetic field information under the consideration of the physical coupling processes. Although rather challenging, this concept plays the most important role to reach the main objectives of the FA-GSWR, namely the development of an

(1) improved electron density model of the ionosphere including the plasmasphere and an

(2) improved model of the neutral density in the thermosphere.

In a study, members of the FA-GSWR proposed that both the electron density and the neutral density should be interpreted as so-called Essential Geodetic Variables (EGV); consequently, the developed improved models should finally be provided as GGOS products to potential users.

To approach these goals, an IAG GGOS Joint Study Group (JSG) and three IAG GGOS Joint Working Groups (JWG) have been established within the FA-GSWR. These IAG GGOS groups are entitled as

JSG 1: Coupling processes between magnetosphere, thermosphere, and ionosphere (implemented within the IAG ICCT and joint with GGOS)

JWG 1: Electron density modelling (joint with IAG Commission 4)

JWG 2: Improvement of thermosphere models (joint with IAG Commission 4)

JWG 3: Improved understanding of space weather events and their monitoring by satellite missions (joint with IAG Commission 4).

Their achievements in the last 4 years will be presented in more details in what follows.

The special issue 'Observing and Modelling Ionosphere and Thermosphere using in situ and Remote Sensing Techniques' of the journal 'Remote Sensing' was initiated by members of the FA-GSWR. The deadline for manuscript submission was December 31, 2020.

Website

We have significantly updated the GGOS web pages about the FA-GSWR (https://ggos.org/about/org/fa/geodetic-space-weather-research/) by including more information about space weather in general, but also more detailed information about the work in the JSG and the 3 JWGs. Furthermore, we added on the GGOS web page 'Geodetic Products' information about ionosphere and thermosphere products.

2nd IAG Commission 4 'Positioning and Applications' Symposium

Due to the Corona pandemic many of the planned activities at conferences and workshops did not work out during the reporting period and had to be postponed. One example is the 2nd IAG Commission 4 Symposium, which was originally scheduled for September 2020. It finally took place from September 5th to 8th, 2022, at Wissenschaftsetage Potsdam. The Symposium website (https://www.iag-commission4-symposium2022.net/) created by Copernicus GmbH will be available at least for a five-year timeframe. The scientific program of the symposium included altogether nine sessions. Some of them were arranged according to the IAG Commission 4 structure, and others were dedicated to the special topics of the FA-GSWR, namely (1) to Atmospheric Remote Sensing of the Ionosphere and (2) to the topics of the FA itself. The corresponding presentations and posters are part of the open access Symposium Proceedings and can be downloaded from https://zenodo.org/communities/iag-comm4-symp-2022/.

Apart from the scientific programme, a Joint Splinter Meeting of the IAG Sub-Commission 4.3 and the FA-GSWR took place; furthermore, an IAG, FA-GSWR and IAGA (International Association of Geomagnetism and Aeronomy) Splinter Meeting on the specific topic of "Space Weather Research" took place at the end of the symposium. During this meeting it was discussed how a joint inter-association study group on space weather topics within the IUGG can be established. Since there are already examples of this type of joint study group within the IAG, we planned to create a list of objectives for such a joint inter-association study group that would combine the activities of IAG and IAGA. A further discussion is now scheduled for the IUGG 2023 General Assembly, which will be held in Berlin from July 11 to 20, 2023. One of the goals of such a study group will be to develop a roadmap for the establishment of international space weather data centres and space weather services for scientific purposes. While space weather services, including warning systems for the public, must be installed by the governments of countries such as Germany, i.e., they are national institutions, the question here, for example, is how measurements from different scientific fields such as geodesy and solar physics can be combined to enable reliable prediction of space weather events. To solve these and other problems in space weather research, it is necessary to form an international team that brings together as much experience as possible.

Other issues

Many papers related to the scientific content of the JSG 1 and the JWG1 to JWG3 have been written in the last years. Significant progress has also been made in third-party funded national and international projects; the work within these projects is often strongly coupled with the objectives of individual groups of FA-GSWR.

On the next pages an overview of the scientific work of the JWGs of the FA-GSWR within the last four years, i.e. the reporting period 2019 to 2023, is provided.

JSG 1 (JSG T.27): Coupling processes between magnetosphere, thermosphere and ionosphere

Chair: Andres Calabia (China)
Vice-Chair: Munawar Shah (Pakistan)
Research Coordinator: Binod Adhikari (Nepal)

(Led by ICCT; joint with GGOS, Focus Area on Geodetic Space Weather Research and Commission 4, Sub-Commission 4.3)

Members

Christine Amory-Mazaudier (France, Italy)
Astrid Maute (USA)
Yury Yasyukevich (Russia)
Gang Lu (USA)
Anoruo Chukwuma (Nigeria)
Oluwaseyi Emmanuel Jimoh (Nigeria)
Munawar Shah (Pakistan)
Binod Adhikari (Nepal)
Andres Calabia (China)
Piyush M. Mehta (USA)
LiangLiang Yuan (Germany)
Naomi Maruyama (USA)
Toyese Tunde Ayorinde (Brazil)
Charles Owolabi (Nigeria)
Emmanuel Abiodun Ariyibi (Nigeria)
Olawale S. Bolaji (Australia)

Since this study group is part of the Inter-Commission Committee on Theory (ICCT), the mid-term report of JSG 1 (JSG T.27) can be found in the ICCT Section of this report and is not repeated here.

JWG 1: Electron density modelling

Chair: Fabricio dos Santos Prol (Germany)
Vice-Chair: Alberto Garcia-Rigo (Spain)
(Led by GGOS; joint with Commission 4, Sub-Commission 4.3)

Members

A. Goss (Germany)
A. Smirnov (Germany)
B. Nava (Italy)
D. Themens (United Kingdom)
F. Arikan (Turkey)
G. Jerez (Brazil)
G. Seemala (India)
H. Lyu (Spain)
J. Norberg (Finland)
K. Alazo (Italy)
M. Hoque (Germany)
M. Muella (Brazil)
Mir-Reza Razin (Iran)
O. Arikan (Turkey)
S. Jin (China)
S. Karatay (Turkey)
S. Yildiz (Turkey)
T. Gerzen (Germany)
T. Kodikara (Germany)
Y. Migoya-Orue' (Italy)

Activities during the period 2019-2023

The objective of JWG 1 Electron density modelling is to evaluate and improve established methods of 3D electron density estimation in terms of electron density, peak height, Total Electron Content (TEC), or other derived products that can be effectively used for GNSS positioning or studying perturbed conditions due to representative space weather events. Figure 2 shows the main steps planned in the group. The steps were achieved through the realization of three main points:

- Development of a database, where the methods from the group members were evaluated using a common ground in terms of reference data. Besides ionosonde measurements, we have gathered in-situ data from C/NOFS, DMSP, GRACE and SWARM missions. Electron density profiles from Incoherent Scatter Radar and GNSS radio-occultation (RO) were also included in the analysis, as well as TEC measurements from altimeters and other LEO satellites with receivers for precise orbit determination.
- Pragmatic assessment of established methods for 3D electron density was performed to define their accuracy related to specific parameters of high importance for Space Weather and Geodesy.
- Papers were published indicating the space weather conditions and expected errors of the methods.

The first two years (2019-2021) of the project development were devoted to establishing a fair database for our evaluations, selecting proper instruments and pre-processing techniques to the dataset. The remaining two years (2021-2023) were for the model developments and evaluations. A few campaigns were created to carry out a pragmatic model evaluation between the members. We have chosen 4 geomagnetic storms as basis for the analysis in case of disturbed days.

The following activities have been conducted based on the created dataset or within the group cooperation. A direct comparison between several models was investigated by Kodikara et al. (2021). We have conducted a few cross-validations between the electron density measurements provided by the instruments used in the dataset (Smirnov et al. 2021). We have also checked the feasibility of using ionosonde observations to evaluate established TEC models (Jerez et al. 2021). A high-resolution global-scale tomography was developed and evaluated by Prol et al. (2021b). A new climatological model was developed and evaluated by Hoque et al. (2022). Swarm in-situ measurements were used to improve ionospheric forecast of the Coupled Thermosphere Ionosphere Plasmasphere electrodynamics (CTIPe) (Fernandez-Gomez et al., 2022). A novel technique was developed to estimate differential code bias (DCB) based on receivers dedicated to LEO-POD (Hernández-Pajares et al., 2023). A new method was developed to extract electron density RO retrievals based on truncated measurements of the topside ionosphere (Hoque et al., 2023). A novel neural network model of Earth's topside ionosphere was developed (Smirnov et al., 2023).

A crucial problem identified in the current ionospheric models was the lack of a correct description of the topside ionosphere and plasmasphere. We understand now that empirical modelling of electron density needs to be essentially improved above the F2 layer peak (hmF2) for a better characterization of the topside TEC (Prol et al. 2019), which can contribute from 10% to 60% to the ground-based TEC measurements. In this regard, a few studies of the group were devoted to better characterise the upper part of the ionized atmosphere. Recent advances from Prol et al. (2021a) and Prol and Hoque (2021) have shown that great improvements on the topside ionosphere and plasmasphere can be obtained in comparison to typical models, especially during disturbed conditions of storm events. Prol and Hoque (2022) have also investigated the performance of tomography techniques to reconstruct the plasmasphere. Despite limited accuracy, it was feasible to propose a new method to develop further investigations of the region. Prol et al. (2022) have further discovered a way to combine the ionosphere and plasmasphere trough empirical relations.

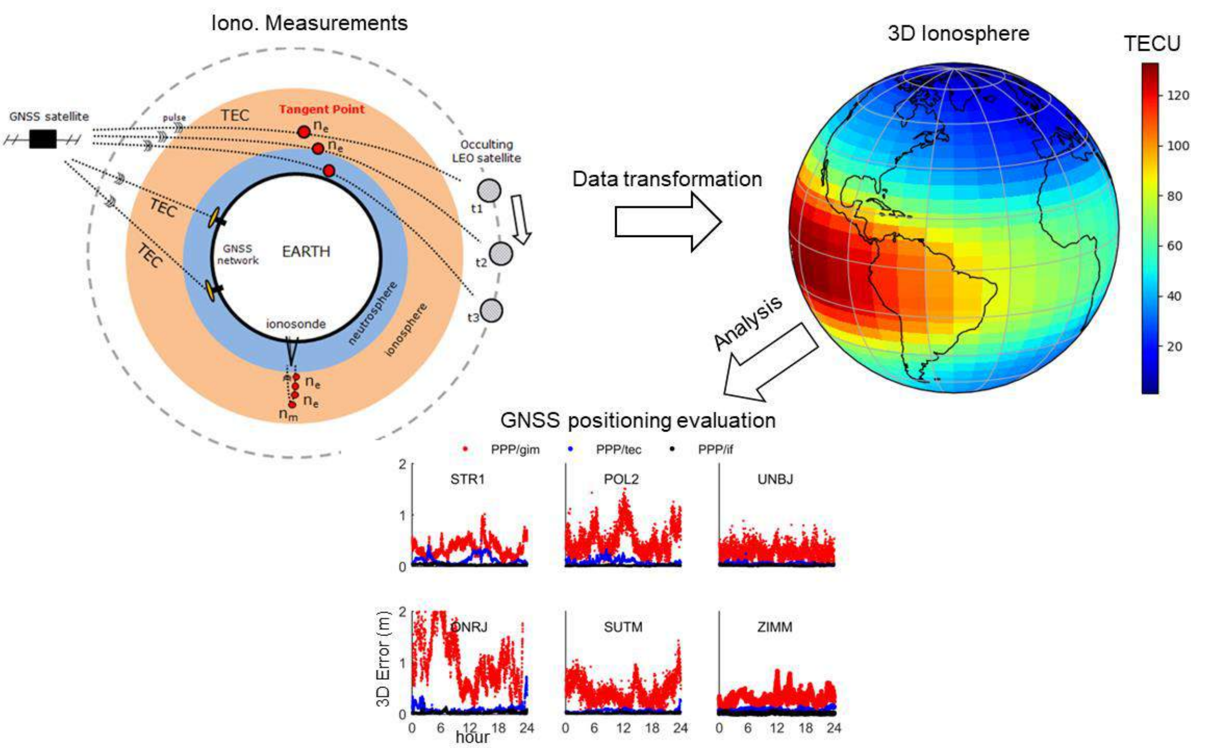

Fig. 2. Steps involved in the group of electron density modelling comprehend: 1) data gathering of electron density measurements; 2) data transformation into 3D grids; 3) evaluation of relevant parameters for the community, such as in terms of GNSS positioning. Positioning results are obtained by a high-accurate ionospheric model (see Prol et al., 2018 for details).

The activities of the group have been disseminated trough several conferences. A remarkable example is shown in Prol (2022), who addressed the current challenges and opportunities for 3D ionospheric imaging. In the future, it is expected to provide a simulated case scenario to be used as basis for a fair data evaluation. A first dataset, which is simulated considering the full environment of the ionosphere and plasmasphere, is complete. An upcoming publication will show details of the simulated dataset (Prol et al., 2023). This dataset not only incorporate TEC measurements from typical ground-based GNSS receivers and POD receivers, but also incorporate upcoming LEO-PNT mega-constellations. As we advance with the group goals, more complex dynamics are planned to be incorporated in the simulations of the ionosphere and plasmasphere.

Publications

Fernandez-Gomez, I., Kodikara, T., Borries, C., Forootan, E., Goss, A., Schmidt, M., Codrescu, M. V. (2022) Improving estimates of the ionosphere during geomagnetic storm conditions through assimilation of thermospheric mass density. Earth Planets Space 74, 121. https://doi.org/10.1186/s40623-022-01678-3

Hernández-Pajares, M.; Olivares-Pulido, G.; Hoque, M.M.; Prol, F.S.; Yuan, L.; Notarpietro, R.; Graffigna, V. (2023) Topside Ionospheric Tomography Exclusively Based on LEO POD GPS Carrier Phases: Application to Autonomous LEO DCB Estimation. Remote Sens. 15, 390. https://doi.org/10.3390/rs15020390

Hoque, M. M., Jakowski, N., Prol, F. S. (2022) A new climatological electron density model for supporting space weather services, J. Space Weather Space Clim., 12, 1. https://doi.org/10.1051/swsc/2021044

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JWG 2: Improvement of thermosphere models

Chair: Christian Siemes (The Netherlands)
Vice-Chair: Kristin Vielberg (Germany)

(Led by GGOS; joint with IAG Commission 4, Sub-Commission 4.3 and ICCC)

Members

Armin Corbin (Germany)
Ehsan Forootan (Denkmark)
Mona Kosary (Iran)
Lea Zeitler (Germany)
Christopher McCullough (USA)
Sandro Krauss (Austria)
Natalia Hladczuk (The Netherlands)
Saniya Behzadpour (Austria)
Aleš Bezděk (Czech Republic)
Sean Bruinsma (France)
Michael Schmidt (Germany)
Barbara Süsser-Rechberger (Austria)
Peter Nagel (USA)
Andres Calabia (Spain)

Activities during the period 2019-2023

This working group was founded in November 2019. Since accurate observations of the thermospheric neutral density are the basis for thermosphere models, we formulate the objective to improve thermosphere models through providing relevant space geodetic observations and increasing consistency between datasets by advancing processing methods. Thus, we assembled a group of scientists with a focus on the processing of thermospheric neutral densities from accelerometers, GNSS and satellite laser ranging observations. Additionally, we attracted group members with expertise in data assimilation of mass densities into models.

Our first ongoing activity is the review of space geodetic observations and state-of-the-art processing methods. We started with a comparison of accelerometer-derived mass densities, since our working group has a large expertise in this area. Figure 3 provides an overview of the processing from accelerometer measurements to thermospheric mass densities including the variety of models used in the intermediate steps. In a living document, we assessed the models used by five different institutes in the processing of the densities, which paves the way to decide on a standard processing algorithm in the future.

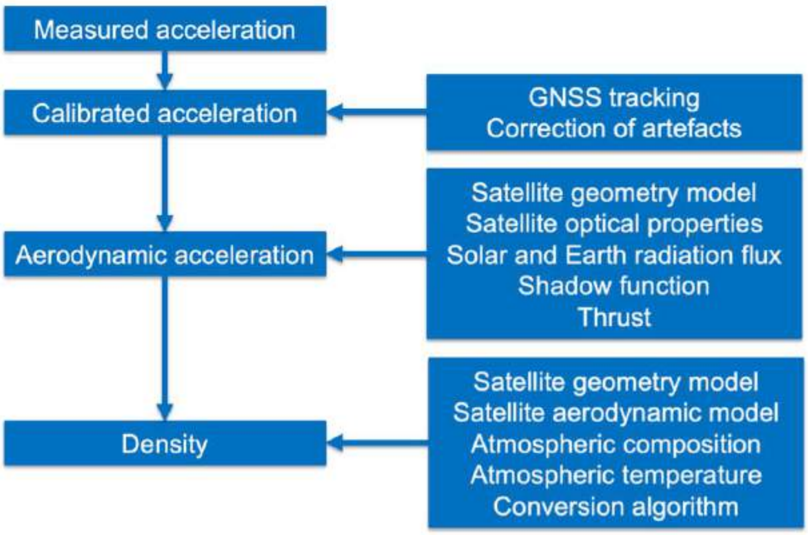

Fig. 3: Processing of measured accelerations to thermospheric mass density including required background models

Besides the theoretical model comparison, we initiated a data comparison. During our group meetings, we agreed on the comparison of GRACE A datasets because this covered all solar and geomagnetic activity and different eclipse conditions. The datasets used in the comparison are listed in **Error! Reference source not found.**. Initially, the Technical University of Graz, the University of Bonn, and the Delft University of Technology contributed their datasets. Later, also the Zentrum für angewandte Raumfahrttechnologie und Mikrogravitation (ZARM) of the Universität Bremen used the datasets for their comparisons.

A key result of the comparison was that the neutral density observations show scale differences of 10 – 60% as demonstrated in Figure 4. The differences need to be interpreted in light of the thermosphere model accuracy of 20 – 30% (Bruinsma et al., 2022). The selected approach of a thorough comparison of observational datasets is therefore a prerequisite for improving the thermosphere models. We identified significant differences in all processing steps, in particular the accelerometer data calibration, radiation pressure modelling, and the aerodynamic force coefficient modelling. Accurately modelling the aerodynamic force coefficient modelling is one of the hardest challenges (Mehta et al., 2022). Though the source of the differences between the datasets is presently not fully understood, identifying the differences was an important activity that provided valuable impulses to improve the modelling capabilities of the involved institutions. In addition to the accelerometer-derived datasets, we also performed a comparison of the Swarm C POD-derived density datasets for 2015 from TU Graz and TU Delft. It was found that the TU Graz density datasets show larger variations in comparison to the TU Delft ones. The TU Graz density dataset reaches low values, indicating that this dataset has some room for improvement. Finally, an overview of SLR-derived density observations was provided by guest speaker Mathis Bloßfeld from TU Munich.

Table 1: GRACE A datasets used for comparison

Dataset	TU Graz	Uni Bonn	TU Delft
Calibrated accelerations	✓	✓	✓
Observed aerodynamic accelerations	✓	✓	✓
Aerodynamic force coefficients	✓	✓	✓
Neutral density observations	✓	✓	✓
Modelled neutral density (along orbit)	✓	✓	✓
Orbit (position and velocity)	✓	✓	✓
Radiation pressure acceleration	✓	✓	✓
Shadow function	✓	✓	✓
F10.7 index	✓	✓	✓
Kp index	✓	✓	✓
ap index	✓	✓	✓
Period	2002-04-05 – 2017-06-29	2002-08-01 – 2009-12-31	2002-04-01 – 2009-12-31

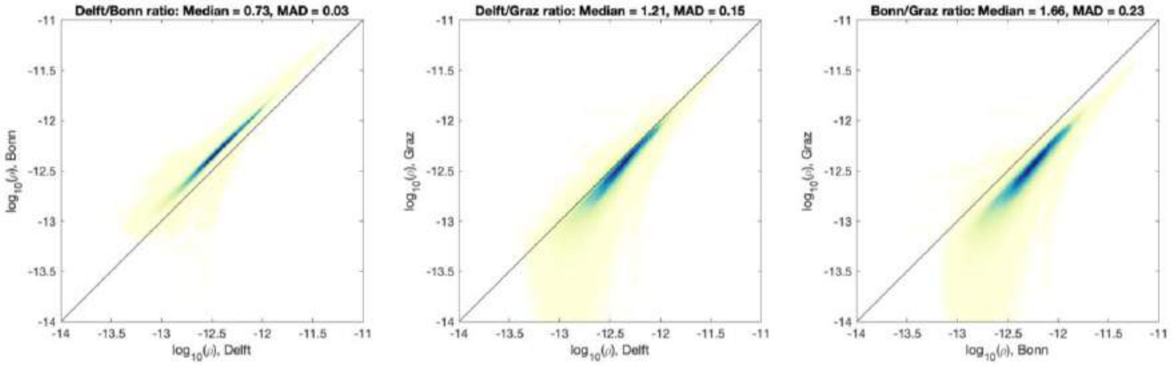

Fig. 4: Comparison of neutral density observations

Beyond the joined activities of the working group, our group members published the following research papers relevant to improving thermospheric densities.

Publications

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JWG 3: Improved understanding of space weather events and their monitoring by satellite missions

Chair: Haixia Lyu (China, 2021 – 2023), Alberto Garcia-Rigo (Spain, 2019 – 2021)
Vice-Chair: Benedikt Soja (Switzerland)

(Joint with IAG Commission 4, Sub-Commission 4.3)

Members

Anna Belehaki (Greece)
Anthony J. Mannucci (USA)
Enric Monte-Monero (Spain)
Rami Qahwaji (UK)
Xiaoqing Pi (USA)
Denise Dettmering (Germany)
Consuelo Cid (Spain)
Jens Berdermann (Germany)
Pietro Zucca (The Netherlands)
Jinsil Lee (Republic of Korea)

Activities during the period 2019-2023

JWG3 aims at gaining a better understanding of space weather events and their effect on Earth's atmosphere and near-Earth environment. In particular, by analysing the correlation between Space Weather data from different sources (including observations from spacecraft and radio telescopes) and perturbed ionospheric/plasmaspheric conditions derived from different space geodetic techniques (e.g. GNSS, DORIS, RO, VLBI, satellite altimetry) and identifying the main parameters that could be useful to improve their real time determination and their forecasts in extreme conditions.

For this purpose, a multidisciplinary team has been assembled. In fact, the members of the WG provide access to complementary models as well as operational products/services linked to ionospheric Total Electron Content determination, ionospheric electron density, geomagnetic disturbances from the Sun to Earth, DORIS ionospheric products, Traveling Ionospheric Disturbances (TIDs) and scintillations, solar flare detection/prediction, EUV flux-rate, CMEs and SEPs, solar corona electron density, dimming and coronal holes, solar wind, polar depletions, among others. Combination of such measurements and estimates can pave the way for a better understanding of space weather events.

At first, an online survey form to gather feedback from JWG 3 members was carried out to have a better understanding of the complementarity within the team, which was helpful to identify the existing background in both geodetic and space weather domains.

Particularly, we identified potential useful data sources to broaden our analysis, as well as the existing models and operational products/services being provided or accessible by the members. Furthermore, applications that could impact positively to end users were listed, complementing the initial considered ones. In addition, it was a way to interchange ideas on the objectives and expectations of what the JWG should be.

At first, a set of three historical representative space weather events were selected. Given these were coincident with the ones selected within JWG 1, we have finally extended the events to be analysed adding a fourth case which was also considered by JWG 1. Thus, we will analyse storm-related periods in 2013, 2015, 2017 and 2018. Also note that the connection between both joint working groups was considered a key objective from the beginning.

Fig 4: Capture of the online survey form

We are currently working on the correlation between SW products and perturbed ionospheric electron density/Total Electron Content, jointly with JWG 1. We have been compiling and/or generating data and plots from different sources (see few plots below) that could be linked to the selected events useful to understand perturbed conditions and features found within JWG 1 analysis. The possibility to provide insights of these correlations could be helpful for JWG 1 and may also be highlighted through their website and database, as part of the coordination process, we are conducting with them. We also keep in mind that for the monitoring and prediction of space weather events and their impact on geodetic measurements, low latency data availability would be of great importance, ideally in real time (RT) or near real time (NRT), also to enable triggering alerts.

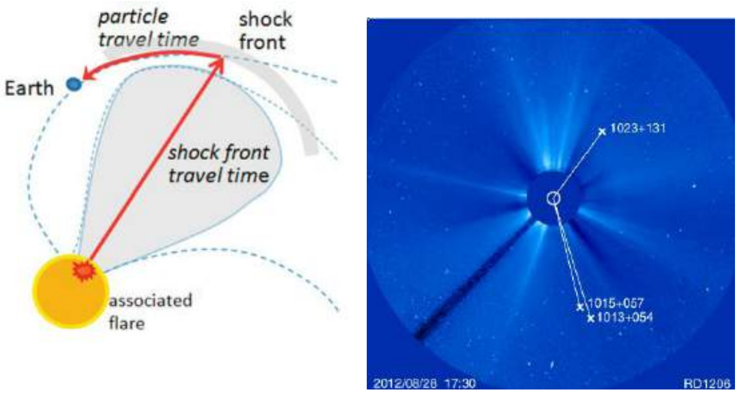

Fig. 5: Left: Shock interaction with the interplanetary magnetic field of SEP events associated to eastern events (Garcia-Rigo et al., 2016). Right: Radio source geometry and coronagraph images for VLBI experiment to assess the electron density of the solar corona (Soja et al., 2014)

The conducted analyses and the combination of measurements and estimates, derived from space geodetic techniques and from solar spacecraft missions, shall lead us to a better understanding of the main parameters that could be useful to improve real time determination as well as predictions derived from geodetic techniques, in case of extreme solar weather conditions. In fact, there is the interest within the team on how well models can reproduce changes during storms, understanding the interactions with the solar wind and magnetosphere, and how correlation of data from different available techniques could be key in this regard.

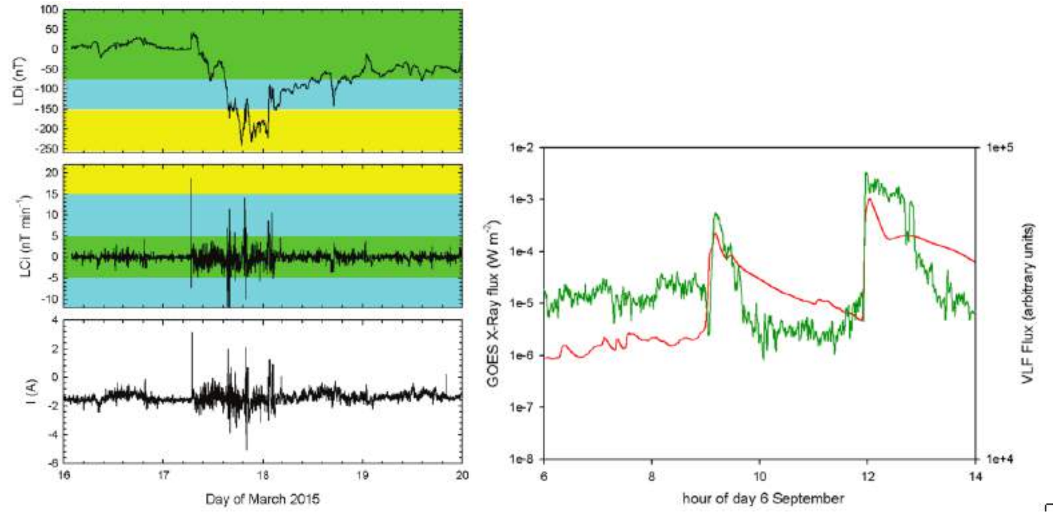

Fig. 6: Left: (from top to bottom) the LDi and LCi geomagnetic indices, and the geomagnetically induced current measured at a substation in the northwest of Spain by REE during the period from 16 to 20 March 2015. Colored areas in panels correspond to the five-level scale introduced to help decision makers in an operational environment (Cid et al., 2020). Right: Superposed plot of the GOES X-ray flux (red) and the amplitude of GQD recorded at UAH receiver (green) from 6 to 14 UT on 6 September 2017 (Guerrero, Cid et al., 2021).

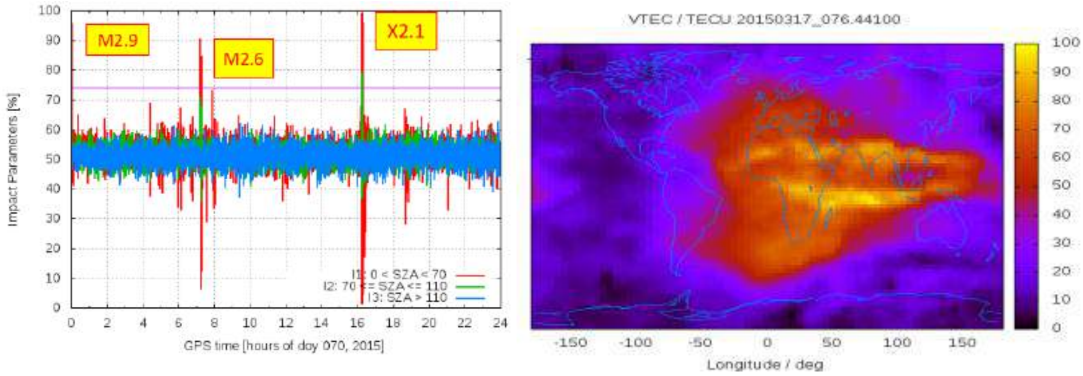

Fig. 7: Left: Detected solar flares prior to St. Patrick’s day 2015 Geomagnetic Storm by means of SISTED detector, which relies on GNSS-based ionosphere monitoring (Garcia-Rigo et al., 2017; Borries et al. 2020). Right: UPC-IonSAT ionospheric TEC GIMs perturbed conditions during St. Patrick’s day 2015.

To foster interdisciplinary cooperation, the Session AS52 “Ionospheric Space Weather Monitoring and Forecasting” at the Asia Oceania Geosciences Society (AOGS) 2023 from July 30 to August 4, 2023, was initiated and 19 abstracts were attracted; see Figure 8. Researchers from Geodesy and Space Physics will meet and exchange knowledge during this event.

AOGS 2023 20th Annual Meeting | Session AS52 "Ionospheric Space Weather Monitoring and Forecasting"

The Asia Oceania Geosciences Society (AOGS) 2023, the 20th annual meeting, will take place in **Singapore between 30 July and 04 August 2023.**

The following session is organized: **AS52 - Ionospheric Space Weather Monitoring and Forecasting**

Conveners:

- Haixia Lyu, Wuhan University, hxlyu@whu.edu.cn
- Sampad Kumar Panda, sampadpanda@gmail.com
- Punyawi Jamjareegulgarn, kjpunyaw@gmail.com

Session Description:

The Earth's ionosphere is highly variable due to the complex interaction in the solar wind-magnetosphere-ionosphere system, and the atmosphere-mesosphere-ionosphere coupling. It exhibits variation in different time scales and in different forms, e.g. gradients, disturbances, storms, etc. These abnormal or irregular behaviors of the ionosphere can adversely affect satellite navigation and communication systems on which nowadays human activities rely, thus the importance of ionosphere state monitoring and forecasting. Presently more and more observation instruments, networks, and satellite missions are built and launched for a better and deeper understanding of ionospheric climate features and space weather events. Benefiting from these observation plans, whether by state and/or commercial initiatives from different countries or by international collaboration, the impact of the ionosphere on GNSS positioning, telecommunication, and other techniques can be analyzed and evaluated. This session will cover the advancements in ionosphere modeling, forecasting, and validation, both globally and regionally. Analysis of the ionospheric space weather impact on the GNSS application and service is also welcome.

Please visit the conference website https://www.asiaoceania.org/aogs2023/public.asp?page=home.asp and submit your abstract to AS52 session by 14 February 2023.

Fig. 8: AOGS 2023 Session AS52 News released by the PITHIA-NRF project website

Among the fruitful research indicated in the publications, a new 3D ionosphere model based on characterizing shape function is constructed (Lyu et al. 2023), which deepens our understanding of the spatial variability of the ionosphere, thus with better prediction of the ionospheric state. This model will be further refined and shared with the JWG1 for assessment in order to facilitate the collaboration between JWG1 and JWG3.

It is worth mentioning that the newly built Chashan Broadband Solar millimeter spectrometer (CBS) has begun its routine observation from 35 to 40 GHz since 2020 and the first solar flare observation was reported by Yan et al. (2022). The CBS provides a new data source for space weather events and more synergy will be done in the future.

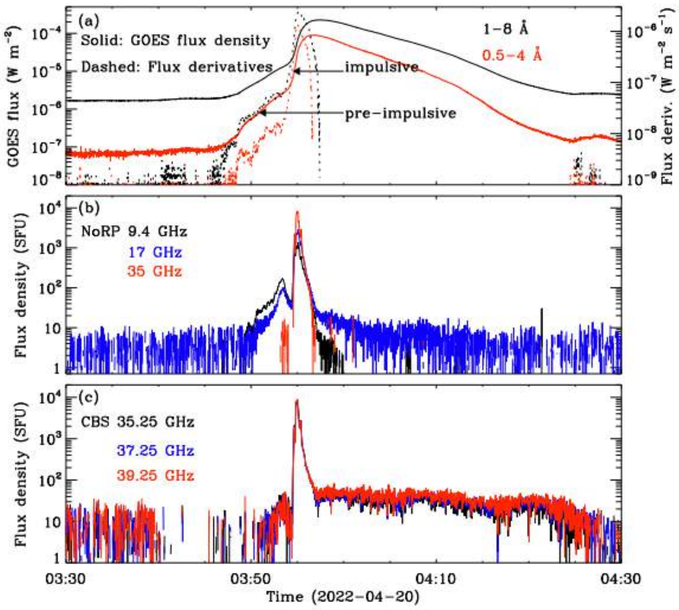

Fig. 9: Overview of the X2.2 flare observed by GOES, NoRP, and CBS on 2022 April 20 (Yan et al., 2022)

In a collaboration between IAG Sub-Commission 4.3 Working Group 4.3.2. “Ionosphere Prediction” and this FA-GSWR JWG 3, predictions of global ionospheric maps (GIMs) have been investigated. ETH Zurich provided predictions of one-day ahead forecasts that were then compared with those of other institutions. Three different types of predictions were computed, with one of them including data related to space weather and geomagnetic activity (“auxiliary data”). Comparisons of the results for quiet days in terms of ionospheric activity are given in Fig. 10, whereas the results for storm days are depicted in Fig. 11. The model that included auxiliary data did not result in improved predictive performance during quiet days, but delivered the best performance during the storm days.

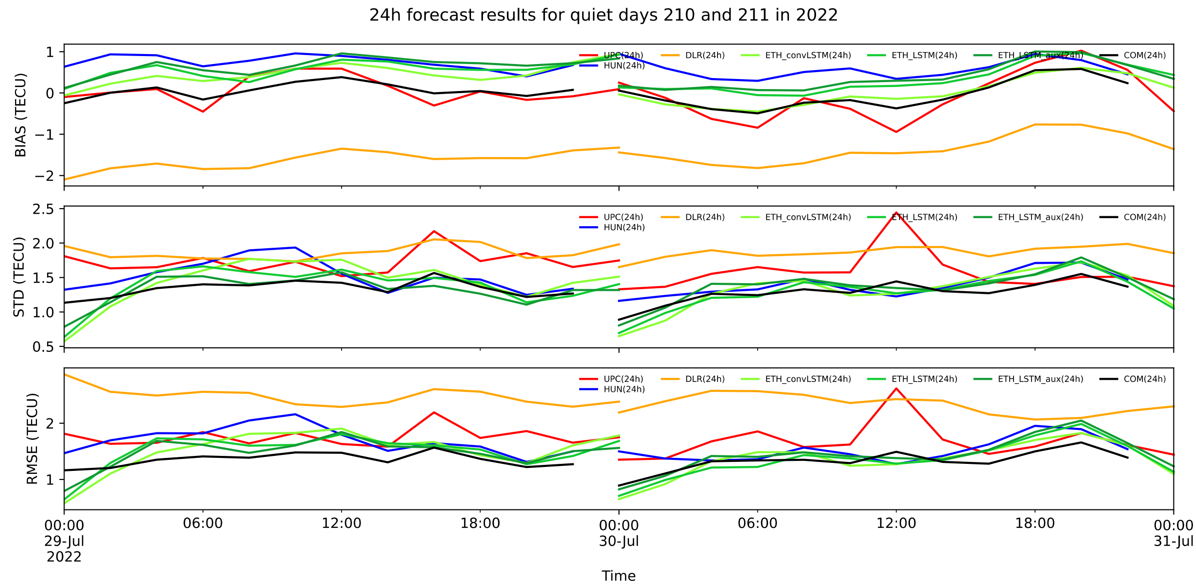

Fig. 10: One day ahead forecast errors of UPC (red), HUN (blue), DLR (orange), ETH models (shades of green; the model with space weather data is in dark green) and COM(black) with respect to IGS final maps on quiet days of 210 and 211 in 2022.

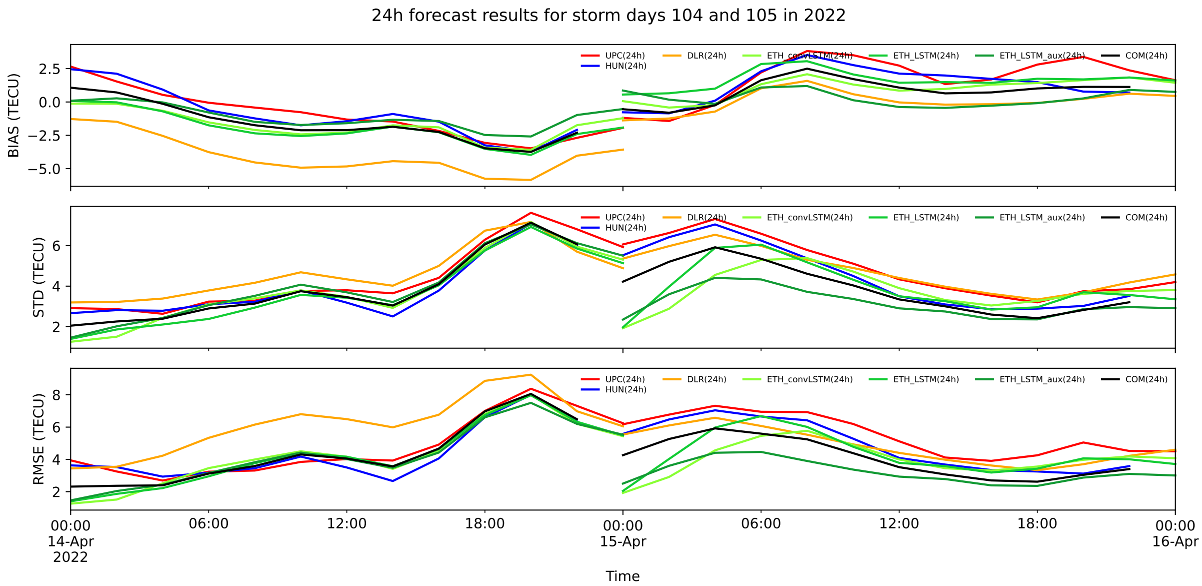

Fig. 11: One day ahead forecast errors of UPC (red), HUN (blue), DLR (orange), ETH models (shades of green; the model with space weather data is in dark green) and COM (black) and COM(black) with respect to IGS final maps on storm days of 104 and 105 in 2022.

In several publications and presentations by Natras et al. (2022a, b, c, d, e, f, 2023), space weather and geomagnetic data were used as input to machine learning models to predict VTEC at different latitudes. As shown in Fig. 12, in certain cases significant feature importance is attributed to the solar and geomagnetic data. This means that they have an impact on the prediction of VTEC. The physical relationship between VTEC and these parameters does not have to be exactly known as the machine learning algorithms learn the relationship between these variables.

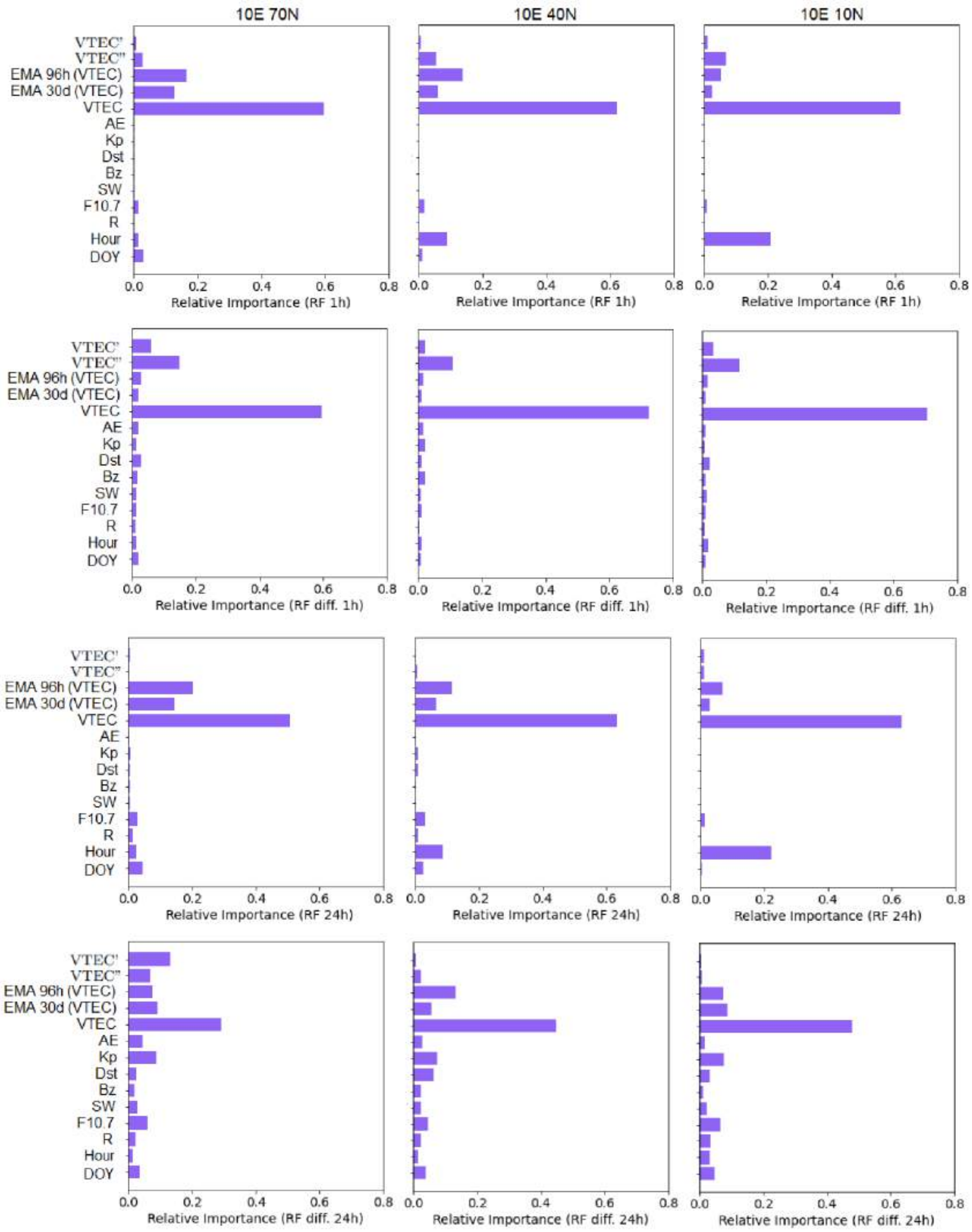

Fig. 12: Relative importance of input variables to VTEC forecast estimated from the Random Forest models. Results are presented for 1 h forecast with non-differenced data (first row) and differenced data (second row), and for 24 h forecast with non-differenced data (third row) and differenced data (fourth row) for high-latitude (left), mid-latitude (middle) and low-latitude (right) VTEC (Natras et al., 2022a).

In Awadaljeed et al. (2022), solar flux data from the Soil Moisture and Ocean Salinity (SMOS) mission was considered for improving predictions of ionospheric VTEC. The inclusion of the highly resolved solar flux data generally had a positive impact on the predictive performance, when included as input to most types of machine learning algorithms (Fig. 13). The work was presented at the “SMOS for Space Weather” workshop organised by ESA and shows how missions that were not originally intended for space weather monitoring can still make an important contribution.

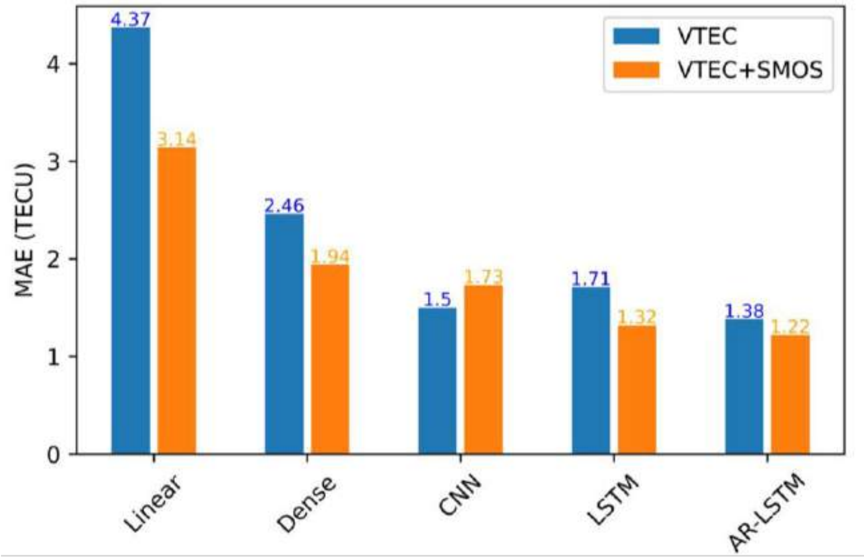

Fig. 13: VTEC prediction errors (in terms of Mean Absolute Error, MAE) of different machine learning algorithms. Blue bars indicate models that have only been trained on VTEC data. Orange bars represent models that include solar flux data from SMOS (Awadeljeed et al., 2022).

Additional next steps include the possibility to conduct extensive simulations, combining different datasets and testing different algorithms, carry out comparisons and validation against external data, as well as deriving impact on end user’ applications (such as in the case of HF communications, GNSS positioning and EGNOS performance degradation, influence on ground and space-based infrastructures, etc.).

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Abed, A. K., Qahwaji, R., Abed, A. (2021). The automated prediction of solar flares from SDO images using deep learning. Advances in Space Research, 67(8), 2544-2557.

Aroca-Farrerons, J., Hernández-Pajares, M., Lyu, H. (2022), Can the GEC be used as Space Weather index? Oral presentation in the 21st International Beacon Satellite Symposium, Boston, USA: 1-5 August 2022

Awadaljeed M., Kłopotek G., Soja B. (2022): "Exploring SMOS Solar Flux Data for Data Fusion with Machine Learning in the CAMALIOT Project"; Talk: 1st workshop on SMOS for Space Weather, ESA-ESRIN, Frascati, Italy; 2022-11-14.

Awadaljeed M., Kłopotek G., Soja B. (2022): "VTEC estimates in the VGOS era: Quality assessment of VTEC derived with the use of the next-generation VLBI system"; Talk: 12th IVS General Meeting, online; 2022-03-28 – 2022-04-01; in: "Abstract book IVS General Meeting 2022", p. 52.

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Focus Area "Artificial Intelligence for Geodesy" (AI4G)

Chair: *Prof. Dr. Benedikt Soja (ETH Zurich, Switzerland)*
Vice-Chair: *Dr. Maria Kaselimi (National Technical University of Athens, Greece)*

With contributions from:
Dr. Milad Asgarimehr (GFZ Potsdam, Germany)
Dr. Lei Liu (University of Colorado Boulder, USA)
Dr. Alexander Sun (University of Texas at Austin, USA)
Dr. Saniya Behzadpour (ETH Zurich, Switzerland)
Dr. Sadegh Modiri (BKG, Germany)
Dr. Justyna Śliwińska (Polish Academy of Sciences, Poland)

On May 12, 2023, the GGOS Coordinating Board accepted the proposal to establish a new GGOS Focus Area on Artificial Intelligence for Geodesy (AI4G). The establishment thus falls barely into the IAG period 2019-2023. As the Focus Area and its Joint Study Groups are currently in the phase of implementation, the report will not include a description of already completed activities, but rather on the goals, objectives, and planned activities of the Focus Area.

The Focus Area will utilize methods from the field of Artificial Intelligence (AI), including machine learning techniques, to improve geodetic observations and products.

Introduction

The field of artificial intelligence has seen rapid progress in recent years, with breakthroughs in areas such as natural language processing, computer vision, and deep learning. This progress has led to the development of new AI applications and technologies and has the potential to transform a wide range of industries and fields.

AI has become increasingly important in science, with applications in fields such as physics, biology, chemistry, and astronomy. It has become well-established in the neighboring disciplines of geodesy, including climate and weather prediction, space sciences, and remote sensing, helping to improve our understanding and prediction of complex natural phenomena. In general, AI can help scientists analyze complex data, identify patterns and relationships, and develop new hypotheses, ultimately accelerating the pace of scientific discovery.

Geodesy has seen a **significant increase in observational data in recent years**, for example in the case of Global Navigation Satellite Systems (GNSS) and InSAR missions. Furthermore, auxiliary data used in the analysis of space-geodetic data such as meteorological or environmental models have seen a significant increase in spatio-temporal resolution. Traditional data processing and analysis techniques that rely largely on human input are not well suited to harvest such rich data sets to their full potential.

Recent advances in the development of machine learning algorithms, in particular efficient implementations of deep neural networks, together with a significant increase in computing power, have the potential to facilitate:

- the automation of data processing,
- the detection of anomalies in time series and image data,
- their classification into different categories,
- modeling complex spatio-temporal data,
- and creating enhanced derivate products in geodesy.

For these reasons, there has been a strong increase in research related to AI and machine learning in geodesy, covering various problems, including those mentioned above in relation to geometric space-geodetic techniques, gravity field, and earth orientation parameters, among other topics.

Objectives

(1) Develop improved geodetic products based on AI and machine learning

The Focus Area aims to explore the potential of AI and machine learning methods in improving the quality and accuracy of geodetic observations and products. The objective is to develop new approaches and methods that can help extract valuable information from large and complex geodetic datasets and use this information to create more accurate and reliable products.

Depending on the application, improved geodetic products could have a higher accuracy, resolution, as well as better performance in in real-time or prediction scenarios. This will often involve assimilating data from different sources.

To achieve the above objective, it is important to **identify the most relevant and suitable geodetic and auxiliary datasets** that can be used for training and validating machine learning algorithms. This will involve selecting datasets that have the right spatio-temporal resolution, accuracy, and other relevant characteristics that can help improve geodetic products.

The Focus Area will also work on **designing appropriate machine learning methods** that can effectively improve the quality of geodetic data. This will involve exploring different machine learning algorithms, such as deep neural networks, and developing new techniques that can be used to analyze geodetic data.

(2) Evaluate improved geodetic products based on AI and machine learning:

Thorough quality assessment is essential for increasing trust in the products produced with the use of AI, especially considering the "black box" nature of deep learning algorithms.

The Focus Area will **compare the performance of different machine learning methods with traditional data analysis approaches**. This will involve identifying the strengths and limitations of each approach and determining the most appropriate method for a given application.

AI4G will pay particular attention to the accuracy, precision, and reliability of the results produced by machine learning algorithms. This will involve developing new techniques for **error assessment and uncertainty quantification**, and identifying potential sources of errors in the results.

Implementation

To achieve the objectives mentioned above, AI4G plans to implement at least three joint study groups, tackling specific topics related to the use of AI in geodetic observations and products. Concretely, we plan to establish study groups that will focus on GNSS remote sensing, gravity field and mass change determination, and Earth orientation parameter prediction.

JSG 1: AI for GNSS Remote Sensing

Chair: *Dr. Milad Asgarimehr (GFZ Potsdam, Germany)*

Vice-chair: *Dr. Lei Liu (University of Colorado Boulder, USA)*

The first study group will focus on GNSS remote sensing and will investigate topics such as ionosphere and troposphere modeling and prediction, as well as the retrieval of wind speed, soil moisture, and other environmental variables through GNSS reflectometry.

JSG 2: AI for Gravity Field and Mass Change

Chair: *Dr. Alexander Sun (University of Texas at Austin, USA)*

Vice-chair: *Dr. Saniya Behzadpour (ETH Zurich, Switzerland)*

The second study group will address the application of AI to improve the determination of the gravity field and the related mass change. The topics that will be covered include the fusion of gravity data with hydrological models, the downscaling of mass anomalies, bridging the gap between GRACE and GRACE-FO missions, and the improved processing of satellite gravimetry data.

JSG 3: AI for Earth Orientation Parameter Prediction
Chair: *Dr. Sadegh Modiri (BKG, Germany)*
Vice-chair: *Dr. Justyna Śliwińska (Polish Academy of Sciences, Poland)*

The third study group will explore the use of AI for predicting Earth orientation parameters. This group will build on the successful Second Earth Orientation Parameter Prediction Comparison Campaign organized by the International Earth Rotation and Reference Systems Service (IERS) and will continue to investigate machine learning for the prediction of Earth orientation parameters and effective angular momentum.

In addition to organizing joint study groups, AI4G also aims to facilitate collaboration beyond these study groups. The goal is to ensure that the methodological progress achieved in these study groups benefits the wider geodetic community. To this end, we plan to **organize events** such as workshops or summer schools in addition to sessions at scientific conferences to disseminate the findings of the joint study groups. The progress of the Focus Area will be documented on a **dedicated website** and advertised on social media.

The AI4G will **collaborate closely with existing components** of the International Association of Geodesy (IAG), in particular the working and study groups of its commissions and committees, as well as other relevant organizations, including the International Telecommunication Union (ITU) and its Focus Group on AI for Natural Disaster Management (FG-AI4NDM). In the case of IAG, the concrete ties will be defined when the working and study groups for the next four-year term are established following the IUGG General Assembly 2023 conference.

Communication and Outreach Branch (COB)

http://www.iag-aig.org

President: Szabolcs Rózsa (Hungary)

Secretary: Gyula Tóth (Hungary)

IAG Newsletter Editor: Gyula Tóth (Hungary)

Activity Report

1. Introduction

The Communication and Outreach Branch (COB) is one of the components of the Association.

According to the new Statues (§5) of the IAG, the COB is the office responsible for the promotional activities of the IAG and the communication with its members. The COB is hosted by the Department of Geodesy and Surveying of the Budapest University of Technology and Economics since 2003.

The Terms of Reference and program of activities of the COB, and a short report on the IAG website ("IAG on the Internet"), were published in The Geodesist's Handbook 2020 (Rózsa and Tóth, 2020; Rózsa, 2012), respectively.

In the reporting period of 2021-2023 COB was active in the maintenance of the standardized web presence of IAG entities. Moreover, the IAG Newsletter has also been further developed and an e-mail marketing system has been introduced to distribute the newsletter, and automate the requests for the contributions.

COB contributed to the Communication and Outreach Focus Group of the UN-GGIM GGRF till the foundation of the GGCE. In the last year of the reporting period we started the preparational discussion to enhance the C&O activities within the IAG with joining our efforts with the GGOS Coordinating Office. A status report and the preliminary plans for establishing this cooperation has been presented to the IAG EC in Paris 2022 and in Vienna, 2023.

2. The IAG Website

The Communication and Outreach Branch maintains not only the IAG Website, but the website of most of the IAG entities. In order to standardize the URL of the Commission webpages, the following notation has been introduced: http://comX.iag-aig.org, where X stands for the number of the commission. Each entity has the opportunity to add contents to its own webpage using a WYSIWYG editor and drag&drop techniques. The webpage of the IAG Office has been transferred to the COB, too (https://office.iag-aig.org).

The website has been operational, no significant downtime has been experienced in the service.

3. The IAG Newsletters

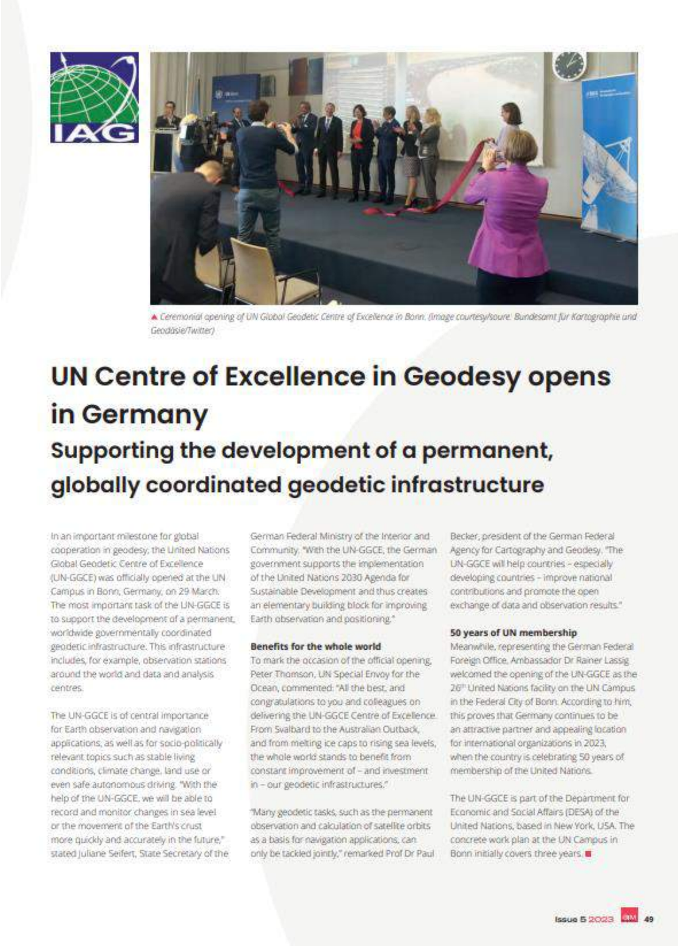
The IAG Newsletters have been published monthly during the COVID pandemia, too. All of the issues have been published on the IAG website in HTML and PDF format and it is sent out to more than 600 e-mail addresses regularly. Since December 2020 the IAG Newsletter is distributed through Mailerlite.com, an online e-mail marketing application. The advantage of this solution is that it is fully GDPR compatible and provides reports of the activities of the recipients. In the past years we had very limited information on the success of the electronic newsletter. In the past 3 years, approximately 35% of the recipients (more than 200 people) opened the e-mail version of the newsletter.

We strive to publish only relevant information by keeping the Newsletter updated on a monthly basis. The call for contributions are automatically sent out to the IAG National Representatives as well as IAG Officers. COB would like to encourage everyone to send us inputs to the Newsletter.

Newsletters were compiled and have been sent regularly to Springer for publication.

4. Outreach Activities

The COB president has been representing IAG in the Communication and Outreach Group of the UN GGIM Subcommittee on Geodesy.
Furthermore, COB is active in collecting IAG related popular information to be published in the GIM International journal. Although the journal was not published in several months in 2020, we have successfully resumed the publication of IAG materials in GIM International (Fig.1.).


▲ Ceremonial opening of UN Global Geodetic Centre of Excellence in Bonn. (Image courtesy/soure: Bundesamt für Kartographie und Geodäsie/Twitter)

UN Centre of Excellence in Geodesy opens in Germany

Supporting the development of a permanent, globally coordinated geodetic infrastructure

In an important milestone for global cooperation in geodesy, the United Nations Global Geodetic Centre of Excellence (UN-GGCE) was officially opened at the UN Campus in Bonn, Germany, on 29 March. The most important task of the UN-GGCE is to support the development of a permanent, worldwide governmentally coordinated geodetic infrastructure. This infrastructure includes, for example, observation stations around the world and data and analysis centres.

The UN-GGCE is of central importance for Earth observation and navigation applications, as well as for socio-politically relevant topics such as stable living conditions, climate change, land use or even safe autonomous driving. "With the help of the UN-GGCE, we will be able to record and monitor changes in sea level or the movement of the Earth's crust more quickly and accurately in the future," stated Juliane Seifert, State Secretary of the German Federal Ministry of the Interior and Community. "With the UN-GGCE, the German government supports the implementation of the United Nations 2030 Agenda for Sustainable Development and thus creates an elementary building block for improving Earth observation and positioning."

Benefits for the whole world

To mark the occasion of the official opening, Peter Thomson, UN Special Envoy for the Ocean, commented: "All the best, and congratulations to you and colleagues on delivering the UN-GGCE Centre of Excellence. From Svalbard to the Australian Outback, and from melting ice caps to rising sea levels, the whole world stands to benefit from constant improvement of – and investment in – our geodetic infrastructures."

"Many geodetic tasks, such as the permanent observation and calculation of satellite orbits as a basis for navigation applications, can only be tackled jointly," remarked Prof Dr Paul Becker, president of the German Federal Agency for Cartography and Geodesy. "The UN-GGCE will help countries – especially developing countries – improve national contributions and promote the open exchange of data and observation results."

50 years of UN membership

Meanwhile, representing the German Federal Foreign Office, Ambassador Dr Rainer Lassig welcomed the opening of the UN-GGCE as the 26th United Nations facility on the UN Campus in the Federal City of Bonn. According to him, this proves that Germany continues to be an attractive partner and appealing location for international organizations in 2023, when the country is celebrating 50 years of membership of the United Nations.

The UN-GGCE is part of the Department for Economic and Social Affairs (DESA) of the United Nations, based in New York, USA. The concrete work plan at the UN Campus in Bonn initially covers three years.

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Figure 1. The IAG Column in the GIM International Magazine (Vol. 2023, Issue 4-5)

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Report 2019–2023 of the IAG Secretary General

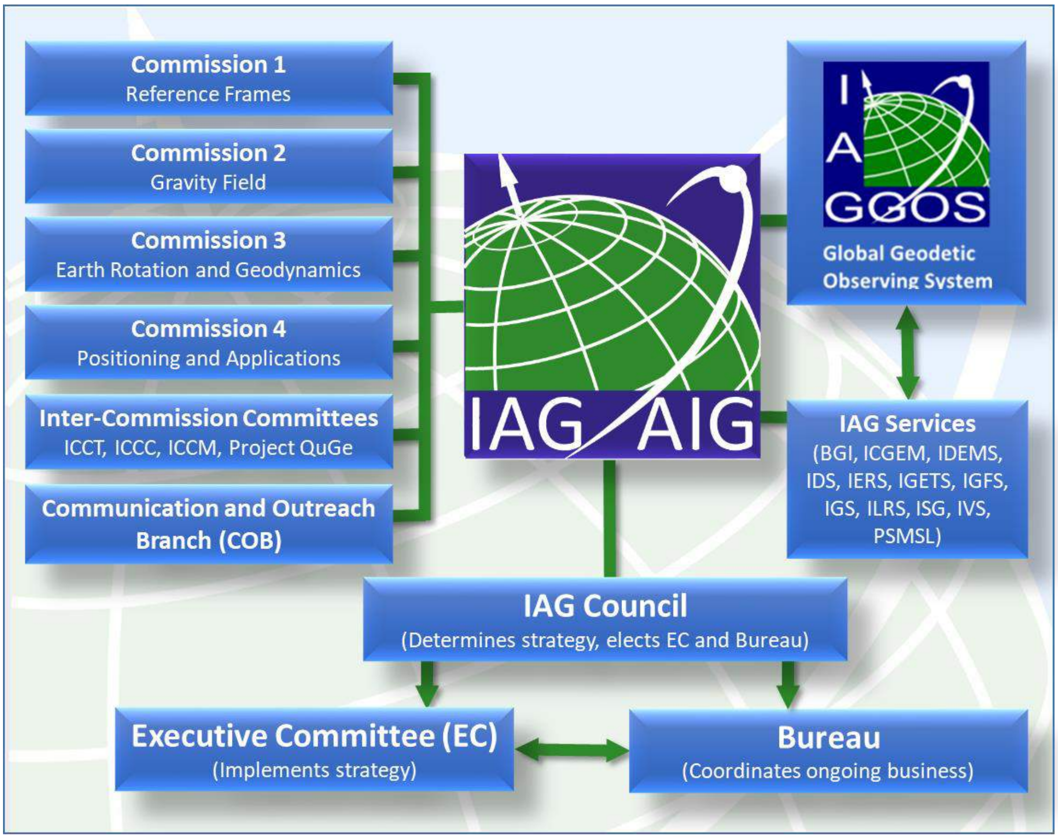
https://www.iag-aig.org

Secretary General: Markku Poutanen (Finland)

Introduction

The IAG General Assembly, the Council, the Executive Committee, and the Office carry out the administration of IAG. The structure of IAG comprises a number of components: four Commissions, the Inter-Commission Committees on Theory (ICCT), Climate Research (ICCC), and Marine Geodesy (ICCM), Project Novel Sensors and Quantum Technology for Geodesy (QuGe), twelve International Scientific Services, the Global Geodetic Observing System (GGOS), and the Communication and Outreach Branch (COB).

According to the IAG Bylaws, the Secretary General serves as secretary of the IUGG/IAG General Assembly, the IAG Scientific Assembly, the Council, the Executive Committee and the Bureau. He arranges meetings of these bodies, distributes promptly the agenda, and prepares and distributes the minutes of all their meetings. He acts as the Director of the IAG Office and manages the affairs of the Association including the finances as per Bylaws §42(b). He continuously attends to the IAG correspondence, preserves the records and circulates all appropriate information related to the Association. He has to prepare the reports of the Association's activities and perform other duties as may be assigned by the Bureau, the Council and the Executive Committee.



The structure of IAG 2019-2023.

Administrative activities

IAG Council

The Council is composed of the delegates appointed by the national adhering bodies. Council meetings took place during the IUGG General Assembly 2019 in Montreal, Canada. Due to the COVID-19 pandemic, physical meetings were not arranged at the IAG Scientific Assembly 2021 which was held as a hybrid meeting. Instead, there was an online meeting and voting on September 2021 to elect the venue of the 2025 IAG Scientific Assembly. The next physical meeting is foreseen at the IUGG General Assembly in Berlin in 2023.

The Council has been informed by the Secretary General's e-mail about the activities of the Bureau and the Executive Committee, and if necessary, voting will be arranged as web-based between the General Assemblies. The list of national correspondents forming the IAG Council is regularly updated in contact with the IUGG Secretary General, who is responsible for the official accreditation.

IAG Executive Committee (EC)

The Executive Committee consists of the IAG Bureau, the immediate Past-President and the immediate Past Secretary General, the four Commission Presidents, four presidents of the Inter-Commission Committees and a Project, the Chair of the GGOS, the President of the COB, three representatives of the Services, and two Members-at-Large.

Four EC meetings were held from July 2019 to May 2021: Montreal (July 2019), San Francisco (December 2019), and due to the Covid-19 Pandemic, virtual meetings were organised twice a year until December 2022, when a hybrid meeting was arranged in Paris. The next hybrid meeting was organised in Vienna, in April 2023, and the last meeting of the current EC is scheduled during the IUGG General Assembly in Berlin, in July 2023. Minutes were prepared for the members, and the meeting summaries are available online at the IAG Website (http://www.iag-aig.org).

The first meeting of the IAG Executive Committee 2019-2023 during the IUGG General Assembly in Montreal 07/2019.

IAG Bureau

The IAG Bureau, i.e. the IAG President, Vice-President and Secretary General, has been communicated by e-mail, and the Bureau has monthly virtual meetings. The topics discussed in the monthly meetings concerned administrative and budget-related running things, actual topics e.g. on UN Subcommittee on Geodesy relations, and EC meeting arrangements. Bureau also decided on travel awards for young scientists to participate and their present scientific results in IAG meetings.

IAG Office

The IAG Office, currently consisting of the Secretary General, treasurer, and the "IAG Secretariat", a registered Society concerning financial matters), took care of the administrative matters of all IAG business, meetings and events. During the period 2019-2023, there was no Assistant Secretary General. Tasks, mainly taken care of by the Secretary General, include budget management, the record-keeping and fee accounting of the individual IAG membership, and the preparation and documentation of all Council and Executive Committee meetings with detailed minutes for the EC members and meeting summaries published in the IAG Newsletters and at the IAG Homepage, and preparing reports to IUGG. The important activity was the preparations for the organization of the IAG Scientific Assembly 2021 in Beijing, China. Due to the COVID-19 pandemic, the meeting will be organized as a virtual Zoom meeting, which created some extra complications in the planning. Planning the IUGG General Assembly started in 2022 which has been one of the major tasks during the year preceding the GA.

The Geodesist's Handbook 2020, i.e. the organisation guide of IAG with the complete report on the past General Assembly, and the description of the upcoming IAG structure (terms of reference and officers of all IAG components and sub-components), the IAG Mid-Term and Quadrennial Reports 2019–2021 and 2019–2023 (Travaux de l'AIG Vol. 42, 43) were edited. The accounting of the Journal of Geodesy and the IAG Symposia series, both published by Springer-Verlag, were controlled. Applications for travel awards of young scientists for participation in IAG-sponsored symposia were evaluated for the decision of the IAG Bureau.

Communication and Outreach Branch (COB)

The COB is responsible for the IAG public relation in particular by maintaining the IAG Homepage (www.iag-aig.org) and publishing the monthly Newsletter online and in the Journal of Geodesy. It also keeps track of all IAG-related events by the meetings calendar. The IAG newsletter is regularly distributed to all IAG Officers, individual members, the Presidents and Secretaries General of the IUGG Associations, IAG liaison bodies, and other interested persons. The COB prepared, printed and distributed the IAG leaflet and IAG brochure and participated in the preparation of the Geodesist's Handbook 2020 and other presentations and publications.

Commissions and Inter-Commission Committee

There are four IAG Commissions (Reference Frames, Gravity Field, Earth Rotation and Geodynamics, Positioning and Applications) and the Inter-Commission Committees on Theory (ICCT), Climate Research (ICCC), and Marine Geodesy (ICCM), Project Novel Sensors and Quantum Technology for Geodesy (QuGe). They were coordinating their subcomponents (Sub-commissions, Study and Working Groups), reported regularly to the EC, and prepared their parts of the IAG Reports for publication in the IAG Reports 2019–2021 and 2019-2023 (Travaux de l'AIG Vols. 42, 43). Each Commission maintained its Homepage and held several symposia, workshops and other meetings. All of them were organising symposia at the IUGG/IAG General Assembly 2019, Scientific Assembly 2021 and will do at the General Assembly in 2023.

Services

The presently twelve IAG Services are split into three general fields: geometry (IERS, IDS, IGS, ILRS, and IVS), gravity (IGFS, ICGEM, IDEMS, IGeS, IGETS and BGI) and overlapping (PSMSL). All of them maintained their own Homepages and data servers and held their administrative meetings (Directing Board or Governing Board, respectively, and sub-components). They published their structure and programme 2019–2023 in the Geodesist's Handbook 2020, and the progress reports in the IAG Reports 2019–2021 and 2019-2023. Services suffered from the COVID-19 pandemic but were by end of 2022 gradually returning to their normal activities. Several in-person, online or hybrid symposia, webinars or seminars were organized during the period.

Global Geodetic Observing System (GGOS)

IAG's Global Geodetic Observing System (GGOS) is to monitor the geodetic and global geodynamic properties of the Earth as a system. A new structure was implemented during the previous period 2015-2019. GGOS includes a Consortium composed of representatives of the Commissions and Services, the Coordinating Board as the decision-making body, the Executive Committee, the Science Panel, the Coordinating Office, two Bureaus with Standing Committees and Working Groups, and four Focus Areas. The GGOS Coordinating Office, responsible for all organizational affairs and the maintenance of the GGOS website (www.ggos.org), moved to the Bundesamt für Eich- und Vermessungswesen (BEV) in Vienna, Austria. Annual GGOS days have been held for the reporting of all the components. Detailed schedule and Agenda can be found in the GGOS report.

Coordination with other organisations

IAG maintains close cooperation with several organizations outside IUGG. These include

- Advisory Board on the Law of the Sea (ABLOS, together with IHO),
- Group on Earth Observation (GEO, with IAG as a participating organization),
- International Standards Organization (ISO, TC211 Geographic Information / Geomatics),
- United Nations Global Geospatial Information Management (UN-GGIM), where IAG became an observer and a Subcommittee on Geodesy was established in 2017,
- UN-GGIM GS (former Joint Board of Geospatial Information Societies, JBGIS),
- United Nations Offices for Outer Space Affairs (UN-OOSA, with participation in Space-based Information for Disaster Management and Emergency Response, UN-SPIDER, and International Committee on Global Navigation Satellite Systems, ICG),

Individual IAG membership

By the end of 2022, there were 186 members, of which 24 were student members. Students and retired members are exempt from the membership fee.

Selected Meetings of IAG Components and IAG Sponsored Meetings in 2019-2022

2019 03 14-20	24th Meeting of the European VLBI Group for Geodesy and Astronomy (EVGA) and 18th IVS Analysis Workshop; Las Palmas, Gran Canaria, Spain
2019 04 15-17	IGS 2019 Analysis Workshop; Potsdam, Germany
2019 05 05-09	10th IVS Technical Operations Workshop; Westford, MA, USA
2019 05 15-17	4th Joint International Symposium on Deformation Monitoring (JISDM); Athens, Greece
2019 05 22-24	EUREF 2019 Symposium; Tallinn, Estonia
2019 07 08-19	27th IUGG General Assembly; Montreal, Canada
2019 09 30-01	DORIS Analysis Working Group meeting; Paris, France
2019 10 01	ILRS Analysis Standing Committee (ASC) meeting; Paris, France
2019 10 01-04	5th IAG Symposium on Terrestrial Gravimetry: Static and Mobile Measurements (TG SMM 2019); Saint Petersburg, Russia
2019 10 02-04	GGOS/IERS Unified Analysis Workshop; Paris, France
2019 10 10	BIPM Workshop on Advanced Time and Frequency Transfer; Sèvres, France
2019 10 21-25	2019 ILRS Technical Workshop; Stuttgart, Germany
2019 11 11-14	GGOS Days 2019; Rio de Janeiro, Brazil
2019 11 11-14	SIRGAS Symposium 2019; Rio de Janeiro, Brazil
2020 06 09	Kick-off meeting of the IAG SC 1.4/IAU/IERS joint working group on the "Consistent realization of TRF, CRF and EOP", 20 participants
2020 11 03	IAG SC 1.3e/UN-GGIM-AP (Geodetic reference frame of the Asia-Pacific region), 86 participants, virtual meeting
2021 06 23-26	Geodynamics and Earth Tides. Wuhan, China. IAG Subcommission 3.1 meeting
2021 06 28-07 02	IAG Scientific Assembly, Beijing, China. The hybrid meeting, in-person for Chinese and online for foreign participants. A total of 1269 participants.
2022 03 22-25	IVS Training School, Helsinki, Finland. Online only; 120 participants, 20 teachers
2022 03 28-04 01	12th IVS General Meeting March 28-April 1, 2022, Helsinki Finland. Online only, 175 participants (a new record of IVS), 98 contributions
2022 04 11-13	IGRF Workshop 2022, Leipzig, Germany (25 in-person, >60 online)
2022 06 01-04	EUREF 2022 Symposium, June 1-4, 2022, Zagreb, Croatia (only online ~100 participants)
2022 06 13-17	X. Hotine-Marussi Symposium on Mathematical Geodesy, Milan, Italy, 13-17 June 2022 (60 participants who contributed 80 papers, Proceedings to be published in the IAG Symposia series)
2022 06 27-07 01	IGS Workshop "IGS 2022: Science from Earth to Space", Boulder CO, USA
2022 09 05-09	2nd International Symposium: Positioning and Applications, Potsdam, Germany (75 participants, of which 45 in-person; Proceedings to be published in the IAG Symposia series)
2022 09 12-16	Gravity, Geoid, and Height Systems 2022 (GGHS2022), Austin TX, USA (87 participants, 59 in-person, proceedings to be published in IAG Symposia series)
2022 10 17-21	REFAG 2022, Thessaloniki, Greece (100 participants from 22 countries; proceedings to be published in the IAG Symposia Series in 2023)
2022 10 22-25	Unified Analysis Workshop (UAW) Thessaloniki, Greece (62 participants, 49 on-site)
2022 10 31-11 02	IDS Workshop 2022, Venice, Italy, In-person meeting with 23 presentations.
2022 11 07-11	22nd International Workshop on Laser Ranging, Guadalajara, Spain, (109 in-person participants and 63 online; from 20 countries)
2022 11 07-09	SIRGAS Symposium, Santiago de Chile, (90 participants in-person and 130 online)
2022 11 14-16	GGOS Days 2022, Munich Germany (33 in-person and 78 online)

All physical meetings, symposia, schools and other planned activities were cancelled in 2020-2021 due to the COVID-19 pandemic. IAG components organized several online activities which can be found in their respective reports.

Participants of IAG International Symposium on Reference Frames for Applications in Geosciences (REFAG 2022), Thessaloniki, Greece on October 17-20, 2022. This was one of the first post-pandemic in-person-only meetings.

Publications

The IAG Newsletter was published monthly online and is accessible via the IAG website

Based on the agreement with Springer Verlag, IAG Symposia Series will be open access, and free of charge to the Symposia participants.

Vol. 148 International Symposium on Gravity, Geoid and Height Systems (2019). Proceedings Organized by IAG Commission 2 and the International Gravity Field Service, Thessaloniki, Greece, September 19-23, 2016

Vol. 149 International Symposium on Advancing Geodesy in a Changing World (2019). Proceedings of the IAG Scientific Assembly, Kobe, Japan, July 30 – August 4, 2017

Vol. 150 Fiducial Reference Measurements for Altimetry (2020). Proceedings of the International Review Workshop on Satellite Altimetry Cal/Val Activities and Applications

Vol. 151 IX Hotine-Marussi Symposium on Mathematical Geodesy (2021). Proceedings of the Symposium in Rome, June 18 – 22, 2018

The number of submissions to the Journal of Geodesy published by Springer remained well above 300, with about a 30% acceptance rate. The impact factor of the Journal is 4.8 (2021). The JoG is within the top ten geosciences-related journals.

The Geodesist's Handbook 2020 was published in the November 2020 issue of the Journal of Geodesy.

The comprehensive (700+ pages) IAG Reports (Travaux de l'AIG) Vol. 41 (2019), Vol. 42 (2021), and Vol. 43 (2023) include detailed reports of all IAG components about their activities in the past period. The reports are available on the IAG website.

Awards, anniversaries, obituaries

Levallois Medal was presented to Professor Christoph Reigber on the occasion of the 80th Anniversary and a Geoscientific Colloquium.

IAG Guy Bomford Prize was awarded to Michal Šprlák on the occasion of the IUGG General Assembly in Montreal, Canada.

On the occasion of the IUGG General Assembly in Montreal, Canada, two young authors' awards were granted. The IAG Young Authors Award 2017 is granted to Minghui Xu for the article "*The impacts of source structure on geodetic parameters demonstrated by the radio source 3C371*", and the 2018 award to Athina Peidou for the article "*On the feasibility of using satellite gravity observations for detecting large-scale solid mass transfer events*"

On the occasion of the IAG Scientific Assembly in Beijing 2021, the Young Authors' Awards were awarded to Susanne Glaser for the 2019 article: *On the impact of local ties on the datum realization of global terrestrial reference frames*, and Khosro Ghobadi-Far for the 2020 article: *GRACE gravitational measurements of tsunamis after the 2004, 2010, and 2011 great earthquakes*.

A total of 20 IAG Travel Awards were granted to young scientists in 2019 and 2022 for participating in and presenting research results at IAG-sponsored Symposia. There were no applications in 2020 and 2021.

An International Colloquium at GFZ, Potsdam, in honour of Professor Helmut Moritz on the occasion of his 85th anniversary. Secretary General represented IAG on the occasion.

An international Symposium was held in Stuttgart on the occasion of the 80th Anniversary of Professor Erik Grafarend. Secretary General represented IAG on the occasion.

IAG Congratulated and published a short presentation in the IAG Newsletter for the Anniversaries of Former IAG President, Professor Ivan I. Mueller on his 90th Birthday and Academician, Professor Fakhraddin A. Kadirov on his 70th Birthday

Obituaries published in the IAG Newsletter

József Ádám (1950-2022)
Ahmet Aksoy (1932-2020)
Rodrigue Blais (1941-2019)
Gerd Boedecker (1944-2022)
Andrzej Borkowski (1959 - 2021)
Bjørn Engen (1941-2022)
Erik Wilhelm Grafarend (1939-2020)
Juhani Kakkuri (1933-2022)
Steve Kenyon (1957-2021)
Helmut Moritz (1933-2022)
Ivan Mueller (1930-2023)
Dezső Nagy (1930-2020)
Richard Henry Rapp (1937-2020)
Tadahiro Sato (1945-2021)
Günter Stangl (1952-2020)
George Veis (1929-2022)

International Earth Rotation and Reference Systems Service (IERS)

http://www.iers.org

Chair of the Directing Board: Tonie van Dam (Luxembourg/USA)
Director of the Central Bureau: Daniela Thaller (Germany)

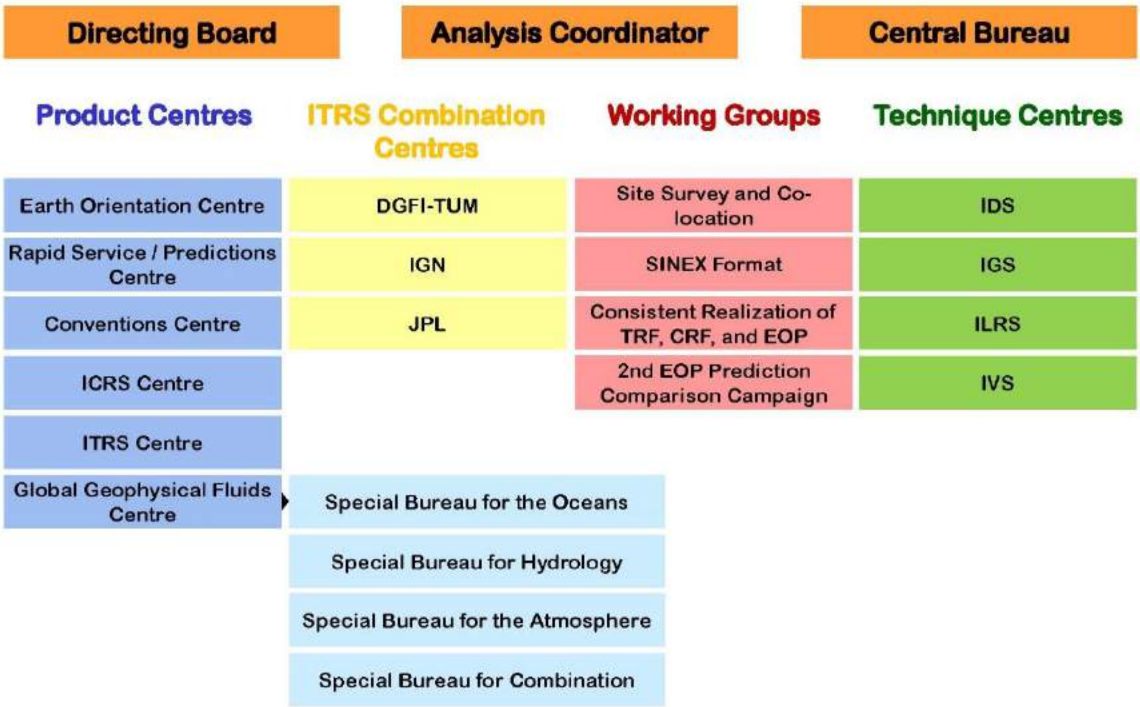
Structure

According to the Terms of Reference, the IERS consists of the following components:

- Directing Board
- Technique Centres
- Product Centres
- ITRS Combination Centre(s)
- Analysis Coordinator
- Central Bureau
- Working Groups

The Technique Centres are autonomous operations, structurally independent from the IERS, but which cooperate with the IERS.

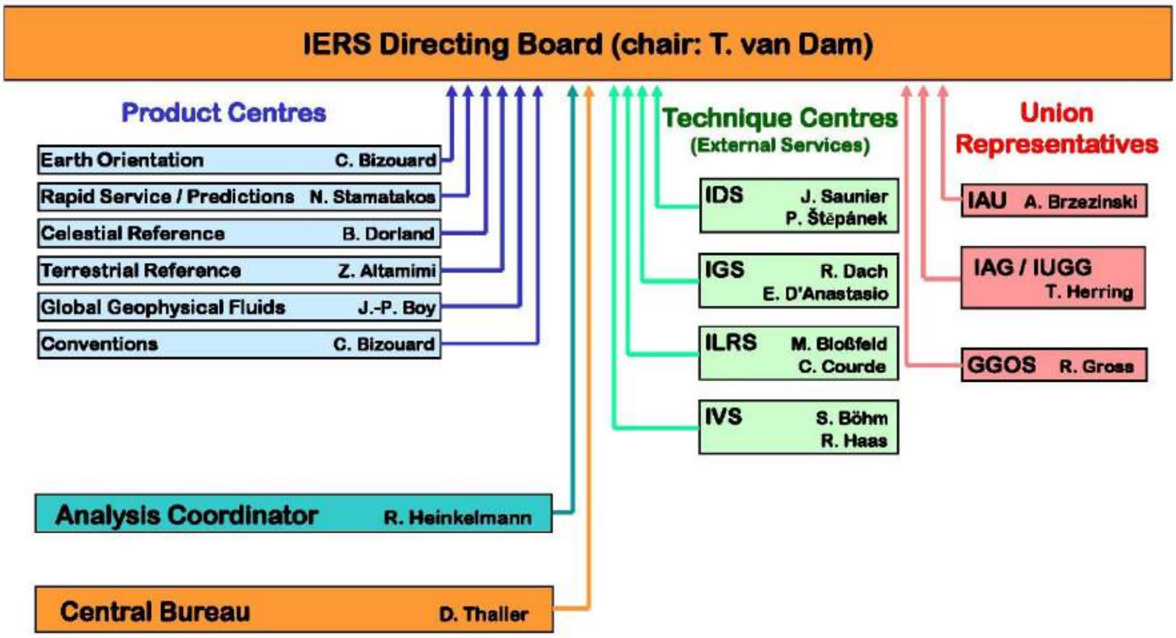
As of June 2023, the IERS consists of the following components:



Responsible persons are (as of June 2023):

- Product centres
    - Earth Orientation Centre: *Christian Bizouard (France)*
    - Rapid Service/Prediction Centre: *Nick Stamatakos (USA)*
    - Conventions Centre: *Christian Bizouard (France), Nick Stamatakos (USA)*
    - ICRS Centre: *Bryan Dorland (USA), Jean Souchay (France)*
    - ITRS Centre: *Zuheir Altamimi (France)*
    - Global Geophysical Fluids Centre: *Jean-Paul Boy (France), Tonie van Dam (Luxembourg)*
        - Special Bureau for the Oceans: *Henryk Dobslaw (Germany)*
        - Special Bureau for Hydrology: *Jianli Chen (Hong Kong)*
        - Special Bureau for the Atmosphere: *David Salstein (USA)*
        - Special Bureau for Combination: *Tonie van Dam (Luxembourg)*
- ITRS Combination Centres
    - Deutsches Geodätisches Forschungsinstitut, Technische Universität München (DGFI-TUM): *Manuela Seitz (Germany)*
    - Institut National de l'Information Géographique et Forestière (IGN): *Zuheir Altamimi (France)*
    - Jet Propulsion Laboratory (JPL): *Richard Gross (USA)*
- Analysis Coordinator: *Robert Heinkelmann (Germany)*
- Central Bureau: *Daniela Thaller (Germany)*
- Working groups
    - IAG/IERS Working Group on Site Survey and Co-location: *Ryan Hippenstiel* (USA), *Sten Bergstrand (Sweden)*
    - Working Group on SINEX Format: *Daniela Thaller (Germany)*
    - IAG/IAU/IERS Joint Working Group on the Consistent Realization of TRF, CRF, and EOP: *Robert Heinkelmann (Germany), Manuela Seitz (Germany)*
    - Working Group on the 2nd Earth Orientation Parameter Prediction Comparison Campaign: *Jolanta Nastula (Poland), Henryk Dobslaw (Germany)*

The current members of the Directing Board (representatives of scientific unions and of IERS' components) are:



Overview

The International Earth Rotation and Reference Systems Service continues to provide Earth orientation data, terrestrial and celestial references frames, as well as geophysical fluids data to the scientific and other operationally oriented communities.

Earth orientation data have been issued on a sub-daily, daily, weekly, and monthly basis, and new global geophysical fluids data were added. The Earth Orientation Centre improved its software and applied several corrections to the 14 C04 EOP series. The Rapid Service / Prediction Centre transitioned their EOP solution to be consistent with the 14 C04 for polar motion, UT1-UTC, and celestial pole offsets.

The IERS continued to ensure that the user community has the most up-to-date terrestrial reference frame by providing the International Terrestrial Reference Frame 2020 (ITRF2020). The three ITRS Combination Centres (DGFI, IGN, JPL) improved their combination software for ITRF2020 and made test analyses with preliminary data. The final re-analysis data from IDS, IGS, ILRS, and IVS were submitted in April 2021, and in April 2022 ITRF2022 was released by the ITRS Centre. The ITRS Combination Centres at DGFI and JPL published DTRF2020 and JTRF2020 in 2023. The ITRS Centre and the corresponding working group also participated in surveys of co-located sites.

A new realization of the International Celestial Reference System (ICRF3) was officially adopted by IAU on January 2019. Comparisons were made between the ICRF3 and preliminary versions of the Gaia optical reference frame.

Work on technical updates to the IERS Conventions (2010) was continued, with updates of existing content, expansion of models, and introducing new topics. Several chapters have been revised by the Conventions Centre. A new printed version of the Conventions is in preparation. This version will incorporate a new style so that the main document will be greatly reduced in length, which will enhance the usability of the conventions for the general practitioner.

Members of the Working Group (WG) on Site Survey and Co-location participated in several local tie measurements. Automated monitoring with terrestrial instruments was further developed. Additional local tie surveys were collected following a call from the ITRS Centre, in preparation for ITRF2020. The WG on SINEX Format worked (with other IERS components) on modifications and revisions of the format, particularly for the provision of loading corrections and of SLR range biases in SINEX files. These new blocks were already applied for SINEX files generated along with the ITRF2020 computation. The WG on Site Coordinate Time Series Format, responsible for the definition of a common exchange format for coordinate time series for all geodetic techniques, was dissolved in May 2020. At the same time the IAG/IAU Joint Working Group on the Consistent Realization of TRF, CRF, and EOP was also established as an IERS WG. It will compute multi-technique CRF-TRF solutions together with EOP in one step, which will serve as a basis to quantify the consistency of the current conventional reference frames and EOP as well as to assess the consistency of reprocessed and predicted EOP. A new WG on the 2nd Earth Orientation Parameter Prediction Comparison Campaign was established in March 2021. It will re-assess the various EOP prediction capabilities by collecting and comparing operationally processed EOP predictions from different agencies and institutions over a representative period of time, with the aim to evaluate the accuracy of final estimates of EOP, to identify accurate (reliable) prediction methodologies, and to assess the inherent uncertainties in present-day EOP predictions.

The IERS continued to issue Technical Notes, Annual Reports, Bulletins, and electronic newsletters. It co-organized two GGOS/IERS Unified Analysis Workshops (UAW), October 2–4, 2019 in Paris and October 21–23, 2022 in Thessaloniki. The final reports provide thorough summaries of the workshops as well as conclusions and recommendations from the discussions (see GGOS and IERS websites).[1]

The IERS Data and Information System (DIS) at the web site www.iers.org, maintained by the Central Bureau, has been updated, improved and enlarged continually. It presents information related to the IERS and the topics of Earth rotation and reference systems. As the central access point to all IERS products it provides tools for searching within the products (data and publications), to work with the products and to download them. The DIS provides links to other servers, among these to about 10 web sites run by other IERS components.

Publications

The following IERS publications and newsletters appeared between mid-2019 and June 2023:

- IERS Technical Note No. 40 (2020): Z. Altamimi and W. R. Dick (eds.): Description and evaluation of DTRF2014, JTRF2014 and ITRF2014
- IERS Annual Report 2018
- IERS Bulletins A, B, C, and D (daily[2] to half-yearly)
- IERS Messages Nos. 378 to 477

IERS Directing Board

The *IERS Directing Board* (DB) met twice each year to decide on important matters of the Service such as structural changes, overall strategy, creating working groups, launching projects, changing Terms of Reference, etc. Due to the pandemic situation, the DB meetings between 2020 and 2022 were held as virtual meetings.

- Meeting No. 69 in San Francisco, December 8, 2019;
- No. 70, video conference, May 13, 2020;
- No. 71, video conference, November 18, 2020;
- No. 72, video conference, May 4 and 20, 2021.
- No. 73, video conference, November 10 and December 9, 2021
- No. 74, video conference, May 12 and June 9, 2022
- No. 75, video conference, December 7, 2022
- No. 76 in Vienna, April 23, 2023

Among the most important decisions made by the DB in 2019–2023 were the following:

- Elected Tonie van Dam as Chair of the Directing Board (2021–2024).
- Confirmed extended list of IERS Associate Members.
- Dissolved Working Group on Site Coordinate Time Series Format.
- Established IAG/IAU Joint Working Group on the Consistent Realization of TRF, CRF, and EOP also as an IERS WG.
- Established Working Group on the 2nd Earth Orientation Parameter Prediction Comparison Campaign.
- Established Working Group for preparing the usage of the GENESIS mission for future reference frame realizations.

[1] https://ggos.org/event/uaw-unified-analysis-workshop-2019/ and https://www.iers.org/IERS/EN/Organization/Workshops/workshops.html

[2] Most users consider the "Bulletin A" IERS RS/PC product to contain EOP estimates updated at both daily and weekly intervals. The daily products are meant to be machine-readable; whereas, the weekly, original Bulletin A product is in a human-readable format and produced on Thursdays.

- Decided on establishing a new procedure for regularly (i.e. yearly) updating ITRF by adding data of the most recent years. The next update is foreseen already for 2024.

Technique Centres

The Technique Centres (TC) are autonomous independent services, which cooperate with the IERS:

- *International GNSS Service* (IGS)
- *International Laser Ranging Service* (ILRS)
- *International VLBI Service for Geodesy and Astrometry* (IVS)
- *International DORIS Service* (IDS)

For details about the work of the TCs, see their individual reports to IAG.

Product Centres

Earth Orientation Centre

Primary scientist: Christian Bizouard (France)

Overview

According to the IERS Terms of Reference, the IERS Earth Orientation Centre (EOC) is responsible for monitoring Earth Orientation Parameters including long-term consistency, publications for time dissemination (DUT1) and leap second announcements. Earth Rotation Parameters (ERPs: Polar motion, Universal Time (UT1), Length of Day (LOD) and Celestial pole offsets) are available to a broad community of users in various domains such as astronomy, geodesy, geophysics, space sciences and time. ERPs are initially collected in the form of combined solutions derived by the Technique Centres (IGS, IVS, ILRS and IDS). Two main solutions are computed: a long-term solution (IERS C01) that starts in 1846 and extends until the end of the previous year and the Bulletin B / C04 given at one-day intervals, which is published monthly with a 30-day. The EOC is located at Paris Observatory.

Activities during the period 2019–2023

The EOC improved its software and applied several corrections to the 14 C04 EOP series. ITRF2020 was implemented in the EOP products starting with 14 February 2023. The official IERS 20 C04 final solution replaced the 14 C04 series. No leap seconds were issued through Bulletin C due to an acceleration of Earth’s rotation.

In October 2019, the EOC organized the *Journées Systèmes de Référence Spatio-temporels “Astrometry, Earth Rotation and Reference System in the Gaia era”* and edited the proceedings. A similar workshop planned for 2020 had to be postponed due to the Corona pandemic.

In addition, members of the EOC had a flourishing scientific activity, reflected by several scientific papers in peer-review journals and a book with de Gruyter.

Selected publications

Bizouard, C. (2020): Geophysical modelling of the polar motion, de Gruyter Studies in Mathematical Physics 31, 370 p., DOI 10.1515/9783110298093

Bizouard, C. (ed.) (2020): Proceedings of the Journées Systèmes de Référence Spatio-temporels 2019 “Astrometry, Earth Rotation and Reference System in the Gaia era”. Paris: Observatoire de Paris. *Includes several contributions by the EOC.*

Bizouard, C.; Nurul Huda, I.; Ziegler, Y.; Lambert, S. (2020): Frequency dependence of polar motion resonance, Geophysical Journal International 220(2):753–758, DOI 10.1093/gji/ggz463

Couhert, A.; Bizouard, C.; Mercier, F.; Chanard, K.; Greff, M.; Exertier, P. (2020): Consistent determination of the three first-degree Earth gravity coefficients, Journal of Geodesy 94(12), DOI 10.1007/s00190-020-01450-z

Lambert, S.; Nurul-Huda, I.; Ziegler, Y.; Richard, J. -Y.; Liu, N.; Gattano, C.; Rosat, S.; Bizouard, C. (2019): Measurement of Earth's Nutation by VLBI: Direct Estimates from VLBI Delays and a Discussion on the Error. In: International VLBI Service for Geodesy and Astrometry 2018 General Meeting Proceedings: "Global Geodesy and the Role of VGOS – Fundamental to Sustainable Development", Eds. K. L. Armstrong, K. D. Baver, D. Behrend, NASA/CP-2019-219039, p. 204–208

Nurul Huda, I.; Lambert; S., Bizouard; C.; Ziegler, Y. (2020), Nutation terms adjustment and implication for the Earth rotation resonance parameters, Geophysical Journal International 220(2), 759–767, DOI 10.1093/gji/ggz468

Nurul Huda, I. (2019): Etude des propriétés rhéologiques globales de la Terre à l'aune des observations VLBI, thèse de doctorat en Astronomie et Astrophysique (Observatoire de Paris)

Puente, V.; Richard, J. Y.; Folgueira, M.; Capitaine, N.; Bizouard, C. (2019): Comparison of VLBI-based Luni-solar Nutation Terms. In: Proceedings of the 24th European VLBI Group for Geodesy and Astrometry Working Meeting, 17–19 March 2019, Las Palmas de Gran Canaria, Spain, Eds. R. Haas, S. Garcia-Espada, and J. A. López Fernández, ISBN 978-84-416-5634-5, pp. 257–226

Rapid Service/Prediction Centre

Primary scientist: Christine Hackman (USA), until Dec. 2020. Nick Stamatakos (USA), since Dec. 2020
Production director and lead project scientist: Nick Stamatakos (USA)

Overview

The Rapid Service/Prediction Centre (RS/PC) provides high-quality Earth orientation estimates/predictions on a rapid turnaround basis, primarily for real-time-users. It issues the weekly IERS Bulletin A and corresponding data files, as well as daily and four-times-daily EOP estimate/prediction values. The centre also conducts research toward improving the accuracy and/or production robustness of its products. Lastly, the centre maintains a web-based Earth orientation matrix calculator that provides the full direction cosine matrix between celestial and terrestrial reference frames based on IERS conventions and given calendar date and time inputs.

Activities and publications during the period 2019–2023

In an effort to improve its EOP combination and short-term prediction results, the RS/PC contracted with Virginia Tech University to develop a better smoothing, weighted cubic spline (SWCP) implementation. The resulting new spline software was developed in MATLAB, and has the ability to combine state and derivate inputs (such as UT1–UTC and LOD). It was used to aid in improving the pre-processing of IGS Ultra Observation LOD and AAM forecasts before using those series as inputs to the newly-developed SWCP. Using the newly developed pre-processing and SWCP resulted in gains of 40% in 0-day prediction accuracy and 25% in 1-day prediction accuracy. Longer term prediction accuracies are still being reviewed (Stamatakos et al. 2021).

The RS/PC continued to study the effects of implementing atmospheric angular momentum (AAM) and oceanic angular momentum (OAM) values/predictions in its Polar Motion EOP estimation/prediction algorithms. Findings were published in posters presented at the AGU 2020 fall meeting and the EGU 2021 spring meeting.

As of 24 October 2019, the U. S. Naval Observatory's IERS RS/PC web/FTP sites (maia.usno.navy.mil and toshi.nofs.navy.mil) and the IERS Conventions web site (maia.usno.navy.mil/conventions), were taken offline as they undergo modernization. An Amazon gov-Cloud site that would host EOP results may be available sometime in late 2021; whereas, a USNO-sponsored site to host the web-based Earth orientation matrix calculator and IERS Conventions would take longer.

Stamatakos, N., McCarthy, D., and Salstein, D.: IERS Rapid Service Prediction Center Use of Atmospheric Angular Momentum for Earth Rotation Predictions, EGU General Assembly 2021, online, 19–30 Apr 2021, EGU21-1917, DOI 10.5194/egusphere-egu21-1917

Conventions Centre

Primary scientists: Christian Bizouard (France), Nick Stamatakos (USA)

Overview

The Conventions Centre is continuing work on technical updates to the IERS Conventions (2010), with updates of existing content, expansion of models, and introducing new topics as needed. The Conventions site is located at: http://iers-conventions.obspm.fr, Observatoire de Paris.

Activities and publications during the period 2019–2023

Until 24 October 2019, the conventions was co-hosted at maia.usno.navy.mil; however, due to a continued modernization effort of the maia site, a USNO-sponsored site to host the Conventions is delayed probably beyond calendar year 2023.

A versioning system has been implemented to handle intermediate updates of the conventions. The centre continued recruiting a group of talented experts in the field to work on updating the IERS Conventions. In 2018, it issued a Call for Participation in the next IERS Conventions. As of June 2023, over 15 experts have agreed to aid with this rewrite of the IERS Conventions.

ICRS Centre

Primary scientists: Bryan Dorland (USA), Jean Souchay (France)

Overview

The IAU has charged the IERS with the responsibility of monitoring the International Celestial Reference System (ICRS), maintaining its current realization, the International Celestial Reference Frame (ICRF), and maintaining and improving the links with other celestial reference frames. Starting in 2001, these activities have been run jointly by the ICRS Centre (Observatoire de Paris and US Naval Observatory) of the IERS and the International VLBI Service for Geodesy and Astrometry (IVS), in coordination with the IAU.

Activities during the period 2019–2023

Involvement by ICRS Centre personnel in the construction of the celestial reference frame from VLBI programs has continued, in particular from the participation in extensive observing programs. The ICRS Centre has fulfilled various tasks devoted to the monitoring of ICRF sources, the link with the dynamical system (in particular through LLR), the construction of new updates of the LQAC (Large Quasar Astrometric Catalogue) and of the LQRF (Large Quasar Reference Frame). A new realization of the International Celestial Reference System

(ICRF3) was officially adopted by IAU on January 2019. Comparisons were made between the ICRF3 and preliminary versions of the Gaia optical reference frame.

Selected publications

Dorland, B.; Secrest, N.; Johnson, M.; Fischer, T.; Zacharias, N.; Souchay, J.; Lambert, S.; Barache, C.; Taris, F. (2020): The Fundamental Reference AGN Monitoring Experiment (FRAMEx). In: Proceedings of the Journées 2019 "Astrometry, Earth Rotation, and Reference Systems in the GAIA era", Observatoire de Paris, Paris, France, 7–9 October 2019, Ed. C. Bizouard, pp. 165–171

Fischer, T.C.; Secrest, N.J.; Johnson, M.C.; Dorland, B.N.; Cigan, P.J.; Fernandez, L.C.; Hunt, L.R.; Koss, M.; Schmitt, H.R.; Zacharias, N.: Fundamental Reference AGN Monitoring Experiment (FRAMEx). I. Jumping Out of the Plane with the VLBA. The Astrophysical Journal 906(2), id. 88, 19 pp., DOI 10.3847/1538-4357/abca3c

ITRS Centre

Primary scientist: Zuheir Altamimi (France)

Overview

The main activities of the ITRS Centre during the period 2019–2023 include the maintenance of the ITRF network, database and website. The ITRS Centre, according to the IERS ToR, is responsible, among other duties, for the maintenance and update of the ITRF network database and its provision to the users through the ITRF website. The ITRS Centre assigns DOMES numbers to geodetic tracking stations or markers as unambiguous identifications of points in space, independently from the technique of their tracking instruments.

The ITRF web site, available at <http://itrf.ign.fr>, provides an interface to consult the IERS network database. Site and point information can be requested online; it contains approximate coordinates of the sites, the list of their points as well as their descriptions, their DOMES numbers and the list of ITRF versions in which they have been computed. Subsets of points can be selected and their ITRF coordinates can be requested at any epoch in any ITRF version if their coordinates are provided in the requested ITRF version.

Main activities and publications during the period 2019–2023

The main activities of the ITRS Centre during this period include:

- Preparation for ITRF2020. After the release of the ITRF2020 Call for Participation (CfP) which was published at the end of 2018 (see: http://itrf.ign.fr/doc_ITRF/CFP-ITRF2020.pdf), the ITRS Center continued the dialog with the 4 Technique Centers (TCs) for the preparation of their inputs to the ITRF2020. The ITRS Center emphasized the need for the TCs to implement the new recommended models which are annexed to the ITRF2020 CfP. The ITRS Center has in particular attended most meetings of the analysis working groups of the Technique Centres (in 2019: IDS, IGS, ILRS and IVS).
- The ITRS Center hosted the Unified Analysis Workshop 2019 at Institut de Physique de Globe de Paris, during 2–4 October, 2019. A number of the technique presentation addressed the preparation for the ITRF2020, including the implementation of updated models and analysis strategies.
- At the initiative of the ITRS Center, and with the help of the IERS Central Bureau, an IERS Technical Note (# 40) was published in order to, primarily; acknowledge the activities of the ITRS Combination Centers at DGFI and JPL, beside the ITRS Combination Center at IGN which is part of the ITRS Center (Altamimi and Dick,

2020). It includes the description of both DTRF2014 and JTRF2014, as well as their inter-comparisons with respect to the official IERS solution, the ITRF2014. The Technical Note was also intended to include evaluations of the three solutions by the IERS Technique Centers (IDS, IGS, ILRS and IVS) who constantly provide input solutions to the ITRF. In addition to DGFI, JPL and ITRS Center contributions, the Technical Note includes contributions from IDS, ILRS and IVS. A specific article by the ITRS Center evaluates the two solutions DTRF2014 and JTRF2014 with respect to the ITRF2014 (see IGN ITRS Combination Center Report below).

- Chapter 4 of the IERS Conventions has been re-written by the ITRS Center team which includes the following updates (IERS ITRS Center, 2019):
    - A description of ITRF2014, with its associated equations, to model the nonlinear station motions due to seasonal signals and post-seismic deformation of stations subject to major earthquakes.
    - A description of the mathematical model used in the ITRF combination.
    - A revision of Table 4.1, listing the transformation parameters relating ITRF2014 to previous ITRFs.
    - Improvements in wording and the removal of unnecessary paragraphs.
- Resolutions on ITRS/ITRF. The ITRS Center has prepared the text of an IUGG resolution on the ITRF which was adopted at the occasion of the IUGG General Assembly 2019 in Montreal, Canada, see: http:\\ www.iugg.org/resolutions/2019%20IUGG%20GA%20Resolutions.pdf.
- At its 9th Session, the UN-GGIM Committee of Experts supported the agreement of the Subcommittee on geodesy on the adoption of the International Terrestrial Reference System and the International Terrestrial Reference Frame as the standard for scientific, geospatial and operational geodetic applications. The ITRS Center has significantly contributed to the text of that agreement.
- Maintenance of the IERS network. The ITRS Centre assigns DOMES numbers to geodetic tracking stations or markers as unambiguous identifications of points in space, independently from the technique of their tracking instruments. The IERS network database, which contains the descriptions of the sites and points, is continuously updated as DOMES numbers are assigned. DOMES number request form can be found on the ITRF web http://itrf.ign.fr, and should be sent to domes@ign.fr. An updated list of all available DOMES number is available at http://itrf.ign.fr/doc_ITRF/iers_sta_list.txt. The IERS site information is available to the users through the ITRF website interface. Several new stations, mainly GNSS permanent stations where added to the ITRF network and database.
- Finalization and publication of the ITRF2020. The ITRF2020 is provided as an augmented terrestrial reference frame that precisely models nonlinear station motions for both seasonal (annual and semi-annual) signals present in the station position time series and Post-Seismic Deformation (PSD) for sites impacted by major earthquakes. We evaluate the accuracy of the ITRF2020 long-term origin position and time evolution by comparison to previous solutions, namely ITRF2014, ITRF2008 and ITRF2005, to be at the level of or better than 5mm and 0.5mm/yr, respectively. The ITRF2020 long-term scale is defined by a rigorous weighted average of selected VLBI sessions up to 2013.75 and SLR weekly solutions covering the 1997.75–2021.0 time span. For the first time of the ITRF history, the scale agreement between SLR and VLBI long-term solutions is at the level of 0.15 ppb (1mm at the equator) at epoch 2015.0, with no drift. To accommodate most of ITRF2020 users, the seasonal station coordinate variations are provided in the CM as well as in the Center of Figure frames, together with a seasonal

geocenter motion model. While the PSD parametric models were determined by fitting GNSS data only, they also fit the station position time series of the three other techniques that are colocated with GNSS, demonstrating their high performance in describing site post-seismic trajectories.

- A website dedicated to the ITRF2020 results was established, providing to the users all the necessary information, including the computational strategy, scale and geocenter time series, station position residual time series and illustrations, as well as SINEX file per technique netoworks. A specific DOI is also assigned to the ITRF2020 data set.
- A full an open access article on ITRF2020 is available (Altamimi et al. 2023), published in Journal of Geodesy, detailing the analysis strategy as well as the main geodetic and geophysical results.

Altamimi, Z. and W.R. Dick (Eds.), (2020), Description and evaluation of DTRF2014, JTRF2014 and ITRF2014, IERS Technical Note 40, Frankfurt am Main: Verlag des Bundesamts für Kartographie und Geodäsie. 167 p., ISBN 978-3-86482-137-0.

Altamimi, Z., Rebischung, P., Collilieux, X., Métivier, L., Chanard, K. (2023) ITRF2020: an augmented reference frame refining the modeling of nonlinear station motions. J Geod 97(47). https://doi.org/10.1007/s00190-023-01738-w

Altamimi, Z., Rebischung, P., Collilieux, X., Métivier, L., Chanard, K. (2022) ITRF2020 [Data set]. IERS ITRS Center Hosted by IGN and IPGP,

https://doi.org/10.18715/IPGP.2023.LDVIOBNL

Altamimi, Z., Rebischung, P., Collilieux, X., Métivier, L., Chanard, K., 2022, ITRF2020 and the IVS contribution, Proceedings of the IVS General Meeting 2022.

IERS ITRS Center, (2019), Chapter 4 of the IERS Conventions (Terrestrial reference systems and frames), available at https://iers-conventions.obspm.fr/chapter4.php.

Global Geophysical Fluids Centre

Primary scientist: Jean-Paul Boy (France)
Co-chair: Tonie van Dam (Luxembourg/USA)

Overview

The Global Geophysical Fluid Centre (GGFC) of the International Earth Rotation and Reference Systems Service (IERS) provides the community with models of geodetic effects (Earth rotation, gravity and deformation) due to the temporal redistribution of the Earth geophysical fluids (http://loading.u-strasbg.fr/GGFC). These include fluid motions with the solid Earth (core and mantle) as well as motions at the Earth's surface (ocean, atmosphere and continental hydrology).

The GGFC is composed of four operational entities: the Special Bureau for the Atmosphere (SBA, chair: D. Salstein), the Special Bureau for the Oceans (SBO, chair: R. Gross until Dec. 2020, H. Dobslaw from Jan. 2021), the Special Bureau for Hydrology (SBH, chair: J.-L. Chen) and the Special Bureau for the Combination Products (SBCP, chair: T. van Dam). The Atmosphere, Hydrology and Ocean SBs have been firmly established since the creation of the GGFC in 1998. The operational Combination Products SB was established in 2009 to host new datasets that model the mass movement of combined environmental fluids such as atmosphere + ocean. There is finally a non-operational component of the GGFC, the GGFC Science and Support Products, serving as a repository for models and data used regularly in data processing, but that do not change often.

Activities and publications during the period 2019–2023

The Special Bureau for the Atmosphere (SBA) is concerned with the atmospheric information that is needed for a number of geodetic issues. During the period of this report, the SBA maintained series of the atmospheric angular momentum (AAM) vector, which can be used for analysis and predictions of Earth rotation parameters.

The Special Bureau for the Oceans (SBO) is responsible for collecting, calculating, analysing, archiving, and distributing data relating to non-tidal changes in oceanic processes affecting the Earth's rotation and related parameters. A new website for the SBO hosted at GFZ Potsdam has been established (https://isdc.gfz-potsdam.de/ggfc-oceans/). The SBO invites all interested colleagues working in the field to contribute new ocean model simulations and/or ocean reanalyses as well as geodetically relevant derived quantities to the GGFC.

The Special Bureau for Hydrology (SBH) provides access to data sets of terrestrial water storage (TWS) variations from major climate and land surface models and GRACE (Gravity Recovery and Climate Experiment) and GRACE Follow-On satellite gravity measurements. The NASA GLDAS and GRACE/GRACE Follow-On data products are updated on a regular basis. SBH also provides gravity spherical harmonic representations of model-derived TWS changes. A new website for the SBH hosted at the Hong Kong Polytechnic University (PolyU), has been established (https://www.polyu.edu.hk/lsgi/ggfc/).

At the beginning of 2017, GFZ Potsdam as one of the providers of combinational products introduced major changes to their data series (atmospheric, oceanic and hydrological loading). The products are consistent with the GRACE/GRACE-FO atmosphere and ocean dealiasing product AOD1B RL06, which is going to be replaced with RL07 by the end of the year 2021. It is expected that the combination product will be reprocessed back to the year 1975 shortly after the publication of AOD1B RL07.

In addition, GGFC produces loading time series (geocenter motion, time-variable gravity field and surface displacements) for the next reference frame ITRF2020. All products are available at http://loading.u-strasbg.fr/GGFC/itrf2020.php.

ITRS Combination Centres

Three ITRS Combination Centres (CCs) are responsible for providing ITRF products by combining ITRF inputs. Within the time frame covered by this report the CCs focused on the computation of the new ITRS realization 2014.

ITRS CC at DGFI-TUM

Primary scientist: Manuela Seitz (Germany)

Overview

DGFI-TUM has been acting as one of the ITRS Combination Centres within the IERS since 2001. The related activities are embedded into DGFI-TUM's research on the realization of Global Terrestrial Reference Frames within the research area Reference Systems.

Realizations of the ITRS are based on the combination of space geodetic observations of the four techniques VLBI, SLR, GNSS, and DORIS at globally distributed geodetic observatories. Respective input data are provided by the corresponding technique services (IVS, ILRS, IGS, IDS). The combination strategy developed at DGFI-TUM is based on the combination of normal equation systems, which allows for a pure physically realization of the origin and scale of the reference frames.

Activities and publications during the period 2019–2023

The CC at DGFI-TUM prepared and calculated the ITRS 2020 realization DTRF2020. In the framework of the development of the DOGS software and the compilation of a new DOGS version, the combination part DOGS-CS was improved with respect to the precision of the reference epochs of the parameters. This improves also all parameter transformations considering parameter epochs (e.g., the epoch transformation and the change of parameterization). Furthermore, now all meta-data given in the SINEX files can be stored in the DOGS internal format and transferred well through the combination process. In addition, the software APROPOS was developed, which allows for the approximation of post-seismic station motions by a combination of logarithmic and exponential functions. Thereby, also the relaxation time is considered as an unknown parameter. Thus, non-linear optimization algorithms are applied. The software is used within the DTRF2020 computation process to approximate post-seismic station motions, which are then reduced from the station positions (on normal equation level) in a preparatory step. During 2020, preliminary input data for the ITRS 2020 realization were provided by all Technique Services. These data were analyzed in order to test the new version of the DOGS-CS software and to give feedback to the Technique Centres.

In 2021 and 2022, the DTRF2020 was calculated covering the input data series from VLBI, SLR, GNSS, and DORIS from the beginning of the observation techniques between 1980 and 1994 to the end of 2020. The DTRF2020 is a linear frame and provides station positions at the reference epoch 2010.0 and velocities for 3594 station solutions for a network of 1829 stations. Consistently with the DTRF2020, Earth Orientation Parameter (EOP) time series are estimated. The DTRF2020 is characterized by the following features: it accounts for non-tidal station position displacements caused by atmospheric, hydrological and oceanic mass re-distributions provided by geophysical models. Moreover, it considers for the first time post-seismic deformations (see above). It is the first TRF solution that combines GNSS with VLBI data to realize the TRF scale. Furthermore, it is based on the combination of normal equation systems which reduces the impact of the technique-specific solutions (inclusive the respective datum realization) on the combined products. The DTRF2020 release contains, besides the solution itself, various data that allow the DTRF2020 to be applied by including non-linear station motions as well as to be used for detailed analyses of station and datum parameter time series. DTRF2020 is computed in parallel with ITRF2020. Due to its identifying features, It can be used as an independent reference frame and for evaluating the ITRF2020 to ensure a high quality of the IERS reference system and EOP products.

Angermann D., Bloßfeld M., Seitz M., Rudenko S.: Comparison of latest ITRS realizations: ITRF2014, DTRF2014 and JTRF2014. In: Altamimi Z., Dick W. R. (Eds.), IERS Technical Note No. 40, 2020

Bloßfeld M., Seitz M., Angermann D., Seitz F.: DTRF2014: DGFI-TUM realization of the International Terrestrial Reference System (ITRS). In: Altamimi Z., Dick W. R. (Eds.), IERS Technical Note No. 40, 2020

Glomsda M., Bloßfeld M., Seitz M., Seitz F. : Benefits of non-tidal loading applied at distinct levels in VLBI analysis. Journal of Geodesy, 94(9), 10.1007/s00190-020-01418-z, 2020

Glomsda M., Bloßfeld M., Seitz M., Seitz F.: Correcting for site displacements at different levels of the Gauss-Markov model – a case study for geodetic VLBI. Advances in Space Research, 10.1016/j.asr.2021.04.006, 2021

Glomsda M., Bloßfeld M., Seitz M., Angermann D., Seitz F.: Comparison of non-tidal loading data for application in a secular terrestrial reference frame. Earth, Planets and Space, 74(1), 10.1186/s40623-022-01634-1, 2022

Seitz M., Bloßfeld M., Angermann D., Seitz F.: DTRF2014: DGFI-TUM's ITRS realization 2014. Advances in Space Research, 69(6), 2391-2420, 10.1016/j.asr.2021.12.037, 2022

ITRS CC at IGN

Primary scientist: Zuheir Altamimi (France)

Main activities and publications during the period 2019–2023

- *Research and development activities*. The members of the IGN CC, often in cooperation with other scientists, conduct research and developments activities relating to the ITRF in particular and reference frames in general. R&D activities include ITRF accuracy evaluation, mean sea level, loading effects, combination strategies, and maintenance and update of CATREF software. Scientific results of specific data analysis and combination are published in peer-reviewed journals, as listed below, but also presented at international scientific meetings.
- *Investigation of the scale discrepancy between SLR and VLBI*. The scale of ITRF2014 was defined in such a way that it has zero scale and zero scale rate with respect to the arithmetic average of the implicit scales of SLR and VLBI solutions as obtained by the stacking of their respective time series. The resulting scale and scale rate differences between the two solutions (SLR and VLBI) are 1.37 ppb at epoch 2010.0 and 0.02 ppb/yr. The level of the scale agreement between SLR and VLBI confirms the ITRF2008 finding and is an indication of the persistent scale offset between the two technique solutions. These results suggest that there is still an urgent need for investigation on the causes of the scale discrepancy, e.g., range biases in case of SLR and possible effects due to VLBI antenna gravity deformations. The ILRS has initiated a pilot project on systematic errors including the range biases which will be estimated in the ILRS solution to ITRF2020. A preliminary SLR test solution was made available to the ITRS Center by Cinzia Luceri from the Italian Space Agency (ASI) where estimated range biases were taken into account. Analysing the time series of this SLR test solution showed a clear scale offset of about 1 ppb with respect to the ILRS solution which was used in the ITRF2014. We expect that this scale offset will greatly minimize the scale discrepancy between SLR and VLBI in the coming ITRF2020 solution.
- *Contribution to the IERS Technical Note 40*. As reported in the ITRS Center report, this issue, an IERS Technical Note (# 40) was published in order to, primarily, acknowledge the activities of the ITRS Combination Centers at DGFI and JPL, beside the ITRS Combination Center at IGN which is part of the ITRS Center (Altamimi and Dick, 2020). The Technical Note includes in particular a specific article by the ITRS Center which evaluates the two solutions DTRF2014 and JTRF2014 with respect to the ITRF2014 (Altamimi et al., 2020). The article concludes in particular that (1) SLR and VLBI intrinsic and discrepant scales coexist in the DTRF and JTRF 2014 solutions, and (2) with respect to ITRF2014 and assuming that its scale is homogeneous, the scale offsets and rates between SLR and VLBI solutions embedded in DTRF2014 and JTRF2014 are respectively 1.32 and 1.21 ppb at epoch 2010.0 and 0.04 and 0.01 ppb/yr. These results are in almost perfect agreement with the results of ITRF2014 analysis.

Altamimi, Z., P. Rebischung, X. Collilieux, and L. Métivier (2020), ITRS Center evaluation of DTRF2014 and JTRF2014 with respect to ITRF2014. In: Altamimi, Z. and W. Dick (Eds.), 2019, IERS Technical Note 40, Frankfurt am Main: Verlag des Bundesamts für Kartographie und Geodäsie, 2020. 167 pp., ISBN 978-3-86482-137-0

Métivier, L., Altamimi, Z., and Rouby, H. (2020), Past and present ITRF solutions from geophysical perspectives, Advances in Space Research (65)12: 2711–2722, DOI 10.1016/j.asr.2020.03.031

Métivier, L., H. Rouby, P. Rebischung, and Z. Altamimi (2019), ITRF2014, Earth figure changes and geocenter velocity: implications for GIA and recent ice melting, Journal of Geophysical Research 125, e2019JB018333, DOI 10.1029/2019JB018333

See also the report of the ITRS Centre above.

ITRS CC at JPL

Primary scientist: Richard Gross (USA)

Overview

The ITRS Combination Centre at JPL focused on research regarding the representation of terrestrial reference frames by time series of smoothed positions of reference stations rather than by a parameterized model of the station positions. A Kalman filter and smoother for reference frames (KALREF) has been developed and used to determine time series representations of terrestrial reference frames. In addition, a square-root information filter for reference frames (SREF) is currently being developed that can be used to not only determine time series representations of terrestrial reference frames but that can also be used to jointly determine time series representations of terrestrial and celestial reference frames.

Activities and publications during the period 2019–2023

During 2019–2023, SREF continued to be developed. SREF allows a variable or fixed time step to be used to propagate the state vector and covariance matrix forward in time, includes a full process noise covariance matrix that will optionally allow regional correlations in station positions to be considered, includes linear, periodic, and postseismic displacement models for the evolution of the station positions, and can optionally process radio source coordinates and celestial pole offsets for joint TRF/CRF determinations. SREF was used to determine JTRF2020, JPL's submission to the IERS for ITRF2020. JTRF2020 was released on February 14, 2023 and SINEX files of the JTRF2020 station positions, including full covariance matrices, are available at <https://sideshow.jpl.nasa.gov/pub/JPL_SREF_PRODUCTS/JTRF2020>. In addition, time series and plots of the JTRF2020 station positions, EOPs, scale, geocenter, and Helmert transformation parameters are available from the JTRF website at <https://www.jpl.nasa.gov/site/jsgt/jtrf/>. Preparations are currently being made to use SREF to extend the JTRF2020 solution forward in time by using newly available observations. The extensions to JTRF2020 are expected to be available on a quarterly basis starting summer 2023.

Abbondanza, C., T. M. Chin, R. S. Gross, M. B. Heflin, J. W. Parker, B. S. Soja, and X. Wu (2020). A sequential estimation approach to terrestrial reference frame determination, Adv. Space Res., 65(4), 1235–1249, DOI 10.1016/j.asr.2019.11.016.

Analysis Coordinator

Analysis Coordinator: Robert Heinkelmann (Germany)

Overview

The Analysis Coordinator is responsible for the long-term and internal consistency of the IERS reference frames and other products. He is responsible for ensuring the appropriate combination of the Technique Centres products into the single set of official IERS products and the archiving of the products at the Central Bureau or elsewhere.

Activities and publications during the period 2019–2023

The work of the Analysis Coordinator focused on an analysis of the ITRF2014 and a comparison with the two other independent solutions: JTRF2014 and DTRF2014. The differences of these three frames are for the post-seismic deformation models, time-series vs. long-term parameters, least squares vs. Kalman filtering, datum definition and in the weighting and application of local ties and co-motion constraints. The analysis of the various differences of the TRFs needs more time and more dedicated investigations as many aspects cannot be clearly associated being caused by specific analysis or combination decisions. Besides the terrestrial reference frame, the new celestial frame, ICRF3, became effective in the beginning of 2019. ICRF3 fits much better to external high-precision star catalogues, such as DR2 and EDR3 of the ESA Gaia mission, than ICRF2 does, for which a small but systematic deformation was identified. ICRF3 also includes a correction for the aberration caused by the non-linear motion of the Milky Way galaxy w.r.t. other galaxies. The main EOP products of IERS, IERS 14 C04 and USNO finals were investigated and compared as well. During 2019 – 2021 several changes have been done to the IERS 14 C04 product, some of which cause significant differences for users. The effects and the necessity of the change are under investigation. Based on VLBI data analysis the consistency of the three products, TRF, CRF, and EOP, were in the focus of the activities. Besides GNSS, SLR, VLBI and DORIS, the LLR technique recently progressed towards more observations. LLR besides VLBI is the only technique capable of providing CPO and dUT1 estimates and hence, presents an important tool for verification of the celestial set of the EOP. The development of VLBI observations at higher frequencies, namely K- and X-/Ka-bands for ICRF3 and in general presents a novel data set for the verification of IERS products and their consistency. The IERS Analysis Coordinator is very much in favour of further fostering and broadening these observations. VLBI at other frequencies has the potential to provide an independent connection of terrestrial and celestial reference frames and EOP and thus qualifies for high accurate control of the IERS products. In the time frame 2019 – 2021, management efforts have been invested in the preparation of ITRF2020. For this product update, model updates had to be implemented, such as a new sub-daily EOP model, VLBI antenna gravitational deformation, and a new linear model of the mean Earth rotation pole applied for the modelling of pole tides. To oversee these model inclusions in the analysis, the IERS Analysis Coordinator took part in several Analysis Workshops of the four main space geodetic techniques. The Analysis Coordinator co-organized the 2019 and 2022 Unified Analysis Workshops held in Paris, France and in Thessaloniki, Greece, respectively, together with IAG GGOS and developed recommendations from it.

Central Bureau

Director: Daniela Thaller (Germany)

Overview

The Central Bureau coordinates the work of the Directing Board and the IERS in general, organizes meetings and issues publications. It replies to questions of users regarding IERS products and general topics of Earth rotation and reference systems. It maintains an IERS Data and Information System (DIS) based on modern technologies for internet-based exchange of data and information like the application of the Extensible Markup Language (XML) and the generation and administration of ISO standardised metadata. The system provides general information on the structure and the components of the IERS, serves as a portal to websites of all IERS components and gives access to all products.

Activities and publications during the period 2019–2023

The IERS DIS is continuously being adapted and extended by new components in order to fulfil the requirements for a modern data management and for the access to the data by the users. Besides routine work like maintenance of the data bases of users, products and web pages, further developments of the IERS DIS concentrated on the enhancement of the data management system and of the interactive tools to visualize and analyse IERS products. Especially security features were updated to meet current standards.

An improved monitoring system was established for the data management system to ensure a timely and error-free provision of the IERS products on the webpages and ftp server. A new feature has been implemented in the data management system, which allows the direct upload of USNO earth rotation data to the servers of the IERS Central Bureau. Further improvements of the IERS DIS included the development of a date converter tool and the availability of csv formatted files on the ftp server. A new user management system has been implemented. A newly developed calendar shows for each IERS product when new product versions were released on the IERS website. For the data exchange in the framework of ITRF 2020, the Central Bureau created internal areas at data server for https upload and download which replaces the former, less secure ftp exchange. In 2022, the ftp server was replaced by HTTPS download and work on a new version of the IERS website was started.

The Central Bureau edited, published and distributed IERS Technical Note No. 40 and IERS Annual Report 2018, as well as IERS Messages Nos. 378 to 477. It compiled reports by IERS to IAU Commission A2 and IAG.

Working Groups

Reports, meeting summaries, presentations and other documents of all working groups are available at the IERS web site.

IAG/IERS Working Group on Site Survey and Co-location

Chair: Sten Bergstrand (Sweden, until Dec. 2019), Ryan Hippenstiel (USA, since Jan. 2020)
Co-chair: John Dawson (Australia, until Dec. 2019), Sten Bergstrand (Sweden, since Jan. 2020)

Overview

Areas of work of the Working Group on Site Survey and Co-location are standards and documentation (guidelines, survey reports, etc.), coordination (share know-how and join efforts between survey teams), research (investigate discrepancies between space geodesy and tie vectors, alignment of tie vectors into a global frame), and cooperation.

Activities and publications during the period 2019–2023

See the report of IAG Commission 1, SC 1.2 (Global Reference Frames), JWG 1.2.2: Methodology for surveying geodetic instrument reference points.

Working Group on SINEX Format

Chair: Daniela Thaller (Germany)

Overview

The SINEX (Solution INdependent EXchange) format is a well-established format used by the technique services of the IERS for several years. The aim of the working group is to maintain the SINEX format according to the needs of the IERS, the technique services (IDS, IGS, ILRS, IVS) and GGOS. The working group is the point of contact if any modifications or extensions are required. In order to have the best possible interaction with the groups working with the SINEX format (either as output or as input), the analysis and combination groups of all the technique services as well as the relevant components of the IERS and GGOS are represented within the working group.

Activities and publications during the period 2019–2023

In the framework of preparing ITRF2020, two aspects have been developed for the SINEX format:

1) A block for storing the corrections for non-tidal loading effects that were applied at the observation level was defined. This allows to un-do this correction when handling the normal equations provided in the SINEX file.
2) A block for providing the information about range and time biases applied during the SLR estimation process was defined.

Both new blocks have been already used for VLBI and SLR SINEX files, respectively, that were generated for ITRF2020.

IAG/IAU/IERS Joint Working Group on the Consistent Realization of TRF, CRF, and EOP

Chair: Robert Heinkelmann (Germany)
Co-Chair: Manuela Seitz (Germany)

Overview

This IAG/IAU/IERS Working Group will compute multi-technique CRF-TRF solutions together with EOP in one step, which will serve as a basis to quantify the consistency of the current conventional reference frames and EOP as well as to assess the consistency of reprocessed and predicted EOP. From 2016 to 2019 this was an IAG Working Group, since 2020 it has become joint with IAU and IERS.

Activities and publications during the period 2020–2023

See the report of IAG Commission 1, SC 1.4 (Interaction of Celestial and Terrestrial Reference Frames), JWG 1.4.3: Consistent realization of TRF, CRF, and EOP.

Working Group on the 2nd Earth Orientation Parameter Prediction Comparison Campaign

Chair: Jolanta Nastula (Poland)
Co-Chair: Henryk Dobslaw (Germany)

Overview

Earth orientation parameters (EOP) comprising of nutation offsets, pole coordinates, and dUT1 represent a critically needed link between the terrestrial and the celestial reference frame. Predictions of EOP are important for a number of operational activities including navigation of deep-space satellite missions, the pointing of astronomical instruments, or satellite-based positioning on Earth. Various agencies and institutions worldwide therefore maintain capacities to rapidly process space geodetic observations to obtain estimates for the EOPs with short latencies as a basis for the subsequent prediction. The strong interest in EOP forecasting ultimately led to the establishment of the Second Earth Orientation Parameters Prediction Comparison Campaign (2nd EOP PCC) by a Working Group of the IERS.

Between September 2021 and December 2022, the operational part of the 2nd EOP PCC has been performed under the auspices of the IERS within the WG on 2nd EOP PCC. The aim of the 2nd EOP PCC was re-assessing various EOP prediction capabilities, in particular: collecting and comparing EOP predictions from different institutions over a representative period of time, evaluating the accuracy of final estimates of EOP, identifying both accurate and robust prediction methodologies, assessing the inherent uncertainties in present-day EOP predictions, analysing the impact of various factors (input data used, method applied, reference data, length of prediction etc.) on prediction accuracy.

The EOP PCC Office maintained by Space Research Centre in Warsaw (Poland) was responsible for creating and maintaining the campaign website (http://eoppcc.cbk.waw.pl/), data collecting, routine visualization and final evaluation of all submitted predictions. Valid predictions of all kind of EOP were collected once per week in an operational setting (each Wednesday before 20 UTC). The support of GFZ Potsdam is kindly acknowledged.

Activities and publications during the period 2021–2023

The first online meeting of the WG took place on May 6th, 2021 to discuss details of the campaign with interested participants. The second online meeting of WG, EOP PCC Office and participants was organized on November 25, 2021 to present submission statistics, preliminary scientific results, discuss next steps and receive feedback from participants. The next meeting took place online on December 8, 2022 and its agenda included update on the campaign results, plans for campaign data sharing, publication plans, and idea to extend the campaign duration.

Before the start of the campaign, preparatory actions were taken, i.e. a website was launched and a server was prepared to store predictions in CBK PAN, instructions for participants and a document with technical requirements were prepared. All technical details including instructions for candidate registration, data submission rules, naming, and file formats convention have been made publicly available in the document with general rules for participation in early June 2021.

An open call for participation in pre-operational phase of the 2nd EOP PCC was announced in June 3, 2021. The aim of the test campaign was to check all technical issues, in particular to test participant registration scheme and check correctness of files sent by participants.

An open call for participation in operational phase of 2nd EOP PCC was announced in July 13, 2021. In total, 22 teams with 66 different forecasting methods registered for the campaign.

During the operational phase of the 2nd EOP PCC, i.e. between September 1, 2021 and December 31, 2022, the EOP PCC received 7327 valid predictions of all kinds of EOPs. The forecasts were routinely checked and validated by comparison with observational data. Validation results were periodically sent to participants in the form of reports, and also presented during meetings with participants and conferences.

Two EOP PCC Workshops were organized to present updated campaign results and to receive feedback from participants: the first on February 15–16, 2022 (online) and the second on March 1–3, 2023 (hybrid on-site and online).

The campaign duration was unofficially extended to collect predictions based on EOP data consistent with the new International Terrestrial Reference Frame ITRF 2020.

Kur, T., Dobslaw, H., Śliwińska, J., Nastula, J., & Wińska, M. (2022). Evaluation of selected short - term predictions of UT1 - UTC and LOD collected in the Second Earth Orientation Parameters Prediction Comparison Campaign. Earth, Planets and Space, 74. https://doi.org/10.1186/s40623-022-01753-9

Śliwińska, J., Kur, T., Wińska, M., Nastula, J., Dobslaw, H., & Partyka, A. (2022). Second Earth Orientation Parameters Prediction Comparison Campaign (2nd EOP PCC): Overview. Artificial Satellites, 57(S1), 237–253. https://doi.org/10.2478/arsa-2022-0021

International DORIS Service (IDS)

https://ids-doris.org/

Chairman of the Governing Board: Frank Lemoine (USA)
Director of the Central Bureau: Laurent Soudarin (France)

Overview

The current report presents the different activities held by all the components of the International DORIS Service (IDS) for the period from the middle of 2019 to the middle of 2023.

The main achievements of the IDS over this period are:
(1) analysis, combination and stacking of the contributions from the four IDS Analysis Centers involved in the realization of the IDS contribution to the ITRF2020;
(2) dissemination of the DORIS data of the brand-new missions HY-2C, Sentinel-6A and HY-2D;
(3) dissemination of DORIS NRT data of Jason-3 mission;
(4) renewal of several positions within the Governing Board;
(5) organization of the first “DORIS days” on November 16, 17 and 18, 2021;
(6) organization of the IDS Workshop on October 31 and November 1, 2022;
(7) publication of articles about the DPOD2014 realization and the IDS contribution to ITRF2020 by the Combination Center;
(8) publication of five newsletter.

The IDS has been impacted by the Covid-19 pandemic. The events planned for 2020 could not take place. The IDS workshop planned in Venice in October 2020 was cancelled and was first postponed to 2021. In the Spring of 2021, the IDS Workshop was again postponed to March 2022. It finally took place in Fall 2022 in Venice, in conjunction with the Ocean Surface Topography Science Team. Similarly, the first edition of the DORIS days, planned as a face-to-face event on Saturday 2 May 2020 at the Technical University of Vienna, Austria, prior to the EGU 2020, was finally held remotely in November 2021.

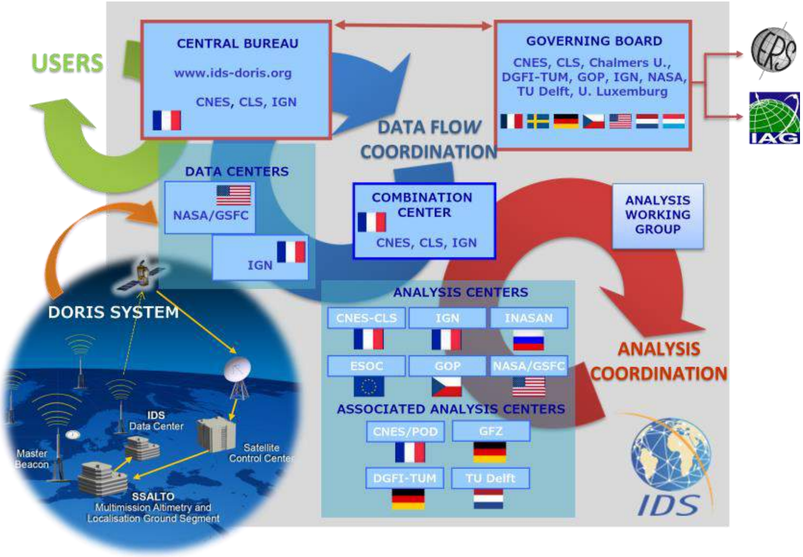
During the period of this report, the DORIS system had its 30th anniversary. The first DORIS measurement was recorded on February 3, 1990, on board SPOT-2.

Note also that on 1 July 2023, the International DORIS Service will celebrate the 20th anniversary of its creation under the umbrella of the International Association of Geodesy.

Structure

The IDS organization is very similar to the other IAG Services. The service accomplishes its mission through the following components:

- Satellites carrying a DORIS receiver
- Network of tracking stations
- Data Centers
- Analysis centers and Analysis Coordinator
- Combination Center
- Working Groups
- Central Bureau
- Governing Board



Activities

DORIS system

1.1 DORIS satellites

As described in **Table 1**, four new satellites were launched over the report period: HY-2C and Sentinel-6A Michael Freilich in 2020, HY-2D in 2021, and SWOT in late 2022. All use the new 7-channel DGXX-S DORIS on-board receiver. During the same period, two missions were decommissioned: Jason-2 and HY-2A.

There are now nine active on-orbit DORIS receivers. This is the first time we have had so many DORIS receivers in simultaneous operation. From 1990 to now, 18 missions were equipped with 3 generations of DORIS receivers: the 1G with 1 channel, the 2G and 2GM with 2 channels, and the last generation DGXX and DGXX-S with 7 channels, able to track up to 7 DORIS stations simultaneously. These satellites have operated or are operating at five different altitudes, from about 700 km to 1336 km for the TOPEX/Jason series, and in four orbit planes: 66° mainly for the oceanic altimetry missions, 78 ° for SWOT and 92 and 98° for the polar orbits.

Table 1. DORIS data available at IDS data centers, as of June 2023.

Satellite	Start	End	Space Agency	Type
SPOT-2	31-MAR-1990 04-NOV-1992	04-JUL-1990 15-JUL-2009	CNES	Remote sensing
TOPEX/Poseidon	25-SEP-1992	01-NOV-2004	NASA/CNES	Altimetry
SPOT-3	01-FEB-1994	09-NOV-1996	CNES	Remote sensing
SPOT-4	01-MAY-1998	24-JUN-2013	CNES	Remote sensing
JASON -1	15-JAN-2002	21-JUN-2013	NASA/CNES	Altimetry
SPOT-5	11-JUN-2002	1-DEC-2015	CNES	Remote sensing
ENVISAT	13-JUN-2002	08-APR-2012	ESA	Altimetry, Environment
JASON -2	12-JUL-2008	10-OCT-2019	NASA/CNES	Altimetry
CRYOSAT-2	30-MAY-2010	PRESENT	ESA	Altimetry, ice caps
HY-2A	1-OCT-2011	14-SEP-2020	CNSA, NSOAS	Altimetry
SARAL/ALTIKA	14-MAR-2013	PRESENT	CNES/ISRO	Altimetry
JASON-3	19-JAN-2016	PRESENT	NASA/CNES/NOAA/ Eumetsat	Altimetry
SENTINEL-3A	23-FEB-2016	PRESENT	GMES/ESA	Altimetry
SENTINEL-3B	25-APR-2018	PRESENT	GMES/ESA	Altimetry
HY-2C	21-SEP-2020	PRESENT	CNSA, NSOAS	Altimetry
SENTINEL-6A	21-NOV-2020	PRESENT	NASA/CNES/NOAA/ Eumetsat/ESA	Altimetry
HY-2D	19-MAY-2021	PRESENT	CNSA, NSOAS	Altimetry
SWOT	16-DEC-2022	PRESENT	NASA/CNES/CSA/ UKSA	Altimetry

In the next few years, more DORIS satellites are planned: (agreed) Sentinel-3C and 3D, Sentinel-6B; (pending approval) Sentinel-6C, HY-2E and F. The GENESIS-1 mission, already approved by the ESA Council of Ministers in November 2022, is in the mission design and implementation phase.

Figure 1 summarizes the evolution of the DORIS constellation since the launch of the SPOT-2 satellite in 1990 and includes satellites that are currently planned. It must be noted that since 2002, five or more DORIS satellites have been available to IDS users, which is a key requirement for the precision of the geodetic products.

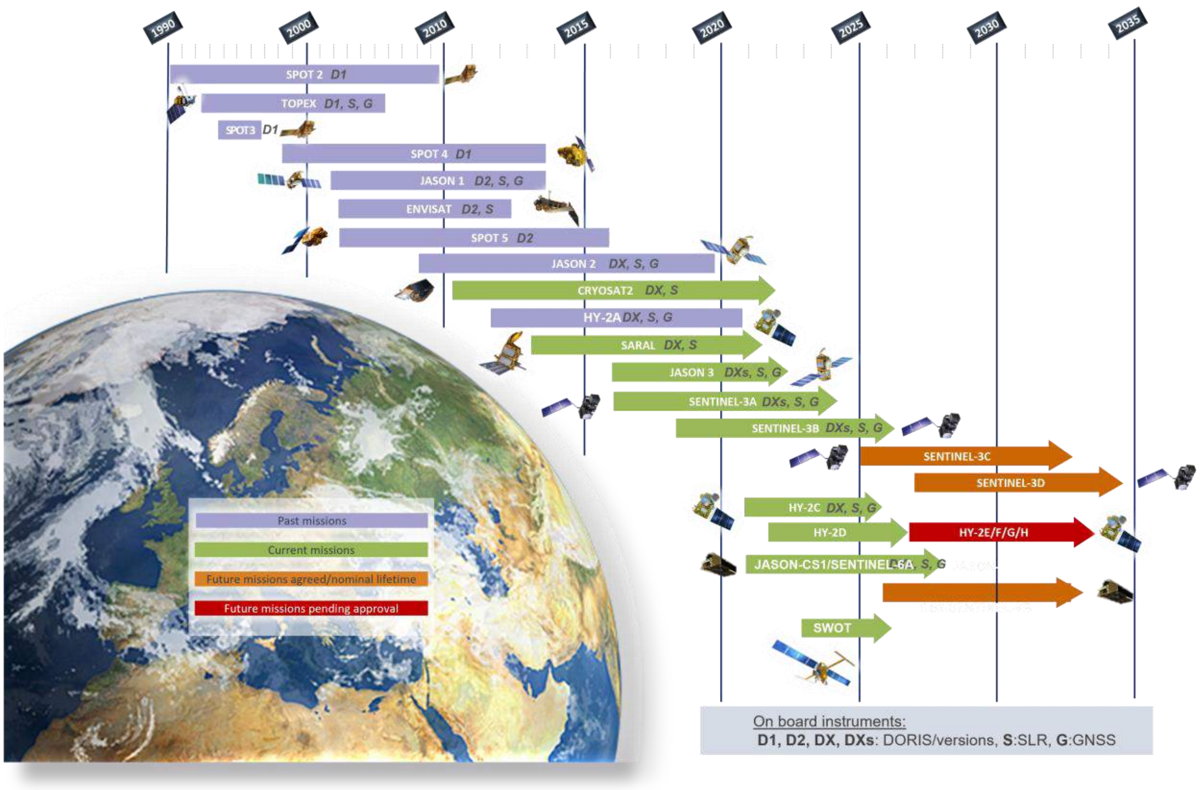


Figure 1. DORIS satellite constellation. As of June 2023.

1.2 DORIS network

General status and operation

DORIS has a globally distributed network of 59 permanent stations dedicated for precise orbit determination and altimetry with four master beacons (Papeete, Hartebeesthoek, Kourou, Toulouse), one time beacon (Terre-Adélie), and one experimental beacon dedicated to IDS for scientific purposes (Wettzell). Mangilao (Guam Island, USA), initially dedicated to IDS, joined the permanent DORIS network in September 2019. In April 2023, the major event on the network was the commissioning of Hanga Roa (Easter Island), which was eagerly awaited for its coverage of the South Pacific.
The map of the DORIS network slightly changed with the new stations and the withdrawal of Krasnoyarsk in Russia which has now been decommissioned. See **Figure 2**.

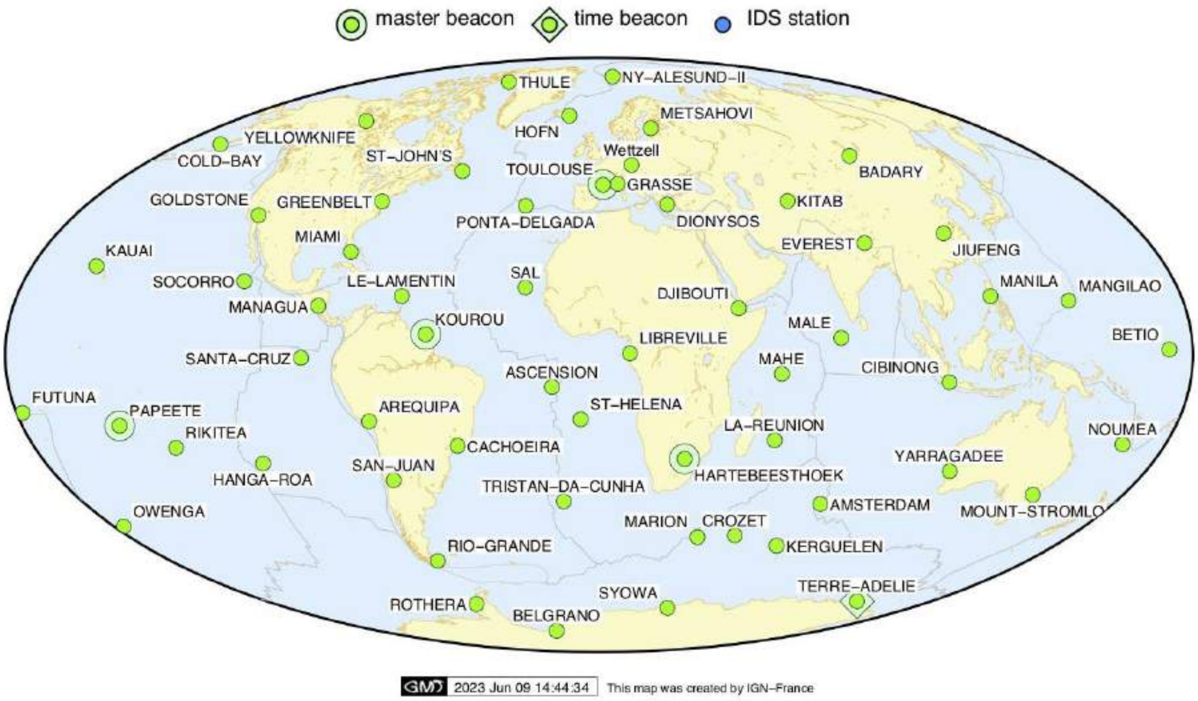


Figure 2. The DORIS permanent network.

As regards maintenance, the good news is that after a very long outage the DORIS station at Santa-Cruz, Galapagos Islands, Ecuador, has been back in operation since December 2019. The station was completely reinstalled, and a new relationship was initiated with the new local staff. In 2020, two stations were fully renovated to enhance performance by changing the antenna environment and upgrading the equipment: an antenna relocation at La Réunion Island (France, Indian Ocean) and a new DORIS site in Höfn (Iceland) in place of Reykjavik. On the other hand, the extensive power outage at Betio has not yet been solved and the two Russian stations (Badary and Krasnoyarsk) are still awaiting authorization from the government authorities for transmission of the DORIS signal.

Notwithstanding those local difficulties and the global health crisis complicating maintenance operations in 2020, the DORIS network provided a reliable service with a mean of 84% of active sites over the two-year period 2019-2020 thanks to the responsiveness of the agencies hosting the stations and an efficient and effective overall management and coordination steered by the CNES and the IGN: 13 failed beacons and 5 failed antennas were replaced.

After the COVID-19 pandemic that considerably complicated field operations and maintenance, 2022 marked the return back to more normal operations. All the projects for the network development that had been put on hold were restarted. On the other hand, the Russo-Ukrainian conflict resulted in the decommissioning of the two Russian DORIS stations (Badary and Krasnoyarsk) after April 2022.

The continuation of the 4th generation beacon deployment, while prioritizing stations out of order or showing signs of a fault, has enabled the network to maintain a high level of service, with a mean of 88% of active sites over the year (see Figure 1). This has been achieved through a strong involvement of the CNES and IGN maintenance teams and the valuable contribution of the local host agencies. After over a year of outage, Cibinong, San Juan, Ny-Alesund II and Futuna were brought back to operation in 2022 (see **Figure 3**).

Figure 3. Network availability 2022: Rate of stations in operation (fortnightly statement)

Evolution and development

2019 was a year marked by the start of the deployment of 4th generation DORIS beacon (B4G), a much-awaited development. Indeed, a new architecture built with up-to-date electronic technology and advanced components will allow reliable operation through 2030+. Moreover, the addition of a signal amplifier at the foot of the antenna to restore the signal to its nominal power after the signal losses during long cable transfer enables increasing the beacon-to-antenna distance (from 15 to 50 m). This offers better options for placing the antenna in an open environment, a major criterion for obtaining good observations.
Although the installation of a site requires balancing different requirements as well as the-specific site and host agency constraints, the goal is to maintain a clear sky visibility down to 10 degrees elevation. The B4G deployment started from mid-2019 at St-John's (Newfoundland), Canada. The deployment strategy consists of replacing gradually the aging equipment, and renovating sites for which the relocation of the antenna will enhance the station performance. By mid-2023, 33 out of 59 sites (56% of the network) will be equipped with the 4th generation beacon (B4G).
Furthermore, we have continued to deploy the new generation of ground antennae (Starec C type) for which the uncertainty in the location of the 2GHz phase center in the vertical direction was significantly reduced to improve the DORIS measurement accuracy. We achieved the antenna replacement of 42% of the network (25 sites) by mid-2023.

The co-location with other space geodetic techniques is also of great interest for geodesy. 49 DORIS stations out of 59 are co-located with at least one other IERS technique: GNSS, SLR, and/or VLBI. Half of the DORIS stations are also co-located with tide gauges enabling better monitoring of the vertical land movement (see **Figure 4**). IGN systematically carries out local tie surveys on the occasion of installations, renovations or dedicated visits on site to contribute to ITRF realizations. All tie vectors at co-located sites with DORIS are available in a maintained file "DORIS_ext_ties.txt" on IDS web (ftp://ftp.ids-doris.org/pub/ids/stations/DORIS_ext_ties.txt) and data centers.

It is also worth noting the long-term life of the DORIS stations: At the end of 2021, half of the current network stations are over 27 years old with 20 of them in continuous operation since the beginning of the DORIS system (1990).

The project of network densification to 70 stations is underway with a number of projects near completion. Five additional sites should be operational in the next two years. The aim is to enhance the network reliability and coverage and to better contribute to geodesy.

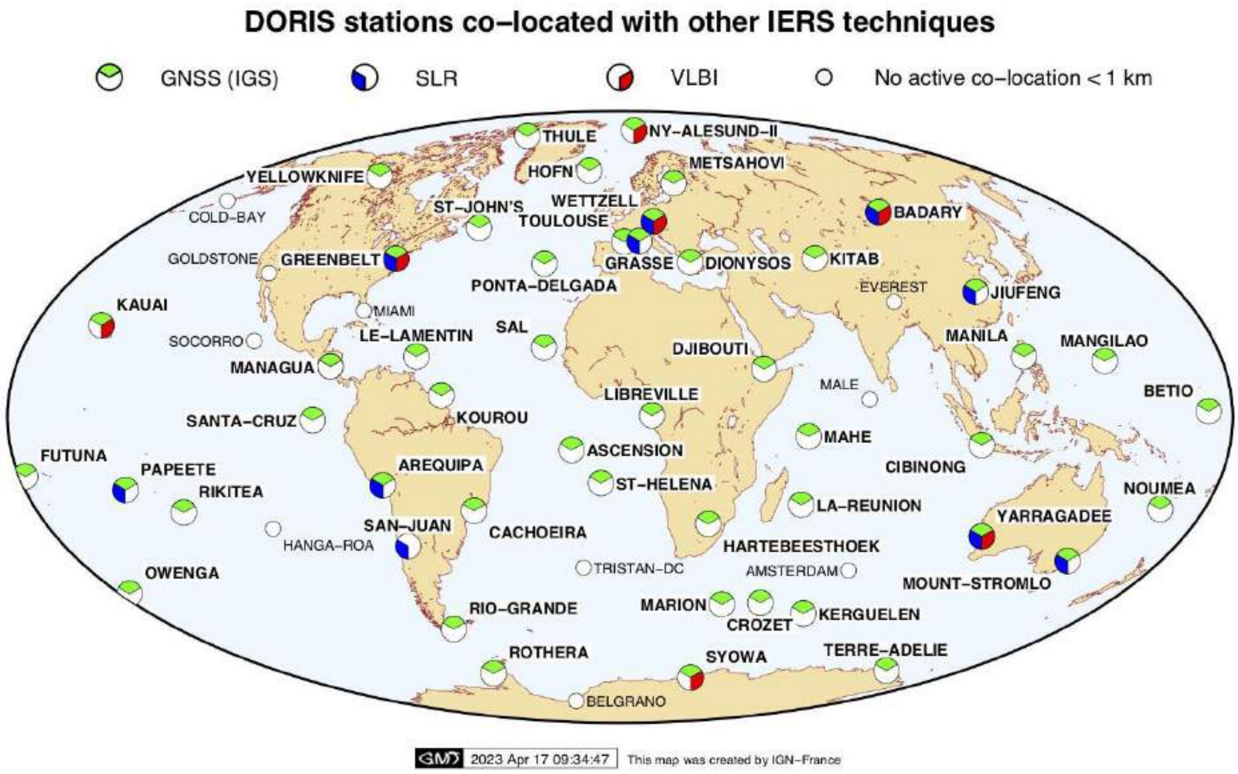


Figure 1. DORIS stations co-located with other IERS techniques and tide gauges

The list of DORIS sites visited during the period covered by this report is as follows:
2019

- B4G testing and site survey at Grasse (France)
- Reconnaissance in Reykjavik and Höfn (Iceland)
- Renovation and site survey at St-John's (Canada)
- B4G installation at Ponta-Delgada (Azores, Portugal)
- Re-installation at Santa-Cruz (Galapagos, Ecuador)
- B4G installing at Saint-Helena (South Atlantic, UK)

2020

- Reconnaissance at Malé (Maldives)
- Renovation of the DORIS station at La Réunion (France)
- B4G installation at Miami (USA)
- Relocation of the Icelandic DORIS station in Höfn
- Reconnaissance in Athens and Crete (Greece)

2021

- Maintenance at La Réunion (France, Western Indian Ocean)
- B4G installation at Metsähovi (Finland)

- Antenna relocation at Malé (Maldives)
- B4G installation at Mahé (Seychelles)

2022

- B4G installation at Kourou (French Guyana)
- B4G installation at Hartebeesthoek (South Africa)
- Reconnaissance at Cachoeira Paulista (Brazil) with a view to relocate the DORIS antenna
- B4G installation at San Juan (Argentina)
- Maintenance at Ny-Ålesund II (Svalbard, Norway)
- B4G installing at Futuna (France)
- B4G installing at Wettzell (Germany)
- B4G installing at Nouméa (New Caledonia, France)
- B4G installing at Owenga (Chatham Island, New Zealand)

In 2023, the overall objectives are:

- Continuation of the deployment of the 4th generation beacon
- Relocation of the DORIS station at Easter Island (Chile)
- Restarting of the DORIS station at Santa-Cruz (Galapagos)
- Installation of a new DORIS site at Gavdos Island (Crete, Greece)
- Station renovation at Everest (Nepal)
- Installation of new DORIS site at Katherine (Australia)
- Renovation at Rikitea (French Polynesia)

2. IDS organization

Like the other IAG Services, an IDS Governing Board (GB), helped by a Central Bureau (CB), organizes the activities done by the Analysis Centers (AC), the Data Centers (DC), and the Combination Center (CC).

2.1 Governing Board

The GB consists of eleven voting members and several nonvoting members. The voting membership of the GB is composed of 5 members elected by the IDS Associates, and 6 appointed members. The elected members have staggered four-year terms, with elections every two years. The Analysis Centers' representative, the Data Centers' representative, and one Member-at-Large are elected during the first two-year election. The Analysis Coordinator and the other Member-at-Large are elected in the second two-year election. Over the period covered by this report, in accordance with the Terms of Reference of the IDS, the membership of the GB was then partially renewed in January 2021 and January 2023 (see **Table2**).

The members who were elected or appointed for the term 2021-2024 are:

- Frank Lemoine (NASA/ GSFC, USA) as Analysis Center Representative,
- Patrick Michael (NASA/GSFC, USA) as Data Center Representative,
- Karine Le Bail (Chalmers University of Technology, Sweden) as Member-at-Large,
- Pascale Ferrage (CNES, France), reappointed by CNES as the DORIS system representative,
- Jérôme Saunier (IGN, France), reappointed by IGN as the Network representative.
- Tonie van Dam (University of Luxembourg, Luxembourg), appointed by IERS as the IERS representative.

The members who were elected or appointed for the term 2023-2025 are:

- Petr Štěpánek (Geodetic Observatory Pecný, Czech Republic) as Analysis Coordinator.
- Laura Sánchez (DGFI-TUM, Germany) as Member-at-large.

In January 2021, the Governing Board re-elected Frank Lemoine as the Chairperson of the IDS Governing Board for 2021-2024.

Denise Dettmering remains an ex officio but non-voting member of the IDS GB, in the role of Chair of the IDS Working Group on Near Real Time Data

Note that Ernst Schrama (TU Delft, The Netherlands) was designated by IAG as its representative within the Governing Board for 2019-2022, to replace Petr Štěpánek (Geodetic Observatory Pecny, Czech Republic), who resigned from this position after he was elected with Hugues Capdeville (CLS, France) to form the Analysis Coordination team for the term 2019-2022.

The IDS GB sincerely thanks the previous members Brian Luzum, Hugues Capdeville and Claudio Abbondanza for serving on the IDS GB for several years.

We would like to say a special thank you to Pascale Ferrage who, after 13 years of involvement in the organization and animation of the IDS, has moved on to other activities in 2022. She is replaced by Arnaud Sellé as CNES/ IDS project manager and representative of the DORIS system within the IDS.

Table 2. Composition of the IDS Governing Board from January 2023.

Position	Term	Status	Name	Affiliation	Country
Analysis coordinator	**2023-2026**	Elected	**Petr Štěpánek**	Geodetic Observatory Pecný	Czech Republic
Data Centers' representative	**2021-2024**	Elected	**Patrick Michael**	NASA/GSFC	USA
Analysis Centers' representative	**2021-2024**	Elected	**Frank Lemoine (chair)**	NASA/GSFC	USA
Member at large	**2023-2026**	Elected	**Laura Sánchez**	DGFI/TUM	Germany
Member at large	**2021-2024**	Elected	**Karine Le Bail**	Chalmers University of Technology	Sweden
Director of the Central Bureau	Since 2003	Appointed	**Laurent Soudarin**	CLS	France
Combination Center representative	Since 2013	Appointed	**Guilhem Moreaux**	CLS	France
Network representative	**2021-2024**	Appointed	**Jérôme Saunier**	IGN	France
DORIS system representative	**2023-2024**	Appointed	**Arnaud Sellé**	CNES	France
IAG representative	**2019-2022**	Appointed	**Ernst Schrama**	TU Delft	The Netherlands
IERS representative	**2021-2024**	Appointed	**Tonie van Dam**	University of Luxembourg	Luxembourg
Chair of WG "NRT DORIS data"	**Nov. 2016-**	Ex-officio (non voting member)	**Denise Dettmering**	DGFI/TUM	Germany

2.2 IDS strategic plan

After the IDS Retreat held in June 2018, the IDS GB worked on the development of a strategic plan for the IDS. In the coming years, IDS will focus on growing the community, extending the DORIS applications, and improving the technology, the infrastructure, and the processing.

2.3 IDS life

The reporting period started sadly because on February 4, 2019, we lost our colleague and friend Richard Biancale, recently retired from the CNES in September 2018, and newly installed at the GFZ (Oberpfaffenhofen) to work with Dr. Frank Flechtner on GRACE Follow-On. A tribute was paid to him in the IDS Newsletter #6:

https://ids-doris.org/images/documents/newsletters/IDS-Newsletter6.pdf#page=5.

IDS also experienced a more joyful departure as in April 2020 Pascal Willis retired from the Institut Géographique National (IGN) after a long and active career promoting analysis and use of DORIS data in geodesy. An article was dedicated to him in the IDS Newsletter #8:

https://ids-doris.org/images/documents/newsletters/IDS-Newsletter8.pdf#page=8.

Arnaud Pollet and Samuel Nahmani will now lead the IGN/DORIS Analysis Center activities following the retirement of Pascal Willis.

The application of the DGFI-TUM (Munich, Germany) to become an Associate Analysis Center was approved by the IDS Governing Board at its meeting on October 1st, 2019. In addition to the six regular Analysis Centers, four Associate Analysis Centers now contribute to the IDS analysis activities.

Frank Lemoine and Laurent Soudarin attended the International Workshop for the Implementation of the Global Geodetic Reference Frame in Latin America held in Buenos Aires, Argentina, from September 16 to 20, 2019. It was the opportunity to meet the friendly colleagues from the agencies hosting DORIS stations in this part of the world.

In 2022, Pascale Ferrage resigned from the IDS GB and was replaced by Arnaud Sellé as CNES/ IDS project manager and representative of the DORIS system within the IDS.

2.4 DORIS days 2021 (November 16, 17 and 18)

The IDS organized online “DORIS Days" on November 16, 17 and 18, 2021. This event was an introductory course to give non-practitioners in DORIS the opportunity to broaden their knowledge of the DORIS technique as well as to provide information on IDS products. Three sessions were given online:

- o "Introduction to DORIS and the International DORIS Service" (118 participants)
- o "Overview of Products Derived from DORIS" (90 participants)
- o "Description DORIS Station Installation and Operations Requirements" (70 participants)

The complete program is available on the IDS website at https://ids-doris.org/ids/reports-mails/meeting-presentations/doris-day-2021.html

This event widely mobilized the members of the Governing Board and the Central Bureau. The organization committee was composed of Pascale Ferrage, Karine Le Bail, Frank Lemoine, Guilhem Moreaux, Jérôme Saunier, Ernst Schrama, Laurent Soudarin. Several external speakers gave presentations in the form of ppt slides or pre-recorded videos.

Prior to the days, the Central Bureau and the organization committee carried out the following actions:

- Preparation of the material: logo mock-up, presentation template, final version of the wallpaper for Teams, pdf of the presentations.
- Communication about the event: dedicated page on the IDS website, announcements on DORISmails and other mailing lists, ...
- Registration management: registration form, follow-up of registrations, sending of confirmation emails
- Management of online meetings with MS Teams: sending invitations, test sessions with speakers, technical support during sessions, retrieving attendance statistics, recording sessions
- Forum management: setting up the https://dorisdays2021.aviso.altimetry.fr/ sub-site, configuration, creation of accounts, uploading of presentations and videos, user support

2.5 DORIS special issue

The journal Advances in Space Research launched in September 2021 a Call for Papers for a Special Topic Issue with the title “New Results from DORIS for Science and Society” and the editors Dr. Ir. Ernst Schrama (TU Delft) and Dr. Ing- Denise Dettmering (DGFI / TU München).

The issue consists of 8 eight papers and is dated 1 July 2023. The list of articles can be found at https://www.sciencedirect.com/journal/advances-in-space-research/vol/72/issue/1.

2.6 IDS call for proposals: hosting a DORIS station

In April 2022, the IDS issued a call for participation with aim at encouraging institutions and agencies involved in geodesy to express their interest in hosting an "IDS Station" and developing scientific collaboration with IDS. An "IDS station" is distinct from the general network dedicated to "orbitography" or "orbit determination" and can have a specific scientific focus.

Eight proposals were submitted. Analysis of the proposals by a committee made up of GB members led to a list of two proposals that best met the selection criteria (location, co-location with other instruments, indoor equipment housing conditions, antenna environment, monument stability, maintenance and security, host agency abilities, scientific collaboration). Remote meetings were organized with each of the two shortlisted groups to meet them and gather additional information. Following these meetings, the GB made its decision and selected the proposal from ITT Kanpur (India). A site reconnaissance will be carried out in order to determine the best suitable location for the antenna with respect to system requirements. The objective is to install the beacon in 2024.

***2.7** Central Bureau*

The Central Bureau, funded by CNES and hosted at CLS, is the executive arm of the Governing Board and as such is responsible for the general management of the IDS consistent with the directives, policies and priorities set by the Governing Board. It brings its support to the IDS components and operates the information system.

The Central Bureau participated in the organization of the AWG meetings (see **3.1**). It documented the Governing Board meetings held on these occasions. The Minutes of the GB meetings are available on the website at https://ids-doris.org/ids/reports-mails/governing-board.html#minutes.

Website

Flash the QR code to visit the IDS website

The Central Bureau maintains the web resources of the IDS. Besides the regular updates of pages and additions of documents, the website (https://ids-doris.org) has been upgraded and was enriched with new information. New features were added to the network viewer (https://apps.ids-doris.org/apps/map.html). IVS and ILRS co-located stations with DORIS sites can now be displayed in addition to the IGS stations. The list of the colocations is based on the file of ties between DORIS and GNSS, VLBI and SLR stations managed (see **Figure 5**). This item completes the list already in place: boundaries of the tectonic plates (Bird, 2003), large Earthquakes (magnitude greater or equal to 6) within a 500 km radius of the DORIS stations (source USGS), horizontal and vertical velocity vectors of the DPOD2014 solution, as well as rates (North, East and Up; in mm/yr) and local events, i.e., the events of the station (dates of installation, change of beacon equipment, Earthquakes in the vicinity).

Figure 5. Screenshot of the network viewer on the IDS web (https://apps.ids-doris.org/apps/map.html).

Newsletter

Launched in April 2016, the IDS Newsletter aims to provide regular information on the DORIS system and the life of IDS to a wide audience, from the host agencies to the other sister services.
The issues are distributed via email to the subscribers to the DORISmail and several identified managers and decision-makers. They are also available from the IDS website (https://ids-doris.org/ids/reports-mails/newsletter.html).
A total of five issues were published in 2019 (#6 in February), 2020 (#7 in January, #8 in December), 2021 (#9 in September), 2023 (#10 in April). A new more dynamic presentation has been adopted since issue #7.

Data dissemination

The Central Bureau works with the SSALTO multi-mission ground segment and the IDS Data Centers (at IGN and the NASA CDDIS) to coordinate the data and products archiving and the dissemination of the related information. Data, metadata, and documentation of the three missions HY-2C, Sentinel-6A and HY-2D were put online the IDS data and information sites as they become available.
Following user requests for rapid dissemination of DORIS data for assimilation in ionospheric models, CNES has been distributing since February 2021 the first DORIS NRT products via the IGN data center. Observation data (RINEX) and orbit information (sp3) for the Jason-3 mission is available with a latency of about three hours. The new products are freely accessible via
the following directories:

ftp://doris.ign.fr/pub/doris/data/ja3/NRT/
ftp://doris.ign.fr/pub/doris/products/orbits/ssa/ja3/NRT/
In 2023, the delivery of NRT products will be extended to additional missions.

DORIS-related articles in peer-reviewed journals
A new web-based tool for the management and consultation of the DORIS bibliography has been implemented on the IDS website. All references are stored in a database. The web component of the tool deployed on the https://ids-doris.org/ids/reports-mails/doris-bibliography/peer-reviewed-journals.html page allows dynamic display of the references and offers search functionalities by filter. The administration part of the tool consists of an input interface for ingesting references and a dashboard providing statistics on the content of the database.

DOI assignment
The Central Office now has the possibility of assigning DOIs to IDS documents and products using the CNES DOI service. For instance, a DOI was- assigned to the IDS16 solution contributing to ITRF2020 (10.24400/312072/i01-2021.001) as well as to the IDS activity report 2021 (10.24400/312072/i02-2023.001).
The Central Bureau participates in the meetings of the GGOS DOI Working Group.

2.8 Data Centers

Two data centers currently support the archiving and distribution of data for the IDS:

- Crustal Dynamics Data Information System (CDDIS), funded by NASA and located in Greenbelt, Maryland USA,
- Institut National de l'Information Géographique et Forestière (IGN) in Marne-la-Vallée France.

Both institutions have archived DORIS data since the launch of TOPEX/Poseidon in 1992. The CDDIS (ftps://gdc.cddis.eosdis.nasa.gov) runs fully redundant systems with both primary and secondary systems at different physical locations with access transparent to the end user. IGN in France uses two sites (ftp://doris.ign.fr) and (ftp://doris.ensg.ign.fr) which are exact mirrors of each other offering continued operations even if one of them is inaccessible due to a temporary failure. The data holdings between CDDIS and IGN are not mirrored between the sites but rely on data providers to upload data and products to both to ensure full coverage at each center.

From mid-2019, CNES developed a new tool to control the SSALTO deliveries of DORIS data and products at both IDS Data Centers (CDDIS and IGN). Missing files and anomalies were identified and fixed for the whole sub-tree of both data centers through detailed joint work between the IDS Central Bureau, SSALTO team and the Data Centers teams. This routine maintenance is now regularly carried out to ensure the integrity of SSALTO data and products (orbits, RINEX, quaternions…).

Following the IDS Retreat in 2019, the provision of Near-Real-Time DORIS data and products was decided. A pilot project was set up at the beginning of 2021 with the IGN Data Center: Jason3 RINEX data and DIODE orbits are distributed with a latency of about 3 hours. The first feedback from the WG "NRT DORIS Data" was quite positive: DORIS data latency up to 2-3 hours enables a contribution to the ultra-rapid ionosphere VTEC modeling; files structure improvements were requested but all may not be taken into account because it will impact the logical organization of the directory structure.

CDDIS Data Center

The NASA CDDIS Data Center stopped providing anonymous ftp services as of 1 November 2020. All users are now requested to use https, and a NASA Earthdata login as a method of access to the CDDIS archive. Instructions and example links are available here: https://cddis.nasa.gov/Data_and_Derived_Products/CDDIS_Archive_Access.html
Unencrypted anonymous ftp services are still available at IGN Data Center for the time being.

At the end of 2022, the CDDIS has devoted 146 GB of disk space (83GB or ~57% for DORIS data, 38GB or ~26% for DORIS products, and 25GB or ~17% for DORIS ancillary data and information) to the archive of DORIS data, products, and information. During the past year, users downloaded 1949 Gbytes (1,033,799 files) of DORIS data, products, and information from the CDDIS.

IGN Data Center

To ensure a more reliable data flow and a better availability of the IGN Data Center, two identical infrastructures and configurations have been set up in two different locations at IGN: (1) Saint-Mandé and (2) Marne-la-Vallée.
Each site offers:

- FTP deposit server for data and analysis centers uploads, requiring special authentication
- Free FTP anonymous access to observations data and products
- Independent Internet links

All the DORIS data and products archived and available at IGN DC may be access through:

1. ftp://doris.ign.fr (Saint-Mandé)
2. ftp://doris.ensg.eu (Marne-la-Vallée)

The mirroring applied between both IGN DORIS Data Centers will be consolidated to have exact identical content.
Finally, the IGN Data Center is thinking about possible evolution regarding file access and transfer by implementing the Secure File Transfer Protocol (SFTP).

After more than 12 years of service for the IGN DORIS Data Center, Bruno Garayt handed over to Jérôme Saunier from January 2019. Thank you Bruno!

2.9 Analysis Centers and Analysis Coordination

The activities of all DORIS analysts were dominated by the preparation in 2019, then by the reprocessing of DORIS data for ITRF2020 in 2020 and early 2021. However, they were profoundly affected by the COVID pandemic in 2020 and 2021. In 2020, all meetings of the Analysis Working Group (AWG) and the IDS workshop were cancelled due to the pandemic. The usual face-to-face AWG meetings were held remotely from 2021 onwards.
Two meetings were held in 2019, in Munich (Germany) in April and in Paris (France) in September/October. The only AWG meeting in 2021 was held online on April 6 and 7. The AWG then met online on June 14, 2022, and April 18, 2023. The group will meet again in person in November 2023.

Analysis Working Group (AWG) meetings

The first AWG meeting of 2019 was held in Munich on April 4, thanks to our hosts Denise Dettmering and Mathis Bloßfeld from DGFI-TUM. As usual, the analysis centers and the combination center gave their processing status. New DORIS groups such as DGFI-TUM and Copernicus POD service presented the results of their processing of DORIS satellite data. The CNES POD team presented studies on the update of the HY-2A SRP model, on the progress of CNES mascon solutions and on the

pre-processing of DORIS phase data for Doppler solutions. The main objective of this meeting was the IDS contribution to ITRF2020.
The second AWG meeting of 2019 took place at CNES headquarters in Paris on September 30 and October 1, thanks to our host Pascale Ferrage. The first part of the meeting was devoted to general IDS presentations, while the second part focused on the most important topics relevant to the 2020 ITRF reprocessing.

Meetings resumed in 2021, with an online meeting in April. The analysis centers involved in the ITRF2020 reanalysis also held periodic virtual meetings with the IDS combination center to discuss issues relating to their contributions and the preparation of the IDS combination for ITRF2020.

The online meeting in June 2022 started typically with DORIS system and network status reports. A major part of the meeting was devoted to the post-ITRF reprocessing plans and activities of IDS analysis centers and associated analysis centers. The CNES POD team presented how to profit from the tandem phase of Jason-3/Sentinel-6A and Sentinel-3A/Sentinel-3B. Also, detail analysis of Tristan Da Cunha data was presented.

The April 2023 meeting was also held online. In addition to the reports from the Analysis Centers and Associate Analysis Centers, presentations were given on the latest gravity field New mean gravity field model CNES_GRGS.RL05MF_combined_GRACE_SLR_DORIS from GRGS (JM Lemoine) and its evaluation by DGFI-TUM (S. Rudenko) using precise orbit determination of TOPEX/Poseidon and Jason satellites, as well as the precise determination of CryoSat-2's orbit in ITRF2020 (E. Schrama).

Presentations from the AWG meetings are available on the IDS website at
https://ids-doris.org/ids/reports-mails/meeting-presentations.html

Analysis Centers and Combination Center

The IDS includes six Analysis Centers (AC) and four Associate Analysis Centers (AAC) who use eight different software packages, as summarized in **Table 3**. Some analysis centers perform POD analyses of DORIS satellites on a routine basis using other geodetic techniques (SLR and GNSS).
Over the recent years, three ACs have fully participated in operational solutions (GSC, GRG, GOP). The ESA AC also participated in the ITRF reprocessing. The ACs IGN and INA are not delivering operational solutions at the present time. The IGN center has not yet restarted its activities after the retirement of its long- time director, Pascal Willis. The IGN AC is presently implementing DORIS processing with the new GipsyX software. The INA analysis center is presently developing a new software package. The IDS has been in contact with the ACs, but we contain to wait for their return to operational status. The Associate Analysis center (AAC) GFZ contributed to ITRF2020 by testing series processing data from chosen set of satellites. The DGFI-TUM AAC has been active in the satellite attitude modeling and the evaluation of reference frames. The CNES AAC continues to provide POD solutions for operational users, including for the new satellites, Sentinel-6A and HY-2C. The CNES AAC POD solutions are delivered regularly to the IDS Data Centers and are usually multi-technique solutions based on DORIS and GNSS.

A Geocenter Working Group was established including CNES, GOP, GRG, and DGFI-TUM.

Name	Center	Location	Contact	Software	Multi-technique
ESA	**AC**	Germany	Michiel Otten	NAPEOS	SLR, GNSS
GOP (Geodetic Observatory Pecny)	**AC**	Czech Republic	Petr Stepanek	Bernese	
GRG (GRGS)	**AC**	France	Hugues Capdeville	GINS	SLR, GNSS
GSC (NASA/GSFC)	**AC**	USA	Frank Lemoine	GEODYN	SLR
IGN	**AC**	France	Pascal Willis	GIPSY	
INA (Inasan)	**AC**	Russia	Sergei Kuzin	GIPSY	
CNES/POD	**AAC**	France	Alexandre Couhert	Zoom	SLR, GNSS
GFZ	**AAC**	Germany	Rolf Koenig	EPOS-OC	SLR, GNSS
TU Delft	**AAC**	The Netherlands	Ernst Schrama	GEODYN	SLR
DGFI-TUM	**AAC**	Germany	Mathis Bloßfeld, Sergei Rudenko	DOGS	SLR

Table 3. Summary of IDS Analysis Centers (AC) and Associate Analysis Centers (AAC)

ITRF2020 reprocessing

Four analysis centers participated in the ITRF 2020 reprocessing: GSC, GRG, GOP, and ESA. GSC, GRG and GOP processed data 1993.0-2020.0. GSC did not include Sentinel-3A and Sentinel-3B data but plans its inclusion in final solution. GOP completely excluded Jason-1 data. The ESA data processing was delayed but with anticipation of full contribution. IGN and INA were not able fully contribute.

The schedule followed by IDS for this reprocessing was as follows:

- 2020, March 30: delivery by ACs of 1993.0 2002.3 (until start of Envisat First DORIS 2G receiver)
- 2020, June 30: delivery by ACs of 2002.3 2011.8 (until start of HY-2A).
- 2020, Sept. 30: delivery by ACs of 2011.8 2020.0.
- 2021, Feb. 10: First delivery of the IDS combined solution to the IERS (1993.0 2020.0).
- 2021, Feb. 14: delivery by ACs of 2020
- 2021, Mar. 15: Complete delivery to the IERS of the IDS combined solution (1993.0-2021.0).

2.10 Combination Center

The IDS Combination Center (CC) performs the routine evaluation and combination of the solutions of the IDS Analysis Centers. In 2019 and 2020, the CC released the two versions of the IDS cumulative position and velocity and DPOD2014 solutions. It also performed some analysis mostly related to the forthcoming realization of the IDS contribution to the ITRF2020 and initialized the analysis and construction of the IDS series for the ITRF2020. In 2021, the CC finalized the IDS contribution to the ITRF2020. Then, it computed and distributed the first version of the DPOD2020.

IDS Routine Evaluation and Combination

At the end of 2020, the time span of the SINEX files of the IDS combined solution was 1993.0-2020.5. These files correspond to the new IDS series 14 which differs from the previous series 13 by a new preprocessing of the inputs, i.e., the weekly SINEX files provided by the Analysis Centers (ACs).

Late 2019, the Combination Center released a new version of the coordinate time series plots which are routinely delivered to the Data Centers. That new version (see **Figure 6**) displays as vertical lines dates of events which may have an impact of the positions and/or velocities. Depending on their origin, three types of events are displayed: seismic, technical (beacon or USO change, antenna displacement…) and unknown.

At the end of the first quarter of 2023, the time span of the SINEX files of the IDS combined solution was 1993.0-2022.0. These files correspond to the new IDS series 20 which can be seen as the time extension of the IDS contribution to the ITRF2020. Note that now the routine evaluation includes the delivery to the IDS Data Centers of the time series of the daily Earth pole coordinate estimations from the IDS ACs and the IDS CC solutions. Over the last two years, the IDS CC also evaluated several single satellite solutions (Jason-3, Sentinle-3A/B, Sentinel-6A mainly) from the IDS ACs as well as from the associated AC GFZ.

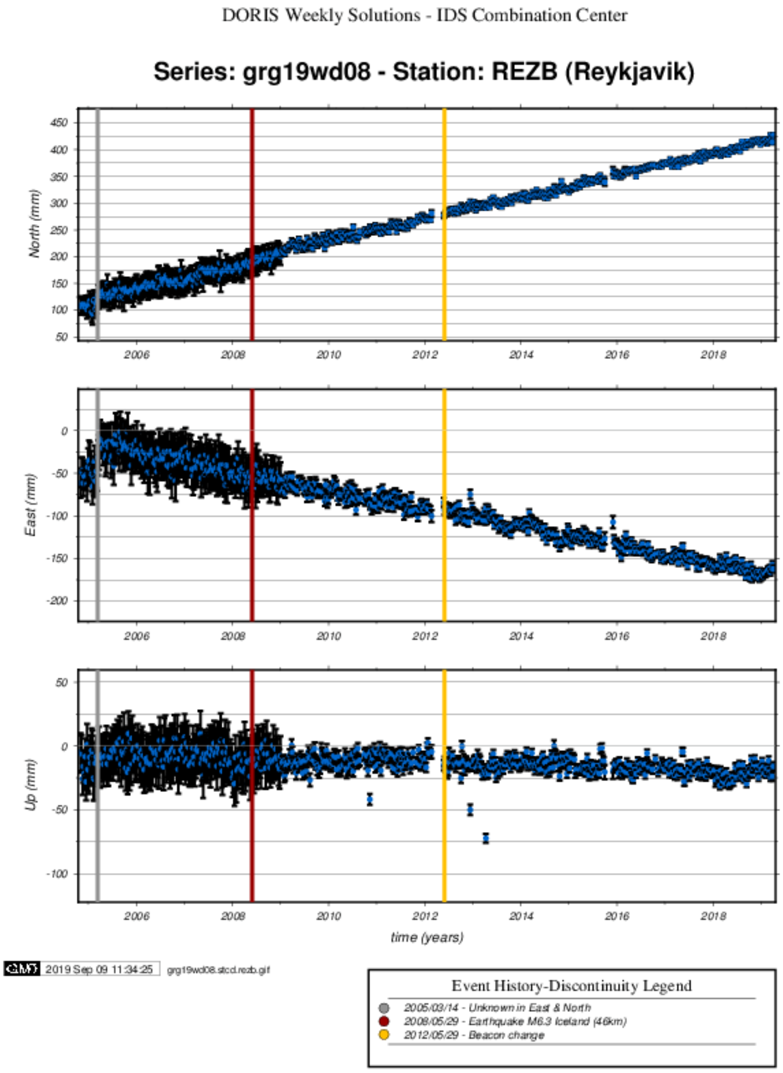


Figure 6. Example of the new version of the coordinate time series plots delivered to the IDS Data Centers for station REZB (Reykjavik).

<u>IDS Cumulative Solution</u>

In 2019, the Combination Center realized and made available (through the IDS Data Centers) the fourth version of the DORIS cumulative solution (ids19d04) which provides the mean positions and velocities of the DORIS stations. That solution is obtained by the stacking of the ids 13 weekly combined solution from 1993.0 to 2019.0. All the cumulative solutions are available in SINEX format at the IDS Data Centers. Internal validation reports as well as plots of the station position residuals (differences between the weekly positions as input and the positions deduced from the mean positions and velocities) are available on the IDS website.

Mid-2020, due to both the evolution of the beacon ground network and of new geophysical events, a new cumulative solution over 1993.0-2020.0 was produced based on the ids13 and ids14 weekly combined solutions.

To better understand the differences between the solutions of the Analysis Centers and their impact on the estimation of the mean positions and velocities, the Combination Center adapted the cumulative processing chain to get position and velocity cumulative solutions for each operational AC. As the IDS cumulative solution, these solutions are also aligned to the ITRF2014 and make use of the same discontinuities.

DPOD2014

In line with the realization of the fourth version of the DORIS cumulative solution, the Combination Center delivered to the IDS community the fourth and fifth versions of the DORIS extension of the ITRF2014, called DPOD2014 (see **Figure 7**). Compared to the cumulative solution, the DPOD2014 contains the stations observed before 1993 as well as the stations turned on after the ending date of the stacking. The DPOD2014 solution is available for download from the IDS Data Centers in both SINEX and text formats.

From the DPOD2014, the Combination Center generates a so-called IDS SINEX Master file containing the names and locations of all the DORIS stations since the start of DORIS. The SINEX Master file is freely available for download from the IDS Central Bureau ftp site at https://ids-doris.org/documents/BC/stations/ids.snx.

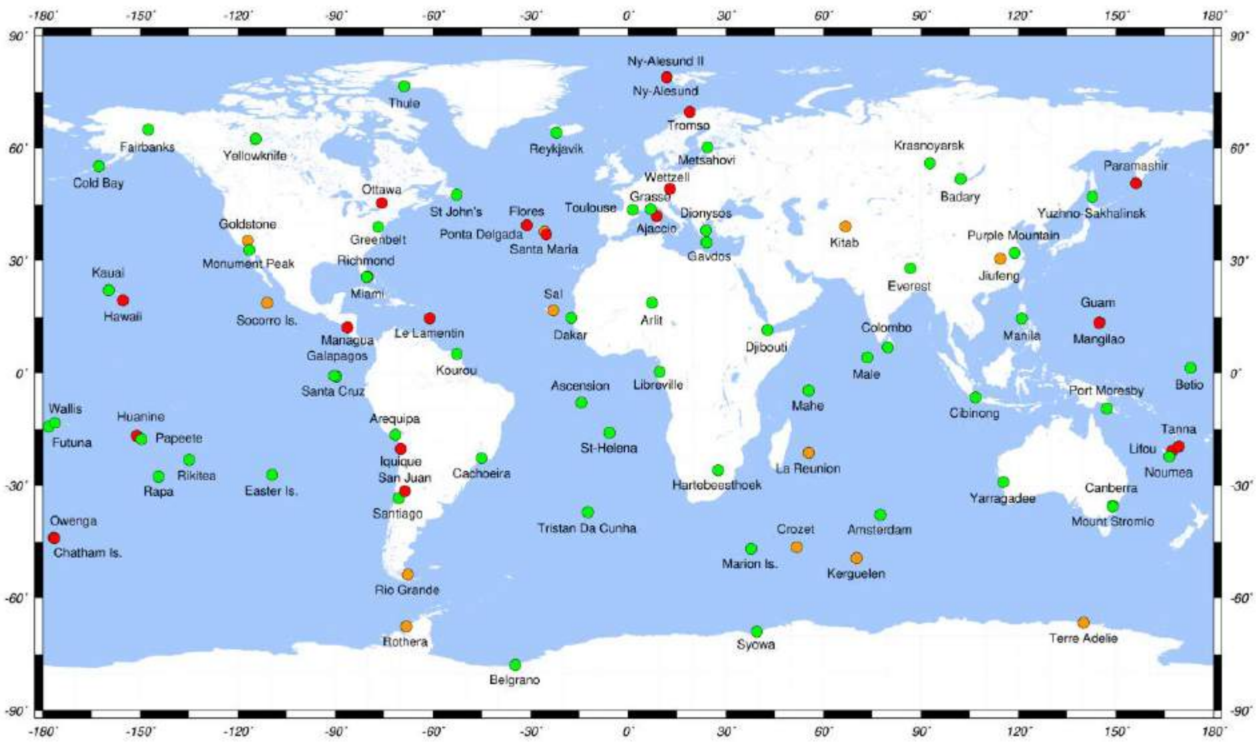


Figure 7. DORIS sites included in the version 5 of the DPOD2014 (i.e., DORIS extension of the ITRF2014). Green: ITRF2014 sites. Orange: ITRF2014 sites with new station(s) since ITRF2014. Red: sites not included in the ITRF2014.

ITRF2020

Nearly fifteen series were delivered by the four IDS ACs (ESA, GOP, GRG and GSC) which agreed to participate to the realization of the DORIS contribution to the ITRF2020. The AC's delivered multiple series to test different models and modes of data processing. The final series delivered for ITRF2020 were fully compliant with the latest IERS standards and recommendations in the ITRF2020 call of participation. The delivery of the ACs was scheduled over time-periods linked with the time evolution of the DORIS satellite constellation: 1993.0-2002.5, 2002.5-2011.7 and 2011.7-2020.0. Due the DORIS data and model latencies, the last year (2020) was delivered by February 2021.

The year 2020 was devoted to evaluating the performance of the received series, analyzing the anomalies, iterating with the Analysis Centers to correct them, improving the combination processing chain, and defining the combination strategy.

Prior to AGU 2020 Fall meeting, the IDS CC made available for evaluation to the IERS combination centers (DGFI, IGN and JPL) a preliminary IDS solution from 1993.0 to 2020.0.

From the contribution of the four IDS ACs (ESA, GOP, GRG and GSC), the IDS CC realized the IDS contribution to the ITRF2020. The final version of the IDS 16 series was delivered to the IERS in July 2021. For all the details of the IDS contribution to the 2020 realization of the ITRF, we refer to the next open access paper:

Moreaux, G., Lemoine, F.G., Capdeville, H., et al., 2023. The International DORIS Service contribution to the 2022 realization of the International Terrestrial Reference Frame. Adv. Space Res., 72(1), 65-91, DOI: 10.1016/j.asr.2022.07.012.

As soon as the ITRF2020, DTRF2020 and JTRF2020 solutions were made available, the IDS CC performed the DORIS evaluation of these solutions and shared the results with the corresponding IERS ITRS centers.

DPOD2020

In 2022, the IDS CC started the realization of the first version of the DPOD2020 (*DORIS extension of the ITRF2020 for Precise Orbit Determination*) based on the IDS 19 weekly combined solution from 1993.0 to 2022.0 (see **Figure 8**). Like with DPOD2014, each DPOD realization relies on the computation of a DORIS position and velocity cumulative solution aligned to the current version of the ITRF and is validated by POD tests performed by GSFC and CNES. The processing strategy and the validation test results of the DPOD2020 version 1.0 were presented at AGU 2022. The DPOD2020 version 1.0 was released to the IDS Data Centers late January 2023 and is available in both text and SINEX formats. Since DPOD2014, the DPOD SINEX files include two new blocks listing the dates and origins of the discontinuities and time periods of some stations which were rejected and may not be used for POD.

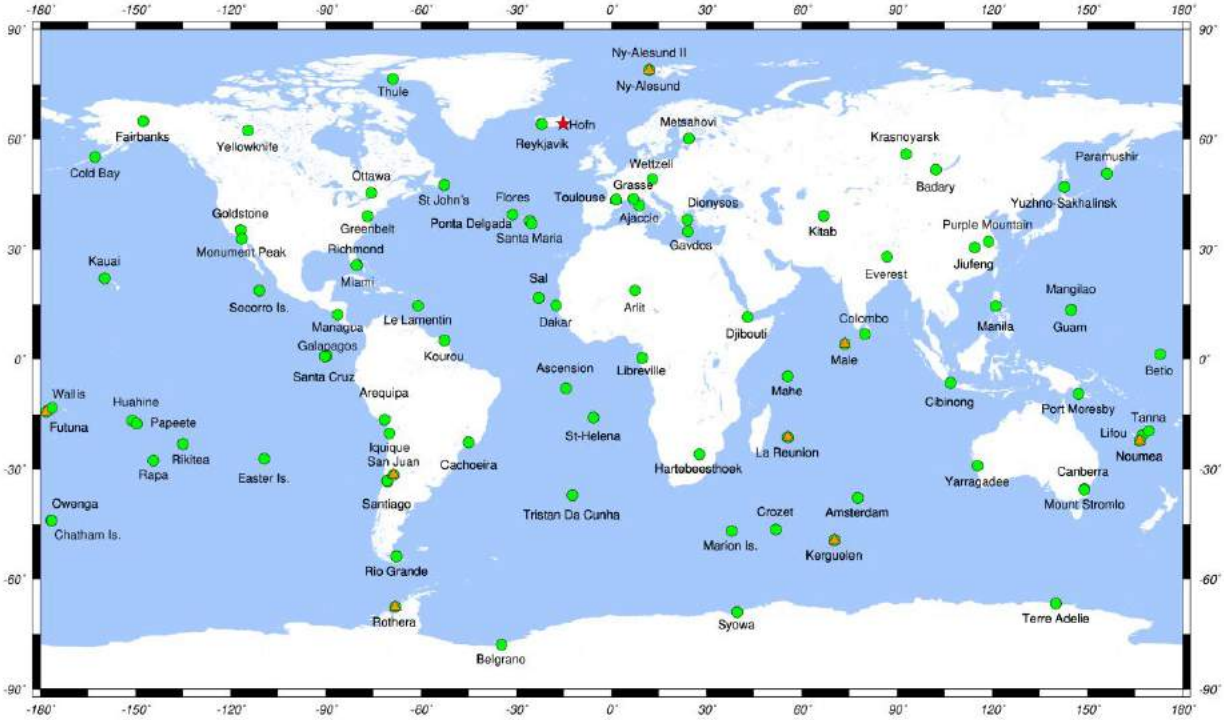


Figure 8. DORIS sites included in the version 1 of the DPOD2020. Green: ITRF2020 sites. Orange: ITRF2020 sites with new station(s) since ITRF2020. Red: sites not included in the ITRF2020.

Since the release of the DPOD2020 version 1.0, the IDS CC initiated some studies on the sensitivity of the HY-2A mission to the South Atlantic Anomaly. From the output of the DORIS position and velocity cumulative solution, the IDS CC also investigated the increase of some station position residuals since 2018-2019.

2.11 Working Group "NRT DORIS DATA"
Chair: Denise Dettmering (DGFI-TUM, Germany)

Following user requests for rapid dissemination of DORIS data for assimilation in ionospheric models, the IDS Governing Board created a Working Group (WG) dealing with near real-time (NRT) DORIS data, on November 1st, 2017, and appointed Denise Dettmering (DGFI-TUM) as chair.
The general objective of this working group is a thorough assessment on benefits, requirements, and prospects of near real-time (NRT) DORIS data with a focus on applications in ionospheric research.

The main topics addressed by the WG are:

- Development of a DORIS ionospheric product (STEC/VTEC or dSTEC/dVTEC),
- Using DORIS data for global real-time ionospheric modeling,
- Using DORIS data to validate the performance of global ionospheric TEC models,
- Improving ionospheric modelling with focus on the combination of different space-based observation datasets,
- Networking with other IAG working groups: GGOS JWG 3 "Improved understanding of space weather events and their monitoring by satellite missions" and IAG JWG 4.3.1 "Real-time ionosphere monitoring and modelling".

Since February 2021, the first DORIS NRT products are distributed via the IGN data center. Within the current evaluation period, observation data (RINEX) and orbit information (sp3) for the Jason-3 mission is available with a latency of about three hours. The new products are freely accessible via the following directories:
ftp://doris.ign.fr/pub/doris/data/ja3/NRT/
ftp://doris.ign.fr/pub/doris/products/orbits/ssa/ja3/NRT/

"Since the data from one mission are too few to have a direct influence on ionosphere modelling, there are no NRT ionosphere models with DORIS data yet. However, the data can already be used to validate existing GNSS-based ionosphere models. For this purpose, relative changes in the slant total electron content (dSTEC) derived from two-frequency measurements along the link between the ground station and the satellite, are calculated for individual overflights of the satellite, always related to the highest elevation of the arc. This method has been used for GNSS observations for a long time (Hernández-Pajares et al. 2017). Liu et al (2023) uses this method to validate real-time (RT) GNSS ionospheric models from different IGS analysis centres (namely from CAS, CNES, UPC, WHU; see Liu et al (2023) for more explanations) and finds that this works as well with DORIS data as with GNSS data and is completely independent of the model input data.
In addition to providing an indication of the accuracy of individual RT ionospheric models, the NRT DORIS data can also be used to weight the models of individual data centres for combination. Wang et al (2022) presents first results of such a weighting and shows through a validation with independent altimeter data from the Jason-3 mission that the new combination achieves a better performance than the combination based on classical methods.

It is planned to make NRT DORIS data available for additional satellite missions (Sentinel-3A, Sentinel-3B, Sentinel-6A) and possibly also to further reduce the latency times. This would then result in numerous further applications for ionospheric modelling." *(source IDS Newsletter #10 https://ids-doris.org/images/documents/newsletters/IDS-Newsletter10.pdf#page=2*)

References

Hernández-Pajares, M., Roma-Dollase, D., Krankowski, A., García-Rigo, A., Orús-Pérez, R. (2017). Methodology and consistency of slant and vertical assessments for ionospheric electron content models. Journal of Geodesy, 91(12). DOI: 10.1007/s00190-017-1032-z

Liu A., Wang N., Dettmering D., Li Z., Schmidt M., Liang W., Yuan H. (2023). Using DORIS Data for Validating Real-Time GNSS Ionosphere Maps. Advances in Space. Research. DOI: 10.1016/j.asr.2023.01.050

Wang, N., Liu, A., Dettmering, D., Li, Z., Schmidt, M. (2022). Using Near-Real-Time DORIS data for validating real-time GNSS ionospheric maps. Presented at the IDS Workshop 2022. DOI: 10.24400/312072/i03-2022.3612

3. IDS meetings and publications

3.1 Meetings

IDS organizes two types of meetings:

- IDS Workshops (every two years), opened to a large public and related to scientific aspects or applications of the DORIS systems.
- Analysis Working Group Meetings (AWG) (when needed), more focused on technical issues, and usually attended by representatives of Analysis Centers.

In addition, for the first time, the IDS organized a special event called "DORIS Days" on November 16, 17 and 18, 2021. This event held online was an introductory course to give non-practitioners in DORIS the opportunity to broaden their knowledge of the DORIS technique as well as to provide information on IDS products.

Table 4 gives the list of the meetings held over the reporting period. Due to the global Covid-19 pandemic, no event was organized in 2020.

Table 4: IDS Meetings and events (2019-2023)

Meeting	Location	Country	Dates
DORIS AWG Meeting	Munich	Germany	4 April 2019
DORIS AWG Meeting	Paris	France	30 September – October 2019
DORIS AWG Meeting	online		6-7 April 2021
DORIS day	online		16-18 November 2021
DORIS AWG Meeting	online		14 June 2022
IDS Workshop	Venice	Italy	31 October - 2 November 2022
DORIS AWG Meeting	online		18 April 2023

3.2 Publications

During the last four years, IDS published the following activity reports:

- International DORIS Service (IDS), Report of the International Association of Geodesy 2015-2019, Travaux de l'Association Internationale de Géodésie, Frank Lemoine (chairman of the Governing Board), 2019.
  https://ids-doris.org/documents/report/IDS_Report_mid2015_mid2019_for_IAG.pdf
- International DORIS Service Activity report 2018, Laurent Soudarin and Pascale Ferrage (Eds), 108 pages, 2019.
  https://ids-doris.org/documents/report/IDS_Report_2018.pdf
- International DORIS Service Activity report 2019-2020, Laurent Soudarin and Pascale Ferrage (Eds), 137 pages, 2021
  https://ids-doris.org/documents/report/IDS_Report_2019-2020.pdf
- International DORIS Service Activity report 2021, Laurent Soudarin and Pascale Ferrage (Eds), 105 pages, 2023
  https://doi.org/10.24400/312072/i02-2023.001

3.3 Peer-reviewed publications related to DORIS

IDS maintains on its Web site a complete list of DORIS-related peer-reviewed articles published in international Journals (https://ids-doris.org/report/publications/peer-reviewed-journals.html). In the last four years, the following articles were published (by year), including the eight papers of the DORIS special issue "New Results from DORIS for Science and Society" published in Advances in Space Research:

2023

Altamimi, Z.; Rebischung, P.; Collilieux, X.; Métivier, L.; Chanard, K., 2023. ITRF2020: an augmented reference frame refining themodeling of nonlinear station motions, JOURNAL OF GEODESY, 97:47, DOI: 10.1007/s00190-023-01738-w **OPEN ACCESS**

Delva, P.; Altamimi, Z.; Blazquez, A.; Bloßfeld, M.; Böhm, J., 2023. GENESIS: co-location of geodetic techniques in space, EARTH PLANETS AND SPACE, 75:5, DOI: 10.1186/s40623-022-01752-w **OPEN ACCESS**

Herscovici-Schiller, O.; Gachet, F.; Couetdic, J.; Meyer, L.; Reynaud, S., 2023. A simple ionospheric correction method for radar-based space surveillance systems, with performance assessment on GRAVES data, in New Results from DORIS for Science and Society, E.J.O. Schrama and D. Dettmering (Eds.), ADVANCES IN SPACE RESEARCH, 72(1):108-114, DOI: 10.1016/j.asr.2022.05.036

Kong, Q.; Zhang, L.; Han, J.; Li, C.; Fang, W.; Wang, T., 2023. Analysis of coordinate time series of DORIS stations on Eurasian plate and the plate motion based on SSA and FFT, GEODESY AND GEODYNAMICS, 14(1):90-97, DOI: 10.1016/j.geog.2022.05.001

Liu, A.; Wang, N.; Dettmering, D.; Li, Z.; Schmidt, M.; Wang, L.; Yuan, H., 2023. Using DORIS Data for Validating Real-Time GNSS Ionosphere Maps, in New Results from DORIS for Science and Society, E.J.O. Schrama and D. Dettmering (Eds.), ADVANCES IN SPACE RESEARCH, 72(1):115-128, DOI: 10.1016/j.asr.2023.01.050

Lösler, M.; Eschelbach, C.; Mähler, S.; Guillory, J.; Truong, D.; Wallerand, J.P., 2023. Operator-software impact in local tie networks, APPLIED GEOMATICS, 15:77-95, DOI: 10.1007/s12518-022-00477-5 OPEN ACCESS

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International GNSS Service (07/2019-06/2023)

Rolf Dach, IGS Governing Board Chair
Astronomical Institute, University of Bern, Bern, Switzerland
Felix Perosanz, IGS Governing Board Former Chair
Centre National d'Etudes Spatiales, Toulouse, France
Allison Craddock, IGS Central Bureau Director
Léo Martire, IGS Central Bureau Deputy Director
Jet Propulsion Laboratory, California Institute of Technology, Pasadena, USA
Additional Contributors: Markus Bradke, Jianghui Geng, Tom Herring, Robert Khachikyan, Brian Kohan, David Maggert, Salim Masoumi, Patrick Michael, Ashley Nilo, Paul Rebischung, Ryan Ruddick.

Overview

Section Authors: Rolf Dach, Allison Craddock.

In 2024, the International GNSS Service will have been fulfilling its mission for thirty years. Still today, the Service and all of its members continue to provide and advocate for freely and openly available high-precision GNSS data and products. The delivery of the IGS core products (reference frame, orbits, clock, and atmospheric products) continues to drive the Service's activities. That being said, as part of its multi-GNSS excellence objective, the IGS also continues its steady transformation into a multi-GNSS service, as more and more multi-GNSS stations are added into the core IGS network. Most of the solutions became multi-GNSS ones with the last reprocessing effort for the ITRF2020. Alongside the introduction of the recent reference frame into the operational chain in November 2022, this also applies on the legacy product lines. The related multi-GNSS orbit combination software is currently in the final development phase.

The IGS is led by the Governing Board (GB), comprised of elected or appointed Associate Members who represent the core of IGS participants. The GB discusses the activities of the various IGS components, sets policies and monitors the progress with respect to the agreed strategic plan and annual implementation plan. In addition, as of today, a total of more than 350 active members continuously and voluntarily contribute to working towards the IGS goals: advocacy for, development of, use of, and consistent provision of freely and openly available high precision GNSS data and products.

The IGS operates as a service of the International Association of Geodesy (IAG), and a contributor to the Global Geodetic Observing System (GGOS), where it facilitates cost-effective geometrical linkages with and among other precise geodetic observing techniques. The IGS contribution is fundamental to generating and accessing the International Terrestrial Reference Frame (ITRF).

The IGS also aims to enhance the sustainability of the global/regional geodetic reference frames through intergovernmental advocacy for geodesy. To this goal, it continues to engage with our international user community as well as various partner organisations - such as the International Committee on GNSS (ICG)[1], as well as the UN Committee of Experts on Global Geospatial Information Management (UN-GGIM) and its Subcommittee on Geodesy. Accordingly, some GB members also participate in the governance of IAG and GGOS bureaux, commissions, and Working Groups (WGs); this ensures that the IGS retains its strong level of international interconnectivity, significance, and sustainability.

Figure 1: "IGS at Glance", showcasing the key numbers describing the IGS, as of June 2023. See also the IGS website, at https://igs.org.

IGS Governance and Membership

The IGS membership consists of the Governing Board (GB) members, the Central Bureau (CB) members, and the Associate Members (AM).

The GB leads the IGS, and is partly elected by Associate Members who represent the core of IGS participants, with other roles elected by Working Groups, strategic appointments, or GB-internal vote. The GB discusses the activities of the various IGS components, sets policies and monitors the progress with respect to the agreed strategic plan and annual implementation plan.

[1] Under the aegis of the United Nations Office for Outer Space Affairs.

The CB work program is shaped by the directives and decisions of the IGS Governing Board (GB), which often tasks members of the CB with representing the outward face of IGS to a diverse global user community and the general public.

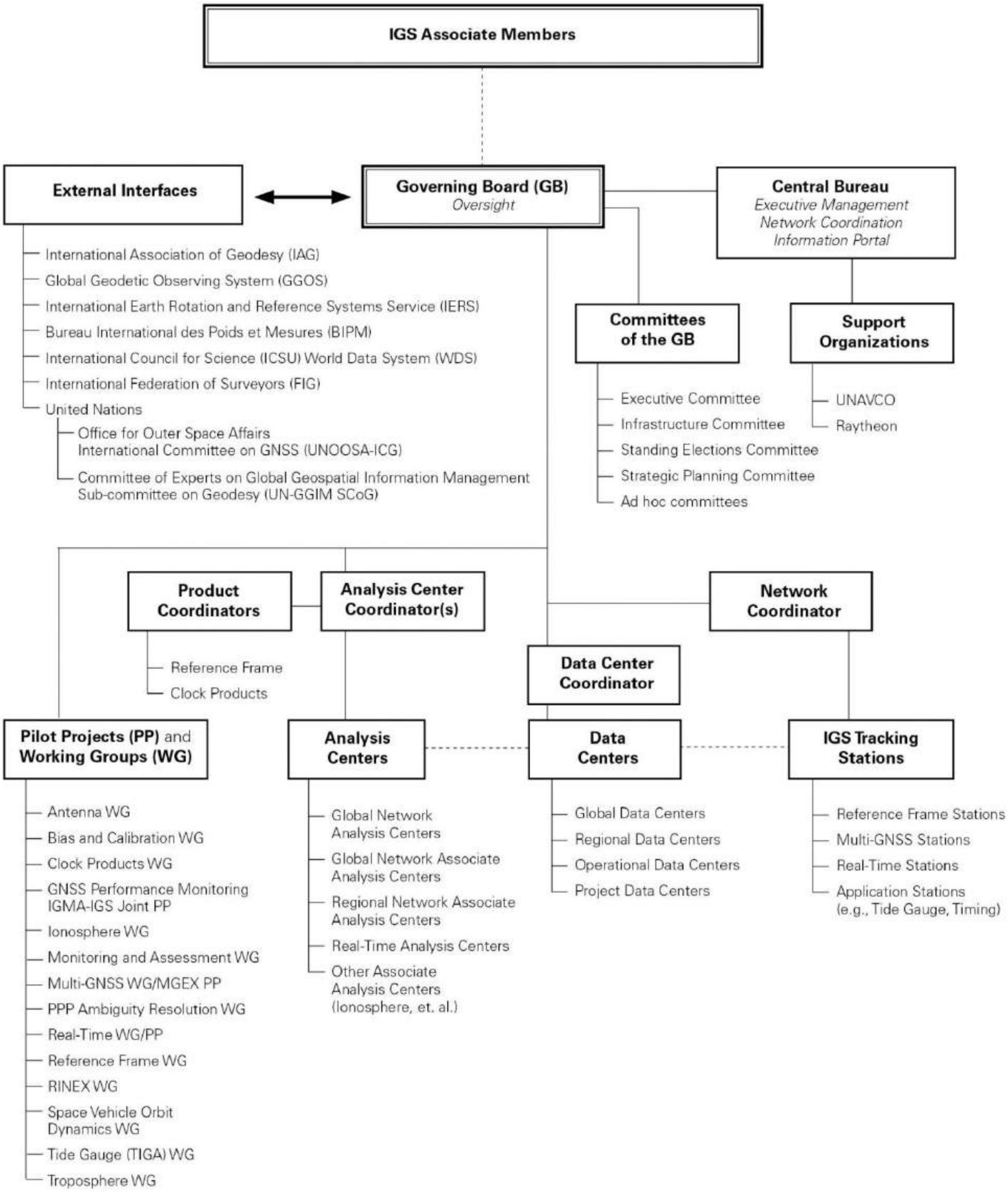

Figure 2: IGS Structure. This structure is currently being reformatted based on the latest information and feedback from the various groups of IGS members. This is the 2020 version of this schematic and an updated structure will be released in 2023.

A schematic of the IGS structure is provided in **Figure 2**. As of early 2023, we count over:

- 350+ AMs (representing 100+ countries/regions),
- 150+ contributing organisations participating within the IGS, including:
  - 100+ agencies operating GNSS Network Tracking Stations,
  - 6 Global Data Centers,
  - 12 Analysis Centers,
  - 5 Product Coordinators,
  - 21 Associate Analysis Centers,
  - 24 Regional/Operational & Project Data Centers,
  - 13 Technical Working Groups, and
  - 2 Active Pilot Projects.

The 44 GB members guide the coordination of all of the aforementioned parties. The CB functions as the executive office of the Service through its 8 members (see Table 2 in Central Bureau Chapter), holding all of the components of the IGS together by providing continuous management and technology.

Governing Board Membership

In May 2020, Gary Johnston (Geoscience Australia) completed his service as Governing Board Chair. Felix Perosanz (CNES) then served as Governing Board Chair from May 2020 to April 2023. Rolf Dach (AIUB), who was elected by the GB in July 2022 as GB Vice Chair, was approved by the GB to be acting GB Chair from April 2023 until July 2023, when the next IGS GB election will take place. **Table 2** summarises the IGS Governing Board Membership from 2019 through to the time of this writing.

Role	Name	Affiliation	Country	Years of Service
GB Chair	Rolf Dach	Astronomisches Institut - Universität Bern (AIUB)	Switzerland	04/2023-present
GB Chair	Felix Perosanz	Centre National d'Etudes Spatiales	France	05/2020-04/2023
GB Chair	Gary Johnston	Geoscience Australia	Australia	2010-05/2020
GB Vice Chair	Rolf Dach	Astronomisches Institut - Universität Bern (AIUB)	Switzerland	05/2020-04/2023
GB Vice Chair	Felix Perosanz	Centre National d'Etudes Spatiales	France	2019-05/2020
GB Executive Secretary	Ashley Nilo	NASA Jet Propulsion Laboratory	USA	07/2022-present

GB Executive Secretary[a]	Mayra Oyola	NASA Jet Propulsion Laboratory	USA	12/2019-06/2022
CB Director	Allison Craddock	NASA Jet Propulsion Laboratory	USA	04/2018-present
CB Deputy Director	Léo Martire	NASA Jet Propulsion Laboratory	USA	07/2022-present
CB Deputy Director[a]	Mayra Oyola	NASA Jet Propulsion Laboratory	USA	12/2019-07/2022
Network Coordinator	David Maggert	EarthScope (formerly UNAVCO)	USA	02/2016-present
Infrastructure Committee Coordinator	Markus Bradke	Helmholtz Centre Potsdam GFZ German Research Centre for Geosciences	Germany	01/2020-present
Infrastructure Committee Coordinator	Ignacio Romero	ESA ESOC Contractor	Germany	2010-12/2019
Appointed Member	Elisabetta D'Anastasio	GNS Science	New Zealand	2021-present
Appointed Member	Werner Enderle	ESA European Space Operations Centre (ESOC)	Germany	2016-present
Appointed Member	Satoshi Kogure	National Space Policy Secretariat	Japan	2014-present
Appointed Member	José Antonio Tarrío Mosquera	University of Santiago de Chile, SIRGAS	Chile	2021-present
Appointed Member	Qile Zhao	Wuhan University	China	2018-2022
Appointed Member	Charles Meertens	UNAVCO	USA	2011-2020
Analysis Center Coordinator	Thomas Herring	Massachusetts Institute of Technology	USA	2016-present
Analysis Center Coordinator	Salim Masoumi	Geoscience Australia	Australia	2021-present
Analysis Center Coordinator	Kevin Choi	National Geodetic Survey (NOAA)	USA	2014-2019
Data Center Coordinator	Carey Noll	NASA Goddard Space Flight Center	USA	2018-2020
Data Center Coordinator[b]	Patrick Michael	NASA Goddard Space Flight Center	USA	2020-present

Data Center Representative	Jianghui Geng	Wuhan University	China	2022-present
Data Center Representative	David Stowers	NASA Jet Propulsion Laboratory	USA	2017-2022
Analysis Center Representative (CNES)[c]	Sylvain Loyer	Collecte Localisation Satellites (CLS)	France	01/2023-present
Analysis Center Representative (JPL)[c]	Paul Ries	NASA Jet Propulsion Laboratory	USA	2020-present
Analysis Center Representative (GFZ)[c]	Benjamin Männel	Helmholtz Centre Potsdam GFZ German Research Centre for Geosciences	Germany	2019-present
Analysis Center Representative (CODE)[c]	Rolf Dach	Astronomisches Institut - Universität Bern (AIUB)	Switzerland	2018-2022
Network Representative	Rui Fernandes	University of Beira Interior (UBI); Institute Dom Luiz (IDL); SEGAL (UBI/IDL)	Portugal	01/2022-present
Network Representative	Ryan Ruddick	Geoscience Australia	Australia	01/2020-present
Network Representative	Wolfgang Söhne	Federal Agency for Cartography and Geodesy (BKG)	Germany	2019-present
Network Representative	Laura Sanchez	Deutsches Geodätisches Forschungsinstitut, Technische Universität München (DGFI-TUM)	Germany	2014-2021
BIPM/CCTF Representative	Patrizia Tavella	Bureau International des Poids et Mesures (BIPM)	France	2022-present
BIPM/CCTF Representative	Gérard Petit	Bureau International des Poids et Mesures (BIPM)	France	2019-2022
IAG Representative	Zuheir Altamimi	Institut National de l'Information Géographique et Forestière (IGN)	France	2011-present
IAG Representative	Basara Miyahara	Geospatial Information Authority of Japan (GSI)	Japan	2019-present
IAG Representative	Chris Rizos	University of New South Wales	Australia	2004-2019

IGS Representative to the IERS[d]	Elisabetta D'Anastasio	GNS Science	New Zealand	01/2021-present
IGS Representative to the IERS[d]	Charles Mertens	UNAVCO	USA	2019-12/2020
IGS Representative to the IERS[d]	Rolf Dach	Astronomisches Institut - Universität Bern (AIUB)	Switzerland	2015-present
IERS Representative to the IGS	Richard Gross	NASA Jet Propulsion Laboratory	USA	2015-present
International Federation of Surveyors (FIG) Representative	Ryan Keenan	Positioning Insights	Australia	01/2023-present
International Federation of Surveyors (FIG) Representative	Suelynn Choy	RMIT University	Australia	04/2019-12/2022
Antenna WG Chair	Arturo Villiger	Astronomisches Institut - Universität Bern (AIUB)	Switzerland	2017-present
Bias&Calibration WG Chair	Stefan Schaer	Federal Office of Topography swisstopo	Switzerland	2007-present
Clock Products Coordinator	Michael Coleman	Naval Research Laboratory (NRL)	USA	2014-present
Ionosphere WG Chair	Andrzej Krankowski	University of Warmia and Mazury in Olsztyn	Poland	2007-present
Multi-GNSS WG Chair	Oliver Montenbruck	Deutsches Zentrum für Luft- und Raumfahrt (DLR)	Germany	2012-present
PPP-AR WG Chair	Jianghui Geng	Wuhan University	China	2022-present
PPP-AR WG Chair	Simon Banville	Natural Resources Canada / Ressources Naturelles Canada	Canada	2018-2022
Real-Time Analysis Coordinator	Loukis Agrotis	ESA ESOC Contractor	Germany	2014-06/2023
Real-Time WG Chair	Axel Rülke	Federal Agency for Cartography and Geodesy (BKG)	Germany	01/2023-present

Real-Time WG Chair	André Hauschild	Deutsches Zentrum für Luft- und Raumfahrt	Germany	2018-01/2023
Reference Frame Coordinator	Paul Rebischung	Institut National de l'Information Géographique et Forestière (IGN)	France	2017-present
RINEX-RTCM WG Chair	Francesco Gini	ESA ESOC	Germany	01/2023-present
RINEX-RTCM WG Chair	Ignacio Romero	ESA ESOC Contractor	Germany	2019-12/2022
Satellite Vehicle Orbit Dynamics WG Chair	VACANT	VACANT	VACANT	01/2023-07/2023
Satellite Vehicle Orbit Dynamics WG Chair	Tim Springer	ESA ESOC Contractor	Germany	2020-01/2023
Satellite Vehicle Orbit Dynamics WG Chair	Marek Ziebart	University College London	United Kingdom	2011-2020
TIGA WG Chair	Tilo Schöne	Helmholtz Centre Potsdam GFZ German Research Centre for Geosciences	Germany	2001-present
Troposphere WG Chair	Sharyl Byram	United States Naval Observatory	USA	2016-present
IGMA-IGS Joint GNSS Monitoring and Assessment Trial Project Chair	Erik Schönemann	ESA ESOC	Germany	01/2023-present
IGMA-IGS Joint GNSS Monitoring and Assessment Trial Project Chair	Tim Springer	ESA ESOC Contractor	Germany	2008-12/2022
Data Center WG Chair[2]	Carey Noll	NASA Goddard Space Flight Center	USA	2006-2019
Weather and Climate Resiliency Pilot Project Chair	Mayra Oyola-Merced	University of Wisconsin-Madison	USA	06/2022-present

Table 1: Roles and membership in the IGS Governing Board over the period of interest (01/07/2019-30/06/2023). Positions that were created during this period are in green, positions that were discontinued are in purple. Affiliations listed here are the last known affiliation for that person in that role. Notes: [a] roles created to hold responsibilities previously held by the CB Director; [b] the role of "Data Center Coordinator" was created to replace the role of "Data Center Working Group Chair" in 2019-2020; [c] there are three elected Analysis Center Representatives at any given time (in 2019, one of these roles was vacant); [d] there are two IGS representatives to the IERS at any given time.

Central Bureau Management

As introduced above, the CB work program is shaped by the directives and decisions of the IGS Governing Board (GB), which often tasks members of the CB with representing the outward face of IGS to a diverse global user community and the general public. In order to sustain the multifaceted efforts of the IGS, the Central Bureau (CB) namely works to support and realise the IGS strategic goals of:

- achieving multi-GNSS technical excellence,
- strengthening public outreach and engagement, and
- building sustainability and resilience.

The CB is funded by the United States National Aeronautics and Space Administration (NASA) and hosted at the Jet Propulsion Laboratory (JPL) in Pasadena, California, USA. This office is led by the CB Director Allison Craddock (NASA JPL, USA) with support from former Deputy Director Mayra Oyola-Merced and current Deputy Director Léo Martire (NASA JPL). The CB also works as the command-and-control centre for tracking network operations, mostly overseen by the Network Coordinator, David Maggert (EarthScope Consortium, formerly UNAVCO, USA). Additionally, the CB manages the primary IGS Information System (CBIS), the principal information portal where the IGS web, data, and mail services are hosted; these tasks are led by Robert Khachikyan (Raytheon, USA) and Ashley Nilo (née Santiago, NASA JPL). A list of the CB members along with their respective roles and responsibilities is given in **Table 2**.

Name	**Affiliation**	**Role**
Allison B. Craddock	NASA JPL	Director
Mayra I. Oyola-Merced	NASA JPL	Deputy Director *(January 2019 until July 2022)*
Léo Martire	NASA JPL	Acting Deputy Director *(from July to December 2022)* Deputy Director *(from December 2022 onwards)*
Ashley Nilo (née Santiago)	NASA JPL	Operations Coordinator
David Maggert	EarthScope (formerly UNAVCO)	Network Coordinator

David Stowers	NASA JPL	CBIS Advisor
Robert Khachikyan	Raytheon Technologies	CBIS Manager
Brian Kohan	Raytheon Technologies	CBIS Engineer

Table 2: IGS Central Bureau staff and responsibilities, over the course of the reporting period 2019-2023. NASA is the National Aeronautics and Space Administration. JPL is the Jet Propulsion Laboratory (Pasadena, USA). UNAVCO is the University Navstar Consortium (Boulder, CO). JPL is managed by the California Institute of Technology (Caltech) for NASA.

The Central Bureau, as part of its work program carrying out the business needs of the IGS, implements actions defined by the GB. This includes routine analysis and refining of the IGS Terms of Reference, supporting the ongoing update of the associate membership and contributing organisations list, coordinating and facilitating GB elections, and ensuring successful organisation of regular IGS Workshops, governance meetings, and community outreach events. Additionally, the Central Bureau works closely with members of the Governing Board's Executive Committee in developing and implementing the IGS Strategic Plan.

Committee on Sustainable Working Group Governance

Section Author: Ryan Ruddick.

Goal 3 of the IGS 2021+ Strategic Plan is to build a sustainable and resilient organisation – the Committee on Sustainable Working Group Governance (CSWGG) is progressing this goal through identifying ways in which the technical Working Groups, Pilot Projects, and Committees can be invigorated to ensure ongoing sustainability and be in a better place to support the IGS in successfully achieving its mission.
During 2022, the Committee on Sustainable Working Group Governance (CSWGG) engaged with the community to develop several recommendations that aim to improve the sustainability of the Working Groups, Pilot Projects and Committees. These recommendations will be delivered throughout 2023 in the form of changes to the Terms of Reference, policy documents, and resources available to support the Working Group and Pilot Project Chairs.

Major Accomplishments and Decisions

The IGS Terms of Reference were also extensively discussed during the 2021-2023 period. Discussions intensified during the 63rd GB Meeting in April 2023. The 64th GB Meeting, which will also be a GB Retreat, will be ground for a final overhaul of the Terms of Reference. A new version will be released during 2023.

The GB approved the RINEX 3.05 format in December 2020, followed by the RINEX 4.0 format in December 2021. In December 2021, per community request (see also the "International Countries Guidelines" Section below), the GB approved the usage of "Country/Region" instead of "Country" in all relevant instances. Furthermore, during the 60th GB meeting in May 2022, the

GB approved the IGS statement on the leap second[2]. Finally, in December 2022, the GB approved new Guidelines for Long Product Filenames[3], which lengthened the product names to provide clear information about Analysis Center, product version, campaign/project, product type, start epoch, sampling, content type, and format.

The GB agreed to submit a letter in support of the GENESIS proposal to ESA in May 2022. The United Nations' (UN) Office for Outer Space Affairs' (OOSA, also known as UNOOSA) International Committee on GNSS (ICG) also submitted a letter of support. The mission was eventually accepted by the ESA member states, in late 2022. GENESIS is a satellite payload combining and co-locating the four main technologies currently used for Earth geodetic measurements: GNSS, VLBI, DORIS, and SLR. At a planned 6000 km altitude orbit, the satellite is supposed to directly connect the four techniques via a globally well distributed space tie.

Virtual IGS 2022 Workshop

Our planet is dynamic and ever changing, and so it seems, was our IGS Workshop planning process, as well. Due to circumstances beyond our control, the IGS needed to postpone the IGS 2020 Boulder Workshop, hosted by UNAVCO and UCAR, to 2022 and ultimately, to a fully virtual format. We used this change of circumstances to help us refocus the IGS Workshop back to being just that – a community workshop. We operated on a compressed schedule to try to be inclusive to as many time zones as possible, and condensed our workshop program to aspects that are the most critical to the function of our Service, specifically a small number of keynote presentations by luminaries and innovators in our community, supported by a comprehensive agenda of working group and/or topical collaboration sessions. The emphasis was on bringing our community together to discuss key issues and brainstorm the next steps toward a multi-GNSS IGS in service to our global community.

The virtual workshop took place the week of 27 June to 1 July, 2022. Key changes included:

- Live Keynote presentations
- Targeted Working Group and topical splinter sessions convened by IGS Working Group Chairs and community leaders
- No Plenaries/Poster sessions, but are effectively already taking place (virtually) via the Tour de l'IGS Mini Workshop Series

Future accompanying events to this workshop include additional/enhanced sessions at the December 2022 AGU Fall Meeting for in-person presentations, an Open Associate Member and Working Group Meeting, and 2022 Workshop networking event. We hope that this new workshop program will help the IGS workshop return to its unique place among our regular meetings, adding value and impact to our profession.

The next iterations of the IGS Community Workshop were also discussed. Between December 2021 and May 2022, it was decided that the Astronomical Institute of the University of Bern (AIUB) would host the next iteration, in Bern (Switzerland) and during the first week of July 2024.

[2] See https://files.igs.org/pub/resource/IGS_LeapSecond_Statement_Final.pdf. In essence, the IGS recommended that
additional leap seconds not be added to UTC.

[3] See https://igs.org/news/updated-guidelines-on-long-product-filenames-in-the-igs/.

IGS 2021+ Strategic Plan

Figure 3: 2021+ IGS Strategic Plan Matrix.

The new IGS Strategic Plan was developed over 2020-2021 by the IGS Governing Board with the help and support of the Central Bureau, and guided by extensive community feedback and discussions. It presents a forward-looking strategy addressing the role of IGS as facilitator, incubator, coordinator, and advocate working towards three major goals in service to our community and beyond. In January 2021, the GB approved the goals and objectives as well as the accompanying text, and the plan was officially published in October 2021.

The 2021 IGS Strategic Plan was built upon the feedback of a plethora of IGS community members, and outlines key points of the IGS goals and the anticipated path to meet its objectives within the next decade. It was created over a two-year development period, released in 2021 and detailed in the corresponding IGS Technical Report (https://igs.org/news/igs-technical-report-2021/). The plan continues in the spirit of its previous strategic plans, striving to serve the community with (a) facilitation, (b) coordination, (c) incubation, and (d) advocacy in three strategic goals: (1) Achieve Multi-GNSS Technical Excellence, (2) Strengthen Outreach and Engagement, and (3) Build Sustainability and Resilience. It focuses on how the IGS maintains and enhances its leadership role within the broader GNSS community, as societal demands for GNSS products and services continue to grow. Central to the goals and objectives are the complementary roles of the IGS as a collaborative research program, as well as an operational service. The plan seeks to maintain appropriate balance of the two roles to ensure ongoing support from associate members and collaborating organisations.

The IGS 2021+ Strategic Plan has been balanced to address both internal and external factors driving IGS organisational growth towards multi-GNSS technical excellence. By setting the first goal to “achieve multi-GNSS technical excellence” IGS strives to increase organisational capability by identifying barriers to multi-GNSS success throughout the IGS, supporting solutions to key challenges, and reinforcing the importance of continuous technical evolution. The second goal is to “strengthen outreach and engagement.” Objectives of this goal will guide advocacy for open access geodetic and GNSS data and products that facilitate collaborations, standardisation, and inclusivity. Looking forward, implementation of this plan will include the third goal of ensuring sustainable and resilient contributions to the IGS community and its work, as it is the diversity of contributors to the IGS as well as their high levels of commitment that have ensured the high level of performance and reliability of product generation and delivery thus far.

The plan continues in the spirit of previous strategic plans in that it is intended to guide our service to the community, and is not intended to be restrictive. It is our hope that the guidance in this plan will ensure the best possible IGS for the ever-growing community of users relying upon its openly available high-quality GNSS data and products. The 2021+ Strategic Plan is available for viewing and download on the IGS website. More details can be found in the reference document, at https://igs.org/strategic-planning/.

IGS Operational Activities

Network and Infrastructure Growth

Section Authors: David Maggert, Markus Bradke.

Between 2019 and 2022, the International GNSS Service (IGS) network witnessed remarkable growth, reflecting its commitment to providing comprehensive geodetic data and products. During this period, the IGS network experienced a substantial expansion with a total of 39 new stations being added while 22 stations were decommissioned, resulting in a net increase of 17 stations. This growth was made possible through the collaborative efforts of numerous institutions and station operators worldwide. The number of multi-GNSS stations within the network surged from 242 to 363, showcasing the adoption and integration of multiple global navigation satellite systems for more accurate positioning and research applications. Additionally, real-time stations within the IGS network increased from 190 to 302, facilitating prompt access to streaming data for a wide range of scientific and practical purposes. The expansion of the IGS network significantly contributed to improved coverage and geographical diversity, ensuring the availability of tracking data and products to a global user base.

In particular, the growth and development of the IGS network in South America owe a lot to the collaboration between the IGS and the Sistema de Referencia Geocéntrico para las Américas (SIRGAS). In the last few years, SIRGAS played a pivotal role in improving and expanding its own geodetic network across South America, and facilitated the integration of their stations into the IGS network (see the 7th issue of the IGS newsletter, https://igs.org/news/newsletter-issue-7/). The IGS expresses sincere appreciation for the dedicated efforts of SIRGAS in fortifying the infrastructure and data availability in the region. By combining their respective resources and expertise, the IGS and SIRGAS successfully enhanced the positioning capabilities, geophysical studies, and geodetic research endeavours throughout South America, benefiting both local users and the broader global scientific community.

The University Corporation for Atmospheric Research (UCAR) has been entrusted with the responsibility of operating the IGS real-time caster since January 2021, disseminating real-time tracking data and products to users worldwide for a wide range of applications. The rcvr_ant.tab file contains essential information about GNSS receiver and antenna combinations utilised by IGS stations, enabling precise positioning and data interpretation. It underwent regular updates over the period of interest, collaboratively implemented by the IGS Antenna Working Group. A total of 284 changes were recorded between 2019 and 2022, keeping pace with evolving technologies and advancements in receiver and antenna hardware. By maintaining an accurate and up-to-date rcvr_ant.tab file, the IGS ensures compatibility, consistency, and standardisation within the network, enabling seamless data processing and analysis for a diverse range of scientific investigations and geodetic applications.

Finally, the Site Log Manager (SLM) witnessed a total of 2247 site log updates between 2019 and 2022 (averaging 50 per month), highlighting the continuous efforts undertaken by the IGS to maintain and enhance the accuracy and completeness of the site log information. The SLM serves as a vital tool for monitoring and managing crucial metadata related to IGS stations, ensuring that comprehensive and up-to-date details are available for researchers, users, and the scientific community. See also the dedicated Section below, detailing exciting new updates to this critical tool alongside the corresponding network map.

Product Generation and Performance

Section Authors: Tom Herring, Salim Masoumi.

Joint management of the IGS Analysis Center Coordinator continued, led by Michael Moore (Geoscience Australia, 2016 - 2021) and Salim Masoumi (Geoscience Australia, 2021 - present) and Tom Herring (Massachusetts Institute of Technology, USA). Operations remain based at Geoscience Australia in Canberra, Australia. The Analysis Center Coordinator combination software is housed on cloud-based servers located in Australia and Europe, and coordination of the IGS product generation continues to be carried out by personnel distributed between Geoscience Australia and the Massachusetts Institute of Technology. The IGS continues to maintain a very high level of product availability. An important achievement is the development of a new orbit and clock product combination software suite at Geoscience Australia, allowing for multi-GNSS combinations. The software is currently used in a prototype phase in parallel to the legacy single system combination environment. This is the last step for the IGS to become the multi-GNSS service that has been targeted for many years.

Reprocessing Campaign #3, ITRF2020 and IGS20/igs20.atx framework

Section Author: Paul Rebischung.

The International Terrestrial Reference Frame (ITRF) serves as a crucial reference system for aligning products of the International GNSS Service (IGS), which in turn provide their users access to the ITRF. The IGS not only provides inputs from the GNSS technique to each new release of the ITRF, but it also updates its reference frame and the associated ground and satellite antenna calibrations (listed in the IGS ANTEX file; currently igs20.atx) after each such new release.

The "repro3" reprocessing campaign was carried out after a decision taken at the 2018 IGS Workshop by ten IGS Analysis Centers (ACs; COD, ESA, GFZ, GRG, JPL, MIT, NGS, TUG, ULR and WHU) in 2020. It aimed to achieve a consistent and accurate reanalysis of GPS data collected since 1994, and provide the IGS input to the latest release of the International Terrestrial Reference Frame 2020 (ITRF2020). Each AC re-analyzed GPS data for the period 1994-2020, with some centres also including GLONASS and Galileo data within specific time ranges in their analyses. Among other products, ACs provided daily terrestrial frame solutions, which were combined by the IGS Reference Frame coordinator. The final repro3 combined terrestrial frame solutions were provided to the IERS in April 2021 as the IGS input to ITRF2020. Throughout the campaign, various modelling updates and strategies were employed, involving antenna modelling, IERS convention updates, orbit dynamics, and other aspects to enhance the accuracy of the reprocessed products.

Following the release of ITRF2020 in April 2022, the IGS introduced the IGS20 reference frame and the igs20.atx set of ground and satellite antenna calibrations. The transition from the previous IGS14/igs14.atx framework to the new IGS20/igs20.atx framework was announced in IGSMAIL-8238 and started with the IGS products of GPS week 2238 (27 November 2022). The IGS operational products also follow since then the same conventions and models as used in the repro3 campaign. Furthermore, the adoption of long filenames for the IGS products enhanced clarity and organisation.

The IGS20 reference frame is essentially an extract of ITRF2020 coordinates - corrected for the ground antenna calibration updates from igsR3.atx to igs20.atx - for a set of 332 current and historical IGS stations selected for their long-term and stable position time series. Within the IGS20 station network, a subset of 55 clusters of stations, was designated as the IGS20 core network. It offers a homogeneous global coverage and the best possible temporal stability, and is hence recommended for the alignment of global solutions to the IGS20 reference frame. Note that while IGS20 is currently provided without seasonal terms, users have the flexibility to experiment by adding the coefficients of annual and semi-annual station displacements from ITRF2020.

The companion ANTEX file, igs20.atx, includes revised values for the radial phase centre offsets (PCOs) of GPS, GLONASS, and Galileo satellites, all consistent with the scale of ITRF2020. Another notable enhancement introduced with igs20.atx is the inclusion of new calibrations for 52 ground antenna types, covering the entire spectrum of GNSS frequencies (namely allowing the consistent inclusion of Galileo and BDS measurements in the processing).

New and Improved Site Log Manager and Network Map

Section Authors: Ashley Nilo, Robert Khachikyan, Brian Kohan.

The International GNSS Service (IGS) aims to promote open access data and collaboration through its Site Log Manager (SLM) and Network Map. Recognising a need for technological improvements, the IGS CB embarked on developing the Site Log Manager 2.0 (SLM 2.0) and Network Map 2.0. The SLM 2.0 is a software system designed to allow station operators to securely manage the metadata across the GNSS ground based sites. The SLM 2.0 is a vital and tremendous service to the global GNSS community. The IGS Network system currently serves as the public interface for any user from all over the world to view station metadata through a comprehensive station list and interactive station map.

The SLM 2.0 (https://slm.igs.org) now utilises Python and the Django web framework, along with improved editing, improved validation, and an improved user interface. Its code is now open source and is currently accessible through the IGS GitHub Repository (https://github.com/International-GNSS-Service/SLM), enabling other organisations to leverage this robust technology for their own purposes. The Network Map 2.0 (https://network.igs.org) now contains better customization options for the map, station lists, and download options, along with improved data accessibility, an improved user interface, and a publicly accessible RESTful API (https://network.igs.org/api/public). Both of these new versions were developed with core user feedback in mind, acquired through several user interviews and usability tests. These advancements help maximise the reliability, accuracy, and searchability of site log metadata information, fostering a more inclusive and standardised approach to geospatial data management.

New and Improved Associate Membership Portal

Section Author: Ashley Nilo.

In 2023, the IGS CB announced the new and improved Associate Membership (AM) Portal. The new AM Registration form and information page can be found at https://igs.org/am. The new AM list can be found at https://igs.org/am/list. This new portal allows more members in the GNSS community to learn more about associate members and enables current IGS AMs to better keep track of their profile information.

For members in the community who wish to become an IGS AM, the registration form and notification process has also been improved. The new form better ensures that each applicant meets the Associate Member requirements prior to applying and allows the IGS Executive Committee (EC) to learn more about the applicant for approval. Notifications on Associate Membership registration form Confirmation and Associate Membership Approval confirmation are now automated for fast notification. We hope and strive to continue serving our community as best as possible.

Data Management

Section Authors: Patrick Michael, Jianghui Geng.

Twelve Analysis Centers and twenty-one Associate Analysis Centers utilise tracking data from between 70 to more than 500 stations to generate precise products up to four times per day. Product coordinators combine these products on a continuous basis and assure the quality of the products made available to the users. Collectively, the IGS produces more than 700 IGS multi-GNSS final, rapid, ultra-rapid orbit and clock product files, as well as those auxiliary product files such as observable-specific signal biases, global ionosphere maps, etc. In particular, troposphere files for more than 400 stations are produced on a daily basis.

ACs have also begun to provide new products such as satellite attitude quaternions and phase biases to enable undifferenced ambiguity resolution on a global scale, which is a significant progress of the IGS in developing advanced and diverse products for users. Delivery of the core reference frame, orbits, clocks, and atmospheric products continued nominally. The IGS has also seen further refinement of the Real Time Service with considerable efforts being targeted towards development of data streaming standards. There are now six institutions streaming continuously satellite orbit and clock products to the IGS, and JPL would join this effort soon. The transition to multi GNSS has been a coordinated and successful effort within the IGS.

The amount of IGS tracking data and products hosted by each of the six global Data Centers on permanently accessible servers increased from 2 terabytes in 2017 to 62 terabytes over 453 million files at the end of 2022, supported by significant additional storage capabilities provided by Regional Data Centers. The intense interest of users in IGS data and products is reflected, e.g., in the user activity recorded by the Crustal Dynamics Data Information System (CDDIS) at the NASA Goddard Space Flight Center:

- a total of 1.3B files equating to 331 terabytes of GNSS data, and
- a total of 186M files equating to 26.4 terabytes of GNSS products.

The monthly averages correspond to:

- 110.7M files equating to 27.6 terabytes GNSS data from around 17K unique users
- 15.5M files equating to 2.2 terabytes GNSS products from around 11K unique users.

The user base wanting IGS data and products not only continues to grow in total numbers yearly but its diversity as well. In 2022, those users registered with NASA’s Earthdata System showed that over 25 science communities were represented in the download of IGS data. This breadth of usage across many disparate user groups showcases the importance of IGS data and products in both the sciences and more importantly the society benefits it provides.

Executive Management

Over the course of the past four years (July 2019 - June 2023), the IGS Central Bureau (CB) coordinated the necessary logistics and administrative organisation for thirteen Governing Board meetings, three AM/WG (Associate Member & Working Groups) meetings, and twenty-four Executive Committee virtual meetings. A detailed list of the first two types of activities can be found in **Table 3**. The Central Bureau also routinely organises and supports meetings of GB committees that are chaired by GB members, such as the Standing Elections Committee, and the Committee for Sustainable and Working Group Governance (CSWGG, see Section above). The CB also supported the organisation and successful execution of the week-long and fully virtual IGS 2022 Boulder Workshop, as well as six of the new "Tour de l'IGS" virtual mini-workshops (see Section below).

Type	Date	Comments
Governing Board Meetings	Apr. 2019 (GB52, Vienna, Austria)	See IGS Technical Report 2019, page 14.
	Jul. 2019 (GB53, Montréal, Canada)	See IGS Technical Report 2019, page 14.
	Dec. 2019 (GB54, San Francisco, CA, USA)	See IGS Technical Report 2019, page 14.
	May 2020 (GB55, virtual)	See IGS Technical Report 2020, pages 12 and 22.
	Aug. 2020 (GB56, virtual)	See IGS Technical Report 2020, pages 12 and 22.
	Dec. 2020 (GB57a, virtual)	See IGS Technical Report 2020, pages 12 and 22.
	Jan. 2021 (GB57b, virtual)	Fully dedicated to deciding Goals and Objectives for the organisation's Strategic Plan. See IGS Technical Report 2021, pages 8 and 20.
	Jul. 2021 (GB58, virtual)	Approval of the final draft of the IGS Strategic Plan. See IGS Technical Report 2021, pages 8 and 20.
	Dec. 2021 (GB59, virtual)	See IGS Technical Report 2021, page 8.
	Mar. 2022 (GB59X, virtual)	Extraordinary meeting to discuss the IAG statement on Ukraine. Following the meeting, the IGS CB added a link to the IAG website on the IGS News page: https://igs.org/news/iag-statement-on-ukraine/. See IGS Technical Report 2022, page 21.
	May 2022 (GB60, virtual)	IGS Workshop planning: 2022 Boulder, 2024 Bern. Clock Products WG statement on leap seconds. Discussion on GDPR requirements. See IGS Technical Report 2022, page 21.
	Jun. 2022 (GB61, virtual)	Discussion on DOIs for geodetic datasets. See IGS Technical Report 2022, page 21.
	Dec. 2022 (GB62, hybrid in Chicago, IL, USA)	Discussion on ITRF2020 (implementation, key issues/concerns identified at REFAG, UAW, and elsewhere). Further discussion on DOIs for geodetic datasets. Presentation of the new United Nations

		ICG Task Force on "Applications of GNSS for Disaster Risk Reduction". See IGS Technical Report 2022, page 21.
	Apr. 2023 (GB63, virtual)	Discuss the transition of GB Chair.
Open Associate Member and Working Group Meetings	Dec. 2019 (3rd meeting, San Francisco, CA, USA)	See IGS Technical Report 2019, page 14.
	2020	*No meeting due to COVID-19 pandemic.*
	Dec. 2021 (4th meeting, virtual)	See IGS Technical Report 2021, page 21.
	Dec. 2022 (5th meeting, hybrid in Chicago, IL, USA)	Working Groups, Pilot Projects, and Committees updates. See IGS Technical Report 2022, page 23.

Table 3: 2019-2022 IGS Meetings; including Strategic Planning Meetings, Governing Board Meetings, and Open Associate Member and Working Group Meetings.

Communications, Advocacy, and Public Information

The IGS acts on a communications plan that is inclusive to Associate Members and engaging across Working Groups. Communications efforts over the last four years introduced a diversified and enhanced portfolio of outreach resources for the IGS community. This was achieved by increasing the direct interaction with the community by virtual workshops, enhanced social network interactions, a regular circulation of Constellations - the newly introduced IGS newsletter, engaging with and celebrating our diverse community of contributors, enhancing our transdisciplinary collaborations (*i.e.*, with new or under-engaged scientific applications communities), and identifying opportunities for IGS engagement and support of the UN GGIM Subcommittee on Geodesy and UN International Committee on GNSS, as well as linkages to the UN Sendai Framework for Disaster Risk Reduction and UN Sustainable Development Goals.

Virtual Technical Mini-Workshop Series: Tour de l'IGS

In 2021, the IGS introduced a series of virtual mini-workshops, dubbed "Tour de l'IGS". Its focus is on topics of interest to the IGS membership, to stakeholders, and to the GNSS community in general. Each individual event in the Tour de l'IGS series is dubbed a "Stop" on a virtual world tour, with the overarching goal of covering a wide range of technical topics - such as space-borne and ground-based instrumentation, technology development, as well as other scientific and societal applications. The agendas of all the Tour de l'IGS stops are available at https://igs.org/tour-de-ligs, and the presentations are available at https://igs.org/tour-de-ligs/presentations. Topics of these mini-workshops included "repro3", "Infrastructure", "GNSS Processing based on IGS Products", "BDS Constellation Spotlight", "GNSS for Natural Hazards in the South Pacific" and "Galileo Constellation Spotlight". Due to significant positive feedback from IGS community members, this workshop series will be continued in the coming years, with the intention to highlight capacity development, regional outreach, and other topics based on community needs.

IGS Representation at the AGU and EGU Meetings

Section Authors: Allison Craddock, Rolf Dach.

The use of GNSS for geoscience, including all technical aspects, has been a longstanding focus at large scale scientific conferences such as the EGU Meetings or the AGU Fall Meetings. Since 2015, the IGS has made efforts to establish a dedicated session at AGU, and this tradition has been maintained from 2019 to 2022, with session chairs from IGS GB and CB. Typically, a portion of the contributions in this session pertain to specific aspects of IGS product generation (around a quarter to a third of all abstracts), while the majority showcase a wide range of high-quality applications based on IGS products. As a result, this session serves as an established platform for knowledge exchange between the various components of IGS and its user community. The IGS Governing Board has continued actively organising AGU sessions over the past four years (2019-2022), focusing on scientific applications utilising IGS products and advancements in GNSS product quality and scope.

Newsletter

In 2021, the IGS CB published the first issue in its quarterly newsletter series, dubbed "Constellations: The Newsletter of the International GNSS Service". Since then and up to the time of writing, seven newsletters have been published by the IGS, highlighting a broad variety of topics and underlining the international character of the Service. Each issue features news relevant to the GNSS community and its stakeholders, and articles on specific topics (https://igs.org/newsletter/). Among the latest issues, the March 2022 (third) issue headlined the Hunga Tonga Hunga Ha'apai eruption, the June 2022 (fourth) issue highlighted a CB-led contributing paper in the 2022 United Nations Global Assessment Report (GAR), the September 2022 (fifth) issue presented the new framework for the IGS products relating to the release of the ITRF2020, the December 2022 (sixth) issue advertised the release of the Galileo satellite metadata, and the April 2023 (seventh) issue gave updates on IGS' efforts to foster collaborations on using GNSS for disaster risk reduction.

Website Traffic

The International GNSS Service (IGS) has been providing open access to high-quality GNSS data products since 1994, serving as the global reference frame for scientific, educational, and commercial applications. However, the IGS website had become outdated and difficult to navigate over time. Recognizing the need for improvement, the Central Bureau decided to redesign the site in 2018, focusing on enhancing user experience and interface.
To address these concerns, a new and secured website, https://igs.org, was spearheaded by Central Bureau staff members Ashley Nilo (née Santiago) and Robert Khachikyan to replace the previous complicated and unsecured site. The transition to the new website took place in December 2020, alongside the transition from FTP to HTTPS. Originally scheduled for April 2020, the transition date was extended due to COVID-related restrictions. During this period, the original site operated alongside the beta site. On December 15, 2020, the beta site (https://igscb.org) transitioned to become the new IGS website (https://igs.org), while the old website was decommissioned. This transition allowed for a simplified domain under NASA's cloud infrastructure powered by Amazon

Web Services, ensuring proper maintenance, security, and identification as a service within the NASA Jet Propulsion Laboratory.
Following the migration, the IGS CB gained better insights into website traffic and engagement. In 2022, the website analytics transitioned from session-based to event-based, providing a deeper understanding of how users interact with the site. These improvements have further enhanced the IGS's ability to support scientific advancements and provide valuable resources to the public.

The IGS website serves as a crucial platform for the IGS CB to support various events, including but not limited to virtual ones. It not only features event advertisements and registration information but also acts as an online catalogue of recorded presentations and other resources accessible to the community. Users can find the latest IGS workshops at https://igs.org/workshops, and explore the Tour de l'IGS series through links such as https://igs.org/tour-de-ligs and https://igs.org/tour-de-ligs-presentations. Additionally, the website provides information on Open Associate Members and Working Group Meetings at https://igs.org/am-meetings, facilitating direct contact and interaction between the IGS and its users.

The total number of users who have visited https://igs.org and https://files.igs.org increased by 35% over 2022 alone. There has also been a 52% increase in the total number of sessions. Additional notable statistics include 735,602 page views, 40,663 file downloads, and a 71% engagement rate (the percentage of sessions longer than 10 seconds or has at least 2 pageviews). Social media referral doubled when compared with previous years. Some statistics have remained the same: most users are desktop users and visit the website between 08:00-16:00 Monday through Friday, and about half of the users arrive at the website via organic search engines. The density of unique visitors in 2022 is shown in **Figure 4**.

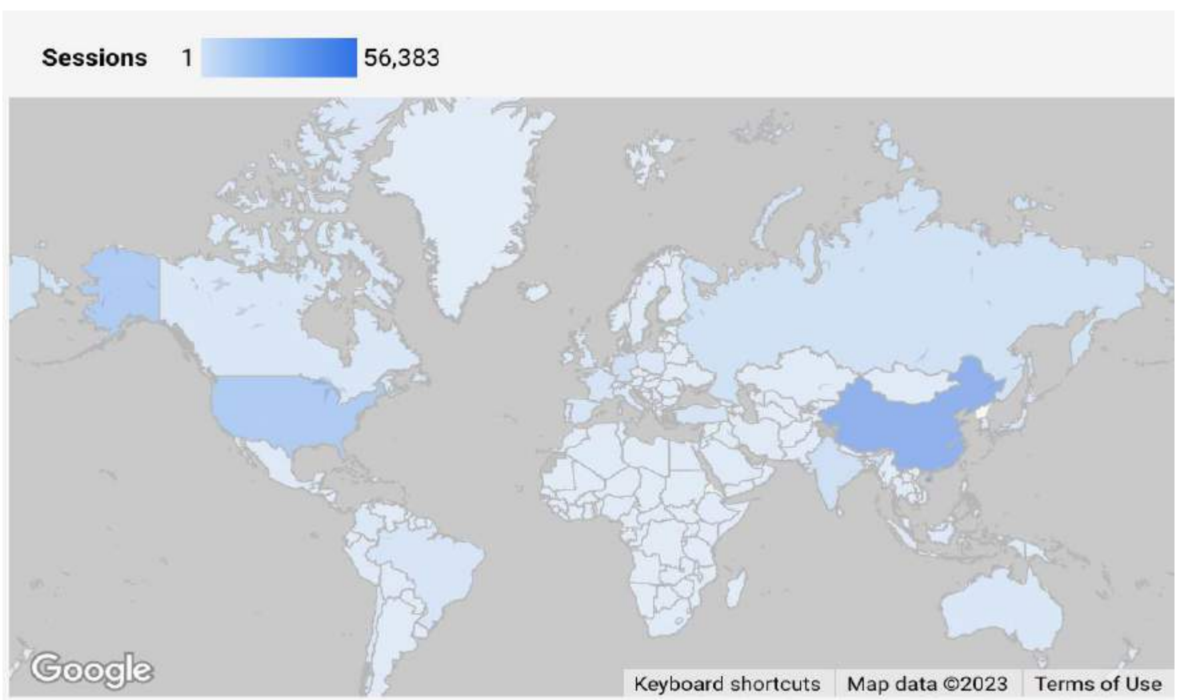

Figure 4: Map showing the distribution of the total number of https://igs.org users around the world in 2022.

Social Media

Over the past three years, the IGS experienced significant growth in its social media following. This was achieved through the establishment and nurturing of mutually beneficial relationships with IGS Contributing Organisation communications representatives, such as UNAVCO, IAG, GGOS, and ITRF. Additionally, the frequency of posting quality content on social media increased, with a total of 74 posts made throughout the year, averaging 6 posts per month. These efforts were led and coordinated by Ashley Nilo, the CB's Operations Coordinator.
In particular, to ensure the clarity and usefulness of community resources, the CB focused on enhancing cross-linking within their website and across various social media platforms. In addition to sharing IGS news and events, the CB engaged with their followers by participating in international holidays and observances, such as #IGSProfessorHighlight for the #InternationalDayofEducation, #WomensHistoryMonth, #NationalInternDay, or #InternationalFriendshipDay.

The latest social media numbers read more than 2000 followers and 25000 profile visits on Twitter (https://twitter.com/igsorg), more than 1400 followers on LinkedIn (https://www.linkedin.com/company/igsorg/), and more than 350 subscribers and 15000 video views on YouTube (https://www.youtube.com/igsorg).

Engagement and External Participation

At the direction of the Governing Board, the Central Bureau works with various components of the International Association of Geodesy (IAG), in order to promote communications and outreach. For instance, the IGS is involved with the IAG Communications and Outreach Branch, and the Global Geodetic Observing System (GGOS). IGS Associate Members (AMs) and GB members also participate actively in the United Nations Initiative on Global Geospatial Information Management (UN GGIM) Sub-Committee on Geodesy (http://ggim.un.org/UN_GGIM_wg1.html), including contributing to the five focus groups developed for the UN GGIM Global Geodetic Reference Frame Roadmap.
In particular, the CB Director represents the IGS on behalf of the Governing Board in the GGOS Coordinating Board. The CB Director also serves as a point of contact between IGS and the US Federal Advisory Board for Space-based Position, Navigation and Timing (PNT). Past IGS CB Deputy Director Mayra Oyola continues to represent the IGS in the new IAG Inter-Commission Committee on Geodesy for Climate Research (ICCC) and in the International Science Council World Data System.
IGS is an Associate Member of the International Committee on GNSS (ICG), based in the United Nations Office for Outer Space Affairs (UNOOSA). Together with the International Federation of Surveyors (FIG), the International Association of Geodesy (IAG), and the Bureau International des Poids et Mesures (BIPM), IGS co-chairs the ICG's Working Group D on "Reference Frames, Timing, and Applications"[4]. The existing joint ICG-IGS International GNSS Monitoring and Assessment (IGMA) project, focusing on performance and interoperability metrics, continued its efforts throughout 2022 and reported at the 16th meeting of the ICG (ICG-16) in October 2022.

[4] See https://www.unoosa.org/oosa/en/ourwork/icg/working-groups/d.html.

Furthermore, at ICG-16, a new Task Force (TF) was established, entitled "Applications of GNSS for Disaster Risk Reduction"; see ICG's WG D's Recommendation #26[5].

Outlook

Fulfilment of Past Goals

Over the period of interest, the International GNSS Service (IGS) has made successful strides toward fulfilling the goals outlined in the 2021+ Strategic Plan. The Service has focused on serving the community as a platform for facilitation, coordination, incubation, and advocacy. To achieve this, the IGS has continually worked towards three major strategic goals: achieving true multi-GNSS technical excellence, improving outreach and engagement, and enhancing sustainability and resilience. Regarding technical excellence, the IGS has made significant progress in advancing the accuracy and reliability of multi-GNSS systems. Through the repro3 campaign and its contributions toward the ITRF2020, the IGS has ensured the dissemination of valuable data and information to the community. Additionally, the IGS has recognized the need for modernization and accessibility by completely rebuilding and upgrading the Site Log Manager and Network Map, as well as making continuous improvements to the IGS.org website and the Associate Member database. On the topic of outreach and engagement, the IGS actively engaged with its key stakeholders, particularly the associate members and ensured it remained aligned with their needs. All of the aforementioned efforts have not only helped build a strong and evermore numerous user base, but also ensured the IGS's sustainability and continued growth.

Next Steps

For the next period of activity, the IGS renews its commitment to meeting the expectations of stakeholders, in particular regarding product timeliness, fidelity, and diversity. The IGS will continue to periodically reassess its mission and goals to ensure alignment with the needs of key stakeholders, particularly the Associate Members. To enhance advocacy for the IGS, the Governing Board (GB), Central Bureau (CB), and Associate Members (AMs) will continue to participate in numerous forums - within and outside the discipline - acknowledging the contributions of all involved parties. The IGS also aims to expand the user base and promote long-term sustainability for the IGS, through these outreach endeavours but also the consistent day-to-day management of the Service and its products.

Expanding the IGS network is a crucial objective for the IGS. Efforts will focus on adding new stations, especially in regions with sparse coverage or underrepresentation within the IGS. The CB will also advocate for the inclusion or conversion of receivers capable of multi-GNSS tracking and real-time casting. Additionally, IGS will internally reviewin, improve, and clarify its Terms of Reference (ToR) as the organisation grows and evolves. The revised ToR is set to be released in 2023, further strengthening the IGS's commitment to long-term organisational sustainability.

Finally, the IGS CB will continue fulfilling its regular administrative tasks, including event coordination, governance support, network coordination, and communications. In particular, the CB will continue to organise and co-lead the technical mini-workshop series as part of the Tour de l'IGS, as well as the biennial IGS Workshops. These workshops will place a particular emphasis

[5] See https://www.unoosa.org/documents/pdf/icg/2022/ICG16/ICG-16_WG-D_Recommendation.pdf.

on engaging with and reaching out to underrepresented countries and regions. Furthermore, the CB will actively promote novel scientific applications of IGS data and products, such as the development of early warning systems for natural hazards.

Publications and Official IGS Citation

It is expected that the work of the IGS is acknowledged in scholarly research and other works by referencing the IGS chapter found in the 2017 Springer Handbook of Global Navigation Satellite Systems:

- Johnston, G., Riddell, A., Hausler, G. (2017). The International GNSS Service. In Teunissen, Peter J. G., and Montenbruck, O. (Eds.), Springer Handbook of Global Navigation Satellite Systems (1st ed., pp. 967-982). Cham, Switzerland: Springer International Publishing. DOI: 10.1007/978-3-319-42928-1.

Other official publications pertaining to the IGS are:

- IGS 2019 Technical Report
- IGS 2020 Technical Report
- IGS 2021 Technical Report
- IGS 2022 Technical Report

International Laser Ranging Service (ILRS)

https://ilrs.gsfc.nasa.gov

E. C. Pavlis[1], M. R. Pearlman[2], C. C. Carabajal[3], R. Ricklefs[4], C. Schwatke[5], M. Wilkinson[6], G. Kirchner[7], V. Luceri[8], T. Otsubo[9], J-M Torre[10], U. Schreiber[11], D. Kucharski[12], C. Courde[13], M. Blossfeld[14], J. Ventura-Traveset[15], P. Delva[16], S. M. Merkowitz[17], R. Sherwood[18], J. Rodriguez[19], A. Couhert[20], F. Lemoine[21]

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[17, 21] *NASA Goddard Space Flight Center, Greenbelt, MD 20771, USA*
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Overview

The International Laser Ranging Service (ILRS) is the international organization that provides Satellite Laser Ranging (SLR) and Lunar Laser Ranging (LLR) observation data and data products for scientific and engineering programs with the main focus on Earth and Lunar applications. The basic observables are the precise two-way time-of-flight of ultra-short laser pulses from ground stations to retroreflector arrays on satellites and the Moon and the one-way and transponded time-of-flight measurements to space-borne receivers. These data sets are made available to the community through the Crustal Dynamics Data Information System (CDDIS) and the EUROLAS Data Center (EDC) archives, and are also used by the ILRS to generate fundamental data products, including: accurate satellite ephemerides, Earth orientation parameters, three-dimensional coordinates and velocities of the ILRS tracking stations, time-varying geocenter coordinates, static and time-varying coefficients of the Earth's gravity field, fundamental physical constants, lunar ephemerides and librations, and lunar orientation parameters. SLR is one of the four space geodetic techniques (along with VLBI, GNSS, and DORIS) whose observations are the basis for the development of the International Terrestrial Reference Frame (ITRF), which is maintained by the IERS. SLR defines the origin of the reference frame, the Earth center-of-mass and, along with VLBI, its scale. The ILRS generates daily a standard product of station positions and Earth orientation based on the analysis of the data collected over the previous seven days, for submission to the IERS, and produces LAGEOS/LARES/Etalon combination solutions for maintenance and improvement of the ITRF. The latest requirement is to improve the reference frame to an accuracy of 1 mm accuracy and 0.1 mm/year stability, a factor of 3 – 5 improvement over the current product. To address this requirement, the SLR community is working to improve the quantity and quality of ranging to the geodetic constellation of satellites (LAGEOS and LAGEOS-2, Etalon-1 and -2, LARES and LARES-2) to support the definition of the reference frame, and to the GNSS constellations to support the global distribution of the reference frame.
The ILRS participates in the Global Geodetic Observing System (GGOS) organized under the IAG to integrate and help coordinate the Service activities and plans.

ILRS Structure
The ILRS Organization (see Figure 1) includes the following permanent components:

- Network of tracking stations
- Operations Centers
- Global Data Centers
- Analysis and Associate Analysis Centers
- Central Bureau
- Governing Board
- Standing Committees (SCs)
    - Analysis
    - Data Formats and Procedures
    - Missions
    - Networks and Engineering
    - Lunar Laser Ranging and Transponders
- Study Groups (SGs) and Boards
    - Laser Ranging to GNSS s/c Experiments
    - Quality Control Board
    - Software Study Group
    - Space Debris Study Group

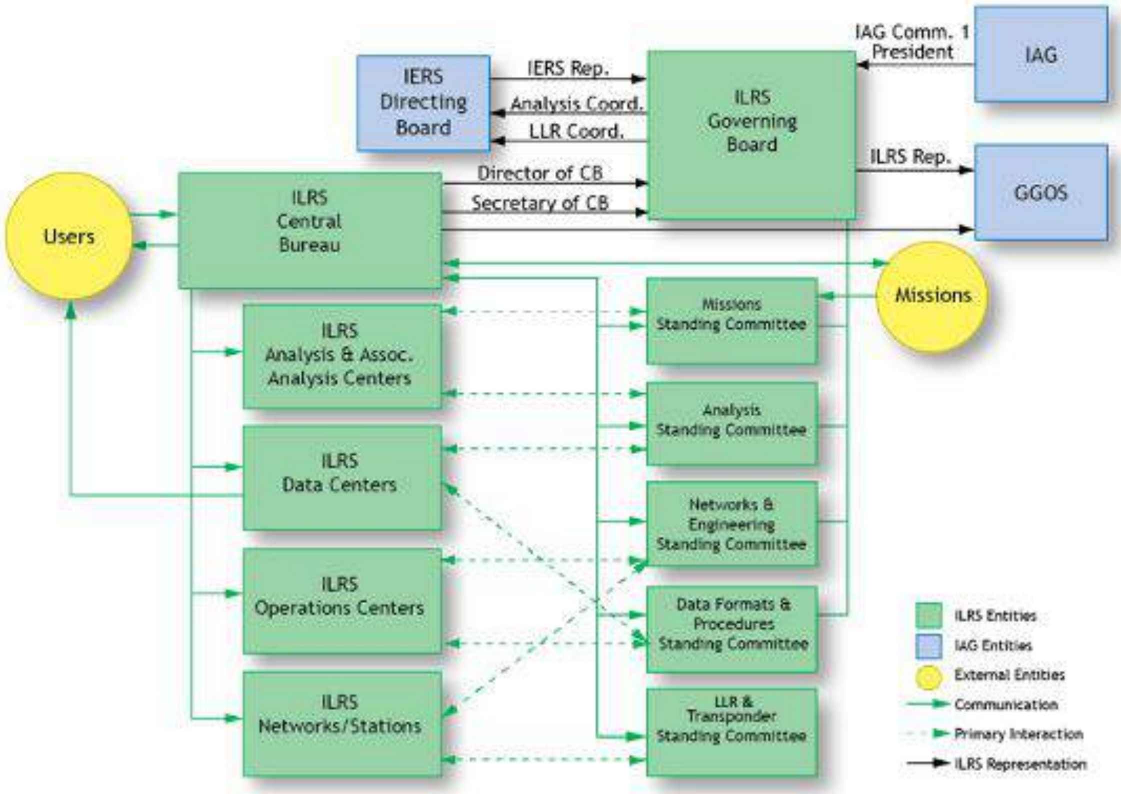

Figure 1. The organization of the International Laser Ranging Service (ILRS).

The role of these components and their inter-relationship is presented on the ILRS website (*https://ilrs.gsfc.nasa.gov/about/organization/index.html*).

The Governing Board (GB) is responsible for the general direction of the Service. It defines official ILRS policy and products, determines satellite-tracking priorities, develops standards and procedures, and interacts with other Services and organizations. The members of the current Governing Board, selected and elected for a two-year term, are listed in Table 1.

The Central Bureau (CB) is responsible for the daily coordination and management of the ILRS in a manner consistent with the directives and policies established by the Governing Board. The primary functions of the CB are to facilitate communications and information transfer within the ILRS and between the ILRS and the external scientific community, coordinate ILRS activities, maintain a list of satellites approved for tracking support and their priorities, promote compliance to ILRS network standards, monitor network operations and quality assurance of data, maintain ILRS documentation and databases, produce reports as required, and organize meetings and workshops. The CB operates the communication center for the ILRS. The CB performs a long-term coordination and communication role to ensure that ILRS participants contribute to the Service in a consistent and continuous manner and that they adhere to ILRS standards.

Permanent Standing Committees (SCs) and temporary Study Groups (SGs) provide the expertise necessary to make technical decisions, to plan programmatic courses of action, and are responsible for reviewing and approving the content of technical and scientific databases maintained by the Central Bureau. All GB members serve on at least one of the five SCs, led by a Chair and Co-Chair (see Table 1). The SCs continue to attract talented people from the general ILRS membership who contributed greatly to the success of these efforts.

Table 1. ILRS Governing Board (as of June, 2023)

Name	Position	Country
Sven Bauer	Elected,Eurolas Network	Germany
James Bennett	Appointed, WPLTN Network	Australia
Mathis Blossfeld	Elected, Analysis Representative, Analysis Standing Committee Deputy Chair	Germany
Claudia Carabajal	Ex-Officio, Secretary, ILRS Central Bureau	USA
Randall Carman	Appointed, At-Large Representative	Australia
Clément Courde	Elected, LLR and Transponders Standing Committee Chair	France
Evan Hoffman	Appointed, NASA Network	USA
Urs Hugentobler	Ex-Officio, Representative of IAG Commission 1	Germany
Vincenza Luceri	Elected, Analysis Representative, Analysis Standing Committee Chair	Italy
Takehiro Matsumoto	Appointed, At-Large Representative	Japan
Stephen Merkowitz	Appointed, NASA Network, ILRS Governing Board Chair (2023-2024)	USA
Michael Pearlman	Ex-Officio, Director, ILRS Central Bureau	USA
Jose Rodriguez	Elected,Eurolas Network, Missions Standing Committee Chair	Spain
Christian Schwatke	Appointed, At-Large, Data Formats and Procedures Standing Committee Chair	Germany
Daniela Thaller	Appointed, IERS Representative to ILRS	Germany
Matt Wilkinson	Elected, At-Large, Networks and Engineering Standing Committee Chair	UK
Justine Woo	Elected, Data Centers Representative	USA
Zhang Zhongping	Appointed, WPLTN Network	China
Former Governing Board Members during 2019-2022		
Giuseppe Bianco	Appointed, EUROLAS Network, Governing Board Chair (2015-2018)	Italy
Wu Bin	Appointed, WPLTN	China
Geoff Blewitt	Ex-Officio, Representative of IAG Commission 1	USA
Ludwig Combrinck	Elected, Lunar Representative	South Africa
Georg Kirchner	Appointed, EUROLAS Network	Austria
Rivers Lamb	Ex-Officio, Secretary, ILRS Central Bureau	USA
David McCormick	Appointed, NASA Network	USA
Jan McGarry	Appointed, NASA Network	USA
Jürgen Müller	Elected, Lunar Representative	Germany
Carey Noll	Ex-Officio, Secretary, ILRS Central Bureau	USA
Toshimichi Otsubo	Elected, At-Large, Governing Board Chair (2019-2022)	Japan
Erricos Pavlis	Elected, Analysis Representative, Analysis Standing Committee Chair	USA
Ulrich Schreiber	Appointed, At-Large, Transponder Standing Committee Chair	Germany
Andrey Sokolov	Appointed, At-Large	Russia
Krzysztof Sośnica	Appointed, At-Large	Poland
Jean-Marie Torre	Elected, Lunar Representative	France

Data Products

The main ILRS analysis products consist of SINEX files of weekly-averaged station coordinates and daily Earth Orientation Parameters (x-pole, y-pole and excess length-of-day—LOD) estimated from 7-day arcs of SLR tracking of the two LAGEOS and two Etalon satellites, soon to be added are the LARES and LARES -2 satellites. As of May 1, 2012, the official ILRS Analysis products are delivered daily by sliding the 7-day period covered by the arc by one day forward every day. This allows the ILRS to respond to two main users of its products: the ITRS Combination Centers and the IERS EOP Prediction Service at USNO. The former requires a single analysis per week, spanning the period Sunday to Saturday; the latter however requires as "fresh" EOP estimates as possible, that the "sliding" daily analysis readily accommodates. Two types of products are distributed for each 7-day period: a loosely constrained estimation of coordinates and EOP and an EOP solution, derived from the previous one and constrained to the ITRF, which was ITRF2014 since June 1, 2017 and it will be switched to ITRF2020 as soon as it is officially adopted by ILRS, presumably in July 2023. With the adoption of the new procedure (SSEM-X) for monitoring systematic errors in the network, a new weekly product became a necessity: a free solution of SSC and EOP parameters along with a freely adjusted weekly averaged range bias for each of the participating stations. This product has an extra week lag compared to the original weekly product in order to ensure that all tracking data have been submitted to the Data Centers and a stable EOP series is available. The range bias estimates from the rigorous combination of the individual contributions will be used to extend every week the bias model, coded into a SINEX-like file named Data handling File (DHF). When a significant and persistent break in the value of a stations mean bias is detected, a break will be introduced in the bias model and a new entry will be initiated. At the same time, the DHF will be updated accordingly and the affected station will be contacted to investigate and rationalize the observed change. The current bias model can be visualized for each site and satellite target via the JCET Portal (http://geodesy.jcet.umbc.edu/ILRS_AWG_MONITORING) selecting the option "MODEL BIAS SSEM-X for SLRF2020". Official ILRS Analysis Centers (ACs) and Combination Centers (CCs) generate these products of individual and combined solutions respectively. Both the individual and combined solutions follow strict standards agreed upon within the ILRS Analysis Standing Committee (ASC) to provide high quality products consistent with the IERS Conventions. This description refers to the status as of May 2023. Each official ILRS solution is obtained through the combination of seven solutions submitted by the seven official ILRS Analysis Centers:

ASI, Agenzia Spaziale Italiana
BKG, Bundesamt für Kartographie und Geodäsie
DGFI/TUM, Deutsches Geodätisches ForschungsInstitut/Technische Universität München
ESA, European Space Agency
GFZ, GeoForschungsZentrum Potsdam
JCET, Joint Center for Earth Systems Technology and Goddard Space Flight Center
NSGF, NERC Space Geodesy Facility

Since 2016, the ILRS publishes online an additional operational product on a weekly basis: precision orbits in standard SP3c formatted files for the four satellite targets (LAGEOS-1, -2, and Etalon-1, -2). These orbits are strictly referenced to the TRF model that is adopted at the time of their release.

The efforts to identify, quantify and contain systematic errors in the SLR data have continued with many new initiatives that ILRS sees necessary in order to improve data quality. The main focus of the Analysis SC activities over the past five years was the estimation and monitoring of systematic errors in the SLR normal point (NP) data and the generation of a model that has been applied a priori during the re-analysis for the development of the ITRF2020 ILRS contribution, (Luceri et al., 2019). All ACs made major efforts to comply with the newly adopted analysis standards and the IERS Conventions 2010 plus their recent modifications, e.g. the adoption of the new secular pole in 2019 (Pavlis, E. C., 2019a), the consistent modeling of low degree time-varying gravitation (Pavlis, E. C., 2019b), etc. The preliminary version of the ILRS contribution to ITRF2020 (Pavlis et al., 2020), was delivered in mid-April 2021, presented at the EGU 2021 (Luceri et al., 2021) and finalized in June 2021. Following that, the ASC focused on completing the final series with the inclusion of the historical LAGEOS data (1983.0 – 1993.0) and the correction of any entries that were found problematic in the preliminary combination.

It is anticipated that a follow up release will include LARES and LARES-2 as additional accurate targets in developing the official products, which the ITRS CCs will evaluate and which will be hopefully included in the next ITRF model.

Following the release of ITRF2020, the ASC issued an extended version of the reference frame, the SLRF2020, which includes ~30 additional SLR sites that were not part of ITRF2020 model. A number of these are historical sites from the early years of SLR, prior to ILRS, and the rest are new stations that were established either during the development of ITRF2020 or after its release; in either case these sites did not have enough data to support their inclusion in the new ITRF. The ILRS products are now carrying a DOI issued by CDDIS:

- ITRF2020 contribution: DOI: https://doi.org/10.5067/SLR/slr_itrf20200_repro2020_001

and are available from the official ILRS Data Centers CDDIS/NASA Goddard Space Flight Center:

- https://cddis.nasa.gov/Data_and_Derived_Products/SLR/Reference_frame.html

and EDC/TUM/DGFI:

and *http://edc.dgfi.tum.de/pub/slr/products/pos+eop*

The individual ILRS AC and CC product contributions as well as the combinations are monitored on a daily basis in graphical and statistical presentation of these time series through a dedicated portal hosted by the JCET AC/CC at:

http://geodesy.jcet.umbc.edu/ILRS_AWG_MONITORING/

The ILRS "Quality Control Board", with members from all areas of expertise within the service, has continued it efforts to identify, quantify and correct any errors in the already collected SLR. Furthermore, it strives to generate tools and procedures that will help the station engineers identify with confidence and as quickly as possible, issues with their data, before they get too far down the production line. A manual on "best practices" for SLR data collection is now in preparation, as an aid to station personnel.

The LLR group is in the process of developing a unique data set of all available LLR data in the officially adopted CRD format, in order to better serve the community and to conform with the ILRS standards. The LLR community is now supported by the LLR and Transponders Standing Committee, approved by the ILRS GB last November, 2022, with Dr. Clément Courde as its Chair.

Satellite Laser Ranging

ILRS Network

The present ILRS network includes over forty stations in 24 countries (see Figure 2). Since 2015, new stations in Russia have joined the ILRS network in Badary, Baikonur, Irkutsk, Svetloe, Zelenchukskaya; in Korea at Sejong and Geochang, and at Brasilia (by the Russians). The Russians have also advanced the idea of co-locating two SLR stations at critical locations to help address the tracking load. New technology Russian SLR systems are in co-location with the legacy SLR systems at Mendeleevo and Irkutsk. They have also co-located a Russian system with the NASA MOBLAS-6 at Hartebeesthoek (South Africa). The Russians are also planning installations at a number of as yet unnamed sites, and they have offered to co-locate new systems at stations currently operated by other organizations. All of this said, progress with Russia and Ukraine has significantly slowed down since the war in Ukraine started in early 2022. Studies to evaluate station placement were undertanken (Kehm et al., 2019). Other new systems and system upgrades have been delayed due to the Pandemic, budgetary constraints, and in some cases protracted importation restrictions. Work continues on the upgrade of the system at Metsahövi (Finland) and the upgrade of the Chinese SLR station in San Juan (Argentina); both now planned for operations in late 2024. Two new stations were planned at Ponmundi and Mt. Abu (India), but substantial delays leave the plan very uncertain.

The NASA Space Geodesy Project (SGP) is building new SLR systems as part of a new Core sites at Ny-Ålesund (Norway) in coordination with the Norwegian Mapping Agency, and as replacement for legacy SLR systems at Core sites at McDonald TX, Maui (HI), and GSFC (MD). Deployment is now projected for the 2024 – 2028 timeframe. Planning is also underway for additional SLR systems as part of Core sites at other current NASA partner locations and new locations to help fill some of the current geographic gaps in the global space geodesy network.

In the past year, the SLR station in Tenerife (Spain) became operational as did the engineering station in Stuttgart (Germany) which is focused on the development of low cost SLR systems for expansion of the network. The new stations in Yebes (Spain) and Tsukuba (Japan) are in testing and should be operational by mid-year. The SLR system in the Argentine-German Core Geodetic Observatory (AGGO) (formally TIGO in Concepción, Chile), has been undergoing upgrade, at La Plata (Argentina); progress has been slower than anticipated, but operations are now expected to resume in the 2023 - 2024 timeframe. Work continues on the upgrade of the Chinese station in San Juan (Argentina); import issues had delayed progress for more than 2 years.

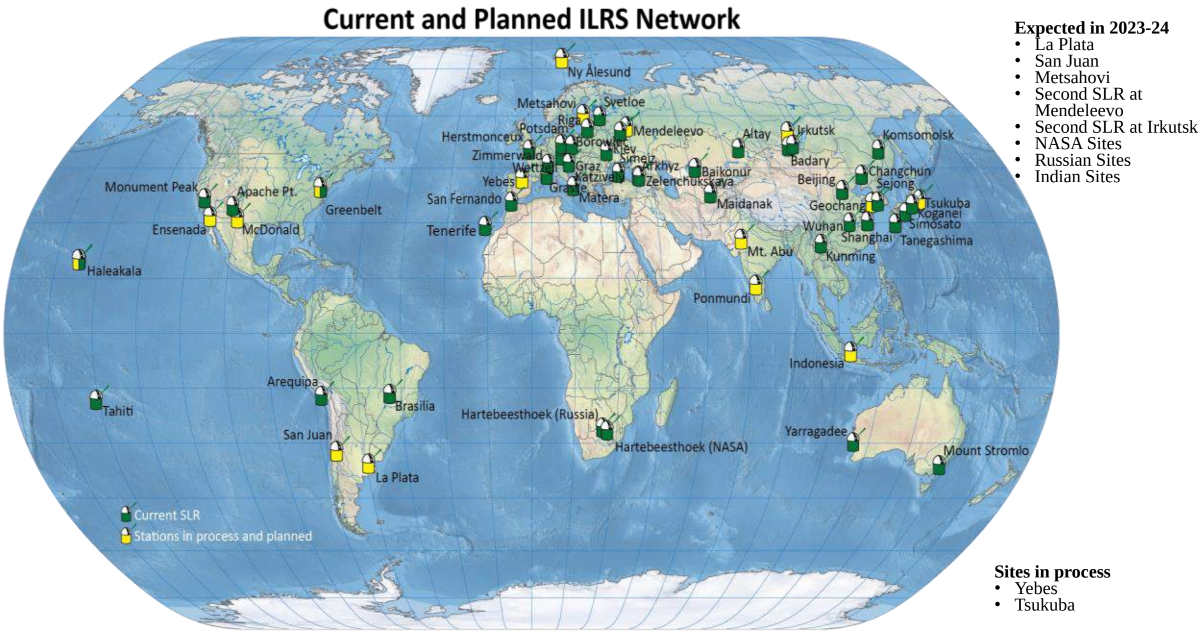

Figure 2. Current and Planned ILRS network (as of June 2023).

Large gaps are still prominent in Africa, Latin America and Oceana; new partnerships are being explored.

Stations designated as operational have met the minimum ILRS qualification for data quantity set at 3500 passes per year. This was approved in 2015 by the ILRS Governing Board, and viewed as an interim step toward a more comprehensive long-term strategy as network performance hopefully improves.

In spite of losses in productivity suffered during the Pandemic in 2020 and 2021, some stations continued to operate well; recent strong performers are shown in Figures 3 through Figure 6 for 1 year periods (May 1st through April 30th) from 2019 through 2023. During those years, sixteen stations met the ILRS minimum requirement for total numbers of passes tracked.

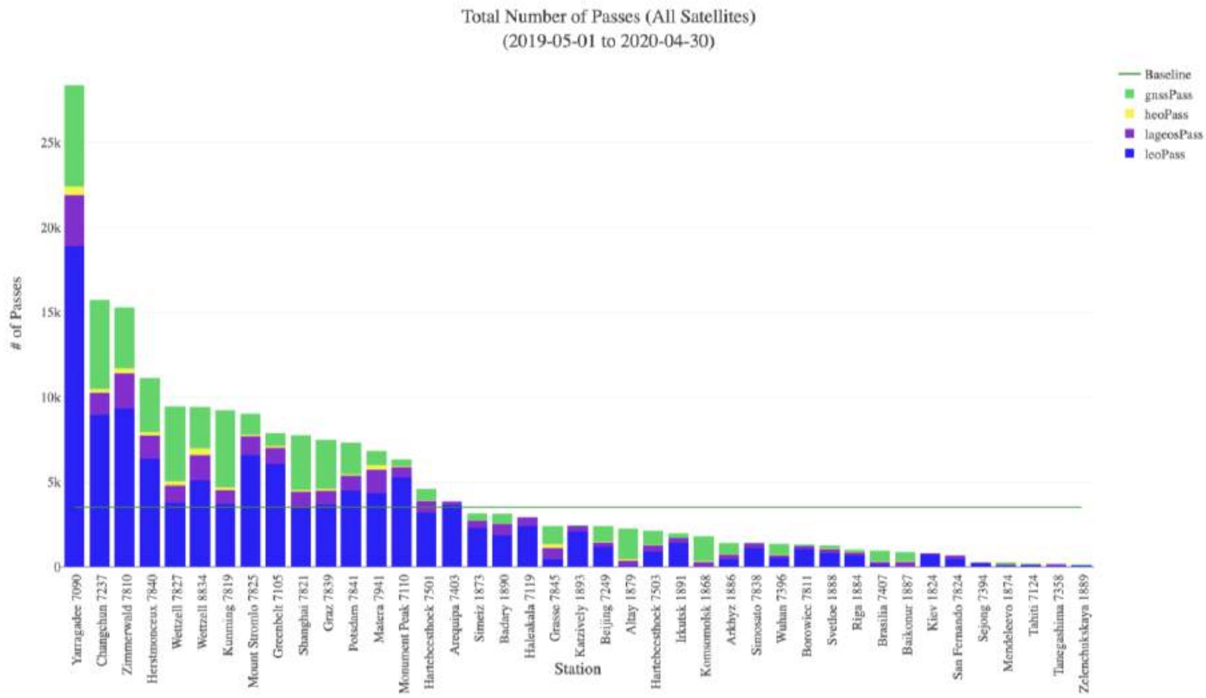

Figure 3. ILRS network performance (Total Number of Passes, all Satellites), May 1st, 2019 to April 30th. 2020.

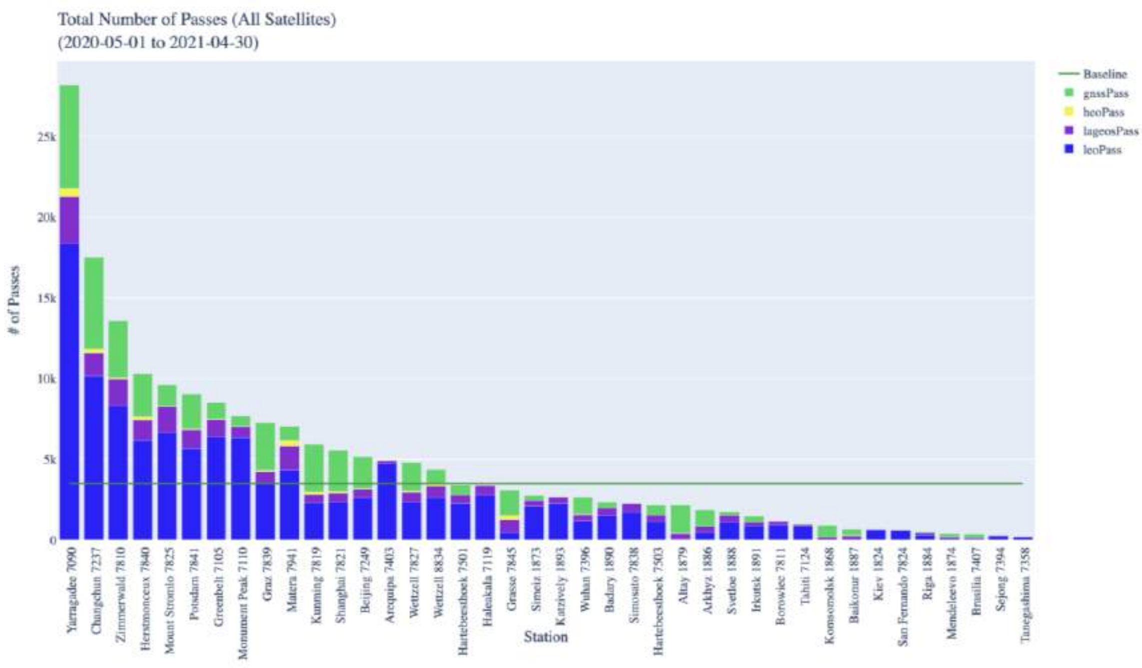

Figure 4. ILRS network performance (Total Number of Passes, all Satellites), May 1st, 2020 to April 30th. 2021.

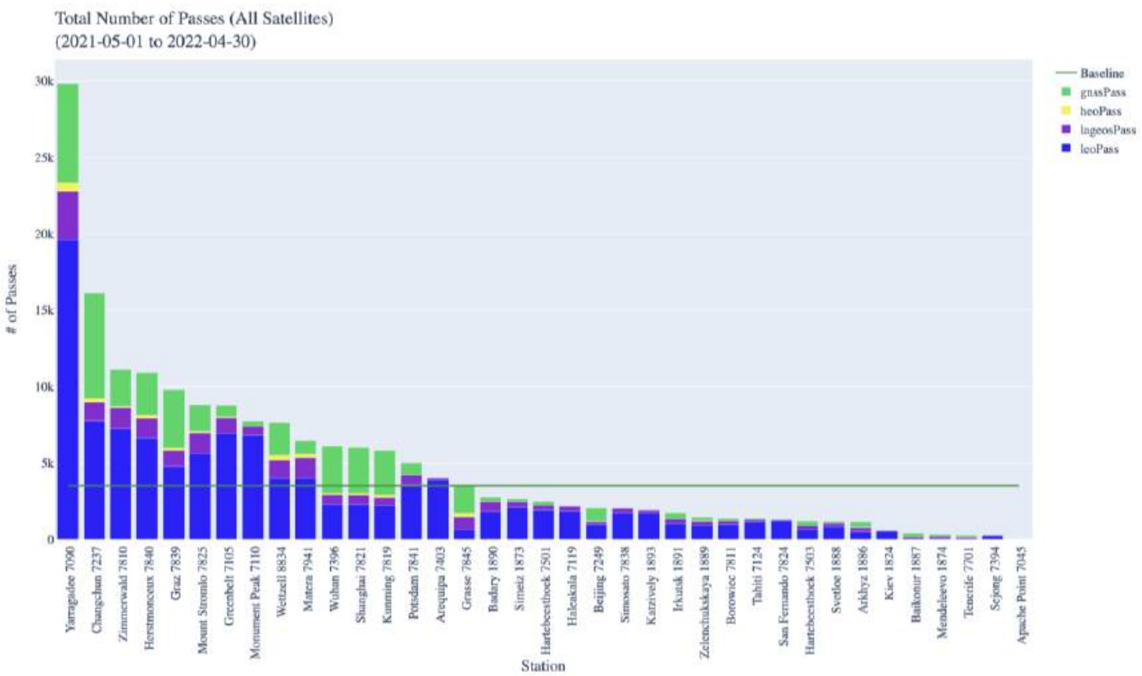

Figure 5. ILRS network performance (Total Number of Passes, all Satellites), May 1st, 2021 to April 30th. 2022.

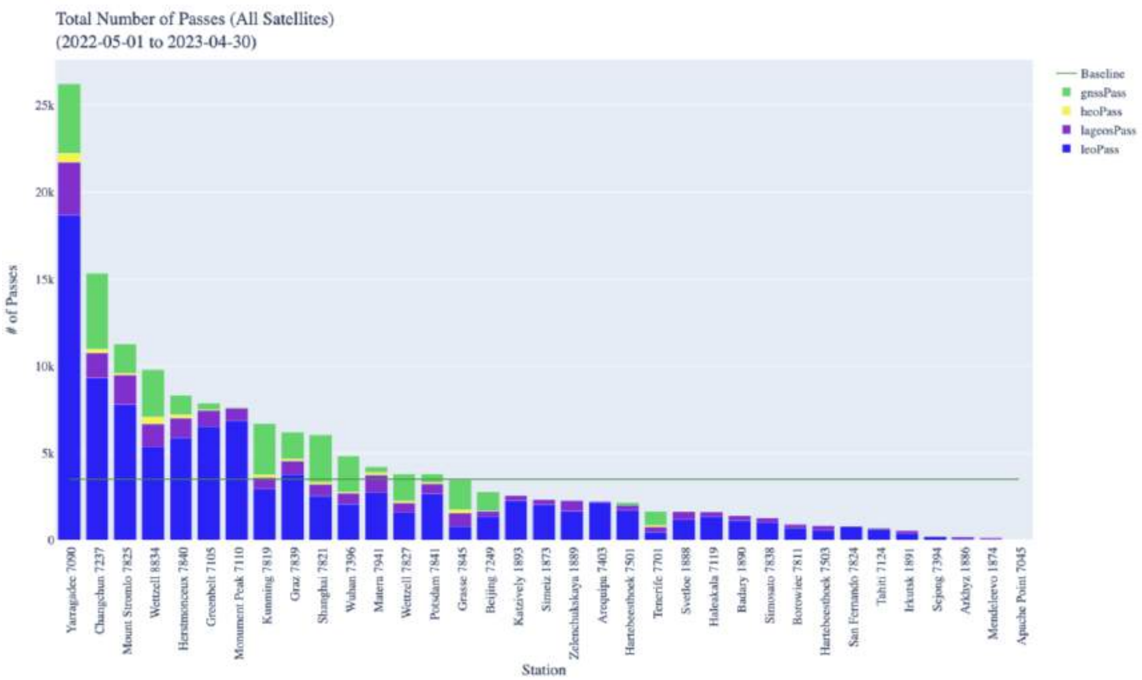

Figure 6. ILRS network performance (Total Number of Passes, all Satellites), May 1st, 2022 to April 30th. 2023.

Stations designated as operational have met the minimum ILRS qualification for data quantity and quality. In 2015, the ILRS Governing Board approved a new ILRS Pass Performance Standard of 3500 passes per year as an interim step toward a more comprehensive long-term strategy:

- 2 passes per week on each LEO satellite (2300 LEO passes per year)
- 4 passes per week on LAGEOS and LARES satellites (600 MEO passes per year)
- 2 passes per week on each HEO satellite (>3000 HEO passes per year)

As shown in Table 2, many stations are now operating at 100 to kilohertz rates, thereby allowing them to interleave tracking on several satellites at a time, and implement automated procedures for unattended tracking to expand operating hours.
Some stations have demonstrated mm precision normal points, a fundamental step toward addressing the new reference frame requirements.

Table 2. High-Repetition Rate ILRS Stations (as of *June* 2023)

CDP ID#	Location	Laser Repetition Rate [Hz]
7816	Uhlandshoehe Research Observatory (UFO)	1000000
7359	Daedeok	5000
7394	Sejong	5000
7249	Beijing SLR Station	2000
7840	Herstmonceux	2000
7841	SLR Potsdam 3	2000
7865	NRL Optical Test Facility	2000
7839	Graz	2000
7249	Beijing SLR Station	1000
7396	JiuFeng	1000
7819	Kunming	1000
7821	Shanghai	1000
7827	Wettzell	1000
7838	Simosato	1000
7840	Herstmonceux	1000
8834	Wettzell	400
7701	Izaña (Tenerife)	400
1868	Komsomolsk-na-Amure	300
1874	Mendeleevo	300
1879	Altay	300
1886	Arkhyz	300
1887	Baikonur	300
1888	Svetloe	300
1889	Zelenchukskaya	300
1890	Badary	300
1891	Irkutsk	300
7407	Brasilia	300
7503	Hartebeesthoek Radio Astronomy Obs.	300
7810	Zimmerwald SLR	110

Satellite Missions

The ILRS is currently tracking approximately 140 artificial satellites, including passive geodetic (geodynamic) satellites, Earth remote sensing satellites (e.g., altimetry, gravity field), navigation satellites (GNSS), and engineering missions (see Figure 7). Due to system limitations, some of the legacy stations are not able to track GNSS and other high altitude satellites. The large list of satellites is saturating some stations that are not fully staffed and strategies are being tried to maximize station data value. Some stations have implemented automated procedures to expand operating hours. The stations with lunar capability are also tracking the lunar reflectors. In response to this large roster of satellites, as well as for support of tandem missions (e.g., GRACE-A/-B, TanDEM-X/TerraSAR-X) and general overlapping schedules, most stations in the ILRS network are tracking satellites with interleaving procedures.

The ILRS assigns satellite priorities in an attempt to maximize data yield on the full satellite complex, while at the same time placing greatest emphasis on the most immediate data needs. Priorities provide guidelines for the network stations, but stations may deviate from these priorities to accommodate local conditions, support regional activities or national initiatives, and expand tracking coverage in regions with multiple stations. General tracking priorities are approved by the Governing Board, based on application to the Central Bureau and recommendation of the Missions Standing Committee (see *https://ilrs.gsfc.nasa.gov/missions/mission_operations/priorities/index.html*).

Missions are added to the ILRS tracking roster as new satellites are launched and as new requirements are adopted; missions for completed programs are removed (see Figure 7). The ILRS provides restricted tracking procedures for satellites with time-varying array visibilities and optically vulnerable payloads (e.g. Sentinel satellites and ICESat-2), to limit ranging to authorized time periods. Some stations in the ILRS network track selected space debris objects to provide ephemerides and orientation data to help with trajectory/safety planning. The tracking approval process begins with the submission of a Missions Support Request Form, which is accessible through the ILRS website:
(https://ilrs.cddis.eosdis.nasa.gov/docs/2016/ilrsmsr_1604.pdf).
The submitted form provides the ILRS with information to assess the appropriateness for ILRS support (does it fit into the ILRS/GGOS objectives) and the likelihood of tracking success, including any special procedures that the mission may require.

Space missions that have requested ILRS tracking support during the tenure of this report are summarized in Table 3, along with their sponsors, intended application, and projected launch dates.

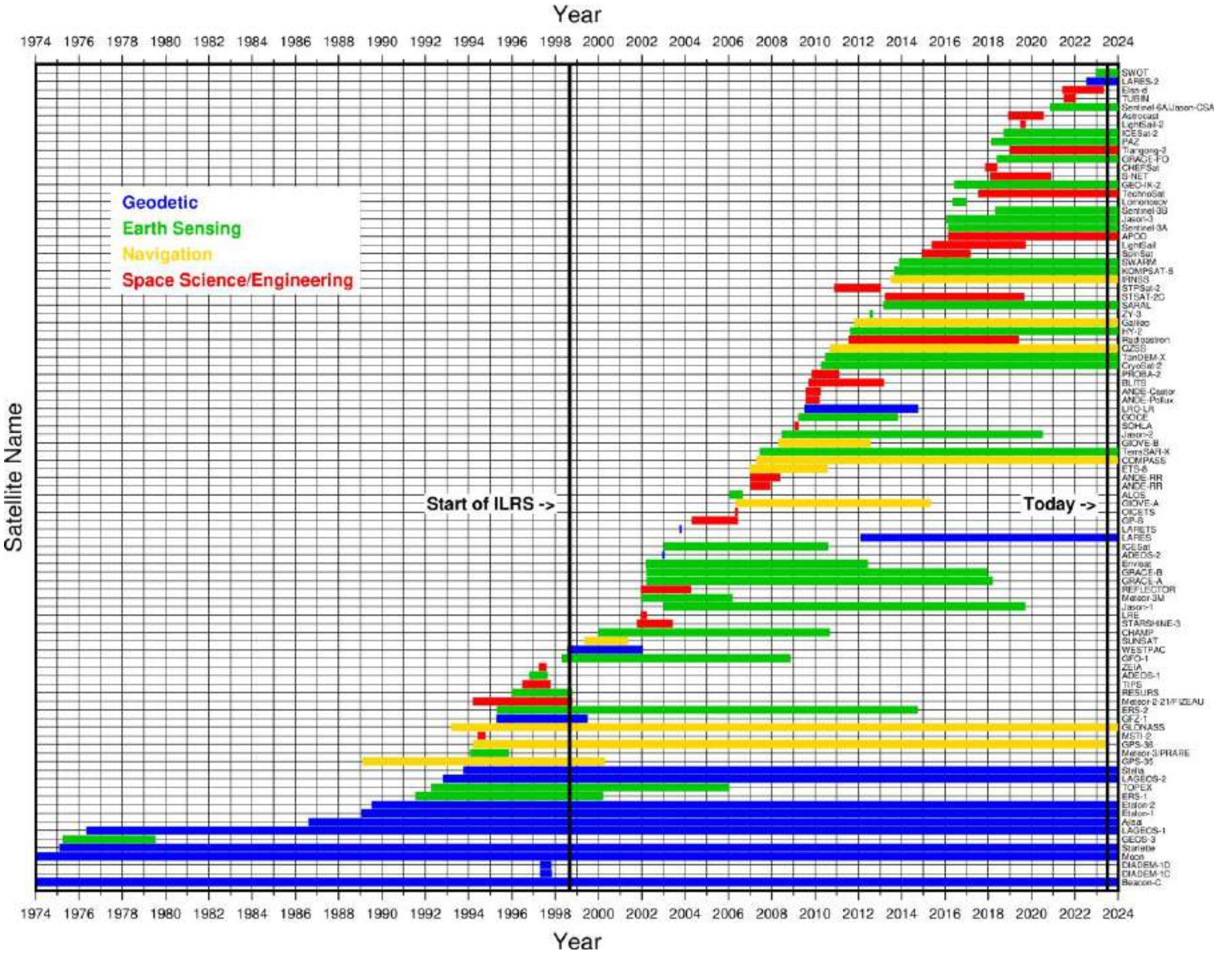

Figure 7. The past and current ILRS satellite tracking list (as of June 2023).

Table 3. Missions Launched During the Tenure of this Report (as of June 2023).

Satellite Name	Sponsor	Purpose	Launch Date
Missions Launched During the Tenure of this Report			
GLONASS 140 and 141	Russian Federation Ministry of Defense	Positioning, navigation, timing	19-July-3, 10-Dec-11
COMPASS-G8	Chinese Defense Ministry	Positioning, navigation, timing	20-Mar-21
Sentinel-6A/Jason-CS-A	EUMETSAT/EC/ESA/NOAA/NASA	Oceanography	20-Nov
H-2C, HY-2D	CNES, CNSA	Marine observation	20-Sep-21, 21-May-19
Galileo 223 and 224	ESA	Positioning, navigation, timing	21-Dec-05
ELSA-d (Mission Completed)	Astroscale Pte Ltd (with HQs in Singapore) and SSTL (Surrey Satellite Technology Ltd. of Surrey, UK)	Orbital debris removal	22-Mar-21
LARES-2	ASI/ESA	Geodetic Satellite	22-Jul-13
SWOT	NASA/CNES	Ocean altimetry and Hydrology (inland water storage)	22-Dec-16

New ILRS Tracking Strategy for GNSS

Since mid-2019, at the request of the IGS and supported by the ICG, the tracking strategy of the GNSS satellite have been changed. Each GNSS constellation is allowed to choose four of its satellites for the priority list; otherwise stations are requested to track all of the remaining GNSS satellites on an as time available basis; selection of targets is determined by the stations, but stations are asked to try to diversify among all three constellations.

In addition, some users will request focused campaigns for eclipse or other studies to better model the effects of solar radiation pressure or other processes.

In the next several years, the next-generation GPS satellites will also include retroreflectors that will bring the GNSS population with retroreflectors to about 100 satellites.

Laser Ranging for High Accuracy Timing

Laser ranging has demonstrated significant capability for Precision Time Transfer with satellites. ILRS tracked the Jason-2 satellite, using the Time Transfer by Laser Link (T2L2) experiment to synchronize the clocks at ILRS stations, as well as to characterize the performance of the DORIS Ultra Stable Oscillator (USO) onboard the Jason-2 spacecraft. The data from T2L2, as well as other information, have been used to derive a detailed model of the DORIS USO behavior, including direct modeling of radiation effects, passage through the South Atlantic Anomaly (SAA) and natural aging of the oscillator. Applying this USO model it was possible to synchronize the clocks used in the Laser Ranging station to the same international time scale (UTC) at around 5 ns accuracy. The analysis of the T2L2 data has revealed that many stations exhibit time biases with respect to UTC, sometimes as high as a few microseconds, well beyond the 200 ns limit requested by the ILRS, and yet still at a level that is hard to resolve from the orbit determination analysis. The past data from T2L2 and data from future similar systems will allow us to characterize station timing behavior and examine its impact on the reference frame and ILRS products. The T2L2 project team led by Dr. Pierre Exertier (Grasse SLR observatory) have provided timing bias estimates for SLR data to the ILRS analysis centers, based on analysis of data from T2L2 over the period 2008-2018 (Exertier et al., 2016).

The proper handling of local time is the key for the identification of station biases, which show up as additional, often variable measurement delays in the ranging process. Since time relates the measurement epoch to the phase angle of the clock frequency, any slip in the phase angle corresponds to a slip in the measured time interval during the ranging process, thus adding an unwanted bias to the measurement itself. Causes for such slips are manifold, like temperature changes in electronic amplifiers, timers and most importantly trigger circuits and impedance mismatches. In order to mitigate these effects, the phase of the clock signal has to be controlled in the ranging hardware over the entire ranging process in a two-way closed loop delay compensation process, which is currently pioneered by the Geodetic Observatory Wettzell (Kodet et al., 2018). It is important to note that this process does not depend on accurate time itself, it is only concerned with the avoidance of additional biases in the handling of time intervals in the ranging process.

A precise clock in space provides a worldwide access to high performance ground clocks. Here SLR plays an important role, by providing accurate range and time between clearly defined reference points on ground and in space. This represents a two-way measurement technique, the main ingredient of the “Einstein Synchronization” process, the only technique that can compare and synchronize remote clocks with high accuracy. The European Space Agency (ESA) is developing the Atomic Clock Ensemble (ACES) (see https://earth.esa.int/web/eoportal/satellite-missions/i/iss-aces) experiment for flight on the International Space Station (ISS). The ELT (European Laser Timing) follows in the path of T2L2. The goal is to demonstrate an accuracy of time transfer at the level of 50 ps, with a perspective of 25 ps. The ELT payload consists of a corner cube retroreflector a SPAD detector, and an event timer. ELT will provide an alternative to time transfer via microwave link (MWL) and will provide superior accuracy.

The potential of SLR to transfer time with unprecedented accuracy over intercontinental distances and thus to tie a globally uniform timescale to the geodetic reference frames may one day together with the availability of accurate optical clocks create a uniform accurate observing system, which integrates the three pillars of geodesy, namely geometry, gravity and Earth rotation into one unified foundation, tied together by time.

Lunar Laser Ranging (LLR)

The LLR results are considered among the most important science return of the Apollo era. The Lunar Laser Ranging (LLR) experiment has accumulated over 50 years of range data with improving accuracy from ground stations to the laser retroreflector arrays (LRAs) on the lunar surface. The upcoming decade offers several opportunities to break new ground in data precision through the deployment of the next generation of single corner-cube lunar retroreflectors (Merkowitz et al., 2007, Porcelli et al., 2021) and active laser transponders (Merkowitz, 2010). Lunar dynamical models and analysis tools have the potential to improve and fully exploit the long temporal baseline and precision allowed by millimetric LLR data. New LLR stations are under development to complete the network. New technical solutions are also envisaged like extending observations at high repetition rate in SLR to LLR or trying to obtain differential measurements. This new proposal is studied and the first simulations are showing that it will help mitigate some of the primary limiting factors and reach unprecedented accuracy (Zhang et al., 2022). Such observations and techniques may enable the detection of several subtle signatures required to understand the dynamics of the Earth-Moon system and the deep lunar interior. LLR model improvements would impact multidisciplinary fields that include lunar and planetary science, Earth science, fundamental physics, celestial mechanics and ephemerides (Müller et al. 2019).

Lunar Analysis Centers

The LLR data analysis is performed by a few major LLR analysis centers, namely the Jet Propulsion Laboratory (JPL), Pasadena, USA, the Paris Observatory Lunar Analysis Center (POLAC), Paris, France, the Institute of Geodesy (IfE), University of Hannover, Germany and the Institute of Applied Astronomy Russian Academy of Sciences (IAARAS), Saint Petersburg, Russia. In the last few years, the National Institute for Nuclear Physics (INFN), Frascati, Italy and the Graduate University for Advanced Studies (SOKENDAI), Tokyo, Japan, have also increased their analysis activities. NASA also formed a new LLR analysis center: Goddard Lunar Data Analysis Center (GLD). The LLR analysis centers focus on different research topics (such as relativity, lunar interior, earth orientation parameter, etc.). Various research projects have been successfully pursued, combining LLR, GRAIL and LRO data.

Lunar Laser Ranging Network:

There are currently four active ILRS observatories, which are technically in the position to track the lunar retroreflectors. These stations are Apache Point (USA), Grasse (France), Matera (Italy) and Wettzell (Germany). For several years, Grasse and Wettzell range in infrared (1064 nm), while Matera and Apache Point range in green (532 nm). New stations are under development in China (Kunming, and Shanghai) and in Russia (Altay Optical-Laser).

Despite the space exploration of the lunar soil, the analysis of the data collected by the APOLLO missions, the space missions in orbit including the GRAIL mission and the 50 years of Laser Moon data (LLR), many questions remain unanswered, in particular concerning the internal physics of the Moon, its liquid core, the structure of its mantle and the presence of a solid core. Although the scenario of the Moon's formation seems to be more or less established thanks to the data from the GRAIL mission, the presence of a fluid core without a solid inner core could call into question the differentiation mechanisms used until now in the scenarios of the formation and evolution of the solar system (Viswanathan et al., 2019 ; the

densification of LLR data as well as a combination of these data with data obtained by space probes are fundamental elements to answer these questions (Briaud et al. 2023).
On the other hand, the Earth-Moon system is also a laboratory for fundamental physics (Biskupek et al., 2021 ; Bourgoin et al. 2021), and LLR data are essential for fundamental physics tests requiring data samples spread over several decades. LLR data are used to test the equivalence principle, which is central to the theory of general relativity.
Regarding Earth science, LLR contributes to terrestrial tidal dissipation and ranging station positions and motions and astronomical constants (with *GM*(Earth+Moon)) (Williams et al., 2022). LLR contributes also to the establishment of terrestrial, lunar, and ephemeris reference frames (Pavlov, 2020).
LLR could also open a new window for detecting gravitational waves. A large hole in the observable gravitational-wave spectrum could in part be filled by exploiting lunar laser ranging with extremely precise measurements of variations in the moon's orbit (Blas et al., 2022).

Recent ILRS Activities

General

The ILRS Governing Board approved an update to the ILRS Terms of Reference (ToR) (*https://ilrs.gsfc.nasa.gov/about/termsofref.html*) in mid-2016; the IAG accepted the revision and the new Terms of Reference (ToR) was adopted in November 2016. The most significant change to the ILRS ToR was the addition of two At-Large members to the ILRS GB are chosen by the GB to add additional technical expertise and geographic coverage the Board. Other changes addressed the addition of new SCs and clarifying terminology.
The GB has appoved at the November of 2022 GB meeting the merging of the Lunar Laser Ranging Study Group with the Transponders Standing Committee, becoming the LLR & Transponders Standing Committee.
The Space Debris Study Group has submitted a proposal to become a Standing Committee.

Standing Committees and Study Group Activities

All ILRS standing committees were active and held meetings during ILRS workshops during this reporting period.

Analysis Standing Committee (ASC)

The official ILRS Analysis products were produced and delivered routinely during the reporting period. The main efforts of the ASC, however, focused on the timely completion of the Station Systematic Error Monitoring—SSEM Pilot Project (PP), which was a prerequisite for the ILRS contribution to the development of the ITRF2020. The key deliverable was a model of systematic errors that described primarily the long-term performance of the ILRS stations.

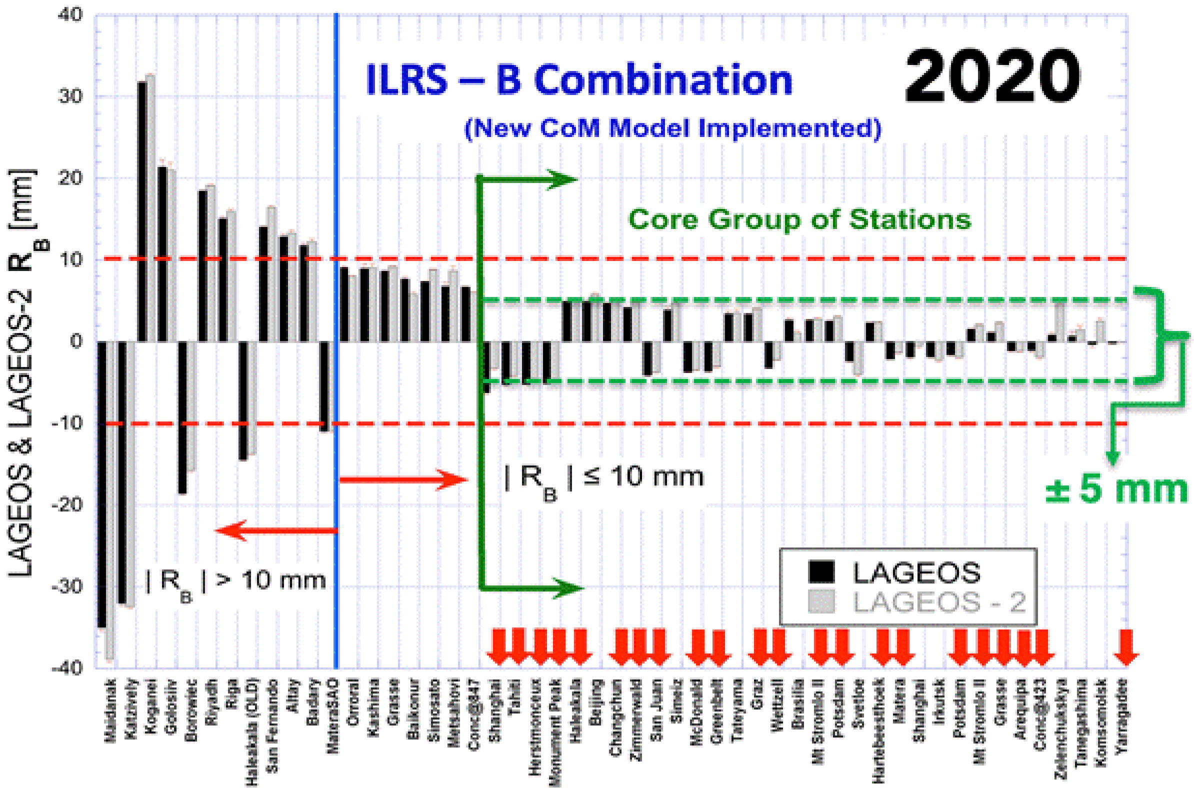

Figure 8. Significant bias-reduction and randomization, especially for the Core stations, as a result of the implementation of improved Target Signature Correction (TSC) models (Luceri et al., 2023).

On a parallel effort, the group of experts in the characterization of the satellite Target Signature Correction (TSC), generated successive versions, each one improving the prior release, until the data reanalysis revealed a much more random distribution of range biases over the entire network (Rodriguez et al., 2019). The long-term mean biases estimated from the final reanalysis were adopted "*a priori*", and pre-applied in the reanalysis that produced the series contributed to ITRF2020. The procedure was documented in (Luceri et al., 2019) and it is now implemented as the standard approach in the operational series. The ASC is developing guidelines for identifying likely errors as they appear in the future, based on a new product, an extension of the SSEM-X procedure, and promptly notifying the affected stations. Upon completion of the reanalysis at the end of 2020 the results were captured in a new version of the "Data Handling File—DHF" which was delivered to the ACs and used in generating their ITRF2020 submissions.

Once ITRF2020 was released, the ASC evaluated the new TRF and subsequently the model was extended to include a number of SLR stations that were not included in the official ITRS release. The majority of these sites come from the early days of SLR, however, a number of newly developed systems were also included since they did not have enough data to participate in the formal process. These sites are assigned very large standard deviations to limit their effect when using the new TRF, until their position and velocity can be improved with increased SLR data. The resulting extended TRF model is called SLRF2020 and follows in format similar previous releases like SLRF2008, SLRF2014, etc. In the comments included with the SLRF2020 SINEX, it is stressed that it should be used along with the appropriate

DHF release and the data should be reduced using very specific TSC models (release of 2022.09.15 or later).
Based on simulation studies that indicated the role that increased Etalon 1 & 2 data could play in the enhancement of ILRS EOP products (Andritsch, 2020), the ASC called for an intensive tracking campaign that was held from February 15 to May 15, 2019. The amount of range data (NPs) that was collected nearly doubled from that over the same period a year ago. The ASC evaluated the benefit from these additional data on the EOP products and recommended that the network make every effort to increase the Etalon 1 & 2 data yield. As a result, ~35 passes on each of the Etalon targets per week are collected on a regular basis, up from ~20 over the previous years. In the last two years these numbers have dropped slightly, due to limited contributions from the Russian sub-network.

A major development in 2022 was the successful launch of new “cannonball” target: the LARES-2 (Paolozzi et al., 2019; Ciufolini et al., 2023). The satellite was placed in orbit supplementary to that of LAGEOS, taking essentially the place of what was originally called “LAGEOS-3”, which was never approved. The design of LARES-2 is very different from that of LARES and LAGEOS. For the first time one of these primary geodetic targets makes use of COTS 1-inch retroreflectors, with a total of 303 densely arranged on the surface of a 424 mm diameter one-piece sphere made of a Nickel alloy, with a mass of 294.8 kg. The tracking data have been evaluated and validated (Pavlis et al., 2023), exhibiting the higher precision as expected, resulting in ~5 mm fits even though we are using only the nominal TSC model (174 mm), while awaiting the development and release of tailored corrections for each of the ILRS tracking systems. It is anticipated that once this TSC model is released, LARES-2 will become the fifth member of the target group that contributes data routinely in the ILRS official products, probably by mid-2023. Other upcoming activities of the ASC include the introduction of LARES as the sixth target to be used for the development of the official ILRS products and at the same time, the delivery of weekly averaged low-degree spherical harmonic coefficients of the gravitational field model. This PP is expected to be completed by the end of 2023.

The co-chairs of the ASC were two of the guest-editors for the special issue (SI) of the Journal of Geodesy dedicated on Laser Ranging. The SI was completed and published online in November 2019 (Pavlis et al., 2019) with 20 contributions.

Data Formats and Procedures Standing Committee (DFPSC)
The DFPSC, in particular the “Data Format Update” study group, released the latest version 2.0 of the ILRS standard CRD (data) and CPF (prediction) formats in September 2019. Since then, OCs, DCs, predictions providers, stations and analysis centers have implemented the new formats. On 1 October 2021, the new CPF format of version 2.0 became the official ILRS prediction format. On 1 October 2022, the new CRD format of version 2.0 became the official ILRS data format. Finally, on 1 January 2023 the transition to the new format was completed with the cessation of processing of old CRD data and CPF prediction of version 1.0 by the ILRS OCs.

The ILRS operates two global data and operation centers. In order to achieve homogeneous data centers, the quality checks applied by the OCs have to be identical. The harmonization of quality checks has been completed. Now, both OCs are working on the implementation of quality checks on SINEX products that will improve the format compliance and file consistency in the future. In the current phase, the new quality checks are being defined, and reviewed and discussed with the ASC.

The open source normal point software *orbitNP.py* developed by the Herstmonceux station has been updated to the latest version 1.2.1 and is now available in the software section of the ILRS website.

Missions Standing Committee (MSC)

The Missions Standing Committee (MSC) reviewed mission support requests from BLITS-M, LARES-2, Sentinel-6A/Jason-CSA, HY-2C, NXD-1-SLAG, ELSA-d, Tubin, Hy2d, ALOS-4, ICEYE-XR1 and SWOT. With the exception of the ICEYE satellites which were found to have inadequate reflector arrays, all requests were approved by the GB. In addition, a request to align the ILRS tracking policy for the Beidou-3 MEO GNSS constellation with that for Galileo and GLONASS was considered and approved. Consequently, all Beidou-3 MEO satellites are formally approved for ILRS tracking with 4 given higher priority. The committee reviewed ILRS policy towards supporting commercial and non-science missions like ELSA-d and found no need to update the policy at this time. The committee also agreed to periodically follow-up with missions to update their tracking needs and assess the value of continued ILRS support. Work has been undertaken to update the Mission Support Request Form (MSRF) to make it more applicable for upcoming lunar missions.

Networks and Engineering Standing Committee (NESC)

NESC draws on the experience, knowledge, and creativity of the global SLR network in order to advance the technique and boost the performance of every station. It aims to strengthen links and promote collaboration, information sharing and best practice. It also provides a practical source of advice to other areas of the ILRS.

NESC has moved to meeting online every two months. Over the last few years it has been difficult for the ILRS community to meet together in person, and so the NESC meetings have provided a welcome connection and a way to keep in touch. Approximately 40 people attend each time and the agenda is made up of contributions from colleagues and invited speakers. Recent meetings have included:

- Station reports from IZN-1, Tenerife and Golosiiv, Ukraine
- Presentations from satellite missions, including the space debris recovery mission ELSA-D and the Surface Water and Ocean Topography (SWOT) satellite.
- Progress reports in the development of new technology, such as the new miniSLR Engineering Station.
- Presentations from outside companies such as GuideTech and EvenTech.
- Analysis feedback on tropospheric bias estimations and calculating centre-of-mass offsets.

NESC also contributes to the design and implementation of ILRS tracking campaigns and will arrange for a calibration barometer to visit every ILRS station in the network.

It was possible to meet in-person in November 2022 at the ILRS Workshop on Laser Ranging in Spain. The NESC meeting was designed to be a discussion on the challenges facing SLR and included different perspectives from geodesy, technology, SLR analysis, lunar laser ranging, atmospheric delays, timing and space debris.

To run alongside these meetings, an online forum exists for the NESC, and for the wider ILRS community, (*http://sgf.rgo.ac.uk/forumNESC*) to encourage knowledge sharing, collaboration and community support.

Transponders Standing Committee (TSC)
Optical time transfer remains to be the main objective of the TSC. In the past few years two-way ranging was successfully demonstrated to the LRO spacecraft orbiting the moon (Mazarico et al., 2020). In a major campaign effort the successful asynchronous transponder ranging between ground stations in Australia, Japan and Europe and the Hayabusa 2 spacecraft at a distance of about 10 mio. km has been achieved, (Noda et al., 2023). The launch of the ACES clocks to the ISS is still awaited. Issues with the major during flight tests, have deferred the launch further. Within the TSC we have explored methods of accurate optical time transfer from ground to ground via a diffuse passive (zero-delay) reflector in space. In this operation one station is transmitting, while more than one station is detecting and timing the transferred laser pulses. An elaborate tumbling motion model links the cooperating observing stations together (Liu et al., 2021). This concept works surprisingly well. For the near future it is intended to extend this concept for reciprocal laser transmission. These efforts for accurate optical time transfer were supported by the development of an active delay compensation method at the ground station (Schreiber and Kodet, 2018).

Quality Control Board (QCB)
The ILRS Quality Control Board was organized at the 19th International Workshop on Laser Ranging to address SLR system biases and other data corruption issues that can degrade ILRS data and derived products. The board is a joint activity under the ASC and the NESC and meets by telecon on a bimonthly basis. The QC reviewed results from the ASC's "Station Systematic Error Monitoring Pilot Project" and worked to diagnose and address error sources, including development of procedures and tools for stations to view system performance and examine systematic errors.
The board has been dealing with the influence of different local data screening procedures, normal point data content, lapses in station operating and reporting procedures, proper backup and redundancy (timing, barometer, etc.), engineering scrutiny of data results, and approaches to modelling systematic errors. The QCB also examines issues of station survey errors, deteriorating calibration stability, and issues with retroreflector array modeling.
Erricos Pavlis and Toshi Otsubo have operational on-line tools and diagnostic assessment for use in reviewing station performance; Van Husson has been performing station by station performance assessments starting with the NASA stations and he has now begun working on other network stations. The Board has been urging stations to be more rigorous in their use of our History Logs so that data inconsistencies can be better diagnosed.
The QCB meeting notes are posted on the ILRS website (https://ilrs.gsfc.nasa.gov/science/qcb/index.html).

Software Study Group (SSG)
The SSG works to identify existing software of use to ILRS stations and analysts. The SSG has worked with the ILRS CB to provide links to these software packages on the ILRS website. The latest versions of the CPF and CRD v2.0 sample software have been added to support implementation of the new format versions. In addition, the open-source normal point software orbitNP.py developed by the Herstmonceux station has been added. The latter software can be of use to stations wanting access to validated software and to analysts wanting to test consistency of normal points from various stations.

Space Debris Study Group (SDSG)
The SDSG was formed in 2014 to coordinate and assist stations in laser ranging to space debris targets. The SG also acts as an interface between the ILRS and the space debris activities within ESA. Early on, the SG organized several campaigns on TOPEX, Envisat, and other SD targets in order to collect accurate range data that is needed to study the orbital dynamics of tumbling satellites under the influence of the environmental forces and torques.

Over the last three years, the number of stations tracking space debris has increased significantly. Graz SLR station is developing laser and detection packages for new stations and upgrading existing towards space debris laser ranging (e.g. ESA's Izana-1 and Izana-2 on Teide, Tenerife). Measurements in multi-static/bi-color debris ranging measurements are being taken to uncooperative targets. "Stare and Chase" is another method for tracking uncooperative targets and has also been successfully tested. Significant results have been seen for science, POD, attitude motion, pre-entry data, and other applications. First successful daylight space debris laser ranging results have been recently published (Tong et al., 2021). Work continues to extend debris laser ranging time into 24/7 operation by pushing a station concept based on a MHz repetition rate laser delivering high precision results for geodetic and space debris laser ranging with one setup. Ground to ground laser time transfer was realized by using diffuse reflections from a tumbling space debris object.
A dedicated server has been set up in Graz, where stations can deposit their laser ranging data from space debris targets; stations can also use this server to download updated CPF/TLE files for space debris targets.

Participants within the space debris laser ranging community (Zimmerwald, Borowiec, Potsdam, Riga) meet frequently. Currently, there are two different project teams that meet regularly: Tumbling motion and Expert Center.

Mission Campaigns

GREAT

Monthly campaigns were conducted on Galileo-201 with Galileo-202 as a backup, to study the behavior of on-board clocks and the gravitational redshift predicted by General Relativity. Launch problems placed in elliptical orbits which induced a periodic modulation of the gravitational redshift at the orbital frequency. In response to a Galileo mission request, the ILRS conducted monthly, week-long campaigns for a period of one year in support of the Galileo gravitational Redshift Experiment with eccentric sATellites (GREAT) experiment.

After more than 2 years of tests, obtained results are beyond initial expectations. Together with a careful conservative modelling and control of other systematic effects, the measurement of the Gravitational redshift has been confirmed with an accuracy 5 times better than previous best estimate, NASA's Gravity Probe-A, a test performed more than 40 years ago and never improved until now. To our knowledge, this represents the first reported improvement on one of the longest standing results in experimental gravitation, the Gravity Probe A hydrogen maser rocket experiment back in 1976.

The results, performed under contract with the European Space Agency, were independently obtained by two research groups working in parallel (SYRTE, Observatoire de Paris, Université PSL, CNRS, Sorbonne Université, LNE in France and ZARM Center of Applied Space Technology and Microgravity in Germany)
Final obtained results were published at (Delva, et al. 2018 and Hermann, et al. 2018).

GASTON Project

The Paris and Cote d'Azur Observatories and the Royal Observatory of Belgium organized the GASTON project (Galileo Survey of Transient Objects Network) to search for evidence of Dark Matter (DM) in the universe. The experiment used the large network of atomic clocks and electromagnetic links from the Galileo constellation as a gigantic detector of 50,000 km aperture to search for Dark Matter (DM). Evidence of DM transients would be in distant clock correlations with the delay predicted by the trajectory of our Solar System within the dark matter halo. The experiment relied on the ILRS network to help maintain the metrology of the aperture over the period January – March 2021. Many of the network stations participated and

maintained concentrated coverage on the Galileo constellation. Tracking priorities were adjusted to put heavy concentration on the Galileo constellation, while at the same time maintaining acceptable coverage on the other network priorities. To ensure this, a dedicated website based on the Eurostat software (AIUB), displayed in real time the status of the observations by the network, presenting the number of stations currently tracking a Galileo satellite. The Gaston experiment explored the challenge of coordinating observations within the ILRS network. The temporal coverage of Galileo observations by the network increased from 40 to 60% on average. We give special thanks to all of the stations that put extra effort to make this all work. We now await the experiment results.
This study has allowed obtaining a dramatic extension of the detection exclusion area of DM transients with respect to previous studies performed with GPS. In particular, the area of transient size from 105 to 109 km has been explored for the first time.
The method used in the GASTON project, based on a frequentist approach, has also shown evidence of several significant events with high SNR. At this stage, the origin of these events remains mysterious, and many hypotheses can be made: a probable artifact in the data analysis, a mismodelling of systematic effects, or a signature of new physics. Whatever its final explanation, it deserves further investigation since we could gain results in the understanding of Galileo products generation in case these high SNR events are not an artifact of the data analysis. A thorough analysis of systematic effects using SLR data is still ongoing. This complementary analysis is going to be launched (July 2023) under contract with the European Space Agency.

Sentinel-6/Jason-3 Tandem Campaign

The Sentinel-6 mission was launched into orbit on November 21, 2020. It is the latest mission to be launched to synoptically measure ocean surface topography (including the change in Global Mean Sea Level) along the TOPEX reference ground track at an inclination of 66°, and a repeat period 9.9156 days. For more than 15 months (December 18, 2020 – April 7, 2022), compared to about 9 months for the previous tandem missions (Jason-2+Jason-3 in 2016, and Jason-2+Jason-1 in 2008-2009), Sentinel-6 flew on the same ground track, 30 seconds behind Jason-3. This tandem mission mode allows a direct inter-calibration of the instruments on the two spacecraft, including the radar altimeters and the water vapor radiometers. The geophysical corrections to the data from the different instrumentation on the two spacecraft, such as the ionosphere correction and the significant wave height (SWH) corrections can also be directly compared. These comparisons are necessary in order to connect the time series of sea surface height measurements from Sentinel-6 with the data from the previous satellites (TOPEX and Jasons 1,2,3). It is for instance very useful for investigating the sources of geographically correlated orbit errors. Indeed, since the two satellites do not share the same shape/design, their non-conservative forces are expected to differ. Thus when identifying similar evolutions between their respective estimated residual empirical accelerations or with respect to independent orbit solutions, one could assess that the modeling error affecting both satellites is of gravitational origin. In the example shown below, a typical geocenter motion modeling difference exhibits geographically.

During this tandem mission, the ILRS stations were asked to interleave their tracking between the two spacecrafts. For the stations preferring not to rapidly move between the targets, they were asked to alternate their tracking passes evenly between the two satellites. On average, 15-20 passes of Sentinel-6 were tracked by SLR. Yarragadee (Australia), Changchun (China), Zimmerwald (Switzerland), Herstmonceux (UK), and Greenbelt (USA) provided most of them. As a consequence, the SLR data contributed by directly measuring orbit errors for the two missions during this important mission phase.

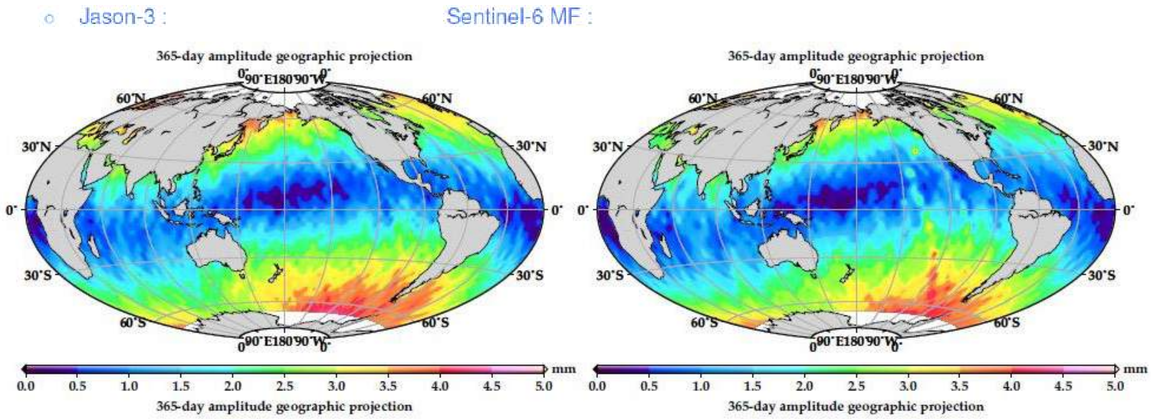

Figure 9. Geographically correlated radial difference (mm) 365-day signals between JPL RLSE-22A and CNES POE-F orbits for Jason-3 (left) and Sentinel-6 MF (right).

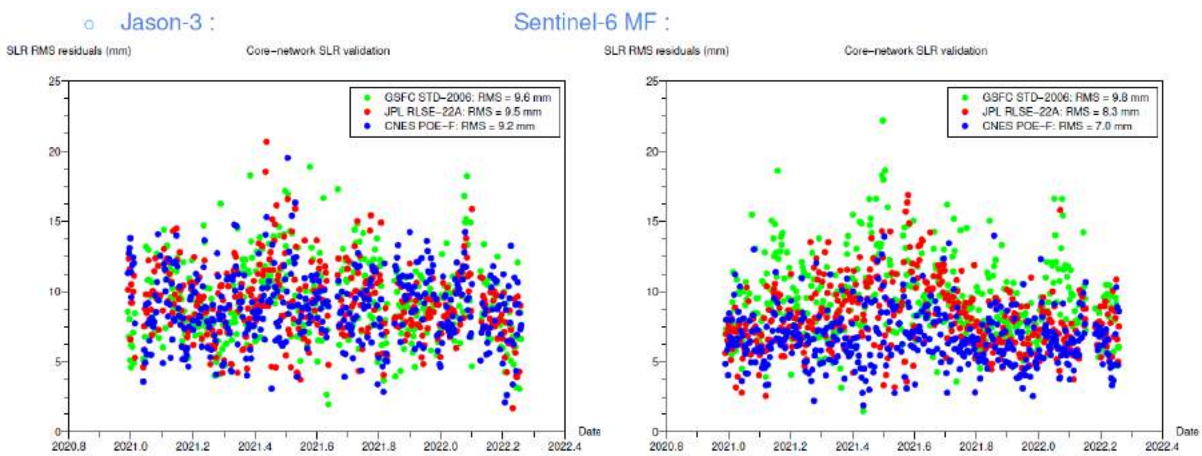

Figure 10. RMS of SLR Core Network residuals (mm) for Jason-3 (left) and Sentinel-6 MF (right) vs. time for the GSFC STD-2006, JPL RLSE-22A, and CNES POE-F orbit solutions.

This is the state-of-the-art technique for an independent and absolute validation of the orbit accuracy.

ILRS Meetings

Workshops

The ILRS holds bi-annual International Workshops on Laser Ranging which cover a wide range of topics throughout the service including scientific, engineering, mission, and infrastructure presentations. In addition, in recent years, the ILRS has conducted Technical Workshops in the intervening years to focus on a few timely topics that impact the quality of ILRS data products and service operations. These workshops are oriented more toward the SLR practitioners and are intended to provide more time to deal with issues carefully, allow for in-depth discussion, and formulate a path forward.

In 2019 an ILRS Technical Workshop, sponsored by the DLR and the ILRS, was held in Stuttgart Germany, October 21 – 25 with the theme "Laser ranging: To improve economy, performance, and adoption of new applications". The workshop focused on addressing the following questions:

- What are the current and anticipated laser ranging requirements for the various satellites and have we defined them properly?
- How do we evaluate our current performance and is it adequate?
- What factors are currently limiting our network performance?
- What operational steps and tools would help us to better meet satellite ranging accuracy and scheduling requirements?
- What automation capabilities have been implemented or are planned for implementation, and what automation capabilities should stations consider?
- Novel concepts to improve the SLR network

With its 150 participants from more than twenty countries and more than seventy presentations (oral and poster), the workshop illustrated the importance of SLR and its application to international scientific research. For more detail on this Workshops see *https://cddis.nasa.gov/2019_Technical_Workshop/*
Prior to the 2019 ILRS Workshop, the ILRS scheduled a one-day introductory course to give non-practitioners in SLR an opportunity to broaden their knowledge about laser ranging to Earth-orbiting satellites and the Moon. More information about the "SLR School" can be found at: *https://ilrs.gsfc.nasa.gov/docs/2019/SLRschool_20191020.pdf*
The 22nd International Workshop on Laser Ranging was scheduled to take place in Kunming China in 2020, and a Technical Workshop was scheduled for Arequipa, Peru in 2021. Both were delayed due to the Pandemic. In place of the Kunming event 2020 the ILRS held a virtual 5 day, 2 hours a day, tour of five SLR stations: Graz, Austria; Zimmerwald, Switzerland; Simosato; Japan; and Yaragadee; Australia. Each site also gave one or two talks on technical information about the site or a technical issue of particular interest to the site team *(see https://cddis.nasa.gov/ILRS_Virtual_World_Tour_2020/).*
A similar event was held in 2021, including station tours at Herstmonceux, UK; Wettzell, Germany; Mendeleevo, Russia; Shanghai, China; and Monument Peak,California. In addition, Specialized talks were given by the Standing Committees, some of the Missions, operational issues, SLR focused science, Lunar Ranging, and space debris *(see https://ilrs.gsfc.nasa.gov/ILRS_Virtual_World_Tour_2021/).*
The 22nd International Laser Ranging Workshop was ultimately held at Guadalahara (Spain). Organised by the Observatory of Yebes, the National Geographic Institute of Spain (IGN/CNIG), and the ILRS, over 170 delegates from 20 different countries participated in the conference, which took place on 7–11 November 2022. With the theme "Reconnecting the ILRS community", this event was for the first time in a hybrid format, with both in person and online participation. After the restrictions imposed during the pandemic, this conference was an excellent opportunity for the experts in the various SLR-related fields to meet, discuss and exchange ideas and new developments.
The station tours gave many people an opportunity to “visit” stations that they would not have the opportunity to do.
The ILRS Technical Workshop then planned for 2023 had to be postponed again tentatively until 2025 due to civil unrest in Peru; the 23rd International Laser Ranging Workshop in Kunming is now scheduled for the latter part of 2024.

ILRS Components Meetings
Meetings of the Governing Board and standing committees are typically held in conjunction with these ILRS workshops. The GB meetings in 2020 and 2021 were held virtually. The meeting Agenda and presentations can be found on the ILRS web site under About/Organizations/ILRS Governing Board/Meetings. The meeting in 2022 was held at the

Laser Workshop and was accessible virtually. Special meetings were also held virtually to deal with timely matters.

The ILRS Central Bureau meets monthly to review network station operations and performance, as well as to coordinate support of upcoming missions, monitor and manage the ILRS infrastructure, and plan future directions and activities. The ILRS Central Bureau continues to maintain the ILRS website, installed on a CDDIS webserver at NASA GSFC. The website, *https://ilrs.gsfc.nasa.gov*, is updated several times per week as required. A bibliography of laser ranging publications is maintained on the website. The ILRS CB meeting notes are available upon request.

The Standing Committees and the Study Groups typically meet during the workshops; special meetings are scheduled as meet as required. See individual briefs above.
A summary of recent and planned ILRS meetings is shown in Table 4. Minutes and presentations from the workshops and these splinter meetings are available from the ILRS website (*https://ilrs.gsfc.nasa.gov/about/reports/workshop/index.html* and *https://ilrs.gsfc.nasa(.gov/about/reports/meeting_reports.html*).

Table 4. Recent and future ILRS Meetings (as of June 2023)

Timeframe	Location	Meeting
October 2019	Stuttgart, Germany	2019 ILRS Technical Workshop, "Laser ranging: To improve economy, performance, and adoption for new applications"
		ILRS Governing Board meeting
		ILRS Standing Committee meetings
November 2020	Virtual Meeting	Virtual Station Tour (in place of the original scheduled Workshop)
December 2020	Virtual Meeting	ILRS Governing Board meeting
October 2021	Virtual Meeting	Virtual Station Tours (in place of the original scheduled Workshop) including Special Scientific Sessions
December 2021	Virtual Meeting	ILRS Governing Board meeting
April 2022	Virtual Focused Meeting	ILRS Governing Board meeting
November 2022	Guadalajara, Spain	22nd International Workshop on Laser Ranging Guadalajara (near Yebes), Spain and Online (Hybrid)
		ILRS Governing Board meeting
		ILRS Standing Committee/Study Group meetings
May 2023	Virtual Meeting	ILRS Governing Board meeting
September 2023	Calern/Grasse (Alpes-Maritimes), France	First Lunar Laser Ranging Meeting
October 2023	Virtual Meeting	Virtual Workshop including Scientific Sessions
October 2024	Kunming, China	23rd International Workshop on Laser Ranging
		ILRS Governing Board meeting
		ILRS Standing Committee/Study Group meetings
October 2025	Arequipa, Peru	23rd International Technical Workshop
		ILRS Analysis Standing Committee meetings
		ILRS Standing Committee/Study Group meetings

Publications and Reports

During the last four years (2019-2023), members of the ILRS contributed papers to a special issue of the Journal of Geodesy, Volume 93, Issue 11, dated November 2019 (Pavlis et al., 2019c). The special issue consists of a collection of twenty articles on Satellite Laser Ranging (SLR). The papers present the current status of SLR applied to Earth and Space science and engineering. The papers include an overview of the ILRS with an outlook for the future; a historical review of the early years prior to the establishment of the ILRS; a presentation of the important target satellites with significant contributions to science; a description of the ground systems comprising the current network and advanced designs for the near future; novel designs of new targets for improved data accuracy; new analysis methods and standards for increased accuracy of the products; interactions and joint projects with other techniques having common scientific goals; independent approaches in validating data accuracy; improvements in the area of network operations; an overview of the data information system that manages, supports and archives for posterity the data and products of laser ranging; and a sample lunar science applications.

The Journal of Geodesy special issue includes a new citation paper for the ILRS that should be included in papers and publications by those using ILRS data or products:

Pearlman M.R., Noll C.E., Pavlis E.C., Lemoine F.G., Combrink L., Degnan J.D., Kirchner G., Schreiber U. (2019). "The ILRS: approaching 20 years and planning for the future", J. Geodesy, 93, 2161-2180, doi:10.1007/s00190-019-01241-1.

The ILRS issues periodic reports summarizing activities within the service over the reporting period. The latest report, for the period 2016 – 2019, is available on the ILRS website, and can be referenced as follows:

International Laser Ranging Service (ILRS) 2016-2019 Report, edited by C. Noll and M. Pearlman, NASA/TP-20205008530, NASA Goddard Space Flight Center, Greenbelt, MD, USA, 2020.

The ILRS organized the 22nd International Workshop on Laser Ranging from 7-11 November, 2022 in Yebes, Spain. This was a hybrid (in-person & virtual) meeting. The leading authors of many of the oral presentations supplied proceedings papers which have been published on the ILRS website: https://ilrs.gsfc.nasa.gov/lw22/Program/index.html

The presentation and minutes from the meetings of the Analysis Standing Committee (April & October 2019, and November 2022), are available on the ILRS website: https://ilrs.gsfc.nasa.gov/science/awg/awgActivities/index.html

The Network and Engineering Study Committee of the ILRS (NESC) held regular meetings from 2019 to 2023. This included in person meetings at the ILRS Technical Workshop 2019 in Stuttgart, Germany and at the 22nd International Laser Ranging Workshop in Yebes, Spain in November 2022. In addition the NESC held 15 virtual meetings from 2019 to 2023. The minutes of these meetings and the presentations are available on the ILRS website: https://ilrs.gsfc.nasa.gov/network/newg/newg_activities.html.

A major activity of the ILRS in this report period, 2019-2023, was the preparation and submission of the ILRS contribution to ITRF2020. A description of the ILRS contribution to ITRF2020 was published on the ITRF website:
https://itrf.ign.fr/docs/solutions/itrf2020/The_ILRS_contribution_to_ITRF2020_description_2022.09.23.pdf

The International Earth Rotation Service (IERS) published IERS Technical Report 40, Description and evaluation of DTRF2014, JTRF2014 and ITRF2014. An ILRS contribution to this report was submitted by J. Rodriguez (formerly of the NERC Space Geodesy Facility, now at the Yebes Observatory, Spain). The citation for this report is as follows:

Rodriguez J. (2020). "Assessment of DTRF2014 and ITRF2014 by Satellite Laser Ranging", in IERS Technical Report 40, Description and evalution of DTRF2014, JTRF2014, and ITRF2014, edited by Z. Altamimi and W. Dick, Verlag des Budesamts für Kartographie und Geodäsie, Frankfurt am Main, Germany, ISBN 978-3-86482-137-0.

In 2012, after several years of deliberation and discussion, the ILRS adopted a new data format for exchange of full-rate, sampled engineering, and normal point data, the Consolidated Laser Ranging Data (CRD) format, Version 1.01. On August 1, 2022, an updated version of the CRD format (Version 2.01) was implemented by the ILRS. All SLR data (full rate and normal point) are now submitted in this new (CRD V2) format. The documentation and description of this new format, CRD V2.01, was published on the ILRS website:

https://ilrs.gsfc.nasa.gov/data_and_products/formats/crd.html

The ILRS Central Bureau continues to maintain the ILRS website, installed on the NASA CDDIS webserver at NASA GSFC. The website, https://ilrs.gsfc.nasa.gov, is updated weekly, as required. ILRS Analysis Center reports and inputs are used by the Central Bureau for review of station performance and to provide feedback to the stations when necessary. Special weekly reports on on-going campaigns are issued via SLRMAIL. The ILRS CB also generates monthly and quarterly Performance Report Cards and posts them to the ILRS website (https://ilrs.gsfc.nasa.gov/network/system_performance/index.html). These Report Cards evaluate data quantity, data quality, and operational compliance for each tracking station relative to ILRS minimum performance standards. These results include independent assessments of station performance from several of the ILRS analysis/associate analysis centers. The statistics are presented in tabular form by station and sorted by total passes in descending order. Plots of data volume (passes, normal points, and minutes of data) and RMS (LAGEOS, Starlette, calibration) are created from this information and available on the ILRS website. Plots, updated frequently, of multiple satellite normal point RMS and number of full-rate points per normal point as a function of local time and range have been added to the ILRS website station pages.

While the "Report Cards" show in tabular form the performance of the network for a 3-month (short-term) or 1-year (long-term) period, to better visualize the evolution of each station's performance in time, JCET has developed a database that is accessed from our portal:

http://geodesy.jcet.umbc.edu/ILRS_AWG_MONITORING/

by selecting the “ILRS Report Card” option and then selecting the station of interest and period of performance. Depending on the choice, monthly or quarterly reports, this tool generates a month-by-month or quarter-by-quarter graph of the performance and its measure of confidence.

The ILRS maintains a Bibliography of peer-reviewed SLR-related publications on the ILRS website: https://ilrs.gsfc.nasa.gov/about/reports/biblio/index.html

The Bibliography at the time of this report contains 463 records for the report period (2019 – 2023). Besides the papers listed in the 2019 Journal of Geodesy special issue, we highlight a few noteworthy SLR-related publications for this report period:

2019:

Abbondanza C., Chin T.M., Gross R.S., et al. (2019). “A sequential estimation approach to terrestrial reference frame determination”, Adv. Space Res., 65(4), 1235-1249, doi: 10.1016/j.asr.2019.11.016.

Ciufolini I., Paolozzi A., Pavlis, E.C. et al. (2019). “An improved test of the general relativistic effect of frame-dragging using the LARES and LAGEOS satellites”, Euro. Phys. Journal C, 79 (10):872, doi: 10.1140/epjc/s10052-019-7386-z.

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2020:

Boisits J., Landskron D., Böhm J. (2020). “VMF3o: the Vienna Mapping Functions for optical frequencies”, J. Geodesy, 94(6), 57, doi: 10.1007/s00190-020-01385-5.

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Loomis B.D., Rachlin K.E., Wiese D.N., et al. (2020), “Replacing GRACE/GRACE-FO C-30 with Satellite Laser Ranging: Impacts on Antarctic Ice Sheet Mass Change", Geopys. Res. Lett., 47(3), e2019GL085488, doi: 10.1029/2019GL085488.

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2021:

Dequal D., Agnesi C., Sarrocco D., et al. (2021). “100 kHz satellite laser ranging demonstration at Matera Laser Ranging Observatory”, J. Geodesy, 95(2), 26, doi: 10.1007/s00190-020-01469-2.

Drożdżewski M. and Sośnica K. (2021). "Tropospheric and range biases in Satellite Laser Ranging", J. Geodesy, 95(9), 100, doi: 10.1007/s00190-021-01554-0.

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Rodriguez J.C and Appleby G.M. (2021). "Satellite Laser Ranging", in Handbook of Laser Technology and Applications: Volume IV, Laser Applications, Medical, Metrology and Communication, pp. 181-198, edited by C. Guo and S.C. Singh, CRC Press (Taylor & Francis Group), Boca Raton, Florida, U.S.A, doi:10.1201/9781003130123-12.

Tao E.Z., Guo N.N., Xu K.X. et al. (2021). "Validation of Multi-Year Galileo Orbits Using Satellite Laser Ranging", Remote Sensing, 13(22), 4634, doi:10.3390/rs13224634.

Thomas T.C., Luthcke S.B., Pennington T.A., et al. (2021). "ICESat-2 precision orbit determination", Earth and Space Science, 8, e2020EA001496, doi:10.1029/2020EA001496.

2022:

Duan B.B. and Hugentobler U. (2022). "Estimating surface optical properties and thermal thrust for Galileo satellite body and solar panels", GPS Solutions, 26(4), 135, doi: 10.1007/s10291-022-01324-1.

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Issues and Challenges

Several challenges are on the horizon for the ILRS as it moves forward. Some of the new stations underway and planned will help address geographic gaps in the network, but many gaps remain, primarily in Latin America, Africa, and Oceania. The ILRS network still consists of a mix of new and old technologies and levels of financial support; the lack of standardization in system hardware and operations introduces data issues that require continued attention. The number of satellite targets, particularly in the GNSS constellations, continues to increase. The ILRS has implemented a new GNSS tracking strategy (see sections on Satellite Missions) to address the increase in the number of GNSS satellites and the increase in user requirements. Furthermore, there is a need to be more selective on the time spent on each target. Data quality issues continue to affect the ILRS products; rapid data review feedback to the stations continues to improve and on-line data evaluation software tools have been implemented. The progress made in the improvement of the geodetic satellite center of mass corrections has been significant, and techniques to address sources of data biases have been much improved.

We need to stress even harder, the need for stations to document even better their engineering activities and to keep their site logs and history logs up to date. Some stations have suffered long period of data lapse.

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International VLBI Service for Geodesy and Astrometry (IVS)

https://ivscc.gsfc.nasa.gov

Chair of the Directing Board: Rüdiger Haas (Sweden)
Director of the Coordinating Center: Dirk Behrend (USA)
Analysis Coordinator: John Gipson(USA)

Overview

This report summarizes the activities and events of the International VLBI Service for Geodesy and Astrometry (IVS) during the report period of 2019–2023. Due to COVID-19 the IVS General Meeting and splinter meetings were cancelled in 2020. The IVS Directing Board developed an Infrastructure Development Plan 2030. Rüdiger Haas was elected IVS Chair for the period from February 2021 through February 2025, succeeding Axel Nothnagel in this position. In January 2023, Alexander Neidhardt replaced Stuart Weston, who had succeeded Ed Himwich in July 2020 in that position, as IVS Network Coordinator. The IVS contributed with results from eleven Analysis Centers to the ITRF2020 effort. In January 2020 the fledgling VGOS network of 8–10 stations was declared operational.

Structure

The International VLBI Service for Geodesy and Astrometry (IVS) is an approved service of the International Association of Geodesy (IAG) since 1999 and of the International Astronomical Union (IAU) since 2000. The goals of the IVS, which is an international collaboration of organizations that operate or support Very Long Baseline Interferometry (VLBI) components, are:

- to provide a service to support geodetic, geophysical and astrometric research and operational activities;
- to promote research and development activities in all aspects of the geodetic and astrometric VLBI technique; and
- to interact with the community of users of VLBI products and to integrate VLBI into a global Earth observing system.

They are realized through seven types of components (Network Stations, Operations Centers, Correlators, Analysis Centers, Data Centers, Technology Development Centers, and the

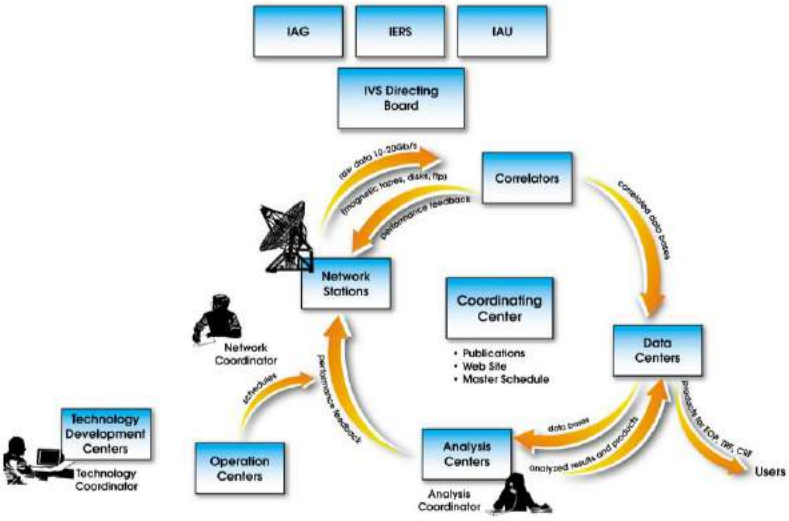

Figure 1. Organizational diagram of the IVS.

Coordinating Center). The structure of the IVS and the interaction among the various components and external organizations is shown in Figure 1.

Being tasked by IAG and IAU with the provision of timely and highly accurate products (Earth Orientation Parameters, EOP; Terrestrial Reference Frame, TRF; Celestial Reference Frame, CRF), but having no funds of its own, IVS strongly depends on the voluntary support of individual agencies that form the IVS.

Activities

Meetings and Organization

The IVS organizes biennial General Meetings and biennial Technical Operations Workshops. Other workshops such as the Analysis Workshops and technical meetings are held in conjunction with larger meetings and are organized once or twice a year. Table 1 gives an overview of the IVS meetings during the report period.

Table 1. IVS meetings during the report period (2019−2023).

Time	**Meeting**	**Location**
18–20 November 2019	8th International VLBI Technology Workshop	Sydney, Australia
~~22 March 2020~~	~~IVS Stakeholders Meeting~~	~~Annapolis, MD, USA~~
~~22–26 March 2020~~	~~11th IVS General Meeting~~	~~Annapolis, MD, USA~~
~~27 March 2020~~	~~21st IVS Analysis Workshop~~	~~Annapolis, MD, USA~~
15–18 March 2021	EVGA Working Meeting 2021	Cyberspace
18 March 2021	22nd IVS Analysis Workshop	Cyberspace
3–5 May 2021	11th IVS Technical Operations Workshop	Cyberspace
6–7 May 2021	VGOS Correlation Workshop	Cyberspace
28–29 October 2021	Second EU-VGOS Workshop	Vienna, Austria (hybrid)
22–25 March 2022	4th VLBI Training School	Cyberspace
27–31 March 2022	12th IVS General Meeting	Cyberspace
1 April 2022	23rd IVS Analysis Workshop	Cyberspace
1–4 May 2023	12th IVS Technical Operations Workshop	Westford, MA, USA
4–5 May 2023	VGOS Correlation Workshop	Westford, MA, USA
12–14 June 2023	EVGA Working Meeting 2023	Bad Kötzting, Germany
15 June 2023	24th IVS Analysis Workshop	Bad Kötzting, Germany
16–18 June 2023	IVS Retreat	Wettzell, Germany

The Eleventh IVS General Meeting plus several splinter meetings were planned for the last week of March 2020. The meetings were canceled two weeks prior to commencement due to the onset of the coronavirus pandemic with travel bans and lockdowns. Most of the meetings in 2021 and 2022, including a VLBI Training School, a Technical Operations Workshop, and a General Meeting, were held in Cyberspace. While these meetings served to keep the community engaged in IVS activities, it also showed that virtual events cannot replace in-person gatherings—in particular, for hands-on workshops or training schools. Here face-to-face interactions are indispensable. On the positive side, however, the online events tended to have a higher attendance level than their in-person counterparts, thus reaching a larger VLBI audience. In 2023, we saw a return to in-person meetings, some with the inclusion of hybrid options.

The Directing Board corresponded with the IVS stakeholders about the service's future and its mandate for the next ten years. The deliberations resulted in a planning document that was finally called the "IVS Infrastructure Development Plan 2030." Based on feedback received, more than 80 percent of the stakeholders saw their agencies' involvement in the IVS driven by service considerations (as opposed to science). See more information below.

The Directing Board determines policies, adopts standards, and approves the scientific and operational goals for IVS. The Directing Board exercises general oversight of the activities of IVS including modifications to the organization that are deemed appropriate and necessary to maintain efficiency and reliability. The Board members are listed in Table 2.

Table 2. Members of the IVS Directing Board during the report period (2019−2023). Listings are alphabetically by last name.

a) *Current Board members (May 2023)*

Directing Board Member	Institution, Country	Functions	Recent Term
Dirk Behrend	NVI, Inc./NASA GSFC, USA	Coordinating Center Director	—
Johannes Böhm	TU Vienna, Austria	IAG Representative	—
Patrick Charlot	Bordeaux Observatory, France	IAU Representative	—
John Gipson	NVI, Inc./NASA GSFC, USA	Analysis Coordinator	—
Rüdiger Haas	Onsala Space Observatory, Sweden	IERS Representative, Chair	—
Phillip Haftings	U.S. Naval Observatory, USA	Correlators and Operation Centers Representative	Feb 2023 − Feb 2027
Hayo Hase	BKG & AGGO, Argentina	At Large Member	Feb 2023 − Feb 2025
Masafumi Ishigaki	Geospatial Information Authority, Japan	At Large Member	Feb 2023 − Feb 2025
Nancy Kotary	Haystack Observatory, USA	Office for Outreach and Communications	—
Lucia McCallum	University of Tasmania, Australia	Networks Representative	Feb 2023 − Feb 2027
Alexander Neidhardt	TU Munich, Germany	Network Coordinator	—
Chet Ruszczyk	Haystack Observatory, USA	Technology Development Centers Representative	Feb 2023 − Feb 2027
Fengchun Shu	Shanghai Astronomical Observatory, China	At Large Member	Feb 2023 − Feb 2025
Oleg Titov	Geoscience Australia, Australia	Analysis and Data Centers Representative	Feb 2021 − Feb 2025
Gino Tuccari	IRA/INAF, Italy	Technology Coordinator	—
Pablo de Vicente	Instituto Geográfico Nacional, Spain	Networks Representative	Feb 2021 − Feb 2025
Anastasiia Walenta	BKG, Germany	Analysis and Data Centers Representative	Apr 2022 − Feb 2027

b) *Previous Board members in 2019−2023*

James Anderson	GFZ Potsdam, Germany	Analysis and Data Centers Representative	Feb 2019 − Apr 2022
Francisco Colomer	Instituto Geográfico Nacional, Spain	Networks Representative	Feb 2017 − Feb 2021
David Hall	U.S. Naval Observatory, USA	Correlators and Operation Centers Representative	Sep 2019 − Feb 2023

Hayo Hase	BKG & AGGO, Argentina	Networks Representative	Feb 2019 − Feb 2023
Ed Himwich	NVI, Inc./NASA GSFC, USA	Network Coordinator	—
Laura La Porta	Reichard GmbH, Max-Planck-Institut für Radioastronomie, Bonn, Germany	Correlators and Operation Centers Representative	Feb 2019 − Sep 2019
Jinling Li	Shanghai Astronomical Observatory, China	At Large Member	Feb 2019 − Feb 2021
Evgeny Nosov	Institute of Applied Astronomy, Russia	At Large Member	Feb 2019 − Feb 2021
Axel Nothnagel	TU Vienna, Austria	Analysis and Data Centers Representative	Feb 2017 − Feb 2021
Nadia Shuygina	Institute of Applied Astronomy, Russia	At Large Member	Feb 2021 − Feb 2023
Yu Takagi	Geospatial Information Authority, Japan	At Large Member	Feb 2021 − Feb 2023
Oleg Titov	Geoscience Australia, Australia	IAG Representative	—
Stuart Weston	Auckland University of Technology, New Zealand	Network Coordinator	—
Alet de Witt	Hartebeesthoek Radio Astronomy Observatory, South Africa	At Large Member	Feb 2021 − Feb 2023

During the report period two Directing Board elections were held. Following the elections at the end of 2020, the Board elected Rüdiger Haas from Chalmers University of Technology, Onsala Space Observatory, Sweden as the new chair of the IVS for the four-year term from February 2021 to February 2025. Dr. Haas succeeded Axel Nothnagel of TU Vienna, who had chaired the IVS in the previous eight years. In July 2020, Stuart Weston of Auckland University of Technology (AUT) in New Zealand took over the position of IVS Network Coordinator from Ed Himwich of NVI, Inc./NASA Goddard Space Flight Center. After 2.5 years in this role, Stuart Weston stepped down because of the funding situation at his home institution (AUT divested itself of Warkworth Observatory). The Board elected Alexander Neidhardt from TU Munich as the new Network Coordinator effective January 2023.

IVS Infrastructure Development Plan 2030

Based on the discussions with the IVS stakeholders, the IVS Directing Board developed an IVS Infrastructure Development Plan 2030. The main goal is to provide overall planning guidelines and to give the stakeholders and IVS Associates reasonable indications for the investments and activities needed. It is hoped that the plan will trigger serious considerations for additional components in order to establish and sustainably maintain elements identified as missing for further progress. Not only should this document motivate existing IVS components but also provide necessary arguments to new players for a serious need for additional contributors and contributions.

UT1−UTC, the highly variable Earth's phase of rotation, is needed for a variety of important applications such as positioning, navigation, and environmental monitoring, preferably in real-time. Since the VLBI technique is the only one to determine this parameter with sufficient accuracy and due to the need for low latency results, regular UT1−UTC determinations have the highest priority in the IVS's endeavours and justify the maintenance of global critical infrastructure. However, the other components of EOP, as well as those of terrestrial and celestial reference frames, though with different latency requirements, are equally essential for numerous applications in science and technology. These products are highly correlated with each other and need to be monitored diligently with the same level of energy.

Starting from its current level of operations, the IVS embarks on organizing IVS observing networks in operation for 24 hours, seven days a week and on producing products with reasonable accuracies and latencies. Within these observing sessions, it will be warranted that all products, i.e., the complete set of EOP components including UT1−UTC as well as terrestrial and celestial reference frames, are produced with the same level of quality.

The IVS relies on voluntary contributions of national agencies and institutions acting in a global context. The workload is large, and the investments are costly. At present, not all of the resources needed for the targets named above, such as coordination, data transfer and *Level 1 Data Analysis*, have been committed in full or even in part. For this reason, much of the progress to be seen in the next ten years will heavily depend on increased commitments and investments of active and new IVS contributors.

Observing Program

The observing program for 2019–2023 with the legacy S/X system (production system) includ ed the following sessions:

- EOP: Daily 1-hour UT1 Intensive measurements: Int1 sessions on five weekdays (Monday through Friday) using the Wettzell (Germany) to Kokee Park (Hawaii, USA) baseline; Int2 sessions on Saturday and Sunday, using the Wettzell (Germany) to Ishioka (Japan) baseline; and Int3 sessions on Monday mornings in the middle of the 36-hour gap between the Int1 and Int2 series with the Wettzell (Germany), Ny-Ålesund (Norway), and Ishioka (Japan) network. A midnight Intensive series, centered on 0 UT with two sessions per week, was introduced in early 2022 to evaluate a possible shift of the Intensive observing program to UT midnight and to gauge the impact on the operational use at the IERS Rapid Service/Prediction Center. Two rapid-turnaround 24-hour sessions each week designed to measure all components of EOP. These mostly used networks of 10–12 globally distributed stations, depending on station availability. In 2020, extended R1 sessions with up to 14 stations were observed roughly every other week. These networks were designed with the goal of having comparable x_p and y_p results. Data is available within 15 days after each session ends.
- TRF: Bi-monthly TRF sessions with 14–18 stations using all stations at least two times per year.
- CRF: Bi-monthly sessions using the Very Long Baseline Array (VLBA) and up to eight geodetic stations, plus astrometric sessions to observe mostly southern sky sources.
- Monthly R&D sessions to investigate instrumental effects, research the network offset problem, and study ways for technique and product improvement.

Although certain sessions have primary goals, such as CRF, all sessions are scheduled so that they contribute to all geodetic and astrometric products. On average, a total of about 1650 station days per year were used in around 200 geodetic sessions during the year keeping the average days per week which are covered by VLBI network sessions at 3.5.

In January 2020, the VGOS network was officially declared operational (and vgosDB files were made available on the data centers for sessions from January 2019 onward). For the years 2019 through 2021, a 24-hour VGOS session (VGOS-OPS) was scheduled every two weeks. In 2022, the cadence was increased to weekly VGOS-OPS sessions. As a backlog of uncorrelated sessions accumulated towards the end of the year, the cadence was changed back to two weeks in the first half of 2023; given a faster turnaround time, it is planned to go back to weekly observing in the second half of the year.

Starting in January 2021, a VGOS Intensive series on the baseline Kokee to Wettzell (K2-Ws, VGOS-INT-A) has been organized concurrently with IVS-INT-1 sessions—initially once a week and then increased to five times a week by the end of the year. After establishing a sufficient time series and proper error estimates, the results have been used operationally by the IERS Rapid Service/Prediction Center since May 2023. A second VGOS Intensive on the baseline Ishioka to Onsala is currently under evaluation.

Analysis

Diurnal and Semidiurnal EOP Variation

Several IVS Analysis Centers participated in the work of the IERS Working Group on Diurnal and Semi-diurnal EOP Variation. Ten different models were evaluated by members of the IVS , the ILRS, and the IGS. Each technique used metrics appropriate to their technique. For exam ple, the IVS looked at baseline repeatability and goodness of fit. The general consensus of all t he techniques was that the two best models were *2017a_astro*, an empirical model derived fro m VLBI data by John Gipson, and a model by Desai and Sibois of JPL derived from a TPX08, an altimetry model due to Egbert. Both models were improvements over the current IERS mo dels, and each model had advantages and disadvantages. In order to avoid technique-specific s ignals, the working group recommended the use of the Desai and Sibois model which is the ne w IERS standard and is used in ITRF2020.

Gravitational Deformations of Radio Telescopes

VLBI antennas are structures, traditionally with a typical size of 30 m or larger, although modern VGOS antennas have dish diameters of 12–13 m. The VLBI antennas deform due the effect of gravity, and the deformation is a function of the elevation angle. In 1988 Per Thomsen and Tom Clark built a finite-element model for the 26-m diameter Gilcreek VLBI antenna and showed that the change in path length could be up to 2.4 mm. This causes a change in the observed differential delay, which in turn causes a change in the estimated geodetic parameters, particularly local Up. Beginning in the early 2000s the deformation of several VLBI antennas was directly measured using surveying techniques, leading to a total of six antennas for which we had models. The change in path length can be as large as 97 mm (as for the 100-m antenna at Effelsberg). First measurements on VGOS antennas show that the path length changes of these modern antennas are on the order of just 1 mm. In preparation for ITRF2020, all IVS Analysis software was modified to be able to incorporate modelling the effect of gravitational deformation.

At the time of the IVS submission to ITRF2020 the IVS used gravitational deformation models of the following six antennas: EFLSBERG, GILCREEK, MEDICINA, NOTO, ONSALA60, and YEBES40.

Loading Effects

The standard IVS analysis includes the effect of pressure loading. Since the other space geodetic techniques do not routinely include these effects, this meant that our estimates of station position were not consistent with other techniques. This is an issue when you are trying to combine data from several techniques. After consultation with the IERS, the IVS came up with the following compromise. We would do our analysis as we normally do, but we would modify the SINEX files that we produced so that loading effects could be removed *a posteriori*. This essentially involves adding in an additional normal equation vector which is due entirely to pressure loading.

ITRF2020

Much of the focus of the last two years was related to the preparation for and participation in the IVS submission for ITRF2020. Eleven Analysis Centers using seven software packages submitted SINEX files. The IVS 2020 submission differed from the 2014 submission in several key ways, mostly modeling changes:

- ITRF2014 used a model from 1996 for High-Frequency EOP. This model had begun to show its age, and the IERS recommended use of a new model due to Desai and Sibois (2016), based on Topex data.
- The IVS also adopted the new IERS pole-tide model.
- This submission included the effects of galactic aberration using the model recommended by IVS Working 8 on Galactic Aberration (MacMillan et al., 2019).
- This submission included models for the effects of gravitational deformation for six antennas: EFLSBERG, GILCREEK, MEDICINA, NOTO, ONSALA60, and YEBES40M. Unfortunately, we were not able to include the model for NYALES20 which became available too late.
- Unlike previous submissions, this submission included the effect of pressure loading. In order to be able to combine the results with other techniques that do not routinely apply pressure loading effects, the SINEX files were modified so that pressure loading could be backed up.
- Source positions. The IVS contribution to ITRF2020 included source coordinates.

The IVS community vetted ITRF2020P, the preliminary version of ITRF2020. There was general agreement that ITRF2020 agreed much better with the VLBI data then ITRF2014, particularly for stations which had been scarcely observed at the time of ITRF20214.

Reprocessing of VLBI data and Transition to ITRF2020

The IERS requested that all services transition to using ITRF2020 in early 2023. For the IVS this primarily meant using the Post-Seismic-Deformation models from ITRF2020 instead of the corresponding models from ITRF2014. A priori station positions and velocities were derived from VLBI only reference frame solutions because the values of a few sites in ITRF2020 were bad because of a lack of data, and because of additional VLBI sites became operational after the data was submitted to ITRF2020.

After the submission to ITRF2020, additional antennas were surveyed to model the gravitational deformation. These antennas were: NYALES20, ONSA13NE, ONSA13SW, WETTZELL, WETTZ13S, and WETTZ13N. Since NYALES20 and KOKEE are structurally identical, we can use the same model for both.

When the IVS reprocessed all of the sessions, we used the expanded list of gravitational deformation models. The effect on the reference frame is primarily a (constant) change in the local Up coordinate of the antennas with gravitational deformation models.

Transition to new Masterfile Format and Naming Convention

The naming convention used by the IVS was devised in 1979, 20 years prior to the formation of the IVS. As the number of sessions has increased, various deficiencies of the original naming scheme became apparent. Because of this the IVS transitioned to a new naming scheme on 2023-01-01. Initially all sessions prior to this date will use the original naming scheme, and all sessions that occur in 2023 and later will use the new naming scheme. At some time in the future, we plan on renaming the earlier sessions.

Scale Drift of VLBI with Respect to ITRF2020

The IERS noticed a scale drift in the VLBI data with respect to ITRF2020. This scale drift starts around 2012-2014. JPL noticed a similar effect. Because of this, VLBI data after this time was excluded from setting the scale for ITRF2020.

The IVS formed an ad-hoc working group to study this issue. Although the issue is not entirely resolved, the most promising hypothesis is that this is due to a few stations which exhibit unmodeled non-linear motion in the local-up coordinate. Investigation in this area will continue until we have a satisfactory answer.

Source Structure

The ideal VLBI source is strong and point-like. In reality, all sources have structure. This causes changes in the observed delay. If not correctly accounted for, this will show up as noise in the measurements. In the past few years, several groups have looked at the effect of source structure. Although this is still very much an R&D effort, the results look promising. We anticipate that future VLBI analysis software will include the effect of source structure.

VGOS Intensive data used in operational IERS EOP products.

The IVS Intensive sessions are short-duration (typically 1 hr) small network (2-4 stations) designed primarily to measure UT1 with low latency. The IVS schedules Intensive sessions every day using legacy S/X stations. The turnaround time from scheduling to analysis is typically under 24 hours. UT1 estimates from these sessions are used by the IERS RS/PC at USNO in generating their EOP time series.

During the last four years several groups have investigated using VGOS stations to do Intensive measurements. These include the Onsala–Ishioka baseline, the McDonald-12M – Wettzell-13M baseline, the AuScope array plus Hobart, and the Kokee12M–Wettzell 13M baseline. In April 203 the IERS RS/PC at USNO began using data from the Kokee12M-Wettzell13 baseline in the RS/PC product. This is the first time that VGOS data has been used in an operational near real time product.

Technology Development

Progress was made in realizing the goals of the next-generation VLBI system, the VLBI Global Observing System (VGOS). A network of 8–12 stations observed in 24-hour sessions of the VGOS-OPS series using a weekly cadence in 2022 and on a two-weekly basis during other times of the report period. An operational VGOS Intensive series on the baseline Kokee Park to Wettzell was established with five sessions per week (on weekdays). It is anticipated that the global network will grow in the coming years to almost 30 stations (and possibly beyond) and will eventually replace the legacy S/X system as the IVS production system.

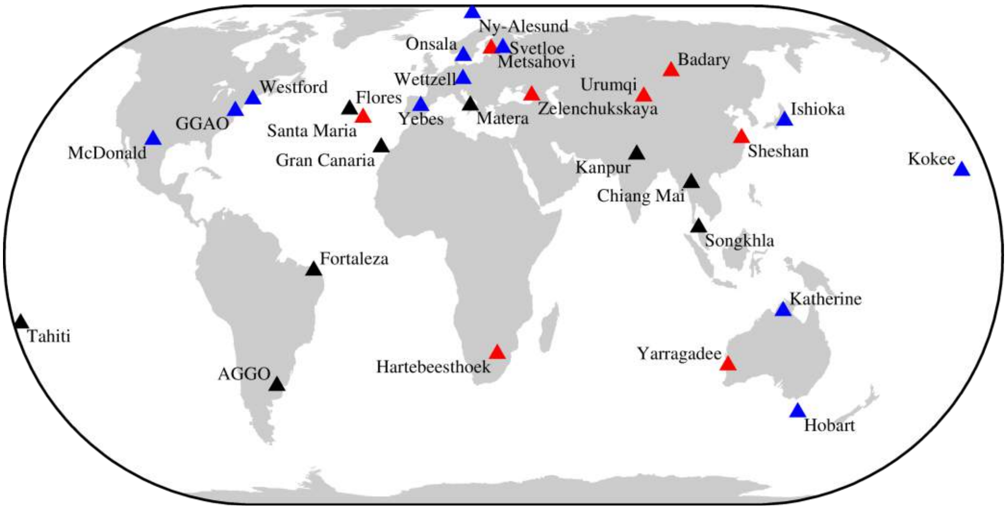

Figure 2. Rollout status of the VGOS station network: ▲ operational station, ▲ antenna built, signal chain work in progress, and ▲ in planning stage.

As part of the modernization process, other infrastructure components of the VLBI processing chain have been further developed as well, including the VGOS correlation and post-processing capabilities as well as VGOS data analysis. At the end of 2020 and the beginning of 2021, several correlators (Washington, Bonn, Vienna, Shanghai) began processing VGOS sessions in addition to the Haystack correlator. Onsala started processing VGOS Intensive sessions in 2020/2021 and a new correlator was established at Wettzell in 2022. Additional efforts are underway at the University of Tasmania and in Tsukuba.

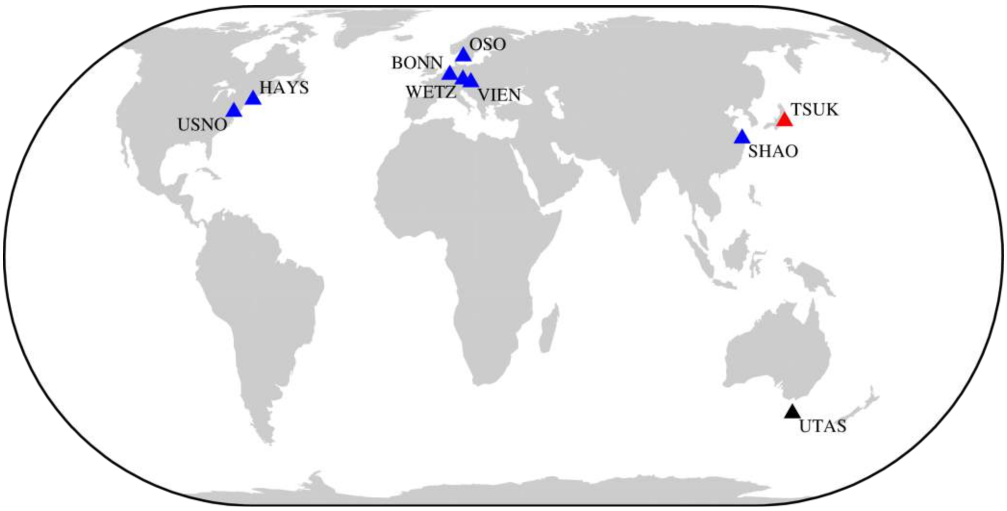

Figure 3. Rollout of VGOS correlation capabilities: ▲ operational correlator, ▲ under verification, and ▲ future correlation center.

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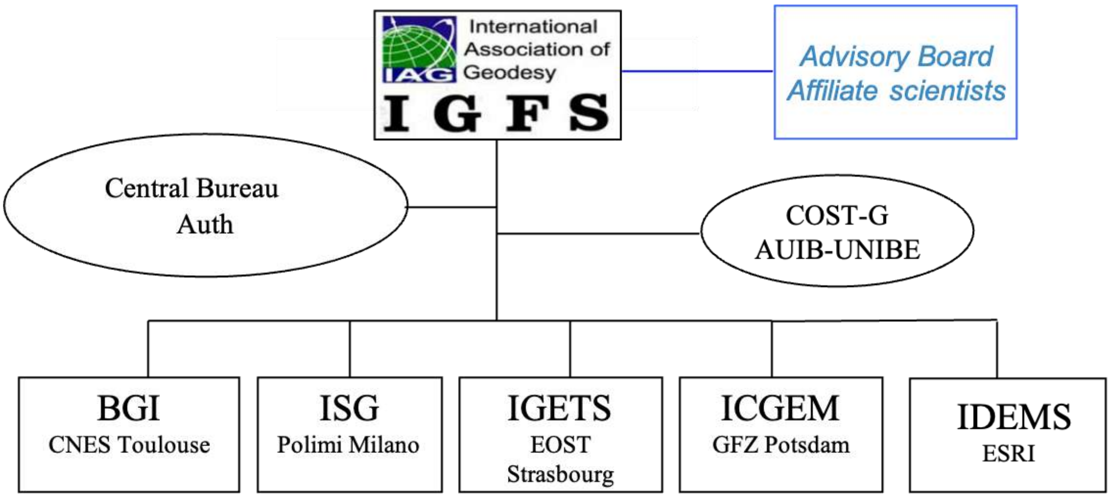
International Gravity Field Service - IGFS

http://igfs.topo.auth.gr/
Chairman: Riccardo Barzaghi (Italy)
Director of the Central Bureau: Georgios Vergos (Greece)

The IGFS structure

The present day IGFS structure is summarized in the following chart



BGI (Bureau Gravimetrique International), Toulouse, (F)
ISG (International Service for the Geoid), POLIMI, (I)
IGETS (International Geodynamics and Earth Tides Service), EOST, Strasbourg, (F)
ICGEM (International Center for Global Earth Models), GFZ, Potsdam, (D)
IDEMS (International Digital Elevation Model Service), ESRI, Redlands, CA (USA)
COST-G (International Combination Service for Time-variable Gravity Fields), AIUB, Bern (CH)
Auth (Aristotle University of Thessaloniki), Thessaloniki (GR)

IGFS coordinates the activities of the Gravity Services (BGI, ISG, IGETS, ICGEM, IDEMS) and of its Product Center COST-G via its Central Bureau at the Aristotle University of Thessaloniki (Greece) and its Advisory Board. In the 2020-2023 period, the members of the IGFS Advisory Board are:

- H. Abd-Elmotaal (Egypt)
- J.-P. Barriot (French Polynesia)
- S. Bonvalot (France)
- S. Bettadpur (USA)
- R. Forsberg (Denmark)
- Y. Fukuda (Japan)
- T. Gruber (Germany)
- J. Huang (Canada)
- E. S. Ince (Germany)
- A. Jäggi (Switzerland)
- K. Kelly (USA)

- U. Marti (Switzerland)
- T. Otsubo (Japan)
- R. Pail (Germany)
- M. Reguzzoni (Italy)
- M. G. Sideris (Canada)
- L. Sanchez (Germany/Columbia)
- I. N. Tziavos (Greece)
- L. Vitushkin (Russia)
- Y. Wang (USA)
- H. Wziontek (Germany)

This structure of IGFS proved to be effective for managing the interaction among the Gravity Services that were able to provide the required gravity products.
IGFS was also active in promoting the contacts among the Gravity Services and GGOS, namely with the GGOS Bureau of Products and Standards, the GGOS Bureau of Networks and Observations and the GGOS Focus Area on Unified Height System.
Finally, IGFS was also involved in the activities of the following IAG Joint Working and Study Groups

- JWG GGOS 0.1.3: Implementation of the International Height Reference Frame (IHRF) (joint with GGOS, Commission 1, Commission 2, ICCT)
- JWG GGOS: Towards a consistent set of parameters for the definition of a new GRS (joint with GGOS, Commissions 1, Commission 2, ICCT, IERS Committee on EGV)
- JSG T.26: Geoid/quasi-geoid modelling for the realization of the geopotential height datum (joint with Commission 2, GGOS, ICCT)
- JSG T.37: Theory and methods related to the combination of high resolution topographic/bathymetric models in geodesy (joint with ICCT, IDEMS)

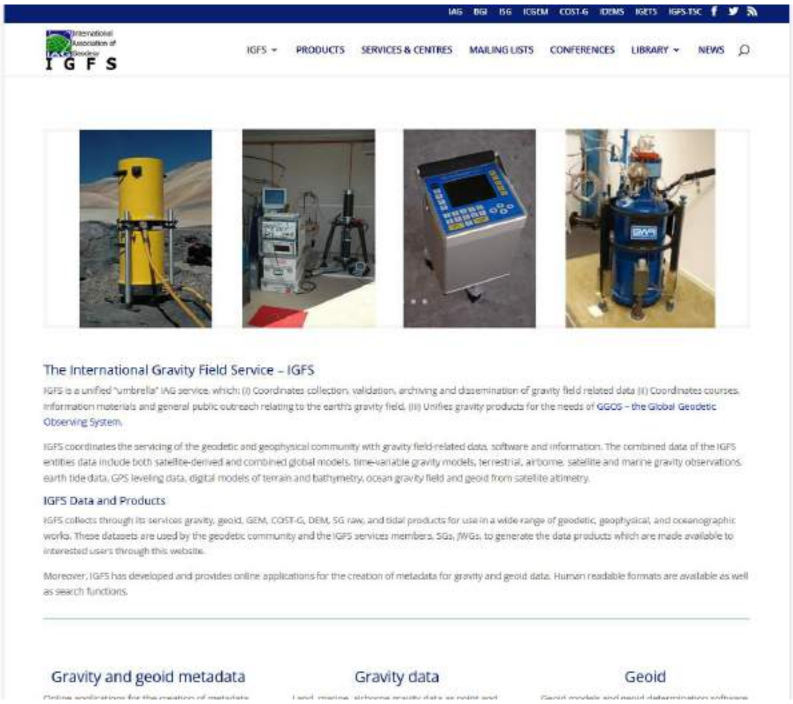
Overview

In the period 2020-2023, the main IGFS activities have been addressed to the improvements of the internal communication among the Gravity Services, to strengthen the connection with GGOS and Commission 2 and to manage the organization of projects and conferences. At the same time, some other standard activities within IGFS have been carried out, such as e.g., to coordinate exchange of software and data for gravity field estimation.
While these activities have been performed in a direct way by the related Gravity Services, though supervised and harmonized by IGFS, the International Combination Service for Time-variable Gravity Fields **(**COST-G) has produced its solutions directly on behalf of IGFS. This is a remarkable activity, providing time variable gravity field solutions that are stored at ICGEM.
As mentioned, another fundamental part of the IGFS actions is performed in connection with GGOS. IGFS actively participated to the GGOS Consortium and its Chair is one of the GGOS-CB members. Through these connections, the Gravity Services activities are documented to GGOS also in order to have a closer cooperation with the Geometric Services of IAG. This also led to the establishment of standards on gravity metadata (based on the GGOS Bureau of Products and Standards recommendations) that were implemented in the IGFS web page. The metadata service refers to both gravity data (http://igfsapps.topo.auth.gr/gmetacreate.php), geoid models in cooperation with ISG

(http://igfsapps.topo.auth.gr/Nmetacreate.php) and a μeta-Locator for existing gravity data sources.
IGFS actions in GGOS were also performed within the framework of the Focus Area on "Unified Height System" for the ongoing definition and establishment of the International Height Reference System/Frame (IHRS/IHRF). This was a main activity for IGFS as the IHRS/IHRF should transform, within the coming period 2013-2017 into a service, and discussions on this materialization through the IGFS are already ongoing.
As previously mentioned, the cooperation between IGFS and IAG Commission 2 is based on the activities of Joint Working and Study Groups that have been established at the last IAG/IUGG Assembly in Montreal (2019) (see the list above).
Also, IGFS and Commission 2 co-organized the 3rd Joint Commission 2 and IGFS Meeting, the "Gravity, Geoid and Height Systems 2022". This is the meeting usually held every two years, following those in Thessaloniki, Greece (September 19-23, 2016) and in Copenhagen, Denmark (September 17-21, 2018). Due to the Covid19 pandemic it was not possible to organize the event in 2020, but it was rather organized in September 2022 by the University of Texas at Austin.
Finally, IGFS is managing the GEOMED2 project, an ESA supported project. This project, based on the co-operation among the IGFS Services (i.e. BGI, ISG, ICGEM and IDEMS), aims at computing the geoid and the DOT in the Mediterranean Sea.

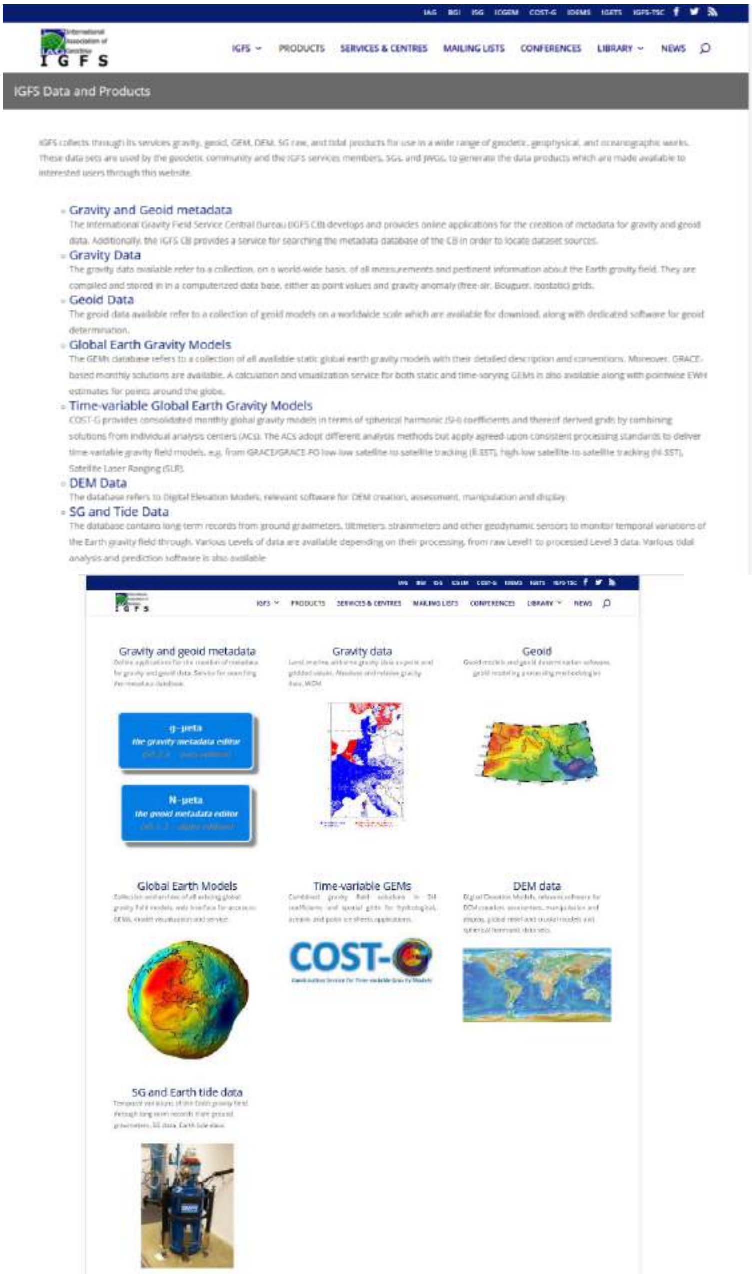
The IGFS Central Bureau and the IGFS web page

With the International Gravity Field Service (IGFS) Central Bureau (CB) being hosted at the Department of Geodesy and Surveying (DGS) of the Aristotle University of Thessaloniki (AUTH) since April 2016, in the period 2020-2023 an effort was put forth in order to update its presence in the web and make the IGFS data and products more visible to the interested scientific and user community. To that respect, the IGFS webpage (igfs.topo.auth.gr) has been updated targeting especially the available IGFS services products.



The updated IGFS webpage since June 2023.

Given the need to promote the work carried out by IGFS Services and Centers, a new updated webpage has been recently created focusing more on the data and products availability, so that interested users can acquire them directly from the available portals (see figures below). In the new webpage layout, the availability of gravity, geoid, time-variable gravity, GEM, DEM, SG and tide data through the IGFS services portal is more visible, while a news section has been created as well to direct to IGFS related conferences, updates, etc..



The updated IGFS webpage, since June 2023.

Moreover, given the update of the GGOS webpage and web front end, the IGFS CB has updated the IGFS presence, as well as that of all IGFS Services and Product Center.

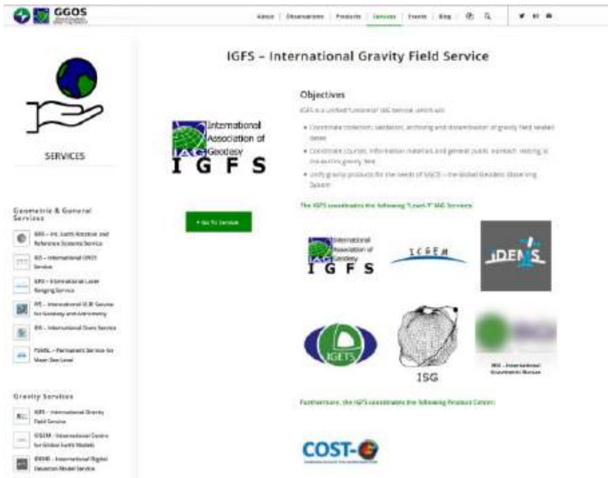
Furthermore, two mailing lists have been developed within IGFS CB:

igfs-products@lists.auth.gr: the scope of this list if to provide updated information on the new data and products that become available from the IGFS Services. New data and products such as GEMs, DEMs, gravity, geoid, SG, tide, etc. will be posted and shared to all list members.

Subscription to the list is free. The list can be accessed at https://lists.auth.gr/sympa/info/igfs-products

igfs-standards@lists.auth.gr: the scope of this list is to provide a forum for idea exchange within the IGFS CB, AB and IAG Commission2 SC, towards the introduction of new and the update of old IGFS conventions and standards. The igfs-standards mailing list is open to all, but pending approval of the IGFS CB, given the more administrative nature of the list. The list can be accessed at https://lists.auth.gr/sympa/info/igfs-standards

Finally, IGFS has gained presence in public media, both in Facebook (@InternationalGravityFieldService) and Twitter (@igfscb) in order to increase both its visibility and the influence of its products.



The recently updated IGFS presence in the GGOS webpage, online since May 2021.

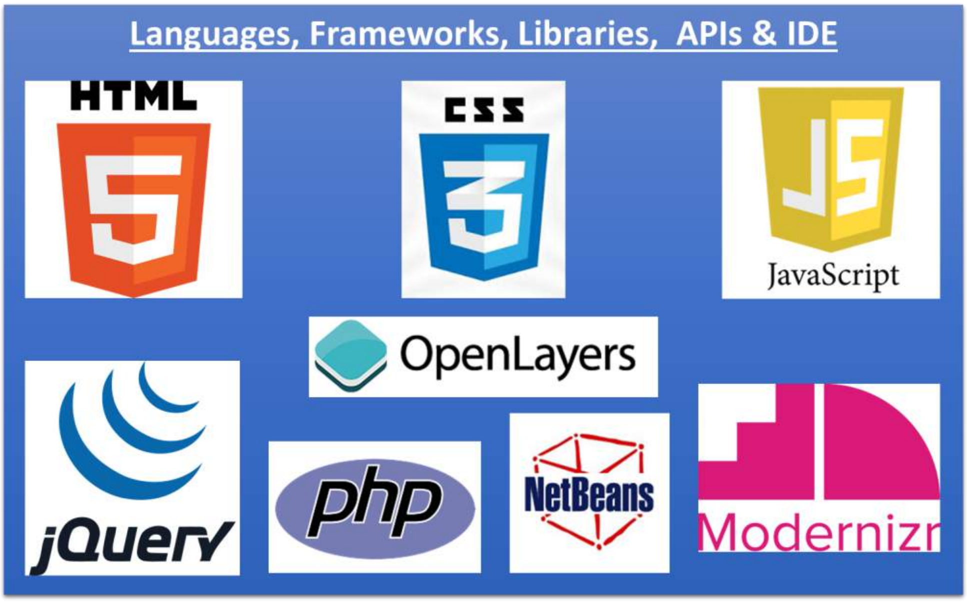
IGFS and GGOS

- Gravity metadata structure g-μeta

The IGFS CB has developed, within the IGFS web-page, an IGFS-applications front-end where three main components have been established. The first one refers to the generation of metadata for both relative and absolute gravity observations, either original and gridded ones. The rest refers to metadata for geoid models as well as a geodatabase and geolocator for the visualization of all products offered by IGFS and its services.

IGFS generated a dedicated web-server hosted by a Virtual Machines Host (VMWare) of the Aristotle University of Thessaloniki targeting at minimum downtime, automatic backup and being monitored automatically for threats. The main technologies and modules employed for the metadata generation are HTML5, CSS3, java scripting, jquery, php, netbeans and Modernizr. The application has succeeded to be lightweight, compatible with portable devices, adhere to user needs and extensible.

The IGFS applications front-end (g-μeta, N-μeta and μeta-Locator)



Technologies and modules used for the development of the IGFS metadata

Moreover, it provides code in popular programming languages for integrating the functionality of g-μeta and N-μeta in existing applications. The g-μeta includes both mandatory and optional fields related to the gravity data acquisition standards, processing methodology, tide corrections applied, owner information, geospatial referencing etc.. It requires a complicated validation procedure carried out both on the client and the server side.

Five main categories have been foreseen as: 1) Identification information, 2) Standards and conventions, 3) Data and Data quality information, 4) Distribution information and 5) Metadata reference information. All categories comply with ISO19115-1 adopted also by GGOS. The sub-categories within each main field are presented in the following figures.

1.Identification Information
Citation
Description
Time Period of Content
Status
Spatial Domain
Keywords
Constraints
Points of Contact
Security Information

2.Standards and Conventions
General Standards and Conventions
Earth's Gravity Field
Earth Orientation Parameters
Tidal Conventions
Station Coordinates and corrections for absolute gravity

3.Data and Data Quality Information	
Attribute Accuracy	Gravity Data Type
Logical Consistency	Gravity Accuracy
Completeness Report	Position Accuracy

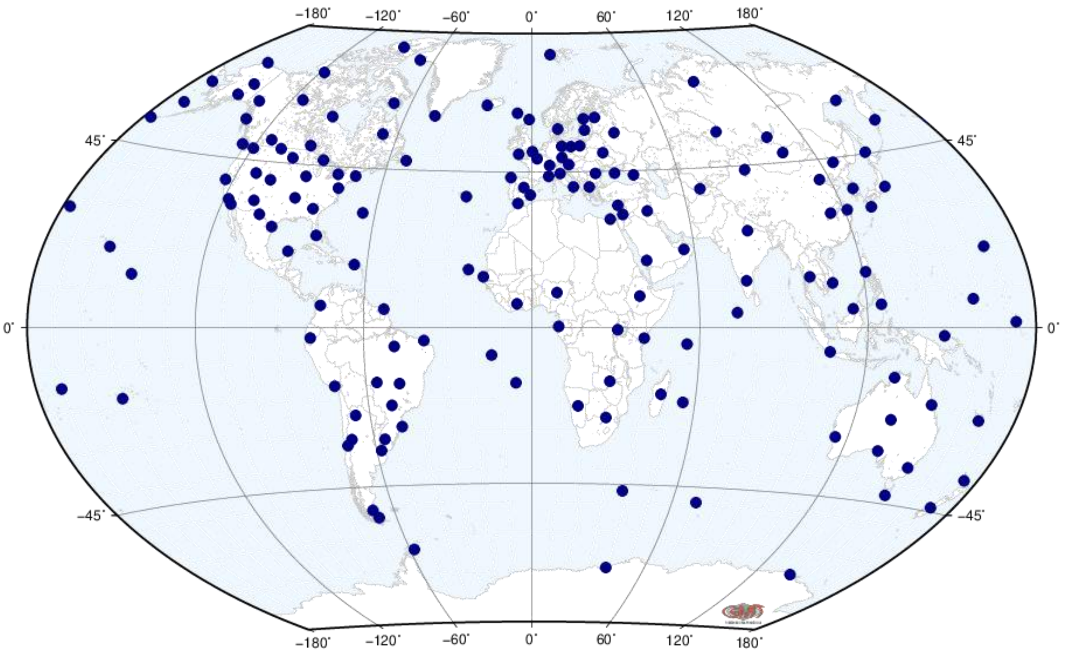
4.Distribution Information
Distributor
Standard Order Process

5.Metadata Reference Information
Metadata Creation Date and Creator Information
Metadata Prototype Information

Implemented categories within the IGFS g-μeta metadata generator.

- *The International Height Reference System/Frame*

The International Height Reference System/Frame (IHRS/IHRF) is one of the key issues in IAG and GGOS. As it is well known, IAG provides the scientific community with the ITRSnn/ITRFnn. This global reference frame is a fundamental infrastructure that allows monitoring e.g geodynamical phenomena such as deformations of the Earth crust in seismogenic areas. On the other hands, a corresponding global physical height reference system/frame is still missing. In 2015, at the IAG/IUGG General Assembly in Prague, IAG established the IHRS/IHRF through its resolution n°1. From that moment on, this project started and is ongoing. At the IAG/IUGG General Assembly in Montreal (2019), the project was further implemented and is now in its realization phase. The draft design of the IHRS/IHRF has been set up (see the figure below) and the computation of the W(P) values in the network points is currently performed.



The IHRF network design (https://ggos.org/item/height-reference-frame/#learn-this)

IGFS has been actively involved in the definition of such a system and strictly co-operated with GGOS focus area on "Unified Height System" and Commission 2 for that. IGFS contributed also to the papers that have been published on this subject (see reference below). At the same time, IGFS is involved in the definition of the Global Geodetic Reference System/Frame (GGRS/GGRS) that includes the definition of the new global gravity reference system that will replace IGSN71, a project that is strictly connected to the IHRS/IHRF topic. For the next period 2023-2027 IGFS is actively planning the realization of the IHRS/IHRF into a service that will be hosted and its products be distributed via the IGFS web-services and front-end.

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R. Barzaghi, C. I. De Gaetani, B. Betti. Rend. Fis. Acc. Lincei (2020), https://doi.org/10.1007/s12210-020-00948-0

Strategy for the realization of the International Height Reference System (IHRS)
L. Sánchez, J. Ågren, J. Huang, Y. M.Wang, J. Mäkinen, R. Pail, R. Barzaghi, G. S. Vergos, K. Ahlgren, Q. Liu. Journal of Geodesy (2021), 95:33, https://doi.org/10.1007/s00190-021-01481-0.

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Barzaghi R., Sánchez L., Vergos G.: Operational infrastructure to ensure the long-term sustainability of the IHRS/IHRF. European Geosciences Union (EGU) General Assembly 2020, Vienna, Austria, 10.5194/egusphere-egu2020-7961, 2020.

Barzaghi R and Vergos GS (2022) Practical implementation of the IHRF employing local gravity data and geoid models. Presented at the 2022 EGU General Assembly, May 23 – 27, Vienna, Austria.

Sánchez L., Barzaghi R.: Activities and plans of the GGOS Focus Area Unified Height System. European Geosciences Union (EGU) General Assembly 2020, 10.5194/egusphere-egu2020-8625, 2020.

Sanchez, L., Huang, J., Barzaghi, R., and Vergos, G. S.: Towards a Global Unified Physical Height System, EGU General Assembly 2021, online, 19–30 Apr 2021, EGU21-1500, https://doi.org/10.5194/egusphere-egu21-1500, 2021.

Sanchez, L., Huang, J., Barzaghi, R., and Vergos, G. S.: GGOS Focus Area Unified Height System: achievements and open challenges, IAG Sceintific Assembly 2021, online, June 28 – July 2, 2021.

Sanchez, L., and IHRF Computation Team: Status of the International Height Reference Frame (IHRF), IAG Sceintific Assembly 2021, online, June 28 – July 2, 2021.

Sanchez, L., and IHRF Computation Team: Status of the International Height Reference Frame (IHRF), Presented at the "Gravity, Geoid and Height Systems 2022 – GGHS2022" IGFS and Commission 2 Confeernce, Septmeber 12-14, 2022, Austin, TX, USA.

Sánchez L, Huang J, Barzaghi R, Vergos GS (2022) Towards an international standard for the precise determination of physical heights. Presented at the 2022 EGU General Assembly, May 23 – 27, Vienna, Austria.

Sánchez L, Huang J, Barzaghi R, Vergos GS (2022) Advances in the determination of a global unified reference frame for physical heights. Presented at the IAG Commission 1 "Reference Frames for Applications in Geosciences" – REFAG2022 Conference, October 17-20, Thessaloniki, Greece.

Sanchez L, Barzaghi R, Vergos GS (2023) Operational infrastructure to ensure the long-term sustainability of the IHRS/IHRF. Presented at the 28th IUGG General Assembly, July 11-20, 2023, Berlin, Germany.

Sanchez L, Barzaghi R, Huang J, Ågren J, Vergos GS and the IHRF Computation Team (2023) A first solution for the International Height Reference Frame (IHRF). Presented at the 28th IUGG General Assembly, July

Sanchez L, Huang J, Barzaghi R, Vergos GS (2023) Advances in the determination of a global unified reference frame for physical heights. Presented at the 28th IUGG General Assembly, July 11-20, 2023, Berlin, Germany. Presented at the 2023 EGU General Assembly, April 23 – 28, Vienna, Austria.

Recent IGFS activities

- 3rd Joint IGFS and Commission 2 Meeting "Gravity, Geoid and Height Systems 2022"

As previously mentioned, the organization of the 3rd Joint IGFS and Commission 2 Meeting was held in September 2022 in Austin, Texas. The topics of the meeting referred to:

- Current and future satellite gravity missions
- Global Gravity Field Modelling
- Local/regional gravity field modelling
- Absolute, Relative and Airborne Gravity - Instrumentation, Analysis, and Applications
- Height systems and vertical datum unification
- Satellite altimetry and applications
- Gravity for Climate & Natural Hazards: Inversion, Modeling, and Processes

In total seven (7) sessions have been organized, spanning the three days of the conference with a total number of 77 oral and poster presentations. A hybrid, in-person and remote attendance has been planned in order to accommodate the needs of the participants. Work is undergoing in order to prepare the next meeting that will be held in person in the Fall of 2024.

- The Geomed2 Project

IGFS has proposed and managed the GEOMED2 Project that started in 2015. Although the project end was planned at the beginning of 2020, its deadline was shifted to the end of 2021 due to the COVID pandemic.

The main aim of the proposed GEOMED2 project is the determination of a high-accuracy and high-resolution geoid model for the Mediterranean Sea using land and marine gravity data, the most recent Global Geopotential Models and an *ad hoc* DTM/bathymetry model. The processing methodology is based on the well-known remove-compute-restore method

following both stochastic and spectral methods for the determination of the geoid and the rigorous combination of heterogeneous data. The main accomplishments of the project have been documented in the paper *GEOMED2: high-resolution geoid of the Mediterranean* (International Association of Geodesy Symposia. Springer, Berlin, Heidelberg, IAG, Kobe. DOI: https://doi.org/10.1007/1345_2018_33) by Barzaghi et al.
Further activities are planned in 2023-2027 that will be focused on refining the gravity database, computing new geoid solutions and deriving an updated estimate of the Mean Dynamic Sea Surface Topography over the whole Mediterranean Sea.
The project is based on the cooperation between IGFS related Services (BGI, ICGEM, ISG) and the following scientific institutions:

- Politecnico di Milano, Italy
- Aristotle University of Thessaloniki, Greece
- GET UMR 5563, Toulouse, France
- SHOM, Brest, France
- OCA/Géoazur, Sophia-Antipolis, France
- DTU Space, Kopenhagen, Denmark
- General Command of Mapping, Ankara, Turkey
- University of Zagreb, Zagreb, Croatia
- University of Jaén, Jaén, Spain

- The COST-G status and its activities

The International Combination Service for Time-variable Gravity Fields (COST-G) is the Product Center of IGFS for time-variable gravity fields. COST-G provides consolidated monthly global gravity models in terms of spherical harmonic (SH) coefficients and global grids by combining existing solutions or normal equations from COST-G analysis centers (ACs) and partner analysis centers (PCs). The COST-G ACs adopt different analysis methods but apply agreed-upon consistent processing standards to deliver time-variable gravity field models, e.g. from GRACE/GRACE-FO low-low satellite-to-satellite tracking (ll-SST), high-low satellite-to-satellite tracking (hl-SST), Satellite Laser Ranging (SLR).
COST-G performs a quality control of the individual contributions before combination and provides:

i) Combined gravity field solutions in SH coefficients (Level-2 products) derived from a weighted combination of individual normal equations (NEQs) supplied by the different ACs,
ii) Spatial grids and other high-level products (Level-3 products) of the Combined Solutions for hydrological, oceanic and polar ice sheets applications.

The Level-2 products are made available through the International Center for Global Earth Models (ICGEM, http://icgem.gfz-potsdam.de), the Level-3 products by the Information System and Data Center (ISDC, https://isdc.gfz-potsdam.de). The Level-3 products can be visualized at the COST-G Plotter (https://cost-g.org) and the Gravity Information Service (GravIS, http://gravis.gfz-potsdam.de) at GFZ Potsdam.

The initial Analysis Centers (AC), in charge of computing time-variable gravity field solutions from GRACE and GRACE-FO are: the Astronomical Institute at University of Bern (AIUB); the Centre National d'Etudes Spatiales (CNES); the German Research Centre for Geosciences (GFZ); the Institute of Geodesy, Graz University of Technology (IFG).
The current Partner Analysis Centers (PAC) are the Center for Space Research (CSR), and NASA's Jet Propulsion Laboratory (JPL).
Just recently, the Institut für Erdmessung of the Leibniz University of Hannover was selected to become also an AC and discussions with various Chinese processing centers such as IGG, SUSTech, Tongji, HUST or Whuhan to be become COST-G ACs are ongoing.

International Centre for Global Earth Models (ICGEM)

http://icgem.gfz-potsdam.de/home

Director: E. Sinem Ince (Germany)

Summary

International Centre for Global Earth Models (ICGEM) is one of the five services coordinated by the International Gravity Field Service (IGFS) of the International Association of Geodesy (IAG) and is part of the Global Geodetic Observing System (GGOS). The primary objective of the ICGEM service is to collect and archive all existing static and temporal global gravity field models and provide an online interactive calculation service for the computation of gravity field functionals freely available to the general public. The ICGEM Service has been hosted and funded by the GFZ-Potsdam German Research Centre for Geosciences and is supported by model developers and service users at an international level.

During the reporting period, 2019-2023, the ICGEM service continued to support scientific activities with additional features and regularly updated research data, in particular new satellite-only and combined static global gravity field models and operational temporal gravity field models. Both Release06 and Release 06.1 GRACE/GRACE-FO series from the three Science Data System centres have been received in this period. Relevant documentation has been uploaded on the temporal models page (http://icgem.gfz-potsdam.de/series) as they become available from the three Science Data System centres. Other operational monthly solutions from other groups have been uploaded in the temporal models page. COST-G (https://cost-g.org, Jaeggi et al. 2020) operational GRACE-FO series and their new release RL02 are also released in this reporting period. They are made publicly available with a DOI number assigned by the GFZ Library and Information Services (LIS). Moreover, CNES RL05 have been released under the same category, temporal gravity field models.

Other models published on ICGEM are: the most recent release of satellite-only models from ESA's GOCE mission, the most recent release of satellite-only mean global gravity field model from CNES, the combined static gravity field model expanded up to very high degree/order (5440) from Technical University of Munich, monthly solutions from ESA's Swarm mission, and finally topographic gravity field models of the Moon. The growing interest in models for other celestial bodies has increased the number of the models submitted to ICGEM in 2019-2020.

Similar to the existing ones, all recently submitted models are provided in the standardised format (Barthelmes and Förste, 2011) and in the form of spherical harmonic coefficients with possibility for DOI number assignment via GFZ Library and Information Services (see Ince et al. 2019). The ICGEM format documentation has been revised in 2023 and published in http://icgem.gfz-potsdam.de/ICGEM-Format-2023.pdf, Förste et al. 2023)

At the moment, **178** static gravity field models, **26** different kinds of temporal gravity field models from GRACE, GRACE-FO, Swarm and SLR measurements, and **10** topographic gravity field models are made available in the ICGEM service. The models are developed by different institutions and agencies and ICGEM keeps track of the documentation of such models by the support of model developers and GFZ Library and Information Services.

During the reporting period, evaluation data derived from GNSS/Levelling measurements have been updated and new data records have been added in the service.

In this documentation, the developments and activities during the previous reporting period 2019-2021 have been updated and extended to 2019-2023. For more information on the ICGEM Terms of References and Services, please refer to our previous IAG reports, our paper published in the Earth System Science Data (Ince et al. 2019, https://www.earth-syst-sci-data.net/11/647/2019), the Geodesist's Handbook 2020: Poutanen M, Rózsa S (2020): The Geodesist's Handbook 2020. J Geod 94, 109, https://doi.org/10.1007/s00190-020-01434-z, and ICGEM article in Encyclopaedia of Geodesy (Ince 2023).

Activities during the period of 2019-2023

1. Models

In 2016, the ICGEM Service was renewed from technical, administration and presentation perspectives. Via this renewed platform, development of a new flexible service for new applications became possible, specifically the GRACE-FO and future gravity missions. Following the launch of GRACE-FO and collection of new data, new products provided by the model developers have been made available under the temporal gravity field models page.

The static models (http://icgem.gfz-potsdam.de/tom_longtime), temporal models (http://icgem.gfz-potsdam.de/series) as well as topographic gravity field models (http://icgem.gfz-potsdam.de/tom_reltopo) can be found under Gravity Field Models. For the static gravity field models, users can access any reference related to the model that was provided to ICGEM on the same page in column 6 and can access the links to download the model coefficients in column 7, calculate the gravity functionals in column 8 and also visualise the geoid and gravity anomalies using the link provided in column 9 corresponding to the model. For the temporal models that are assigned DOI numbers, references and citation information can be found in the header part of the page. Relevant links to the model developer institution's page are indicated when available.

Newly available models during 2019-2023 are listed below.

Static Gravity Field Models (http://icgem.gfz-potsdam.de/tom_longtime):

- Tongji-GGMG2021S (d/o 300): Developed based on satellite only data retrieved from GRACE and GOCE (Cheng, J. et al. 2022)
- SGG-UGM-2 (d/o* 2190): Developed based on Altimetry, EGM2008, GRACE and GOCE data (Liang, W. et al. 2020)
- XGM2019e_2159 (d/o 5540, 2190, 760): Developed based on Altimetry, satellite-only combined model GOCO06s, ground measurements and topography information.
- GO_CONS_GCF_2_TIM_R6e (d/o 300): Developed based on GOCE-only and ground measurements in the polar areas (Zingerle et al. 2019).
- ITSG-Grace2018s (d/o 200): Developed based on GRACE measurements only (Mayer-Gürr, T. et al. 2018).
- EIGEN-GRGS.RL04.MEAN-FIELD (d/o 300): Developed based on satellite-only data (Lemoine J.M. et al. 2019).
- GOCO06s (d/o 300): Developed based on satellite-only data (Kvas, A. et al. 2021).
- GO_CONS_GCF_2_TIM_R6 (d/o 300): Developed based on GOCE only data (Brockmann JM

et al. 2021.

- GO_CONS_GCF_2_DIR_R6 (d/o 300): Developed based on satellite-only data (Förste et al. 2019).

*(d/o refers to degree and order).

Temporal Gravity Field Models:

Please note that the links from the interim report 2019-2021 have been updated.

- Monthly updated GRACE-FO RL06.1 solutions from the 3 Science Data System (SDS) centres CSR (60x60, 96x96), GFZ (60x60, 96x96), and JPL (60x60, 96x96) are operational and updated monthly on the following links:
  http://icgem.gfz-potsdam.de/series/10.5067/GFL20-MC061
  http://icgem.gfz-potsdam.de/series/01_GRACE/GFZ/GFZ Release 06.1 (GFO)
  http://icgem.gfz-potsdam.de/series/10.5067/GFL20-MJ061
- Monthly GRACE-FO solutions from the 3 Science Data System (SDS) centres CSR (60x60, 96x96), GFZ (60x60, 96x96), and JPL (60x60, 96x96) are operational and updated monthly on the following links:
  http://icgem.gfz-potsdam.de/series/01_GRACE/CSR/CSR Release 06 (GFO)
  http://icgem.gfz-potsdam.de/series/01_GRACE/GFZ/GFZ Release 06 (GFO)
  http://icgem.gfz-potsdam.de/series/01_GRACE/JPL/JPL Release 06 (GFO)
- Relevant GAX products are made available on the same pages
- CNES RL05 series, namely RL05 monthly gravity fields and RL05 10-day gravity fields are available on
  http://icgem.gfz-potsdam.de/series/03_other/CNES/CNES_GRGS_RL05/monthly
  http://icgem.gfz-potsdam.de/series/03_other/CNES/CNES_GRGS_RL05/10-daily
  Moreover, RL05 developed using standard unregularized Cholesky inversion is also made available on: http://icgem.gfz-potsdam.de/series/03_other/CNES/CNES_GRGS_RL05_CHOL
- Monthly GRACE-FO series (60x60, 96x96, 120x120) developed at the Institute of Theoretical Geodesy and Satellite Geodesy, TU GRAZ (Technical University of Graz) are added monthly on http://icgem.gfz-potsdam.de/series/03_other/ITSG/ITSG-Grace_op
- Monthly reprocessed GRACE series (60x60, 96x96, 120x120) from TU GRAZ are made available on http://icgem.gfz-potsdam.de/series/03_other/ITSG/ITSG-Grace2018/monthly
- Monthly GRACE-FO series developed at LUH (Leibniz University Hannover) are operational and updated monthly on http://icgem.gfz-potsdam.de/series/03_other/LUH/LUH-GRACE-FO-2020
- Monthly GRACE series developed at LUH are made available on http://icgem.gfz-potsdam.de/series/03_other/LUH/LUH-Grace2018
- COST-G (International Combination Service for Time-variable Gravity Field
  - Combined solutions and GAX products for GRACE are available on http://icgem.gfz-potsdam.de/series/02_COST-G/Grace_RL01
  - Combined solutions for GRACE-FO operational series are available on http://icgem.gfz-potsdam.de/series/02_COST-G/Grace-FO_RL01
  - GRACE-FO updated operational series from COST-G
    http://icgem.gfz-potsdam.de/series/02_COST-G/Grace-FO_RL02
  - Swarm monthly solutions and GAX products are available on http://icgem.gfz-potsdam.de/series/02_COST-G/Swarm

    - COST-G quarterly fitted signal models are operational and updated on http://icgem.gfz-potsdam.de/series/02_COST-G/FSM/quarterly
- Monthly operational series developed at AIUB (Astronomical Institute of University Bern) are available on: http://icgem.gfz-potsdam.de/series/03_other/AIUB/AIUB-GRACE-FO_op
- Monthly AIUB G3P gravity field solutions added on http://icgem.gfz-potsdam.de/series/03_other/AIUB/AIUB-G3P
- Hybrid models (6 different versions) developed in the Institute of Geodesy and Geoinformation, University Bonn based on SLR data are available on http://icgem.gfz-potsdam.de/series/04_SLR/IGG_SLR_HYBRID
- Monthly series (60x60, 90x90) developed at the Institute of Geophysics, HUST (Huazhong University of Science and Technology) are available on http://icgem.gfz-potsdam.de/series/03_other/HUST/HUST-Grace2020
- Monthly series of combined HLSST and SLR solutions developed at Quantum Frontiers are available on http://icgem.gfz-potsdam.de/series/03_other/QuantumFrontiers/HLSST_SLR_COMB2019s
- Monthly series developed at Tongji University are available on http://icgem.gfz-potsdam.de/series/03_other/Tongji/Tongji-Grace2018, http://icgem.gfz-potsdam.de/series/03_other/Tongji/Tongji-LEO2021
- Monthly series developed at CNES based on GRACE and SLR data are available on http://icgem.gfz-potsdam.de/series/03_other/CNES/CNES_GRGS_RL04

*References can be found under the links.

Topographic Gravity Field Models (http://icgem.gfz-potsdam.de/tom_reltopo)

- ROLI_EllApprox_SphN_3660 (ROLI_EllApprox_SphN_3660_plusGRS80): The model is developed at Department 1: Geodesy, GFZ-Potsdam based on Earth2014 global relief model is available on http://icgem.gfz-potsdam.de/tom_reltopo (Abrykosov O. et al. 2019).

Other Celestial Bodies (http://icgem.gfz-potsdam.de/tom_celestial)

- AIUB-GRL350A and AIUB-GRL360B (d/o 350): Gravity field models of the Moon derived from GRAIL measurements are available (Bertone S. et al. 2021)
- densityMoon (d/o 89): Moon density model derived from GRAIL measurements (Sprlak M. et al 2020)
- STU_MoonTopo720 (STU_MoonTopo720_plusNormalField) (d/o 2160): Moon gravity field model developed based on the Runge-Krarup theorem (Bucha B. et al 2019)
- sphericalRFM_MOON_2519 (SphericalRFM_MOON_2519_plusNormalField) (d/o 2519): Forward modelled gravity field model of the Moon (Sprlak M. et al. 2020)
- sphericalRFM_CERES_2519 (d/o 2519): Forward modelled gravity field model of Ceres (Sprlak M. et al. 2020)

Statistics of the ICGEM visits in 2019-2023, papers per year citing the ICGEM paper (https://essd.copernicus.org/articles/11/647/2019/) in May 2019 as the main reference of the service and its activities, and model downloads for 2022 are presented in Figures 1 to 5. Figure 1 shows the total ICGEM visits during the last 3,5 years, whereas Figure 2 represents the number of citations of the ICGEM paper (Ince et al. 2019) per year. The figures show that ICGEM has been continuously used for model downloads and calculation and visualisation services during the reporting period.

Figure 3 shows the list of downloaded static gravity field models and number of downloads. It shows that the topographic models are now also being downloaded with increasing rate. Moreover, high degree order combined static gravity field models are the most downloaded models for geodetic and geophysical research.

Figure 4 shows the downloads of temporal gravity field models generated by different institutions since late 2017. Users prefer to test and use different models for different applications. One needs to note that COST-G is a recent product centre of IAG, and its products are available since 2019.

Finally, Figure 5 shows that the ICGEM is particularly important in collecting temporal gravity field models developed by different institutions and agencies in addition to the three 3SDS. The users can download 3SDS models from different platforms (e.g., ISDC, GravIS) but the models from other groups are collected uniquely in the ICGEM. ICGEM provides access to Level 2 temporal gravity field models. Users who are interested in Level 3 products can refer to other services such as GravIS (http://gravis.gfz-potsdam.de/home) and the COST-G plotter (https://cost-g.org)

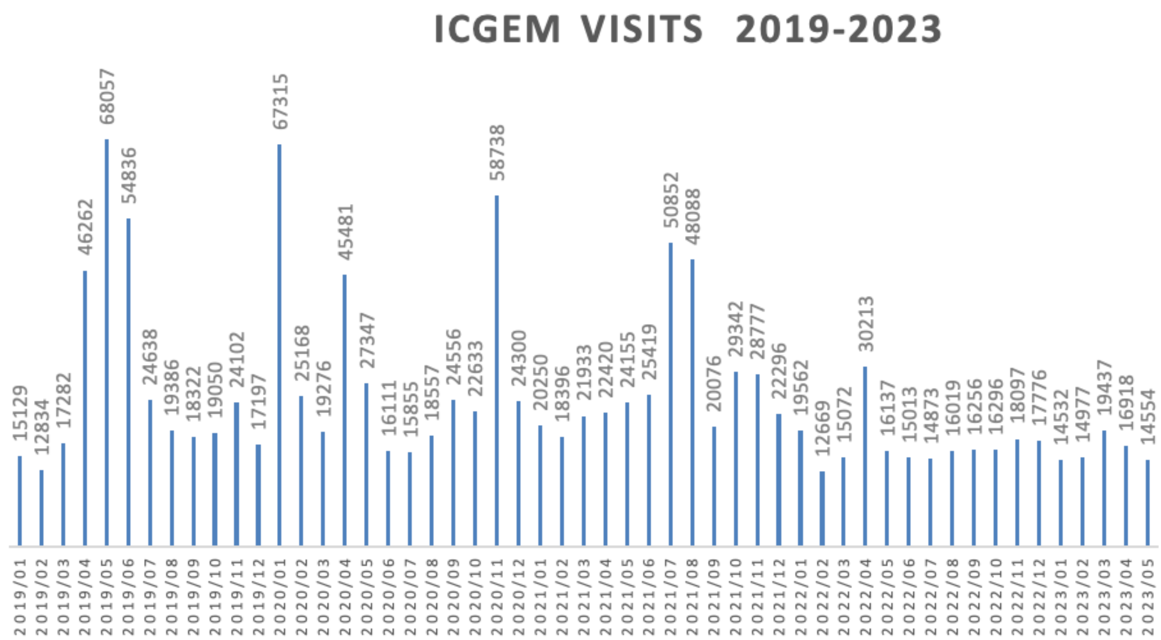

Fig. 1: Statistics of ICGEM visits in 2019-2023. The decrease after 2021 is due to the change of the algorithm used in the calculation of the visits.

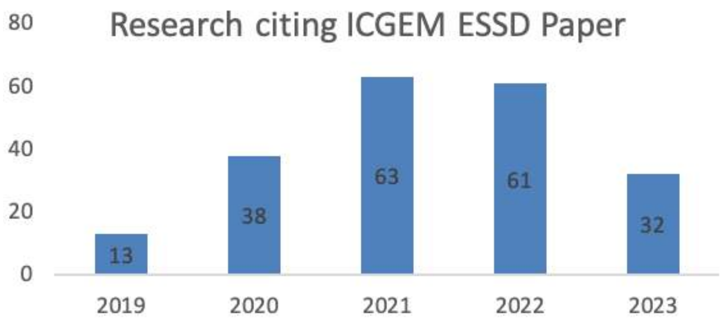

Fig. 2: Research citing the paper describing the ICGEM service (Ince et al. 2019) (Source: Googlescholar)

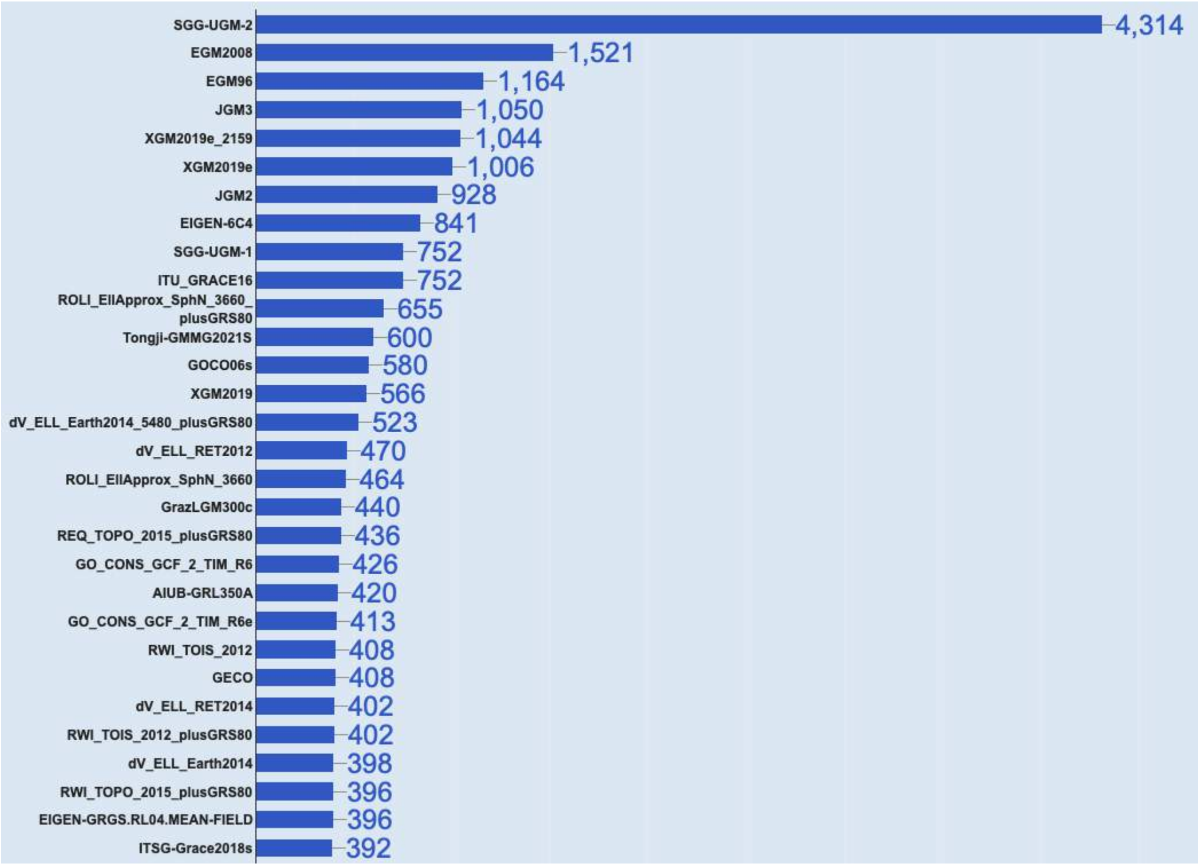

Fig. 3: Download of static and topographic gravity field models in 2022. The total number is 62231.

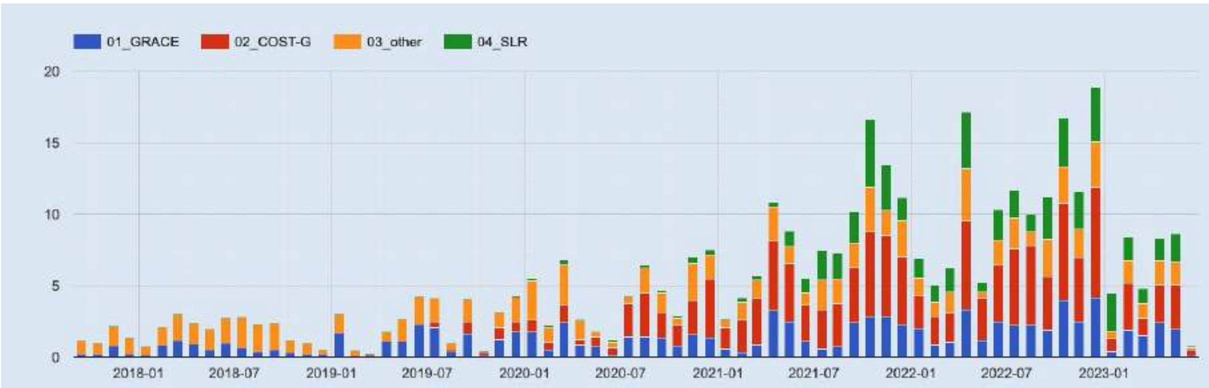

Fig. 4: Downloads of temporal gravity field models in 2017-2023. Note that COST-G started its activities in 2019. The number reported are complete downloads of the series.

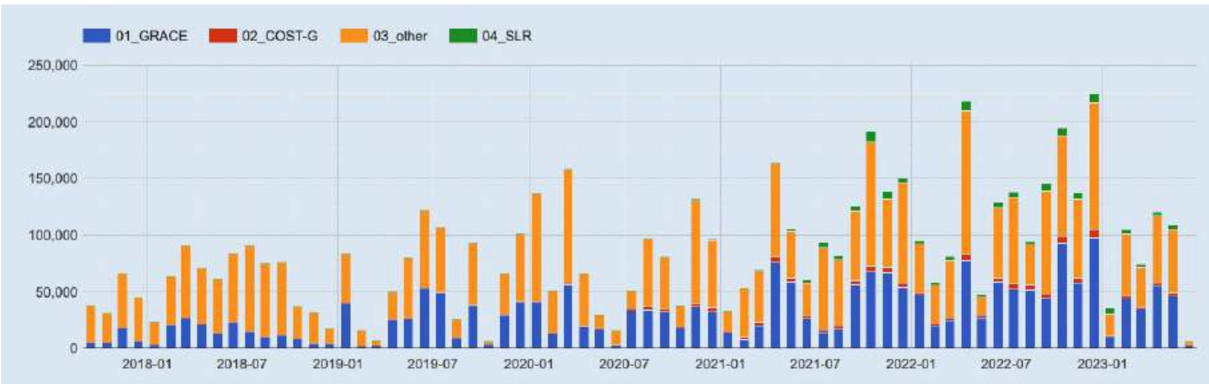

Fig. 5. Downloads of temporal gravity field models in 2017-2023. Note that COST-G started its activities in 2019. The stats show the download of singles files.

2. Calculation Service

Beside collecting and archiving Level 2 gravity field models, ICGEM provides gravity field functionals computed based on these models. Such functionals can be considered as Level 3 products that are useful for many Earth science related research topics. ICGEM offers calculations for grids and on any user defined points. Figure 6 shows the distribution of the most frequently calculated gravity field functionals in the Grid calculation service in 2020. Geoid, gravity anomaly, height anomaly, Bouguer gravity anomaly and gravity disturbance are the most frequently calculated functionals. ICGEM plans to provide readily computed high resolution grids of these gravity field functionals in the future.

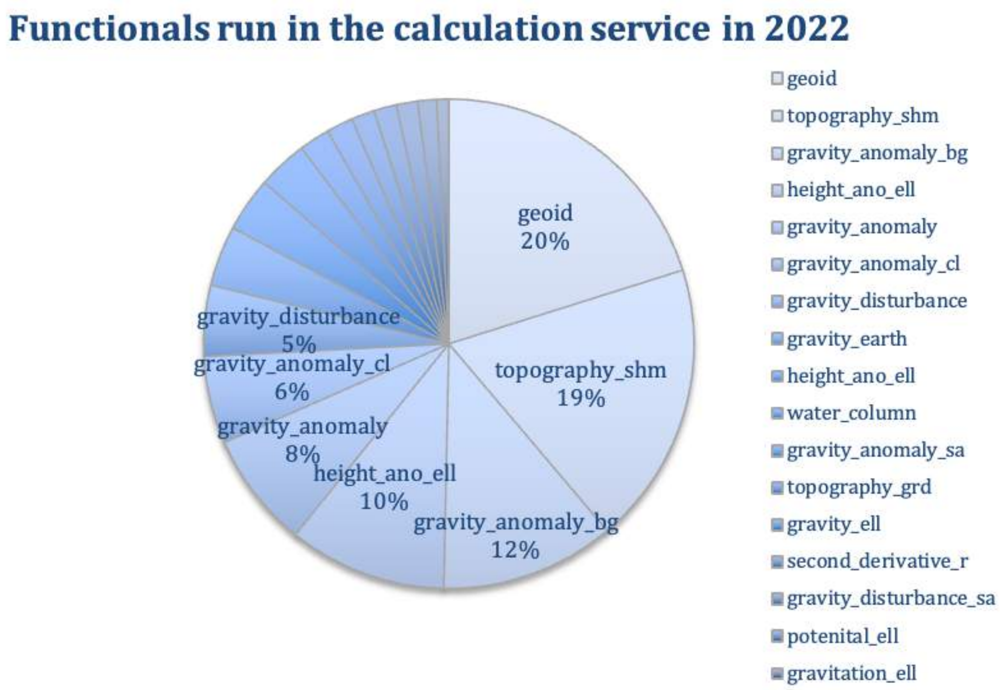

Fig. 6: Gravity field functionals requested for grid calculation in 2022.

3. Evaluation

Our evaluations for the static gravity field models are in both spectral domain and w.r.t. GNSS/levelling derived geoid undulations. Spectral comparisons of the models with respect to one of the latest combined models, EIGEN-6C4 can be found under "Spectral domain" (http://icgem.gfz-potsdam.de/evalm). The GNSS/levelling derived geoid undulation comparisons in 7 different countries and continents (USA, Canada, Europe, Australia, Japan, Brazil and Mexico) are provided in "GNSS/Levelling" (http://icgem.gfz-potsdam.de/tom_gpslev). The columns can be re-ordered by clicking on the title of the column.

In 2021, the comparison of geoid/quasi-geoid heights derived from the models with GNS/Levelling derived values from Australia, Brazil, and Canada has been updated and comparisons w.r.t. GNSS/Levelling derived geoid at benchmarks in Mexico have been added in the table representation (http://icgem.gfz-potsdam.de/tom_gpslev). The USA data are still to be updated after quality check analysis. The references for the GNSS/Levelling data used in the ICGEM Static gravity field model evaluation are the following:

- USA; Milbert, National Geodetic Survey, NOAA (1998)
- Canada; Marc Veronneau, Canadian Geodetic Survey, Natural Resources Canada, 2019

- Europe; Ihde et al., 2002
- Australia; W. E. Featherstone, N. J. Brown, J. C. McCubbine & M. S. Filmer (2018): Description and release of Australian gravity field model testing data, Australian Journal of Earth Sciences, DOI: 10.1080/08120099.2018.1412353
- Japan; Tokuro Kodama, Geospatial Information Authority of Japan, personal communication
- Brazil; Roberto Teixeira Luz and Sonia Costa, Brazilian Geography and Statistics Institute (IBGE), 2019
- Mexico; National Institute of Statistics and Geography (INEGI), 2019

We acknowledge the contribution of these institutions to the scientific evaluation of the static global gravity field models and we welcome similar datasets from all interested colleagues.

4. DOI Service

DOI Service was developed as a request by the user community in cooperation with GFZ Data Services. This makes it possible to refer in publications to the most recent dataset, instead of referring to a paper that described a previous version of the dataset. To reduce the heterogeneity in data documentation for static global gravity field models, standardised metadata templates for describing the models were developed. At the moment, all models with assigned DOIs are published under the Creative Commons Attribution 4.0 International Licence (CC BY 4.0). Since its implementation in late 2015, we have assigned DOIs to more than 25 static and various temporal global gravity field models, mostly at the time of their first publication via ICGEM.

5. Documentation

The online documentation section of the ICGEM Service contains five subsections together to support the scientific community and user interaction. This ensures that the explanation, data, calculation and references are available at the same place. These five subsections are: Frequently asked questions, theory, references, latest changes, and a discussion forum with regular updates. This is separate from the documentation of individual models that is provided on ICGEM as discussed above. New model releases, new documentation, conference and symposium presentations and ICGEM's recent activities can be found in the ICGEM Home page and in the list of latest changes. All relevant sources are listed in the references.

6. User e-mail list

ICGEM user e-mail list has been active since July 2019 and has more than 150 subscribers. The User mailing list is indented to be used to update the community with the new products and changes and stimulate communication especially for early career scientists and users from diverse backgrounds. Users are welcome to send their questions and updates to the e-mail list at icgemusers@gfz-potsdam.de. We hope this platform will support the gravity field community and use of gravity field products and make each people feel more involved especially when it is not possible to meet in person. Please feel free to send your gravity related questions, comments, ideas to this e-mail list or to us directly icgem@gfz-potsdam.de. Please bring the platform to the attention of graduate students and encourage them to sign up for the mailing list.

7. Scientific events and presentation

ICGEM is a member of:

- Global Geodetic Observing System (GGOS),
- Member of GGOS DOI Working group with regular attendance to monthly meetings,
- Member of COST-G Directing Board and member of Essential Geodetic Variables.

Other scientific activities in 2019-2023 are as follows:

Ince, E. S. (2023). International Centre for Global Earth Models (ICGEM), Earth Series Sciences, Encyclopedia of Geodesy (to be added).

Angermann, D., Bock, Y., Bonvalot, S., Botha, R., Bradke, M., Bradshaw, E., Bruyninx, C., Carrion, D., Coetzer, G., Elger, K., Fridez, P., Ince, E. S., Lamothe, P., Navarro, V., Noll, C., Reguzzoni, M., Riley, J., Roman, D., Soudarin, L., Thaller, D., Yokota, Y., Amponsah, G., Blevins, S., Coloma, F., Craddock, A., Craymer, M., Damiani, T., Galetzka, J., Hippenstiel, R., Michael, P., Miyahara, B., Pearlman, M., Romero, N., Sellars, I., Sehnal, M., Tyahla, L. (2023): The world of DOIs for geodetic data – metadata recommendations and status report of the GGOS DOI Working Group - Abstracts, EGU General Assembly 2023 (Vienna, Austria 2023).

Elger, K., GGOS DOI Working Group (2022): News from the GGOS DOI Working Group - Abstracts, EGU General Assembly 2022 (Vienna, Austria and Online 2022). https://meetingorganizer.copernicus.org/EGU22/EGU22-10982.html

Elger K, Angermann D, Bock Y, Bonvalot S, Botha R, Bradke M, Bradshaw E, Bruyninx C, Carrion D, Coetzer G, Elger K, Fridez P, Ince ES, Lamothe P, Navarro V, Noll C, Reguzzoni M, Riley J, Roman D, Soudarin L, Thaller D, Yokota Y, Members A, Amponsah, G, Blevins S, Craddock A, Craymer M, Michael P, Miyahara B, Pearlman M, Romero N, Schwatke C, Sehnal M, Tyahla L (**2021**): News from the GGOS DOI Working Group - Abstracts, EGU General Assembly 2021 (Online 2021). https://doi.org/10.5194/egusphere-egu21-15081

Ince ES, Reißland S, Barthelmes F (**2020**): Sirgas Americas Symposium 2020, Gravimetry and Geoid, https://www.youtube.com/watch?v=VUeQvaHW1AY, invited talk.

Förste C, Ince ES, Reißland S, Elger K, Flechtner F, Barthelmes F (**2020**): The International Centre for Global Earth Models (ICGEM) - Abstracts, EGU General Assembly 2020 (Online 2020). https://doi.org/10.5194/egusphere-egu2020-3511

Ince ES, Reißland S, Barthelmes F and Elger K (**2019**): ICGEM- International Centre for Global Earth Models, Implemenation of the Global Geodetic Reference Frame (GGRF), Sep 16-19, 2019, invited talk

Ince ES, Barthelmes F, Reißland S, Elger K, Förste C, Flechtner F (**2019**): ICGEM – 15 years of Successful collection and Distribution of Gravity Field Models, Association Services and Future Plans, IUGG General Assembly, Montreal, Canada, July 8-18

Ince ES, Barthelmes F, Reißland S, Elger K, Förste C, Flechtner F (**2019**): New Features and Future Plans of the International Centre for Global Earth Models (ICGEM), (Geophysical Research Abstracts, Vol. 21, EGU2019-15513), General Assembly European Geosciences Union (Vienna 2019).

8. Upcoming G3 Browser

As mentioned previously, the ICGEM portal has been renewed in 2016 to accommodate new needs. The last remaining component of the previous ICGEM portal, G3 Browser, has now been upgraded and integrated into the existing ICGEM portal. The updated Browser will be released at IUGG2023. The G3 Browser computes time series of equivalent water height interactively and gives users the opportunity to compare different series and introduce corrections (e.g., GIA, C20) as well as compare the impact of various filters. The G3 Browser is complementary to existing services such as GFZ's GravIS portal (http://gravis.gfz-potsdam.de/home). GravIS provides ready-to-use products based on GFZ and COST-G solutions with applied corrections and filters. The ICGEM G3 Browser includes time series from other processing centres and institutions and different filtering options. Its main aim is to provide an educational portal for students, teachers and researchers.

Data Policy

Access to global gravity field models, derived products and tutorials, once offered by the centre, is unrestricted.

ICGEM Team

The staff is allocated part-time and responds to queries on a best-effort basis.
Elmas Sinem Ince
Sven Reißland
Christoph Förste

Point of Contact

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GFZ German Research Centre for Geosciences
Telegrafenberg, D-14473 Potsdam, Germany
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References

Barthelmes F (2013): Definition of Functionals of the Geopotential and Their Calculation from Spherical Harmonic Models: Theory and formulas used by the calculation service of the International Centre for Global Earth Models (ICGEM). Scientific Technical Report STR09/02, Revised Edition, January 2013. Deutsches GeoForschungZentrum GFZ, http://doi.org/10.2312/GFZ.b103-0902-26.

Barthelmes F, Förste C (2019): The ICGEM-format. Potsdam: GFZ German Research Centre for Geosciences, URL: http://icgem.gfz-potsdam.de/ICGEM-Format-2011.pdf, last access 30 January.

Barthelmes F, Koehler W (2012): International Centre for Global Earth Models (ICGEM). In: Dreves: The Geodesists Handbook 2012, Journal of Geodesy, 86(10): 932-934, https://doi.org/10.1007/s00190-012-0584-1.

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Bucha B, Hirt C, Kuhn M (2019): Divergence-free spherical harmonic gravity field modelling based on the Runge-Krarup theorem: a case study for the Moon. Journal of Geodesy 93, 489-513, https://doi.org/10.1007/s00190-018-1177-4.

Förste C, Abrykosov O, Bruinsma S, Dahle C, König R, Lemoine JM (2019): ESA's Release 6 GOCE gravity field model by means of the direct approach based on improved filtering of the reprocessed gradients of the entire mission (GO_CONS_GCF_2_DIR_R6). GFZ Data Services. https://doi.org/10.5880/ICGEM.2019.004

Förste C, Barthelmes F, Ince ES (2019): The ICGEM-format. Potsdam: GFZ German Research Centre for Geosciences, URL: http://icgem.gfz-potsdam.de/ICGEM-Format-2023.pdf, last access 13 June 2023.

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Ince, E. S. (2023). International Centre for Global Earth Models (ICGEM), Earth Series Sciences, Encyclopedia of Geodesy (to be added).

Jäggi A. et al. (2020) International Combination Service for Time-Variable Gravity Fields (COST-G). In: International Association of Geodesy Symposia. Springer, Berlin, Heidelberg, https://link.springer.com/chapter/10.1007%2F1345_2020_109.

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Lemoine JM, Bourgogne S, Biancale R (†), Reinquin F and Bruinsma S (2019): EIGEN-GRGS.RL04.MEAN-FIELD – Mean Earth gravity field model with a time-variable part from CNES/GRGS RL04.

Liang W, Li J, Xu X, Zhang S, Zhao Y (2020): A High-Resolution Earth's Gravity Field Model SGG-UGM-2 from GOCE, GRACE, Satellite Altimetry, and EGM2008. Engineering, 860-878, doi: 10.1016/j.eng.2020.05.008.

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Sprlak M, Han S-C, Featherstone W (2020): Spheroidal Forward Modelling of the Gravitational Fields of 1 Ceres and the Moon. Icarus 335, doi: https://doi.org/10.1016/j.icarus.2019.113412.

Sprlak M, Han S-C, Featherstone W (2020): Crustal Density and Global Gravitational Field Estimation of the Moon from GRAIL and LOLA Satellite Data, Planetary and Space Science, 192, 105032, doi: https://doi.org/10.1016/j.pss.2020.105032.

Zingerle P, Brockmann JM, Pail R, Gruber T, Willberg M (2019): The polar extended gravity field model TIM_R6, doi: 10.5880/ICGEM.2019.005 2019.

Zingerle P, Pail R, Gruber T. et al. (2020): The combined global gravity field model XGM2019e.J Geod 94, 66, https://doi.org/10.1007/s00190-020-01398-0.

International Digital Elevation Model Service (IDEMS)

https://idems.maps.arcgis.com/home/index.html

Director, **Mr Kevin M. Kelly** (USA)

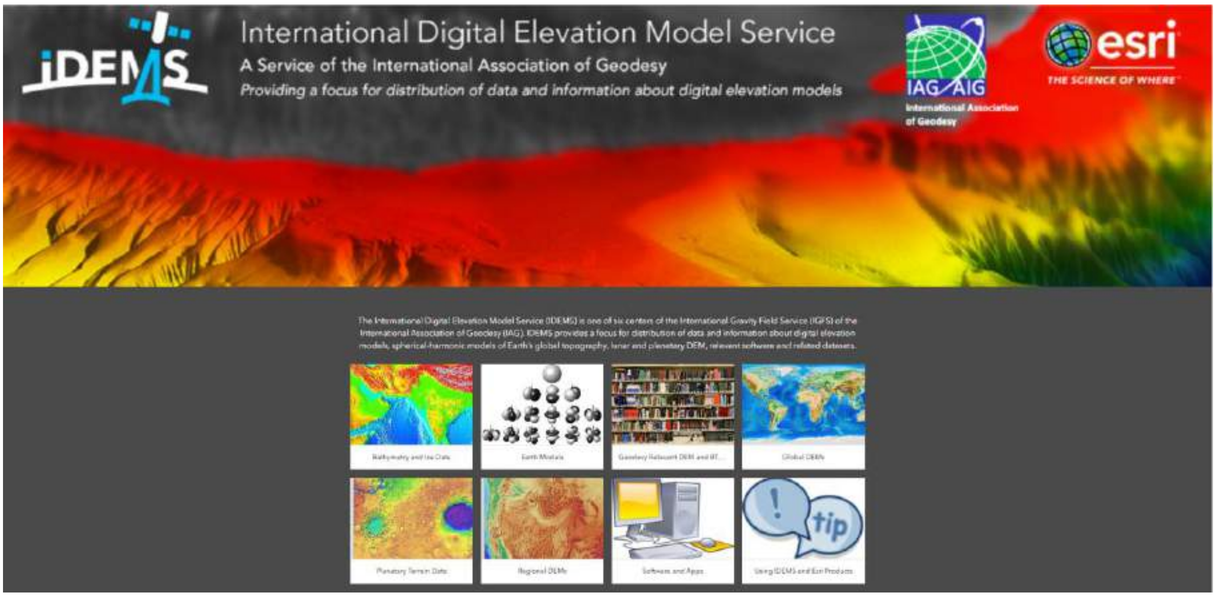
Structure

The Governing Board (GB) of IDEMS consists of five members who oversee the operation and general activities of the service. The GB is structured as follows:

Director of IDEMS:	Mr Kevin M Kelly
Deputy Director of IDEMS:	Dr Fei Wang
IAG/IGFS representative:	Dr Riccardo Barzhagi
Advisory member:	Dr Christian Hirt
Advisory member:	Dr Michael Kuhn

Overview

IDEMS is a service of IAG operated by Environmental Systems Research Institute (Esri) (http://www.esri.com/). The service became operational in 2016. The IDEMS website was developed and is maintained by Mr Kevin M. Kelly of Esri, and scientific content provided by Dr Christian Hirt of TU Munich. IDEMS provides a focus for distribution of data and information about digital elevation models, spherical-harmonic models of Earth's global topography, lunar and planetary DEM, relevant software and related datasets (including representation of Inland Water within Digital Elevation Models) which are available in the public domain.



Screenshot of home page of IDEMS showing DEM and related content categories.

IDEMS Products

IDEMS currently hosts 32 sources of terrestrial and planetary DEM data providers, 5 earth model sources (see Table 1) and 131 references of DEM and bathymetry research papers relevant to geodesy and Earth sciences. The IDEMS bibliography is updated periodically to provide the user community with an up-to-date overview over key developments in DEM production, validation, and applications. The IDEMS bibliography includes recent and seminal papers describing relevant data sets of Earth's topography, bathymetry, ice data and composite elevation models. Some DEM sources appear in multiple categories to facilitate source discovery for the researcher. IDEMS serves as a repository of links to DEM data providers rather than a DEM data storage facility. The site also provides access to Esri's free ***ArcGIS Earth*** (https://www.esri.com/en-us/arcgis/products/arcgis-earth/overview) which is fully integrated with the ArcGIS platform for accessing, sharing, and publishing maps and data.

The IDEMS website is periodically updated with new terrestrial and planetary DEM datasets and related Earth models as they become available. Table 1 lists the current content available through the IDEMS website.

Table 1. DEM and Related Data Sources Hosted on IDEMS

Bathymetry and Ice Data (13)	Antarctica CryoSat-2 DEM
	Bedmap2
	BOEM Northern Gulf of Mexico Bathymetry
	Elevation Coverage Map (Esri)
	Global Bathymetry BTM (Esri)
	Global Water Body Map (G3WBM)
	Ice, Cloud, and Land Elevation (ICESat / GLAS Data)
	MH370 Bathymetry
	Polar Geospatial Center
	Randolph Glacier Inventory (RGI 6.0)
	SRTM30_PLUS (30 arc-sec grid), 2014
	SRTM15 V2.0
	Svalbard Time-Lapse Terrain Model
Global DEMs (16)	ALOS/PRISM AW3D30
	ASTER GDEM v2
	EarthDEM (Polar Geospatial Center)
	Elevation Coverage Map (Esri)
	Esri Elevation Layers
	ETOPO1 (60 arc-sec grid), 2009
	Global Terrain DEM (Esri)
	Global Water Body Map (G3WBM)
	MERIT DEM (SRTM-based Bare-Earth model), 2017
	NASADEM (reprocessed SRTM model), 2017
	SRTM v3 (NASA)
	SRTM v4.1 (CGIAR-CSI)
	SRTM15 V2.0
	SRTM30_PLUS (30 arc-sec grid), 2014
	TanDEM-X DEM
	Viewfinder Panorama DEMs (2014)
Regional DEMs (7)	Antarctica CryoSat-2 DEM
	Arctic DEM Explorer
	OpenTopography
	Elevation Coverage Map (Esri)
	Esri Elevation Layers
	Polar Geospatial Center
	Svalbard Time-Lapse Terrain Model
Planetary Terrain Data (3)	NASA Planetary Data System (PDS) Geosciences Node
	Planetary topography data archive

	USGS Astrogeology Science Center
Earth Models (5)	Earth2014 (60 arc-sec), 2014
	ICE-6G GIA Model
	Preliminary Reference Earth Model (PREM)
	Topographic Earth Models (LMU Munich)
	SRTM2gravity(2018)

IDEMS Website Usage

Table 2 below shows IDEMS activity from 6/2016 to 6/2023. Since inception IDEMS has received very good use considering the small community it serves. The total views of all content on IDEMS reached 23,409. The top three items viewed, shown in bold in Table 2, amounted to 77% of all views of all content on IDEMS.

Table 2. IDEMS activity by number of views of all content. Top three items number of views is shown in bold.

Data Type	No. of item views
ALOS/PRISM AW3D30	165
Antarctica CryoSat-2 DEM	93
ArcGIS Earth (Esri)	131
Arctic DEM Explorer	148
ASTER GDEM v2	306
BedMap2	190
BOEM Northern Gulf of Mexico Bathymetry	66
DEM and BTM Research Papers	199
Digital Terrain Models, C. Hirt (2015)	148
Earth2014 (60 arcsec), 2014	334
EarthDEM (Polar Geospatial Center)	4
Elevation Coverage Map (Esri)	**1,700**
Esri Elevation Layers	154
ETOPO1 (60 arc-sec grid), 2009	30
Getting Started with IDEMS	163
Global bathymetry (Esri)	**1,747**
Global Geospatial Data from Earth Observation (2016)	85
Global Terrain DEM (Esri)	**14,562**
Global Water Body Map (G3WBM)	131
IAU Cartographic Coordinates and Rotational Elements (WGCCRE)	122
Ice, Cloud, and Land Elevation (ICESat / GLAS Data)	137
ICE-6G GIA Model	18
Introducing Esri's World Elevation Services	181
Introduction to DEMs and SRTM versions (2013)	20
MERIT DEM (SRTM-based Bare-Earth model), 2017	137
MH370 Bathymetry	98
NASA Planetary Data System (PDS) Geosciences Node	78
NASADEM (reprocessed SRTM model), 2017	174
OpenTopography	53
Planetary topography data archive	147
Polar Geospatial Center	145
Preliminary Reference Earth Model (PREM)	150
Randolph Glacier Inventory (RGI 6.0)	136
SRTM v3 (NASA)	241
SRTM v4.1 (CGIAR-CSI)	209
SRTM15 V2.0	53
SRTM30_PLUS (30 arc-sec grid), 2014	185

SRTM2gravity (2018)	88
Status report on Digital Elevation Models (2015)	85
Svalbard Time-Lapse Terrain Model	88
TanDEM-X DEM	197
Topographic Earth Models	53
USGS Astrogeology Science Center	140
Viewfinder Panorama DEMs (2014)	118
Total	**23,409**

IDEMS Research Activities

IDEMS participated in JSG T.37: *Theory and methods related to the combination of high-resolution topographic/bathymetric models in geodesy*, which aims at studying the available topographic and bathymetric models and at exploring their limitations, particularly concerning the transition along the coasts. Preliminary results were presented at X Hotine-Marussi Symposium, Politecnico di Milano, Milano – June 13-17, 2022: Carrion D, Barzaghi R, Crespi M, Grigoriadis V, Jacobsen K, Kelly K, Kuhn M, Nagi R, Palcu D, Slobbe CD: The impact of DTM/DBM land-sea transition for geoid computation: a test case in southern Italy

International Geodynamics and Earth Tide Service (IGETS)

http://igets.u-strasbg.fr/

Chair of the Directing Board: Hartmut Wziontek (Germany)
Director of the Central Bureau: Jean-Paul Boy (France)

Structure

- Directing Board: H. Wziontek, J.-P. Boy, V. Palinkas, J.-P. Barriot, C. Förste, H.-P. Sun, C. Voigt, D. Crossley, J. Hinderer, B. Meurers, S. Rosat, S. Bonvalot, N. Sneeuw
- Central Bureau: J.-P. Boy
- Data Center: C. Förste, C. Voigt

Overview

The primary objective of the International Geodynamics and Earth Tide Service (IGETS) is to provide a service to monitor temporal variations of the Earth gravity field through long-term records from ground gravimeters, tiltmeters, strainmeters and other geodynamic sensors. IGETS continues the activities of the Global Geodynamic Project since it was established at the IUGG general assembly in Prague 2015.

Status of the IGETS Data Center

The IGETS data sets are stored on an FTP server and are freely available after user registration. The number of IGETS users is increasing steadily since the launch in Summer 2016 (see Fig. 1). The data base server is hosted by GFZ Potsdam (Germany) and is accessible via http://igets.gfz-potsdam.de.
In June 2023, data from 47 stations and 67 sensors are available, globally distributed, provided by 33 producers covering a time span of up to 35 years. New stations were included since 2019: Helgoland, Zugspitze (Germany), Rochefort (Belgium), Aubure (France), Hurbanovo (Slovakia) and Walferdange (Luxembourg). Records from superconducting gravimeters made by GWR of compact (CT) and observatory (OSG) type are predominant, while the number of GWR iGrav superconducting gravimeter and Micro-g LaCoste gPhone gravimeter data has grown at most.

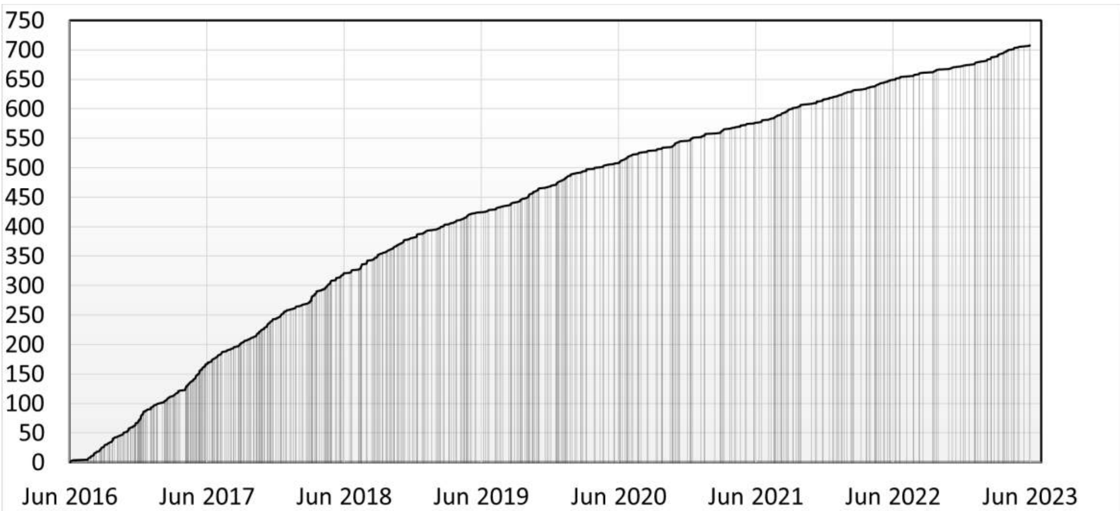


Fig. 1: Number of IGETS data base users since the launch in summer 2016.

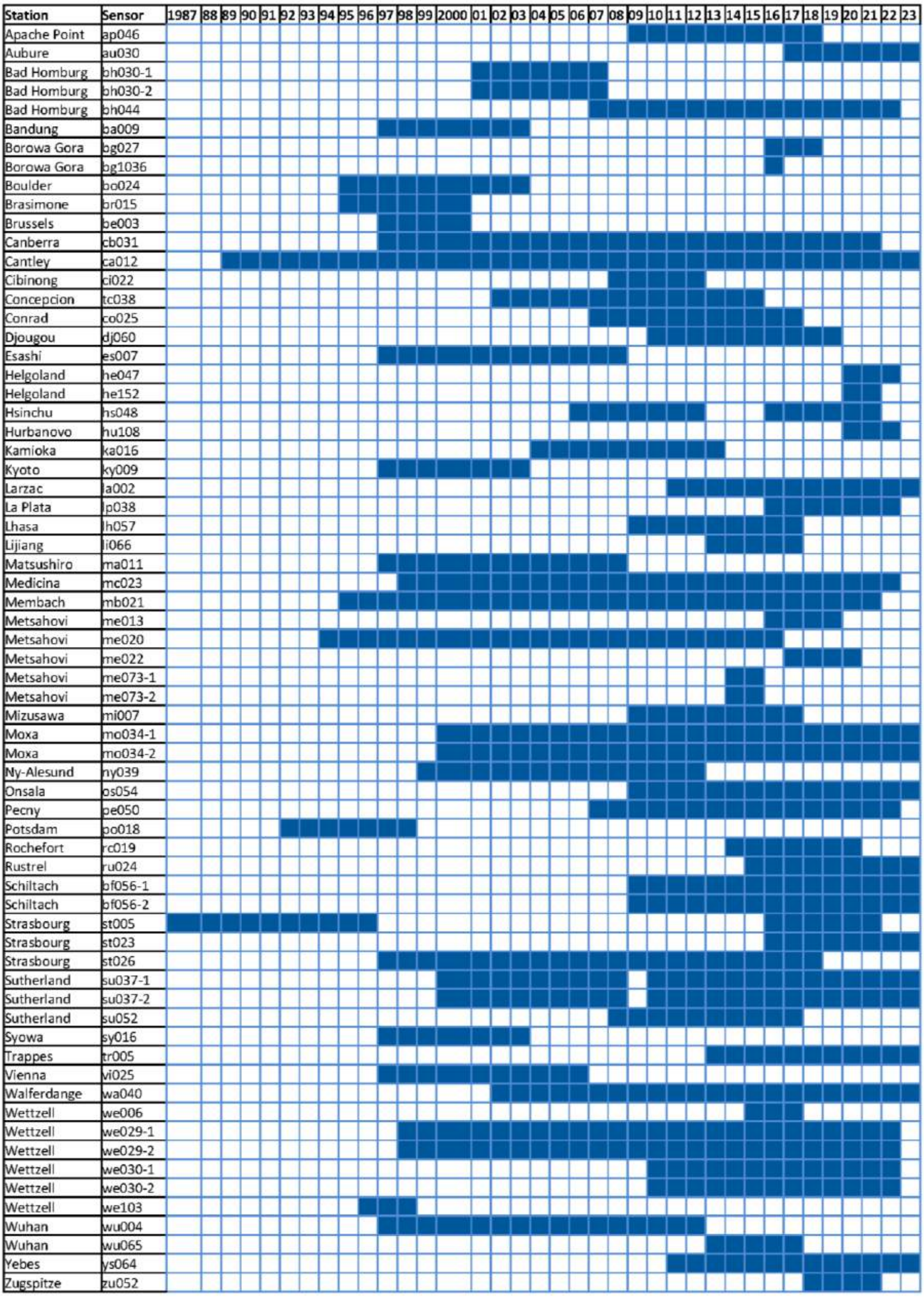


Fig. 1: Time span of the data coverage of the IGETS data base until 2023.

All relevant information on the IGETS data base were compiled in the scientific technical report Voigt et.al. (2016), comprising station and sensor information, available data sets, directory structure, file name convention, repair codes and file formats. Data descriptions originating to a large part from Global Geodynamics Project (GGP) were updated and extended for IGETS.

Status of the Analysis Centers

Different product levels are derived from the gravity and atmospheric pressure data recorded with the superconducting gravimeters. Products of Level-1 are the raw data without pre-processing which are down-sampled to 1 min. resolution but also provided at the original resolution of 1 sec. for a total of 47 stations (for a total of 67 different time series). The pre-processing of these data, i.e. elimination of gaps, spikes, steps and disturbance is continued as a Level-2 product.
Two IGETS Analysis Centers, at the University of French Polynesia (Tahiti) and at the University of Strasbourg/ EOST (Strasbourg, France) provide different products. While the first is in charge of processing Level-2 data from the raw Level-1 data, i.e. gravity and pressure data corrected for all major disturbances, the second center is mainly in charge of producing the Level-3 data, i.e. gravity residuals after correction of all major geophysical signals, but also produces alternate Level-2 data.

The Level-2 data, i.e. gravity and pressure, are corrected for major instrumental disturbance using a remove/restore technique based on a local tide model.

The Level-3 data, i.e. gravity residuals sampled at 1 minute, are derived from the Level-2 data produced by EOST, by subtracting solid Earth tides, tidal ocean loading using FES2014 (Lyard et al., 2021), Polar Motion and Length-Of-Day induced effects, including a static ocean response, atmospheric loading based on ERA5 reanalysis (Hersbach et al. et al., 2020) from ECMWF (European Centre for Medium-Range Weather Forecasts) assuming an inverted barometer ocean response to pressure forcing and an instrumental drift. Loading models are also available on the EOST Loading Service (Boy and Lyard, 2008; Boy and Hinderer, 2006; http://loading.u-strasbg.fr/).

Table 1 provides all the data (Level-1, various Level-2 and Level-3) available at the IGETS datacenter.

		Level1			Level2 (station)			Level2 (UPF)			Level2 (EOST)			Level3 (EOST)		
		nb month	start	end	nb month	start	end	nb month	start	end	nb month	start	end	nb month	start	end
Apache-Point	ap046	118	200902	201809	102	200904	201809	101	200904	201808	94	201001	201809	94	201001	201809
Aubure	au030	72	201706	202305							71	201706	202304	71	201706	202304
Bad-Homburg	bh030-1	75	200102	200704	64	200201	200704	81	200102	200704	75	200102	200704	75	200102	200704
Bad-Homburg	bh030-2	75	200102	200704				79	200102	200704	75	200102	200704	75	200102	200704
Bad-Homburg	bh044	170	200702	202209	113	200702	201606	122	200702	201703	122	200702	201703	122	200702	201703
Bandung	ba009	67	199712	200306				55	199712	200306						
Borowa-Gora	bg027				10	201605	201702									
Boulder	bo024	103	199504	200310				82	199701	200310						
Brasimone	br015	46	199512	200001				46	199512	200001						
Canberra	cb031	293	199707	202112				293	199707	202112	294	199707	202112	294	199707	202112
Cantley	ca012	346	198911	202305				265	199707	202003	280	199707	202207	282	199707	202207
Cibinong	ci022	33	200811	201205				33	200811	201205	32	200812	201205	32	200812	201205
Concepcion	tc038	132	200212	201504				131	200212	201504	149	200212	201504	149	200212	201504
Conrad	co025	143	200711	201811				98	200711	201703	113	200711	201703	133	200711	201811
Djougou	dj060	103	201007	201901				99	201007	201810	101	201007	201811	103	201007	201901
Esashi	es007	138	199707	200812				117	199707	200703						
Helgoland	he047	24	202003	202202				16	202003	202106	24	202003	202202	24	202003	202202
Helgoland	he152	17	202002	202106												
Hsinchu	hs048	124	200604	202106				33	200604	200812				116	200604	202009
Hurbanovo	hu108	29	202007	202211				29	202007	202211						
Kamioka	ka016	106	200410	201307				107	200410	201307	106	200410	201307	106	200410	201307
La-Plata	lp038	82	201601	202210				38	201601	201902	60	201601	202012	60	201601	202012
Larzac	la002	145	201105	202305							125	201105	202304	125	201105	202304
Lhasa	lh057	91	200912	201706	89	200912	201706	89	200912	201706	91	200912	201706	91	200912	201706
Lijiang	li066	52	201303	201706	52	201303	201706	50	201304	201706	51	201304	201706	51	201304	201706
Matsushiro	ma011	133	199705	200806				132	199705	200806						
Medicina	mc023	293	199801	202210	218	199801	201602	256	199801	201904	275	199801	202011	256	199801	201904
Membach	mb021	308	199508	202103				206	199508	201209	308	199508	202103	308	199508	202103
Metsahovi	me013	34	201605	201902							34	201605	201902	34	201605	201902
Metsahovi	me020	260	199408	201609				237	199707	201609	245	199408	201504	245	199408	201504
Metsahovi	me022	26	201701	201902				26	201701	201902						
Metsahovi	me073-1	12	201402	201501				12	201402	201501						
Metsahovi	me073-2	15	201402	201504				13	201402	201504						
Mizusawa	mi007	100	200907	201710				98	200907	201710						
Moxa	mo034-1	290	200001	202303				242	200001	202112	252	200001	202206	252	200001	202206
Moxa	mo034-2	290	200001	202303				243	200001	202112	252	200001	202206	252	200001	202206
Ny-Alesund	ny039	149	199909	201201				148	199909	201201	154	199909	201206	154	199909	201206
Onsala	os054	176	200906	202305				166	200906	202302	159	200906	202208	159	200906	202208
Pecny	pe050	180	200705	202205				179	200705	202203	180	200705	202205	181	200705	202205
Potsdam	po018	73	199207	199808	74	199207	199809									
Rochefort	rc019	73	201412	202012							73	201412	202012	73	201412	202012
Rustrel	ru024	79	201510	202305							72	201510	202302	72	201510	202302
Schiltach	bf056-1	162	200910	202305				148	200910	202201	155	200910	202208	155	200910	202208
Schiltach	bf056-2	162	200910	202305				147	200910	202112	155	200910	202208	155	200910	202208
Strasbourg	st023	88	201602	202305				73	201602	202202	88	201602	202304	87	201602	202304
Strasbourg	st026	273	199702	201811				254	199703	201810	262	199702	201811	262	199702	201811
Sutherland	su037-1	240	200003	202206							231	200012	202206	231	200012	202206
Sutherland	su037-2	234	200009	202206							231	200012	202206	231	200012	202206
Sutherland	su052	109	200809	201709							109	200809	201709	109	200809	201709
Syowa	sy016	67	199707	200301				56	199707	200301						
Trappes	tr005	119	201302	202303							119	201302	202303	119	201302	202303
Vienna	vi025	114	199707	200612				114	199707	200612	114	199707	200612	114	199707	200612
Walferdange	wa040	246	200201	202304				25	201503	201703	255	200202	202304	255	200202	202304
Wettzell	we029-1	205	199811	202212	131	199912	201010	210	199811	201803	212	199811	201803	212	199811	201803
Wettzell	we029-2	204	199811	202212				212	199811	201803	212	199811	201803	212	199811	201803
Wettzell	we030-1	148	201006	202209	71	201006	201604	94	201006	201803	94	201006	201803	94	201006	201803
Wettzell	we030-2	148	201006	202209	71	201006	201604	94	201006	201803	94	201006	201803	94	201006	201803
Wettzell	we103	27	199607	199809				27	199607	199809						
Wuhan	wu004	176	199712	201207	176	199712	201207	100	199906	200905						
Wuhan	wu065	52	201303	201706	52	201303	201706	68	201208	201803	52	201303	201706	52	201303	201706
Yebes	ys064	133	201112	202212				79	201507	202201	126	201112	202207	128	201112	202207
Zugspitze	zu052	31	201809	202103				30	201809	202103	31	201809	202103	31	201809	202103

Table 1: Status of Level-1 (raw gravity and pressure), Level-2 (preprocessed gravity and pressure data) and Level-3 (gravity residuals) data in June 2023.

Data Publication and Citation – DOI

IGETS established the provision of digital object identifiers (DOI) for the data sets of every station. DOIs are unique and persistent identifiers used to reference and link the individual data sets. The advantages are a clear reference to data sets, to link scientific results with associated publications, an improvement of the access to scientific data and an enhancement of the visibility of research data, encouraging new research to be conducted, and foster scientific cooperation.

For Level-1 data, the DOI is assigned for each station, i.e. one for all sensors of a station referencing the station operators. The DOIs of the Level-1 data sets resolve to DOI landing pages with an overview of the station and the data. For data of Level-2 and Level-3, the DOI are assigned for all IGETS stations in total.

Further activities

A web page for IGETS was prepared within the relaunch of the GGOS web site https://ggos.org/item/igets/ which presents the service, illustrates the goals and gives impressions about the stations.
At the IUGG General Assembly in Montreal, a business meeting was held on July, 13 2019 where product updates presented and site reports were given. An online business meeting was held on June, 24 2021 during the 19th International Symposium on Geodynamics and Earth Tides in Wuhan.

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Boy J-.P., Barriot J.-P., Förste C., Voigt C., Wziontek H. (2020). Achievements of the First 4 Years of the International Geodynamics and Earth Tide Service (IGETS) 2015–2019. In: International Association of Geodesy Symposia. Springer, Berlin, Heidelberg. https://doi.org/10.1007/1345_2020_94.

Hersbach, H, Bell, B, Berrisford, P, et al. (2020). The ERA5 global reanalysis. Q. J. R. Meteorol. Soc., 146: 1999-2049. https://doi.org/10.1002/qj.3803.

Lyard, F. H., Allain, D. J., Cancet, M., Carrère, L., and Picot, N. (2021). FES2014 global ocean tide atlas: design and performance, Ocean Sci., 17, 615–649, doi: 10.5194/os-17-615-2021.

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Voigt, C., Förste, C., Wziontek, H., Crossley, D., Meurers, B., Pálinkáš, V., Hinderer, J., Boy, J.-P., Barriot, J.-P., Sun, H. (2017). The Data Base of the International Geodynamics and Earth Tide Service (IGETS), Geophysical Research Abstracts, Vol. 19, EGU2017-4947, EGU General Assembly 2017.

Bibliography

A list of publications related to IGETS was compiled and is available at the IGETS web page at http://igets.u-strasbg.fr/biblio.php.

International Gravimetric Bureau (Bureau Gravimétrique International, BGI)

http://bgi.obs-mip.fr

Bureau Gravimétrique International
International Gravimetric Bureau

Director: Sylvain Bonvalot (France)

2021-2023 part will be added soon

Structure

The BGI is the scientific service of IAG aimed at ensuring the data inventory and the long term availability of the gravity measurements acquired at the Earth surface. Its main task is the collection, validation and archiving of all gravity measurements (relative or absolute) acquired from land, marine or airborne surveys and the diffusion of the derived data and products to a large variety of users for scientific purposes. The BGI activities are coordinated with those of other IAG gravity services (ISG, IGETS, ICGEM, IDEMS) through the International Gravity Field Service (IGFS).

The BGI has its central bureau in Toulouse (France) and operates with the support of various institutions from France (CNES, CNRS/INSU, IGN, IRD, SHOM, BRGM, IFREMER, Universities of Toulouse, Paris, Strasbourg, Montpellier and Le Mans) and from Germany (BKG). Its directing board includes representative of the supporting institutions and a representative of IAG and of IGFS.

For more information on the BGI structure and membership, see the following references:

- The International Gravimetric Bureau. In: The Geodesist's Handbook 2020 (Eds. Poutanen, M., Rózsa, S.). Journal of Geodesy. https://doi.org/10.1007/s00190-020-01434-z
- BGI website : http://bgi.obs-mip.fr/

Overview

During the 2019-2021 reporting period, the BGI has continued to support scientific and other users of gravity data. The BGI maintains the 4 global reference databases for relative gravity measurements (from land and marine surveys), for absolute gravity measurements and for reference gravity stations. BGI continues its activity of compilation, validation, archiving and distribution of the surface measurements of the Earth's gravity field. It also realize and distributes derived products (global or regional grids of gravity anomaly) and gravity processing or analysis software's. During the 2019-2021 period, also has carried out regional gravity data compilation and validation for international projects related with geoid or gravity anomaly computations (i.e. GEOMED-2, ALP-Array, Vietnam) and has supported the realization of absolute gravity reference networks in several countries. BGI also supports the activities of IAG Sub-commission 2 and participates as co-chair of the IAG Joint Working Group 2.1.1 for the realization of the International Gravity Data Reference System and Frame (IGRS/IGRF). Finally, BGI is also involved in the evaluation of innovative instrumentations for static and dynamic measurements of the Earth gravity such as absolute gravity meters based on cold-atoms technologies. Apart from the above mentioned collaborations, BGI has operated during the reporting period in close collaboration with other IGFS services and with various institutions such as POLIMI Italy, AUTh Greece, DTU Denmark, VÚGTK Czech Republic, NGA USA.

Activities

1. Global gravity databases and products

Most of the databases and services provided are available from the BGI website (http://bgi.obs-mip.fr). It gives access to the 4 global database of gravity observations: 1) Relative measurements from land surveys; 2) Relative measurements from marine surveys; 3) Reference gravity stations related to the former IGSN71 & Potsdam 1930 networks, 4) Absolute measurements.

1.1. Relative gravity database

The most frequent service BGI can provide is the consultation and retrieval of gravity data and information over local or regional areas. Data requests are made through the BGI website at the following links. Few millions of relative data are currently distributed each year to scientific users. For larger areas (regional to global), BGI also propose grids of gravity anomalies (free air, Bouguer, isostatic).

- Land database: http://bgi.obs-mip.fr/data-products/Gravity-Databases/Land-Gravity-data
- Marine database: http://bgi.obs-mip.fr/data-products/Gravity-Databases/Marine-Gravity-data

1.2. Absolute gravity database

The global database for absolute gravity measurements is jointly operated by BGI and BKG (Bundesamt für Kartographie und Geodäsie, Germany). This AGrav database is capable of storing information about stations, instruments, observations and involved institutions. By this, it allows the exchange of meta-data and the provision of contact details of the responsible institutions as well as the storage and long term availability of gravity data and processing details. The database can be accessed from two mirrored sites at BGI and BKG.

- Absolute database: http://bgi.obs-mip.fr/data-products/Gravity-Databases/Absolute-Gravity-data ; http://agrav.bkg.bund.de/agrav-meta/

A simple exchange format (project files) which includes all relevant information and is known by the majority of users, was selected. In this way the upload of data to the database is possible by any contributor, using a web based upload form. The provided information ranges from meta-data (localization of stations) up to full information on the absolute determination of the gravity field on a given site (raw or processed data, description of measurement sites, etc.).

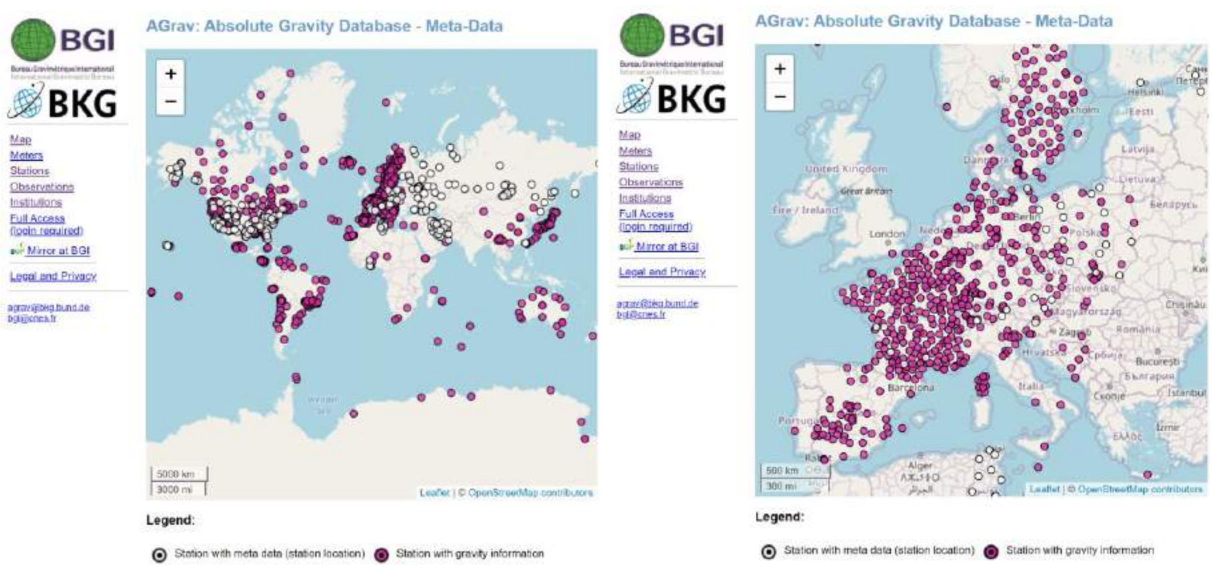

Figure 1: WEB interface of the Absolute Gravity database (BGI-BKG)

Current status (06/2021): 1373 stations / 5146 observations / 78 instruments / 65 institutions

1.3. Regional or global gravity anomaly grids

The BGI continued to provide access or links to high resolution global or regional grids of gravity anomaly such as those derived from the World Gravity Map (Bonvalot et al., *CGMW World Gravity Map*, 2012 ; Balmino et al., *Journal of Geodesy*, 2012) ; EGM2008 (Pavlis et al., *JGR* 2012) or GGMPlus (Hirt et al., *GRL*, 2013) as well as gravity derived crustal thickness model of Antarctica (Llubes et al., 2018)

2. Contribution to regional gravity projects

Regional data compilation & geoid computation

During the reporting period, BGI has contributed to the GEOMED2 project which aims at computing a high resolution geoid in the **Mediterranean area**. It has specially performed gravity data compilation and validation using marine gravity measurements collected over the entire Mediterranean basin. The final release of the GEOMED2 products has been delayed due to the Covid situation. BGI has also supported the realization of gravity data compilation for the **Alp-Array project** (Götze et al., 2019) and for a new geoid model computation for **Vietnam** and surrounding areas (Vu et al., 2019 ; 2020 ; 2021).

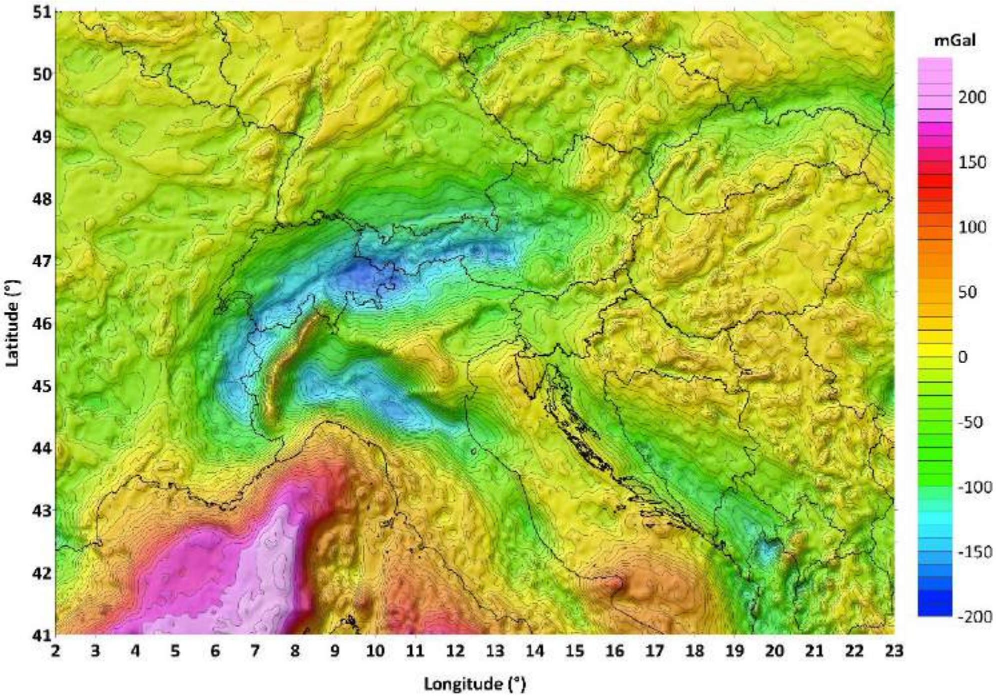

Fig. 3: Gravity compilation realized by the Alp Array Gravity Group
The first pan-Alpine surface-gravity database (Zahorec et al., 2021).

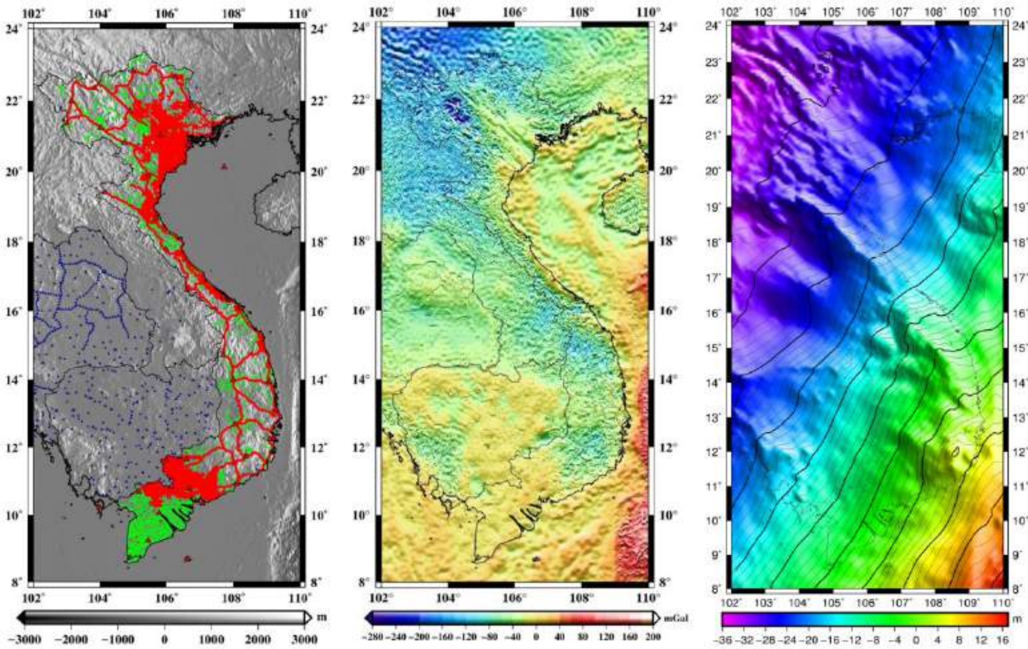

Fig. 4: Gravity data compilation over Vietnam and surrounding areas: a) Data distribution; b) Complete Bouguer anomaly ; c) Quasigeoid. Vu et al. (2019, 2020, 2021).

<u>*Establishment of absolute gravity reference networks*</u>

BGI contributes with its partners to the realization of absolute gravity networks. For instance, IGN France has renewed its gravity reference networks in France and overseas (French Antillas, Guyana, Mayotte, etc.) by combining absolute and relative gravity surveys (contribution to absolute gravity database). BGI has also supported in the last few years the realization of absolute gravity reference network in South America (Chile, Argentina, Peru).

3. Contribution to the definition of the International Gravity Reference System

BGI coo-chairs the IAG JWG 2.1.1 "Establishment of the International Gravity Reference System & Frame" (Chair: H. Wziontek, Co-Chair: S. Bonvalot). This IGRS aims at fulfilling the following objectives:

- The need for accurate and long term stable reference provided by a primary network of reference stations where gravity is monitored with absolute gravimeters. Such primary network is already a central part of the IAG resolution 2 (2015) and should also contribute to the infrastructure of GGOS Core sites.
- The need for secondary network of gravity stations which ensures accessibility of the system by a global set of sites, compatible with the above defined reference level, to any user. The aim of this secondary network is to identify and make accessible the largest number of absolute gravity values observed worldwide from field surveys of laboratory measurements to provide absolute reference to any purpose (relative gravity surveys, calibration lines, etc.). This network must be considered as the future replacement of the IGSN71 network.

The reference paper for the IGRS/IGRF project can be found in Wziontek et al. (2021)

4. Contribution to cold-atom absolute gravimetry

BGI follows the technical innovations for measuring the Earth gravity field by means of cold-atoms gravity sensors with several research lab in France (Toulouse, Brest, Montpellier and Paris).

A first contribution has been done in the frame of RESIF project (https://www.resif.fr/) with the development of the new Absolute Quantum Gravity (AQG) meter achieved by MUQUANS (https://www.muquans.com). It has led to the evaluation of performances and comparisons with reference gravity meters (MGL FG5 and A10) as well as with the cold-atoms gravity meter (CAG) from LNE-SYRTE. A second contribution is the evaluation of the GIRAFE-2 instrument developed by ONERA France (https://www.onera.fr/fr). This hybrid meter (including accelerometers and a cold atom sensor) has the ability to measure the Earth's gravity continuously on a moving platform. It has been successfully operated along with classical gravity meters and inertial sensors during an airborne survey carried out in 2019 (Collab. BGI, ONERA, DTU, SHOM, CNES, SAFIRE).

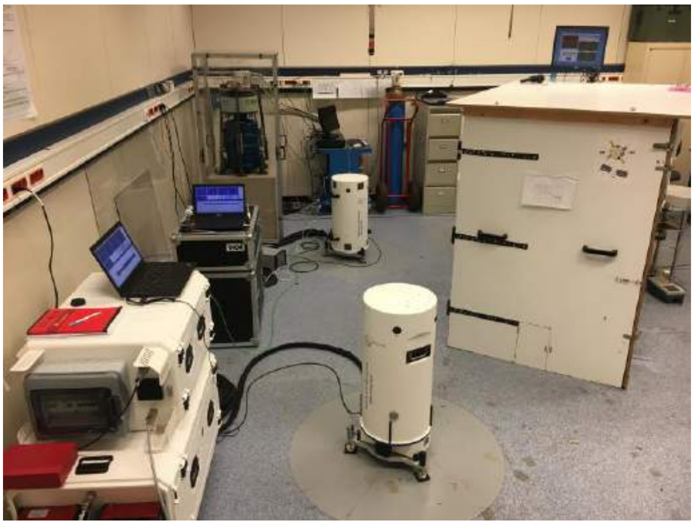

Figure 5a: Inter-comparison of 3 Absolute Quantum Gravimeter (AQG A01, AQG B01 from MUQUANS and CAG) and iGrav at LNE/SYRTE, France.

Figure 5b : GIRAFE-2 cold-atom gravimeter (ONERA) during airborne survey in spring 2019.

Scientific events

International meetings

- 07/2019 : IUGG General Assembly 2019 ; Montreal, CA
- 12/2019 : AGU General Assembly 2019 ; San Francisco, USA
- 04/2020 : EGU General Assembly 2020 ;
- 12/2020 : AGU General Assembly 2020;
- 04/2021 : EGU General Assembly 2021 ;

Participation to IAG structure & working groups

- IAG Sub-commission 2.1: « Land, marine & Airborne gravimetry » (Chair. D. VanWestrum, USA ; P. Dykowski, Poland)
- IAG JWG 2.1.1 : "Establishment of a International Gravity Reference System & Frame (IGRS/IGRF)" (Chair: H. Wziontek, Germany ; Co-Chair: S. Bonvalot, France)
- IAG JWG 2.1.2 : "Unified file formats and processing software for high-precision gravimetry" (Chair: Ilya Oshchepkov, Russia)
- IGFS Advisory Board - http://igfs.topo.auth.gr/structure.html/
- GGOS Consortium - http://www.ggos.org/
- CCM / CIPM (Consultative Committee for Mass and Related Quantities- Working Group "Gravimetry" : https://www.bipm.org/en/committees/cc/wg/ccm-wgg.html

Publications 2019-2021

Bonvalot et al. The International Gravimetric Bureau. In: The Geodesist's Handbook 2020 (Eds. Poutanen, M., Rózsa, S.). Journal of Geodesy (2020). https://doi.org/10.1007/s00190-020-01434-z

Dufrechou G., Martin R., Bonvalot S., Bruinsma S. Insight on the western Mediterranean lithospheric structure from GOCE satellite gravity data. Journal of Geodynamics (2019) - https://doi.org/10.1016/j.jog.2019.01.006

Pallero J.L., Fernandez-Martinez J. L., Fernández-Muñiz Z., Bonvalot S., Gabalda G., Nalpas T. GravPSO2D: A Matlab package for 2D gravity inversion in sedimentary basins using the Particle Swarm Optimization algorithm Computers & Geosciences (2021). https://doi.org/10.1016/j.cageo.2020.104653

Vu D.T., Bonvalot S., Bruinsma S., Bui L.K. A local lithospheric structure model for Vietnam derived from a high-resolution gravimetric geoid. Earth, Planets and Space (2021). https://doi.org/10.1186/s40623-021-01415-2

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Vu Toan D., Bruinsma S., Bonvalot S. A high resolution gravimetric geoid model for Vietnam Earth, Planets and Space (2019) - https://doi.org/10.1186/s40623-019-1045-3

Vu Toan D., Bruinsma S., Bonvalot S., Vergos G. A quasigeoid derived transformation model accounting for land subsidence in the Mekong Delta towards height system unification in Vietnam. Remote Sensing (2020). https://doi.org/10.3390/rs12050817

Wziontek H., Bonvalot S., Falk R., Gabalda G., Mäkinen J., Palinkas V., Vitushkin L. Status of the Intenational Gravity Reference System and Frame. Journal of Geodesy (2021) 95:7. https://doi.org/10.1007/s00190-020-01438-9

Zahorec et al. The first pan-Alpine surface-gravity database, a modern compilation that crosses frontiers. Earth System Science Data, 2021. Earth Syst. Sci. Data, 13, 2165–2209, 2021 https://doi.org/10.5194/essd-13-2165-2021

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R. Falk, Germany
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R. Barzaghi, Italy
S. Merlet, France
M. Diament, France
T. Gattacceca, France
O. Jamet, France
M-F. Lalancette-Lequentrec, France
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J. Hinderer, France

International Service for the Geoid (ISG)

http://www.isgeoid.polimi.it/

President: Mirko Reguzzoni (Italy)
Director: Daniela Carrion (Italy)

Structure

The Service is hosted by the Department of Civil and Environmental Engineering at Politecnico di Milano (Italy).

In addition to the president and the director, the ISG staff is composed by other scientists (F. Sansò, R. Barzaghi, G. Sona, A. Albertella, C.I. De Gaetani, L. Rossi, K. Batsukh and J.F. Toro Herrera), as well as a secretary (C. Vajani).

The ISG advisory board is composed by the following scientists with expertise in the field of geoid determination:

- N. Pavlis (USA)
- M. Sideris (Canada)
- J. Huang (Canada)
- R. Forsberg (Denmark)
- J. Ågren (Sweden)
- U. Marti (Switzerland)
- H. Denker (Germany)
- L. Sánchez (Germany)
- K. Elger (Germany)
- I. Tziavos (Greece)
- D. Blitzkow (Brazil)
- W. Featherstone (Australia) † 2022
- H. Abd-Elmotaal (Egypt)
- C. Hwang (Chinese Taipei)

In the period 2019-2023, ISG has been involved in the Joint Working Group JWG 2.2.1 of IAG Sub-Commission 2.2 “Error assessment of the 1 cm geoid experiment”.

Overview

In the period 2019-2023, ISG research has been mainly related to local geoid computation and height datum unification. In addition to that, most activities have been devoted to standardise the information and increase the offer of services on the available archive of geoid and quasi-geoid models, namely:

- the update of the ISG data format, which is common to all models;
- the establishment of a DOI service, in cooperation with GFZ;
- the establishment of a (preliminary) web-service for height conversion and the development of other services for clipping and merging models;
- the distribution of the Colorado experiment and the Auvergne test datasets and results, through the ISG website.

ISG activities have been disseminated through the participation to international events with oral and poster presentations. A paper on ISG has been published on Earth System Science Data, as well. According to tradition, ISG organized an International School on "The Determination and Use of the Geoid" during this four-year period. For the first time, the school was held online due to the Covid-19 limitations.

Last but not least, the ISG geoid repository has been continuously updated, significantly increasing the number of collected models. The ISG website has been modified accordingly. In the next future it is planned to improve both the repository and the website, storing models and information into a database and adding WebGIS functionalities into a more modern website.

Research activities

Most of the research studies were devoted to local/regional geoid determination and the height datum unification problem. The former mainly consists in the refinement of the collocation approach that is the technique traditionally applied for the geoid determination by the research group managing ISG. In this framework, it has to be mentioned the provided contribution to the Colorado experiment and the support to the results assessment and publication.
As for the latter issue, namely the height datum unification problem, the large availability of local/regional geoid/quasi-geoid models in the ISG repository fosters the study of a merging strategy to produce unified models between neighbour countries. The proposed method consists of first estimating biases and systematic effects by a least-squares adjustment of the local geoid residuals with respect to a satellite-only global gravity model, and then correcting the remaining distortions along the national borders to better join the local geoid models. This investigation was initially performed in the framework of the JWG2.2.1 "Integration and validation of local geoid estimates" of IAG Commission 2 in the period 2015-2019 and then continued during this period, also leading to a prototype of web-service implemented in Python.
Among the contributions to the realization of an International Height Reference System/Frame (IHRS/IHRF), it has to be mentioned the study performed in Ecuador (Carrion et al., 2023). The vertical offset between the official Ecuador Vertical Datum (EVD) at "La Libertad" tide gauge and the IHRF was estimated based on the fixed geodetic boundary value problem approach. The determination of the anomalous potential at the EVD point, which in turn enables the determination of the corresponding geopotential value, was carried out by applying the remove-compute-restore methodology based on gravity disturbance data and considering the GO_CONS_GCF_2_DIR_R5 satellite model at d/o 200 and 300. Thus, two estimates of the EVD offset with respect to the IHRF were obtained that amount to 0.911 m and 0.901 m, respectively. Furthermore, a computation were performed and presented at EGU2022 General Assembly concerning the IHRF estimation over the Matera (Italy) and AUT1 (Greece) EUREF stations using local gravity data and geoid models.

Update of the ISG data format

ISG manages and preserves a repository of regional, national and continental geoid models at a worldwide scale. The repository aims at storing and redistributing geoid models in a standardised data format, also providing ancillary information useful for gravity related analysis. To this aim, the geoids are collected both in the format provided by the owners and in ISG format, a standardised ASCII format with the .isg extension. The first version of the ISG ASCII format was released in 2015 and updated in 2018 (version 1.01). In July 2020, a major new release, version 2.0, was published, mainly introducing more metadata to better characterize the content of the file, and also allowing to store sparse point data. All the new models will be published with version 2.0.

Each individual data file consists of three sections: a) the optional comment section; b) the header section, which contains textual and numerical parameters; c) the data section, which contains the undulation values. To increase data interoperability, section (a) and (b) were designed with the same scheme of the .gfc file, distributed by ICGEM and providing global model coefficients.

In the comment section (a), three paragraphs are strongly recommended, the first one with the licence under which the data are distributed, the second one with the reference to cite when using the data, the third one indicating the data provider and the institution distributing the model.

In ISG format, the header section (b) is composed by structured metadata. It can be conceptually divided into three parts. The first contains textual metadata that are required to characterize the model, such as:

- the name of the model and the year of computation,
- the type of the model (gravimetric, geometric or hybrid),
- the classification between geoid and quasi-geoid,
- the fact that the data are sparse or gridded, and in case the ordering of the gridded data,
- the reference ellipsoid and datum, the reference frame, and the tidal system,
- the fact that the coordinates are geodetic or projected and, in case, the type of projection,
- the units of the undulation data and the coordinate units.

The second part contains numerical metadata that are mainly required to georeferencing the undulation values, such as

- the bounding box of the undulation dataset, i.e. minimum and maximum coordinates,
- the grid step and the number of rows and columns if the data are gridded (the number of rows can be used in sparse data to specify the number of points),
- the no-data value for missing points inside the grid structure.

Finally, the third part contains information about the file, such as the creation date and the format version. Metadata and their keywords depend on the format version. The file format specifications for all the possible versions are available at a dedicated page on the ISG website (https://www.isgeoid.polimi.it/Geoid/format_specs.html).

The data section was originally developed to contain the gridded undulation values, but from the format version 2.0 it is also possible to store sparse data by providing the point coordinates along with the undulation values. In case of gridded data, the point coordinates are defined in the header section and the undulation values are always stored row by row, being the default ordering from North to South, each row going from West to East.

Establishment of a DOI service

Geoid models that are collected by ISG are validated and standardized by converting them into a unique ASCII file format. In order to further improve interoperability and reusability of these models, it is crucial to univocally identify the data file (also by stable links), to assign metadata, to grant proper credit to research authors, and to allow for data citation.

In the framework of the GGOS working group “DOIs for Geodetic Data Sets”, ISG and GFZ are cooperating for developing a DOI minting service for local/regional geoid/quasi-geoid models collected and published via the International Service for the Geoid. The service includes the DOI assignment to the models, the collection and provision of standardised metadata and an additional backup of the models through GFZ Data Services, guaranteeing a persistent data access (the rights for publication of the models have been addressed by ISG and the data are already available for public download via the ISG geoid repository).

Since summer 2020, when the service was activated, the geoid/quasi-geoid distribution has been changed as follows:

• ISG geoid and quasi-geoid models in standardised ISG format (ASCII) can be labelled by DOIs. It is not foreseen to apply DOIs to the models in "original" format (as provided by the authors).
• The models that are labelled by DOIs are published under the Creative Commons Attribution 4-0 International Licence (CC BY 4.0) unless otherwise stated.
• The models that are labelled by DOIs are additionally publicly accessible via machine-readable DOI landing pages and the data catalogue of GFZ Data Services.
• The DOI landing pages have a specific layout for ISG.
• The geoid repository at ISG remains the first access point of ISG geoid models.
• A copy of the models will be archived at GFZ (backup).

Figure 1 provides an overview on the relation between the ISG and the GFZ Data Services for an example of DOI-referenced model. Both the quasi-geoid and geoid solutions, constituting the example model, can be accessed via the dedicated webpage in the ISG geoid repository (on the left) and via the DOI landing pages in the GFZ Data Services (on the right). The "File" section of the DOI landing page includes the links to the model file and the corresponding webpage in the ISG repository. On the other side, the ISG model webpage is enhanced with the recommended citations of the DOI-assigned models and the links to the DOI landing pages at the GFZ Data Services. The arrows show the cross-references between the two webpages.
At the date of 31 May 2023, DOIs were assigned to 64 models stored in the ISG repository, that is about 30% of the total number of open-access models.

In addition to the DOI assignment, the agreement between ISG and Clarivate is still active, thus indexing all ISG geoid and quasi-geoid models in the Data Citation Index and providing the corresponding accession number on the ISG website of the model.

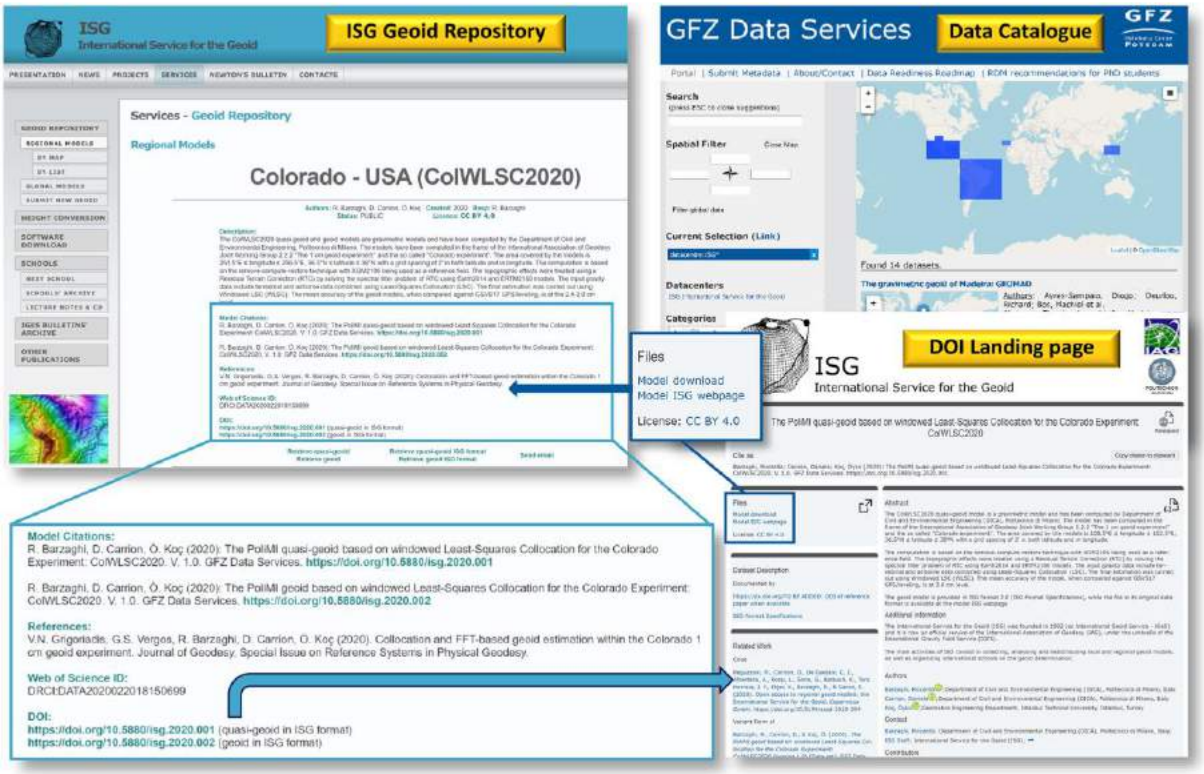

Figure 1: Overview on the relation between the ISG and the GFZ Data Services for an example of DOI-referenced model.

Establishment of a web-service for height conversion

In summer 2020, ISG activated a height conversion web-service to the users. They can provide the coordinates of one or more points (in the latter case through a CSV file containing three columns, namely latitude, longitude and height to be converted) and, after selecting the geoid model and the interpolation method, the web-service returns the conversion from ellipsoidal to orthometric height or vice versa. Once the user provides the point coordinates, only the geoid models containing at least one of these points are listed and can be selected by the user for the height conversion. This is possible by exploiting the model bounding box information that is available in the model file header as defined according to the ISG format.
As for the algorithmic point of view, the conversion is based on the formula $H = h - N$, relating the ellipsoidal height h and the orthometric height H through the geoid undulation N. Due to the fact that geoid models used by this service are given on a grid, the currently available interpolation methods are a bilinear interpolation among the four closest grid knots to the input point and the inverse distance weighting interpolation. Other interpolation methods may be made available in the future. The distinction between geoid and quasi-geoid will be performed soon, also mentioning the different reference systems/frame involved in the conversion. In this respect, the implemented web-service has to be considered as a preliminary solution.
As for the software implementation point of view, the web-service is divided into front-end and back-end, the former providing a user interface and the latter performing the calculations. The front-end is the "visible" part of the application (see Figure 2), it is implemented by using an HTML page and JavaScript. The HTML page contains a form with all the needed fields for the height conversion according to the web-service created on the back-end. The interface is designed to change as the user interacts with the application and selects the different options (single or multiple point coordinates). There are also checks on the input file size and format when the user asks for the conversion of more than one point.

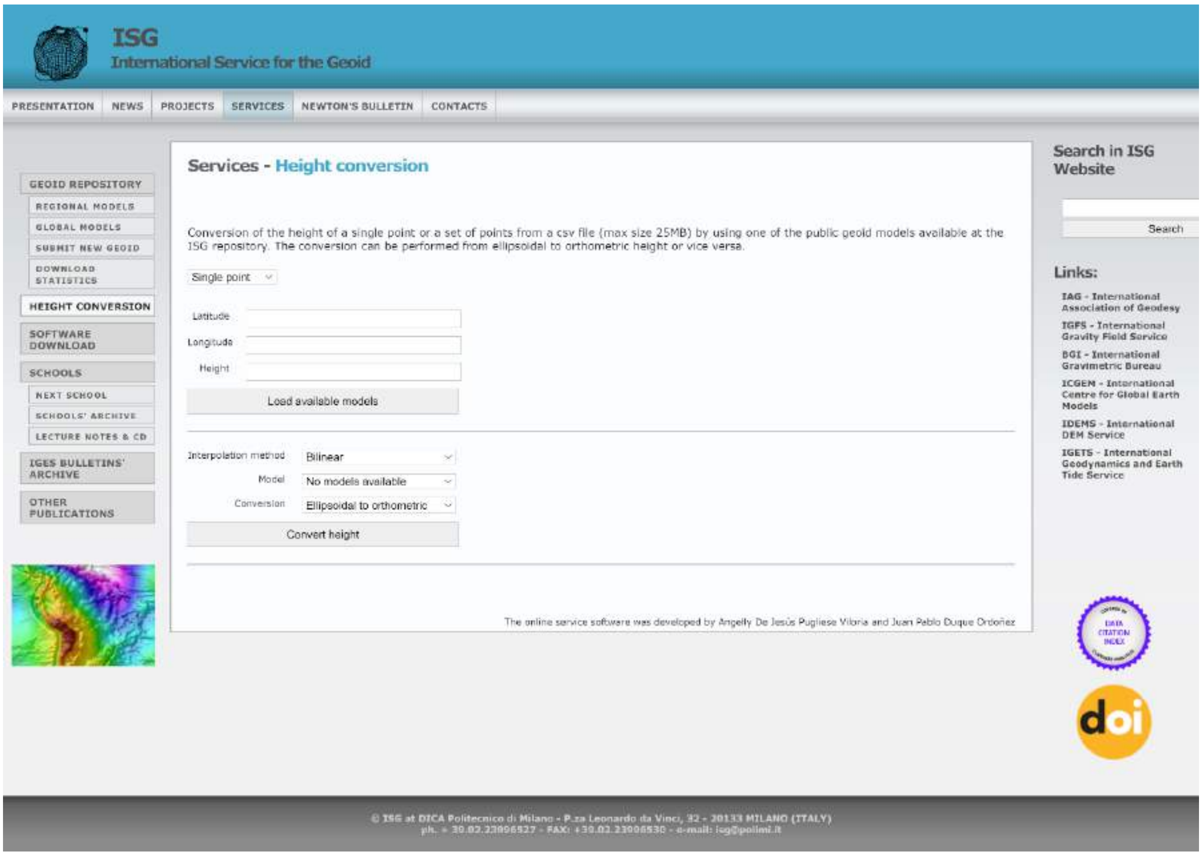

Figure 2: Webpage to access the ISG height conversion web-service.

The back-end is the core of the web-service, performing the required computation without increasing the burden of the front-end. In this way the web-service can be modified or updated without interfering with the front-end. In order to implement the back-end, a REST API (Representational State Transfer Application Programming Interface) was created in Django, a high-level Python web framework that allows performing mathematical calculations using Python with the NumPy library. Four different endpoints were created for the geoid model research and the height conversion, both for a single point and a set of points.
All requests from the front-end to the back-end rely on the HTTP POST method, i.e. enclosing the data in the body of the request messages instead of storing it, while the answers from the back-end are transmitted through a JSON file, which is directly visualized in the HTML page.
The service is currently being updated to work with models stored in the version 2.0 of the ISG format. Since this new version gives the possibility of discriminating between geoid and quasi-geoid models from the header information, the service will inform users whether the conversion is between ellipsoid and orthometric heights, or between ellipsoidal and normal heights.

Development of a service for extracting geoid subsets

In the last year, ISG developed (but not yet made available online) a service to select a data subset from an existing local, regional or continental geoid model, among those that are stored in the ISG repository and are publicly available to users. The selection is performed through a graphical user interface and implies a data resampling by interpolation techniques. Finally, a file format conversion can be performed to import the selected and potentially clipped geoid models into commercial GNSS/GPS receivers or GIS software.
The tool has been developed in Python language by means of the Django framework. In particular, the implementation has been designed to provide static html pages from the backend and to manage the interaction with the user completely on the client side through asynchronous AJAX calls with JavaScript.
As for the area selection, three options are available: 1) to take the entire grid, 2) to extract a sub-grid from corners, 3) to cut the grid along a contour line given by a shapefile. In the latter case, no-data values are attributed to points belonging to the exported sub-grid but laying outside the shapefile contour (see Figure 3). As for the data interpolation, when required to change the original grid step, again three resampling options are available: 1) nearest-neighbor, 2) bilinear, 3) bicubic (see Figure 4). As an example, the EGG97 European model has been cut along the Italian border shapefile, then resampling the extracted grid at higher spatial resolution by bilinear interpolation (see Figure 5).

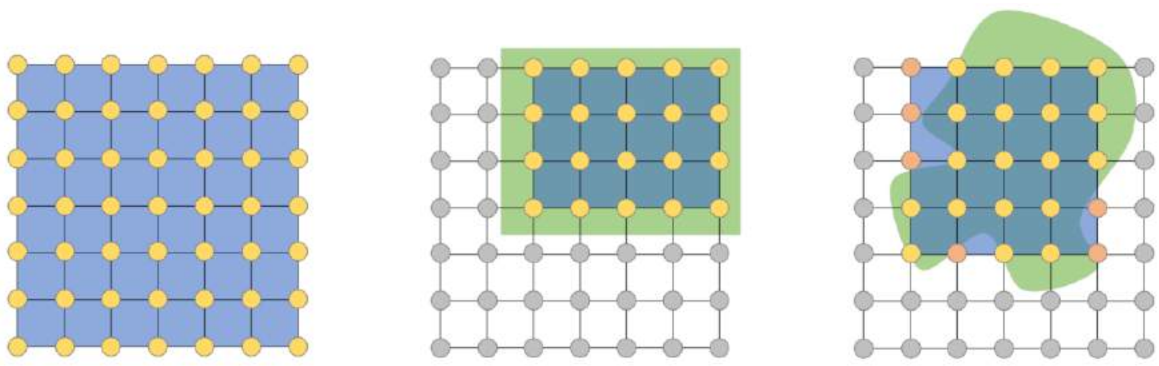

Figure 3: Subset selection options: entire grid (on the left), sub-grid from corners (in the center), sub-grid from georeferenced shapefile setting no-data values externally (on the right).

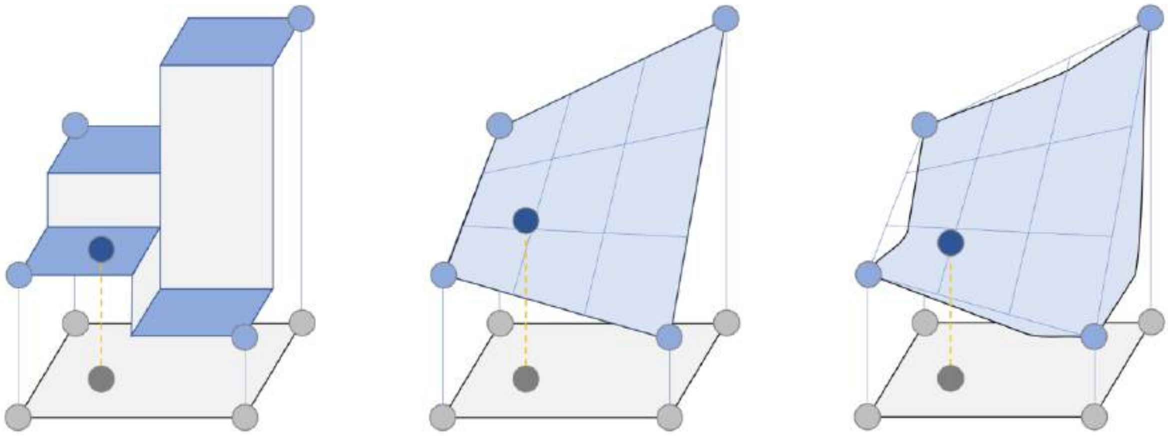

Figure 4: Resampling options: nearest-neighbor (on the left), bilinear (in the center), bicubic (on the right).

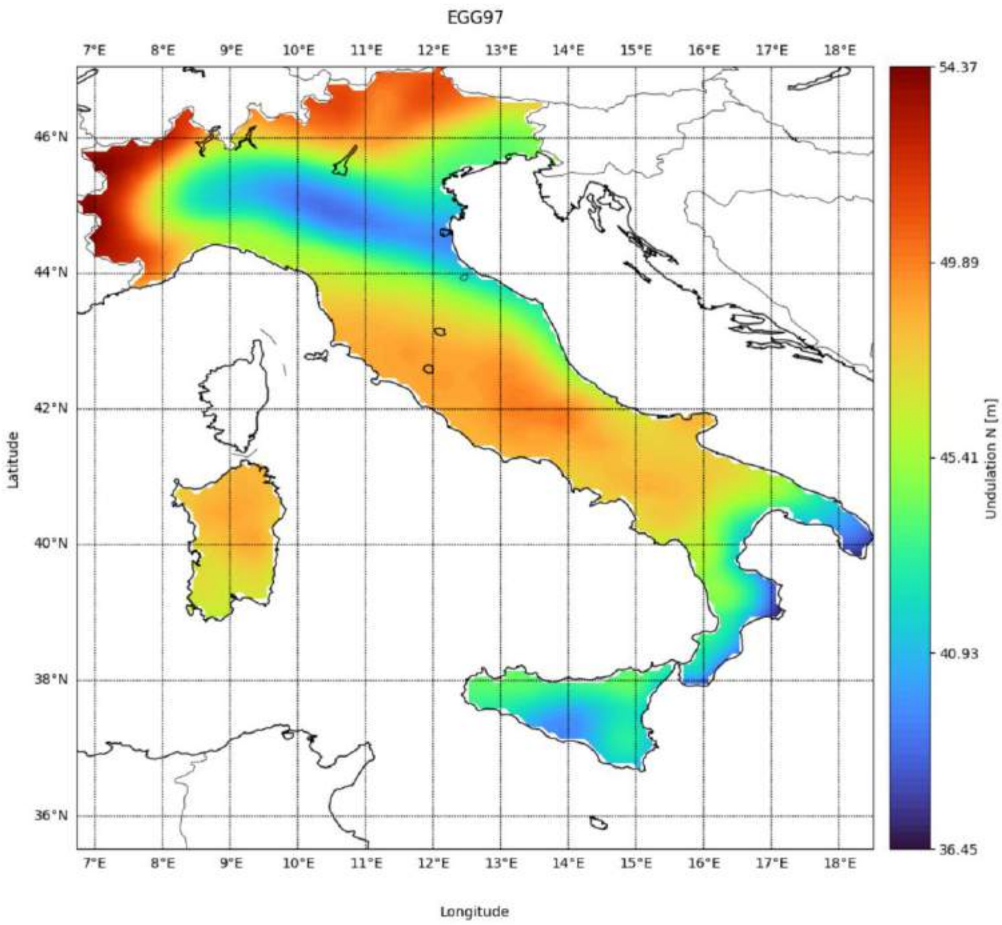

Figure 5: Extracted model from shapefile contour with a bilinear resampling.

Finally, it has to be mentioned that the currently implemented format conversions allow to export the extracted grids in one of the following formats:

- Internal format (.isg) - version ISG1.01 and ISG2.00
- Comma Separated Values (.csv)
- Carlson Geoid Separation File (.gsf)
- GeoTIFF Elevation (.tif)
- GEOCOL (.gri)

Further formats will be implemented in the next future. Along with the data file, a .png image files is also generated and made available to the user.

Development of a service for merging geoid models

ISG also developed a service to merge geoid models at national borders. The tool consists of the following steps:

- reading two or more models from the existing ISG repository;
- removing the contribution of a global model to all of them to setup the long wavelengths;
- removing also a bilinear surface for each model to manage differences in their reference frames;
- merging the geoid residuals by an inverse distance weighting (IDW) in the surroundings of the national borders;
- applying a suitable resampling technique to generate a unique grid of geoid residuals;
- adding back the contribution of the global model;
- if one of the model is taken as reference, adding back its removed bilinear surface over the whole extension of the merged grid to restore the corresponding reference frame.

The tool is developed in Python language through the Django framework. It is still at a prototype level and, therefore, it has not yet been made available online.

Distribution of the Colorado experiment data and results

In the period 2015-2019, the 1-cm geoid experiment (also called Colorado experiment) was setup as a joint effort of the Focus Area Unified Height System of the Global Geodetic Observing System (GGOS), the IAG Sub-commission 2.2, IAG Inter-Commission Committee on Theory (ICCT), and many related studies and working groups. The main objective of the experiment was the estimation and comparison of geoid undulations and height anomalies in Colorado using the same input data (provided by the US National Geodetic Survey, NGS) and different methodologies for the gravity field modelling. ISG offered the possibility of publishing both input data and results (in terms of geoid and quasi-geoid models) on its website. To this aim, dedicated webpages are now online, one for each solution computed in the frame of the Colorado experiment. A homepage summarizing the project and providing input and validation data is available too. As it is done for any other model in the ISG repository, information about names and institutions of the authors, the publication year of the model, key reference publication(s) and a brief description on the computational method of the model is provided for the Colorado solutions too. Moreover, DOIs are assigned to almost all solutions, making it possible to directly cite geoid and quasi-geoid models in scientific publications. Finally, the availability of the input data and possible comparisons with the already existing solutions can foster other researchers to test their own algorithm on this dataset, even if the official experiment is closed. ISG will also publish these additional results.

For the moment, 15 solutions have been published on the ISG website, all but one have been already labelled with DOIs (geoid and quasi-geoid models have different DOIs even if they refer to the same solution). This activity has been carried out in the frame of Joint Working Groups JWG 2.2.1 of Sub-Commission 2.2 “Error assessment of the 1 cm geoid experiment”.

Distribution of the Auvergne test data and results

In 2004, the French Institut Géographique National (IGN), upon the request of the steering committee of the European Gravity and Geoid Project (EGGP), prepared a dataset to test geoid determination methods and software. The Auvergne region, located in the centre of France, was selected as the target area. The dataset consists of about 240,000 gravity points, a digital terrain model and 75 GPS/levelling points, allowing for the computation and evaluation of a 3°×2° geoid is feasible. At that time, it was agreed that IGeS (now ISG) would have published both input data and results on its website. After renewing the agreement with IGN, some webpages on the Auvergne test dataset have been setup, also considering that some research groups are still using it for evaluation purposing. Similarly to the Colorado experiment, users can find a homepage providing input and validation data with the information required for their use, as well as webpages dedicated to each solution that is available in the ISG repository.

For the moment, 5 solutions have been published on the ISG website, including the original one by Duquenne (2006). Further solutions will be collected in the next future and we will continue to encourage researchers to share their results on the Auvergne test through the ISG website to have a wide comparison among different computation methods.

Participation to conferences and publications

ISG members took part to some international conferences/events, presenting the activities performed by the service. In particular, the following three oral presentations were given:
- “The International Service for the Geoid and its role in South America” at the workshop on the “Implementation of the United Nations’ Resolution on the Global Geodetic Reference Frame (UN-GGRF) for Sustainable Development in Latin America” held in Buenos Aires, Argentina, 16-20 September 2019.
- “The International Service for the Geoid: focus on Asia-Pacific region” at the first Asia Pacific geoid workshop for IAG-Sub-Commission 2.4e, held in Taiwan, 29 October 2020.
- “The International Service for the Geoid” at the IAG Joint Working Group 2.2.1 meeting, held online, 8 December 2021.

ISG contributed to the presentation entitled “The IGFS gravity field observations and products contributions to GGOS infrastructure” at EGU General Assembly in 2020. Two posters entitled “Assigning Digital Object Identifiers to Geoid Models in the ISG Repository” and “The International Service for the Geoid and its repository of regional geoid models” were presented at IAG Scientific Assembly in 2021 and GGHS Symposium in 2022, respectively. Finally, the design of the new ISG database was presented at the ISPRS Congress in 2022.

As for the publications, a paper focussing on ISG and mainly on its geoid repository has been published on Earth System Science Data, please see M. Reguzzoni, D. Carrion, et al. (2021). Users are encouraged to cite this paper any time they download geoid models from the ISG repository or in general when using ISG services. Other published papers in journal special issues containing conference proceedings are those by De Gaetani et al. (2022) and Toro Herrera et al. (2022).

School organization and scientific support to researchers on geoid estimation

One of the main tasks of ISG consists in organizing schools on geoid estimation and related topics. In 2016 an international school was held in Mongolia, at the Geodesy Department of Mongolian University of Science and Technology (MUST), Ulaanbaatar. The planning was to organize a new edition in 2020, but the advent of the Covid-19 pandemic led to postpone the school organization when the worldwide health situation would have improved to make travelling and hosting safer. To overcome these limitations, it was decided for the first time to offer the school online. In cooperation with the Dept. of Geodesy and Geodynamics Research and Development in Ethiopian Space Science and Technology Institute (ESSTI) of Addis Ababa (Ethiopia), the 13th International School on "The Determination and Use of the Geoid" was held online on Microsoft Teams platform, from 13 October to 17 November 2021. Overall, 35 people attended the School, including PhD students, researchers and professionals. Among the attendees, a group of 13 people was hosted in Addis Ababa at ESSTI premises, for local support; 8 attendees were connected from Europe; 6 from the USA; 3 from Peru; 2 from Argentina; 2 from Morocco and 1 from Nepal. All participants received a certificate of attendance at the end of the school. The programme was in accordance with that of the most recent schools and the schedule was planned with the aim of matching the different time zones (see Table 1).

Wednesday 13/10/2021	14:00	18:00	Prof. Fernando Sansò	General theory on gravity field
Friday 15/10/2021	14:00	18:00	ISG staff	Check of software installation on attendee's computers
Monday 18/10/2021	14:00	18:00	Prof. Nikos Pavlis	Global geopotential models
Tuesday 19/10/2021	14:00	18:00	Prof. Nikos Pavlis	Practical exercises: global geopotential models
Wednesday 20/10/2021	14:00	18:00	Prof. Rene Forsberg	Terrain effect computation and remove/restore, including practical exercises
Thursday 21/10/2021	14:00	18:00	Prof. Riccardo Barzaghi	Residual geoid estimation
Friday 22/10/2021	14:00	18:00	Prof. Riccardo Barzaghi	Practical exercises: residual geoid estimation
Tuesday 26/10/2021	14:00	18:00	Prof. Hussein Abd-Elmotaal Prof. Yan Wang Prof. George Vergos	The African Geoid project The Colorado experiment The computation of the Mediterranean Geoid
Wednesday 17/11/2021	14:00	18:00	Prof. Laura Sanchez	The height datum unification

Table 1: Schedule, programme and teachers of the 13th International School on "The Determination and Use of the Geoid".

As for the future, the 14th edition of the school has been already organized in cooperation with SIRGAS and will take place at Instituto Geográfico Nacional in Buenos Aires, Argentina, from 13 to 17 November 2023.

Finally, it has to be mentioned that ISG traditionally provides also tailored training courses on geoid estimation at Politecnico di Milano. Again, this activity became unfeasible because of the Covid-19 pandemic. Although the online option was considered, no training course was organized in the period 2019-2023, but we expect that the currently improved situation should give the possibility of restarting this activity as well. In this context, a visit of researchers and technicians from Jordan for their national geoid computation is planned for the end of this year.

ISG geoid repository and website update

In the last four years, the ISG archive of local, regional and continental geoid and quasi-geoid models has been continuously updated. Not only the latest release of a model is stored in the archive, but also previous versions are collected to keep memory of the work done in the past and to allow for comparisons. The full (or almost the full) series of the official geoid models are available for many countries. Three possible policy rules are considered for the model distribution: “public” if it can be freely downloaded from the website, “on demand” in case the authors asked to be informed before distributing the model, and “private” if it is just included in the archive but it cannot be distributed to the users. Therefore, the aim of the “private” policy is to inform users that a model exists without publishing any data through the ISG service. Currently, 275 models are available in the ISG database, whose composition is reported in Tables 2, 3 and 4 (last update of the statistics was on 31 May 2023). The global coverage of the available gridded geoid models, together with their spatial resolution, is shown in Figure 6.

Europe	90
North America	72
Asia	43
Oceania	22
Africa	21
South America	19
Antarctica	4
Arctic	4
Total	275

Table 2: Number of models per continent in the ISG archive.

< 1991	4
1991 – 1995	15
1996 – 2000	41
2001 – 2005	31
2006 – 2010	57
2011 – 2015	52
2016 – 2020	63
> 2020	12
Total	275

Table 3: Number of models per year in the ISG archive.

Public	209
On-Demand	21
Private	45
Total	275

Table 4: Number of models per policy-rule in the ISG archive.

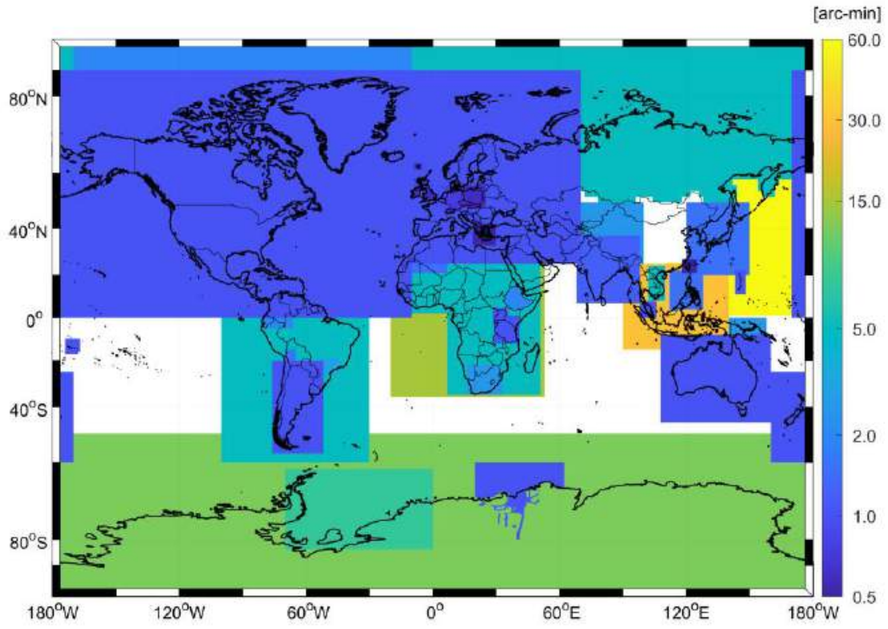

Figure 6: Spatial coverage of the gridded geoid models available at ISG. The colour-bar shows the highest spatial resolution per location (log10 scale, unit: arc-minutes).

The ISG website is updated simultaneously to the ISG archive. For each geoid model that is stored in the archive, a dedicated webpage is available on the website, containing information about the model name, year, authors, contact person, type (gravimetric, geometric or hybrid, geoid or quasi-geoid) and policy rule. There is a short description of the model characteristics, at least one bibliographic reference and a model figure. When a DOI is attributed to the model, the corresponding citation is provided, along with the data license (CC BY 4.0), see Figure 7.
If the model is classified as "public", the corresponding data file can be downloaded from the webpage in a unique ASCII format (.isg), whose specifications are provided in the website. After authors' authorization, the "on demand" models can be distributed to users in the same ASCII file format. The webpage of each model can be reached from a complete list of available geoids or by clicking on a geographical map.
Apart from the geoid repository, the website has been updated in the homepage and in the section dedicated to the software, adding some Matlab functions to read and write geoid and quasi-geoid models in ISG format. News section has been continuously kept up-to-date. Since no papers were submitted to Newton's Bulletin, a new editorial collocation will be investigated to make the journal more appealing for geodesists. The current homepage of the ISG service is shown in Figure 8. Some statistics on the website access are displayed in Figure 9.

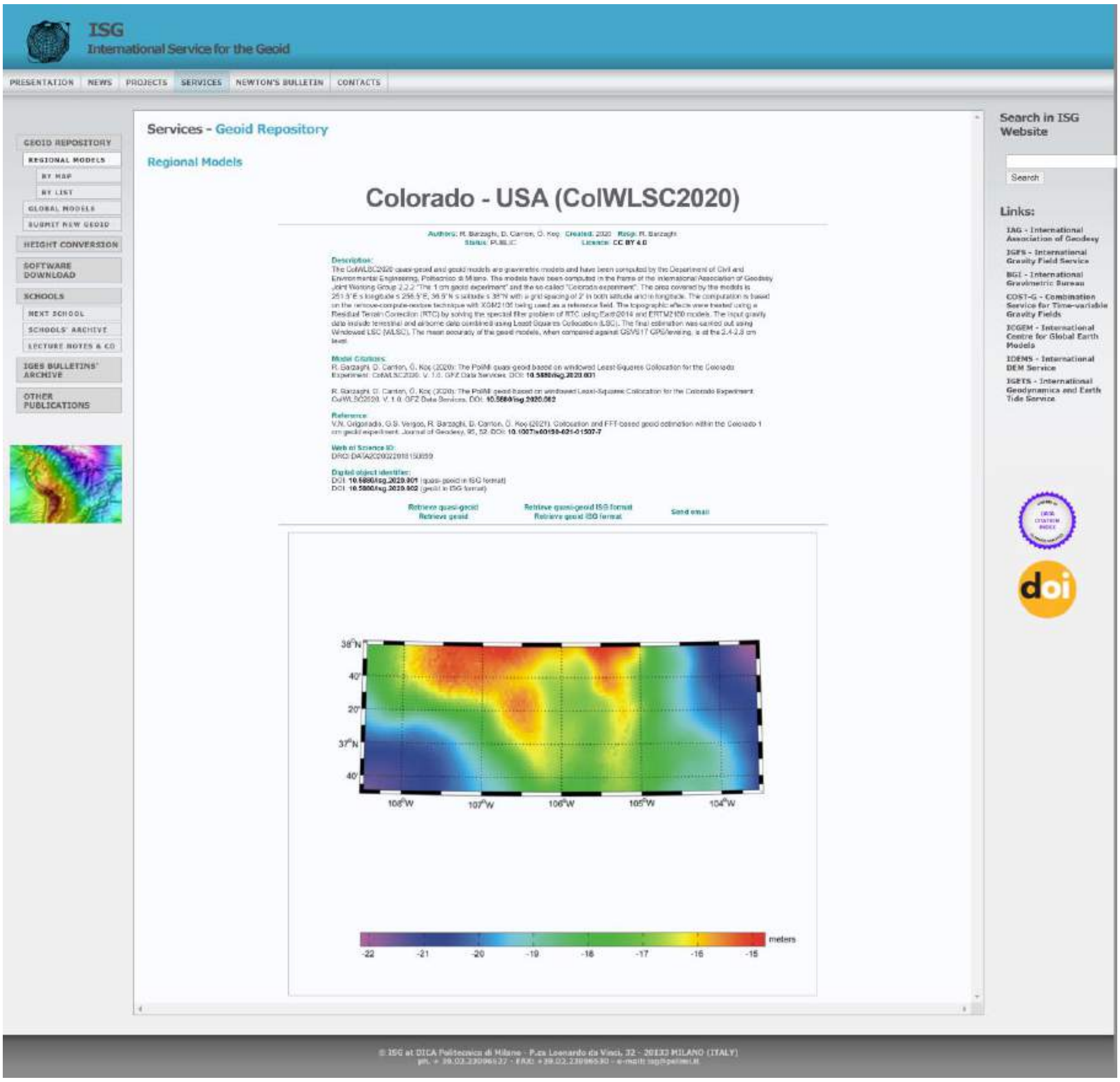

Figure 7: Example of a webpage describing a model stored in the geoid repository (https://www.isgeoid.polimi.it/Geoid/America/USA/Colorado20WLSC_g.html).

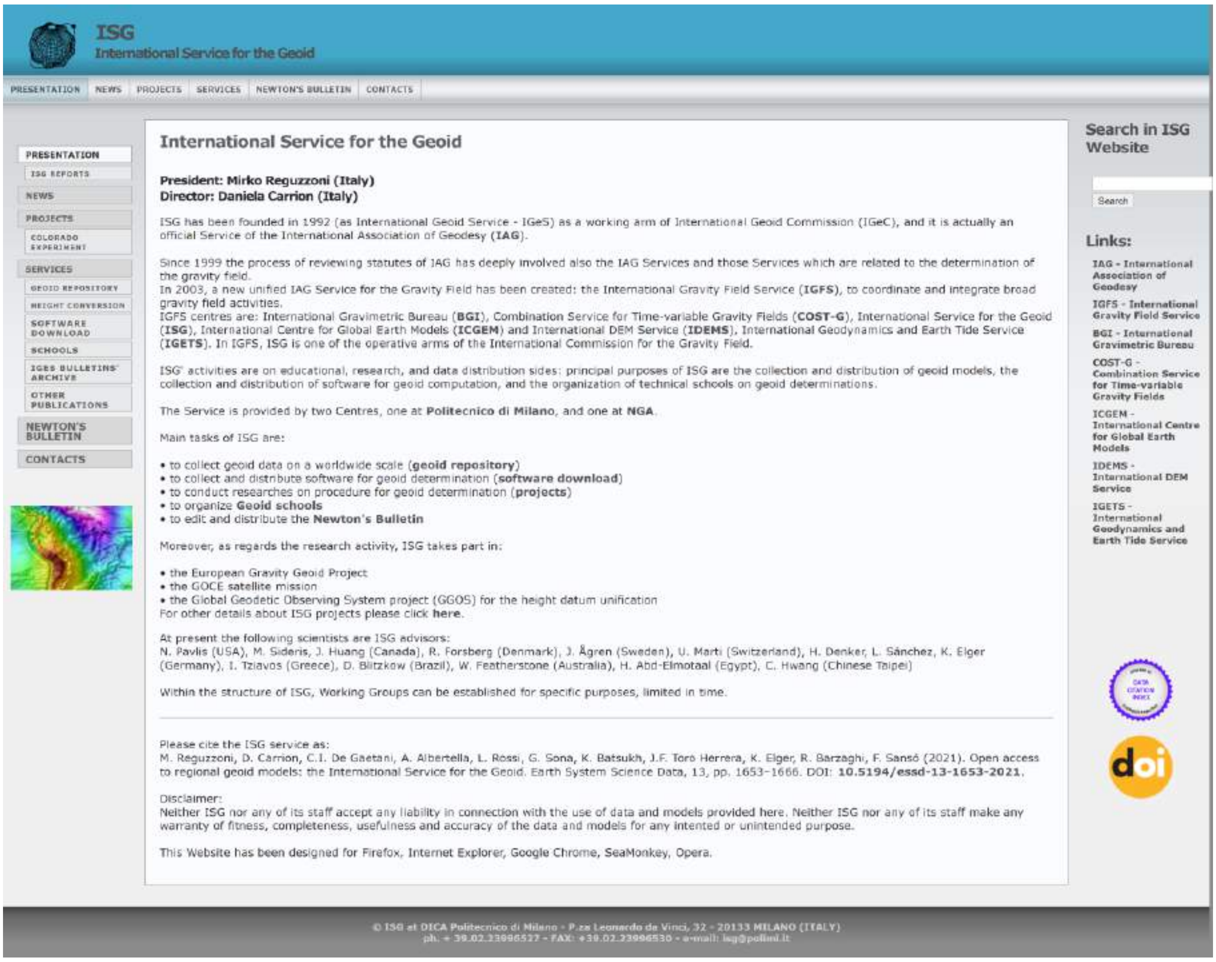

Figure 8: Homepage of the ISG website (https://www.isgeoid.polimi.it/).

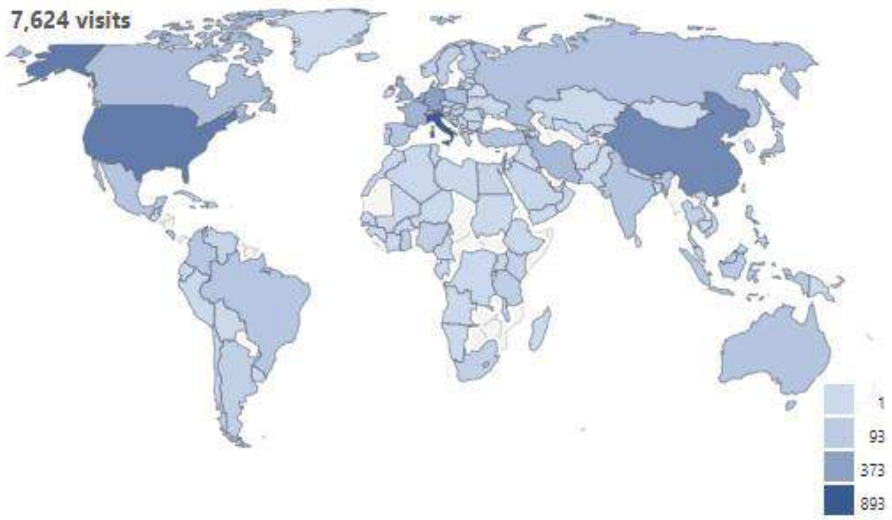

Figure 9: Statistics on the number of visitors per week (upper panel) and per country (lower panel) for the ISG website from December 2022 till May 2023 (last six months).

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Report by the Permanent Service for Mean Sea Level (PSMSL)

https://www.psmsl.org/

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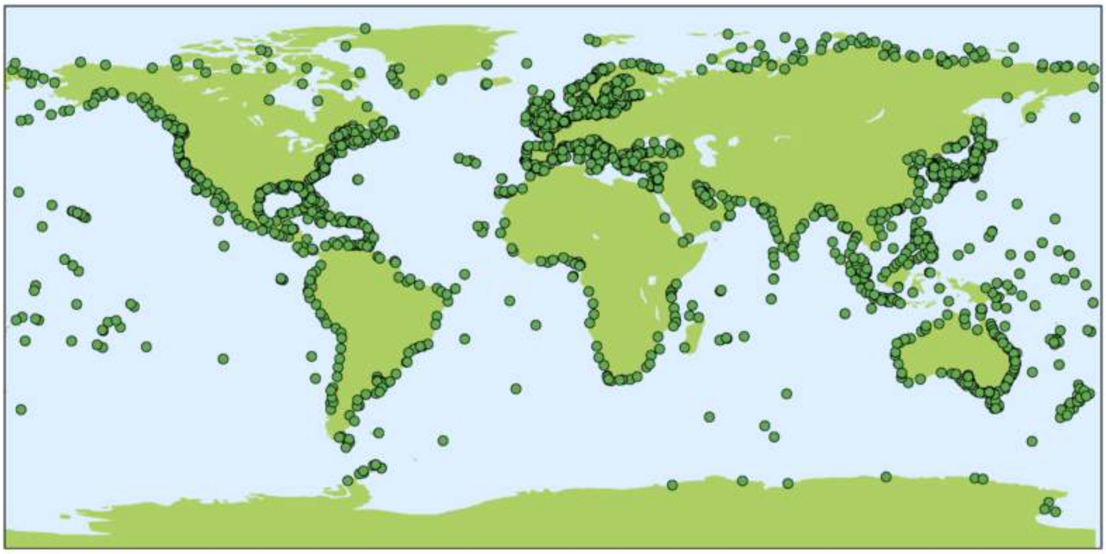
National Oceanography Centre, Liverpool, UK

Introduction

Since 1933, the Permanent Service for Mean Sea Level (PSMSL) has been responsible for the collection, publication, analysis and interpretation of sea level data from the global network of tide gauges. The PSMSL is hosted and funded by the National Oceanography Centre (NOC) and on the 1st November 2019, the NOC began operating as an independent self-governing organisation – a charitable company limited by guarantee.

The PSMSL is a service of the International Association of Geodesy (IAG), a Member of the Global Geodetic Observing System (GGOS) Bureau of Networks & Observations, and continues to be one of the main data centres for the International Association for Physical Sciences of the Oceans (IAPSO). The PSMSL operates under the auspices of the International Science Council (ISC) and reports formally to IAPSO's Commission on Mean Sea Level and Tides. The PSMSL is a regular member of the World Data System (WDS) of ISC.

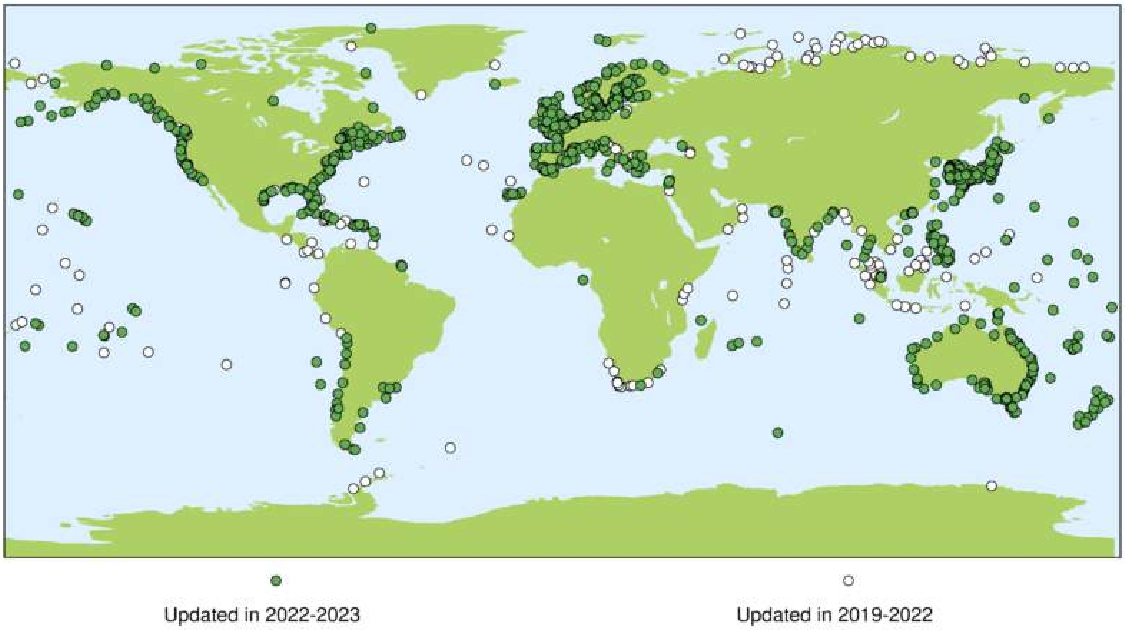


Stations in the PSMSL dataset

Changing sea levels will have a major impact on human life over the next 100 years. We need mean sea level data to study climate change, the impact of human activities on densely populated areas, the economic impacts of sea level rise and to plan coastal engineering. The mission of the PSMSL is to provide the community with a full service for the acquisition, analysis and interpretation of sea level data. Aside from its central role of operation of the global sea level data bank, the PSMSL provides advice to tide gauge operators and analysts. It occupies a central management role in the development of the Global Sea Level Observing System (GLOSS) and hosts important international study groups and meetings on relevant themes.

MSL data received

The database of the PSMSL contains over 72000 station-years of monthly and annual values of mean sea level (MSL) from over 2360 tide gauge stations around the world received from approximately 200 national authorities. On average, approximately 800 stations per year are entered into the database. This database is used extensively throughout the sciences of climate change, oceanography, geodesy and geology, and is the main source of information for international study groups such as the Intergovernmental Panel on Climate Change (IPCC).



Stations updated since 2019

The supply of data has remained constant over the last few years, although we have continued to see a decline in data supplied from Arctic gauges. We have also seen a reduction in supply from gauges in Africa, although new instruments have been installed, for example in Ghana.

We are also aware of a lack of delayed mode quality-controlled data being processed from gauges that are reporting in Near Real Time (NRT). This may be due to a lack of resource to process the data, such as funding, time or software required. There have been several new gauges installed in the Caribbean and we have been involved in projects to develop automatic quality control software, to try to process these data. There are also several gauges in South America that report NRT data, but do not process monthly and annual means.

GNSS-IR data processing and delivery

The PSMSL received funding from the European Union Horizon 2020 EuroSea project to create an international archive to preserve and deliver Global Navigation Satellite Systems Interferometric Reflectometry (GNSS-IR) data and to integrate these data with existing sea level observing networks. GNSS-IR sensors provide an alternative method to observe sea level. As well as recording the sea level, these sensors will also provide vertical land movement information from the site.

The GNSS-IR archive has been launched at https://psmsl.org/data/gnssir and provides delayed mode data from nearly 280 sites, each of which will has a dedicated page containing information about the site and links to the information about the GNSS receiver and nearby tide gauges. The distributed data includes information about the signal used to calculate each data point, allowing users to separate data using particular frequencies, or for example, to separate reflections from inside and outside a harbour. We have also demonstrated that these technologies can be used in near real time, and are working towards delivering this via interoperable ERDDAP servers (https://coastwatch.pfeg.noaa.gov/erddap/index.html).

The final processed data are generated from RINEX files obtained from a variety of data banks. Operators of GNSS sites near bodies of water can assist us by ensuring the signal-to-noise ratio is recorded in RINEX files, ideally using RINEX version 3 or 4, and recording all constellations and frequencies possible. You can also tell us about your site by emailing psmsl@noc.ac.uk - photographs and maps of the site are particularly useful for establishing areas around the receiver likely to produce genuine reflections off the surface of the water.

In 2020, the EuroGOOS tide gauge task team (of which several PSMSL staff are members) reviewed the metadata relating to tide gauges and co-located GNSS receivers on behalf of the European Environment Agency. There has historically been a lack of information regarding the geodetic ties between tide gauges and nearby GNSS receivers, often because they are operated by different organisations. Although this work focused on Europe, we would appreciate help to establish the ellipsoidal height estimation of tide gauge benchmarks globally:
https://eurogoos.eu/download/other_documents/task_teams/SONEL_EuroGOOS_GNSS@TG_metadata_campaign_report.pdf

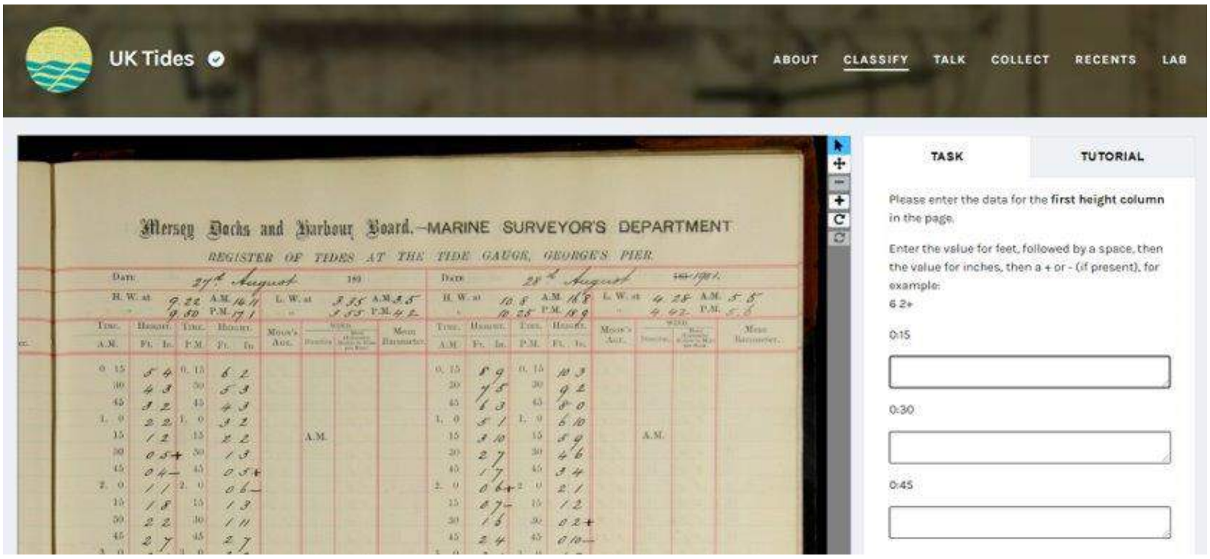
GNSS-IR sea level data portal

Data rescue

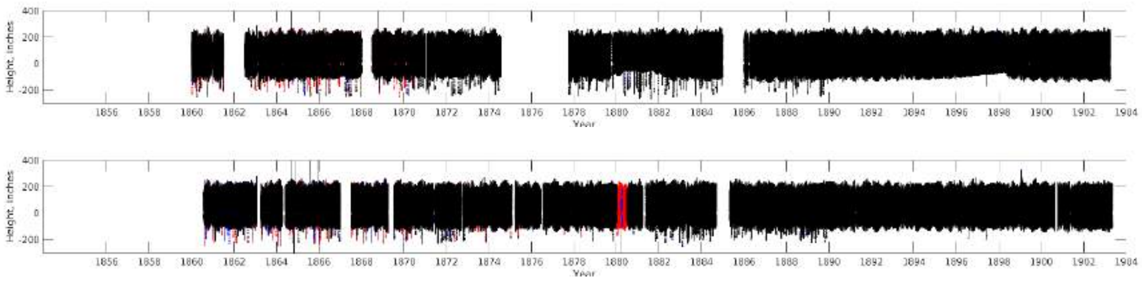
The PSMSL continues to play a leading role in sea level data rescue and helped organise the GLOSS/International Hydrographic Organization/International Union of Geodesy and Geophysics/IAPSO Sea Level Data Archaeology Workshop (meeting report - https://unesdoc.unesco.org/ark:/48223/pf0000373327) (Paris, March 2020). The main outcome of the workshop was the recommendation to establish a Data Rescue Working Group.

Attendees at the workshop on sea level data archaeology

Another recommendation was to explore a pilot project using the Zooniverse Citizen Science platform (https://www.zooniverse.org/). The UK Tides Citizen Science Project, built using the using the Zooniverse project builder (www.zooniverse.org/lab), was launched by the NOC in January 2021 to transcribe handwritten tide data from two gauges in Hilbre Island and George's Pier between 1853-1903. The handwritten historic data was transcribed by over 3,800 volunteers during the project, with over 315,000 columns of tide gauge data, including repeats used to cross-check entries, being completed. The study highlighted interesting challenges with handwriting, showing that using machine learning may still need a little help from people for a while to come. The global team made more than 6,000 classifications each week over the course of 12 months. The number of hours worked by the volunteers was the equivalent of five full-time research experts working solely on this data collection for a year (https://www.zooniverse.org/projects/psmsl/uk-tides).



UK Tides data entry interface



Digitised data from George's Pier, Liverpool (top) and Hilbre Island (bottom)

The data are now undergoing quality control, comparing the two tide gauge sites and other available parameters e.g. met data. The data for George's Pier, Liverpool, shows the gauge drying out at low water from 1896-1898. Computed tidal predictions will then be archived and made available for analysis, helping us to understand historical tide and sea level changes and enable us to predict future changes.

Developing metadata

It is important to the PSMSL that we are able to demonstrate where the data we distribute came from, give credit to those involved in the data lifecycle, and be able to produce a full audit trail. If we have updated records, we need to be able to document why. This information needs to be delivered alongside the data. Currently, it is difficult to uniquely identify tide gauge locations, sensors and suppliers, which can lead to duplicate data on data aggregator websites. It may also be difficult to get a true picture of the status of a network, such as how many gauges are currently operating.

We are working towards developing sea level metadata that will help make the data FAIR (Findable, Accessible, Interoperable and Reusable). Three technical working groups were set up following action items from the EuroGOOS Tide Gauge Task Team Meeting in July 2020. Andy Matthews is a member of the working group on site/station definition, Elizabeth Bradshaw is the lead of the working group on unique ID definition and both joined the working group on minimum metadata and common vocabularies and definition. Recommendations from these working groups formed part of the EuroSea project deliverable D3.3 New Tide Gauge Data Flow Strategy - https://oceanrep.geomar.de/52175/1/D3.3_New_Tide_Gauge_Data_Flow_Strategy.pdf.

We have also been working with the Global Ocean Observing System (GOOS) Observations Coordination Group (OCG) and OceanOPS to standardise ocean observing system network metadata. PSMSL staff attended the OCG Data Mapping and Metadata workshop in March 2021 and the OCG 12 Workshop: Data & Metadata in May 2021.

Global Extreme Sea Level Analysis (GESLA)-3

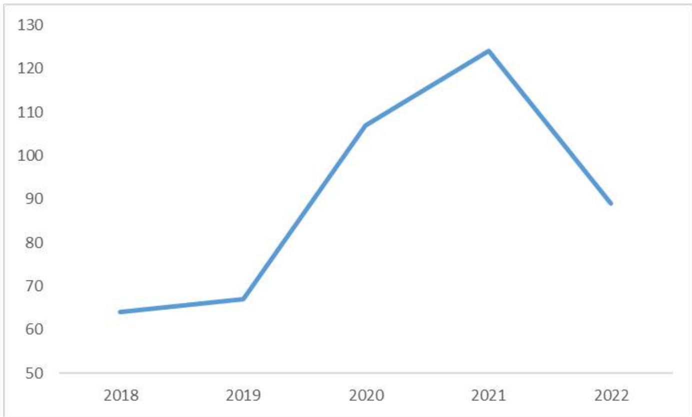
GESLA-1 and 2 were global coverage high frequency delayed mode datasets, developed originally for extreme sea level analysis. The current working group is led by Ivan Haigh (University of Southampton), with support from Marta Marcos (University of the Balearic Islands), Philip Woodworth (National Oceanography Centre, Liverpool), John Hunter (University of Tasmania), Arne Arns (University of Rostock, Germany), Ben Hague (Bureau of Meteorology, Australia) and Stefan Talke (California Polytechnic State University, USA).

In 2019 the working group began the next update of the dataset, GESLA-3. The new dataset will add more stations, station-years and remove duplicates. PSMSL staff have attended working group meetings and provided advice on updating the data format (including adding a netCDF option alongside the previous ASCII data), improving metadata, and considering data policies. We have also had discussions on improving the FAIR data compliance.

Papers using PSMSL data, 2018-2022

PSMSL collates statistics annually on the number of peer-reviewed published papers that use the PSMSL dataset. We search for papers that have cited Holgate et al (2013) as recommended (https://www.psmsl.org/data/obtaining/reference.php) or Woodworth and Player (2003), using Web of Science, ScienceDirect and Scopus. Several papers don't use the preferred reference format, so we also use full text searches for the terms "PSMSL" or "Permanent Service". We then manually filter the results to remove duplicates and papers that don't actually make use of the dataset, e.g. those that refer to tidal analysis software packages. Currently this method is likely to miss papers that use the PSMSL dataset due to indirect referencing, and our statistics are likely to be biased low.

Number of Citations



Year of publication

Papers per year citing the PSMSL dataset

In the years 2018-2022 there were 451 papers published in 182 journals. 14 of these journals had an Impact Factor greater than 10, and 38 papers were published in these 14 journals. The top three journals in terms of Impact Factor were Nature, Reviews of Geophysics and Nature Climate Change. The top three journals in terms of publications were Advances in Space Research (21 publications), Remote Sensing (18) and Geophysical Research Letters (16). It is interesting to note the wide-ranging subject areas of publication e.g. from climate studies, satellite altimetry, marine engineering, environmental assessment and geology.

In September 2019 the Intergovernmental Panel on Climate Change published the special report, which made use of the PSMSL dataset:

IPCC, 2019: Summary for Policymakers. In: IPCC Special Report on the Ocean and Cryosphere in a Changing Climate [H.-O. Pörtner, D.C. Roberts, V. Masson-Delmotte, P. Zhai, M. Tignor, E. Poloczanska, K. Mintenbeck, A. Alegría, M. Nicolai, A. Okem, J. Petzold, B. Rama, N.M. Weyer (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 3–35. https://doi.org/10.1017/9781009157964.001

The PSMSL dataset was used in the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, Climate Change 2021: The Physical Science Basis, to help estimate background rates of relative sea level change,

"Background rates of RSL change, including glacial-isostatic adjustment as well as other factors contributing to long-term vertical land motion, are estimated from tide-gauge data following the Gaussian process regression method of Kopp et al. (2014). The method was applied to annual-mean tide-gauge data downloaded from the Permanent Service for Mean Sea Level (Holgate et al., 2013) on 18 October 2020.".

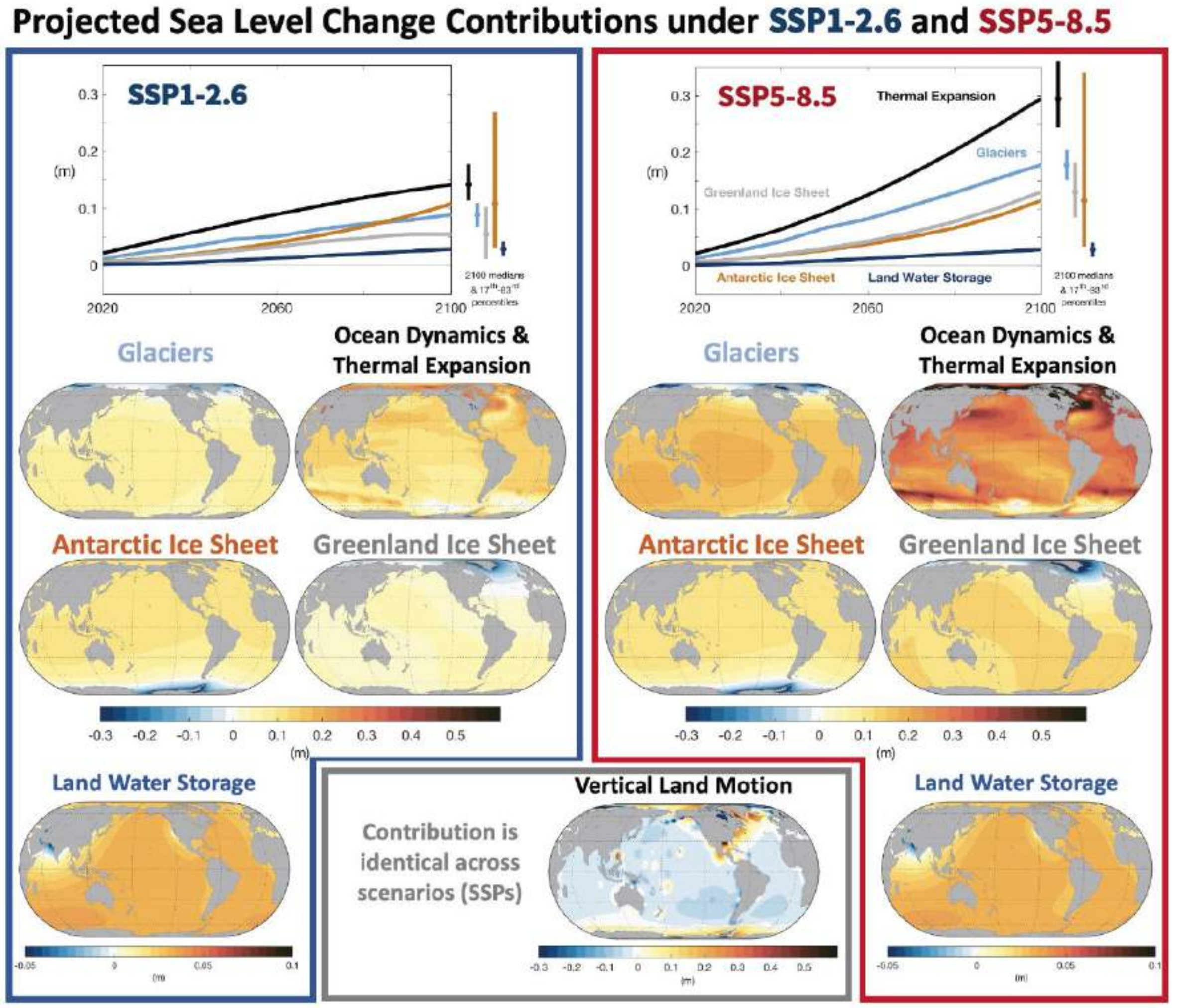


Figure 9.26 | Median global mean and regional relative sea level projections (m) by contribution for the SSP1-2.6 and SSP5-8.5 scenarios. Upper time series: Global mean contributions to sea level change as a function of time, relative to 1995–2014. Lower maps: Regional projections of the sea level contributions in 2100 relative to 1995–2014 for SSP5-8.5 and SSP1-2.6. Vertical land motion is common to both Shared Socio-economic Pathways (SSPs). Further details on data sources and processing are available in the chapter data table (Table 9.SM.9).

Figure from IPCC Chapter 9, using PSMSL data (IPCC, 2021)

Meetings and media

Andy Matthews attended OceanObs’19 (Hawaii, September 2019) and presented a poster “The Permanent Service for Mean Sea Level (PSMSL): looking ahead”, which focused on plans to incorporate new data resulting from projects such as the European Union funded Horizon 2020 AtlantOS into long term, internationally recognised data banks, and ongoing efforts to ensure distributed data follow the FAIR data management principles (i.e. making data findable, accessible, interoperable, reusable). Highlights of the meeting included discussion sessions on Ocean Best Practices, which stressed the need for best practice documents for quality control and tidal analysis of tide gauge data, and Open Source Software, which highlighted the importance of clear licensing statements on released data and code. Andy also had the opportunity to meet with the Director of the

University of Hawaii Sea Level Center to develop plans to distribute sea level data in a common, interoperable NetCDF format.

Elizabeth Bradshaw attended the Unified Analysis Workshop (Paris, October 2019) and gave a presentation "How the Permanent Service for Mean Sea Level is responding to change" as part of the Global Space Geodesy Infrastructure session. She also agreed to represent the PSMSL on the GGOS Working Group on Digital Object Identifiers (DOIs).

Andy Matthews and Elizabeth Bradshaw remotely attended the GGOS Days 2019 (November 2019) and participated in the discussions on the future of Focus Area 3 (Sea Level) and the Bureau of Networks and Observations open meeting. There was interest from the other services in the GNSS-IR at tide gauges.

Andy Matthews attended the Atmospheric Circulation Reconstructions over the Earth (ACRE) British Isles workshop (Reading, UK, February 2020) and gave a presentation on incorporating rescued data into the PSMSL dataset entitled "Recovered historical sea level data: what happens next?".

PSMSL staff organised and attended several sessions at the virtual European Geosciences Union (EGU) Assembly in May 2020. Svetlana Jevrejeva convened a session on sea level rise and Joanne Williams convened a session on tides. Andy Matthews discussed his presentation, "An International Data Centre for GNSS Interferometric Reflectometry Data for Observing Sea Level Change" (https://meetingorganizer.copernicus.org/EGU2020/EGU2020-9706.html) in the Sea level rise: past, present and future session. Elizabeth Bradshaw discussed her presentation "Sea level in the Global Geodetic Observing System" (https://meetingorganizer.copernicus.org/EGU2020/EGU2020-3054.html) in the Global Geodetic Observing System: Improving infrastructure for future science session. After the GGOS EGU session, Elizabeth Bradshaw joined the GGOS DOI working group in May 2020 and has attended the monthly meetings of the group, to contribute from a PSMSL perspective.

Both Elizabeth Bradshaw and Andy Matthews attended the eighth EuroGOOS Tide Gauge Task Team meeting by videoconference in July 2020. Andy Matthews gave a presentation on the PSMSL's role as a GLOSS data centre, discussing data flow, products and web tools for users.

Elizabeth Bradshaw and Andy Matthews attended the World Data System Members' Forum in September 2020. Elizabeth Bradshaw gave a presentation entitled "The Permanent Service for Mean Sea Level - Navigating the digital ocean", focussing on the main goals and challenges for PSMSL over the coming five years.

Andy Matthews attended the World Meteorological Organization theme 1 preparatory workshop "Changing landscape of weather, climate and water data" in September 2020.

PSMSL staff were involved in a number of posters and presentations at the AGU fall meeting in December 2020. Andy Matthews gave a presentation entitled, "Extending Sea Level Records by Rescuing Historical Data using a Citizen Science Platform" and gave an eLightning presentation on "Updating the Permanent Service for Mean Sea Level Archive for the TRUST Era". Elizabeth Bradshaw contributed to the GGOS presentation "GGOS Bureau of Networks and Observations: Network Infrastructure and Related Activities".

Andy Matthews, Elizabeth Bradshaw and Angela Hibbert were on the organising committee of the 1st EuroSea Tide Gauge Network Workshop, held in January 2021. Andy Matthews gave a presentation on the Citizen Science data rescue work and Elizabeth Bradshaw talked about "Global sea level data - moving towards a free and FAIR flow".

In January Elizabeth Bradshaw appeared on BBC local radio to discuss the UK tides Citizen Science project. Andy Matthews was interviewed by NPR radio about the same project, and the interview appeared in March on NPR morning edition.

In March the UK Met Office hosted a Climate Data Challenge virtual hackathon. Elizabeth Bradshaw attended on behalf of PSMSL as a sea level data expert, and Andy Matthews participated in the event, working on a project that used webcams and machine learning to look at wave overtopping.

In April, Andy Matthews attended the International Conference on Marine Data and Information Systems 2021 and presented “Using citizen science to rescue tide gauge data”.

Andy Matthews attended the EGU General Assembly 2021 on behalf of PSMSL and gave a presentation on “Rescuing historical sea level data using a citizen science platform”. Elizabeth Bradshaw also contributed to the presentation “The use of ERDDAP in a self-monitoring and nowcast hazard alerting coastal flood system” and the presentation given by the GGOS DOI Working Group, “News from the GGOS DOI Working Group”. Joanne Williams convened a session on tides and Svetlana Jevrejeva convened a session on sea level rise.

Elizabeth Bradshaw was on the organising committee of the UK sea level workshop, “The Science of Global and UK Sea-Level Projections: Progress, Challenges and Future Directions”. An executive summary and workshop report are available online from https://blogs.exeter.ac.uk/sealevelworkshop/files/2021/10/SeaLevelWorkshop_Report_22.11.21.pdf.

Angela Hibbert, Svetlana Jevrejeva and Elizabeth Bradshaw attended the United Natons Climate Change Conference (COP26) Earth Information Poster Session, representing the NOC with a poster entitled “Sea level rise poses economic threat to coastal communities”.

Elizabeth Bradshaw and Andy Matthews virtually attended the International Ocean Data Conference of the International Oceanographic Data Exchange (IODE) in February 2022. We presented posters on data rescue (“Using citizen science to rescue sea level data”, and GNSS-IR (“A new service providing water level data using GNSS sensors”).

Andy Matthews, along with several other staff from the NOC, attended the EGU Assembly in May 2022. Posters and talks were presented on GNSS-IR (“A new service providing sea level height data using GNSS sensors from around the globe”), data rescue (“Using citizen science to digitise 3 million hand-written tide-gauge data entries”), climate projects (“Sea level projections portal for communicating impacts to policymakers”), the GESLA dataset (“GESLA Version 3: A major update to the global higher-frequency sea-level dataset”) and the activities of GGOS (“An Update on the GGOS Bureau of Networks and Observations”).

Andy Matthews, Joanne Williams and Elizabeth Bradshaw gave a seminar, “Using citizen science to rescue data in danger” at the NOC in June 2022.

The seventeenth session of the GLOSS Group of Experts was held in Paris in November 2022. Andy Matthews, Chanmi Kim, Philip Woodworth and Svetlana Jevrejeva attended the meeting in person and Elizabeth Bradshaw and Lesley Rickards attended several of the sessions virtually. Andy gave a presentation on the recent activities of the PSMSL and the BODC and Elizabeth presented the work of the IOC Data Policy working group.

Elizabeth Bradshaw and Andy Matthews virtually attended the GGOS days meeting in November 2022. Elizabeth Bradshaw gave a presentation “The Permanent Service for Mean Sea Level – Nearly 90 years of service”, reporting on recent activities of the PSMSL. The presentation is available from GGOS Days 2022 - Day 2.

Elizabeth Bradshaw, Angela Hibbert and Andy Matthews were on the organising committee of the second EuroSea Tide Gauge Network workshop, held in May 2023. Andy Matthews gave a presentation on International programs and data portals.

Training and visitors

Unfortunately, during the period covered by this report, we have been unable to host as many visitors or training courses as we would typically have done. However, we did have visitors to the National Oceanography Centre, Liverpool in October 2019 who met with the sea level group. We also demonstrated the Doodson-Légé tidal prediction machine.

Angela Hibbert hosted one-to-one sea level and MATLAB training in Mozambique in February 2020. Angela then ran two virtual training courses to Madagascar, one on tides in December 2020, and one on sea level and extremes in January 2021.

Elizabeth Bradshaw, Angela Hibbert and Andy Matthews were on the organising committee for the 1st EuroSea Tide Gauge Network Workshop on in situ measurements held online in January 2021, and the hybrid 2nd workshop on tide gauge data quality control, held in May 2023.

In memoriam: David Pugh

We are saddened to report the death of Dr David Pugh, OBE (13 July 1943 - 1 August 2022). David was director of the PSMSL from 1979 to 1987. David was interested in many areas of sea level science, and he developed the bubbler gauge, still in use in the UK tide gauge network today. As director of the PSMSL, together with Klaus Wyrtki (Hawaii), David realised that in order to continue to develop the PSMSL, considerable further efforts in monitoring had to be made at the intergovernmental level. This led to the proposal for the Global Sea Level Observing System (GLOSS) of the Intergovernmental Oceanographic Commission (IOC). GLOSS was set up to establish a core network of ~300 stations around the world, with related regional networks and to serve scientific research in oceanography and climate change. Countries were required to make formal commitments for monitoring sea levels and for delivering data to the PSMSL.

For a more in-depth history of David's career in and contributions to oceanography, please see https://noc.ac.uk/files/documents/downloads/David_Pugh_In_Memoriam.pdf.

David Pugh, Elaine Spencer and Philip Woodworth, Bidston, 1985

Staff and advisory group

In 2019 Elizabeth Bradshaw replaced Lesley Rickards as head of PSMSL, with Lesley continuing to provide support as an advisor. We are grateful to Lesley for leaving PSMSL on a solid footing, with a clear remit.

In October 2022 we recruited a full-time data manager, Chanmi Kim, to replace the previous part-time data manager who left due to retirement. We would like to thank Kathy Gordon for her dedicated years of service. Kathy was instrumental in keeping the PSMSL running and ensuring we fulfil our fundamental purpose of acquiring data and making it available.

At the time of writing, three members of staff work for PSMSL and we are supported by the NOC Sea Level sub-group. The sub-group provides technical and scientific advice and represents PSMSL at meetings and workshops.

- Elizabeth Bradshaw, Head of the PSMSL
- Andrew Matthews, Technical lead, PSMSL
- Chanmi Kim, PSMSL data manager
- Lesley Rickards, outgoing Director
- Kathy Gordon, outgoing PSMSL data manager

NOC advisory group

- Angela Hibbert, capacity building
- Chris Hughes, scientific advisor
- Svetlana Jevrejeva, projections, impact and adaptation
- Joanne Williams, surges, extremes and tides
- Simon Williams, GNSS and vertical land motion (VLM)
- Chris Wilson, ocean circulation and modelling
- Philip Woodworth, scientific advisor

The PSMSL reports formally to the IAPSO Commission on Mean Sea Level and Tides (President Prof. G.T. Mitchum, USA). The PSMSL has been served by an external Advisory Group, but the group is currently under review and membership will be updated in 2023.

Summary

The period 2019-2022 saw some great challenges and big changes, but the PSMSL managed to maintain business as usual when adding new data to the databank, and we continued to explore new funding streams to help us develop our systems. We have been able to attend more conferences and meetings, due to not having to travel, and have focussed on the Citizen Science data rescue pilot study. We have seen an increase in the papers published using the PSMSL dataset, which may be due to a decrease in the ability of users to collect new data, and encouraging reuse of existing data.

We have worked on a number of European and International projects that have been aligned with the goals of the PSMSL, but we would like to maintain or increase our base level funding to allow us to perform system upgrades. 2023 will be the 90th anniversary of the PSMSL, and we will be hosting a conference later in the year to celebrate.

Future plans include:

- Improving our delivery of GNSS-IR data

The development of GNSS-Interferometric Reflectometry (GNSS-IR) and the use of low cost GNSS sensors to measure sea level may help fill in gaps in the current global tide gauge network. Installing GNSS-IR for sea level at a site would also enable the monitoring of vertical land motion, and help measure and maintain geodetic ties between tide gauges and GNSS receivers. We are developing a mechanism to deliver NRT GNSS-IR data through ERDDAP.

- Improving our metadata in the context of FAIR, TRUST and CARE principles

We are working towards FAIR (Findable, Accessible, Interoperable, and Reusable), TRUST (Transparency, Responsibility, User Focus, Sustainability and Technology) and CARE (Collective benefit, Authority to control, Responsibility, and Ethics) principles. The GLOSS 2012 implementation plan emphasised the need for an open data policy with timely, unrestricted access for all. Clarity over the source and provenance of data can be helped by developing unique identifiers for sites and instruments, and by the exchange of data via well-described data services using controlled vocabularies.

We will continue to improve ocean observation metadata and will work with the Observations Coordination Group and OceanOPS on the metadata harmonisation working group. We are working with the EuroGOOS tide gauge task team to improve lineage metadata. PSMSL staff lead or sit on the technical working groups for site/station definition, unique ID definition and minimum metadata definition.

We will undertake an international sea level data flow mapping exercise to help identify gaps, duplicates and differences in data streams.

- Sea level data rescue

We will participate in the new GLOSS data rescue working group that was formed at the Seventeenth Session of the Group of Experts for the Global Sea Level Observing System in November 2022. We will also issue the Zooniverse data with a DOI and publish a data rescue paper. We are currently exploring other techniques to digitise tide gauge charts, which may require the use of machine reading and learning techniques so data can be recovered algorithmically.

- Improving the PSMSL website

We will continue to update and improve the PSMSL website and are working towards distributing our data in netCDF format via our ERDDAP server. We will make available automatic quality control software in MATLAB and Python to encourage the quality control of sea level data and improve the data flow of monthly and annual mean sea level data. We are working on improving links with other services e.g., we will link to the GGOS IDS web service to show DORIS beacons at tide gauges.

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Annex 1: Selected publications

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Annex 2: Stations received by country, 2019-2022

Country	2019	2020	2021	2022
Åland Islands	1	0	1	0
American Samoa	1	1	1	1
Antarctica	4	2	1	1
Argentina	3	1	3	0
Australia	74	65	75	66
Bahamas	0	1	0	0
Bangladesh	0	1	0	0
Belgium	0	3	0	0
Bermuda	1	1	0	0
British Indian Ocean Territory	0	1	0	0
Canada	47	47	47	0
Cape Verde	0	1	0	0
Chile	15	14	14	14
China	5	6	0	6
Cocos (Keeling) Islands	1	1	1	1
Colombia	0	1	0	0
Cook Islands	1	2	1	1
Costa Rica	0	2	0	0
Croatia	5	0	1	0
Cuba	10	11	11	13
Curaçao	0	1	0	0
Dominican Republic	0	2	0	0
Ecuador	0	3	0	0
El Salvador	0	1	0	0
Fiji	3	2	2	2
Finland	13	0	13	0
France	36	35	33	41
French Guiana	2	1	1	2
French Polynesia	3	5	1	5
French Southern Territories	0	0	0	1
Georgia	0	2	0	0
Germany	8	0	3	6
Greece	15	16	16	0

Greenland	3	3	3	0
Grenada	0	1	0	0
Guadeloupe	0	1	1	1
Guam	2	2	2	2
Haiti	0	1	0	0
Hong Kong	6	5	5	5
Iceland	1	0	0	0
India	0	11	2	16
Indonesia	0	8	0	0
Ireland	0	0	0	2
Isle Of Man	1	1	1	1
Israel	7	3	3	3
Italy	3	3	2	3
Japan	98	98	97	97
Jersey	1	0	0	1
Kenya	0	2	0	0
Kiribati	1	3	1	1
Korea, Republic Of	43	45	0	43
Lithuania	1	0	0	0
Malaysia	18	0	0	0
Maldives	0	3	0	0
Malta	1	0	1	1
Marshall Islands	3	3	3	3
Martinique	1	1	1	1
Mauritius	2	2	2	2
Mayotte	1	1	0	1
Micronesia, Federated States Of	1	3	1	1
Monaco	1	1	1	1
Myanmar	0	2	0	0
Nauru	1	1	1	1
Netherlands, Kingdom Of The	11	11	11	11
New Caledonia	3	5	3	5
New Zealand	13	12	13	13
Northern Mariana Islands	0	1	0	0
Norway	23	23	23	23
Oman	0	3	0	0
Palau	0	1	0	0
Panama	1	0	1	0
Papua New Guinea	1	1	1	1
Peru	0	2	0	0
Philippines	22	22	7	22
Portugal	5	2	2	2
Puerto Rico	7	4	4	4

Réunion	1	2	1	2
Russian Federation	44	15	10	5
Saint Pierre And Miquelon	1	1	1	0
Samoa	1	1	1	1
Sao Tome And Principe	0	0	0	1
Senegal	0	1	0	0
Seychelles	0	1	0	0
Singapore	10	10	8	0
Slovenia	0	0	0	0
Solomon Islands	1	1	1	1
South Africa	9	0	0	0
South Georgia And The South Sandwich Islands	1	0	1	0
Spain	49	37	2	33
Svalbard And Jan Mayen	3	2	1	2
Sweden	27	25	24	48
Tanzania, United Republic Of	0	1	0	0
Thailand	5	5	5	5
Tonga	1	1	1	1
Trinidad And Tobago	0	0	0	1
Tuvalu	1	1	1	1
United Kingdom	31	27	32	32
United States	125	127	124	121
United States Minor Outlying Islands	1	3	1	1
Uruguay	2	0	0	1
Vanuatu	1	1	1	1
Viet Nam	0	2	0	0
Virgin Islands, U.S.	4	4	4	4
Wallis And Futuna	1	2	0	0

Annex 3: Data suppliers, 2019-2020 (number of stations)

Supplier	**Country**	**2019**	**2020**	**2021**	**2022**	**2023**
SERVICIO DE HIDROGRAFIA NAVAL, ARGENTINA	ARGENTINA	3	0	3	0	4
C.S.I.R.O., TASMANIA, AUSTRALIA	AUSTRALIA	0	0	0	0	1
NATIONAL TIDAL CENTRE	AUSTRALIA	78	78	81	81	37
MANLY HYDRAULICS LABORATORY	AUSTRALIA	11	2	9	0	8
AGENCY FOR MARITIME AND COASTAL SERVICES	BELGIUM	0	3	0	0	3
CANADIAN HYDROGRAPHIC SERVICE	CANADA	47	47	47	0	48
HYDROGRAPHIC AND OCEANOGRAPHIC SERVICE OF THE CHILEAN NAVY	CHILE	16	15	15	15	14

NATIONAL MARINE DATA AND INFORMATION SERVICE (NMDIS)	CHINA	5	6	0	6	5
HIDROGRAFSKI INSTITUT, SPLIT	CROATIA	5	0	1	0	0
NEGOCIADO DE HIDROGRAFIA, HAVANA, CUBA	CUBA	0	0	0	1	0
CUBAN NATIONAL TIDAL SERVICE	CUBA	10	11	11	12	0
DANISH NATIONAL SPACE CENTER	DENMARK	3	3	3	0	0
FINNISH METEOROLOGICAL INSTITUTE	FINLAND	14	0	14	0	14
SERVICE HYD. ET OCEAN. DE LA MARINE	FRANCE	50	52	41	57	0
INSTITUT GEOGRAPHIQUE NATIONAL, FRANCE	FRANCE	1	1	1	1	0
DEPT. OF OCEANOLOGY AND METEOROLOGY, GEORGIA	GEORGIA	0	2	0	0	0
BUNDESAMT FUR SEESCHIFFFAHRT UND HYDROGRAPHIE HAMBURG	GERMANY	8	0	3	6	8
HELLENIC NAVY HYDROGRAPHIC SERVICE	GREECE	15	16	16	0	15
HONG KONG OBSERVATORY	HONG KONG	6	5	5	5	0
ICELANDIC COAST GUARD - HYDROGRAPHIC DEPT.	ICELAND	1	0	0	0	1
SURVEY OF INDIA	INDIA	0	11	2	16	12
ORDNANCE SURVEY OFFICE, DUBLIN	IRELAND	0	0	0	2	0
ISRAEL OCEANOGRAPHIC AND LIMNOLOGICAL RES. LTD.	ISRAEL	1	0	0	0	1
SURVEY OF ISRAEL	ISRAEL	6	3	3	3	2
INSTITUTO IDROGRAFICO DELLA MARINA, GENOVA	ITALY	0	0	0	1	0
CNR - ISTITUTO DI SCIENZE MARINE	ITALY	1	1	1	1	0
ISPRA	ITALY	0	0	0	0	7
ARPAE - EMILIA ROMAGNA	ITALY	1	1	1	1	0
UNIVERSITY OF BOLOGNA	ITALY	1	1	0	0	0
JAPAN OCEANOGRAPHIC DATA CENTRE, M.S.A.	JAPAN	20	20	20	20	20
JAPAN METEOROLOGICAL AGENCY	JAPAN	53	53	52	52	51
GEOGRAPHICAL SURVEY INSTITUTE	JAPAN	25	25	25	25	25
PUBLIC BUILDING AND WORKS, JERSEY	JERSEY	0	0	0	0	1
KOREA HYDROGRAPHIC AND OCEANOGRAPHIC AGENCY (KHOA)	KOREA, REPUBLIC OF	43	45	0	43	0
GEODETIC INSTITUTE, VILNIUS GEDIMINAS TECHNICAL UNIVERSITY	LITHUANIA	1	0	0	0	0
DEPARTMENT OF SURVEY AND MAPPING	MALAYSIA	18	0	0	0	0
MALTA MARITIME AUTHORITY	MALTA	1	0	1	1	0

METEO - FRANCE	MARTINIQUE	0	1	1	1	0
METEOROLOGICAL SERVICES, MAURITIUS	MAURITIUS	2	2	2	2	2
RIJKSWATERSTAAT	NETHERLANDS, KINGDOM OF THE	11	11	11	11	0
LAND INFORMATION NEW ZEALAND (LINZ)	NEW ZEALAND	12	11	12	12	0
STATENS KARTVERK	NORWAY	0	0	0	0	1
NORWEGIAN MAPPING AUTHORITY	NORWAY	24	24	24	24	24
NATIONAL MAPPING AND RESOURCE INFORMATION AUTHORITY	PHILIPPINES	22	22	7	22	0
HYDROGRAPHIC INSTITUTE	PORTUGAL	5	2	2	2	2
WORLD DATA CENTER B1	RUSSIAN FEDERATION	6	6	0	6	0
ARCTIC AND ANTARCTIC RESEARCH INSTITUTE	RUSSIAN FEDERATION	40	10	10	0	0
MARITIME PORT AUTHORITY OF SINGAPORE	SINGAPORE	10	10	8	0	10
HYDROMETEOROLOGICAL INSTITUTE OF SLOVENIA	SLOVENIA	0	0	0	0	1
DIRECTORATE OF HYDROGRAPHY, S.A.	SOUTH AFRICA	9	0	0	0	3
INSTITUTO GEOGRAFICO NACIONAL, MADRID	SPAIN	0	0	2	0	0
INSTITUTO ESPANOL DE OCEANOGRAFIA	SPAIN	11	0	0	0	0
DR. JOSEP PASCUAL MASSAGUER	SPAIN	1	1	0	0	1
PUERTOS DEL ESTADO	SPAIN	36	35	0	33	0
GEOLAB	SPAIN	1	1	0	0	0
SWEDISH MET. AND HYD. INSTITUTE	SWEDEN	27	25	24	24	0
SWEDISH MARITIME ADMINISTRATION	SWEDEN	0	0	0	20	0
SWEDISH NUCLEAR FUEL AND WASTE MANAGEMENT COMPANY	SWEDEN	0	0	0	1	0
GOTHENBURG HARBOUR	SWEDEN	0	0	0	3	0
OCEANOGRAPHIC DIVISION, HYDROGRAPHIC DEPT.	THAILAND	5	5	5	5	0
HYDROGRAPHIC UNIT, PORT OF SPAIN	TRINIDAD AND TOBAGO	0	0	0	1	0
N.O.C.	UNITED KINGDOM	36	28	34	34	30
N.O.A.A. / N.O.S.	UNITED STATES	143	140	138	135	133
PANAMA CANAL COMMISSION	UNITED STATES	1	0	1	0	0
UNIVERSITY OF HAWAII SEA LEVEL CENTER	UNITED STATES	1	55	0	2	0
SOHMA	URUGUAY	2	0	0	1	2

Annex 4: Acronyms

ACRE	Atmospheric Circulation Reconstructions over the Earth
DOI	Digital Object Identifier
EGU	European Geosciences Union
EuroGOOS	European Global Ocean Observing System
GESLA	Global Extreme Sea Level Analysis
GGOS	Global Geodetic Observing System
GLOSS	Global Sea Level Observing System
GNSS-IR	Global Navigation Satellite Systems Interferometric Reflectometry
GOOS	Global Ocean Observing System
GRL	Geophysical Research Letters
IAG	International Association of Geodesy
IAPSO	International Association for Physical Sciences of the Oceans
IHO	International Hydrographic Organization
IPCC	Intergovernmental Panel on Climate Change
ISC	International Science Council
IUGG	International Union of Geodesy and Geophysics
JGR	Journal of Geophysical Research
NERC	Natural Environment Research Council
NOAA	National Oceanic and Atmospheric Administration
NOC	National Oceanography Centre
NOS	National Ocean Service
NRT	Near Real Time
MSL	Mean Sea Level
OCG	Observations Coordination Group
PNAS	Proceedings of the National Academy of Sciences of the United States of America
PSMSL	Permanent Service for Mean Sea Level
WDS	World Data System

Journal of Geodesy

http://link.springer.com/journal/190

Editor-in-Chief: Jürgen Kusche (Germany)
Assistant-Editor-in-Chief: Peiliang Xu (Japan)

Activity Report

Journal of Geodesy (JoG) is an international journal concerned with the science of geodesy and related inter-disciplinary sciences. JoG is the official scientific journal of the IAG and it publishes monthly research articles, review papers, and short notes. Its publishing company, based on an agreement with IAG, is Springer Heidelberg.

The Editor-in-Chief (EiC) is responsible for the scientific content of the journal. He, and since 2021 the Assistant-Editor-in-Chief (AEiC), make the final decision on whether a manuscript is accepted for publication, advised by an Editorial Board (EB). The 2019-2023 EB comprises currently 27 members (associate editors) from 16 countries:

T. Balz (China), J. Benveniste (Italy), T. v. Dam (Luxemburg), Y. Gao (Canada), S.-C. Han (Australia), S. Glaser (Germany), B. Gunter (USA), C. Huang (China), U. Hugentobler (Germany), A. Jäggi (Switzerland), T. Hadas (Poland), A. Klos (Poland), H.-J. Kutterer (Germany), F. Lemoine (USA), Z. Malkin (Russia), V. Michel (Germany), F.G. Nievinski (Brazil), N. Penna (UK), R. Riva (The Netherlands), M. Schindelegger (Germany), Y. Shen (China), B. Soja (Switzerland), I. Tziavos (Greece), M. Vermeer (Finland), P. Wielgosz (Poland), Y. Yokota (Japan), Y. Yuan (China)

JoG uses the Editorial Manager (EM), a web-based peer review system, which allows easy manuscript submission, provides author information and e-mail updates, and helps reducing the turnaround time. In recent years, EM has added automated workflows e.g. for plagiarism checking and authorship change requests.

JoG publishes special issues on topics of general interest to the geodetic community, where all contributions must be of highest standards (these are sometimes called “topical collections”). The most recently published and nearly completed Special Issues were devoted to the topics “Reference Systems in Physical Geodesy” and “CONT17”.

Indeed, JoG would like to encourage authors to (1) submit review papers and (2) initiate Special Issues related to topics of high interest to the geodetic community. JoG publishes also short notes once in a while, when topics are timely and of interest to a broad readership.

Impact Factor

The Impact Factor (IF) of JoG has shown some variability over the last years; the current (2021) Impact Factor is 4.809, based on Clarivate's JCR (Journal Citation Report). Measured by the IF, JoG is 2021 among the top journals within Springer's topical journal collections: rank 13 out of 34 in Remote Sensing journals (i.e. Q2), and rank 16 out of 87 in Geochemistry and Geophysics journals (i.e. Q1). For the last years JoG has seen the following evolution of the IF (the 2022 IF will likely be published in July 2023):

Table 1: JoG Impact Factor for 2015-2019

Year	Impact Factor
2015	2.486
2016	2.949
2017	4.633
2018	4.528
2019	4.806
2020	4.260
2021	4.809

Submissions and acceptance

The number of submissions has steadily increased with on average about 10% additional submissions each year, after a slight dent in 2021. The countries with the highest number of submissions are China, Germany, USA, , Egypt, Poland, Turkey, Canada, Ethopia and France.

Table 2: JoG submitted and accepted manuscripts (per calendar year) for 2015-2022

Year	submitted	accepted
2015	247	77
2016	271	97
2017	260	97
2018	307	103
2019	364	101
2020	389	114
2021	338	103
2022	349	91

The acceptance rate has slightly gone down to around 25% now. This is mostly due to the fact that the rate of formal rejections has increased over recent years (e.g. submissions that miss the scope of the JoG, or that lack mandatory declarations such as the Author Contribution Statement or the Data Availability Statement).

Review statistics and turnaround time

The JoG knows a nominal review period of 28 days. Table 3 shows some statistics of the review process. Indeed, the average number of days to complete an initial review is nearly stable at about 32 – 35. However, as it is obvious from the table, in order to obtain three reviews (which is nominal) the associate editors have to invite, on average, five to six potential reviewers. The other observation is that turnaround time measured in days from submission to first decision had increased in 2019; this can be largely explained by the increased editorial load from receiving more submissions but it appears to be brought back since 2020.

The EB has formulated and communicated to Springer a number of suggestions on how the turnaround times could be improved via modifications in the submission system (e.g. reviewer recommendations, reminder scheduling).

Table 3: JoG number of review invitations and completed reviews and average turnaround time (submission to first decision in days) for 2015-2022

Year	Review invitations	Completed reviews	Average Turnaround time
2015	953	596	56
2016	1297	787	60
2017	1212	761	70
2018	1446	829	70
2019	1717	849	92
2020	1796	953	79
2021	1574	746	86
2022	1474	702	83

Editorial policy

The journal’s editorial policy is continuously developed through discussions among the EB, with Springer and with the IAG EC, and based on author and reviewer communications. A summary of the most important editorial policies and recent updates with respect to workflows is provided in Kusche and Xu (2021).

Several editors experienced difficulties in finding qualified reviewers for manuscripts of certain topics, and this contributes to delays in turnaround times. Kusche and Xu (2023) have published an opinion document in the IAG Newsletter, where they call on thesis supervisors, geodesy lecturers, (IAG) conferences, workshops and summer schools organizers to include scientific reviewing in the educational packages for early career scientists, on geodetic institutions to allow and encourage staff scientists spending time for reviewing or editing papers as a service to the community, and on job and tenure reviewing committees to recognize reviewing as a valuable service to the society.

Nowadays, journal self-citation rates (the number of times that papers in a given journal have been cited by other papers in the same journal, compared to the total number of citations that these papers receive) are closely monitored by publishers and bibliometric institutions. The contribution of JoG self-citations to the IF is around 17% which is in a medium range compared to other geoscientific journals. It is the EB’s policy to prevent a further growth of the self-citation rate.

The EB had also clarified its point of view regarding the use of Large Language Models in writing for the Journal, in addition to Springer’s policy.

IAG Young Authors Award

This award is to draw attention to important contributions by young scientists in the Journal of Geodesy and to foster excellence in scientific writing. On the basis of suggestions made by the EB, the EiC provides a shortlist of award candidates to the IAG EC every two years.

IAG Best Reviewer Award

In recognition of the above mentioned 'reviewer crisis', the IAG EC had agreed to create a Best Reviewer Award, to foster excellence in reviewing in the Journal. On the basis of suggestions made by the EB, the EiC provides a shortlist of award candidates to the IAG EC every two years, similar as with the Young Author Award. The Best Reviewer Award will be presented for the first time during the IUGG 2023.

Kusche J. and P. Xu (2021): Journal of Geodesy: editorial policies in view of increased new paper submissions, *J. Geodesy* 95:61

Kusche J. and P. Xu (2023): Good reviewing needs recognition: a new IAG best reviewer award for the Journal of Geodesy. Is peer review important for geodesists? *IAG Newsletter*, January 2023

IAG Symposia Series

Editor-in-Chief: Jeff Freymueller, USA
Assistant Editor-in-Chief: Laura Sánchez, Germany

Transition to Electronic Books and Open Access

A key decision was made for the series during the 2015-2019 period, which was to complete the transition from paper books to electronic books, and for the papers/volumes to be Open Access. These decisions came into effect starting with the Montreal volume for papers presented at the 2019 IUGG meeting. A new contract is now in place with Springer, and this makes small volumes much more affordable than in the past. IAG pays for the open access fees for the volumes for the General Assemblies and Scientific Assemblies, and depending on meeting size may need to contribute to the cost for other symposia. The new policies are:

- All IAG sponsored Symposia are expected to publish a Proceedings volume in the series
- Symposia organizers will include $50 in their registration fees for the cost of the Proceedings

The IAGS series editors are not certain whether all symposia organizers are indeed dedicating a portion of the fees to cover the cost of the Proceedings, although some definitely are doing so. It would be useful for the IAG Secretary General to collect those funds soon after each Symposium and hold them until publication, as the fees will not be due to Springer for 1-2 years after the Symposium.

The Springer contract contains a few breakpoints where the fees increase (based on the number of pages). In Fall 2022, we decided to produce a single combined volume for the three IAG Symposia held within about a 6-week span that year. This proved to be a cost-effective approach, which should be about half the cost of producing three separate, very small volumes.

Completion of pre-2019 Symposia volumes

The publishing of two older volumes, for Symposia held before July 2019, was completed in 2019-2023:

- Volume 150. Fiducial Reference Measurements for Altimetry: Proceedings of the International Review Workshop on Satellite Altimetry Cal/Val Activities and Applications
- Volume 151. Proceedings of the IX Hotine-Marussi Symposium

Completed volumes from Symposia in 2019-2023

The COVID-19 pandemic caused delay or cancellation of a number of planned symposia in 2020 and 2021. Three symposia have been held that have volumes in the series:

- Volume 152. Beyond 100: The Next Century in Geodesy *[Montreal IUGG]*
- Volume 153. 5th IAG Symposium on Terrestrial Gravimetry: Static and Mobile Measurements
- Volume 154. IAG Scientific Assembly: Geodesy for a Sustainable Earth *[Beijing IAG]*

Ongoing volumes

Because of COVID-19 pandemic delays, several IAG Symposia were held closely together in Fall 2022. As a result, we are preparing a combined volume for these three Commission 4 Symposium, GGHS 2022, and REFAG 2022. The Hotine-Marussi symposium has also produced its own volume.

- Volume 155. X Hotine-Marussi Symposium *[25 papers submitted. editorial work in late stages, working on final papers]*
- Volume 156. Gravity, Positioning and Reference Frames: Proceedings of three IAG Symposia in Fall 2022 *[35 papers submitted, about 50% of papers at final decision]*
  - *GGHS2022: 9 papers*
  - *REFAG 2022: 18 papers*
  - *Commission 4: 8 papers*

Restricting papers to those presented at IAG Symposia

There was an awkward situation that arose with the IX Hotine-Marussi volume. One paper was submitted that had not been presented at the symposium, although the author attended. The paper was peer reviewed through the regular process, handled by one of the symposium organizers as AE, and then accepted based on that review. The paper happened to be critical of some ideas presented by one of the presentations made at the meeting, and this was a cause of unhappiness on the part of those who had been criticized (and whose own paper was not published). To our knowledge, this is the first time that we have had a paper submitted that was not presented at the symposium; the usual case is that people present at the meeting but do not submit a paper.

After discussion with the IAG EC, we decided that papers in the series needed to be based on presentations that were made at the symposium in question. There were pros and cons discussed by the EC, and there will be judgement calls needed given that sometimes work is improved between the meeting and the paper submission, and we do not wish to discourage this. We are asking Springer if they can add a question to their website submission form to identify the presentation at the meeting that the paper is based upon, and checking this is now part of our standard procedure when handling papers.

Other Notable Points and Future Outlook

- Communication with Springer has not always been simple, as it was not always clear who should be the point of contact for different things. This has been clarified, and Annett Büttner is the primary point of contact there for the series, for issues that go above the purely technical (such as handling of papers in EM). This is working more smoothly than in the past.
- In consultation with the EC, we decided to increase the maximum paper length for IAG Symposia series papers from 6 pages to 8 pages, or 10 pages for invited papers. The editors may extend these limits further for individual papers, if needed. Because of the way the Springer contract scales this is unlikely to increase costs for IAG (it is unlikely but possible that it would bump a volume up to the next price tier).
- Indexing of the volumes remains a challenge. Springer needs to submit the volumes to the indexing services, but then those services decide whether or not to index. Indexing is critical for the future success of these volumes, and we have had to repeatedly remind Springer to submit and appeal as needed.