A REAL-TIME EIRP LEVEL 1 CALIBRATION ALGORITHM FOR THE CYGNSS MISSION USING THE ZENITH MEASUREMENTS

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ABSTRACT

Level 1 calibration of the Cyclone Global Navigation Satellite System (CYGNSS) measurements requires an accurate estimate of the effective isotropic radiated power (EIRP) of the GPS transmitter in the direction of specular reflection. Variable transmit power by numerous Block IIF and IIR-M GPS space vehicles was observed due to their flex power mode. GPS antenna gain patterns feature azimuthal asymmetry, further complicating EIRP estimation. As a result, all Block IIF observations by CYGNSS are flagged and not used to measure ocean winds. A new (version 3.0) Level 1 calibration algorithm is developed which uses measurements by the direct (zenith) antenna to estimate the specular GPS EIRP used to calculate the bistatic radar cross section (BRCS) of the ocean surface. Direct signal measurements are used to estimate GPS transmitter EIRP in the direction of the CYGNSS spacecraft. By applying corrections to the direct signal EIRP, it is possible to estimate the GPS EIRP in the direction of the specular reflection point. This real-time EIRP calibration algorithm instantaneously detects and corrects power fluctuations in all GPS block transmitters and significantly reduces errors due to the GPS antenna gain azimuthal asymmetry. It also allows observations with Block IIF transmitters (approximately 37% of the entire dataset) to be included in the standard data products.

Index Terms— Antenna pattern, calibration, CYGNSS, EIRP, flex power, GNSS-reflectometry, GPS, zenith antenna

1. INTRODUCTION

The Cyclone Global Navigation Satellite System (CYGNSS) mission measures the reflected signal of Global Positioning System (GPS) to remotely sense the ocean surface roughness and wind speed, as well as the land soil moisture and flood inundation [1, 2]. The GPS effective isotropic radiated power (EIRP), defined as the product of transmit power and antenna gain, is the key parameter that determines the power incident on the Earth surface and therefore is very significant to the calibration of Level 1 normalized bistatic radar cross section (NBRCS) [3].

The major challenges in the estimate of the GPS EIRP were summarized in [4]: 1) the variation of the transmit power; 2) limited knowledge of the transmit antenna gain pattern; 3) the gain uncertainty due to pattern asymmetry and yaw maneuver [5, 6]. A custom built and calibrated GPS constellation power monitor (GCPM) system was designed, implemented, and installed at the University of Michigan to measure the direct GPS signal [6, 7]. The calibrated received power was used to estimate the effective transmit power (L1 C/A) of all GPS satellites. These estimated constant power values were implemented in the CYGNSS version 2.1 (v2.1) calibration algorithm and also proved to have successfully reduced the Level 1 and 2 data products' dependence on the block type and PRN of the GPS transmitter [8].

However, a flex power mode of the Block IIR-M and IIF GPS satellites was developed and implemented to redistribute the transmit power between the individual signal components of the C/A, P(Y), and M codes for increased protection against jamming in certain regions [9]. On February 7th and 8th, 2017, 7 active IIR-M satellites performed a commanded redistribution of transmit power from M-code to C/A code and P(Y) code. The measured carrier-to-noise (C/N_0) density ratio from different geodetic receivers experienced an approximately 1.5 dB-Hz increase on average [10, 11]. Since January 2017, 10 Block IIF GPS satellites have implemented a geographically driven flex power mode, which enables a ~ 2.5 dB increase and decrease in every orbit. This flex power mode was observed by the GCPM system: significant power increases and decrease over several seconds repeat at the same geographical location over consecutive days [12]. Because of this power flex mode, observations from all IIF satellites are currently flagged out. This reduces the CYGNSS measurement coverage by approximately 37%.

A second order challenge is the uncertainty of the GPS transmit antenna gain pattern and its azimuthal asymmetry. The published pre-launch antenna patterns in [5] are not sufficient for the CYGNSS Level 1 calibration: 1) the resolution is low, 2 degrees in off-boresight angle and 10 degrees in around-boresight angle; 2) the measurement does not account for possible changes when antennas are mounted on the satellites; 3) the antenna patterns for IIF satellites have not been published. The CYGNSS v2.1 calibration algorithm uses an off-boresight polynomial fit of the azimuthally averaged antenna gain. It is also difficult to estimate the full pattern, and the GPS satellite orientation is complicated by its recurring yaw maneuvers. An absolute calibration algorithm would require replacement of simple off-boresight models with full GPS antenna pattern estimates and GPS satellite yaw state modelling for each transmitter. It is possible but would be rather cumbersome to implement and would increase data latency in order to obtain the necessary GPS satellite yaw states.

To solve or mitigate the above two issues, we use the measurements from the CYGNSS direct (zenith) antenna to estimate the specular GPS EIRP and then make a correction to the Level 1 BRCS. The dense zenith measurements over a relatively short time demonstrate that it is a viable technique to retrieve the full antenna pattern over the terrestrial service volume of GPS satellites [4, 12]. The absolute calibration scheme includes: 1) conversion of the raw measured counts into received power in watts; 2) calibration the CYGNSS zenith antenna pattern using zenith measurements and multiple GPS pre-knowledge patterns in [5]; 3) derivation of the full GPS transmit antenna patterns using zenith signals and multiple calibrated zenith antenna patterns.

Using the improved knowledge of the GPS transmit antenna pattern, we convert the 8 CYGNSS zenith receivers into 8 real-time GPS power monitors. The received direct signal power is used to solve the zenith GPS transmitter EIRP and then to estimate the EIRP in the direction of the reflected signal specular point. The corrections include both hardware and geometry differences between the direct and reflected channels. By making direct, temporally coincidence, estimates of the GPS EIRP, this v3.0 real-time EIRP calibration algorithm will instantaneously detect and correct for power fluctuations in all GPS block transmitters. It should significantly reduce errors due to the GPS antenna gain azimuthal asymmetry because the geometry correction between the zenith and nadir estimates of the EIRP is much less sensitive to GPS antenna pattern asymmetry. The new calibration algorithm will bring back all flagged observations from the GPS Block IIF (approximately 37% of the entire dataset) to be included in the standard science data products.

2. CALIBRATION

2.1 Calibration of Zenith Measurement

The CYGNSS zenith low noise amplifiers (LNAs) were commanded to a fixed constant gain mode in August 2018. The downlinked zenith measurements are in the format of raw counts. An end-to-end calibration experiment using an engineering (Eng) model of the CYGNSS Delay-Doppler Mapping Receiver (DMR) and a GPS signal simulator (GSS) was conducted to convert the raw counts into power in watts, as shown in Figure 1. The DMR, zenith low noise amplifier (LNA) and GSS are used to emulate the on-orbit zenith measurement. A second order polynomial fitting gives a calibration equation to convert the on-orbit zenith measured raw counts into power in watts.

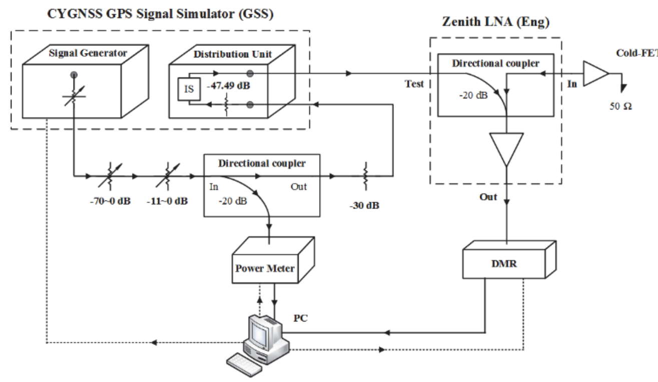

Figure 1. Configuration of DMR-GSS calibration

The received power is modelled using the Friis equation

$$P_R = \frac{P_T G_T(\theta_T, \phi_T)}{4\pi R^2}\left(\frac{\lambda^2}{4\pi}\right) G_R(\theta_R, \phi_R) G_{LNA}(T_{LNA}) \quad (1)$$

where P_T is the transmit power, G_T is the transmit antenna gain, R is the distance between the transmitter and the receiver, λ is the wavelength for GPS L1 signals, G_R is the gain of the receiver antenna, and G_{LNA} is the gain of the LNA.

2.2 Calibration of Zenith Antenna Pattern

The accuracy of the direct observation estimate of the GPS EIRP depends on accurate knowledge of the CYGNSS zenith antenna pattern. In-lab measurements show that the pattern can easily be affected by the solar panel and other electrical elements on the CYGNSS satellites. Therefore, the zenith antennas need to be characterized individually using a large set of on-orbit direct measurements.

Based on Equation (1), we use the calibrated zenith measurements and multiple pre-knowledge GPS antenna patterns [5] to calibrate the zenith antenna pattern. Figure 2 shows the retrieved zenith antenna gain pattern for CYGNSS

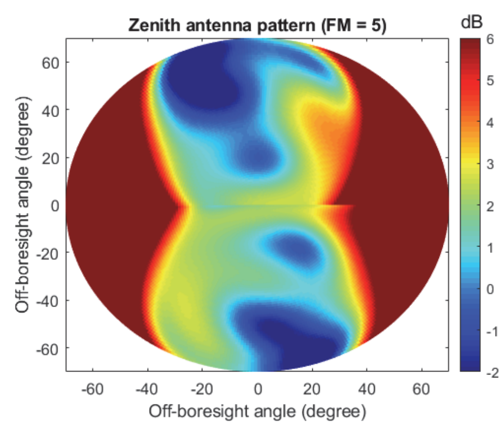

Figure 2. The spherical harmonic fitted pattern of the zenith antenna of CYGNSS FM 5 satellite

FM (Flight Model) 5 satellite using large amounts of direct signal measurements over several months. A spherical harmonic fitting is performed using both the retrieved pattern (derived from the zenith measurement) and the weighting function (based on measurement number density).

2.3 Calibration of GPS Antenna Pattern

The GPS transmit antenna pattern is then calibrated using the direct measurements made by 8 CYGNSS zenith receivers and their calibrated antenna gain patterns. The calibration using multiple observatories would help us to complete the consistency checking between the estimated CYGNSS zenith and GPS transmitter antenna patterns and minimize the errors in the retrieval process. A yaw angle correction is made based on the GPS yaw attitude model [13] and the corresponding GNSS-Inferred Positioning System and Orbit Analysis Simulation Software (GIPSY-OASIS) [14].

Figure 3 shows a preliminary derived antenna pattern of GPS PRN 16, with a very high resolution of 0.5 by 0.5 degree in both off-boresight and around-boresight angles (2 by 10 degrees for published patterns). The antenna patterns of all 32 GPS satellites are calibrated and used to derive the zenith-to-specular ratio (ZSR) functions in Section 3.

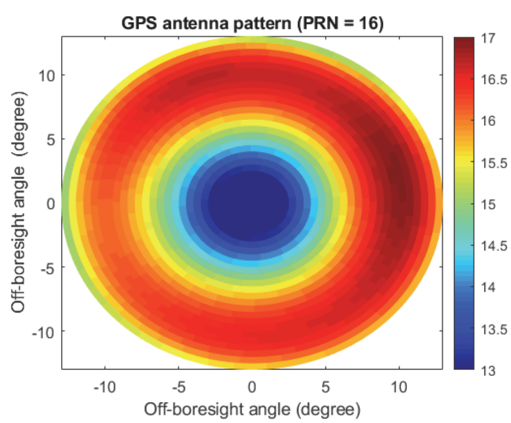

Figure 3. The spherical harmonic fitted pattern of the GPS PRN 16 using all 8 CYGNSS FMs' measurements

3. REAL-TIME EIRP CALIBRATION ALGORITHM

A novel idea of the v3.0 real-time EIRP calibration algorithm is to use the measured EIRP in the direction of zenith antenna (E_Z) to estimate the EIRP in the direction of specular point (E_S) (see Figure 4), as

$$E_S = E_Z/\text{ZSR}\ (\text{SV},\ \theta_{inc}) \quad (2)$$

where 1) E_Z is computed from the calibrated received power, receiver antenna gain and the Friis equation in Section 2; 2) ZSR, the zenith-to-specular antenna gain ratio, is the average ratio of the GPS transmit antenna gain in the direction of the zenith antenna to the gain in the direction of the specular point. The average is taken over all azimuth angles of the GPS antenna pattern. As the arguments to ZSR indicate, the ratio is a function of GPS space vehicle (SV) number and of the incidence angle of the specular reflection point.

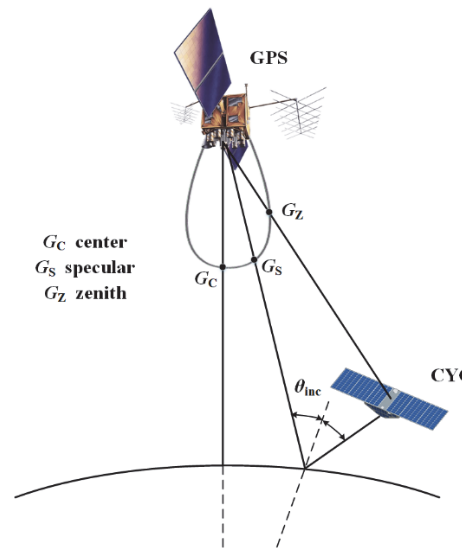

Figure 4. Concept of v3.0 calibration algorithm (GPS antenna nominally points toward center of Earth)

The ZSR functions are derived from the calibrated GPS antenna patterns in Section 2.3, with a composite merging with the pre-launch patterns for high incidence angles. The ZSR functions are mapped to the specular incidence angle, as shown in Figure 5.

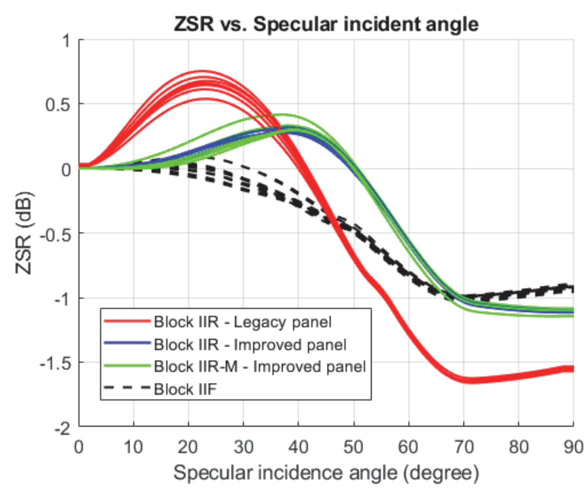

Figure 5. Preliminary ZSR vs. Specular incidence angle

The difference is a function of incidence angle only, since both paths lie in the plane of incidence of propagation and so correspond to the same azimuth angle of the GPS antenna pattern. This greatly reduces the effects of azimuthal variations in the pattern and allows for a correction ratio between the zenith and nadir channels as a function of specular incidence angle only.

The specular EIRP, E_S, is used by the L1B calibration algorithm when computing the BRCS σ_0. A preliminary test of a selected CYGNSS ocean observation track demonstrates that the v3.0 real-time EIRP algorithm successfully corrects the calibration of the Level 1 observables, as shown in Figure 6. In the figure, green and blue samples are v2.1 products and black samples are v3.0. A flex power event, at time ~720, affects the v2.1 samples but not v3.0.

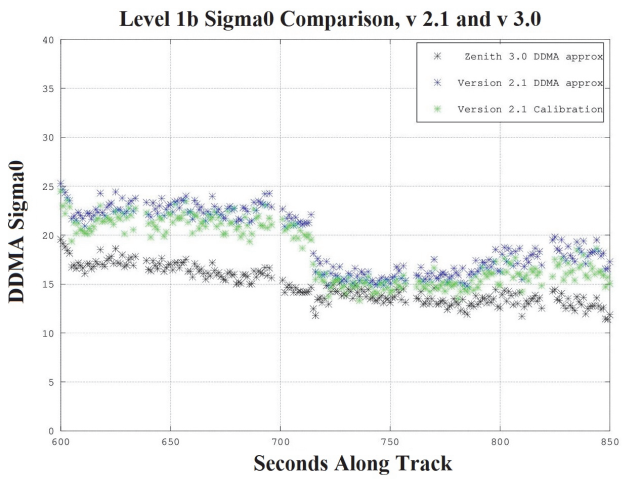

Figure 6. Comparison of Level 1b σ_0 calibrations

4. SUMMARY

This paper introduces a real-time EIRP Level 1 calibration algorithm for the NASA CYGNSS mission. This approach takes advantage of the dense measurements made by the CYGNSS zenith antenna and accurately retrieves the gain patterns of the CYGNSS zenith and GPS transmit antennas (over the terrestrial service volume). It converts the 8 zenith receivers into real-time GPS power monitors and uses the measured EIRP in the direction of the zenith antenna to estimate the EIRP in the direction of the specular point. This algorithm instantaneously detects power fluctuations in all GPS transmitters and compensates for them in the calibration of Level 1 NBRCS. It greatly reduces the effects of azimuthal asymmetry in the GPS patterns by use of the ZSR functions. It will allow observations from the GPS Block IIF (approximately 37% of the entire dataset) to be included in the standard science data products.

More testing of the calibration algorithm and validation using the entire CYGNSS dataset are currently in progress, and the results will be reported in the conference presentation.

5. REFERENCES

[1] C. S. Ruf, A. Lyons, M. Unwin, J. Dickinson, R. Rose, D. Rose, and M. Vincent, "CYGNSS: Enabling the future of hurricane prediction," *IEEE Geoscience and Remote Sensing Magazine*, vol. 1, no. 2, pp. 52-67, June 2013.

[2] C. S. Ruf, C. Chew, T. Lang, M. G. Morris, K. Nave, A. Ridley, and R. Balasubramaniam, "A new paradigm in Earth environmental monitoring with the CYGNSS small satellite constellation," *Scientific Reports*, vol. 8, no. 1, 8782, June 2018.

[3] S. Gleason, C. S. Ruf, A. J. O'Brien and D. S. McKague, "The CYGNSS Level 1 Calibration Algorithm and Error Analysis Based on On-Orbit Measurements," in *IEEE J Sel Top Appl Earth Obs Remote Sens*. doi: 10.1109/JSTARS.2018.2832981.

[4] T. Wang, C. Ruf, B. Block and D. McKague, "Characterization of the Transmit Power and Antenna Pattern of the GPS Constellation for the CYGNSS Mission," *IGARSS'18*, pp. 4011-4014, July 2018.

[5] W. A. Marquis and D. L. Reigh, "The GPS Block IIR and IIR-M Broadcast L-band Antenna Panel: Its Pattern and Performance," *Navigation*, vol. 62, no. 4, pp. 329-347, Dec. 2015.

[6] T. Wang, C. Ruf, S. Gleason, B. Block, D. McKague, and D. Provost, "Development of GPS Constellation Power Monitor System for High Accuracy Calibration/Validation of the CYGNSS L1B Data," *IGARSS*'17, pp. 1008-1011, July 2017.

[7] T. Wang, C. S. Ruf, B. Block, D. S. McKague and S. Gleason, "Design and Performance of a GPS Constellation Power Monitor System for Improved CYGNSS L1B Calibration," in *IEEE J Sel Top Appl Earth Obs Remote Sens*. doi: 10.1109/JSTARS.2018.2867773.

[8] F. Saïd, Z. Jelenak, P. S. Chang and S. Soisuvarn, "An Assessment of CYGNSS Normalized Bistatic Radar Cross Section Calibration," in *IEEE J Sel Top Appl Earth Obs Remote Sens*. doi: 10.1109/JSTARS.2018.2849323.

[9] P. Steigenberger, S. Thölert, S., and O. Montenbruck, "Flex power on GPS Block IIR-M and IIF", *GPS Solutions*, vol. 23, no.8, pp. 1-12, Nov. 2018.

[10] P. Steigenberger, A. Hauschild, S. Thoelert, and R. Langley, "US air force puts more power into GPS block IIR-M C/A-code," *GPS World*, vol. 28, no. 4, pp. 8–9, Apr. 2017.

[11] S. Thoelert, A. Hauschild, P. Steigenberger, and R. Langley, "GPS IIR-M L1 transmit power redistribution: Analysis of GNSS receiver and high gain antenna data," in *Proc. 30th Int. Tech. Meeting Satellite Div. Inst. Navig.*, Portland, OR, USA, Sep. 2017, pp. 1589–1602.

[12] T. Wang, C. S. Ruf, B. Block, D. McKague, and S. Gleason, "Characterization of GPS L1 EIRP: Transmit power and antenna gain pattern," *31st ION GNSS+*, pp. 2879 – 2890, Miami, FL, Sept. 2018.

[13] Y. E. Bar-Sever, "A new model for GPS yaw attitude," *J. Geodesy*, vol. 70, no. 11, pp. 714–723, Nov. 1996.

[14] NASA JPL, "GNSS-Inferred Positioning System and Orbit Analysis Simulation Software (GIPSY-OASIS)," Internet: https:// gipsy-oasis.jpl.nasa.gov/.