Validation of GNSS Multipath Model for Space Proximity Operations Using the Hubble Servicing Mission 4 Experiment

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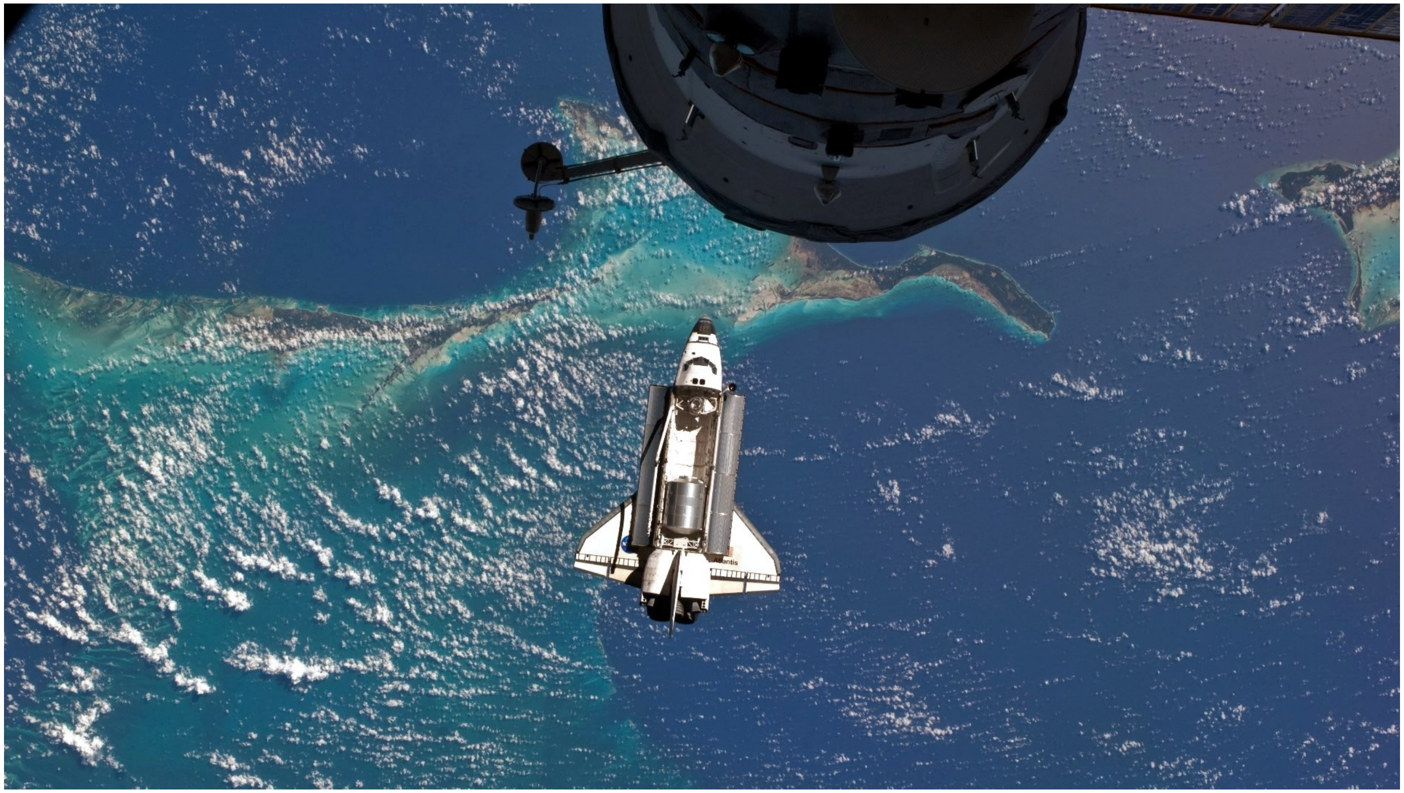
Objectives

- Accurately model the raw GNSS signal received during rendezvous and close proximity operations around large space structures
- Validate this model using experimental data
- Use this information to improve relative navigation accuracy and integrity



Discovery docking with ISS May 29, 1999 [1]

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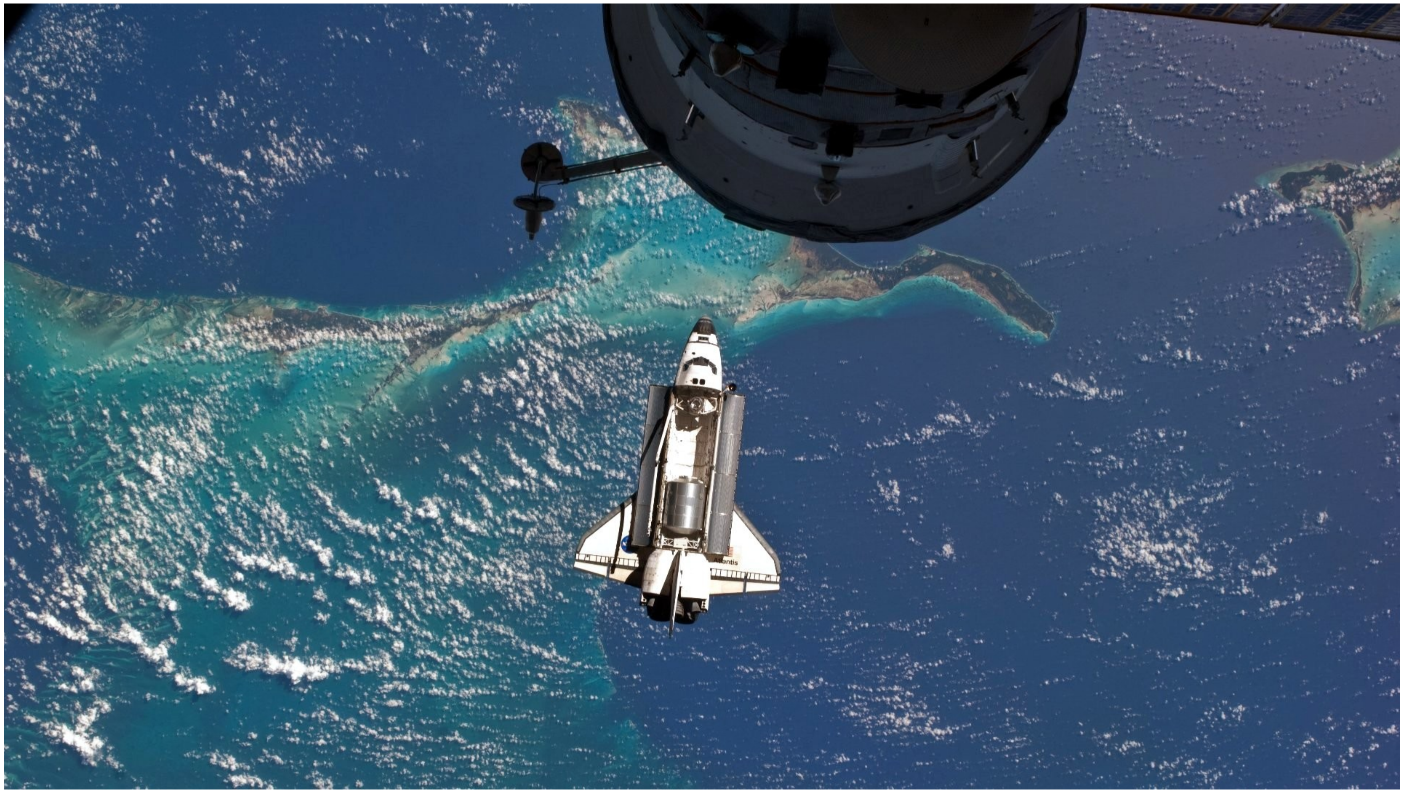

Discovery docking with ISS May 29, 1999 [1]

Outline

I. Background

II. Hubble Servicing Mission 4

III. Simulation

IV. Results

V. Conclusions and Future Work

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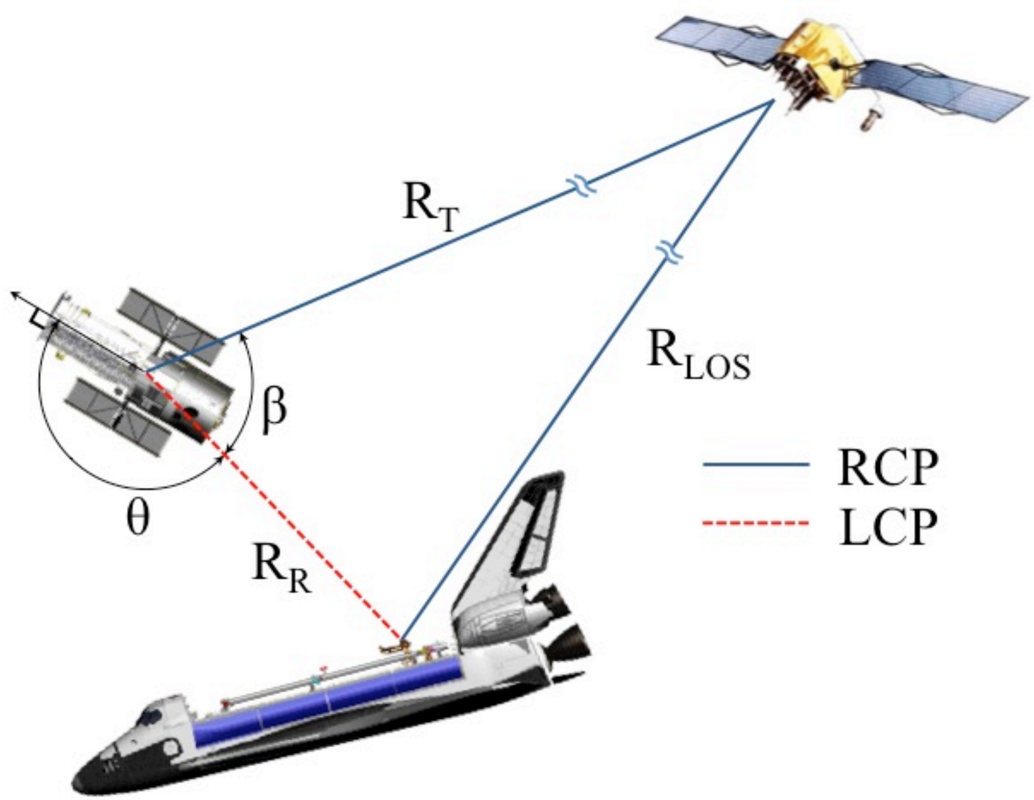
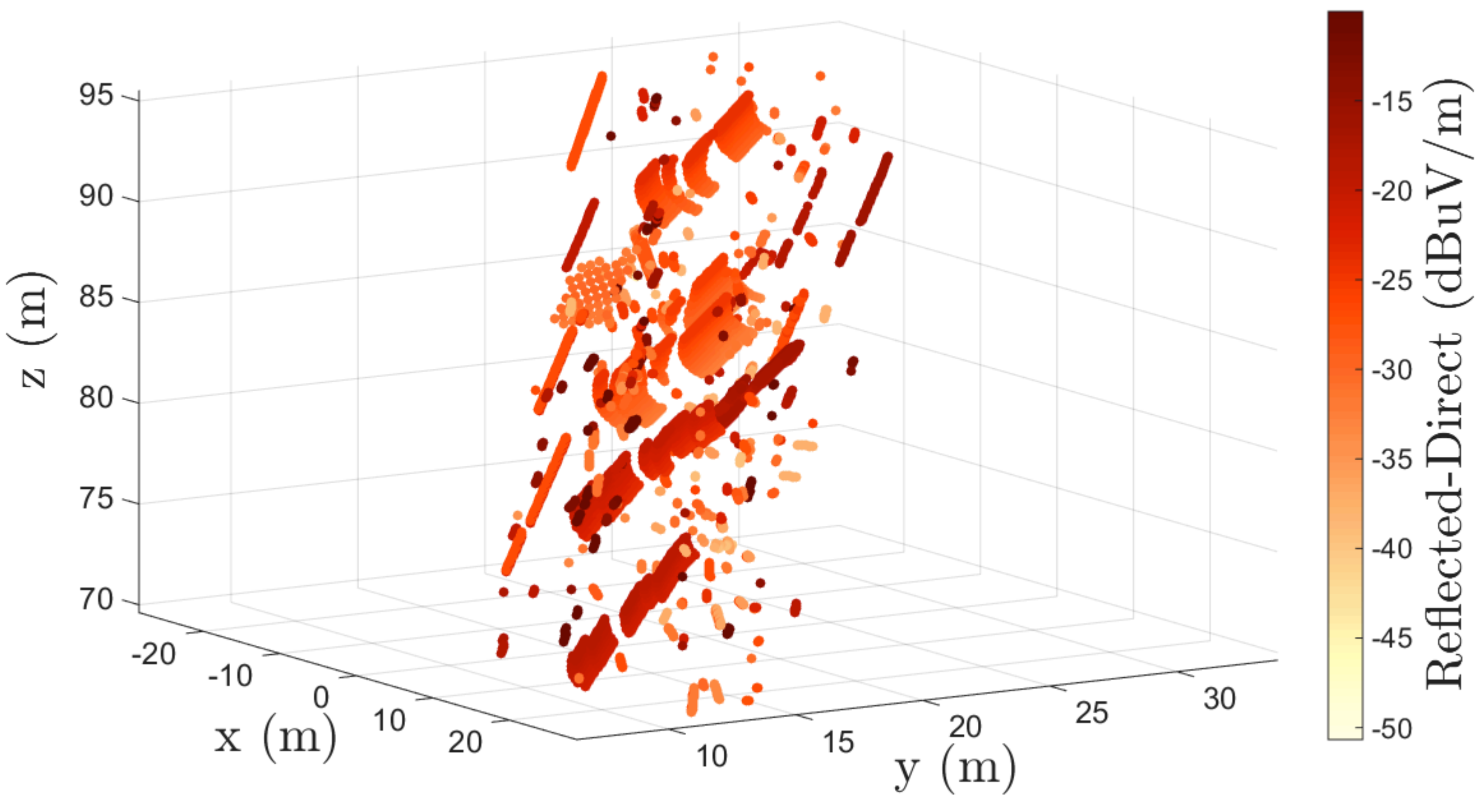
Background

- During docking, GNSS navigation of the chaser spacecraft is corrupted by GNSS signals reflected off the passive target spacecraft
- These reflected signals, i.e., multipath, could potentially be used as a source of information about the distance of the target from the receiver



Background (continued)

- A model has been presented previously [2] that uses electromagnetic (EM) ray tracing and a MATLAB signal simulator to generate raw, multipath-corrupted GNSS data from environment features
- Hubble Servicing Mission 4 (HSM4) is used as a case study, and space data collected during this mission is used here to validate the model



Background – Signal Model

- Received direct signal (GPS C/A signal on the L1 carrier)

$$y(t) = ad(t - \tau_{code}(t))c(t - \tau_{code}(t)) \cos(2\pi f_{L1} t + \theta(t))$$

with carrier phase

$$\theta(t) = -2\pi f_{L1} \tau_{carr}(t) + \theta_0$$

- Reflected signals are received as delayed, attenuated replicas of the line of sight signal. For M reflected signals:

$$y(t) = \sum_{m=0}^{M} a_m d(t - \tau_{code,m}(t))c(t - \tau_{code,m}(t)) \cos(2\pi f_{L1} t + \theta_m(t))$$

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- Characterize reflected signals in terms of relative **amplitude**, code delay, and carrier phase with respect to the line of sight signal:

$$\alpha_m = E_m \sqrt{\frac{G_{R\times}}{G_R}} = \sqrt{\frac{a_m}{a_0}}$$

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$$\psi_m(t) = \theta_0(t) - \theta_m(t)$$

Background – Multipath Fading

- As the excess path length traveled by a reflected signal changes the relative carrier phase will cycle through phases that add to the line of sight signal constructively and destructively
- This effect is known as multipath fading, resulting in a characteristic oscillation of received power
- Multipath fading is driven by the carrier phase rate of change:

$$\dot{\psi}_m(t) = \frac{2\pi f_{L1}}{v_{carr}} \dot{r}_{\Delta,m}(t)$$

- This can be related to the rate of change of the relative code delay:

$$\dot{\psi}_m(t) = \frac{1}{\lambda_{L1}} \left(\frac{v_{code}}{v_{carr}} \right) \dot{\delta}_m(t)$$

- Ignoring dispersion effects:

$$\dot{\psi}_m(t) \approx \frac{1}{\lambda_{L1}} \dot{\delta}_m(t)$$

- This relationship is used to validate the signal simulation - the simulated reflected signal path length rate of change is compared to the measured fading frequency.

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Hubble Servicing Mission 4

- STS-125 was performed by the crew of the space shuttle *Atlantis* May 11-24, 2009; docked with Hubble on May 13th
- Relative Navigation Sensor (RNS) experiment
  - Tested vision processing algorithms that estimated Hubble's relative position and attitude using imagery from three cameras mounted in the shuttle bay
  - Two oppositely-polarized GPS antennas were mounted in the shuttle cargo bay (RHCP and LHCP) collecting hours of sampled, intermediate frequency GPS data

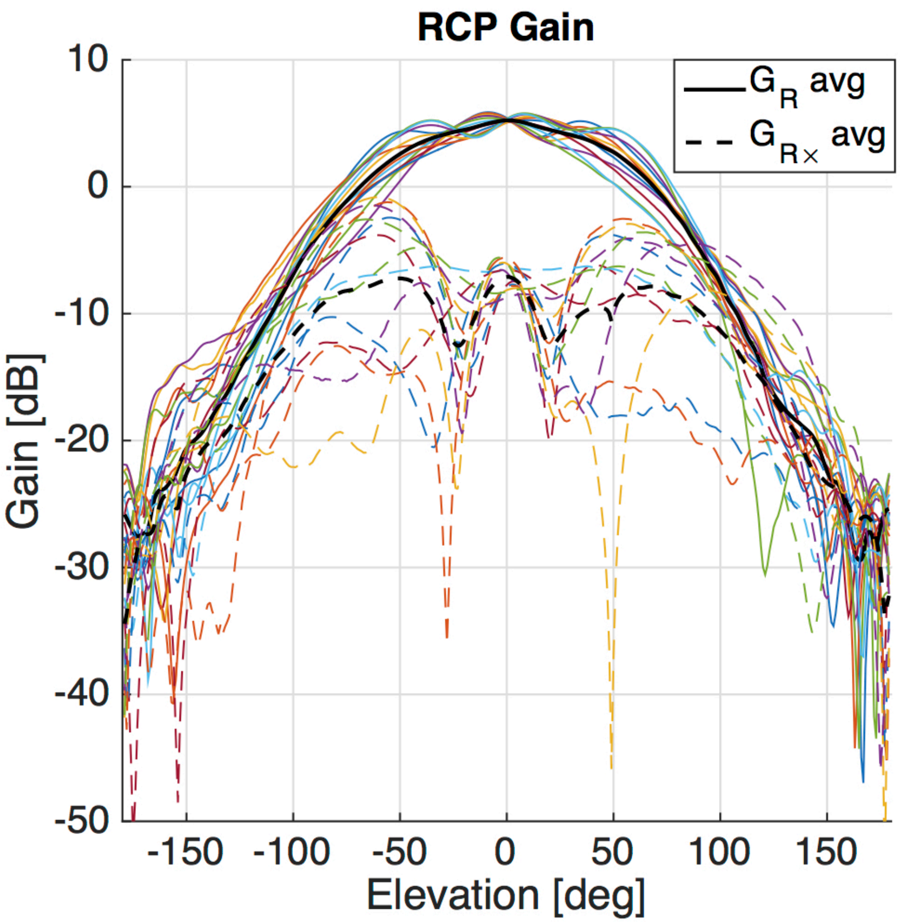
Atlantis docking with Hubble May 13, 2009 [3]

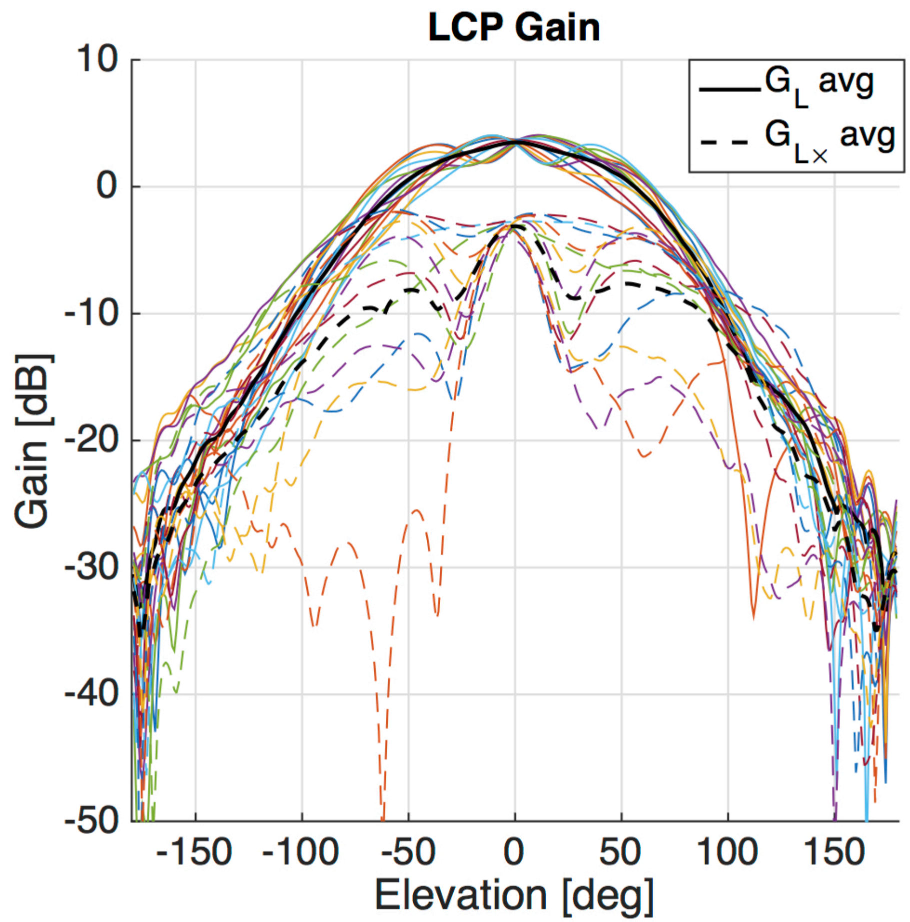
HSM4 - Antennas

- Sensor Systems RCP and LCP antennas flown to receive direct and reflected signals respectively
- Separability of direct and reflected signals depends on polarization reversal at reflection and antenna cross-pole discrimination
- Antennas were measured in the Goddard ElectroMagnetic Anechoic Chamber (GEMAC)
    - Attenuation of LCP signal at RCP antenna boresight is 12 dB
    - Attenuation of RCP signal at LCP antenna boresight is 7 dB
    - Azimuthal variation due to asymmetric mounting plate

Antenna testing in GEMAC with antenna mount-plate reconstruction

HSM4 – Antennas (continued)





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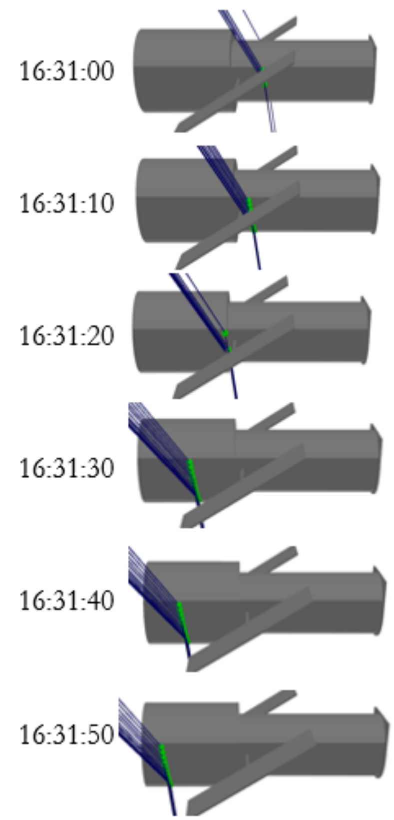
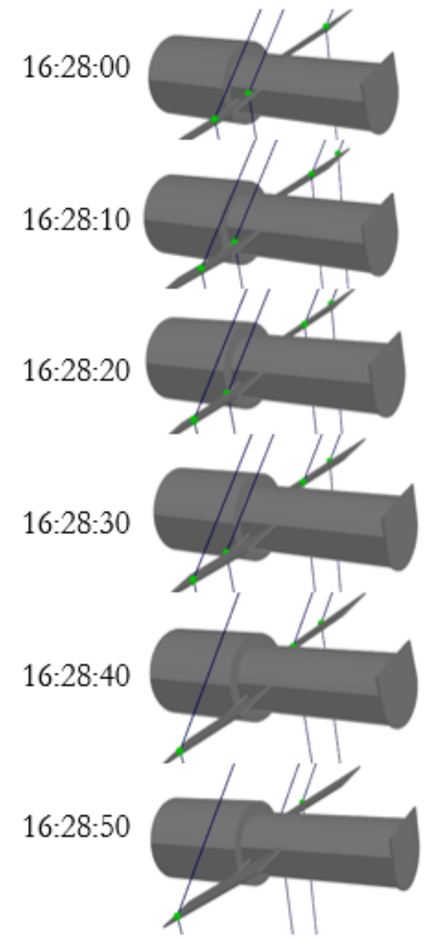
Simulation

- Simulation presented previously [2]:
  - Dynamics of Hubble and GPS satellites reproduced in the WinProp© electromagnetic ray tracing software using a CAD model of Hubble
  - Modified GSFC Siggen was used to produce GPS data from the ray-tracing results and a custom MATLAB software receiver was used to track simulated and HSM4 data



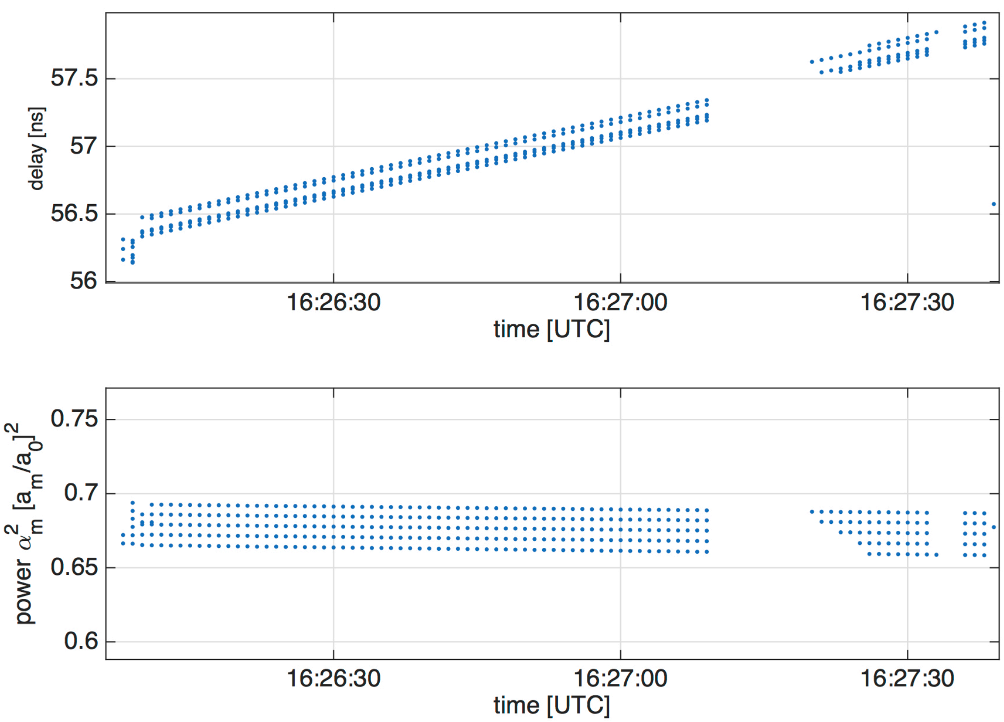
PRN 28 interactions



PRN 17 interactions

Simulation (continued)

- Ray tracing output consists of relative path length and electric field strength for each ray
  - Simultaneous arrival of nearly identical rays resolved through curve fitting
  - 165 second segment considered here: May 13th, 2009, 16:25:27-16:28:12 UTC (inter-vehicle range ~85 meters)



PRN 26 relative delay and power

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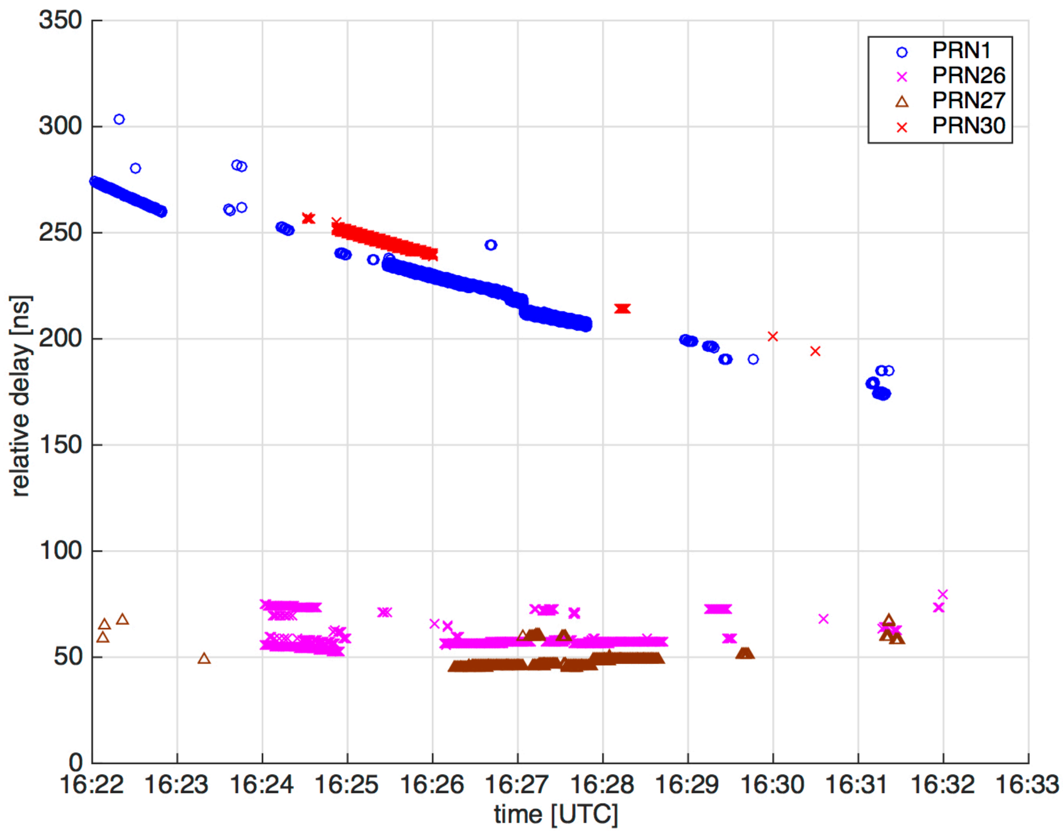
Results

- Simulated parameters of reflected signals for four PRNs (FFT resolution = 0.0061 Hz)

PRN	δ_0 [m]	$\dot{\delta}$ [cm/s]	α_m^2/α_0^2	$\dot{\psi}$ [Hz]
1	70.80	-4.94	0.45	0.2595
26	16.75	0.44	0.66	0.0230
27	16.32	0.47	0.67	0.0246
30	73.84	-5.73	0.38	0.3012



Results – PRN 1 (simulation)

- Simulated parameters of reflected signals for four PRNs (FFT resolution = 0.0061 Hz)

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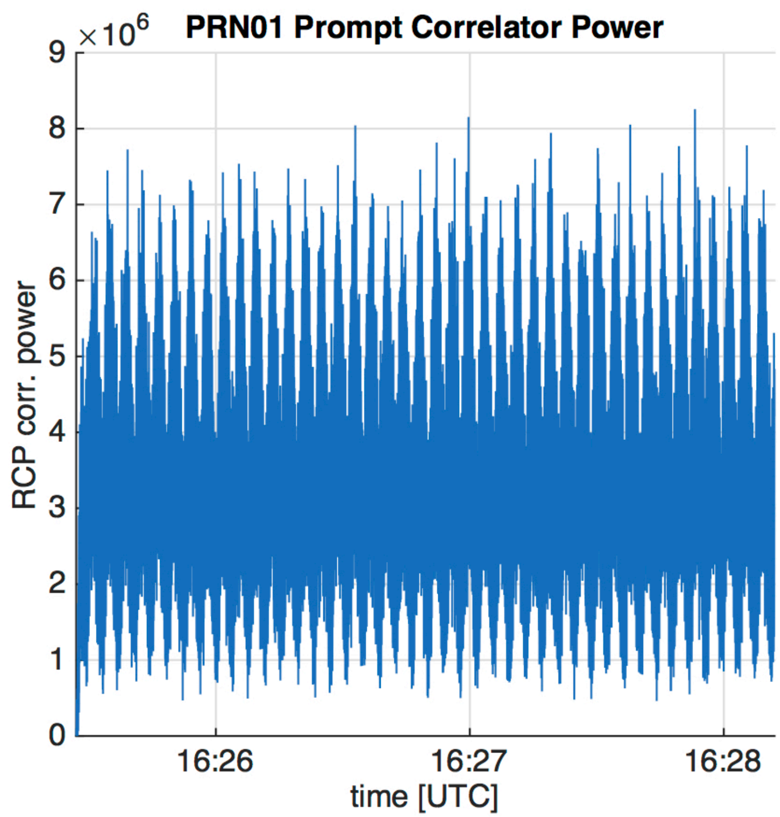

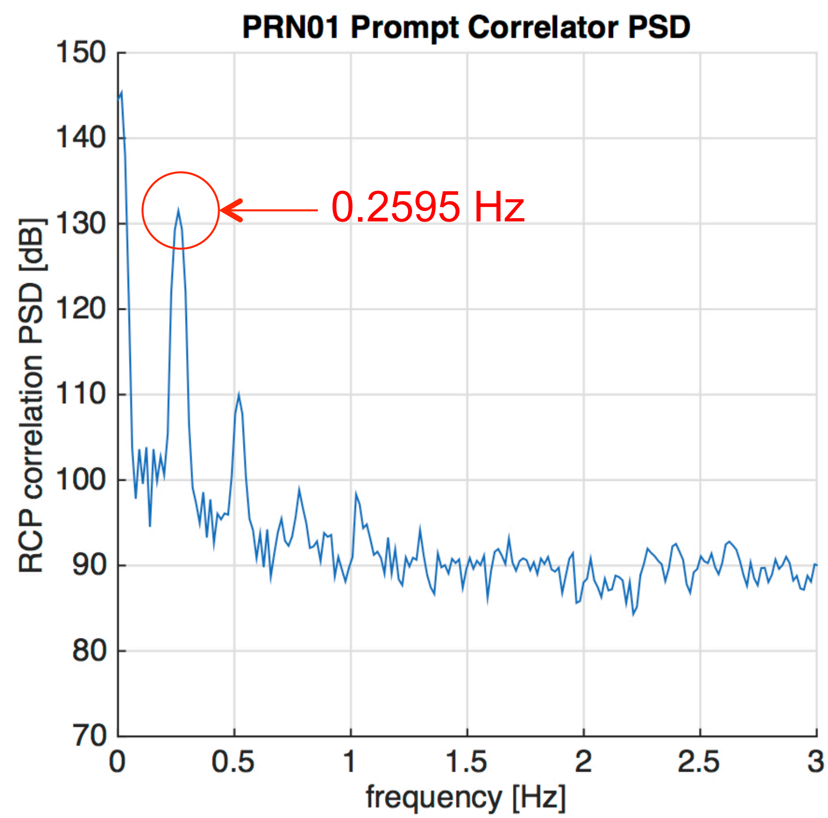

Results – PRN 1 (experimental)

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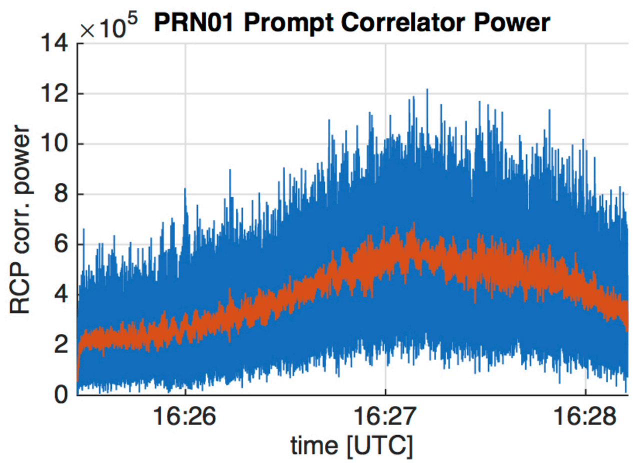

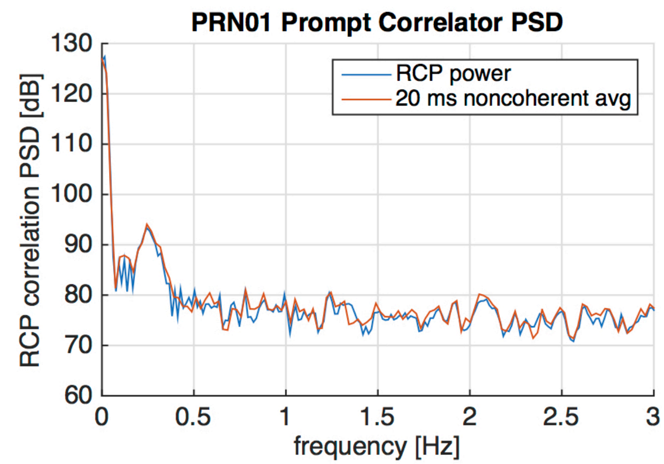

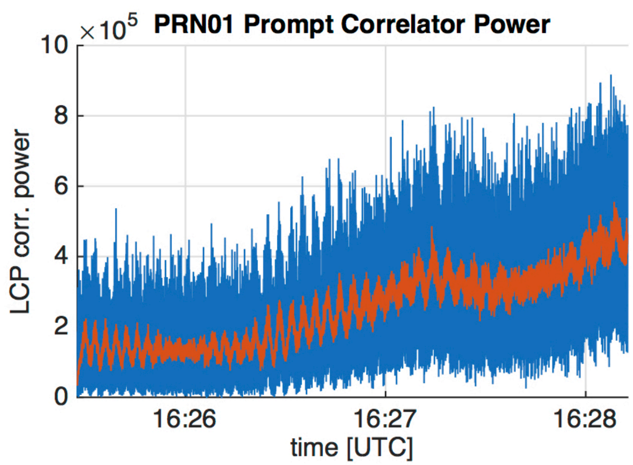

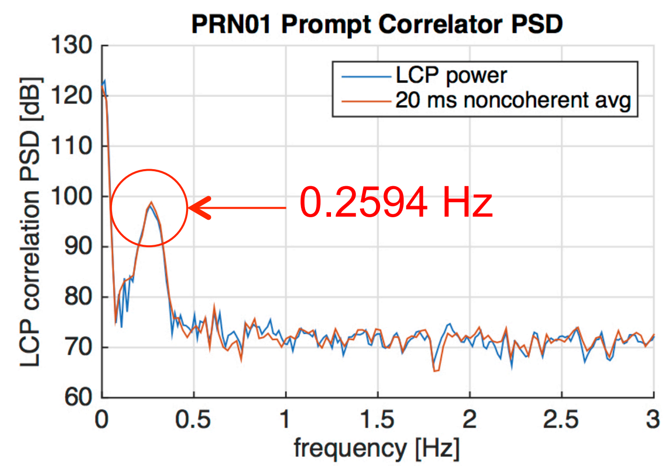

Results – PRN 30 (simulation)

- Simulated parameters of reflected signals for four PRNs (FFT resolution = 0.0061 Hz)

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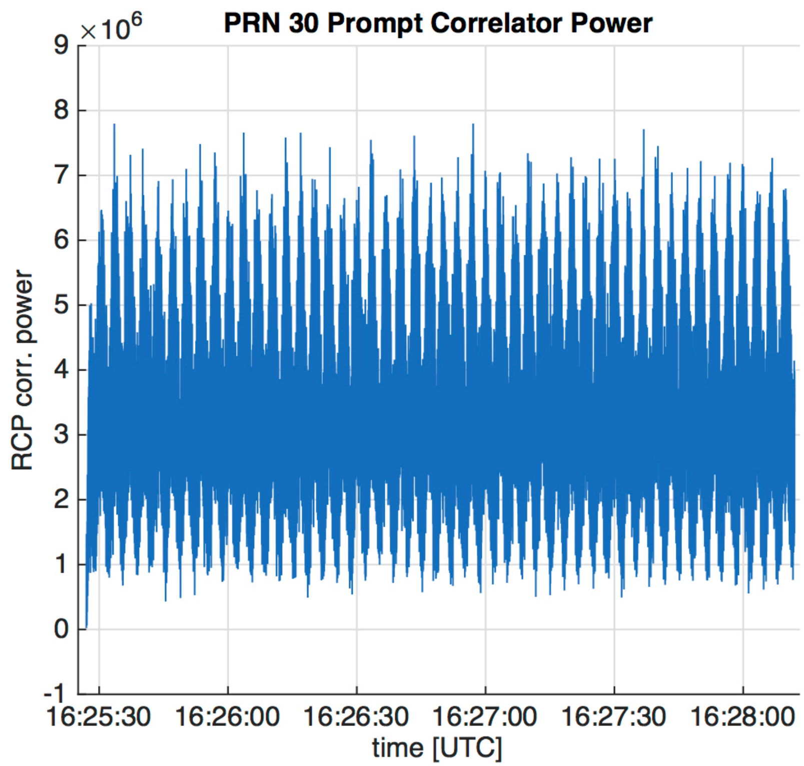

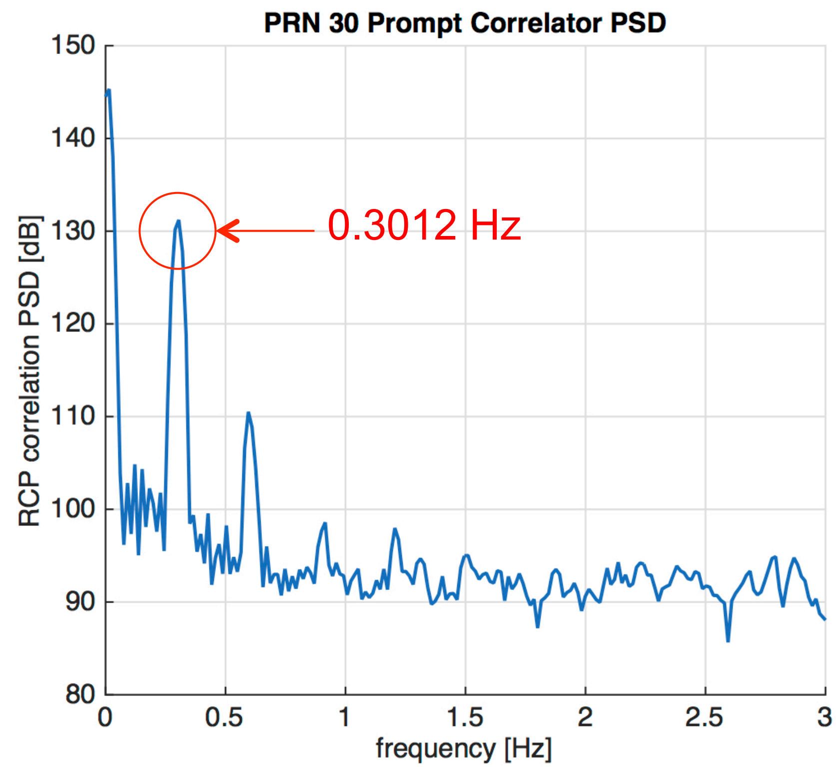

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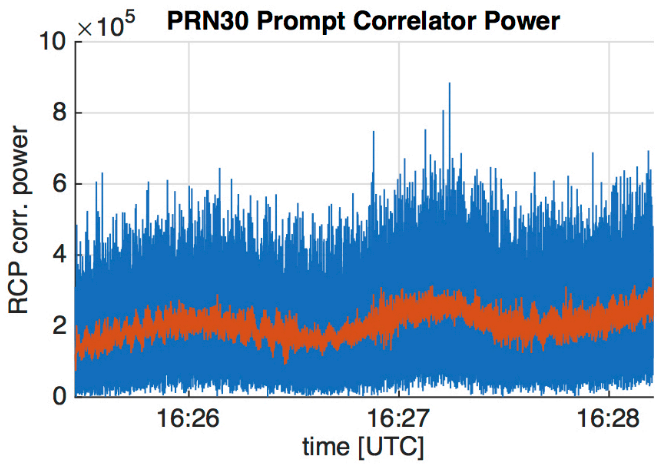

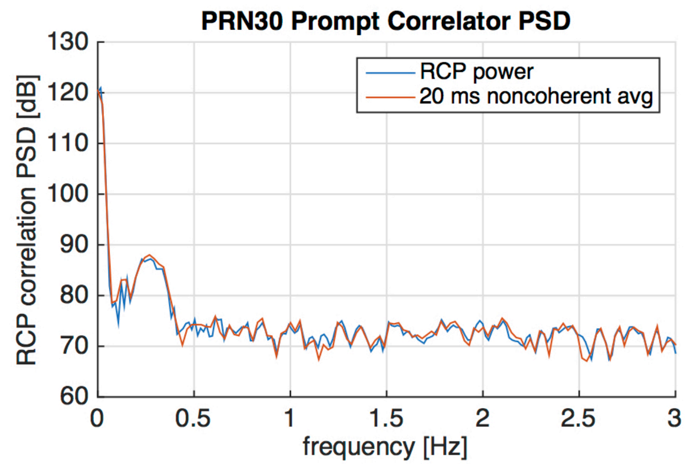

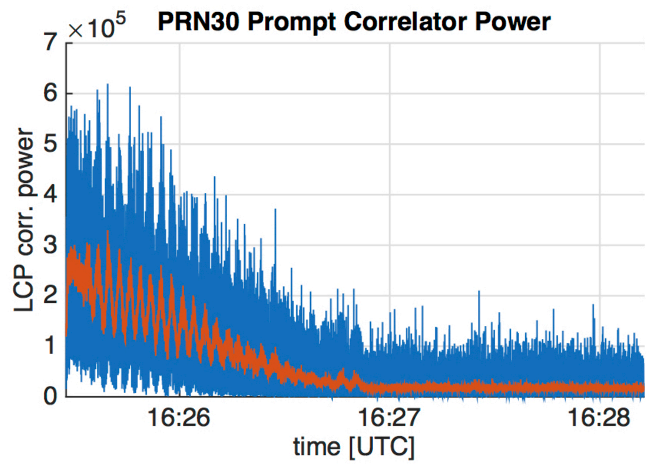

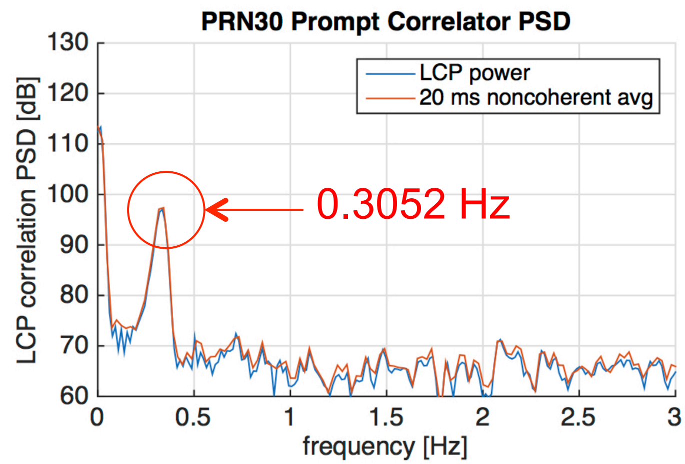

Results – PRN 26 (simulation)

- Simulated parameters of reflected signals for four PRNs (FFT resolution = 0.0061 Hz)

PRN	δ_0 [m]	$\dot{\delta}$ [cm/s]	α_m^2/α_0^2	$\dot{\psi}$ [Hz]
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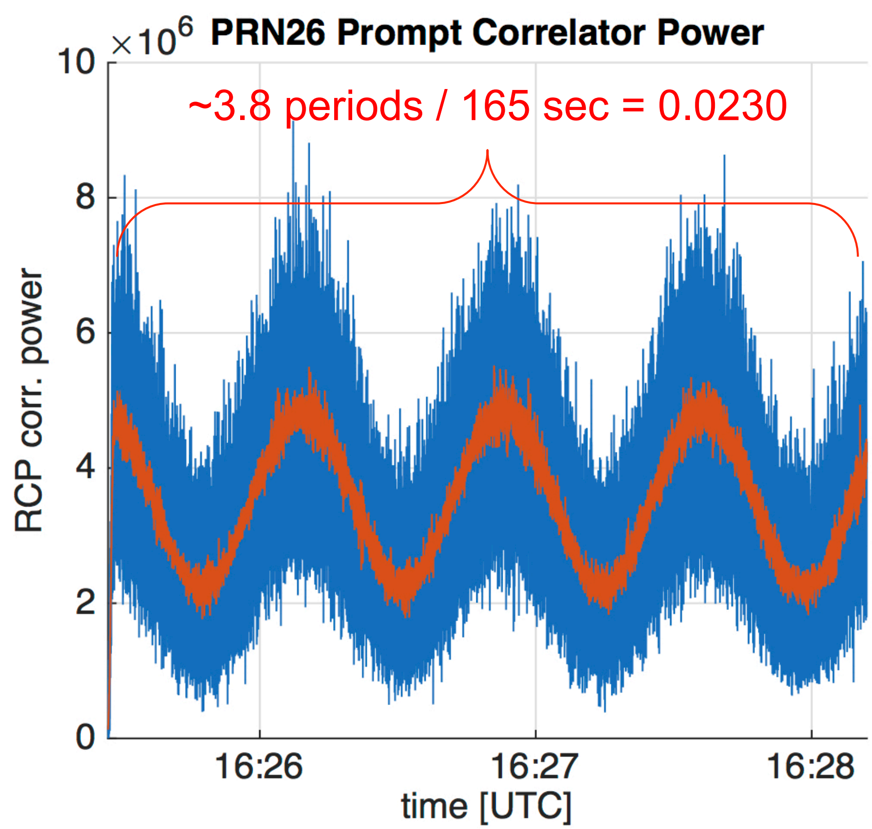

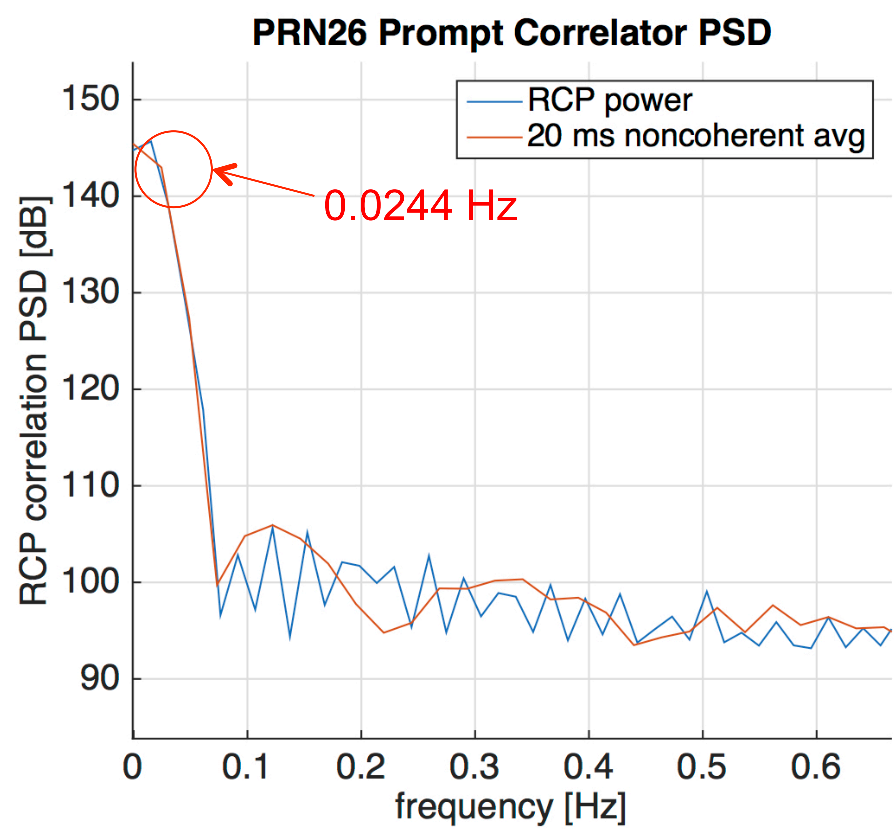

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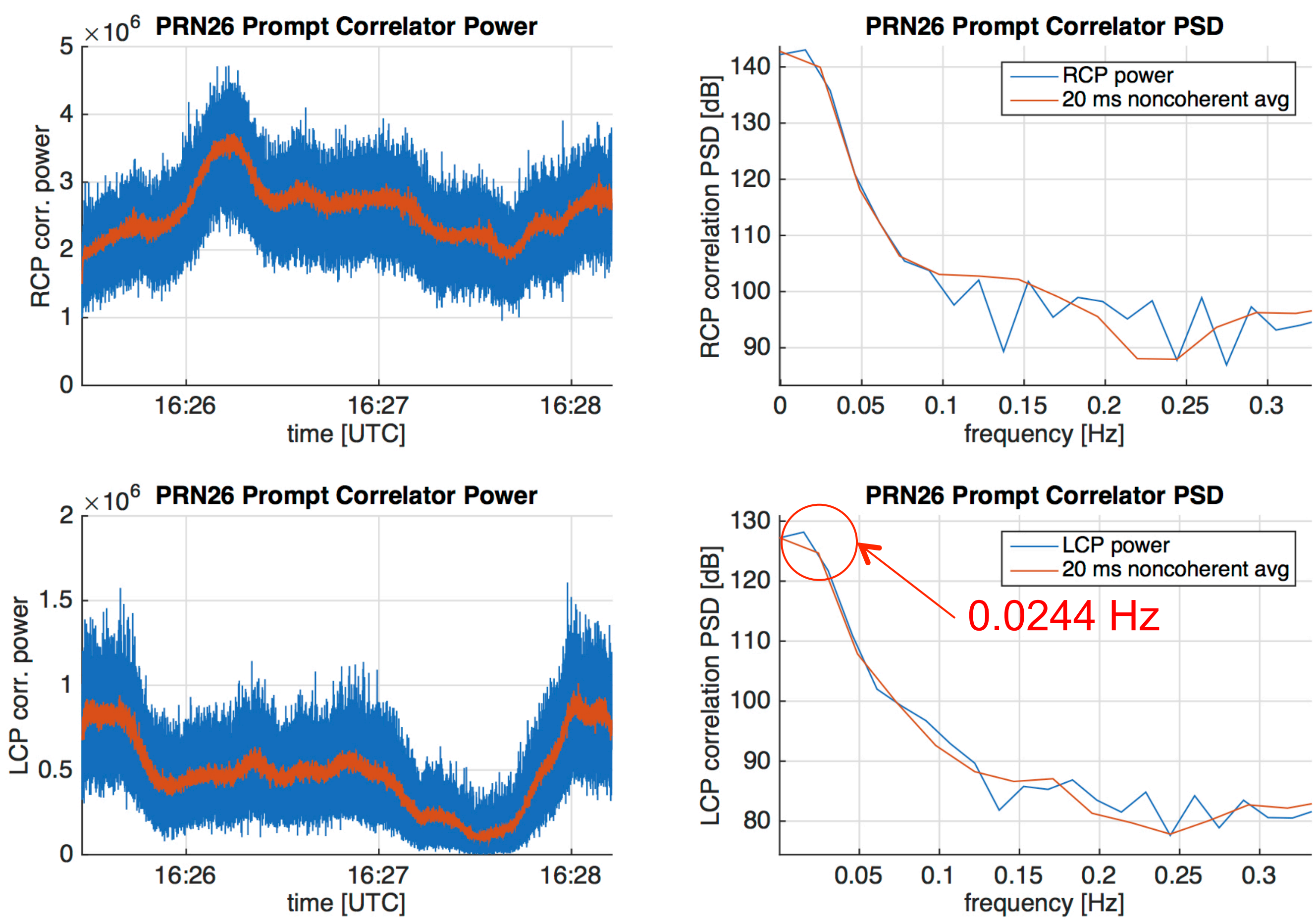

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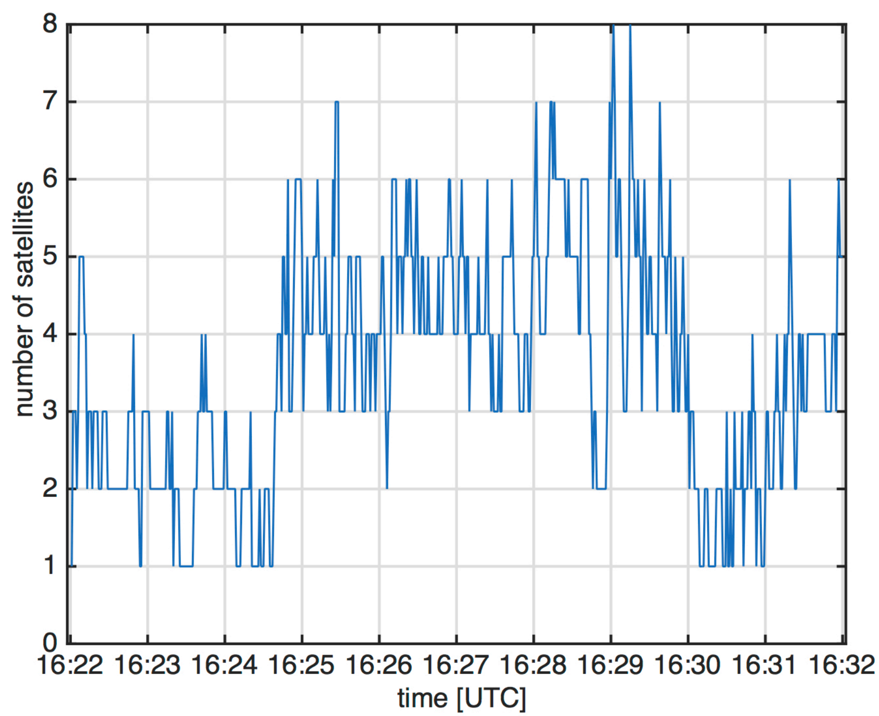
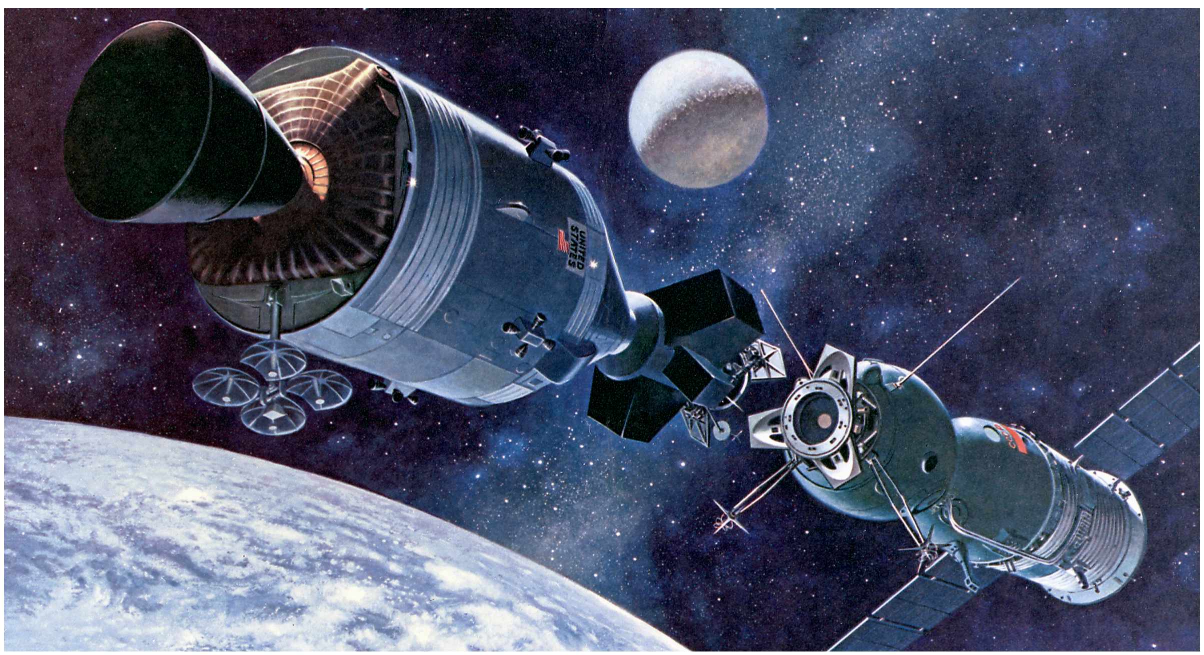
Conclusions

- Multipath fading confirms the presence of reflected signals in the HSM4 data
- General agreement of these features with the effects of simulated Hubble-reflected signals provides validation that the multipath model correctly represents the GNSS reflections received during docking
- Ray tracing results support the hypothesis that there are reflections off Hubble of sufficient strength and duration to be useful for relative navigation



Future Work

- Resolve azimuth uncertainty and incorporate complete antenna gain patterns
- Extract range information from reflected signals, as explored in other work [4]
  - Estimation of multipath parameters from code correlation deformation – relies on a wide receiver bandwidth (HSM4 data bandwidth = 2 MHz)
  - Independent tracking of reflected signals – relies on reflected signal isolation (e.g., LCP cross-pole discrimination > 10 dB)



Apollo and *Soyuz* docking 1975 [5]

References

1. http://share.cat/wp-content/uploads/2015/07/IS9.jpg
2. B. Ashman, J. Veldman, J. Garrison and P. Axelrad, “Evaluation of the GNSS Multipath Environment in Space Proximity Operations: Experimental and Simulation Studies of Code Correlations in Hubble Servicing Mission 4,” in *Proceedings of the ION 2015 Pacific PNT Meeting*, (Honolulu, HI), pp. 863–871, Institute of Navigation, April 2015.
3. http://www.spacetelescope.org/static/archives/images/screen/sts103_713_048.jpg
4. B. Ashman, *Incorporation of GNSS Multipath to Improve Autonomous Rendezvous, Docking, and Proximity Operations in Space*. PhD thesis, Purdue University, 2016.
5. http://history.nasa.gov/astp/artist%20illustration%20ASTP%20docking.jpg

NASA

Backup – Signal Model

If we let $\theta(t) = -2\pi f_{L1}\tau_{carr}(t) + \theta_0$, then

$$y(t) = ad(t - \tau_{code}(t))c(t - \tau_{code}(t))\cos(2\pi f_{L1}t + \theta(t)). \quad (5)$$

Note that if Doppler is approximated as constant and $f_D = f_{L1}\dot{r}(0)t/c$ is substituted, $\theta(t) = -2\pi f_{L1}r(0)/c + f_D t$. The received signal can be rewritten by grouping f_{L1} and f_D, with the phase $\tilde{\theta}(t) = -2\pi f_{L1}r(0)/c + \theta_0$:

$$y(t) = ad(t - \tau_{code}(t))c(t - \tau_{code}(t))\cos(2\pi(f_{L1} + f_D)t + \tilde{\theta}(t)), \quad (6)$$

$$\tau_{code}(t) = \frac{1}{v_{code}}(r(0) + \dot{r}(0)t + \mathcal{O})$$

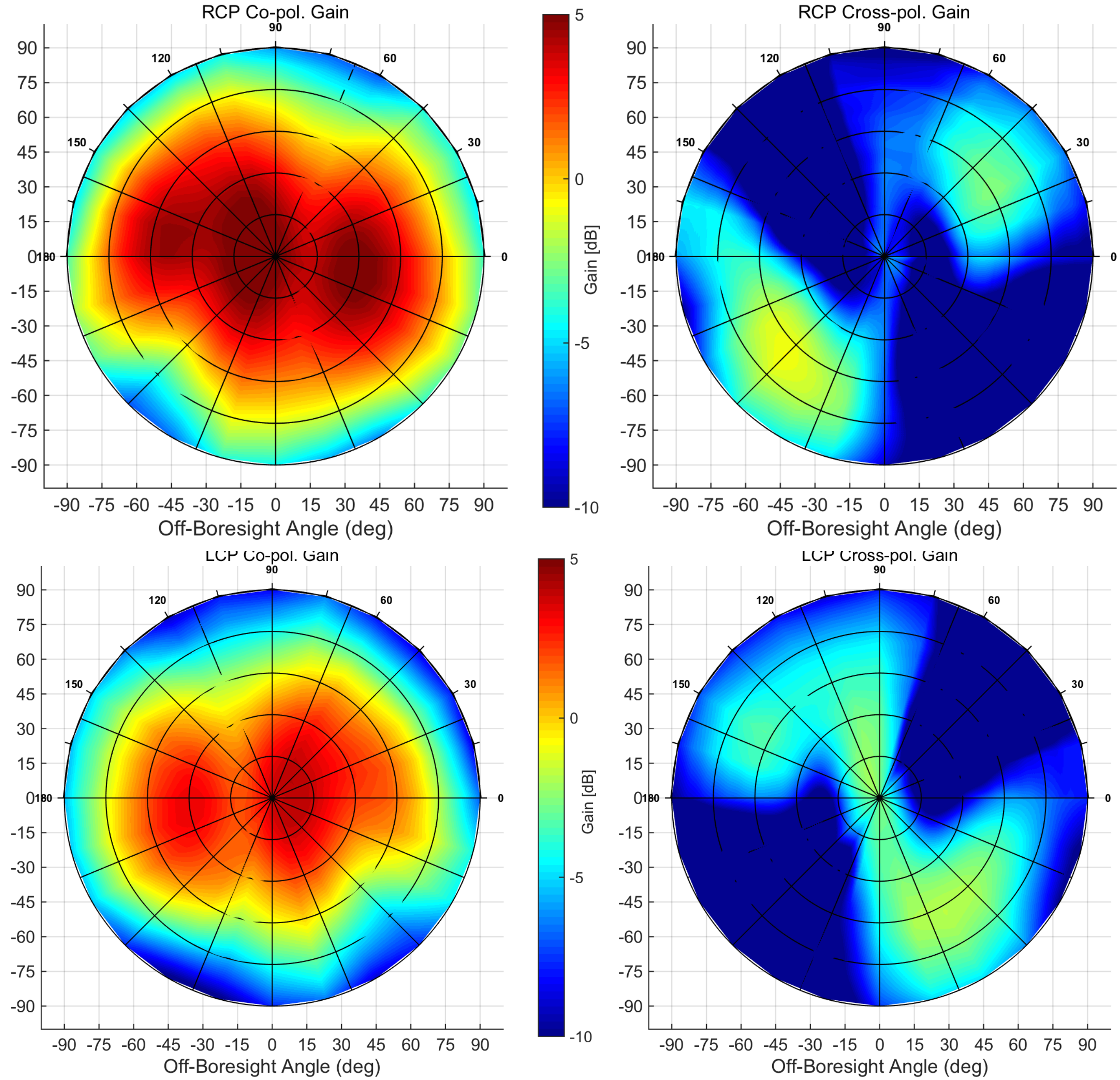
$$\tau_{carr}(t) = \frac{1}{v_{carr}}(r(0) + \dot{r}(0)t + \mathcal{O})$$

$$\dot{\psi}_m(t) = \dot{\theta}_0(t) - \dot{\theta}_m(t) = -2\pi f_{L1}(\dot{\tau}_{carr,0}(t) - \dot{\tau}_{carr,m}(t)).$$

$$\dot{\psi}_m(t) = -2\pi f_{L1}\left(\frac{\dot{r}_0(0)}{v_{carr}} - \frac{\dot{r}_m(0)}{v_{carr}}\right) \longrightarrow \dot{\psi}_m(t) = \frac{2\pi f_{L1}}{v_{carr}}\dot{r}_{\Delta,m}(0).$$

$$\dot{\delta}_m(t) = c(\dot{\tau}_{code,m}(t) - \dot{\tau}_{code,0}(t)) = \frac{c}{v_{code}}(\dot{r}_m(t) - \dot{r}_0(t)) = \frac{c}{v_{code}}\dot{r}_{\Delta,m}(0).$$

Backup – Antennas

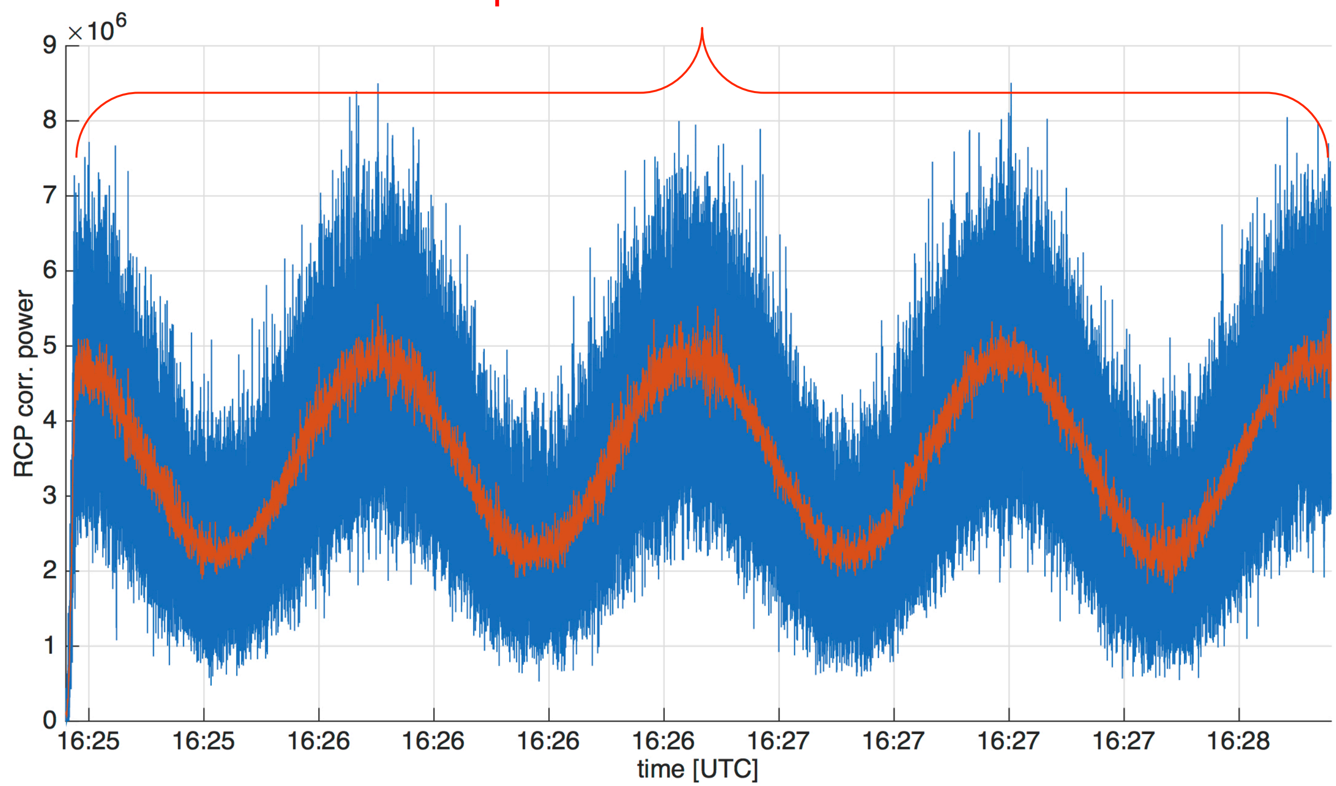


Backup – PRN 27 (simulation)

- Simulated parameters of reflected signals for four PRNs (FFT resolution = 0.0061 Hz)

PRN	δ_0 [m]	$\dot{\delta}$ [cm/s]	α_m^2/α_0^2	$\dot{\psi}$ [Hz]
27	16.32	0.47	0.67	0.0246

- ~4 periods / 165 sec = 0.0242



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- Note: LCP tracking of HSM4 data failed for PRN 27 and is not shown