# Exploring the Moon with GNSS

Applications of GNSS Within and Beyond the Space Service Volume

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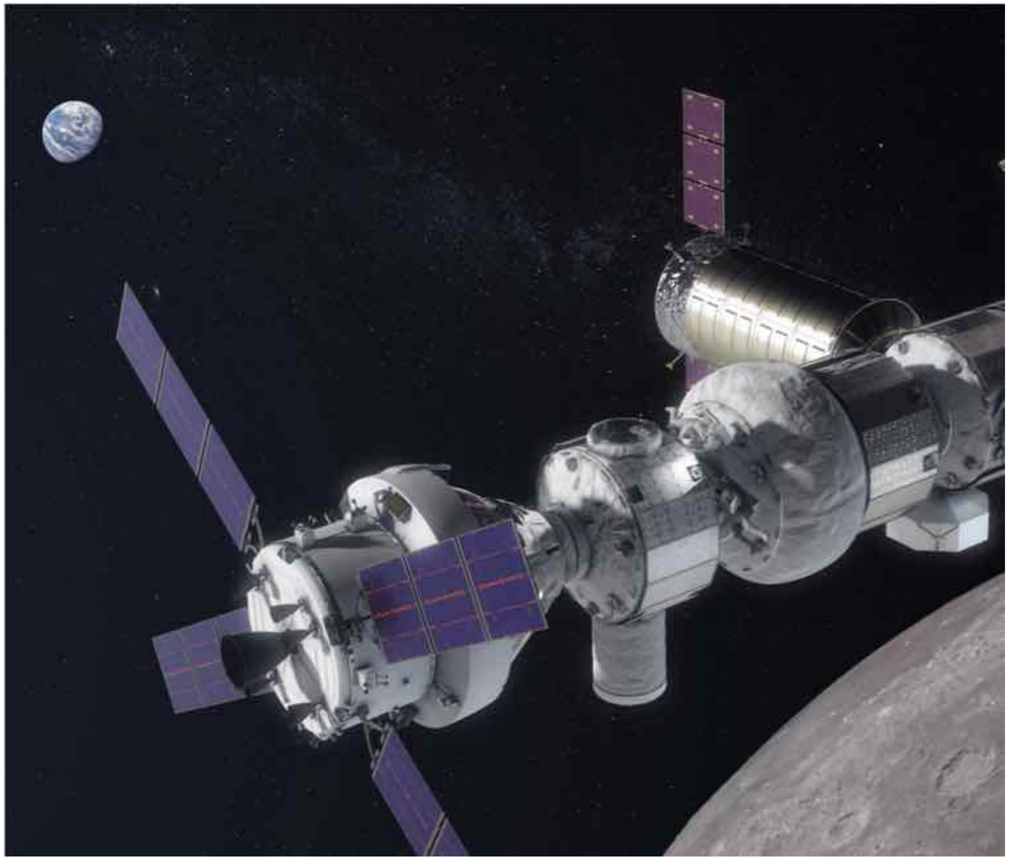
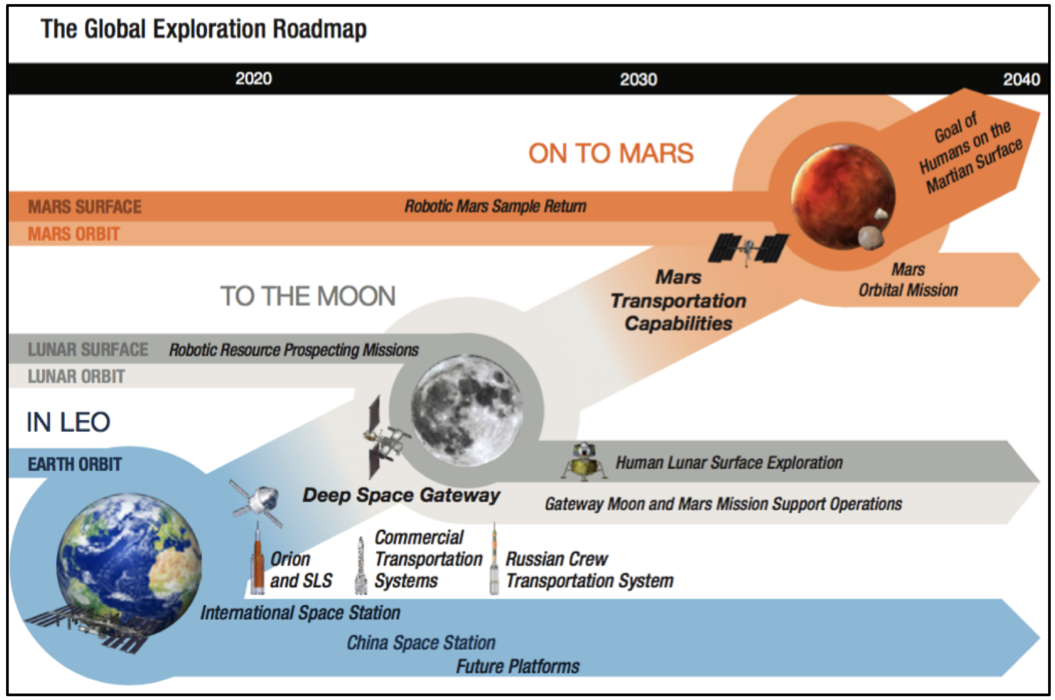
# Renewed Interest in Lunar Exploration

- The 14 space agencies of the International Space Exploration Coordination Group (ISECG) state a desire to return to the moon in the next decade in the 2018 Global Exploration Roadmap (GER)
- GER lists more than a dozen upcoming robotic lunar missions
- US plans to return to human exploration of the Moon and cislunar space with EM-1 and EM-2 in the early 2020s
- NASA and international partners plan to establish a Gateway, a permanent way-station in the vicinity of the Moon



# Renewed Interest in Lunar Exploration

- Critical technology gaps identified by the GER:
    - AR&D Proximity Operations, Target  Relative Navigation
    - Beyond-LEO crew autonomy
- GNSS on lunar missions would:
    - enable *autonomous* navigation
    - reduce tracking and operations costs
    - provide a backup/redundant navigation for human safety
    - provide timing source for hosted payloads
    - reduce risk for commercial development

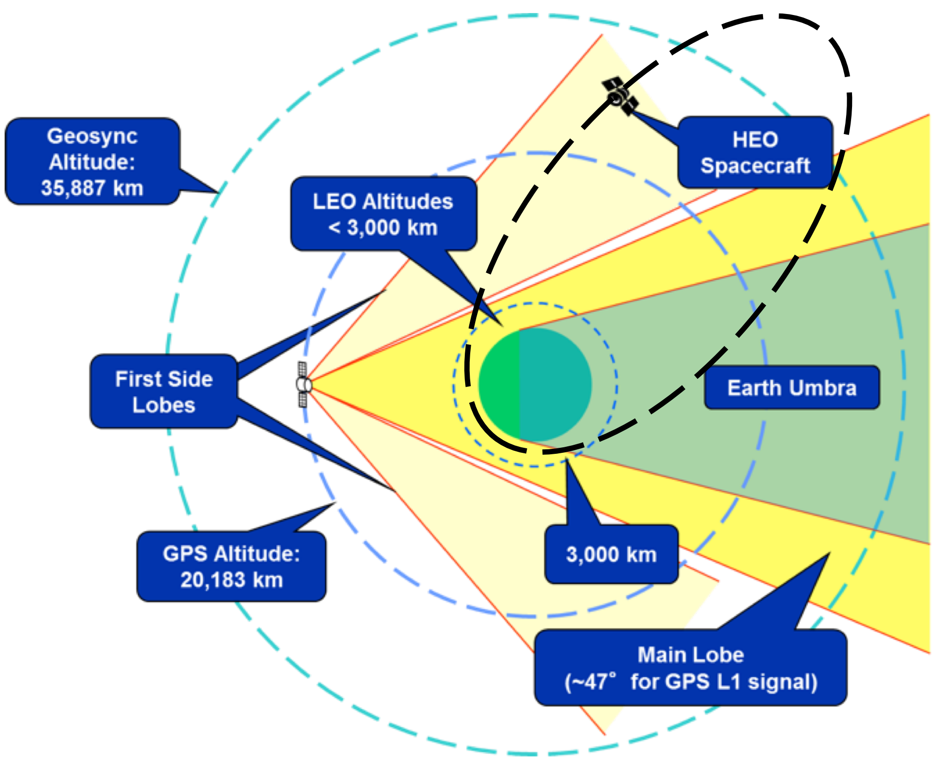



***Recent advances in high-altitude GNSS can benefit and enable future lunar missions***

# GNSS in the Space Service Volume

# Space Service Volume (SSV)

- The Space Service Volume (SSV) is the volume of space surrounding the Earth from the edge of LEO to GEO, i.e., **3,000 km to 36,000 km altitude**

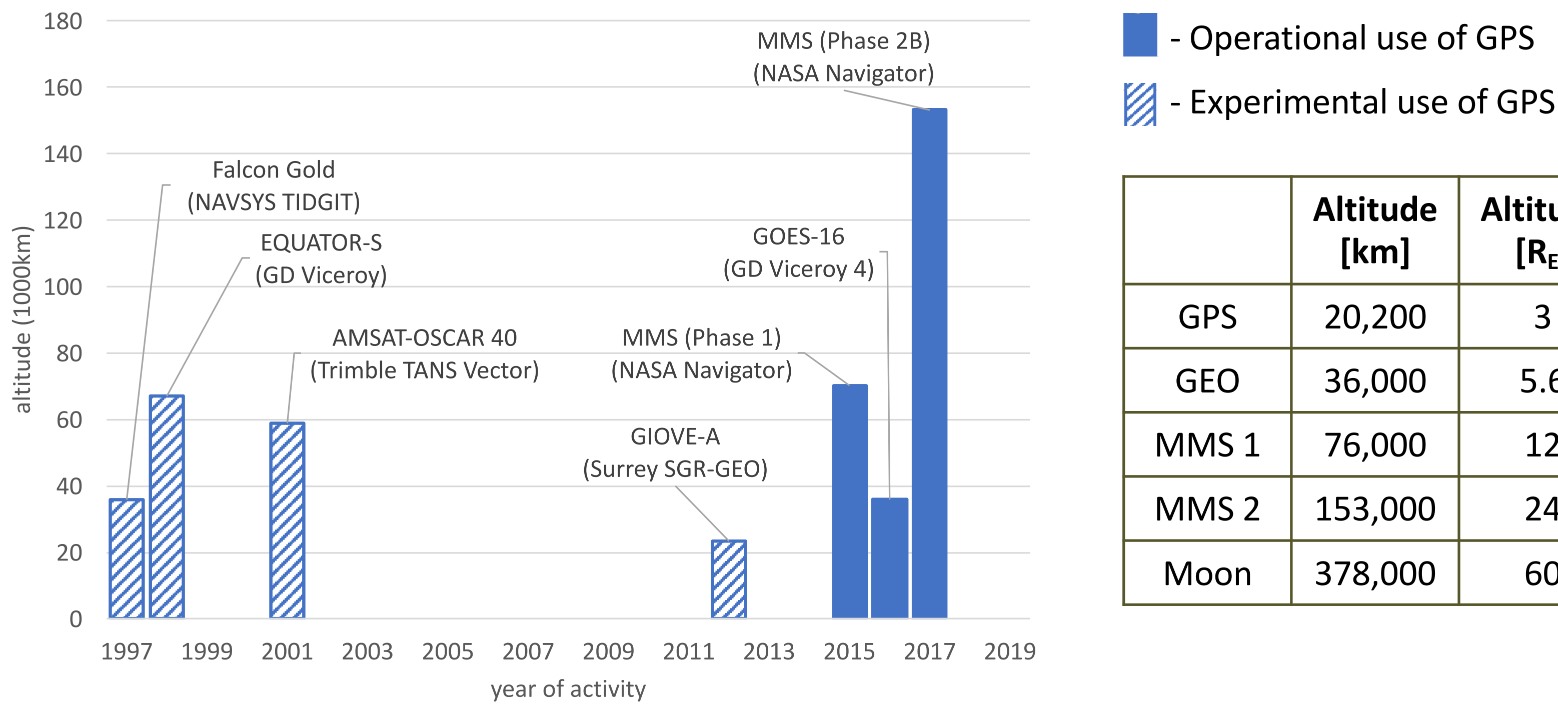



- The SSV overlaps and extends beyond the GNSS constellations, so use of signals in this region often requires signal reception from satellites on the opposite side of the Earth – main lobes and sidelobes
- Signal availability constrained by poor geometry, Earth occultation, and weak signal strength
- Formal altitude limit of GNSS usage in space is 36,000 km, but the practical limit is unknown
- Spacecraft use of GNSS in TSV & SSV enables:
  - reduced post-maneuver recovery time
  - improved operations cadence
  - increased satellite autonomy
  - more precise real-time navigation and timing performance

# High-Altitude GPS

**Transition from experimentation to operational use (selected milestones):**

- 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
- 2001: AMSAT OSCAR-40 mapped GPS main and sidelobe signals
- 2015: MMS employed GPS operationally at 76,000 km and recently 153,000 km
- 2016: GOES-16 employed GPS operationally at GEO



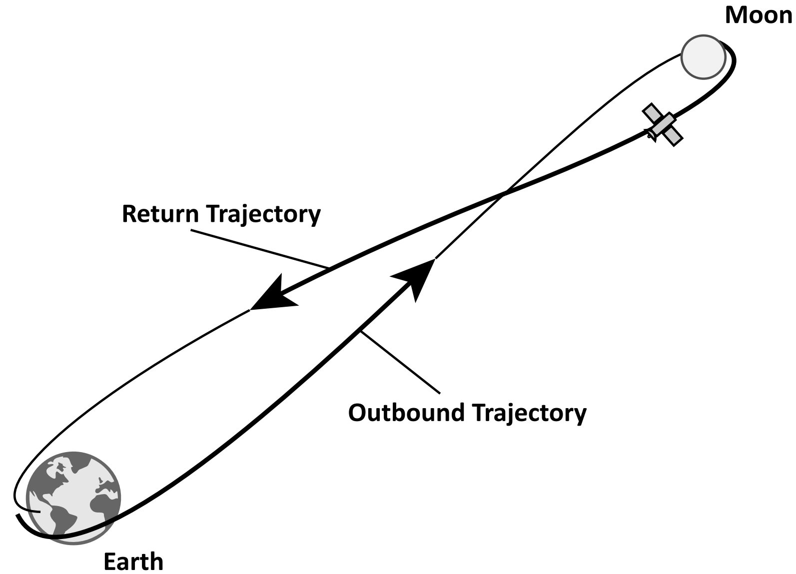

| | Altitude [km] | Altitude [$R_E$] |
|---|---|---|
| GPS | 20,200 | 3 |
| GEO | 36,000 | 5.6 |
| MMS 1 | 76,000 | 12 |
| MMS 2 | 153,000 | 24 |
| Moon | 378,000 | 60 |

# Projected GNSS Performance at the Moon

# ICG WGB: SSV Booklet Lunar Case

- Working Group B SSV booklet supports international space user characterization of PNT performance in SSV
- Booklet lunar case—simple ballistic cislunar trajectory from low-Earth orbit to lunar orbit insertion
- Each GNSS constellation simulated with conservative assumptions  according to minimum performance metrics from providers
- Receiver model:
  - zenith-pointing antenna, 5 dB peak gain
  - nadir-pointing antenna, 9 dB peak gain
  - 20 db-Hz acquisition/tracking threshold

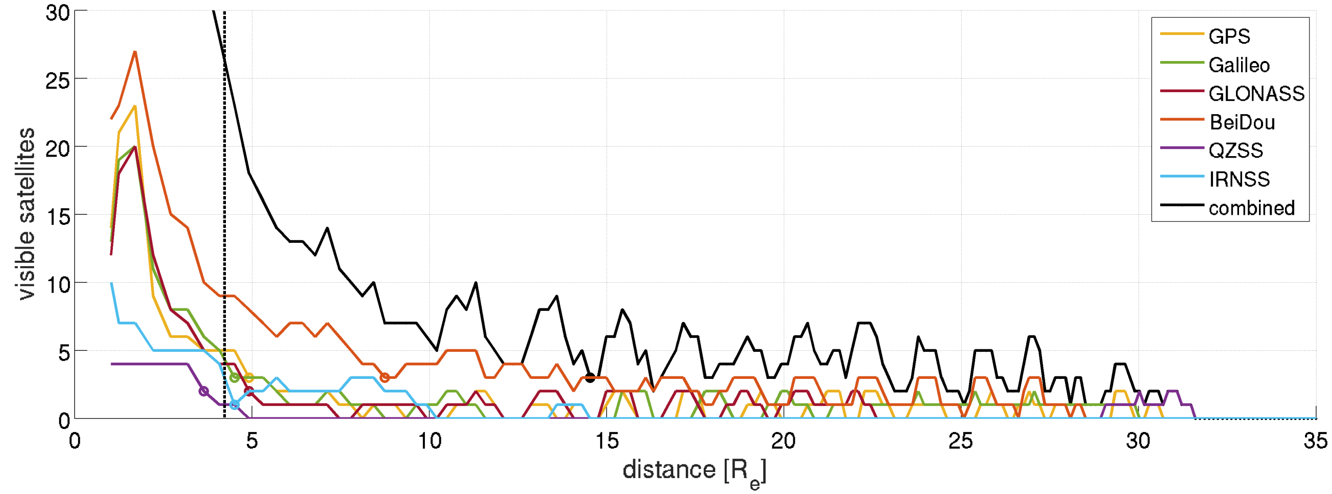
| | |
|---|---|
| **Mission** | Simplified lunar transfer, similar to Apollo 11, Exploration Mission 1 (EM-1) |
| **Description** | Free-return lunar trajectory with optional lunar orbit  and return phases |



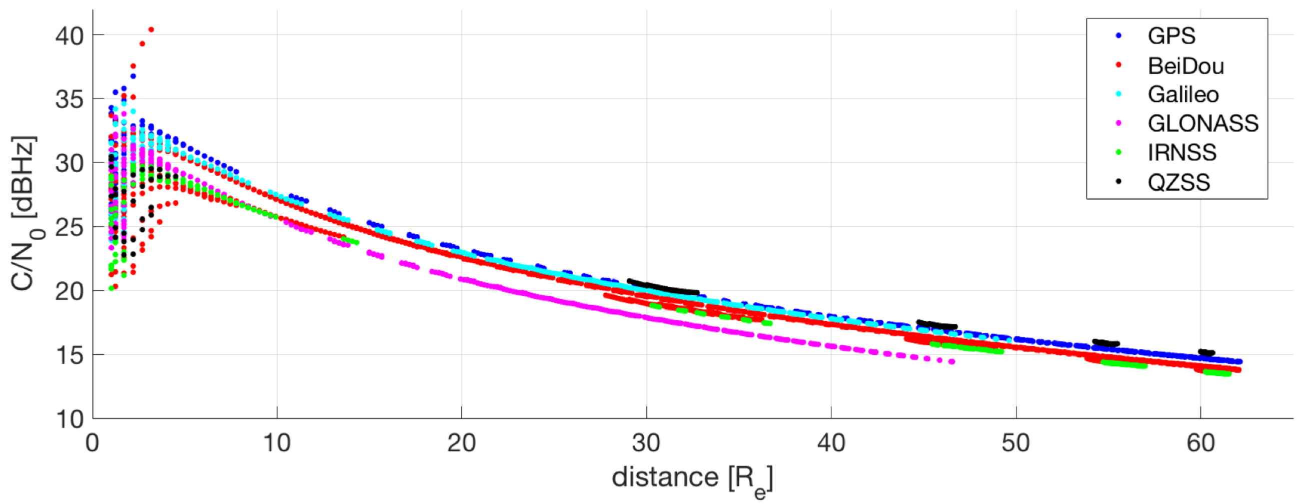

| | |
|---|---|
| **Earth Periapsis** | 185 km alt |
| **Moon Periapsis** | 100 km alt |
| **Earth Inclination** | 32° |
| **Duration** | 4 days |
| **Attitude profile** | Nadir-pointing |
| **Receive antennas** | Patch (zenith) + High-gain (nadir) |

# ICG WGB: SSV Booklet Lunar Case

- Signal availability over altitude



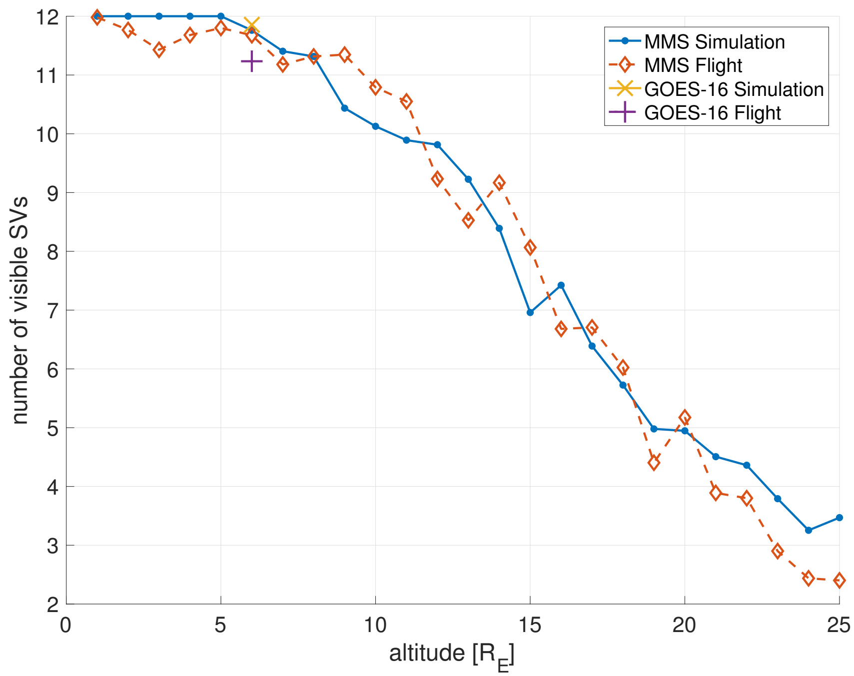

- Received signal strength over altitude



# Ashman et al. 2018: lunar GPS study

- GPS constellation modeled as accurately as possible, validated with GOES-16 and MMS flight data
  - Sidelobes included
  - 31 SVs with block composition consistent with validation flight data epochs (spring 2017)
  - Transmitter antenna patterns: IIR/IIR*/IIR-M patterns public, IIA used for IIF
- 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

**Simulation validation with MMS and GOES-16 flight data: number of SVs visible over altitude**



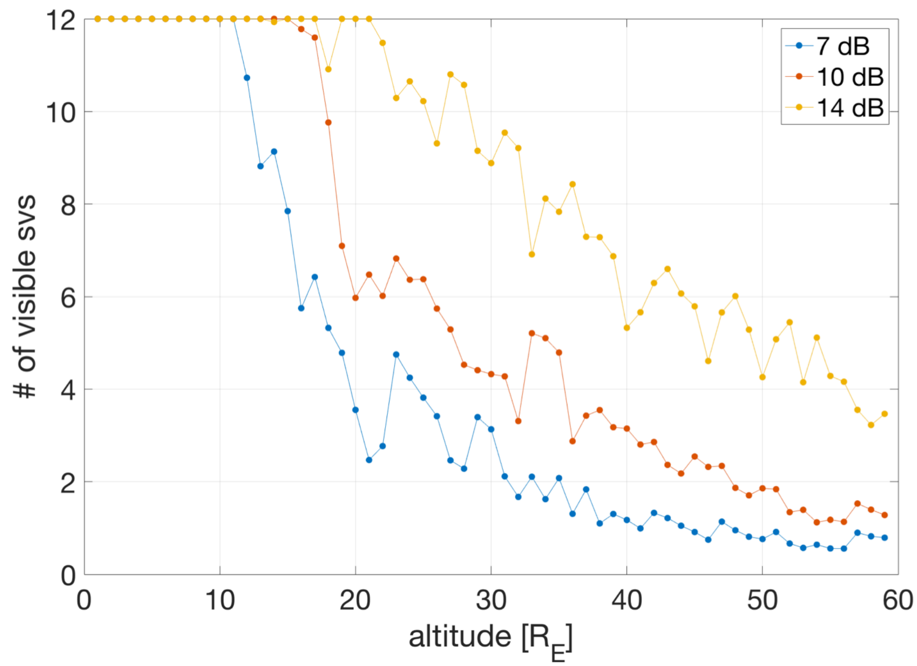
# Ashman et al. 2018: lunar GPS study

- Near Rectilinear Halo Orbit (NRHO) is one proposed orbit for the Gateway; this is used here for the lunar simulation with only the outbound cruise
- 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 antenna gain or enhanced GNSS receiver sensitivity increases coverage significantly

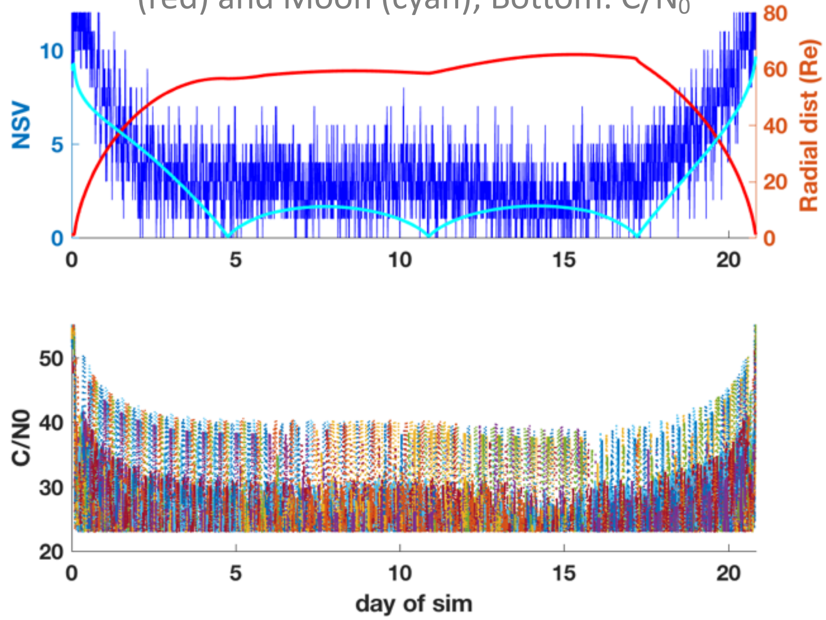
**Number of satellites visible over altitude for different antenna gains**



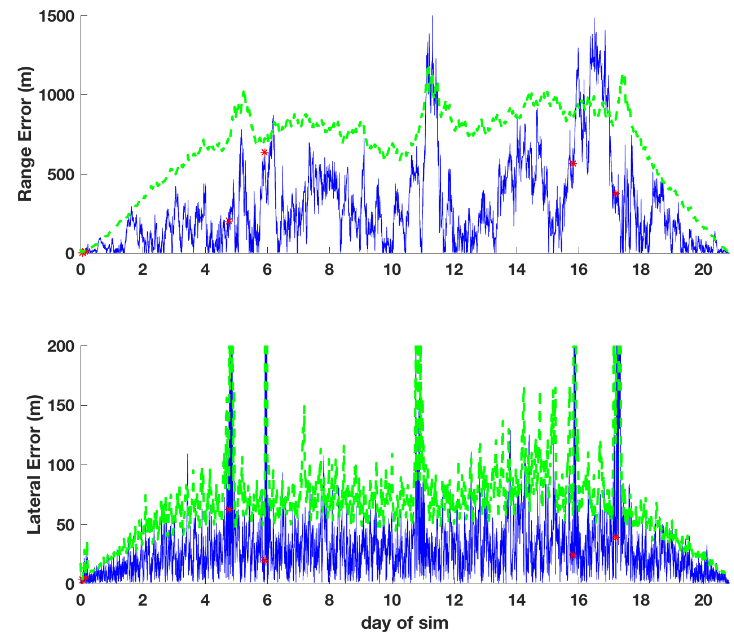
# Winternitz et al. 2017: MMS Lunar mission study

- Study: How will MMS receiver perform if used on a conceptual Lunar mission with 14dBi high-gain antenna?
- Concept lunar trajectory similar to EM-1: LEO -> translunar -> Lunar (libration) orbit -> return
- GPS measurements simulated & processed using same filter onboard MMS
- Visibility similar to MMS Phase 2B, as high-gain makes up for additional path loss
- Due to poor geometry, range/clock-bias errors dominate but could be resolved to meter-level precision with an atomic clock or other timing source

Top: Signals tracked and radial distance to Earth (red) and Moon (cyan); Bottom: $C/N_0$




Filter position formal (3σ) and actual errors



# Conclusions

- There is renewed interest in the Moon as a target for rovers, landers, and human exploration
  - 2018 Global Exploration Roadmap reaffirms intention of 14 space agencies to go to the Moon in the next decade
- Advances in high-altitude use of GNSS are extending operational usage well beyond the formal limit of the SSV (i.e., GEO)
- Increased understanding of signal performance at high altitudes (e.g., transmit antenna patterns and operational usage) has informed GNSS studies that suggest sufficient signals are available for navigation at the Moon
- ICG WG B Recommendation in Kyoto (ICG-12):
  - *WG-B will lead and Service providers, Space Agencies and Research Institutions are invited to contribute to investigations/developments related to use of the full potential of the GNSS SSV, also considering the support of exploration activities in cis-Lunar space and beyond.*

# Near-term Work

- ICG WG B expanding SSV analyses
- American Astronautical Society GN&C conference in Breckenridge, CO, USA February 2019 session focused on lunar exploration activities and the international Lunar Orbital Platform Gateway concept
- NASA Goddard Space Flight Center continuing to study Earth-facing, Navigator-like system in NRHO; Gateway exploring the possibility of employing GNSS

# Backup Slides

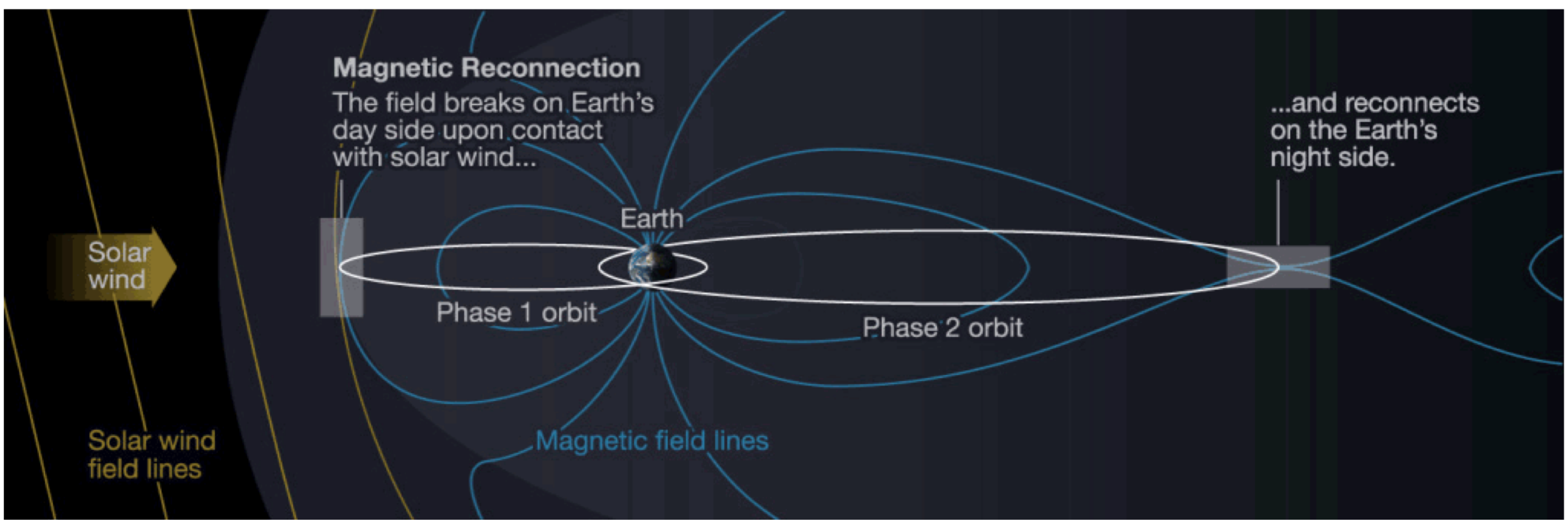
# Recent SSV Experiences: NASA Magnetospheric Multi-Scale (MMS)

## Magnetospheric Multi-Scale (MMS)

- Launched March 12, 2015
- Four spacecraft form a tetrahedron near apogee for performing magnetospheric science measurements (space weather)
- Four spacecraft in highly eccentric orbits
  - Phase 1: 1.2 x 12 Earth Radii (Re) Orbit (7,600 km x 76,000 km)
  - Phase 2B: Extends apogee to 25 Re (~150,000 km) **(40% of way to Moon)**

## MMS Navigator System

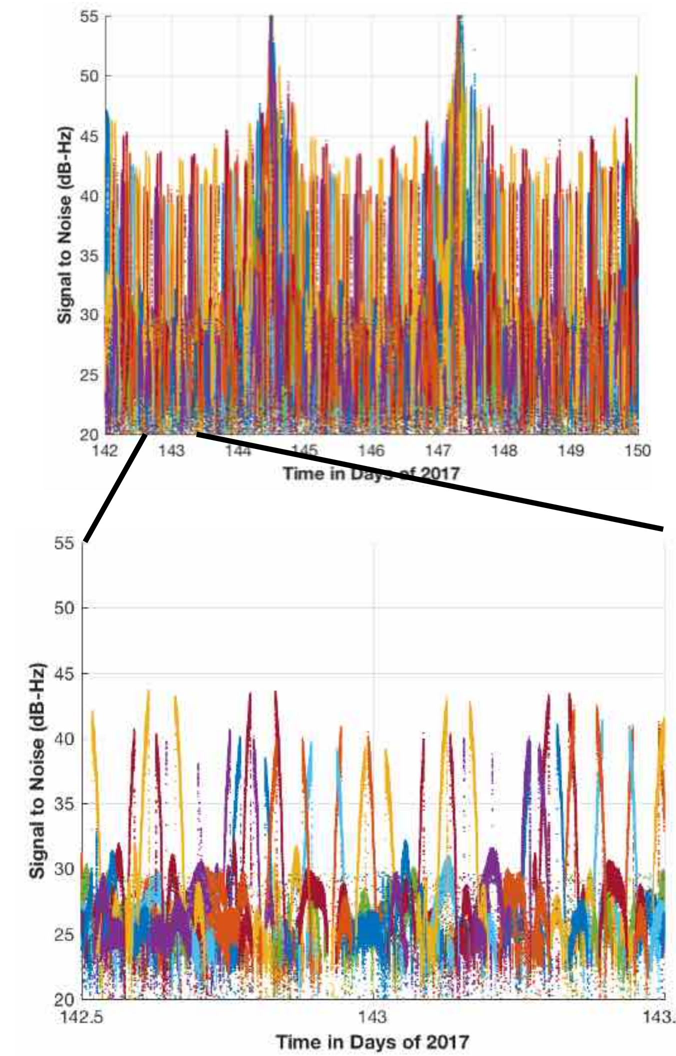
- GPS enables onboard (autonomous) navigation and near autonomous station-keeping
- MMS Navigator system exceeds all expectations
- At the highest point of the MMS orbit Navigator set Guinness world record for the highest reception of signals and onboard navigation solutions by an operational GPS receiver in space
- At the lowest point of the MMS orbit Navigator set Guinness world for fastest operational GPS receiver in space, at velocities over 35,000 km/h



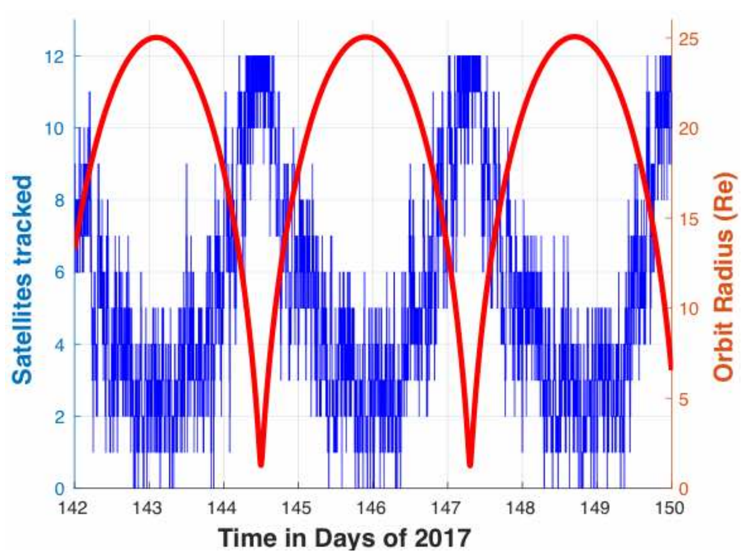
# MMS on-orbit Phase 2B results: signal tracking

- Results from 8-day period early in Phase 2B shown here
- Sidelobes dominate signals tracked above the GPS constellation
- Long term trend shows average of ~3 signals tracked near apogee, with up to 8 observed.
- Visibility exceeds preflight expectations significantly

$C/N_0$ vs. time, near apogee

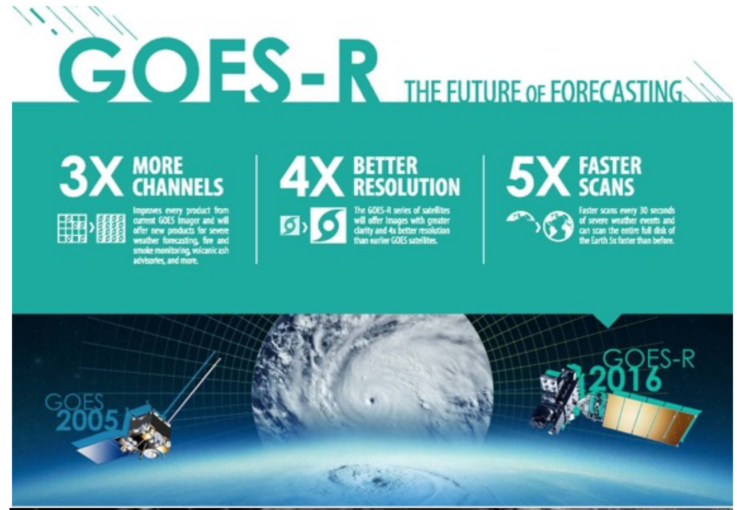


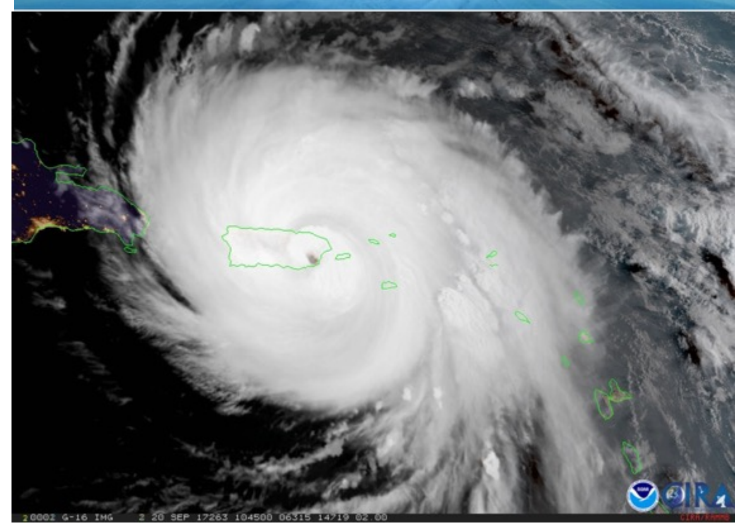

Signals tracked



# GOES-R Series Weather Satellites

- GOES-R, -S, -T, -U: 4th generation NOAA operational weather satellites
- GOES-R/GOES-16 Launch: 19 Nov 2016
- GOES-S/GOES-17 Launch: 1 March 2018
- 15 year life, series operational through mid-2030s
- Features new CONOPS over previous generation:
  - Daily low-thrust station-keeping maneuvers, rather than annual high-thrust events
  - Continuous data collection through maneuvers, <120 min of outage per year
  - Tighter navigation accuracy requirements and faster cadence needed to support highly increased operational tempo
- Employs on-board GPS at GEO to meet stringent navigation requirements
- Utilizes GPS sidelobe signals to increase SSV performance and ensure continuous availability



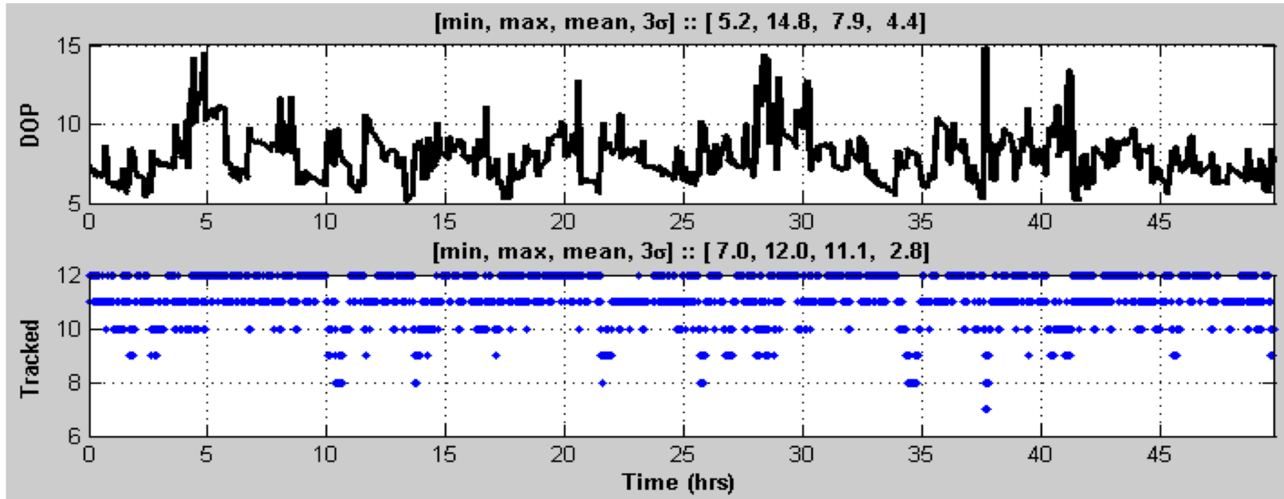



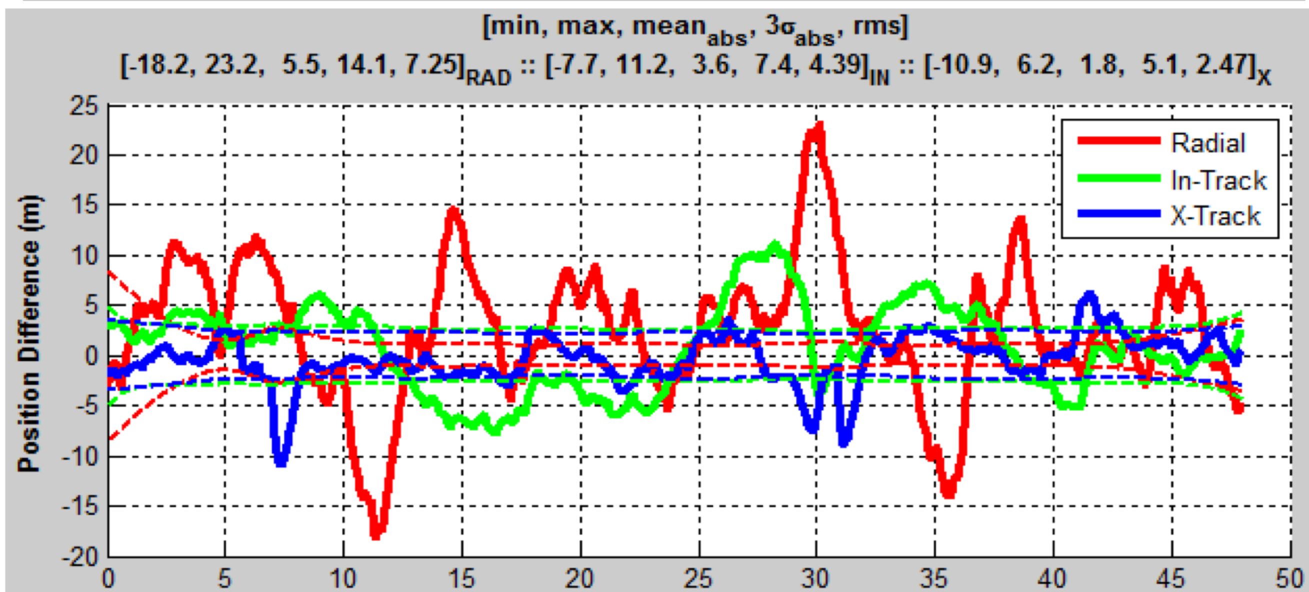
GOES-16 Image of Hurricane Maria Making Landfall over Puerto Rico

# GOES-R/GOES-16 In-Flight Performance

**GPS Visibility**
- Minimum SVs visible: 7
- DOP: 5–15
- Major improvement over guaranteed performance spec
  (4+ SVs visible 100% of time)

**Navigation Performance**
- 3σ position difference from smoothed ground solution:
  - Radial: 14.1 m
  - In-track: 7.4 m
  - Cross-track: 5.1 m
- Compare to requirement: (100, 75, 75) m



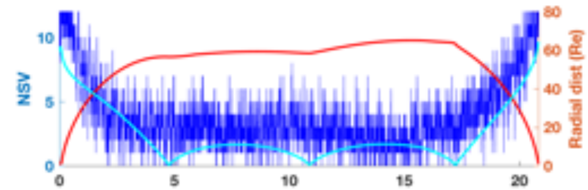




Source: Winkler, S., Ramsey, G., Frey, C., Chapel, J., Chu, D., Freesland, D., Krimchansky, A., and Concha, M., "GPS Receiver On-Orbit Performance for the GOES-R Spacecraft," ESA GNC 2017, 29 May-2 Jun 2017, Salzburg, Austria.

# Highlight: Lunar GNSS & Gateway

- NASA is the leader in high altitude GPS policy, technology, operations, and commercialization
- MMS-Navigator was first civ. operational GPS system above constellation
  - Set altitude record at 40% lunar distance apogee
  - Flight calibrated simulations of MMS-navigation system predict excellent performance in cislunar and lunar regimes, current focus on Gateway NRHO

- Benefits of GPS on Gateway
  – Enables *autonomous* navigation, fulfills requirement
  – Reduces tracking and operations costs
  – Backup/redundant nav for human safety
  – provides for onboard and lunar navigation infrastructure
  – Major risk reduction for commercial development
- Current status
  – Gateway DCB has identified GPS as highly desirable
  – Actively pursuing Gateway GPS DTO with JSC



Signals tracked with distance from Earth (red) and Moon (cyan) for a simulated EM3 trajectory