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MONITORING GPS EIRP FOR CYGNSS LEVEL 1 CALIBRATION

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ABSTRACT

The effective isotropic radiated power (EIRP) of the Global Positioning System (GPS) determines the power incident on the Earth surface. It is critical to the CYGNSS mission's Level 1 calibration of normalized bistatic radar cross section (NBRCS). This paper reports a dynamic EIRP calibration algorithm that uses the CYGNSS direct signal to correct the GPS EIRP in the direction to the specular reflection point. This approach can instantaneously detect any transmit power fluctuation in all GPS transmitters and any change of the receiver system gain, and then automatically applied to correct the science measurement. It also helps mitigate the error caused by the azimuthal asymmetry of the GPS antenna gain pattern without knowing the exact yaw attitude of the GPS satellite. The dynamic EIRP calibration algorithm brings back flagged observations from the Block IIF (~37% of the entire dataset) to the CYGNSS standard science data products. It will also help improve the accuracy of Level 2 wind speed retrieval.

***Index Terms*—** Calibration, CYGNSS, GPS EIRP, flex power, GNSS-Reflectometry (GNSS-R), bistatic radar

1. INTRODUCTION

The Cyclone Global Navigation Satellite System (CYGNSS) mission uses the reflected Global Positioning System (GPS) signal to remotely sense ocean surface wind speed and land soil moisture [1, 2]. The effective isotropic radiated power (EIRP) determines the power incident on the Earth surface, and thus is very significant to the calibration of Level 1 normalized bistatic radar cross section (NBRCS) [3].

The GPS EIRP has the following sources of uncertainty: 1) each GPS satellite has a unique transmit power level; 2) the transmit power of Block IIR-M and IIF satellites varies in time and across different regions due to their flex power mode [4, 5]; 3) insufficient knowledge of the GPS transmit antenna gain pattern [6]; 4) uncertainty in antenna gain in direction of specular reflection caused by pattern asymmetry and space vehicle yaw maneuvers [6, 7].

To address these challenges, a dynamic EIRP calibration algorithm is developed which uses the direct signal measured by the CYGNSS zenith antenna to calculate the GPS EIRP in the direction to the CYGNSS satellite, and then to estimate the GPS EIRP in the direction to the specular reflection point. This approach can instantaneously detect any transmit power fluctuation in all GPS transmitters and use it to correct the calibration of the NBRCS [8].

Calibration of the zenith CYGNSS and GPS transmitting antenna patterns have been discussed in [8, 9]. In this paper, we provide the methodology and details of the dynamic EIRP calibration algorithm. A global map of the retrieved EIRP is shown to demonstrate that the CYGNSS direct signal successfully captures fluctuations in the GPS transmit power. It is also shown that by using the zenith-to-specular ratio function, we are able to minimize the error incurred by azimuthal asymmetry in the GPS antenna patterns without requiring additional information about GPS yaw attitude [10]. The impact of this algorithm on the CYGNSS Level 1 data coverage and quality are also discussed.

2. DYNAMIC EIRP CALIBRATION ALGORITHM

The dynamic EIRP calibration algorithm estimates the GPS EIRP in the direction of the specular reflection point on the Earth surface without direct knowledge of the GPS transmit power nor absolute antenna patterns. The concept of this algorithm is shown in Fig. 1. The first step is to derive the GPS EIRP in the direction of the CYGNSS satellite zenith antenna E_Z using the Friis equation

$$E_Z = P_T G_{TZ} = \frac{P_R}{G_R}\left(\frac{4\pi R}{\lambda}\right)^2 \quad (1)$$

where P_T is the transmit power, G_{TZ} is the transmit antenna gain in the direction of CYGNSS satellite, P_R is the received power at the CYGNSS satellite zenith antenna port, G_R is the antenna gain of the zenith receive antenna in the GPS satellite direction, R is the distance between the transmitter and the receiver, and λ is the wavelength for GPS L1 signals.

The parameter used in the CYGNSS Level 1 calibration is the GPS satellite EIRP in the direction of specular point E_S, defined as

$$E_S = P_T G_{TS} \quad (2)$$

where G_{TS} is the transmit antenna gain in the direction of specular point. By comparing Eq. (1) and (2), we notice that the transmit power term P_T can be canceled out by combining the two equations. E_S can then be written as

$$E_S = \frac{E_Z}{ZSR_G} \quad (3)$$

Here, ZSR_G is the zenith-to-specular antenna gain ratio, defined as the GPS transmit antenna gain in the direction of the zenith antenna to the gain in the direction of the specular point,

$$ZSR_G = \frac{G_{TZ}}{G_{TS}} \quad (4)$$

When using E_S to calibrate the CYGNSS Level 1 data, the ratio of the zenith channel receiver gain and the specular channel receiver gain is compensated for using additional ancillary information. In this way, any abrupt change of the GPS transmit power will be captured in the received power of the direct signal and automatically applied to correct the science measurement in the specular direction.

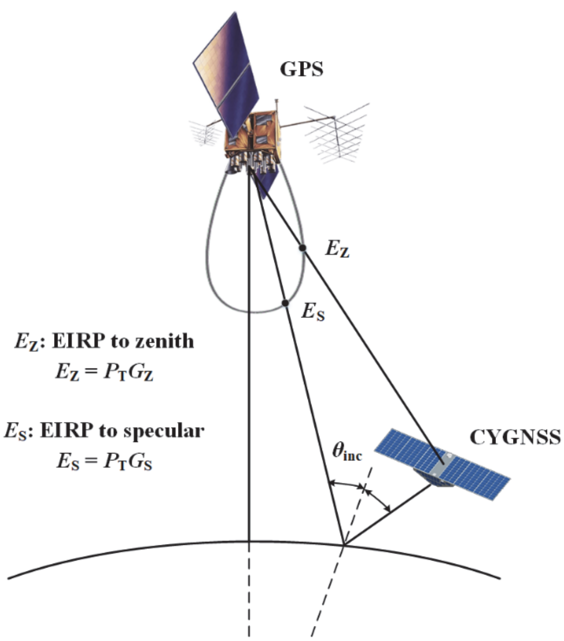


Fig. 1. Concept of the dynamic EIRP calibration

ZSR_G is calculated by taking an average of computed ZSR_G functions over all azimuth angles of the GPS antenna pattern [8]. The off-boresight angles (from GPS to zenith and GPS to specular) are both mapped into the specular incident angle using an empirical function based on the observation geometry over more than 1 year's data. The standard deviation of the gain to the specular point and that of the ZSR_G function of GPS PRN 16 are shown in Fig. 2. Both of them are calculated using the antenna gain pattern published in [6]. It can be observed that the standard deviation of the ZSR_G function is much smaller than that of the direct calculation of the GPS gain to the specular point. Therefore error caused by azimuthal asymmetry in the GPS pattern is significantly reduced without the need to know the exact GPS yaw attitude.

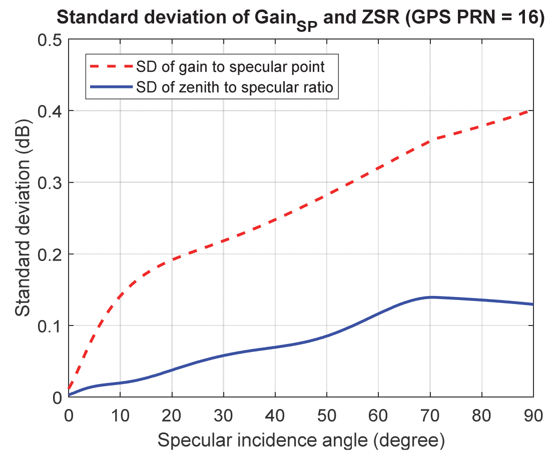


Fig. 2. Zenith-to-specular ratio vs. specular incidence

3. MONITORING GPS EIRP WITH ZENITH SIGNAL

3.1 Detecting Flex Power Events Using Zenith Signal

Fig. 3 shows multiple ground tracks of the EIRP to zenith E_Z with a GPS off-boresight angle less than 0.5 degree (approximately nadir pointing) for FM 1-PRN 1 observations. The color shows the EIRP in dB. This demonstrates that a flex power change (around 2.5 dB) can be detected using the zenith channel. The repeatability of these flex power events over a long time span demonstrates that it is a geographically-driven commanded change as shown in [4].

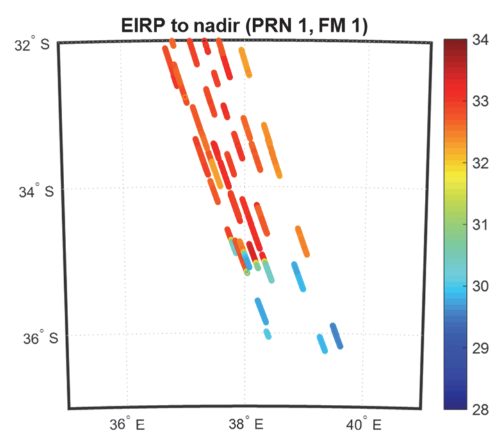
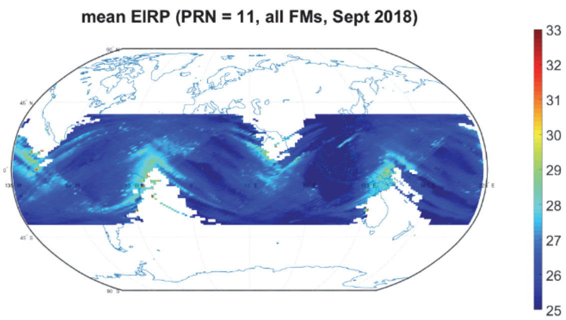


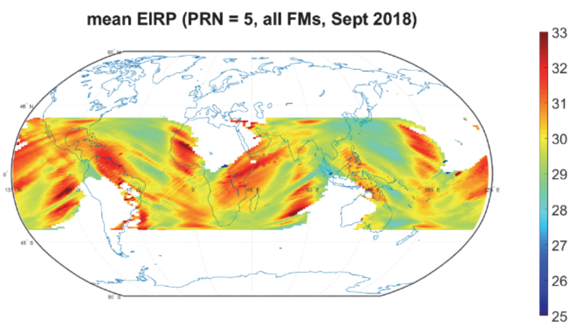
Fig. 3. EIRP to zenith E_Z estimated using the zenith signal

3.2 Global Map of Estimated GPS EIRP to Specular Point

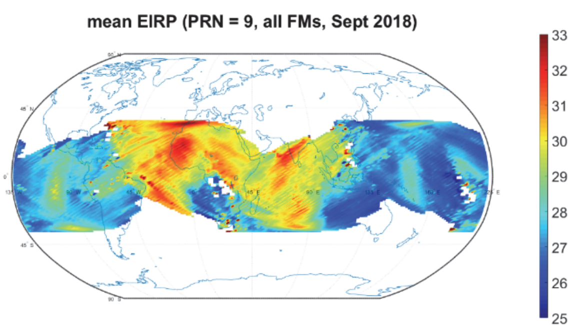
Fig. 4 shows a global map of estimated GPS EIRP to the specular point E_S for three different GPS transmitters (PRN 11, 5, 9 of Block IIR, IIR-M, and IIF, respectively). The estimated GPS EIRP to the specular point for all 8 CYGNSS FMs is binned in 1 by 1 degree latitude and longitude, with all specular incident angles included. Firstly, it is obvious that the Block IIR SV has relatively low EIRP, while IIR-M SV has relatively high EIRP, as demonstrated by the estimated GPS transmit power levels in [11]. Secondly, in Fig. 4c, it is noticed that there are different levels of EIRPs over different regions for the Block IIF SV.



(a)



(b)



(c)

Fig. 4. Global map of estimated EIRP to the specular point: (a). PRN 11, Block IIR, (b). PRN 5 Block IIR-M, (c) PRN 9, Block IIF

4. IMPROVED CYGNSS LEVEL 1 CALIBRATION

4.1 Case Study during the Flex Power Event

An example of a flex power event (GPS year 2018, day 213; measured by CYGNSS FM 6) is illustrated in Fig. 5. The GPS transmit power increases by ~ 2.5 dB, as shown by the black dashed line as the zenith received power at the DMR input port.

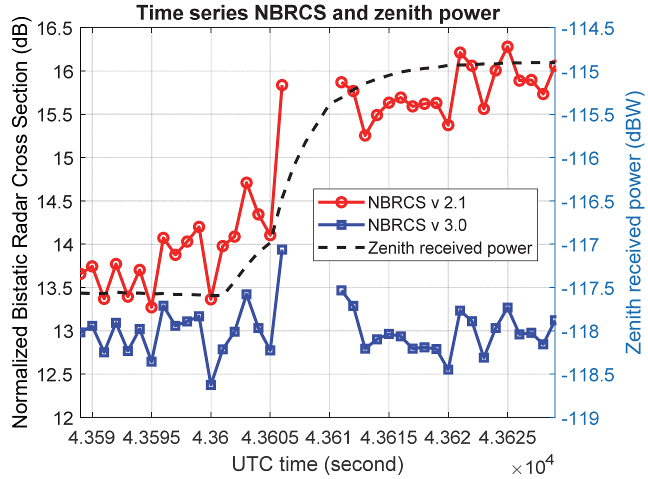


Fig. 5. NBRCS calibration during a GPS flex power event

The nadir science measurements are over an open ocean which has a relatively stable surface wind speed (~7 m/s). The red line shows the version 2.1 calibrated Level 1 NBRCS (using a static transmit power for the GPS EIRP estimation) and features the same abrupt change as the zenith power. The non-physical NRBCS shows that the change of the transmit power is not accounted for. Using the dynamic EIRP calibration algorithm, the version 3.0 NBRCS is plotted as the blue line. The new NBRCS can be seen to be more physically reasonable for a GNSS-R measurement over a uniform open ocean.

4.2 Histogram of the v3.0 Level 1 NBRCS

Fig. 6 presents histograms of the version 3.0 NBRCS with signal source of all Block IIF SVs and all Block IIR SVs for one month's data. This show that the Block IIF data are correctly calibrated and can be included in the official Level 1 data products for higher level applications.

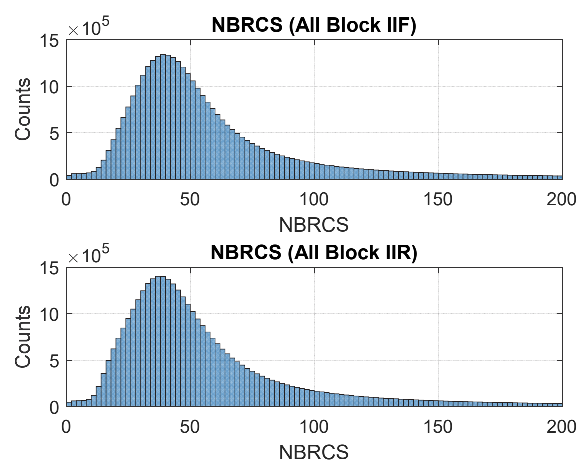


Fig. 6. Histograms of the version 3.0 Level NBRCS

5. SUMMARY

This paper reviews recent progress with a dynamic EIRP calibration algorithm that uses the CYGNSS direct signal to improve EIRP estimate in the direction of the specular point for CYGNSS Level 1 calibration. It is shown that flex power events can be successfully detected by the zenith signal. The dynamic EIRP calibration algorithm successfully recovers flagged observations from the Block IIF (~37% of the entire dataset) to the standard science data products. It also mitigates the error brought by the antenna pattern asymmetry and will further improve the accuracy of Level 2 wind speed retrieval.

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