Development of GPS Constellation Power Monitor System for High Accuracy Calibration/Validation of CYGNSS L1B Data

Tianlin Wang[1], Christopher S. Ruf[1], Scott Gleason[2], Bruce Block[1], Darren McKague[1], Damen Provost[1]
[1]Department of Climate and Space Sciences and Engineering, University of Michigan, Ann Arbor, MI [2]Southwest Research Institute, Boulder, CO

Cyclone Global Navigation Satellite System

- Constellation of 8 LEO satellites
- GNSS-R bi-static configuration
- Measure ocean surface wind speed
  - In inner core of tropical cyclone
  - With extremely short revisit time
- Launched on December 15, 2016
- Operating on Science Mode

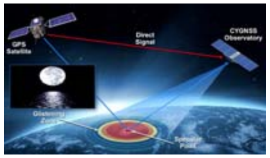

Figure 1 Bi-static configuration

Table 1 CYGNSS science data products

Level	Description
0	Unprocessed DDMs and metadata
1A	Decompressed, calibrated DDMs, power in Watts
1B	Calibrated DDMs, bistatic radar cross section
2A	Time tagged wind speed of a 25×25 km cell centered on the specular point
2B	Time tagged mean square slope of a 25×25 km cell centered on the specular point
3A	Wind Speed, gridded in time and space
3B	Wind Speed optimized for observing system experiment data assimilation

Global Positioning System (GPS)

- Constellation of 32 MEO satellites
- Orbital height 12,540 miles (~12 hours period)

Block	Year	Antenna Panel	# of Satellites
IIR	1997-2004	Legacy	8
		Improved	4
IIR-M	2005-2009	Improved	8
IIF	2010-2016	Improved	12

Figure 2 GPS constellation

Transmit Power and Antenna Patterns of GPS

- Transmit power of GPS satellite is about 25 watts.
- IIR/IIR-M built by Lockheed Martin and IIF built by Boeing.
- Only 12 IIR and 8 IIR-M GPS satellites' antenna patterns are published.

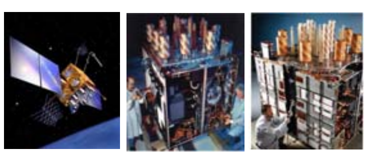

Figure 3 GPS satellite, legacy panel, and improved panel

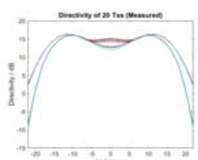

Figure 4 Azimuth averaged patterns

Pattern Asymmetry and GPS Yaw Attitude

- The antenna pattern of GPS satellites are azimuthally asymmetric.
- Yawing of GPS satellites affects the gain of transmit antenna.
- For θ=±12°, the difference between can be as large as 0.5 dB.

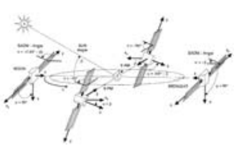

Figure 5 Satellite yawing

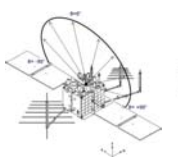

Figure 6 SV coordinate system

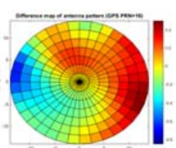

Figure 7 Pattern diff. map

Research Objectives and Science Goal

- Develop a ground-based GPS constellation power monitor (GCPM) system
- Concurrently monitor the GPS yaw attitude and assess its effect on the received power.
- Retrieve transmit power and antenna pattern of all GPS satellites.
- Accurately and precisely characterize GPS EIRP for CYGNSS L1B calibration algorithm to improve accuracy and reliability of Level 1 BRCS data
- Provide better estimate of ocean surface wind speed

Forward Model and Retrieval Algorithm

- Forward model is based on Friis radar equation

$$\frac{P_r}{P_t} = G_t(\theta_t,\phi_t)G_r(\theta_r,\phi_r)\left(\frac{\lambda}{4\pi r}\right)^2 L_A$$

- The objective is to retrieve P_t and $G_t(\theta_t,\phi_t)$ from the time series received signal.
- Initial value: transmit power = 25 watts; antenna pattern = 5th order polynomial fitting of azimuthally averaged radiation patterns from Lockheed Martin.
- Retrieval algorithm: The minimum-squared-error solution is that value which minimizes the squared difference between $\bar{y}$ and F($\bar{x}$), $\bar{x}_{MSE} = \min_{\bar{x}} \{|\bar{y} - F(\bar{x})|^2\}$. $\bar{x}_{MSE}$ is estimated iteratively $\bar{x}_{i+1} = \bar{x}_i + (J^T J + R)^{-1} J^T [\bar{y} - F(\bar{x}_i)]$.

GPS Constellation Power Monitor

Figure 8 System design of GPS constellation power monitor

- The antenna and thermal box for LNA and calibration system are mounted on the roof top of Space Research Building, University of Michigan, Ann Arbor.
- The Septentrio GPS receiver and GCPM computer are located in GPS Moldwin Lab.
- The processed data will be forwarded to the Science Operation Center of CYGNSS.
- Javad RingAnt-DM antenna is used to receive GPS signals. Full radiation pattern measured at OSU. Elevation mask is set to 20° to filter out the multipath signal.

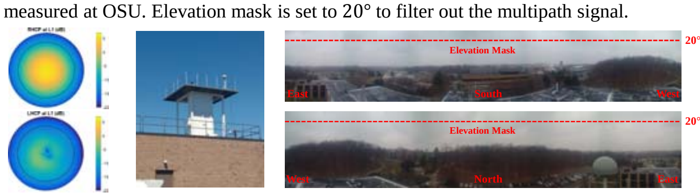

Figure 9 Javad RingAnt-DM: antenna pattern, location, and panoramic view

Scaled Simulation and Uncalibrated Measurement

- The measurement power is computed as I^2+Q^2. The simulation data is computed from the forward model. A scale factor is applied to the simulated data.
- Simulation and measurement matches best with corrected azimuth angle.
- Strong peak due to increase of LNA gain at sunrise (Local time 8AM).

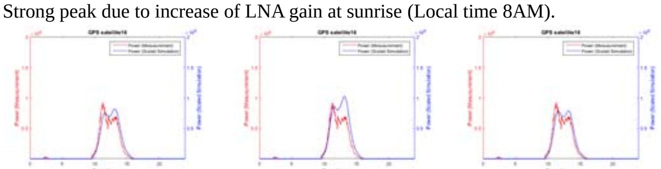

Figure 10 Model prediction and measurement: no azimuth; with azimuth; with corrected azimuth

Thermal Box with LNA&Calibration Subsystem

- LNA and calibration subsystem are designed and implemented on a PID controlled thermal baseplate.
- System bandwidth is 5 MHz centered at 1.57542 GHz (GPS L1).
- Rabbit SBC is used to control and record system states.
- It has solar reflective white coating.

Figure 11 Picture of thermal Box

Radiometric Calibration

- 6 states: EXT LN2 Start, INT Cold, INT Cold+ND, INT Ambient, INT Ambient+ND, EXT LN2 End.
- Measure each state for 0.5 hour. One routine gives 3 hour data. Do 3 routines.
- External LN2 and Internal Ambient load are used as references.
- Use Maury noise calibration systems MT7000 series.
- TB of LN2 cold load is 80.5 K. Equivalent TB of LN2 load at K2 is 120.7666 K.

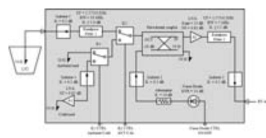

Figure 12 Calibration diagram

Figure 13 Liquid nitrogen calibration

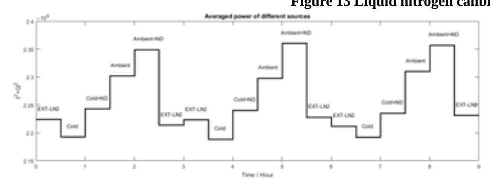

Figure 14 Averaged power of different sources

Table 2 Calibrated brightness temperature of internal sources

Source	Brightness temperature (K)
Internal cold load	59.3937
Excess Noise diode ($TB_{Ambient+ND} - TB_{Ambient}$)	110.8693
Excess noise diode ($TB_{Cold+ND} - TB_{Cold}$)	110.1614

Conclusion

- Yaw attitude and maneuver of GPS satellites do affect the received power from GPS satellites because of the antenna pattern asymmetry.
- The radiometric calibration system has been designed and implemented. The liquid nitrogen calibration is performed.

Future Work

- Move the thermal box to the roof and calibrate the received power.
- Include yaw attitude data from GIPSY-OASIS to the forward model.
- Incorporate the retrieved GPS parameters to CYGNSS L1B calibration.
- Error analysis of GCPM and CYGNSS L1B data.

Acknowledgements

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