UPC-IonSAT recent contributions to ionospheric modelling: monitoring with Global Ionospheric Maps of VTEC in general, storm, polar and real-time conditions

IGS 2022 Virtual Workshop “Science from Earth to Space”
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by

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Summary

We are going to present an executive summary of the positive answers recently found on the following questions on the Global Ionospheric Maps (GIMs) of Vertical Total Electron Content (VTEC): UQRG **rapid** & UADG **real-time** (RT) GIMs generated by UPC-IonSAT for IGS with a time res. of 15 minutes:

Can the rapid GIMs:

1) show **realistic features of the polar ionosphere** electron content distribution?

2) provide **reliable estimation of the spatial and temporal components of the VTEC gradients** with comparable results to the corresponding indices proposed and generated from raw GNSS data (Jakowski & Hoque 2019)?

3) provide a **sensitive Ionospheric storm scale index**, with comparable results to the I-scale index proposed and generated by (Nishioka et al. 2017) from raw GNSS data?

4) provide a general **reliable monitoring of the ionospheric VTEC**?

5) **Can the RT VTEC interpolation**, one bottleneck in the accuracy of RT-GIMs, **be significantly improved**?

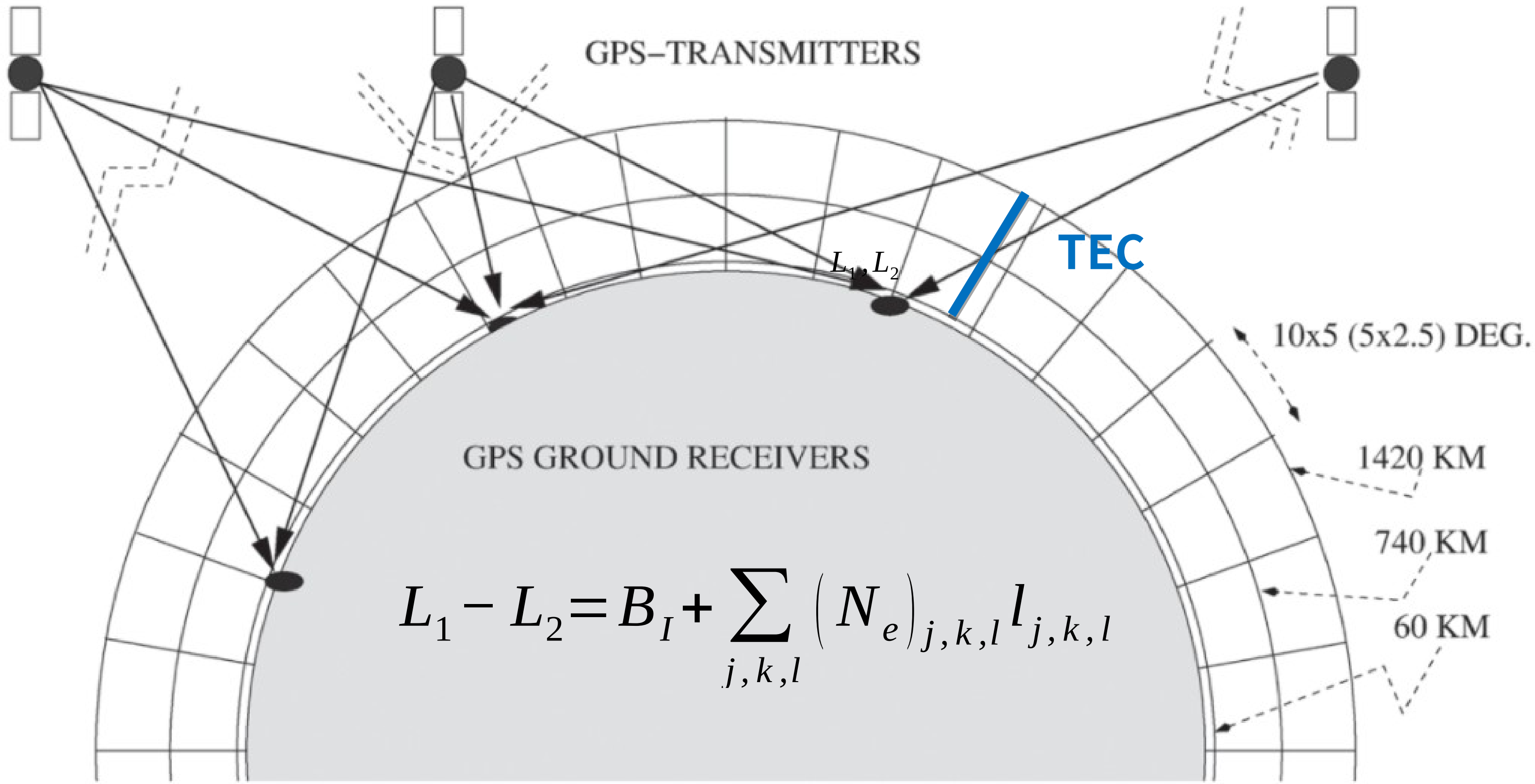
Context: GNSS-based UQRG Global Ionospheric Map (GIM)

LOS Carrier phases in length units: **L1-L2** (measurement, corrected from wind-up)

Associated L1-L2 ambiguity, **BI** (unknown)

Electron density of LOS illuminated voxels: **Ne** (unknowns)

Straight line LOS length within given voxel: **l_{j,k,l}**



$$L_1 - L_2 = B_I + \sum_{j,k,l} \left(N_e \right)_{j,k,l} l_{j,k,l}$$

UPC Quarter-of-an-hour time resolution Rapid GIM (UQRG)

Two-Layer voxel tomographic estimation **without ionospheric background model** and with **dual-frequency carrier phase input data only**. with in-house TOMION software.

Kriging **interpolation** which **preserves the details**

Resolution: 15min x 5º x 2.5º in time x lon.xlat

Context: TOMION software

- TOMION is a data driven ionospheric model originally developed by MHP, in continuous development during the latest 25 years
- It allows a tomographic estimation of the density of free ionospheric electrons from GNSS carrier phase dual-frequency data only, without any background model.
- It incorporates a Kalman filter and a kriging-based interpolation for the vertically integrated electron density (the vertical total electron content, VTEC, see Hernández-Pajares et al. 1997, 1999, Orús et al. 2005).
- TOMION is the software used in the generation of UPC-IonSAT global ionospheric maps (GIMs) of VTEC for the International GNSS Service (IGS), such as the UQRG one, one of the outperforming GIMs, or even the best behaving GIM in IGS (Hernández-Pajares et al. 2009,2017, Roma-Dollase et al. 2018).
- UQRG GIM produced by TOMION is, for instance, able to detect realistic features of the polar ionosphere as well (Hernández-Pajares et al. 2020a) and to provide a realistic and sensitive storm index (Qi et al. 2021).
- The tomography performed by TOMION is able to ingest different geometries and types of input measurements (Hernández-Pajares et al. 2020b), in agreement with independent measurements and models (Kotov et al. 2018, 2019).

1) Can the rapid GIMs show realistic features of the polar ionosphere electron content distribution?

- The electron content distribution of the north and south polar ionosphere from 2001 to the beginning of 2019 was analyzed by using the UQRG global ionospheric map (GIM) of vertical total electron content (VTEC), computed every 15 min by UPC-IonSAT with a tomographic-kriging combined technique. We first showed that the accuracy of UQRG GIM is slightly better than that of the GIMs of other analysis centers on the whole and also over both poles.
- Second, we showed examples of polar VTEC features in UQRG GIM, previously reported by different authors and with higher-resolution techniques.
- Third, by means of an unsupervised clustering algorithm, learning vector quantization, we characterized the main features of the ionospheric electron content climatology, separately for the north and south polar regions.

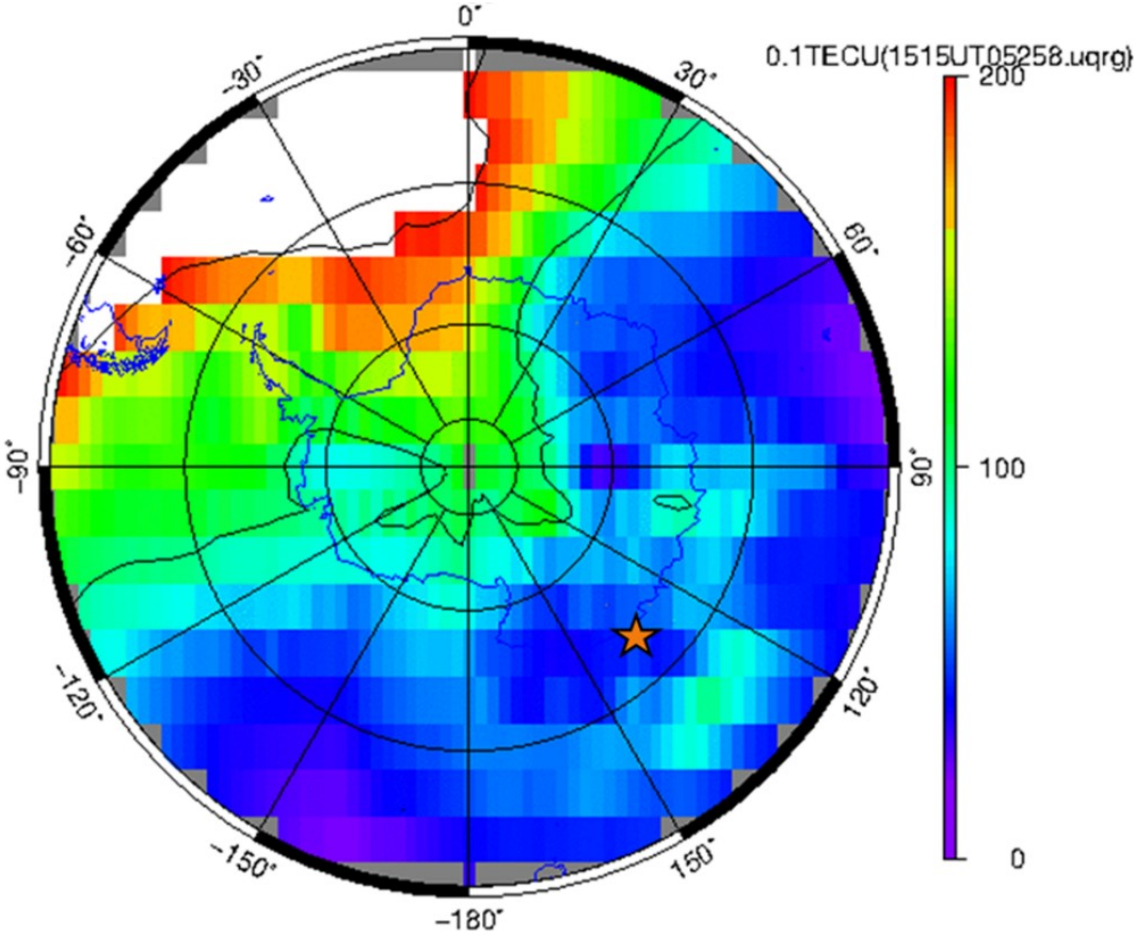


Figure: VTEC in South Pole region during 15 September, Day 258, of year 2005 at 1915 UT (extracted from UQRG GIM; the red star represents the corresponding magnetic pole).

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IonSAT

The summary of the research associated to point 1 can be found in:

JGR Space Physics

RESEARCH ARTICLE

10.1029/2019JA027677

Polar Electron Content From GPS Data-Based Global Ionospheric Maps: Assessment, Case Studies, and Climatology

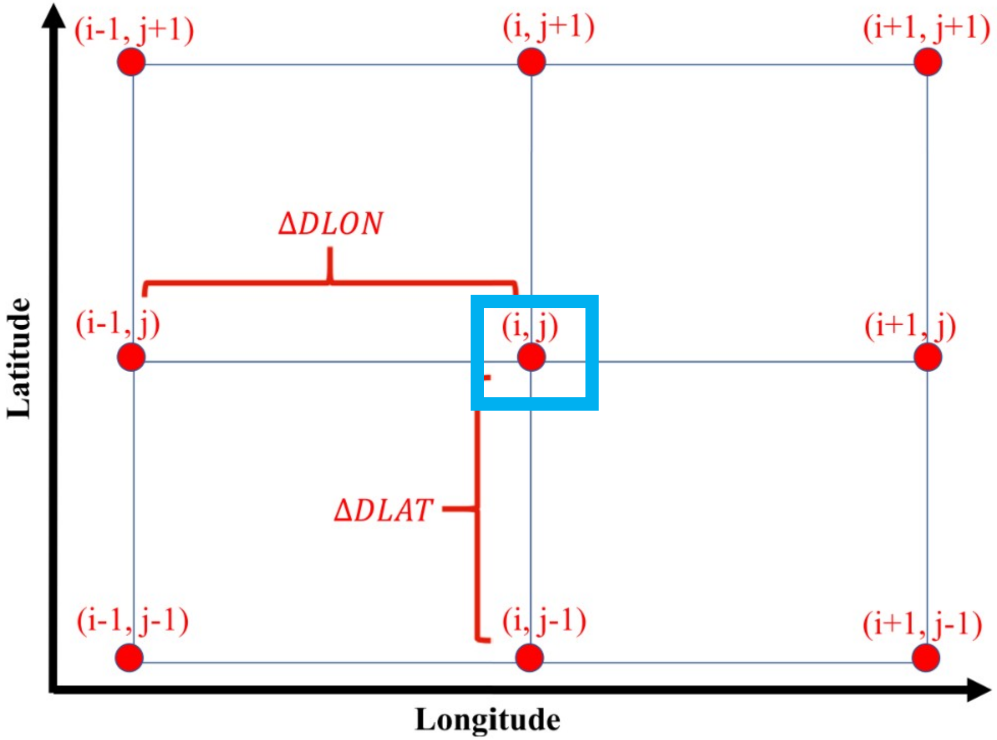
Manuel Hernández-Pajares[1,2], Haixia Lyu[1,2], Àngela Aragón-Àngel[3], Enric Monte-Moreno[4], Jingbin Liu[5,6,7], Jiachun An[8], and Hu Jiang[8]

[1]UPC-IonSAT, Barcelona, Spain, [2]IEEC, Barcelona, Spain, [3]Joint Research Centre (JRC), European Commission, Ispra, Italy, [4]UPC-TALP, Barcelona, Spain, [5]State Key Laboratory of Information Engineering in Surveying, Mapping and Remote Sensing, Wuhan University, Wuhan, China, [6]Collaborative Innovation Center of Geospatial Technology, Wuhan University, China, [7]Department of Remote Sensing and Photogrammetry and the Center of Excellence in Laser Scanning Research, Finnish Geospatial Research Institute, Masala, Finland, [8]Chinese Antarctic Center of Surveying and Mapping, Wuhan University, Wuhan, China

Key Points:

- The UPC GIM has been analyzed over both poles during 1.5 solar cycles confirming its slightly better performance compared to other IGS GIMs
- It presents realistic VTEC features over two poles, in agreement with previous higher resolution works and using non-GNSS measurements
- The climatology of the main VTEC polar features is obtained by means of the learning vector quantization (LVQ) unsupervised technique

2) Can the rapid GIMs provide reliable estimation of the spatial and temporal components of the VTEC gradients?



The **spatial and temporal components of VTEC gradient at grid points of** UQRG **GIM** on a global scale are introduced.

The VTEC gradient derived from UQRG GIMs (VgUG, Liu et al. 2022), **allows** to obtain full (non-relative) values of TEC spatial gradients and temporal variations **separately at any worldwide grid point**, considering the distances on the corresponding parallels and meridians at the ionospheric efective height, ΔDLON & ΔDLAT, separated 5º & 2.5º respectively, and the time difference between GIMs Δt (30 minutes, centered, 15 minutes, uncentered).

$$\begin{cases} \nabla V_{x,i,j} = (VTEC_{i,j} - VTEC_{i-1,j})/\Delta DLON \\ \nabla V_{y,i,j} = (VTEC_{i,j} - VTEC_{i,j-1})/\Delta DLAT \\ \nabla V_{i,j} = \sqrt{\nabla V_{x,i,j}^2 + \nabla V_{y,i,j}^2} \\ \vec{\nabla V} = (\nabla V_{x,i,j}, \nabla V_{y,i,j}) \end{cases}$$

$$\dot{V}_{i,j} = \Delta VTEC_{i,j}/\Delta t = (VTEC_{i,j,t} - VTEC_{i,j,t-1})/\Delta t$$

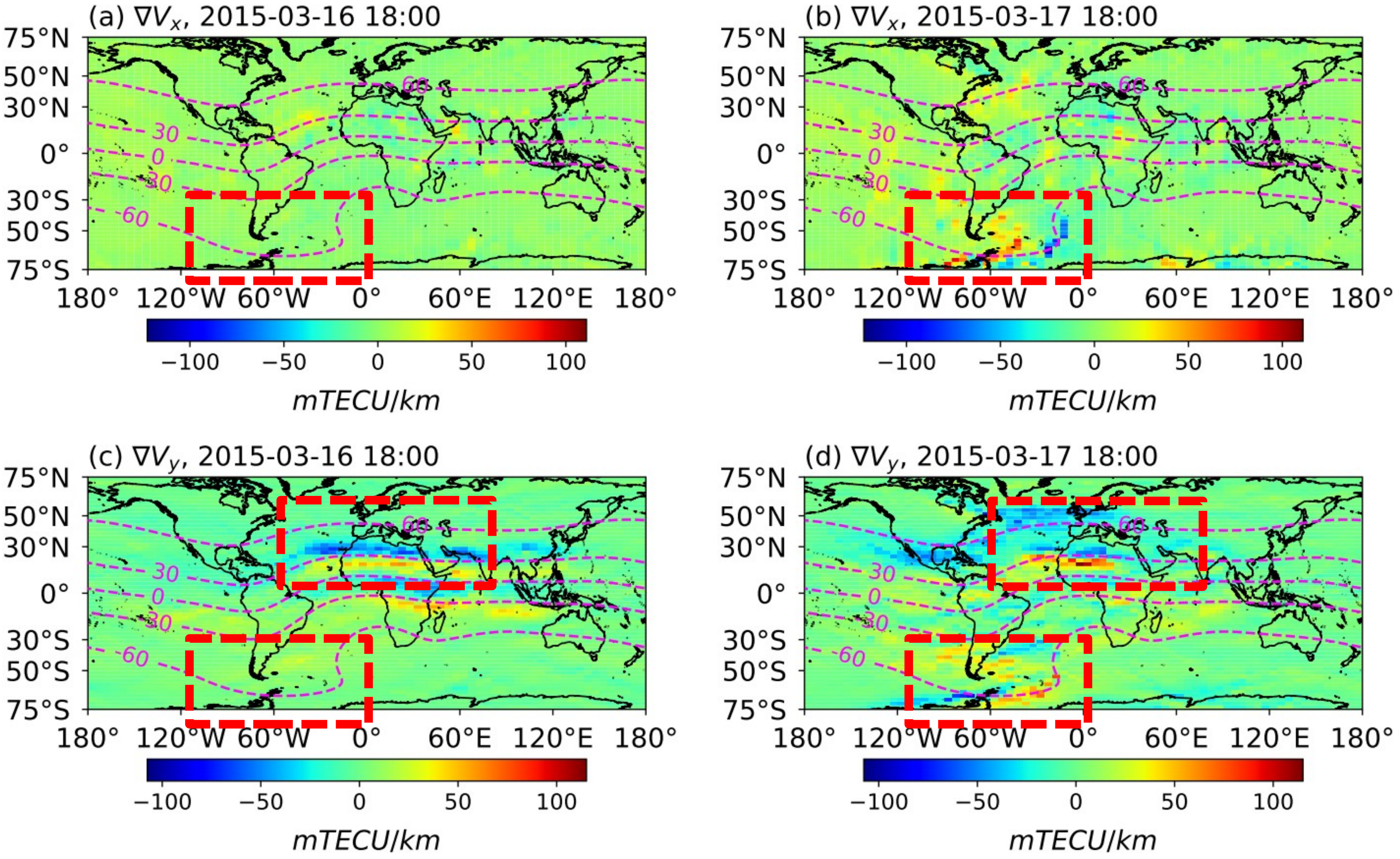
Example of global distribution of VTEC spatial gradient

Compared with the quiet ionospheric state, the VTEC spatial and temporal gradient directly derived from the GIM are able to capture the extraordinary VTEC variations during the disturbed ionospheric state, splted in north, east and time components.

St. Patrick's Day 2015 Geomagnetic Storm

Quiet

St. Patrick’s day storm

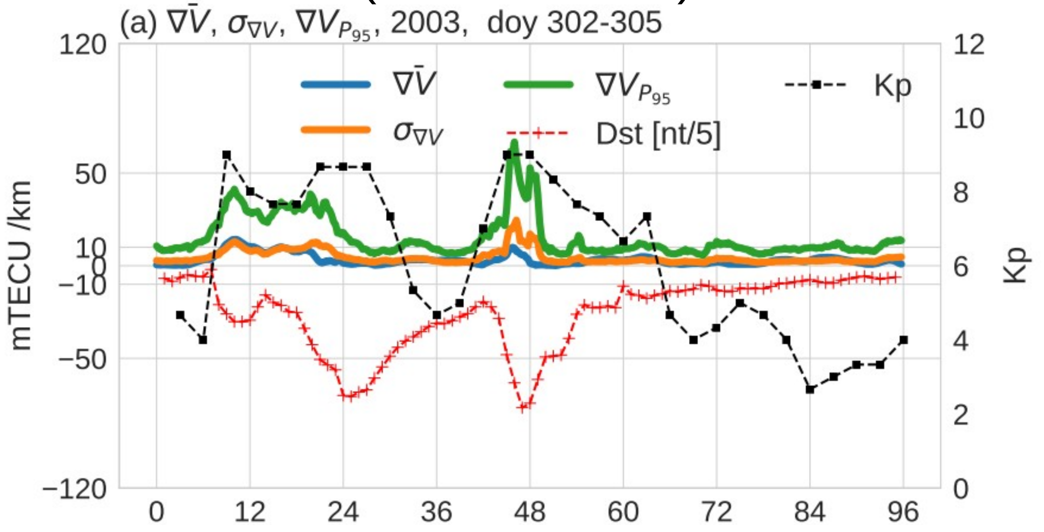


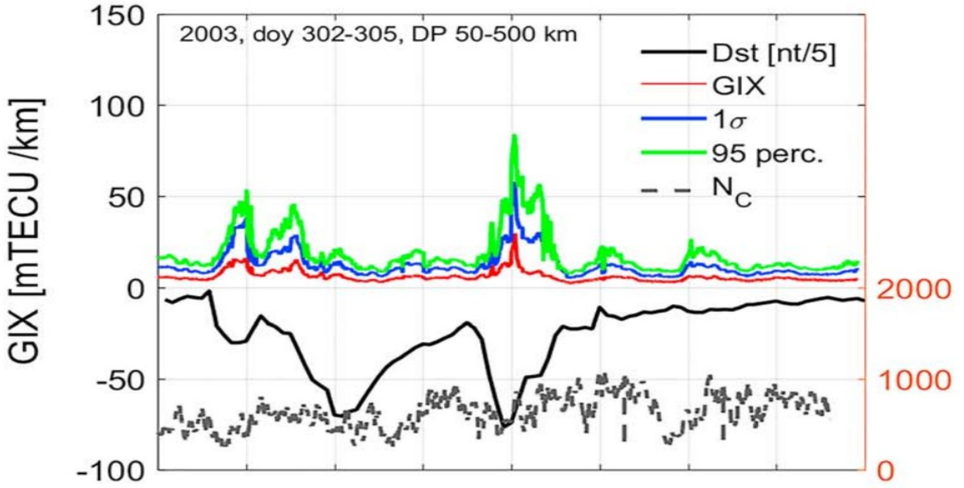
Example of comparison of GIM- vs raw-GNSS data- based regional **spatial** indices over Europe: **Halloween storm** (28 Oct -1 Nov 2003)

From **UQRG GIM (VgUG)**
(Liu et al. 2022)

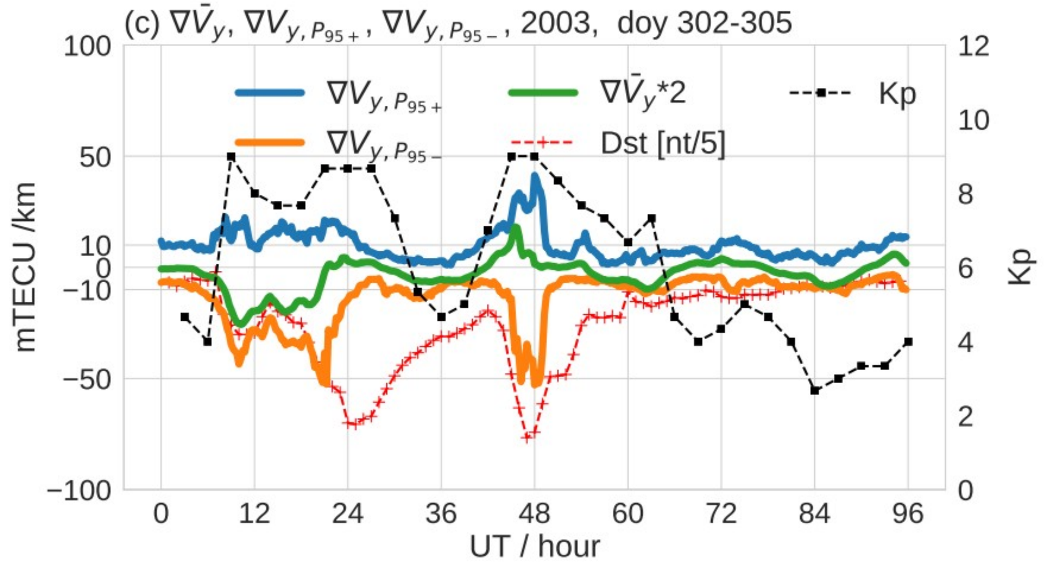
From **raw GNSS data**
(Jakowski & Hoque (2017)

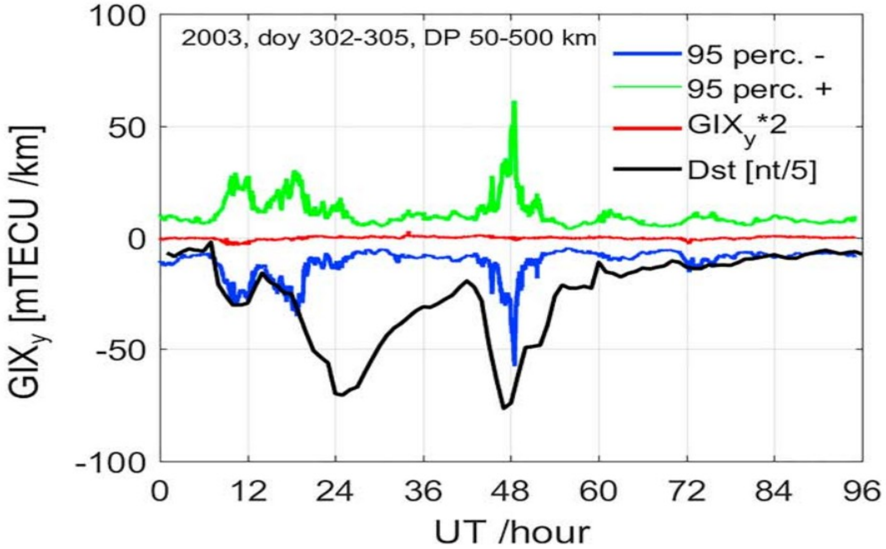
Spatial gradient norm





Latitudinal gradient component





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The summary of the research associated to point 2 can be found in:

Space Weather®

RESEARCH ARTICLE

10.1029/2021SW002926

Key Points:

- A new ionospheric temporal and spatial gradient index based on UPC-IonSAT Global Ionosphere Maps (UQRG) are presented at the selected region
- The new ionospheric spatial gradients indices at grid points of UQRG are presented
- The derived ionospheric spatial gradients and temporal variations indices are analyzed during quiet and disturbed ionosphere states

A New Way of Estimating the Spatial and Temporal Components of the Vertical Total Electron Content Gradient Based on UPC-IonSAT Global Ionosphere Maps

Qi Liu[1], Manuel Hernández-Pajares[1,2], Heng Yang[1,3], Enric Monte-Moreno[4], Alberto García-Rigo[1,2], Haixia Lyu[1,5], Germán Olivares-Pulido[1], and Raül Orús-Pérez[6]

[1]Universitat Politècnica de Catalunya (UPC-IonSAT), Barcelona, Spain, [2]Institut d'Estudis Espacials de Catalunya (IEEC), Barcelona, Spain, [3]School of Electronic Information and Engineering, Yangtze Normal University, Chongqing, China, [4]Department of TSC, TALP, Universitat Politècnica de Catalunya, Barcelona, Spain, [5]GNSS Research Center, Wuhan University, Wuhan, China, [6]Wave Interaction and Propagation Section (TEC-EFW) ESA ESTEC, Noordwijk, The Netherlands

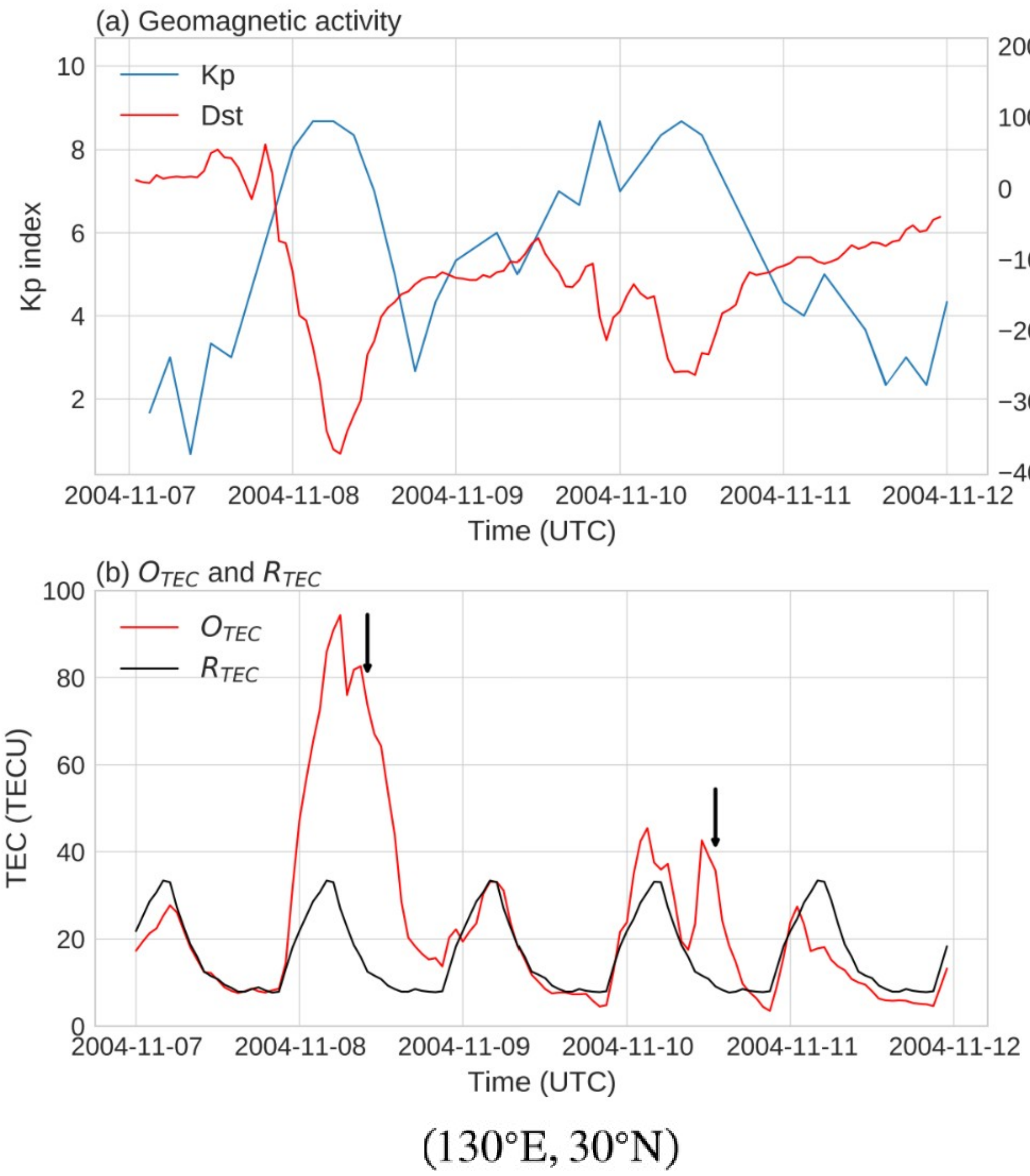
3) Can the rapid GIMs provide a sensitive Ionospheric storm scale index?

We propose the Ionospheric Storm Scale Index Based on UQRG (IsUG) as a direct extension of the I-scale index proposed at regional level (Japan) and from raw GNSS data by Nishioka et al. (2017):

$$P_{TEC} = \frac{100 \times (O_{TEC} - R_{TEC})}{R_{TEC}} \qquad \hat{P}_{TEC} = \frac{P_{TEC} - \mu}{\sigma}$$

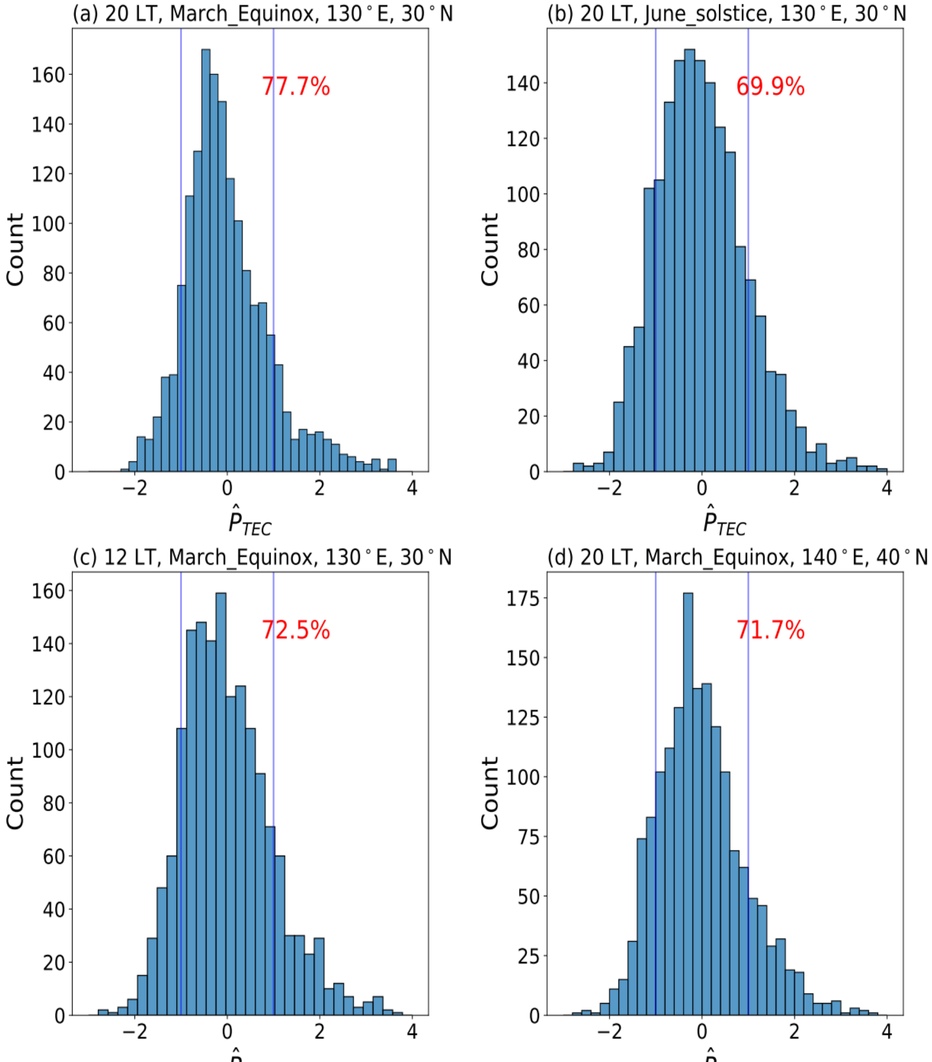
It is defined as the standardized Ptec, $\hat{P}_{TEC}$, where Ptec is the percentage deviation of VTEC, Otec is the hourly median VTEC derived at grid points of GIM. The hourly median VTEC is the median of the five VTEC values during 1-h interval, under the GIM VTEC temporal resolution of 15 min. The hourly median VTEC is calculated every hour (for example, 0, 1, 2 UT). Rtec is the reference median value at the same local time and geographic location in the past 27 days.

IsUG	Description	Definition	Probability on a global scale (%)
IP3	Severe positive storm	$5 < \hat{P}$	0.17
IP2	Strong positive storm	$3 < \hat{P} \leq 5$	0.72
IP1	Moderate positive storm	$1 < \hat{P} \leq 3$	12.43
I0	Quiet	$-1 < \hat{P} \leq 1$	73.96
IN1	Moderate negative storm	$-2 < \hat{P} \leq -1$	11.72
IN2	Strong negative storm	$-3 < \hat{P} \leq -2$	0.95
IN3	Severe negative storm	$\hat{P} < -3$	0.06

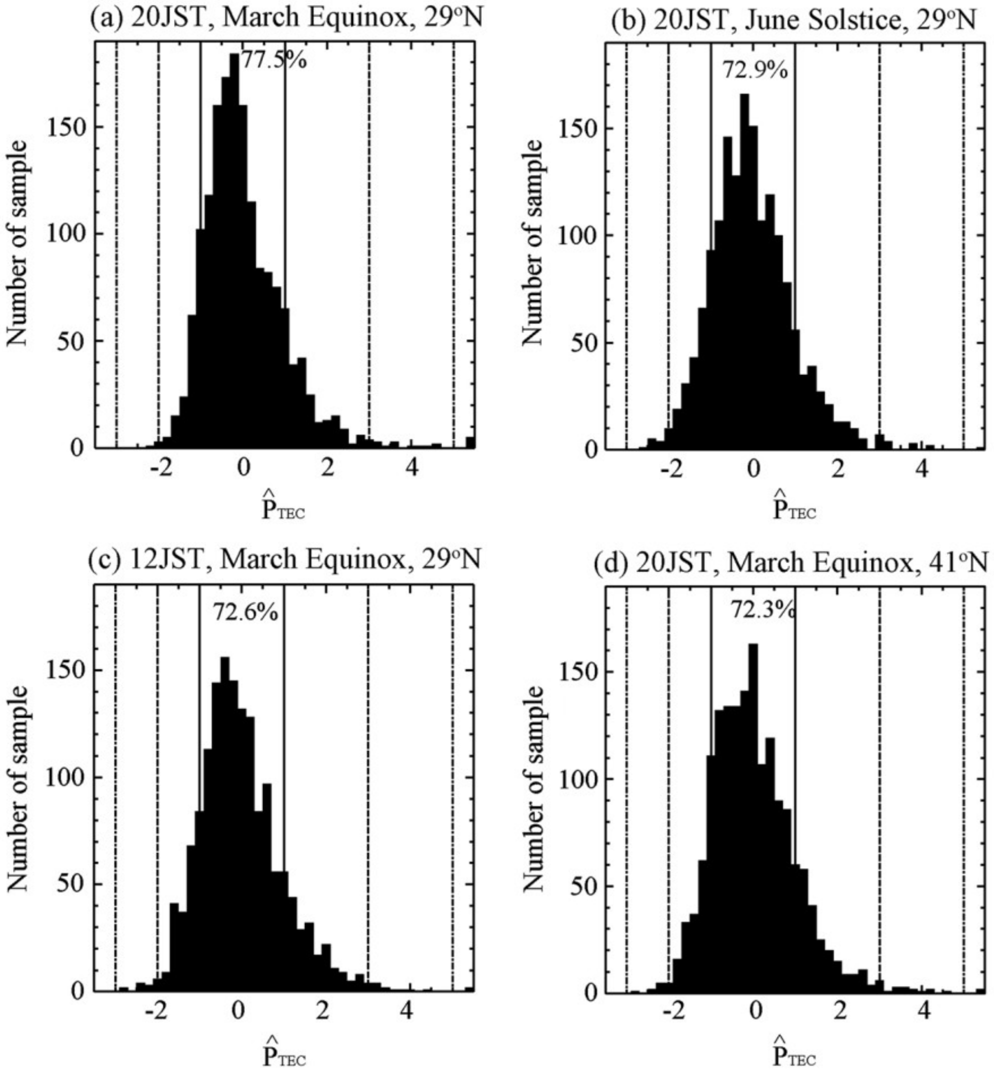


Comparing $\hat{P}_{TEC}$ n GIM $\hat{P}_{TEC}$ n raw GNSS data over Japan since 1997 to 2014 (3 months of seasonal data per year)

From **UQRG GIM (VgUG)**
(Liu et al. 2021)



From **raw GNSS data**
(Nishioka et al., 2017))



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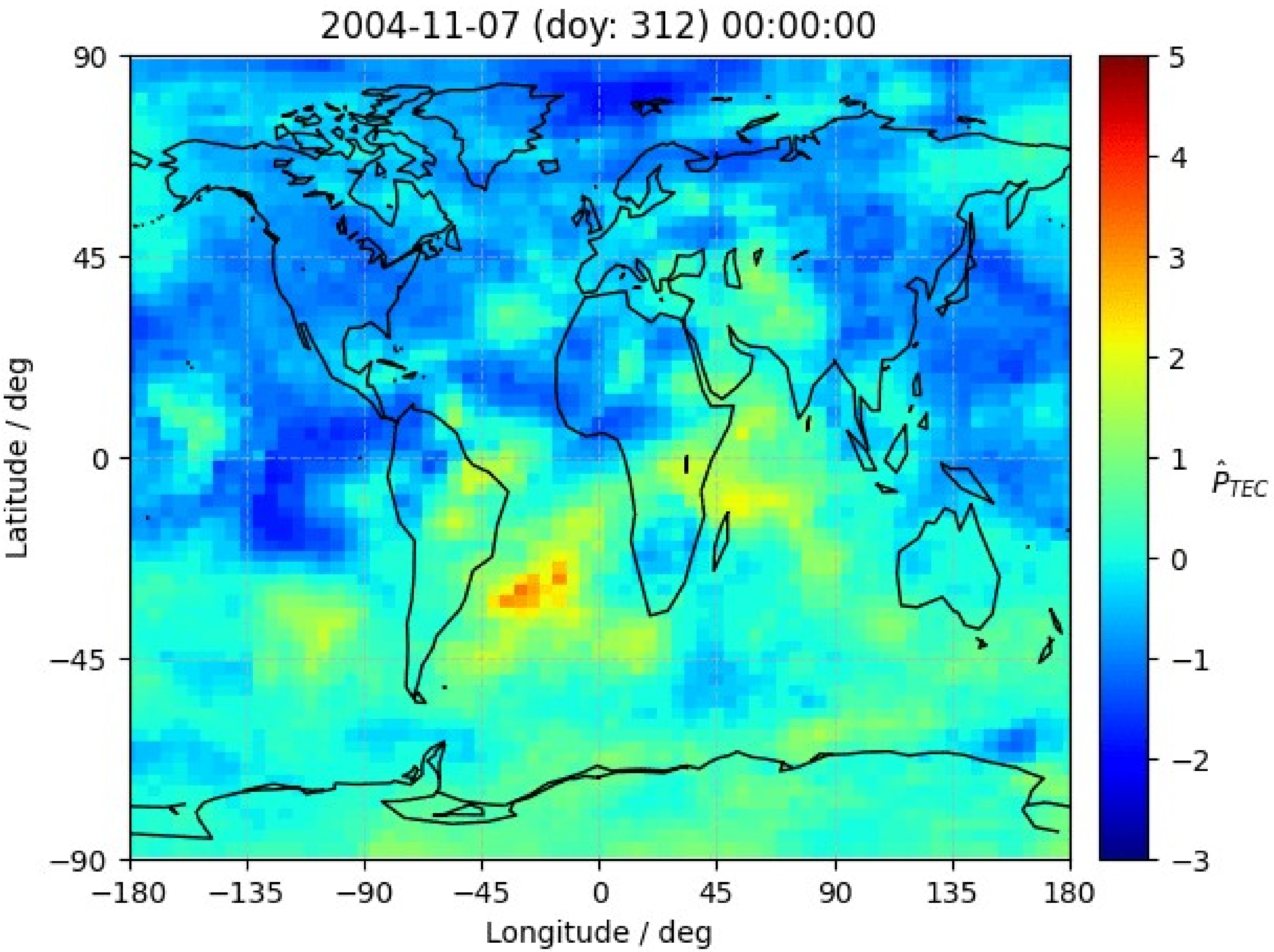
Animation of IsUG maps during a ionospheric storm period



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The summary of the research associated to point 3 can be found in:

Space Weather®

RESEARCH ARTICLE

10.1029/2021SW002853

Ionospheric Storm Scale Index Based on High Time Resolution UPC-IonSAT Global Ionospheric Maps (IsUG)

Qi Liu[1], Manuel Hernández-Pajares[1,2], Haixia Lyu[3,1], Michi Nishioka[4], Heng Yang[5,1], Enric Monte-Moreno[6], Tamara Gulyaeva[7], Yannick Béniguel[8], Volker Wilken[9], Germán Olivares-Pulido[1], and Raül Orús-Pérez[10]

[1]Universitat Politècnica de Catalunya (UPC-IonSAT), Barcelona, Spain, [2]Institut d'Estudis Espacials de Catalunya (IEEC), Barcelona, Spain, [3]GNSS Research Center, Wuhan University, China, [4]National Institute of Information and Communications Technology (NICT), Tokyo, Japan, [5]School of Electronic Information and Engineering, Yangtze Normal University, Chongqing, China, [6]Department of TSC, TALP, Universitat Politècnica de Catalunya, Barcelona, Spain, [7]IZMIRAN, Moscow, Russia, [8]Informatique, Electromagnétisme, Electronique, Analyse numérique (IEEA), Courbevoie, France, [9]German Aerospace Center (DLR), Neustrelitz, Germany, [10]Wave Interaction and Propagation Section (TEC-EFW) ESA ESTEC, Noordwijk, The Netherlands

Key Points:

- The new ionospheric storm scale, IsUG, is presented
- The IsUG is based on the high resolution and rapid UPC-IonSAT Global Ionosphere Maps (UQRG)
- Statistical analysis is carried out on a global scale from 1997 to 2014 comparing well with the available raw GNSS data based I-scale index

Supporting Information:

Supporting Information may be found in the online version of this article.

4) Can the rapid GIMs provide a general reliable monitoring of the ionospheric VTEC?

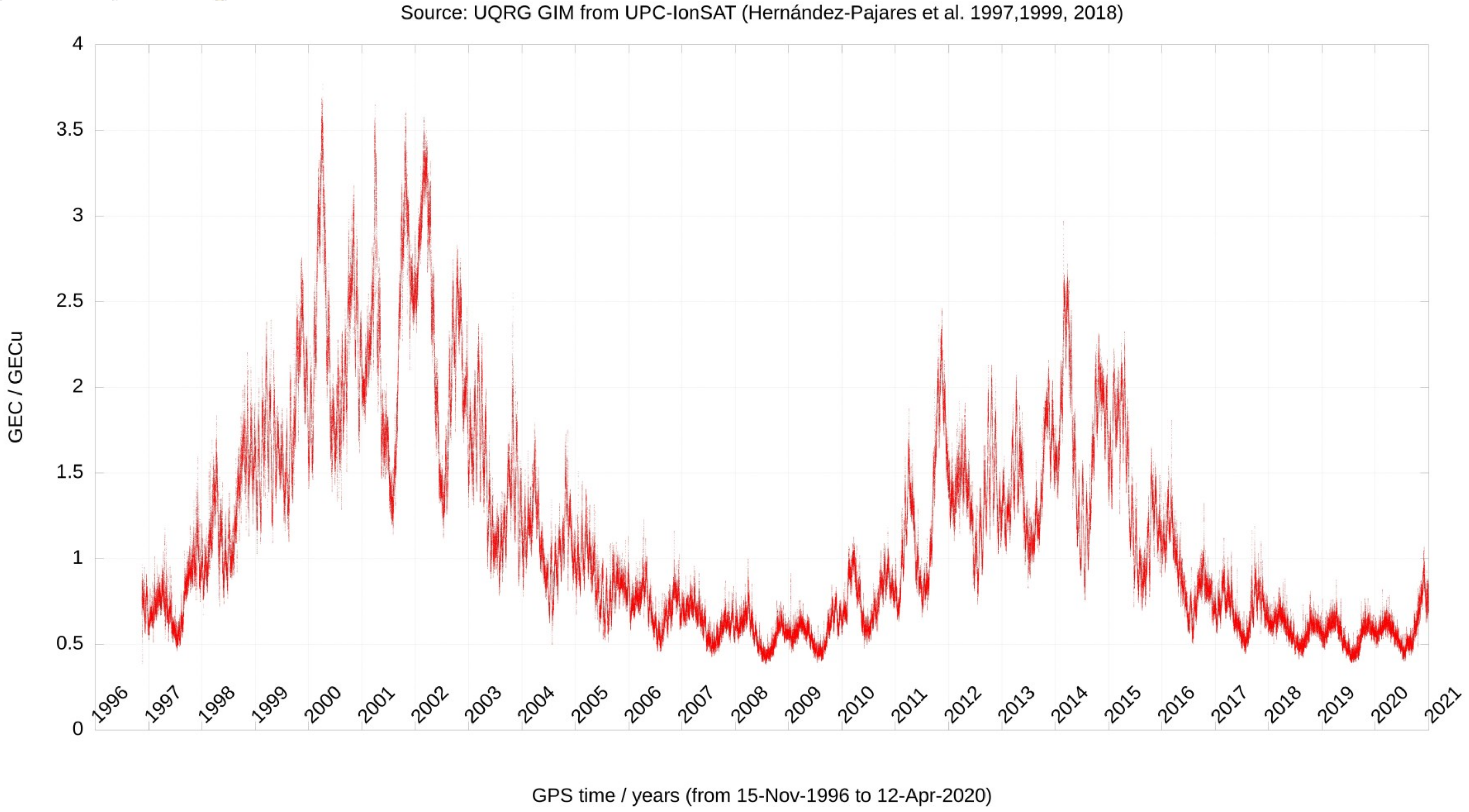

Table 2 Summary of the GIMs assessment versus +190 millions of altimeter VTEC measurements, including an overall period of up to almost 5000 days and a common period of 21 days (remarks: [*] For the newest period of EMRG product submission to IGS only, days 117–365, 2015; [**] Very limited sample)

GIM Id.	Up to more than 1 solar cycle, within days 180, 2001 to 007, 2016			21 common days, within 117, 2015 to 007, 2016	
	# days	Std. dev./TECU	Rel. error %	Std. dev. /TECU	Rel. error %
IGSG	4927	3.9	19.9	4.6	21.1
CODG	4934	4.3	22.0	4.8	21.8
ESAG	4926	5.3	26.6	5.6	25.5
JPLG	4912	4.1	21.2	4.8	21.9
UPCG	4925	3.9	19.7	4.2	19.1
CASG	4914	3.9	20.9	4.6	21.1
EMRG	255[*]	(4.8)	(26.2)	5.9	26.5
WHRG	4416	4.6	24.8	5.5	25.0
WHUG	42[**]	(5.9)	(26.9)	5.5	25.0
UQRG	3063	3.6	17.8	3.6	16.3

The summary of the research associated to point 4 can be found in:

Journal of Geodesy
https://doi.org/10.1007/s00190-017-1088-9

ORIGINAL ARTICLE

CrossMark

Consistency of seven different GNSS global ionospheric mapping techniques during one solar cycle

David Roma-Dollase[1,2] · Manuel Hernández-Pajares[1] · Andrzej Krankowski[3] · Kacper Kotulak[3] · Reza Ghoddousi-Fard[4] · Yunbin Yuan[5] · Zishen Li[6] · Hongping Zhang[7] · Chuang Shi[7] · Cheng Wang[7] · Joachim Feltens[8] · Panagiotis Vergados[9] · Attila Komjathy[9] · Stefan Schaer[10] · Alberto García-Rigo[1] · José M. Gómez-Cama[2]

Received: 26 May 2017 / Accepted: 12 November 2017

5) Can the RT VTEC interpolation, one bottleneck in the accuracy of RT-GIMs, be significantly improved?

- We proposed a method for the generation of real-time global ionospheric map (RT-GIM) of vertical total electron content (VTEC) from GNSS measurements.
- The need for interpolation arises from the fact that the ionospheric pierce point (IPP) measurements from satellites to stations are not distributed uniformly over the ionosphere, leaving unfilled gaps at oceans or poles.
- The method we propose is based on using a high-quality historical database of post-processed GIMs that comprises more than two solar cycles, calculates the GIM by weighted superposition on a subset of the database with the compatible solar condition.
- The linear combination of GIMs in the database was obtained by minimizing a _x0002_ L2 distance between VTEC measurements at the IPPs and the VTECs from the database, adding a L1 penalization on the weights to assure a sparse solution. The process uses a Sun-fixed geomagnetic reference frame.
- This method uses the atomic decomposition/least absolute shrinkage and selection operator (LASSO), which will be denoted as atomic decomposition interpolator of GIMs (ADIGIM). As the computation is done in milliseconds, the interpolation is performed in real time.

Table 6 Summary of GIMs assessment by 4,253,502 common altimeter JASON3 VTEC measurement (in TECUs), for a period of +200 days, from day 258 of 2019 to day 155 of 2020

GIM Id	Latency	Bias	SD	RMS	ERR%
IGSG	>15 days	−1.93	**2.33**	3.03	38.5
CODG	~5 days	−1.34	2.46	2.80	35.6
JPLG	~4 days	−3.34	2.45	4.15	52.7
UPCG	~15 h	−2.23	2.38	3.26	41.4
ESAG	~4 days	−0.87	2.83	2.96	37.6
WHUG	~4 days	−1.39	2.52	2.87	36.5
CASG	~4 days	−1.50	2.46	2.88	36.6
EMRG	~2 days	−1.69	2.61	3.11	39.5
CORG	~7 h	−1.29	2.64	2.94	37.4
JPRG	~7 h	−3.44	2.48	4.24	53.9
UQRG	~16 h	−2.14	**2.30**	3.14	39.9
ESRG	~2 h	−1.01	2.86	3.04	38.6
WHRG	~20 h	−1.35	2.55	2.89	36.6
CARG	~10 h	−1.51	2.59	3.00	38.1
EHRG	~3 h	−1.07	2.69	2.90	36.8
CASR	RT[a]	−1.14	2.80	3.02	38.4
CLK9	RT	−0.53	2.98	3.03	38.5
USRG	RT	−1.41	2.85	3.18	40.4
UARG	~20 h	−2.09	**2.32**	3.13	39.7
UADG	RT	−1.34	**2.43**	2.77	35.1

[a]Latency of UADG is the delay for RT-GIM for each epoch

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The summary of the research associated to point 5 can be found in:

Journal of Geodesy (2021) 95:71
https://doi.org/10.1007/s00190-021-01525-5

ORIGINAL ARTICLE

Check for updates

Real-time interpolation of global ionospheric maps by means of sparse representation

Heng Yang[1,2,3] · Enric Monte-Moreno[1] · Manuel Hernández-Pajares[3] · David Roma-Dollase[4]

Received: 2 December 2020 / Accepted: 28 May 2021

The impact of the improvement of UPC-IonSAT RT GIM on the RT IGS combination will be shown tomorrow, Tuesday 28-J, in the first talk of RT IGS session.

Summary

We have presented an executive summary of the positive answers recently found on the following questions on the Global Ionospheric Maps (GIMs) of Vertical Total Electron Content (VTEC): UQRG **rapid** & UADG **real-time** (RT) GIMs generated by UPC-IonSAT for IGS with a time res. of 15 minutes:

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4) provide a general **reliable monitoring of the ionospheric VTEC**?

5) **Can the RT VTEC interpolation**, one bottleneck in the accuracy of RT-GIMs, **be significantly improved**?

Thanks for your attention!

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