National Aeronautics and Space Administration

Exploring the Limits of High Altitude GPS for Future Lunar Missions

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Objective

- Characterize the GPS signal visibility that is possible in distant, cislunar orbit regimes, in order to understand the practical upper altitude limit to GPS-based navigation.

Outline

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I. Background

II. Simulation

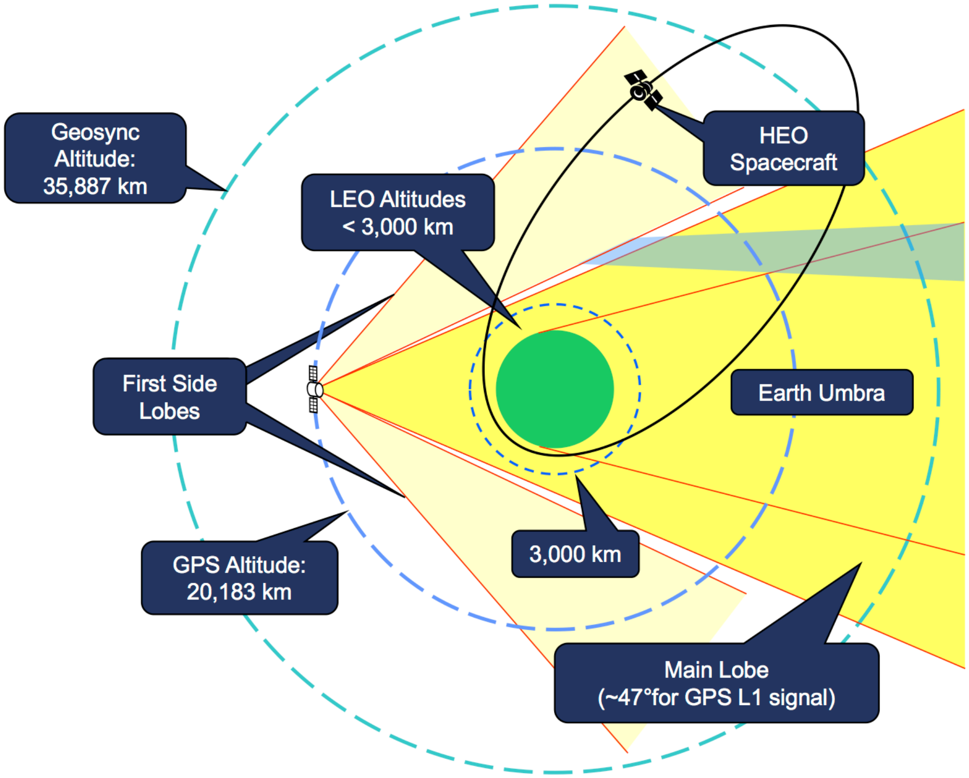
III. Validation

IV. Lunar Simulation and Results

V. Conclusions

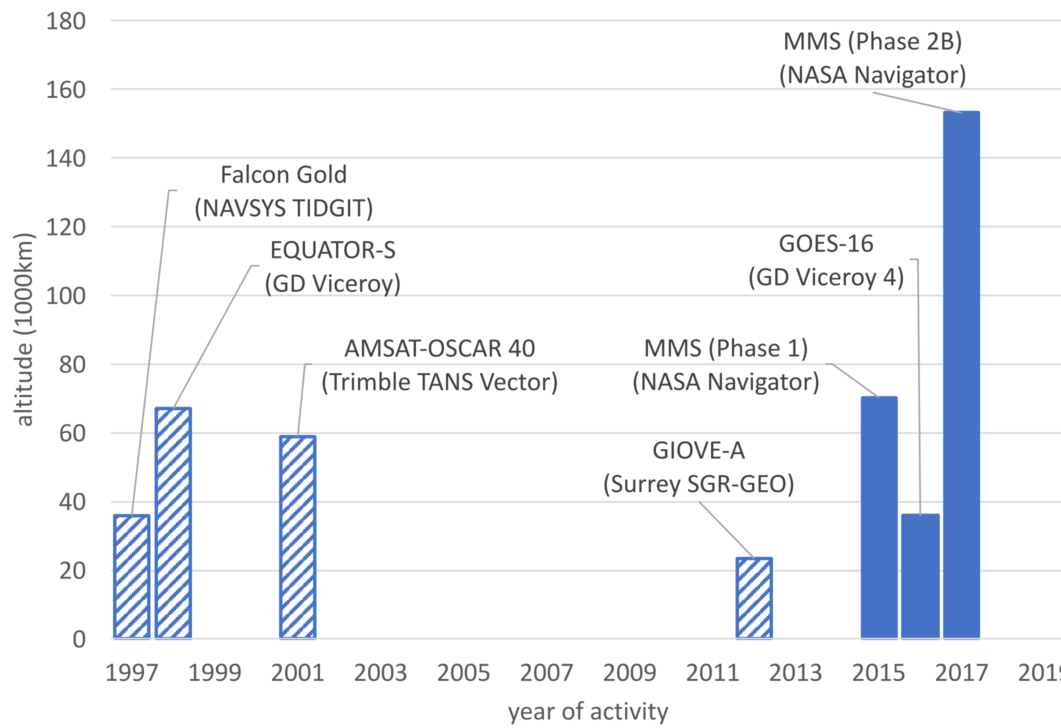
Space Service Volume

- The Space Service Volume (SSV) is defined as the volume of space surrounding the Earth from the edge of LEO to GEO, i.e., **3,000 km to 36,000 km altitude**
- The SSV overlaps and extends beyond the GNSS constellations, so use of signals in this region often requires signal reception from satellites on the opposite side of the Earth – main lobes and sidelobes
- Signal availability constrained by poor geometry, Earth occultation, and weak signal strength
- Formal altitude limit of GNSS usage in space is 36,000 km, but the practical limit is known to extend well beyond this.



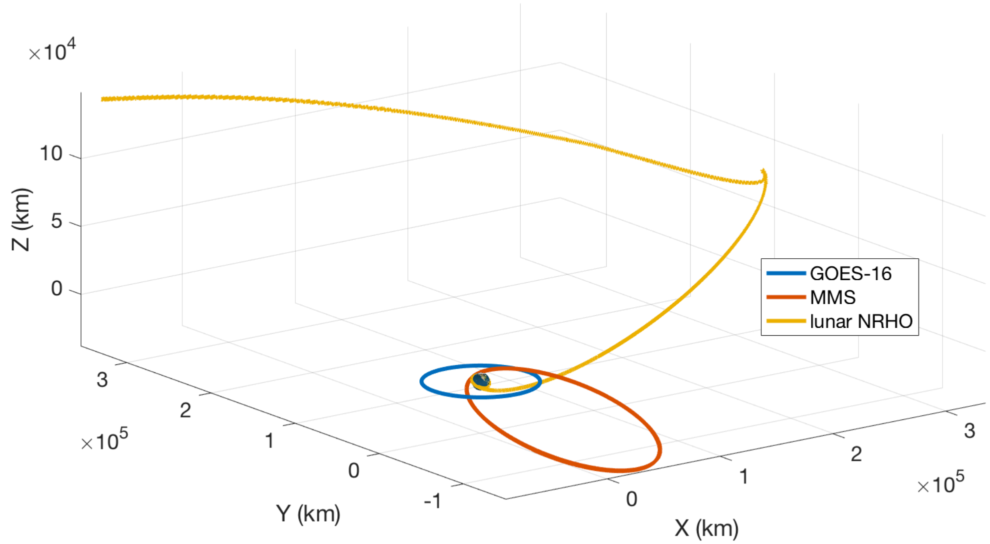
High-Altitude GPS

- 1990s: Early flight experiments demonstrated basic feasibility – Equator-S, Falcon Gold
- 2000: Reliable GPS orbit determination demonstrated at GEO employing a bent pipe architecture and ground-based receiver (Kronman 2000)
- 2001: AMSAT OSCAR-40 mapped GPS main and sidelobe signals (Davis et al. 2001)
- 2015: MMS employed GPS operationally at 76,000 km and recently 150,000 km
- 2016: GOES-16 employed GPS operationally at GEO



Lunar GPS

- Barton et al. 1993 concluded signal availability limited to <190,800 km with 9 dB antenna gain and 26 dB-Hz acq/trk threshold – sufficient for trans-lunar injection burn and mid-course correction burn
- Vision for Space Exploration era (2001-2009)
  - Carpenter et al. 2004, Bamford et al. 2008, Winternitz et al. 2009, Lee et al. 2009
- Recent
  - Winternigg et al. 2015,Capuano et al. 2015, Shehaj et al. 2017
  - Winternitz et al. 2017
    - Simulated MMS GPS system with high-gain antenna in Lunar exploration trajectory, concluded strong navigation possible (~1km radial, ~100m lateral)
- Deep Space Gateway, EM-1, EM-2
  - Permanent, international way-station in the vicinity of the moon for staging deep space activity
  - Near Rectilinear Halo Orbit (NRHO) is one of those proposed – outbound cruise and NRHO used here



	Altitude [km]	Altitude [R_E]
GPS	20,200	3
GEO	36,000	5.6
MMS 1	76,000	12
MMS 2	153,000	24
Moon	378,000	60

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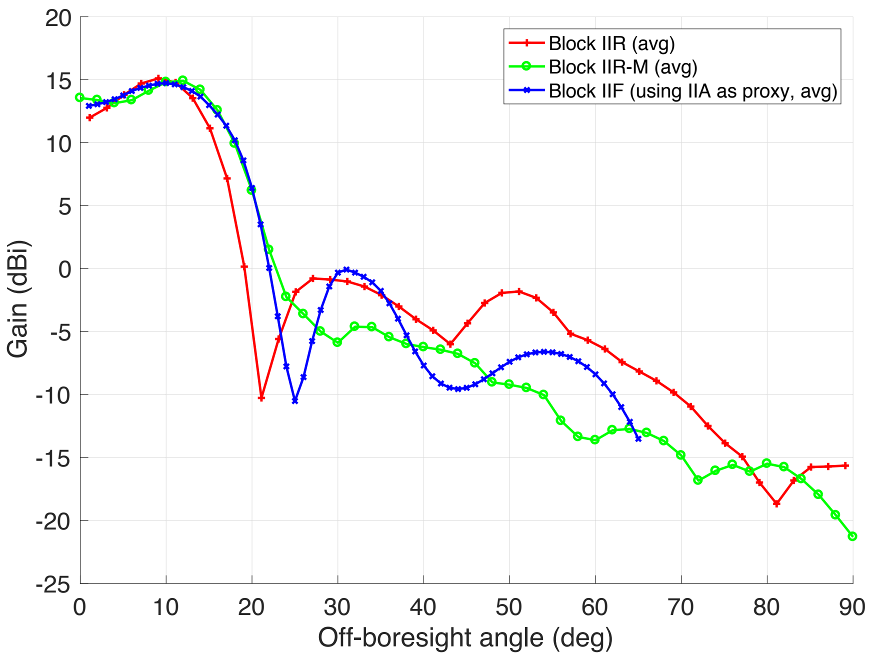
Simulation

- GPS signals visible if 1) line of sight is unobstructed and 2) carrier-to-noise spectral density (C/N_0) exceeds receiver acquisition/tracking threshold
- Orbit Determination Toolbox (ODTBX) used to simulate user receiver properties, geometry, and transmitter properties necessary to compute C/N_0
- Constellation model
  - 31 SVs with block composition consistent with validation flight data epochs (spring 2017)
  - IIR/IIR*/IIR-M patterns public, IIA used for IIF

Block	IIR	IIR*	IIR-M	IIF
Number of SVs	8	4	7	12
SVs	41, 43–46, 51, 54, 56	47, 59, 60–61	48, 50, 52–53, 55, 57–58	62–73
TX antenna pattern	GPS IIR, 0–90° el coverage, spacing: 2° el, 10° az,	GPS IIR-M, 0–90° el coverage, spacing: 2° el, 10° az	GPS IIR-M, 0–90° el coverage, spacing: 2° el, 10° az	GPS IIA (1D), 0–65° el coverage, 1° el spacing
TX transmit power	13.5 dBW	12.8 dBW	12.8 dBW	12.8 dBW

IIR* refers to Block IIR SVs with the modernized IIR-M antenna panel.



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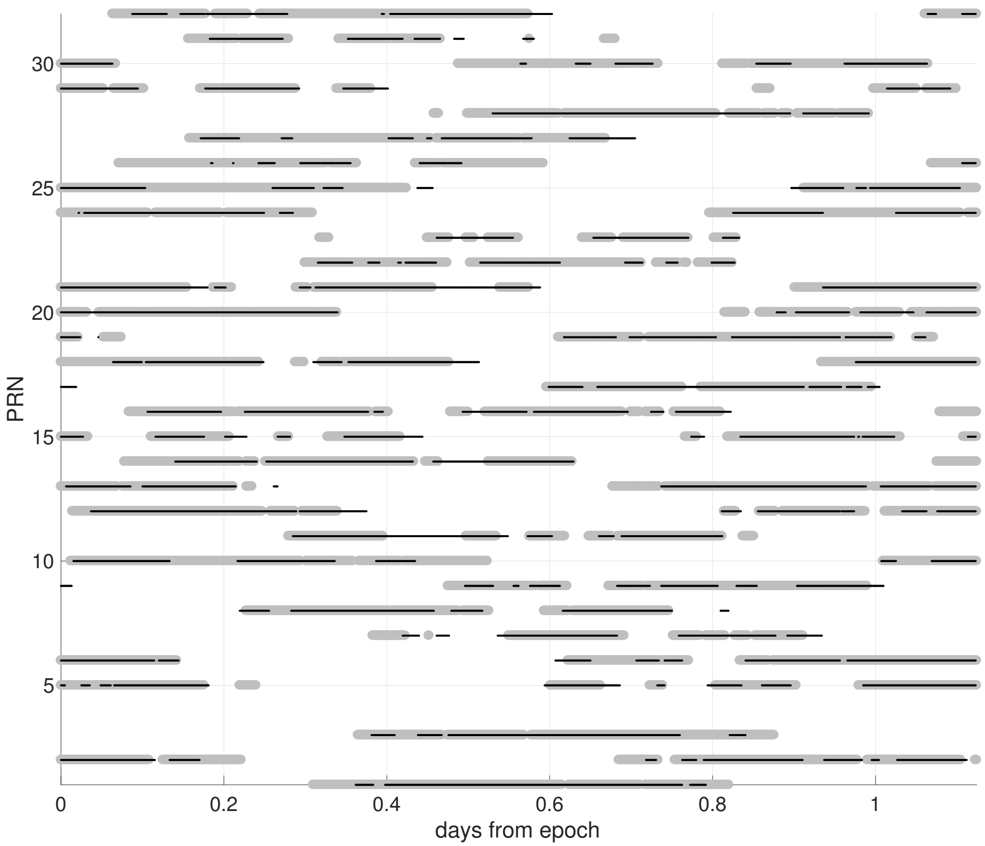
Verification with GOES-16 Flight Data

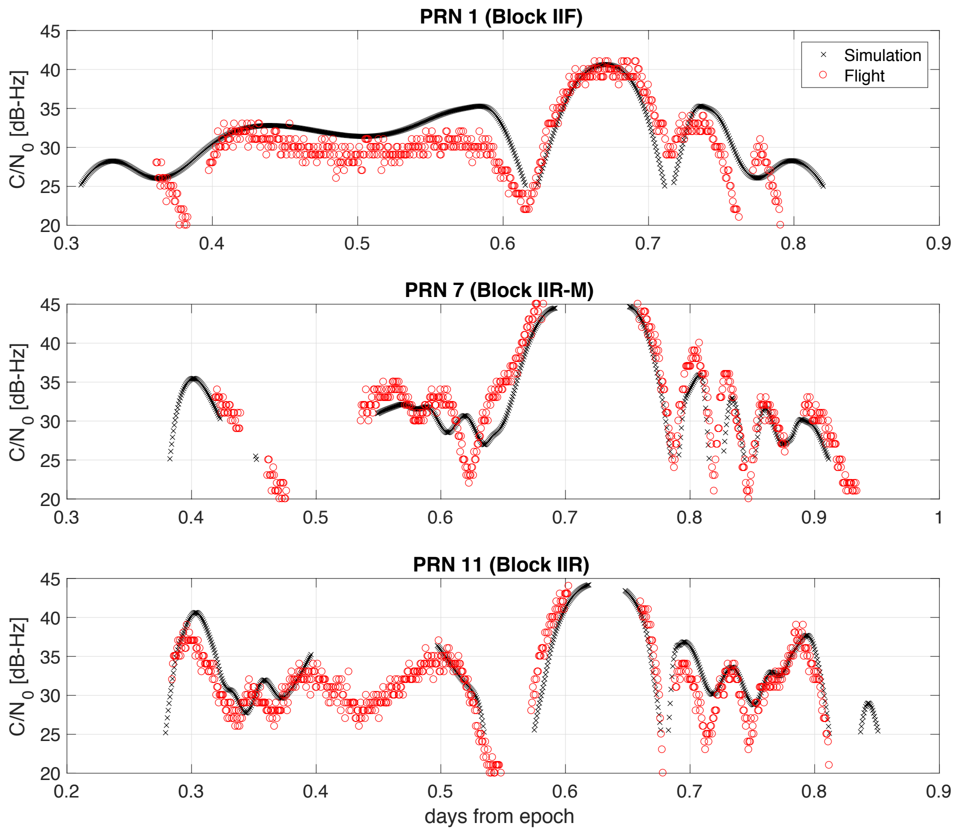
- Geostationary Operational Environmental Satellite 16 (GOES-16) mission
  - First operational use of GPS for a civilian GEO satellite – the formal limit of the SSV
  - Early demonstrated performance: >11 satellites visible on average, no outages (Winkler et al. 2017)
- Simulation configuration
  - 27 hour span at 18:00 UTC March 30, 2017
  - GPS antenna for GEO – 11 dB peak gain at 22 deg off-boresight, 40 deg half-beamwidth
  - 12 channel receiver with 25 dB-Hz acq/trk treshold
- Results
  - 11.8 satellites visible on average in simulation, 11.2 in flight data – sim has less outages
  - Visibility per SV shown on following slide as well as C/N_0 comparisons for representative SVs

Verification with GOES-16 Flight Data

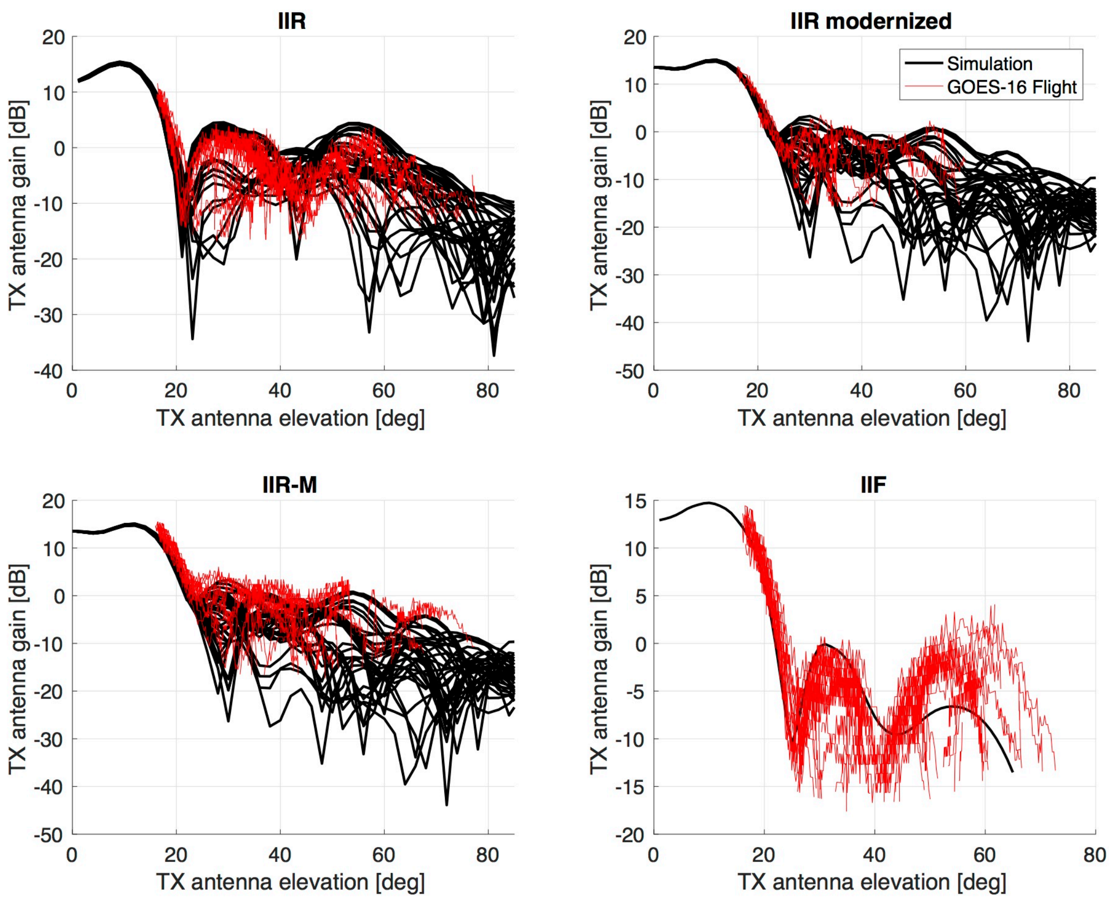
GOES-16 GPS visibility per SV – simulation (grey) and flight data (black)



GOES-16 received C/N$_0$ for PRNs 1, 7, and 11



Validation with GOES-16 Flight Data (cont.)



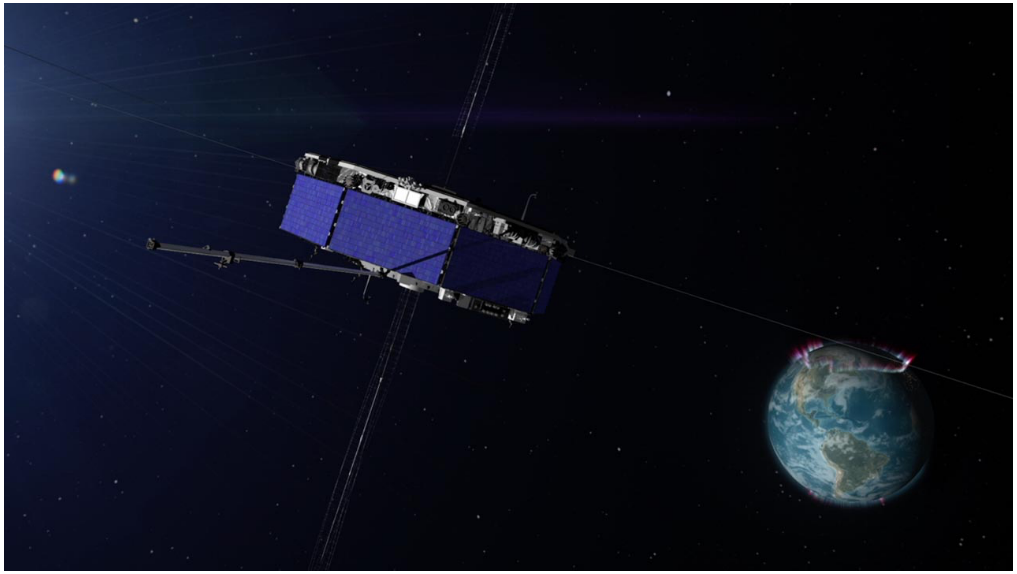
- Shape of C/N_0 profile primarily driven by transmit antenna patterns
- GOES-16 provides an opportunity to evaluate the reference patterns used in the simulation
- Back-calculation of transmit antenna patterns from flight data C/N_0 and simulation parameters:

$$G_T = C/N_0 - P_T - G_R - A_d + (T_s + k + Nf)$$

- Main lobes and first sidelobes show good agreement, azimuthal variation in IIF not captured in reference pattern

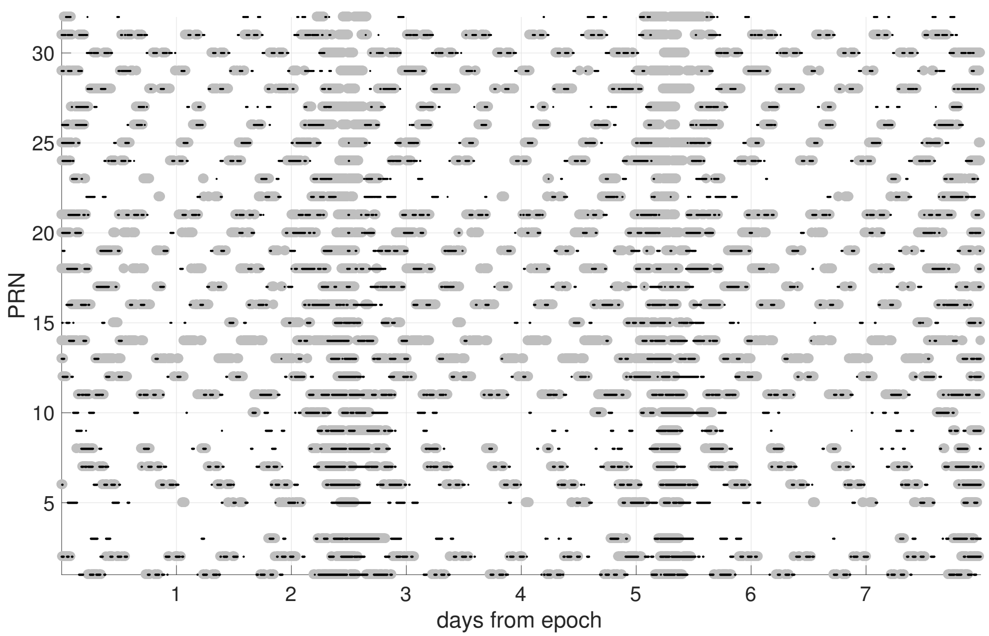
Verification with MMS Flight Data

- Magnetospheric Multiscale (MMS) mission
  - Transitioned to Phase 2 in early 2017 – highly elliptical orbit, apogee altitudes ~153,000 km
  - Highest altitude operational use of GPS
  - Published results demonstrate 3 signals tracked near apogee on average, 1+ 99% of the time, 4+ 70% of the time (Winternitz et al. 2017)
- Simulation configuration
  - 8 day span from May 22, 2017
  - GPS antenna approximation of spinning/multiple on-board antennas: pointed toward ecliptic north, 7 dB peak gain at 90 degrees
  - 12 channel receiver with 22 dB-Hz acq/trk treshold
- Results
  - 4+ SVs visible well past formal limit of SSV
  - Visibility per SV shown on following slide as well as average number of SVs over altitude

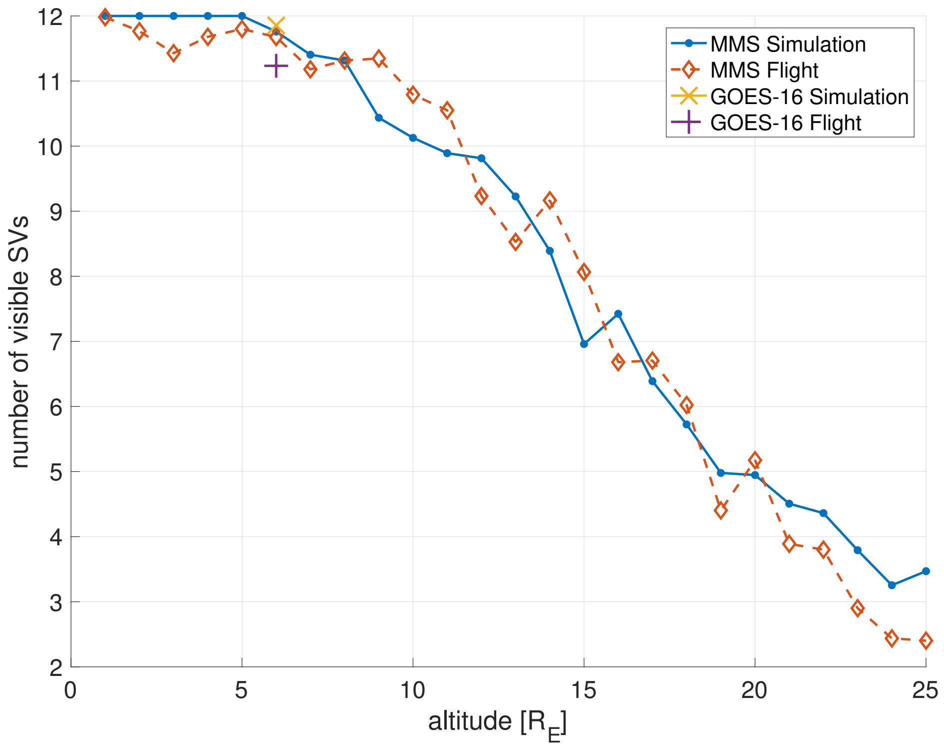


Verification with MMS Flight Data (cont.)

MMS GPS Visibility per SV – simulation (grey) and flight data (black)



MMS and GOES-16: number of SVs visible over altitude



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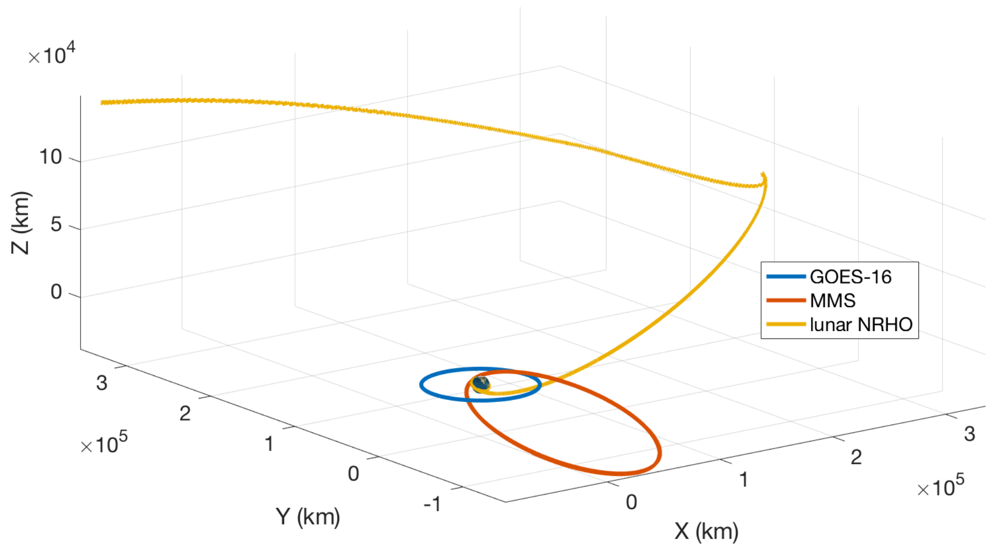
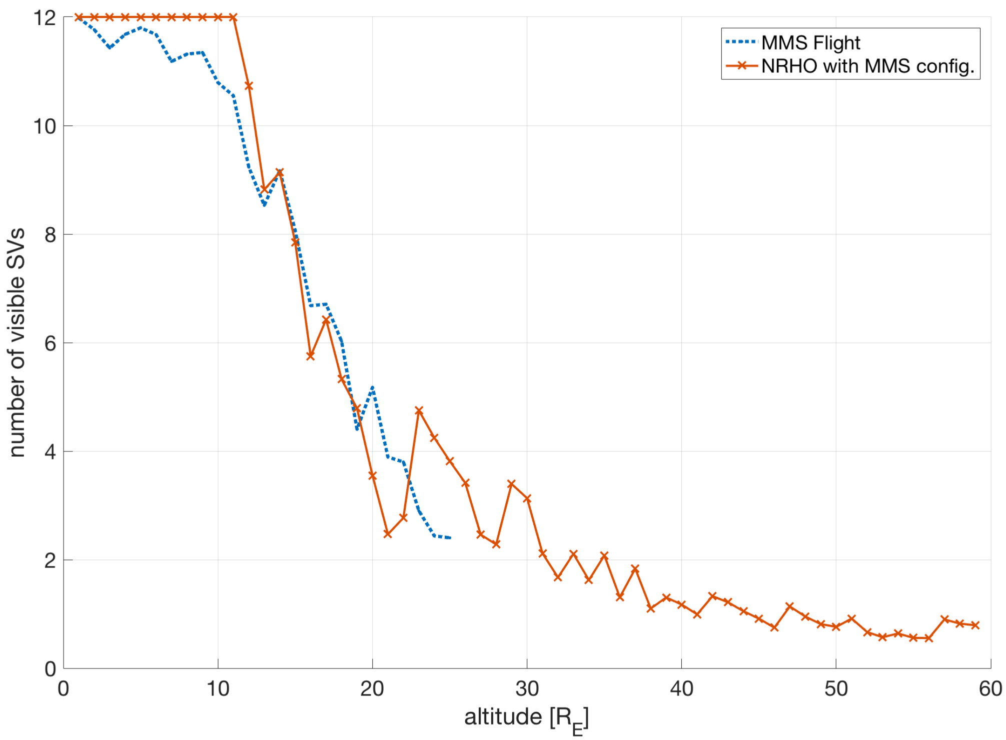
Lunar Simulation

- US plans to return to human exploration of the Moon and cislunar space with EM-1 and EM-2; one long-term objective is the Deep Space Gateway, an international, permanent way-station in the vicinity of the moon
- Near Rectilinear Halo Orbit (NRHO) is one proposed orbit; this is used here for the lunar simulation with only the outbound cruise
- Three mission configurations:
    - Validation – same antenna gain (7 dB peak), pointing, and receiver acq/trk thresholds as MMS (22 dB-Hz)
    - High gain antenna – 10 and 14 dB peak gain, same 22 dB-Hz receiver acq/trk thresholds
    - Receiver design baseline – 10 dB peak gain antenna, but 1 dB-Hz receiver thresholds

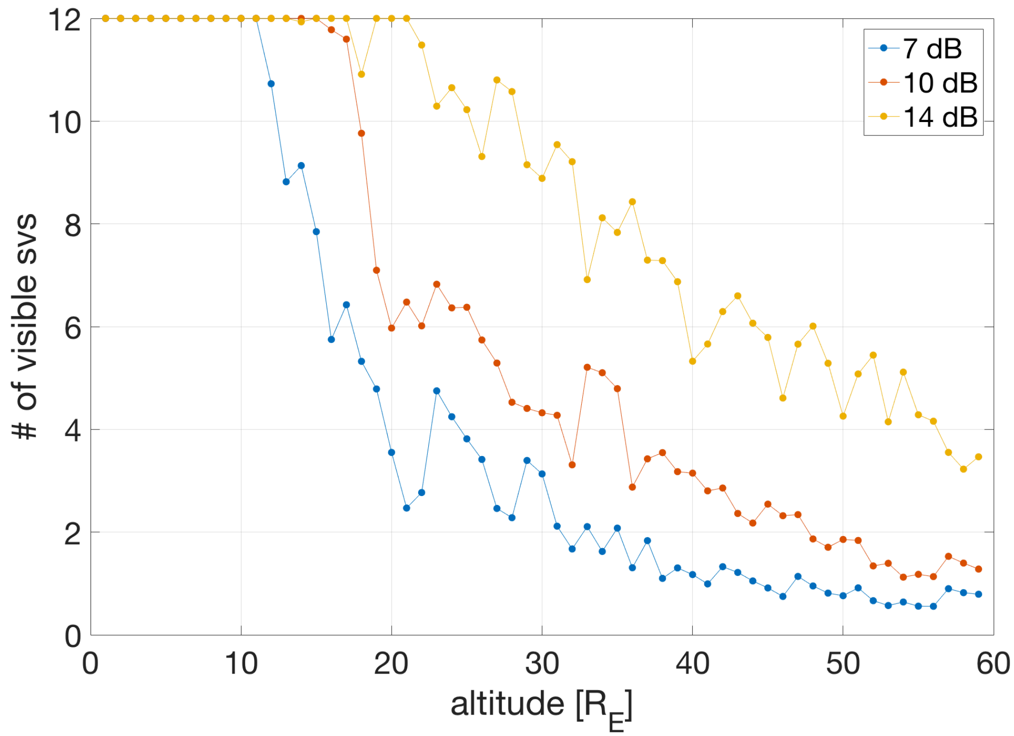


Lunar Simulation

Lunar trajectory: number of SVs visible over altitude



Number of satellites visible over altitude for different antenna gains



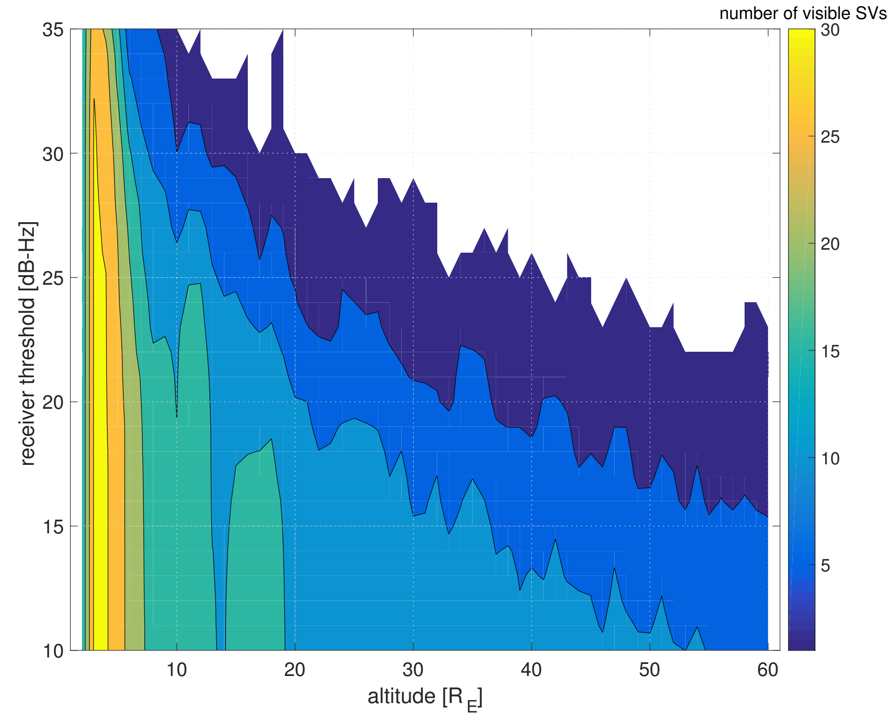
Lunar Simulation

- Outbound lunar NRHO visibility with 22 dB-Hz acq/trk threshold:

Peak Antenna Gain	1+	4+	Maximum Outage
7 dB	63%	8%	140 min
10 dB	82%	17%	84 min
14 dB	99 %	65%	11 min

- A modest amount of additional gain or sensitivity increases coverage significantly

Number of satellites visible over altitude and receiver threshold



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Conclusions

- At altitudes as high as 25 R_E, available models provide consistency between our simulations and available flight data to within a few percent in overall visibility metrics
- A modest amount of additional gain or sensitivity increases coverage significantly
- Future work must translate this availability to mission-level navigation performance, considering the effects of Dilution of Precision, etc.
- Efforts are underway through the United Nations International Committee on GNSS (ICG) to formalize and document the multi-GNSS SSV – further study must extend the results of this paper to include the combined capability of all six GNSS constellations

Apollo 12 Hasselblad image from film magazine 50/Q

Image Sources

- GOES-16: http://www.spaceflightinsider.com/wp-content/uploads/2017/02/GOES-R_Earth-Reflection-2012_rsz-1600x1060.jpg
- MMS: https://svs.gsfc.nasa.gov/vis/a010000/a011500/a011551/MMS.jpg
- Moon: https://boingboing.net/2015/10/02/nasa-just-released-8400-apoll.html