Deployment of a Ground-Based Beacon System for On-Orbit Calibration of the CYGNSS Satellites

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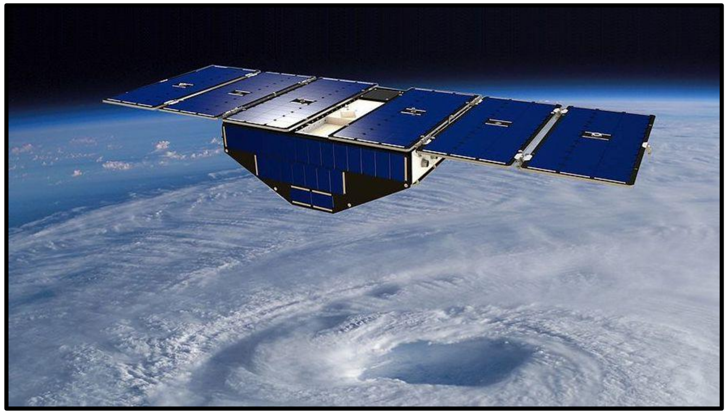
Overview

- Motivation & Beacon Concept
- CYGNSS Beacon Campaign Planning
- Beacon System Hardware and Software Design
- Performance Goals

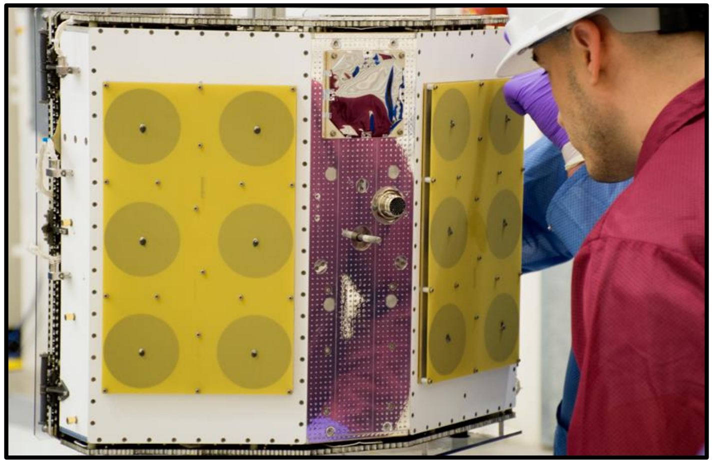
Background: CYGNSS Antenna Calibration

- CYGNSS estimates of ocean surface wind speed (primary science product) require measurements of received power accurate to within a small fraction of a dB
- This requires very accurate receive antenna pattern knowledge
- The CYGNSS Team has spent the past year improving Zenith Antenna calibration to cancel out effects of GPS transmit pattern and transmit power variations in new Version 3.0 data product
- There is still the need for accurate CYGNSS Nadir Science Antenna pattern calibration

CYGNSS Satellite



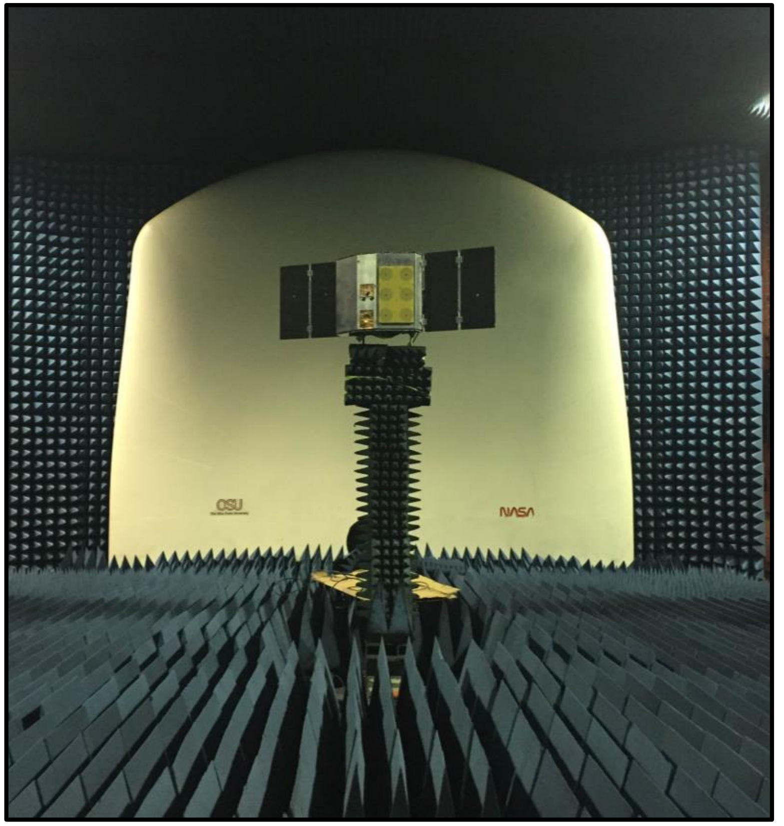
CYGNSS Nadir Science Antennas



Background: CYGNSS Antenna Calibration

- Prior to launch, a CYGNSS science antenna was measured on an RF model of the satellite in a Compact Antenna Range
- Measurement of every antenna on the actual satellites was cost & time prohibitive
- SwRI performed subsequent EM simulations to enhance measured pattern accuracy
- On-orbit calibration is important to account for deployment of solar panels and long-term exposure to the space environment.
- Some improved patterns in Version 2.0 were produced based on large-scale analysis of measured CYGNSS data (Darren McKague, UM)
- Still a need for additional data to refine on-orbit antenna pattern knowledge

CYGNSS Antenna Measurement on RF Model

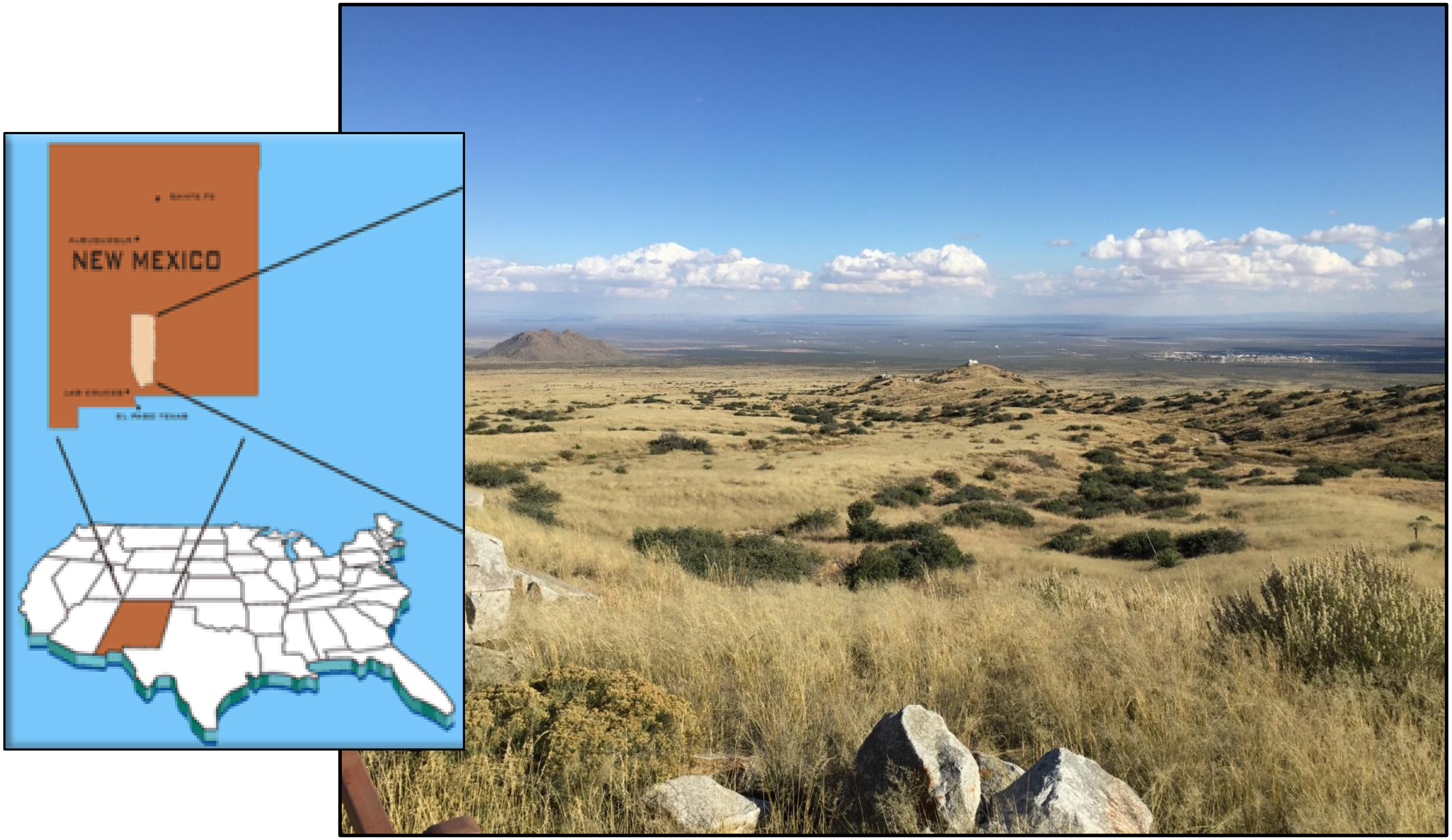


CYGNSS Beacon Concept

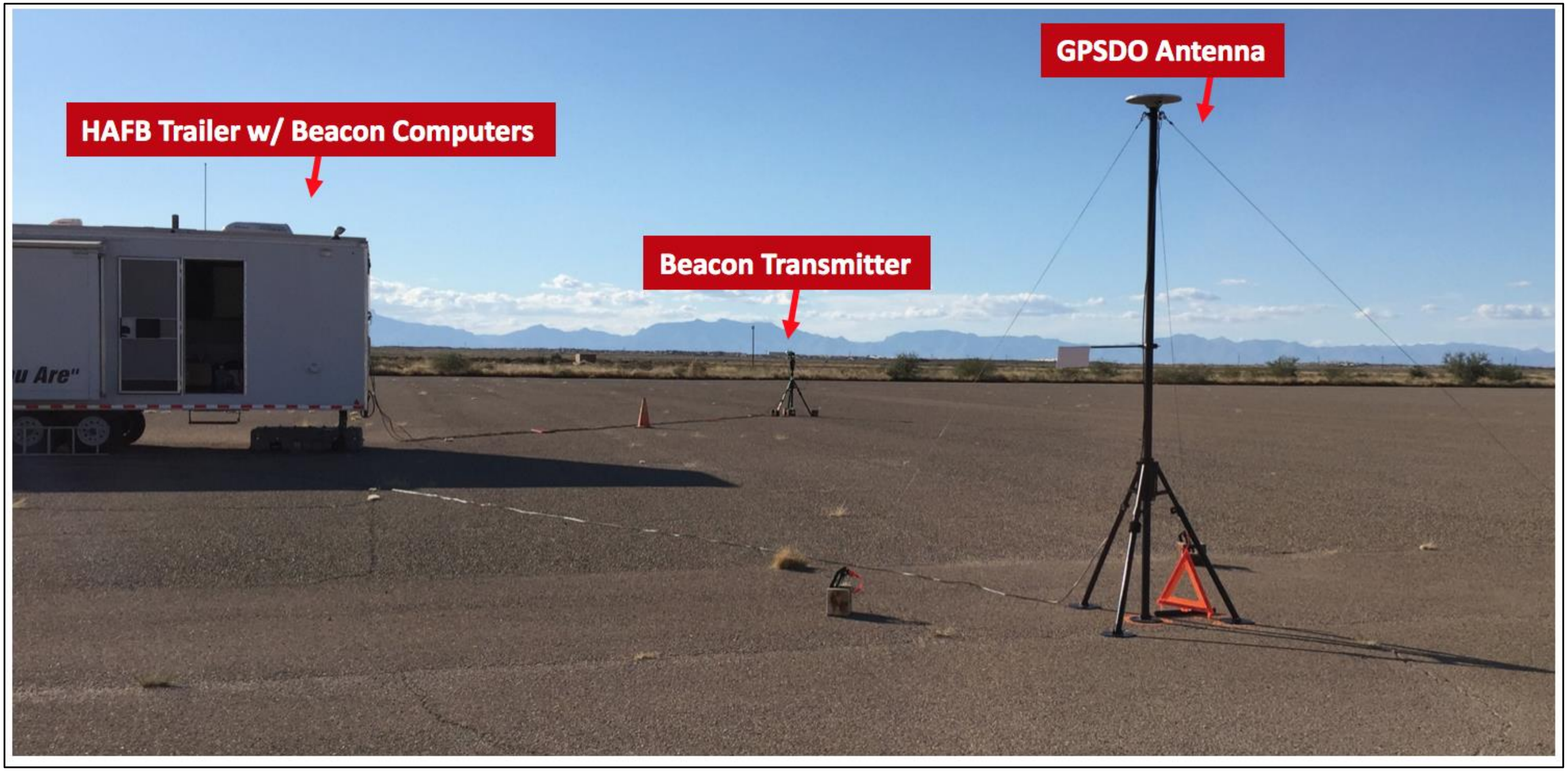
- The Beacon System is a ground-based transmitter that is capable of broadcasting a signal on GPS L1 frequencies up to CYGNSS to be received by the DDMI Science Instrument
- Main objectives of the Beacon System is to provide a known signal in the CYGNSS measurements as a means of on-orbit verification of the received power, satellite antenna gain pattern, or to serve as a tool to resolve unforeseen problems
- A ground-based Beacon for space borne GNSS remote sensing instruments is a unique capability and has great potential as well as great challenges
- Use of GPS frequencies mean the beacon can only operate at special government test ranges

CYGNSS Beacon System

Beacon Location: Holloman Air Force Base, New Mexico



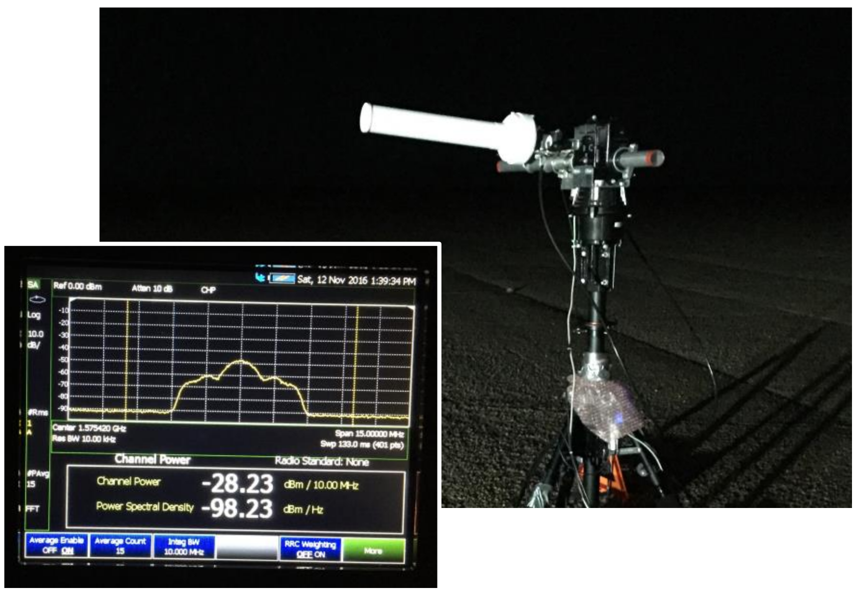
Beacon System Deployment



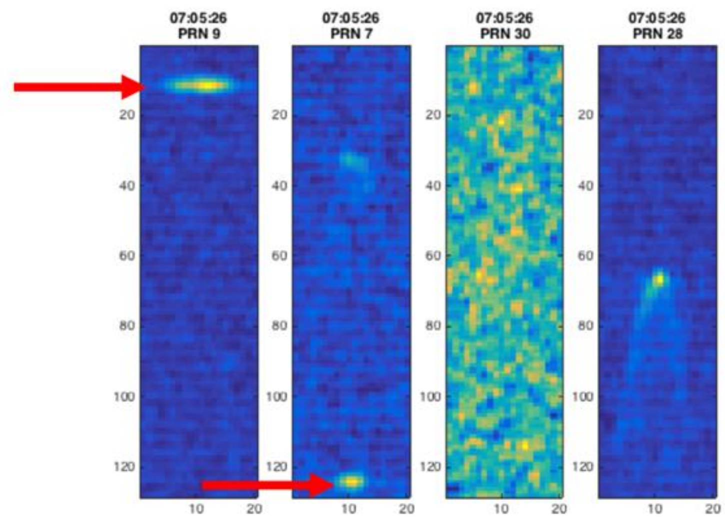
TDS Beacon Campaign 2016

- Figure shows actual on-orbit measurements made by the TDS-1 with the CYGNSS beacon signal was tested in November 2016.
- Test confirmed that both the signal generation and hardware timing synchronization had been successfully accomplished.
- 1 satellite with 1 antenna performing 2 passes over 2 days

Beacon During TDS-1 Campaign



On-Orbit TDS-1 DDMs with Beacon Signal

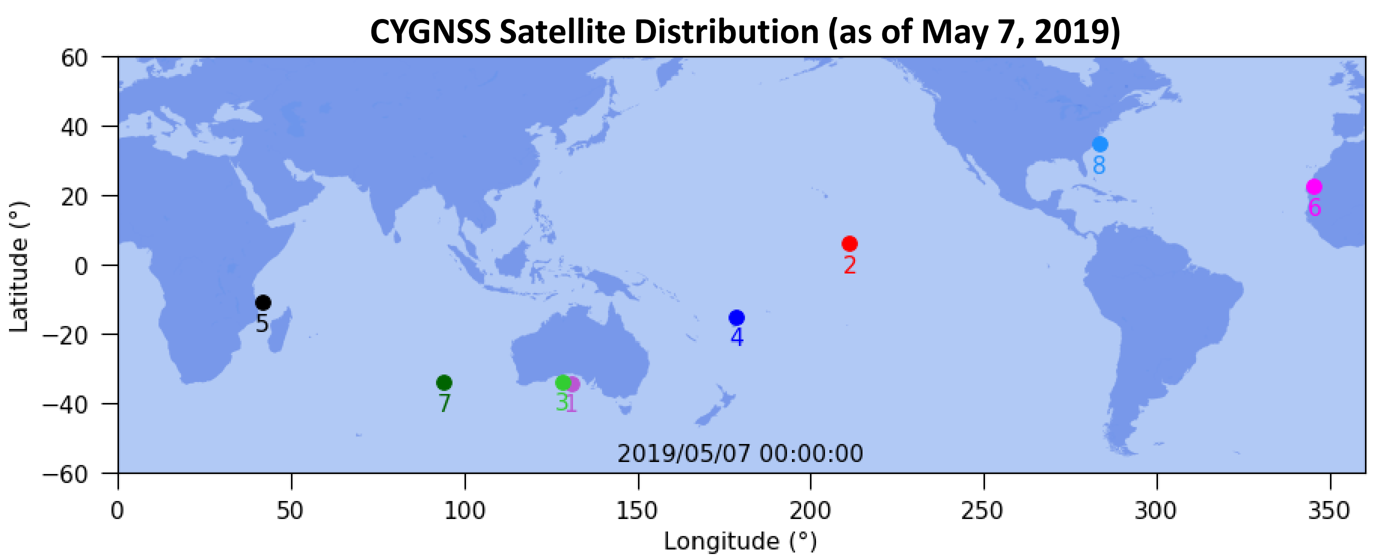


CYGNSS Beacon Campaign 2019

- The beacon system was originally scheduled to be deployed in April 22-26, 2019. However, the US Government shutdown caused large a schedule backlog at Holloman AFB.
- Initial results from this campaign were originally expected to be available in time to be presented here at GNSS+R. Instead, we will talk more about our preparations for the campaign.
- Due to the complications of shutting down local airspace, we can only transmit between 00:00-06:00 local time each night. This limits days of year where the CYGNSS satellites fly over the beacon in an optimal way
- We have reserved 1 week of range time at Holloman AFB, **June 10-14** (transmit for 5 evenings)
- **Objective**: to provide antenna calibration data for both science antennas for each of the 8 spacecraft

CYGNSS Overpass Planning

- The current separation between CYGNSS satellites is not uniform
- Some are too close together and we will only be able to target one or the other for an overpass.
- The spacing between others is close enough that one is rising on the horizon before another has set. We manually make choices when to switch from one CYGNSS satellite to another. This will only effect non-critical antenna pattern angles.

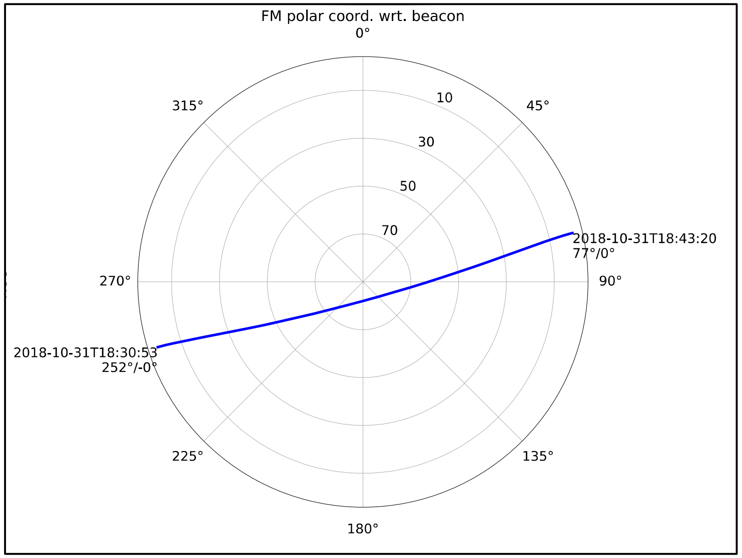


https://cygnss-spock.com/operations/orbit-status.php

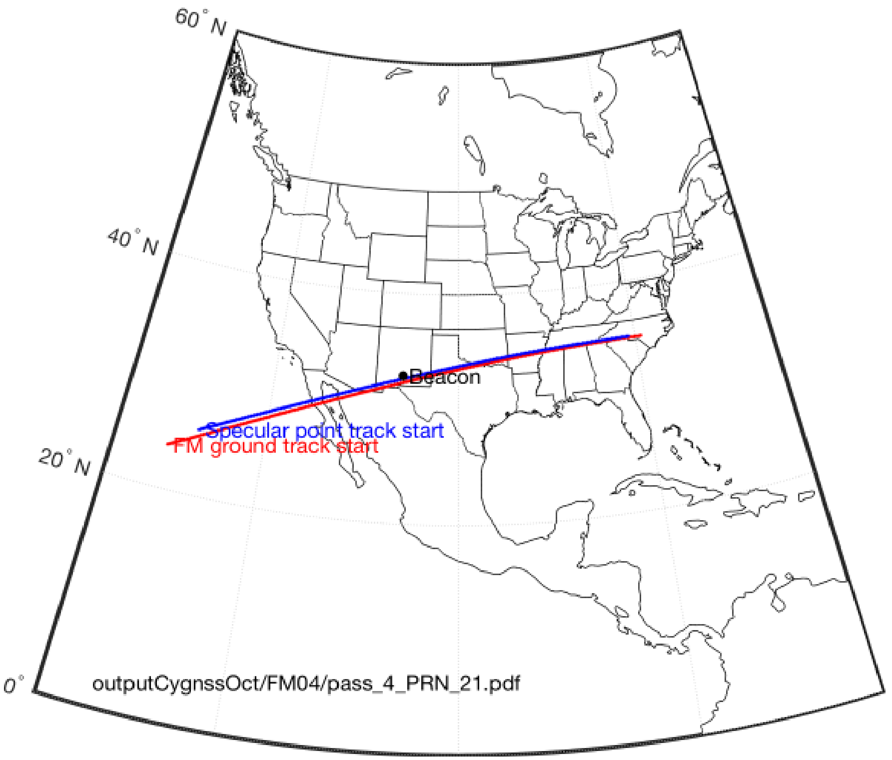
CYGNSS Overpass Planning (cont.)

- Figure shows example of a CYGNSS satellite overpass.
- Specular point track for each overpass covers entire continental USA

View of CYGNSS Satellite from Beacon



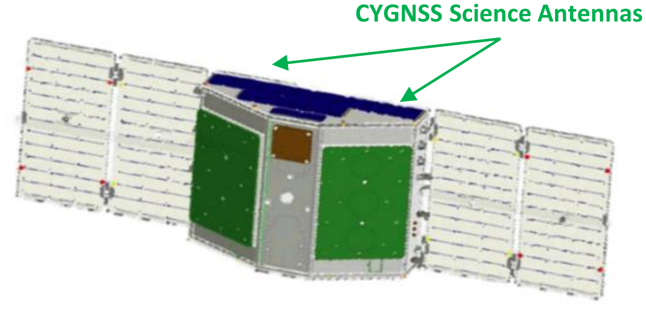
CYGNSS Satellite Overpass of Beacon Location



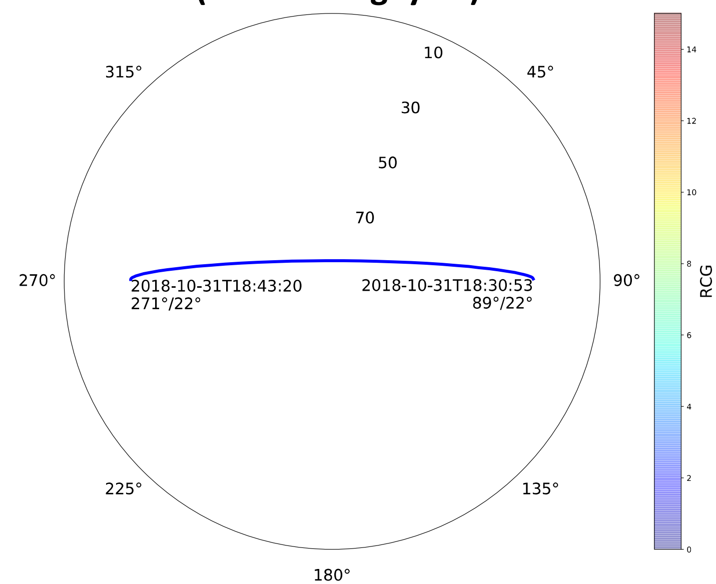
FM polar coord. wrt. beacon
0°

CYGNSS Antenna Pattern Cuts

- Ideally, we want to measure both science antennas. The standard satellite orientation not well suited for this
- CYGNSS satellites will be yawed 90 degrees so that one cut of the beacon will cross both beams (although the success of this depends on the instrument)
- Figure shows and example of the antenna pattern cut for a typical beacon overpass
- Yawing the satellite affects the power margins (campaign occurs during worst case beta angle)



CYGNSS Antenna Pattern Cut for One Overpass (with 90°deg. yaw)

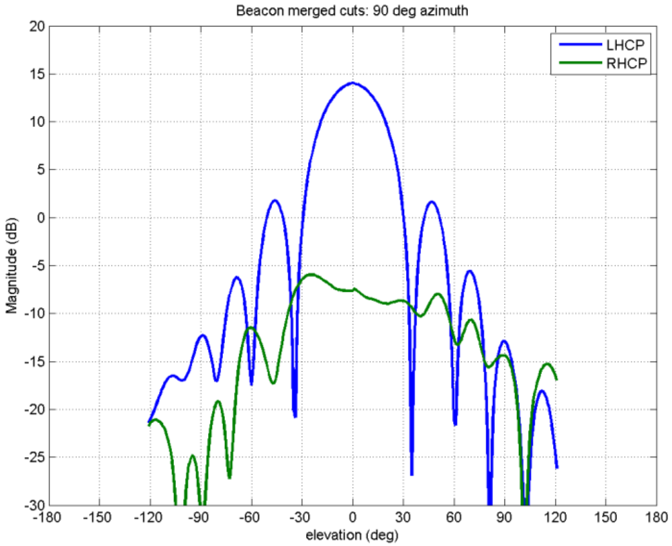


Beacon Transmitter Hardware

- Mounted on a low-cost motorized dual-axis antenna pointing system.
- An automated pointing system is used to ensure the transmit antenna is directed toward the passing CYGNSS satellites.
- Planning software is used to predict the location of the satellites and to choose optimal transmission times.
- The antenna is connected to a software defined radio (USRP N210) that outputs a pre-generated beacon signal waveform from a PC
- Using an external amplifier, the maximum input power at the antenna port is 5W

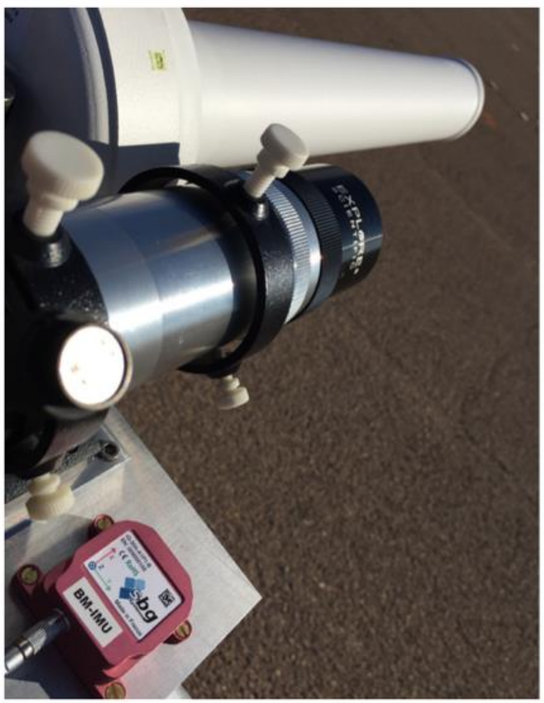
Beacon Transmitter Antenna

- The Beacon transmit antenna is a high-gain (14 dB) LHCP helical antenna with 30 deg. beamwidth
- The gain pattern of the beacon antenna has been measured precisely in an antenna measurement chamber, and an IMU is used to record pointing angle to better than 1-degree accuracy.
- The measured beacon antenna gain pattern was used to translate the pointing angle errors into a gain versus time



Beacon Hardware Components

- Beacon Transmitter also includes: Scope for precision alignment, IMU for recording precise orientation information to a log file, power meter for recording precise output power

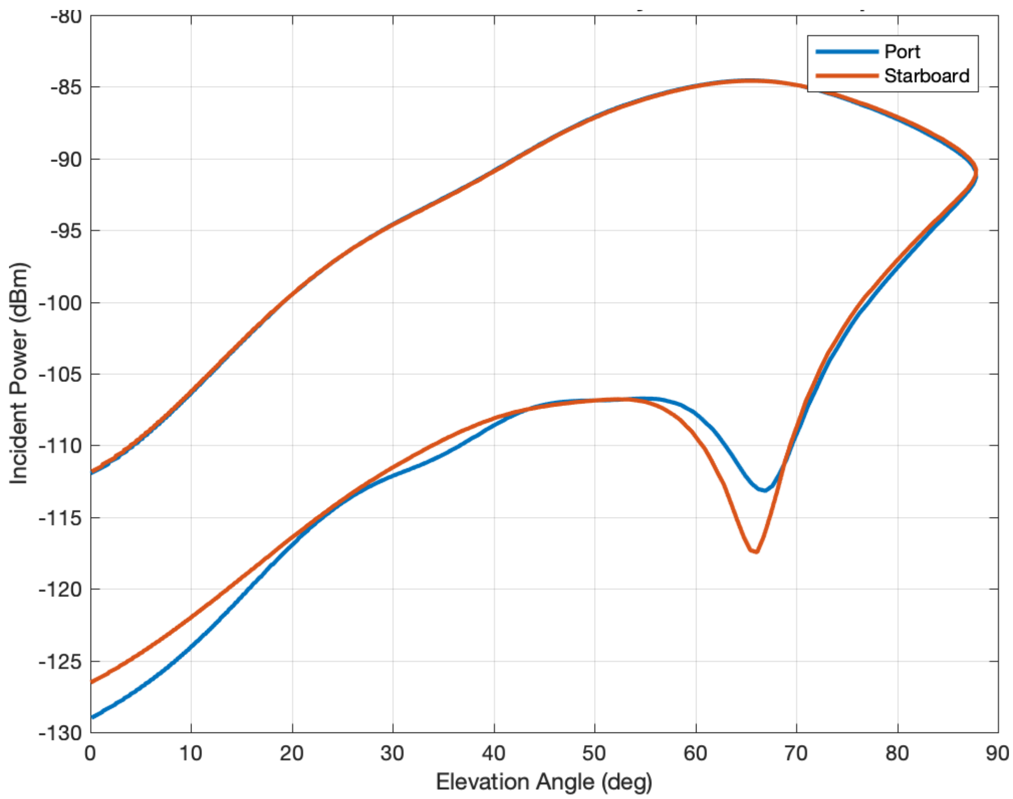


Beacon Transmitter Power Budget

Figure shows power budget for typical CYGNSS overpass of the beacon site (CYGNSS port antenna blue, starboard antenna red)

Indicates sufficient incident signal power - even over weaker portions of the antenna pattern.

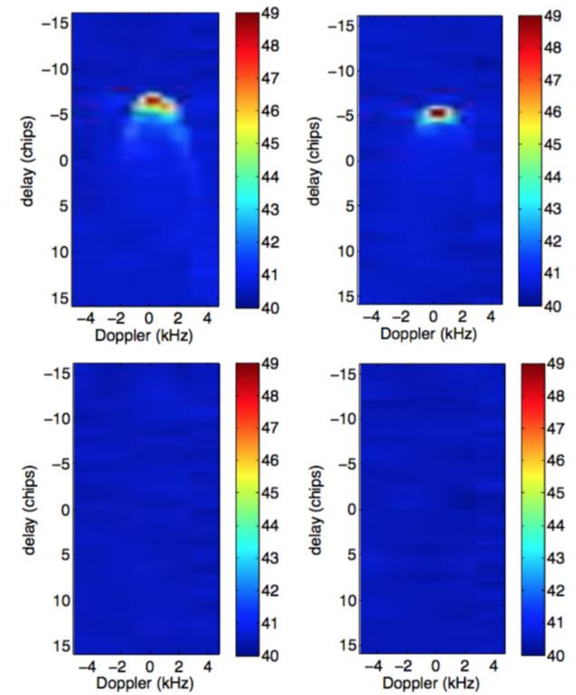
Power (dBm) incident on the CYGNSS Satellite vs. Satellite Elevation Angle in the Sky



Beacon Signal Contents

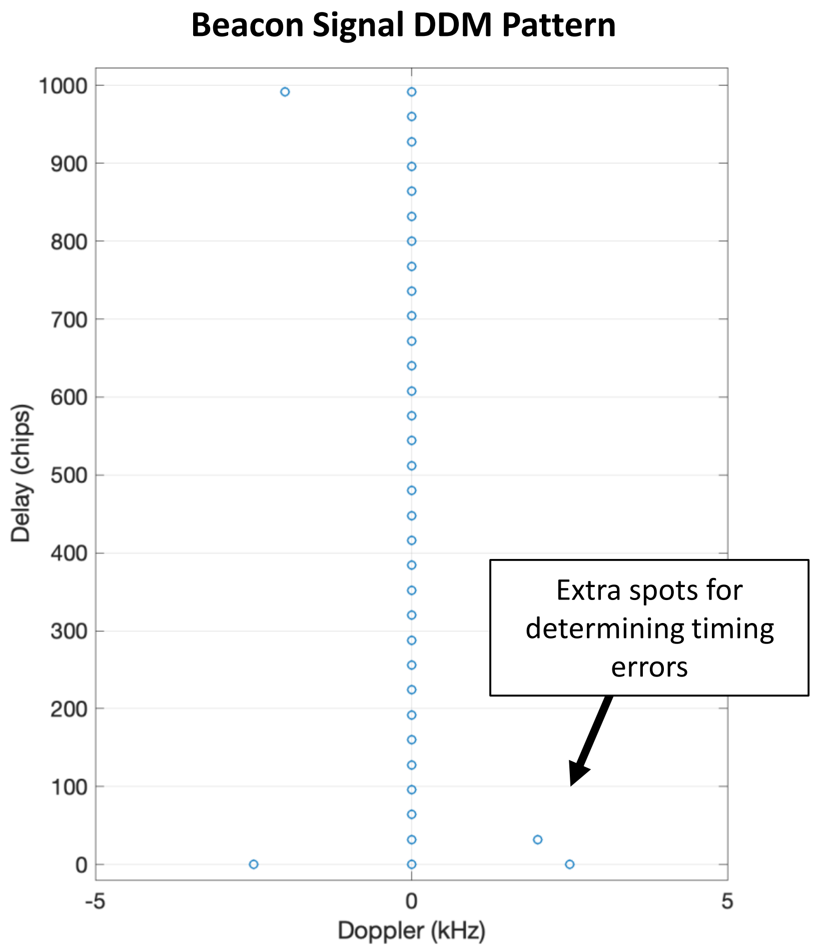
- CYGNSS instruments will operate in their standard science mode, except they will also be commanded to record full DDMs (128x20) rather than compressed DDMs (17x10)
- Beacon Signal consists of a summation of GPS C/A coded replicas. Replicas appear as peaks, or “hotspots”, in the DDM at their relative delay and Doppler offsets
- We must carefully place the hot-spots in the delay-Doppler region where the satellite is looking for them.
- CYGNSS Full DDMs only provide measurements over a delay-Doppler range of ± 16 microseconds in delay and ± 5 kHz in Doppler, centered around the specular reflection delay and Doppler
- We will transmit 2 PRNs at a time

Land Reflections Full-DDMs Over New Mexico



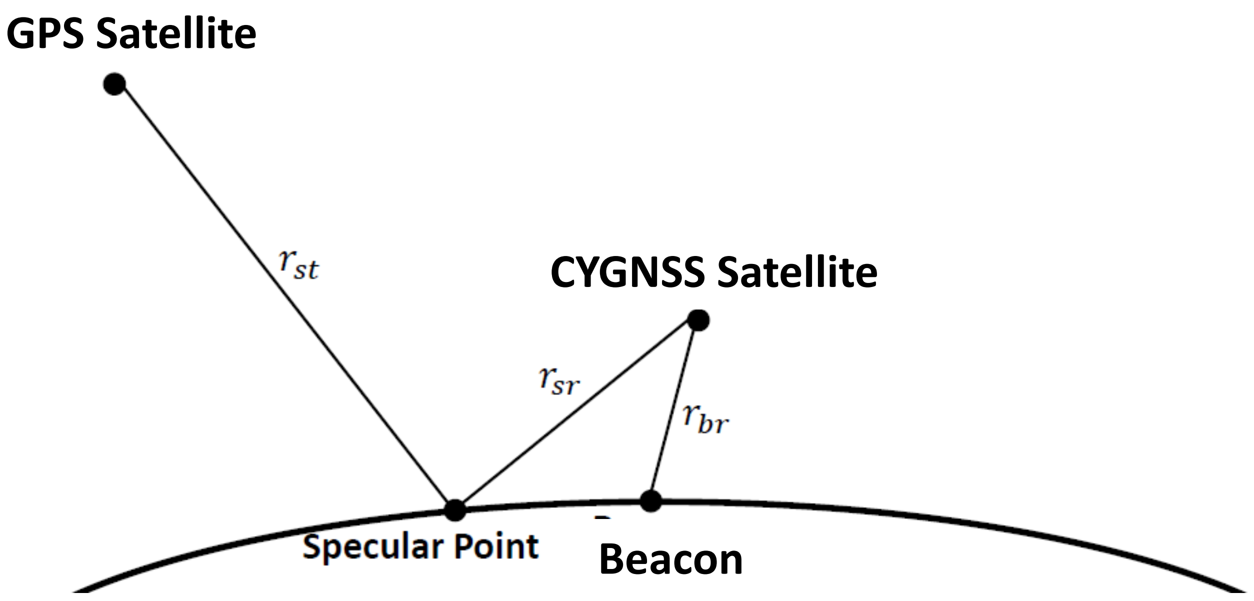
Beacon Signal Hot-Spot Pattern

- The transmitted beacon signal contains 34 delayed and Doppler shifted GPS C/A code replicas
- Result in a pattern of hot-spots spread out in Delay and Doppler space
- Provided that the Doppler is close, the pattern is designed to guarantee at least one hot-spot should appear.
- The location of the hot-spots are arranged uniquely to help determine modest timing errors
- The same pattern is transmitted for each PRN. More hot-spots is also a bad thing!
  - More noise (cross-correlation)
  - Less power per hot-spot



Beacon Signal Timing

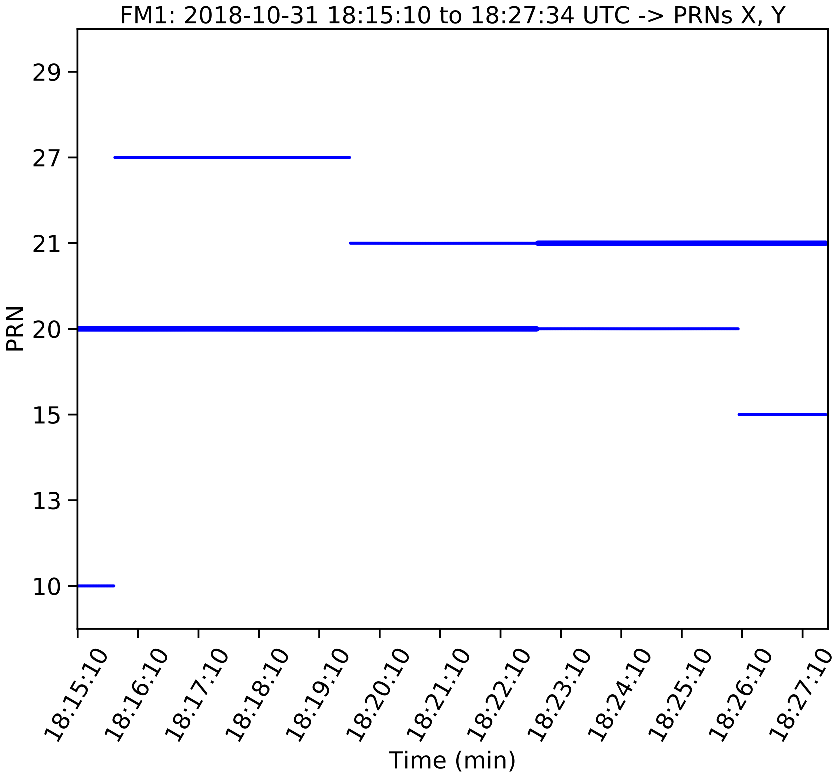
- Beacon GPS C/A coded signal's Delay and Doppler offsets need to be precisely chosen so that a signal originating from the Beacon's location arrives with the same delay and Doppler as a signal reflected from the specular point of each PRN (Not easy!)



Predicting CYGNSS PRN Selection

- The CYGNSS satellites only track 4 GPS PRNs at a time
- Unfortunately, we do not have the ability to force the tracking of specific PRNs (or unused PRNs) due to firmware issues
- We will use custom-designed overpass prediction is used to predict which PRNs that CYGNSS is likely to track in the future
- We transmit two PRNs at a time to make sure we have a very high likelihood of getting at least one PRN over the entire overpass

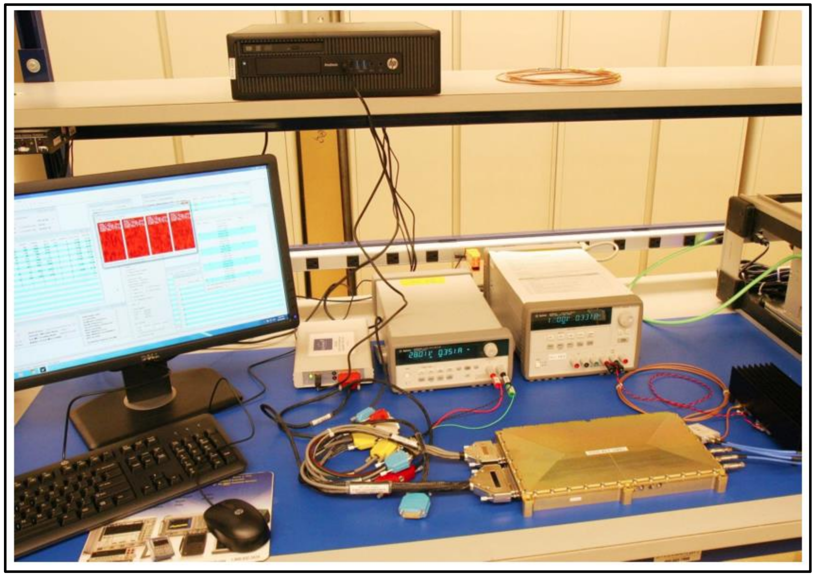
Custom Software to Predict the GPS PRNs the CYGNSS will track in the future

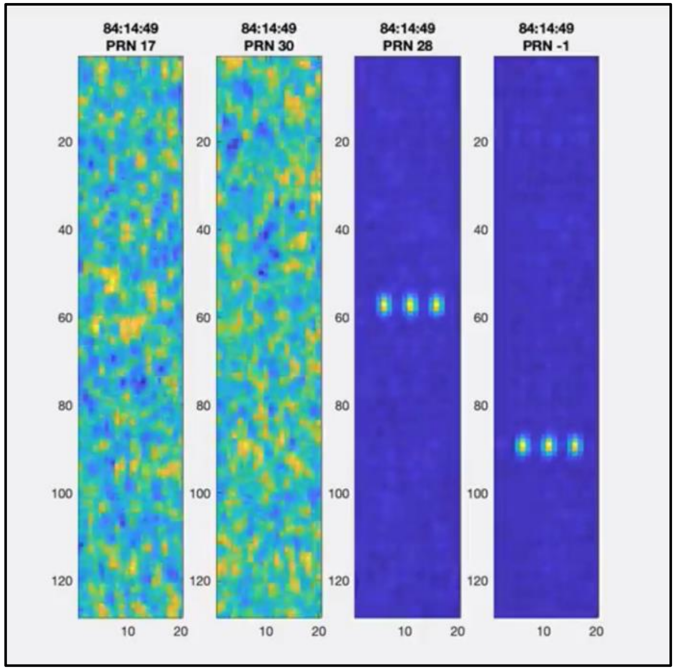


Bench Tests of Beacon Hardware

- Bench tested Beacon Hardware for several months in order to achieve microsecond-level synchronization of the system

Example Beacon Signal During Bench Testing

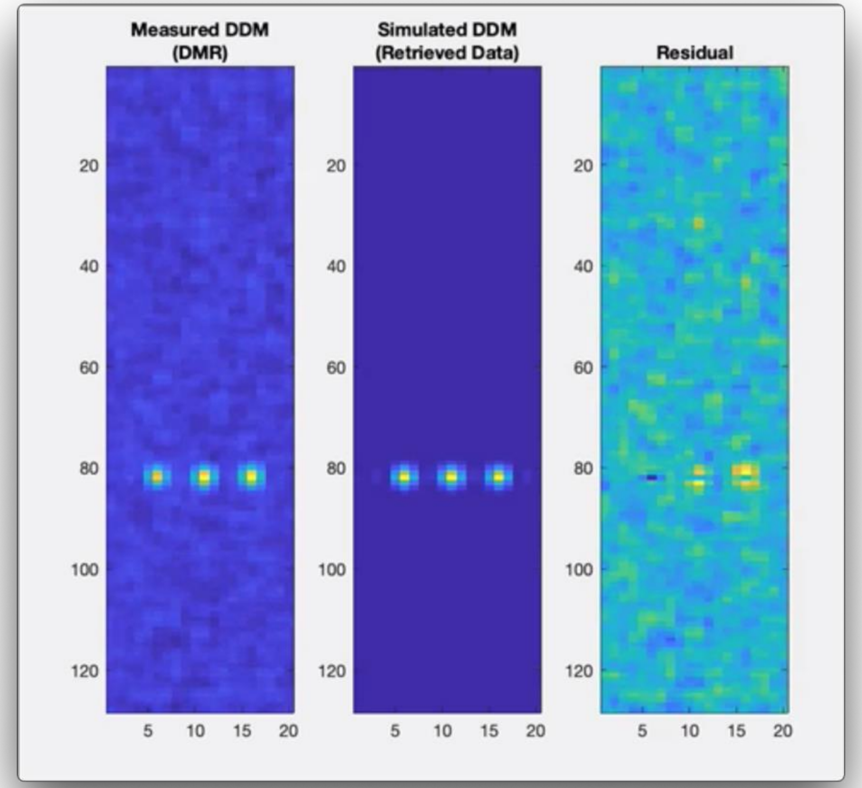




Retrieval of Received Power

- Beacon signal pattern is matched up (least squares) to the measured signal power from the DDMs
- Sub-pixel delay offset search is used
- Retrieval of incident signal power and ultimately the receive antenna pattern will require precise calibration of the complete beacon system

Least-Squares Retrieval of Poewr from Beacon Signal in the DDM



Beacon System Calibration

Factors to be calibrated that can affect power retrieval:

- Antenna pointing accuracy – measured using IMU
- SDR and amplifier power output - measured using in-line power monitor
- Power of digital signal contents – known exactly through use of software defined radio
- Instrument DDM formation – calibrated using bench-top EM model

In order to ensure the hot-spots are utilized (improved SNR over simple noise floor increase), we need very precise timing dependent on:

- Predict Position, velocity, and clock bias of GPS Satellites
- Predict Position and Velocity of CYGNSS Satellites
- Start transmission of the signal to within a microsecond
- Need precise system timing despite jamming GPS itself during transmission
- Predict correct PRN selection on on-board algorithm

Summary

- CYGNSS Beacon Campaign will take place June 10-14, 2019
- Will produce several pattern cuts of each CYGNSS Science Antenna in the constellation
- Provides a precisely known power source for improving antenna calibration knowledge.
- This will ultimately improve the accuracy and/or confidence with the Science Antenna pattern, and could improve the ocean wind speed retrieval accuracy

Beacon Operations Rehearsal at University of Michigan

Acknowledgments

- Thanks to the support staff at the US Air Force 746th Test Squadron at Holloman AFB for the help coordinating and assiting with our experiments.