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GPS Operations in High Earth Orbit

Recent Experiences and Future Opportunities

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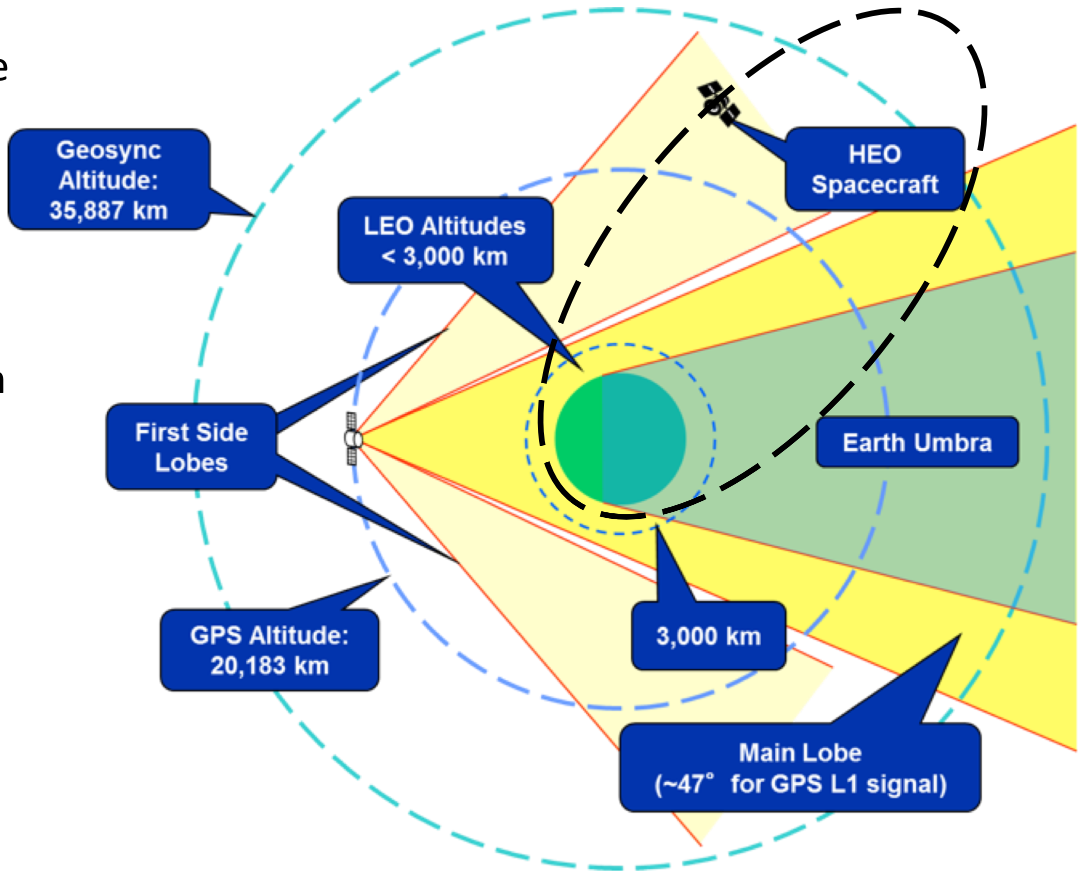
GPS Signals in the Space Service Volume (SSV)

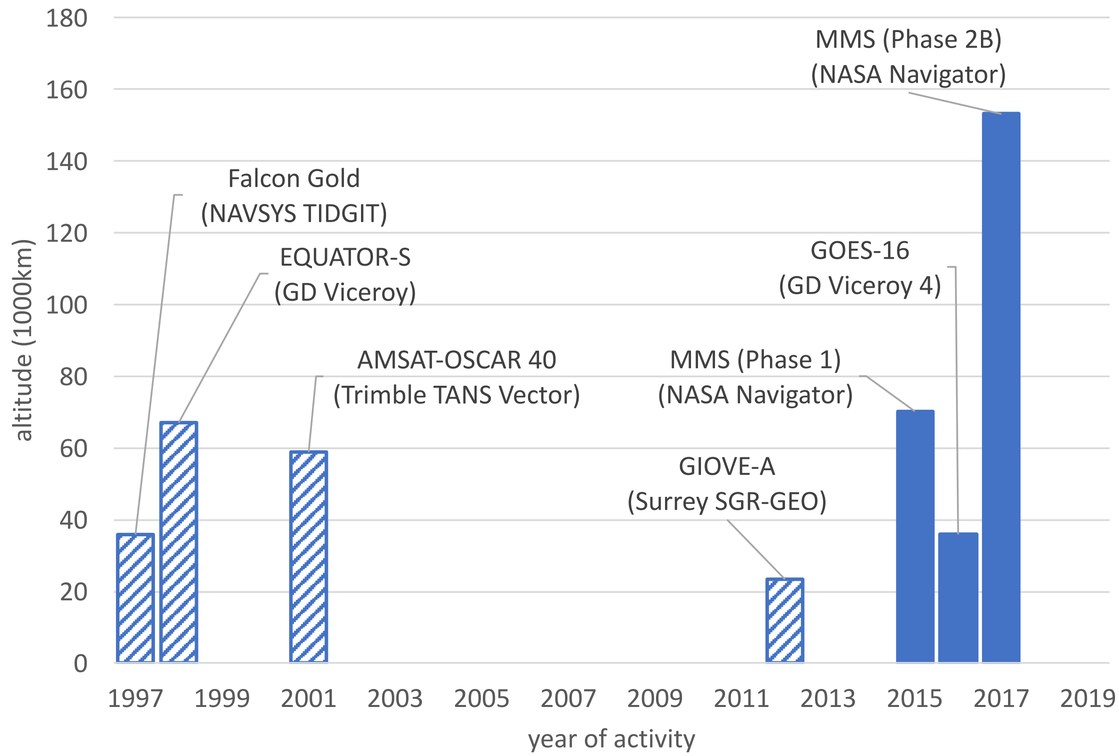
- The Terrestrial Service Volume (TSV) is defined as the volume of space including the surface of the Earth and LEO, i.e., up to 3,000 km
- The Space Service Volume (SSV) is defined as the volume of space surrounding the Earth from the edge of LEO to GEO, i.e., **3,000 km to 36,000 km altitude**
- The 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
- Use of GPS in the SSV increasing despite geometry, Earth occultation, and weak signal strength challenges
- Spacecraft use of GPS 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:

- 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

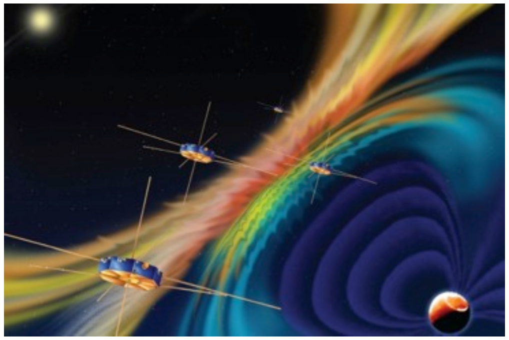


Benefits of Real-Time GPS Navigation in the SSV

Benefits of GNSS use in SSV:

- Supports **fast trajectory maneuver recovery** (from: 5-10 hours to: minutes)
- Significantly **improves real-time navigation performance** (from: km-class to: meter-class)
- GNSS timing **reduces need for expensive on-board clocks** (from: $100sK-$1M to: $15K–$50K)
- Supports **increased satellite autonomy**, lowering mission operations costs (savings up to $500-750K/year)
- Enables new/enhanced capabilities and better performance for **High Earth Orbit (HEO) and Geosynchronous Earth Orbit (GEO) missions,** such as:

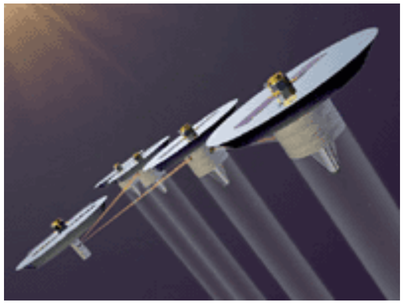
Earth Weather Prediction using Advanced Weather Satellites



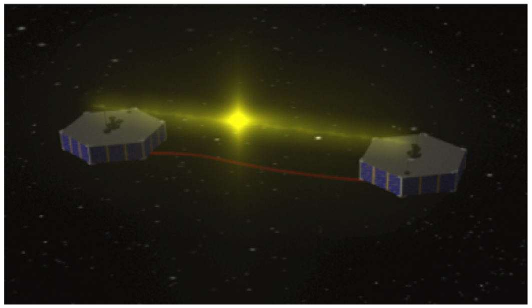
Space Weather Observations

Precise Relative Positioning

Launch Vehicle Upper Stages and Beyond-GEO applications



Formation Flying, Space Situational Awareness, Proximity Operations

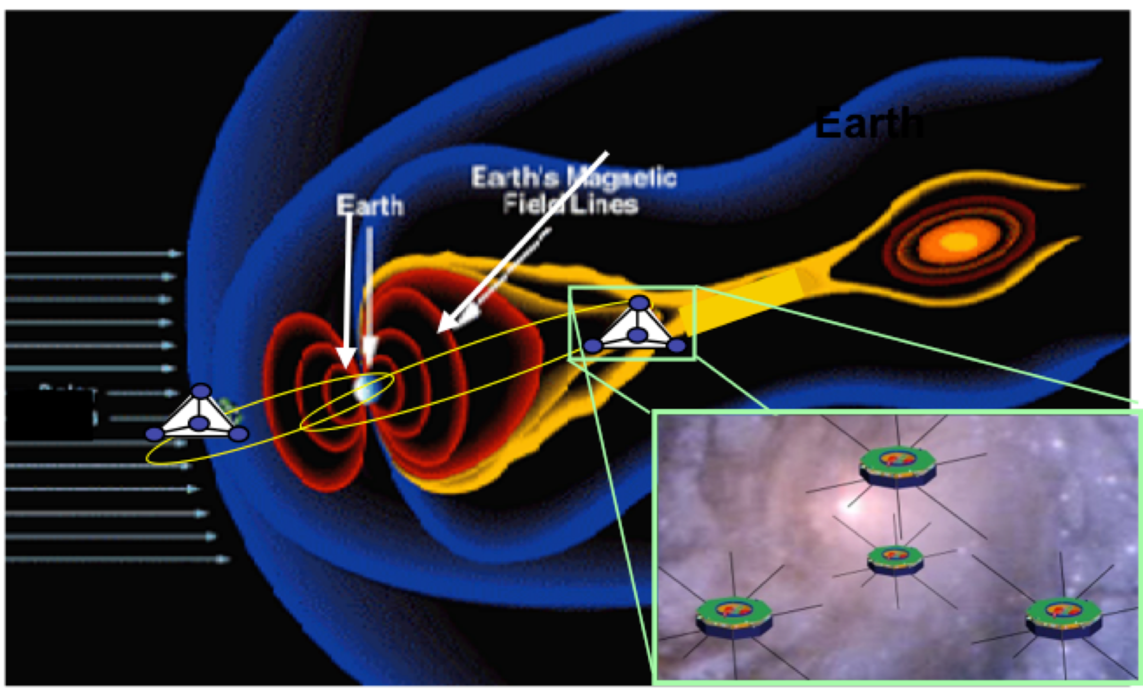


Precise Position Knowledge and Control at GEO

Recent Experiences: MMS and GOES-16

Recent SSV Experiences: NASA's Magnetospheric MultiScale (MMS) Mission

- **Goal**: Study the fundamental plasma physics process of reconnection in the Earth's magnetosphere
- Obtains coordinated measurements from tetrahedral formation of four spacecraft with scale sizes from 400 km to 10 km
- Flying in two highly elliptic orbits in two mission phases
  - Phase 1 1.2x12 R_E (magnetopause) Mar '14-Feb '17
  - Phase 2B 1.2x25 R_E (magnetotail) May '17-present



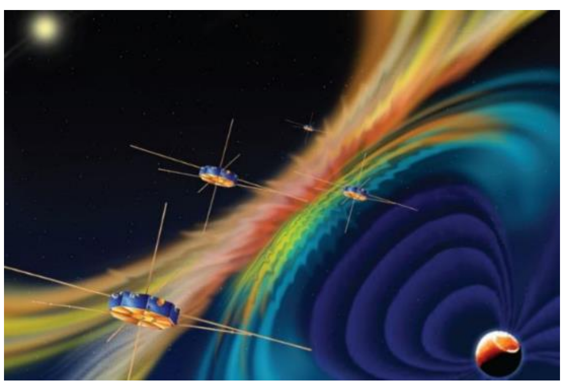
Recent SSV Experiences: NASA MMS Mission

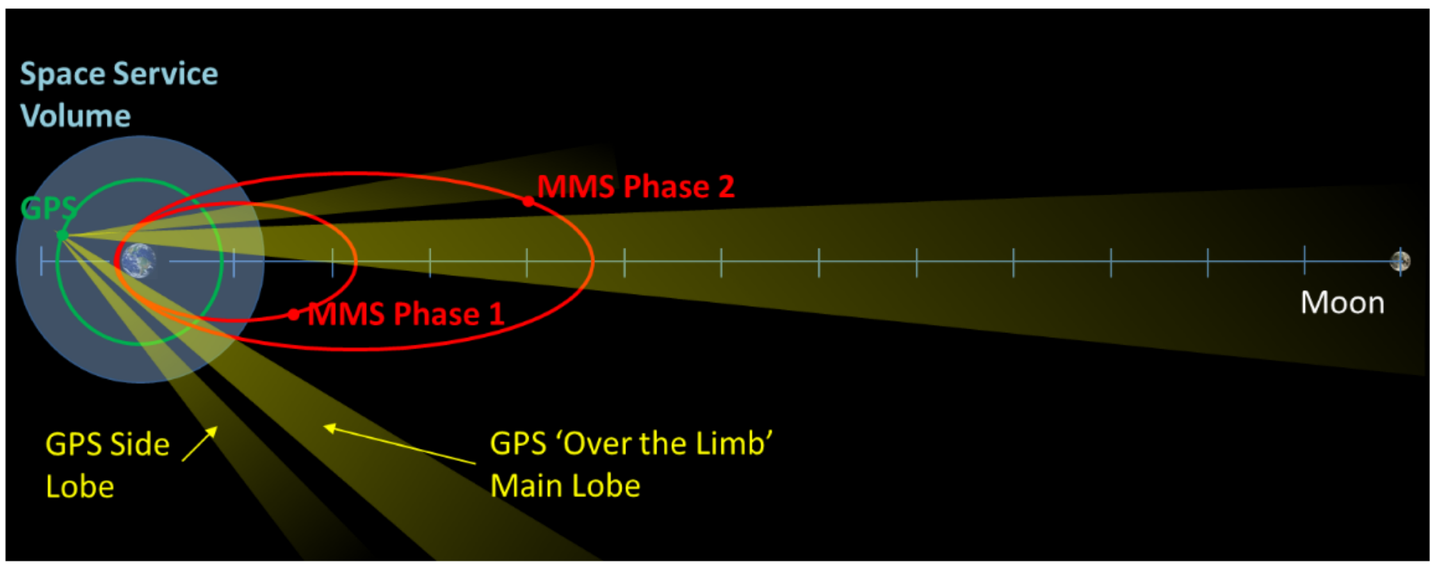
Magnetospheric Multi-Scale (MMS)

- 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

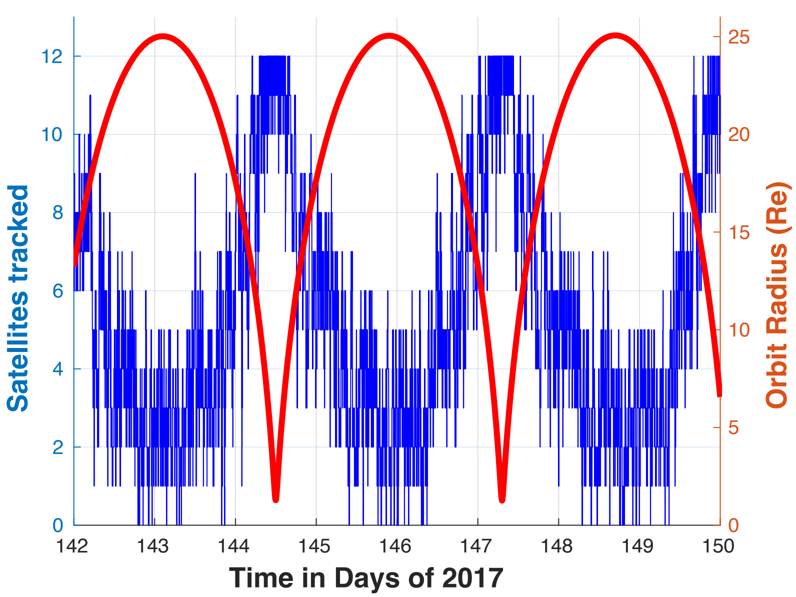




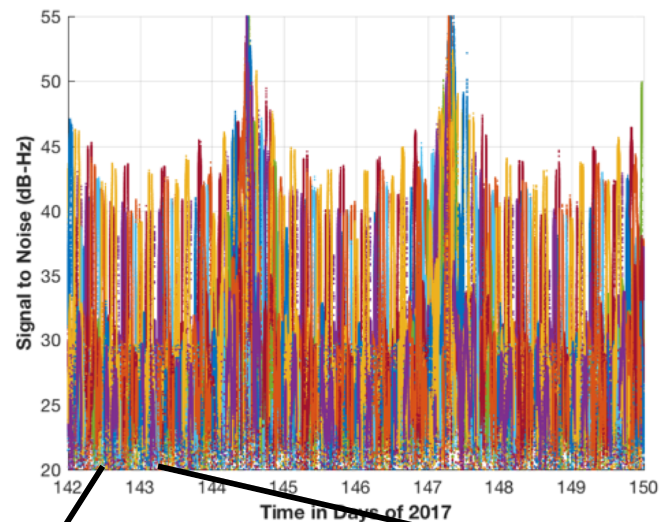
MMS on-orbit Phase 2B results: signal tracking

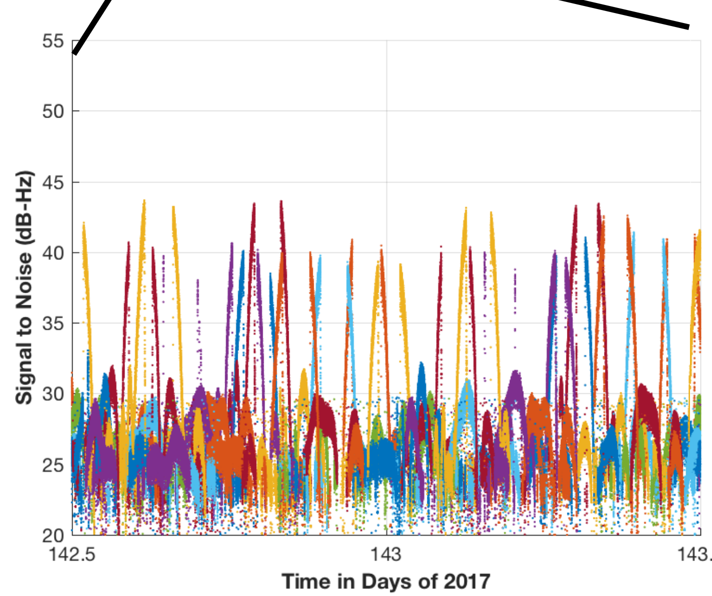
- Consider 8-day period early in Phase 2B
- Above GPS constellation, majority of signals are still sidelobes
- Long term trend shows average of ~3 signals tracked near apogee, with up to 8 observed.
- Visibility exceeds preflight expectations significantly

Signals tracked



C/N_0 vs. time, near apogee



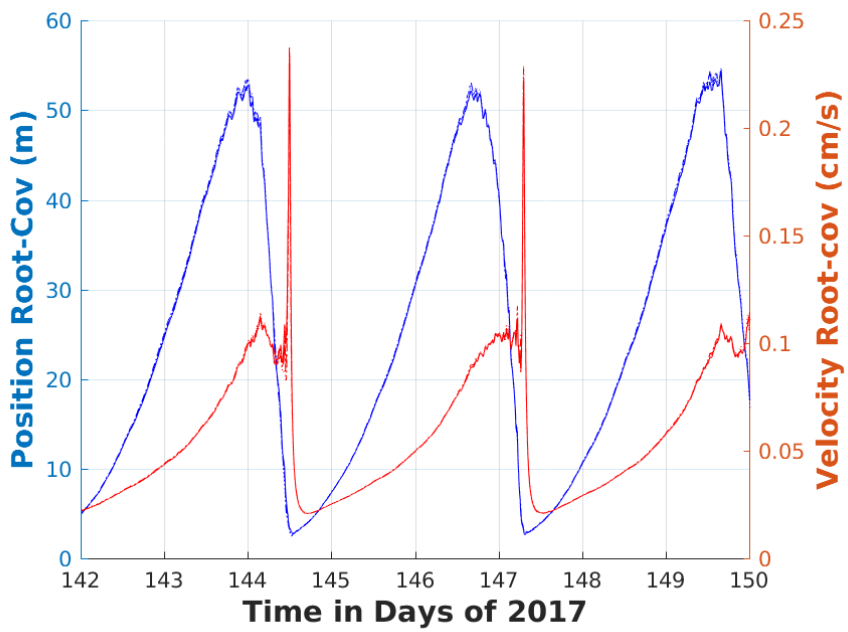


MMS on-orbit Phase 2B results: measurement and navigation performance

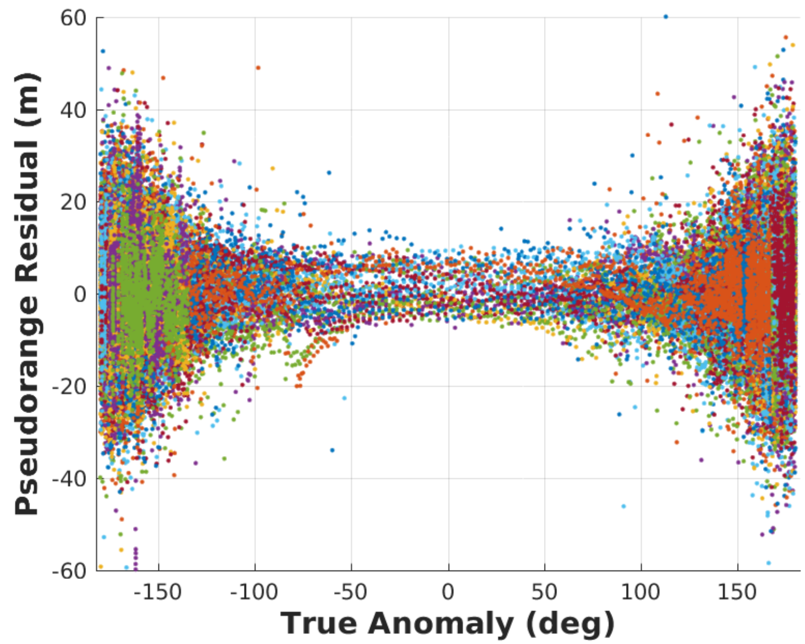
- GEONS filter RSS 1-sigma formal errors reach maximum of ~50m and briefly 5mm/s (typically <1mm/s)
- Measurement residuals are zero mean, of expected variation <10m 1-sigma.
  - Suggests sidelobe measurements are of high quality.

Description	Requirement	Phase 1	Phase 2B
Semi-major axis est. under 3 R_E (99%)	50 m (Phase 1) 100 m (Phase 2B)	6 m	15 m
Orbit position estimation (99%)	100 km RSS	65 m	55 m

Filter formal pos/vel errors (1σ root cov)

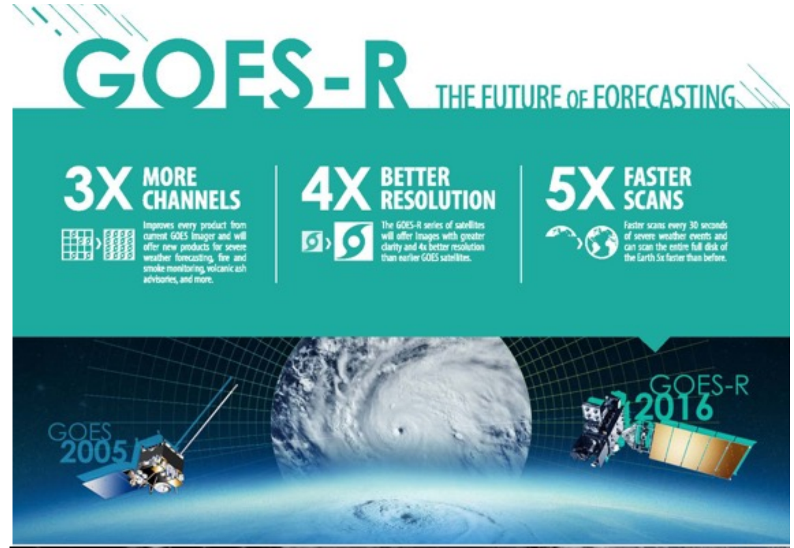


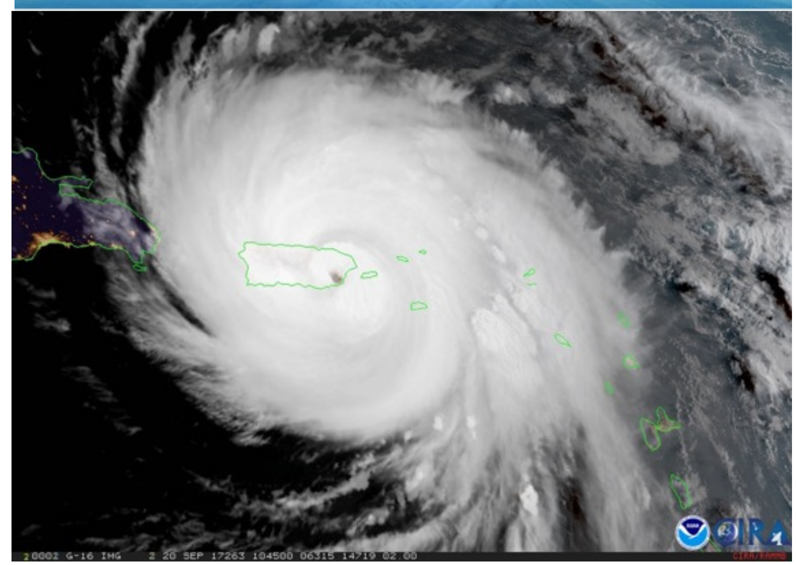
Pseudorange residuals



GOES-R Series Weather Satellites

- GOES-R, -S, -T, -U: 4th generation NOAA operational weather satellites
- GOES-R/GOES-16 Launch: 19 Nov 2016
- 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



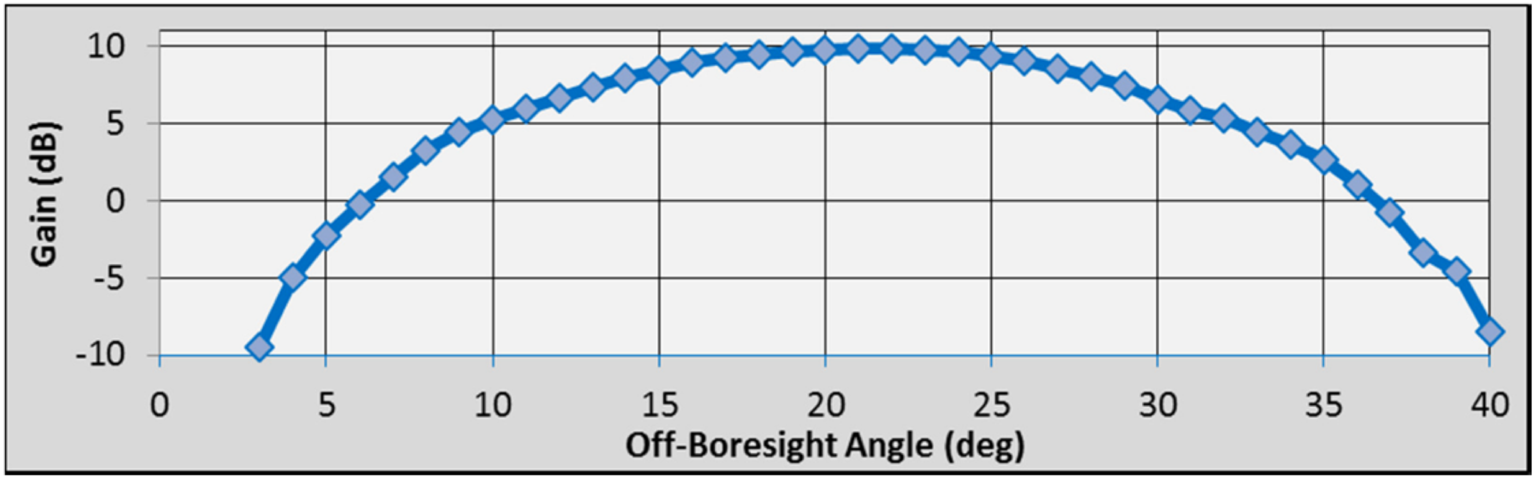


GOES-16 Image of Hurricane Maria Making Landfall over Puerto Rico

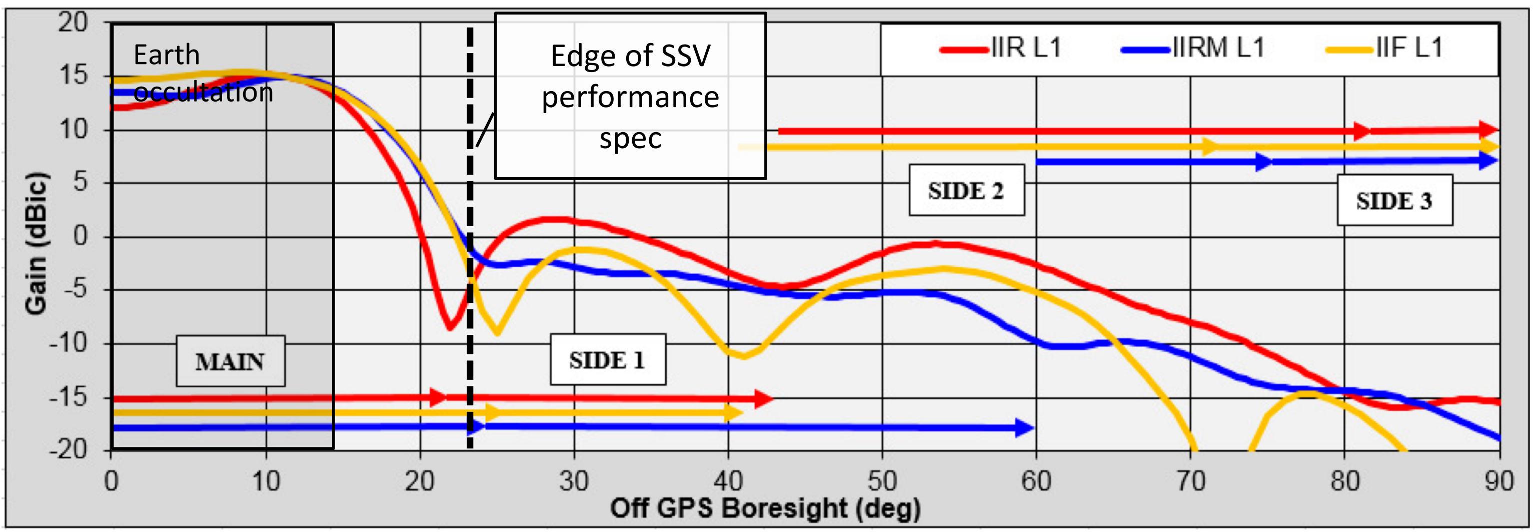
GOES-R/GOES-16 Signal Reception

- GPS L1 C/A only
- Receive antenna designed for above-the-constellation use
- Max gain @20 deg off-nadir angle
- Tuned to process main lobe spillover + first side lobe

Antenna patterns



RX



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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.

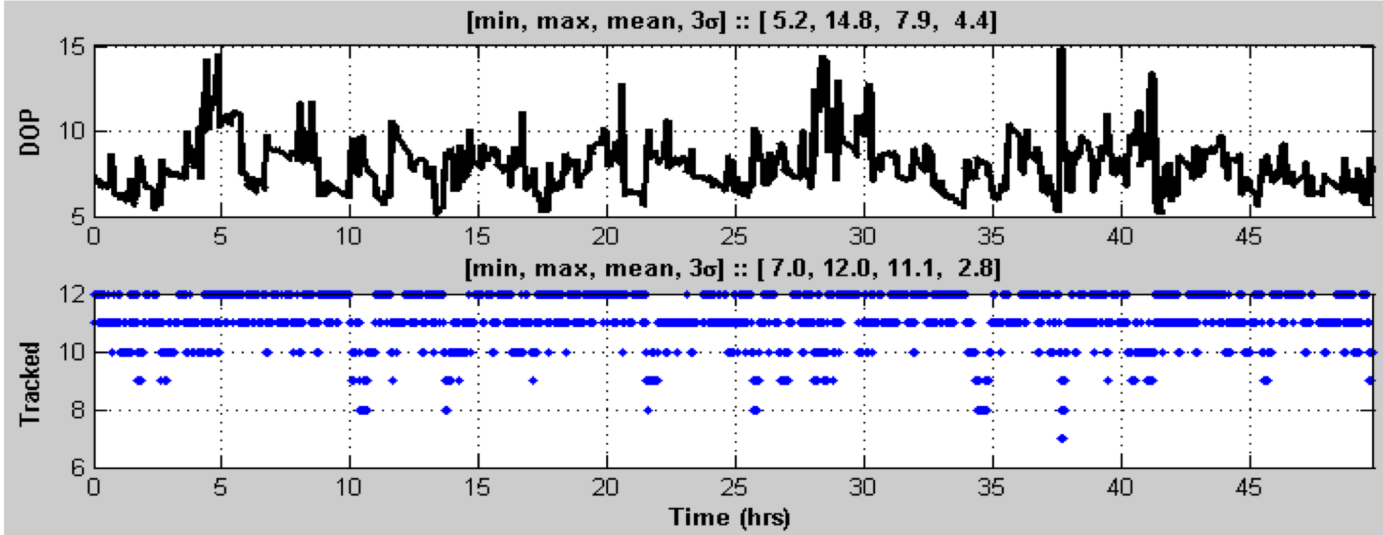
GOES-R/GOES-16 In-Flight Performance

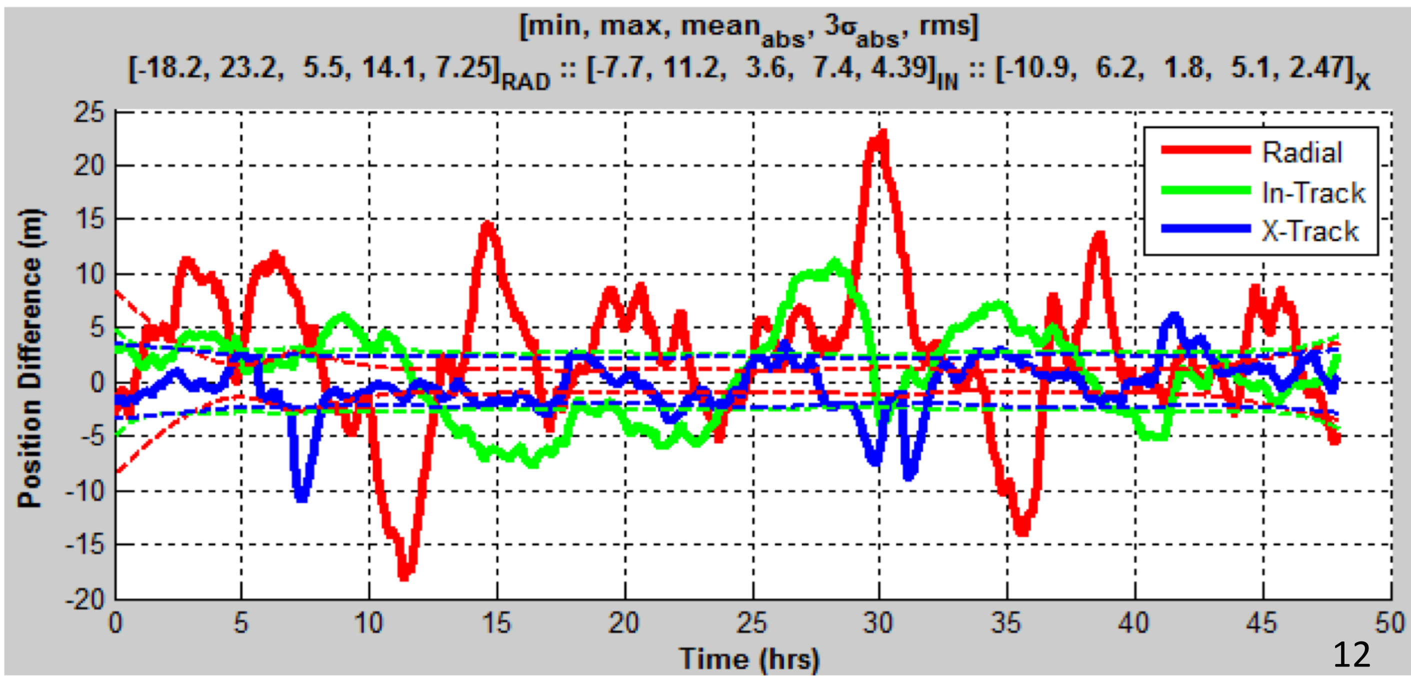
GPS Visibility

- Minimum SVs visible: 7
- DOP: 5–15
- Major improvement over guaranteed performance spec
  (4+ SVs visible 1% of time)

Navigation Performance

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





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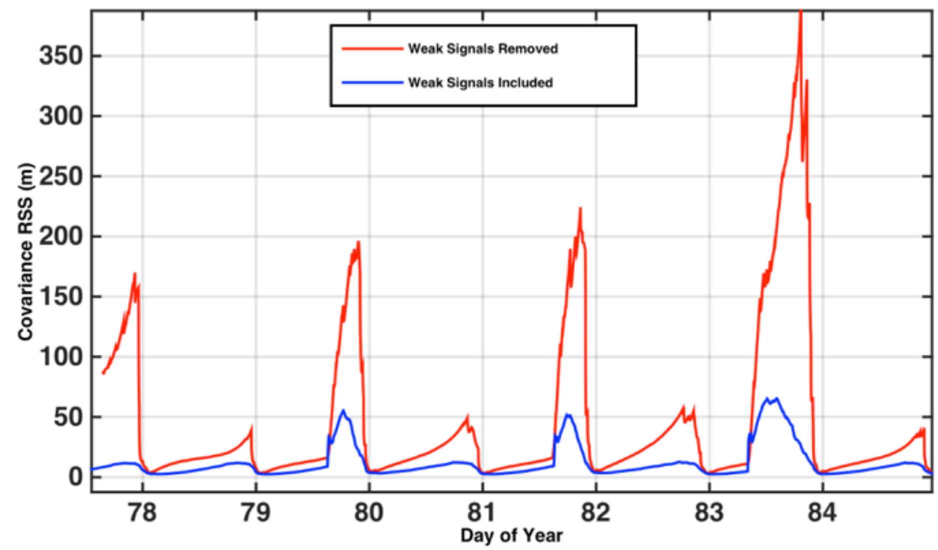
GOES-16 & MMS SSV Lessons Learned

- Flight data presents real-world snapshot of current GPS SSV performance, especially the substantial enhancements afforded by side-lobe signals
- Side-lobe signals:
  - Shown to significantly improve availability and GDOP out to cis-Lunar space
  - Substantial enhancement of maneuver recovery for vehicles in SSV (graphic)
  - Integrity of signals sufficient enough to enable outstanding, real-time navigation out to cis-Lunar distances
- Operational use of side-lobe signals is an increasing area of interest & multiple operational examples are on-orbit and in development
- WG-B team should consider whether beyond main-lobe (aggregate) signals should be documented and protected to optimize the utility of the SSV



MMS response to apogee maneuvers with side-lobe signals (blue) and without (red)

Notes:
1) Blue—flight data
2) Red—simulated data based on flight signal availability
3) MMS Phase 1 (70,000 km apogee)

SSV: Future Civil Applications

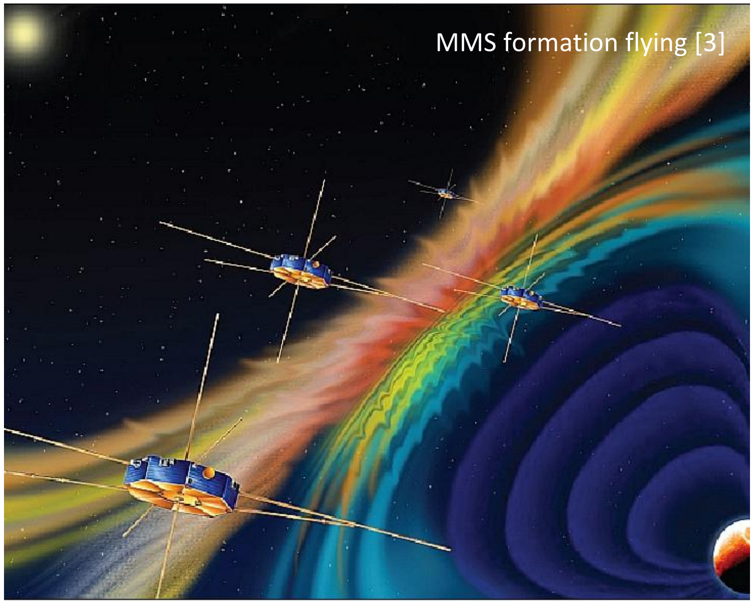
SSV: Future Civil Applications

- Earth Weather Missions
  - Objectives: Improve weather forecasting from 3-5 days to 5-7 days; protecting people and property through early warning of tornados, flash floods, and wildfires
  - Role of the SSV: Accurate orbit prediction (position and velocity), fast recovery from trajectory maneuvers, navigation stability to prevent internal image and image to image pixel, and timing
- Space Weather and Heliospheric Science Missions
  - Objectives: Enable High Earth Orbit and Cislunar observations of the magnetosphere to improve understanding of space weather and to potentially start space weather prediction.
  - Role of the SSV: Improved navigation performance (e.g. 10-meter to 1-meter class) and fast recovery from trajectory maneuvers (minute class) for accurate placement of space weather phenomenon; improved operations cadence and increased satellite autonomy to support constellation or formation flying missions; Precise timing enabling lower cost clock alternatives

SSV: Future Civil Applications (cont.)

- Satellite Servicing
  - Objectives: Extend the lives of satellites through upgrade, repair, refueling, and orbit adjustment; debris removal; in-orbit construction or installation
  - Role of the SSV:
    - Fast recovery from trajectory maneuvers required—on the order of minutes during critical rendezvous, proximity operations, and docking
    - Near-continuous GPS signal availability needed to support satellite responsiveness and autonomy
    - Highly accurate absolute orbit state (position and velocity) are necessary to support far-field rendezvous—as a general rule of thumb, position must be known to an accuracy of 10% the inter-vehicle range
- Formation Flying Missions
  - Objectives: Enable new classes of missions and new scientific viewpoints through formation flying; spans full spectrum of vehicle sizes (CubeSats to ISS class) and mission orbits (MEO, HEO, GEO, Cislunar.
  - Role of the SSV: Precise navigation and timing, fast recovery from trajectory maneuvers, enhanced operations cadence, and increased satellite autonomy. Requirements as low as meter-class navigation in real time, cm-level relative navigation and micro- to nanosecond timing synchronization.


Restore-L satellite servicing mission [2]


MMS formation flying [3]

SSV: Future Civil Applications (cont.)

- Commercial GEO Missions
  - Objectives: Densify most coveted real estate in space, benefiting commercial and civil space users
  - Role of the SSV: Accurate position and velocity measurements and near-continuous GPS signal availability needed to enable accurate, autonomous vehicle station keeping during near-continuous low thrust maneuvering
- Launch Vehicle Upper Stages & Deep Space Missions, En Route, and Return
  - Objectives: Improve real-time vehicle insertion and trajectory accuracy reducing fuel requirements and improving payload mass capacities
  - Role of the SSV: High accuracy, high cadence position, velocity, and time knowledge to minimize the trajectory propagation errors of the vehicle during flight


Space Launch System (SLS) [4]

SSV: Future Civil Applications (cont.)

- Lunar Missions
  - Objectives: There is a renewed interest in the moon as a target for rovers, landers, and human exploration. The US plans to return to human exploration of the moon and cislunar space in the next few years with Exploration Missions (EM) 1 and 2. EM-3 may begin construction of a “gateway”—a permanent way-station in the vicinity of the moon for staging deep space activity
  - Role of the SSV:
    - GPS can provide measurements for mid-course correction burns during outbound and return cruise
    - Simulations have shown that GPS signal availability can be extended to lunar distances by augmenting existing high-altitude GPS navigation systems (such as MMS) with a high-gain antenna (Winternitz et al. 2017, Ashman et al., 2018)
    - Navigation backup for the crew capsule, Orion, if communications link is lost
    - Lunar platform like the gateway could use GPS for position, velocity, and attitude, as well as a stable and accurate timing source for hosted science and technology payloads

Next Generation SSV

Next Generation SSV

- **Current capability status:**
  - High-altitude GPS (and GLONASS) is currently being used operationally by multiple international users
  - SSV utilizing main-lobe signal to 23.5deg off-boresight angle is formal part of GPS requirements
  - Current SSV users are using GPS sidelobe signals as well to drastically increase signal availability and navigation performance
  - Meter-class position knowledge and continuous availability at GEO; <100 m at 40% lunar distance
- **Paths forward for next-generation SSV capability:**
  - Evolution of existing GPS SSV: What on-orbit capability will GPS Block III provide?
  - Multi-GNSS SSV
    - All providers are collaborating under United Nations International Committee on GNSS on combined constellation performance expectations publication (summer/fall 2018)
    - Document will focus on main-lobe SSV contributions, and will represent expectations, not specifications
    - Combined performance likely to reach 100% availability at GEO using only main-lobe signals
  - Expansion of SSV concept to include augmentations:
    - Specification of sidelobe signals for all constellations
    - Utilization of ranging signals on intersatellite links (cross-links) or existing augmentations (WAAS/EGNOS)
    - Possible design of future SSV-specific augmentations – terrestrial or planetary beacons, SSV-specific transmitters at Lagrance points, etc.

Conclusions

- GPS has become routine for spacecraft navigation in LEO
- High-altitude GPS utilization has reached turning point since its first demonstration in late 1990s
  - First US operational users, MMS and GOES-R, are expanding knowledge of what is possible in the SSV
- The SSV concept is continually evolving – multiple avenues exist for expansion and formalization in the future to support future mission needs.
- To support this growth, the community must ensure that:
  1. The existing SSV capability is protected and improved
  2. All GNSS providers cooperate fully on the expansion to Multi-GNSS SSV
  3. Receiver developers continue development of innovative high-altitude spacecraft receivers, including ultra-weak signal tracking and high-altitude onboard precise orbit determination.
  4. High-altitude users continue to take advantage of the SSV to demonstration next-generation mission benefits

Image Sources

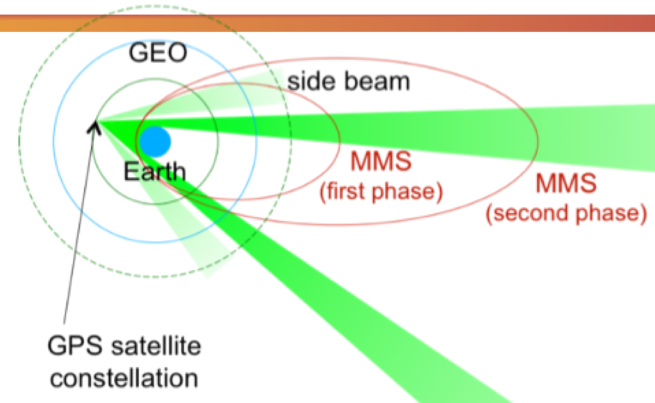
1. https://scitechdaily.com/new-iss-image-of-the-pacific-northwest-and-an-aurora/
2. https://www.aerospace-technology.com/news/restore-l-satellite-servicing-mission-passes-nasa-design-review/
3. https://eoportal.org/web/eoportal/satellite-missions/content/-/article/mms-observatory
4. https://www.nasaspaceflight.com/2016/09/nasa-sls-block-1b-universal-stage-adapter/
5. https://www.flickr.com/photos/projectapolloarchive/21764833108/in/album-72157659453355752/

References

- J.Kronman,“ExperienceUsingGPSForOrbitDeterminationofaGeosynchronousSatellite,”Proceedings of the Institute of Navigation GPS, Salt Lake City, UT, September 2000.
- G. Davis, M. Moreau, J. Carpenter, and F. Bauer, “GPS-Based Navigation and Orbit Determination for the AMSAT AO-40 Satellite,” Proceedings of the Guidance, Navigation, and Control Conference, Reston, VA, August 2002.
- S. Winkler, G. Ramsey, C. Frey, J. Chapel, D. Chu, D. Freesland, A. Krimchansky, and M. Concha, “GPS Receiver On-Orbit Performance for the GOES-R Spacecraft,” Proceedings of the 10th International ESA Conference on Guidance, Navigation and Control Systems, Salzburg, Austria, European Space Agency, May 2017.
- L. B. Winternitz, W. A. Bamford, and S. R. Price, “New High-Altitude GPS Navigation Results from the Magnetospheric Multiscale Spacecraft and Simulations at Lunar Distances,” Proceedings of the 30th International Technical Meeting of The Satellite Division of the Institute of Navigation (ION GNSS+ 2017), Portland, OR, Institute of Navigation, September 2017.
- B. Ashman, J. Parker, F. H. Bauer, M. Esswein, “Exploring the Limits of High Altitude GPS for Lunar Missions,” AAS GN&C Conference, Breckenridge, CO, American Astronautical Society, February 2018.

Backup Slides

MMS Navigation



- **MMS baselined GSFC Navigator + GEONS Orbit Determination (OD) filter software as sole means of navigation (mid 2000's)**
  - Original design included crosslink, later descoped
- **Trade vs. Ground OD (2005)**
  - Estimated >$2.4M lifecycle savings over ground-based OD
  - Enhanced flexibility wrt maneuver support
  - Quicker return to science after maneuvers
- **Main challenge #1: Sparse, weak, poorly characterized signal environment**
  - MMS Navigator acquires and tracks below 25dB-Hz (around -178dBW)
  - GEONS navigation filter runs embedded on the Navigator processor
  - Ultra stable crystal oscillator (Freq. Electronics, Inc.) supports filter propagation
- **Main challenge #2: Spacecraft are spin stabilized at 3 rpm with obstructions on top and bottom of spacecraft**
  - Four GPS antennas with independent front end electronics placed around perimeter achieve full sky coverage with low noise
  - Receiver designed to hand off from one antenna to next every 5s

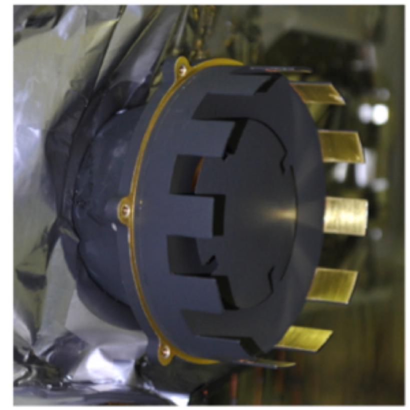
MMS Navigator GPS Hardware

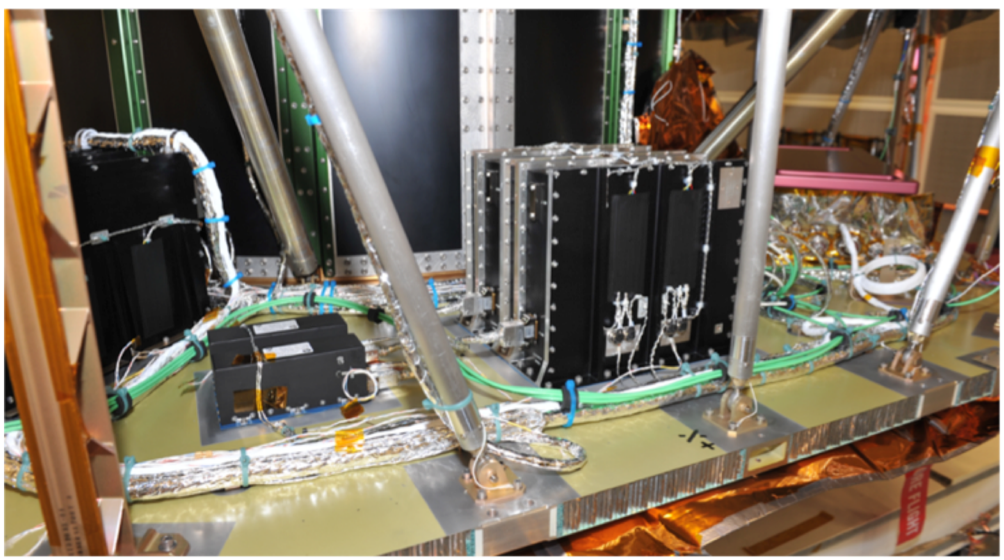
- GPS hardware all developed and tested at GSFC. Altogether, 8 electronics boxes, 8 USOs, 32 antennas and front ends.

Ultra Stable Osc.

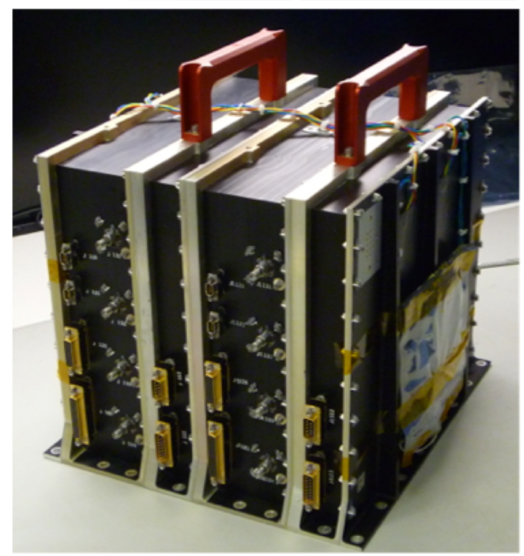
Front end electronics assembly

GPS antenna





Receiver and USO on spacecraft deck

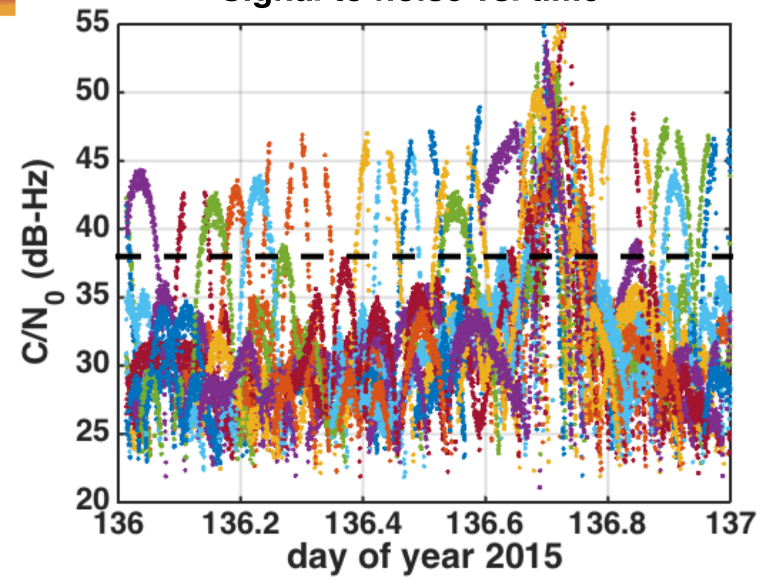


Redundant receiver electronics

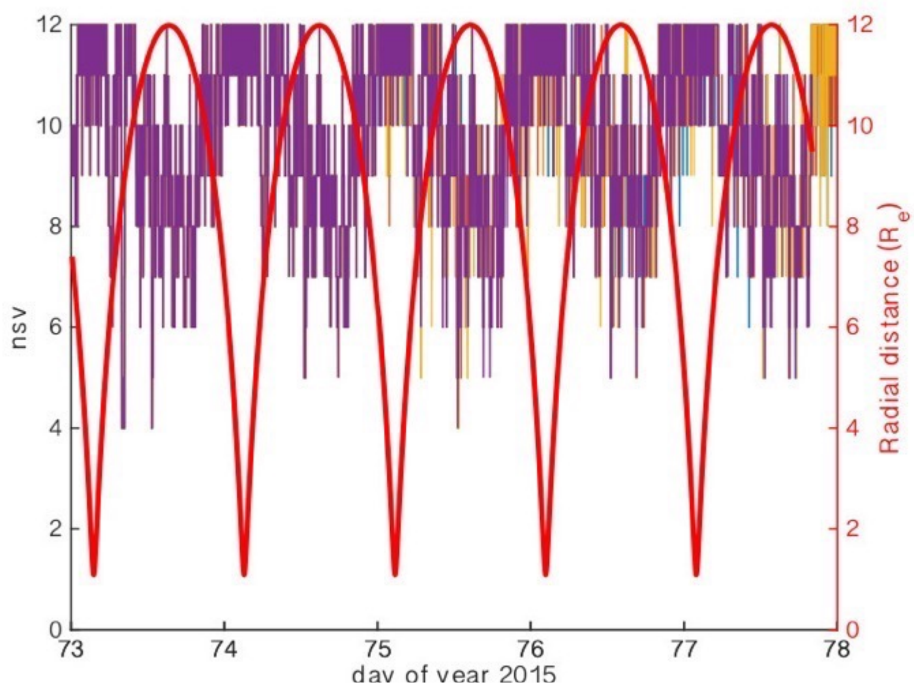
Phase 1 Performance: Signal Tracking

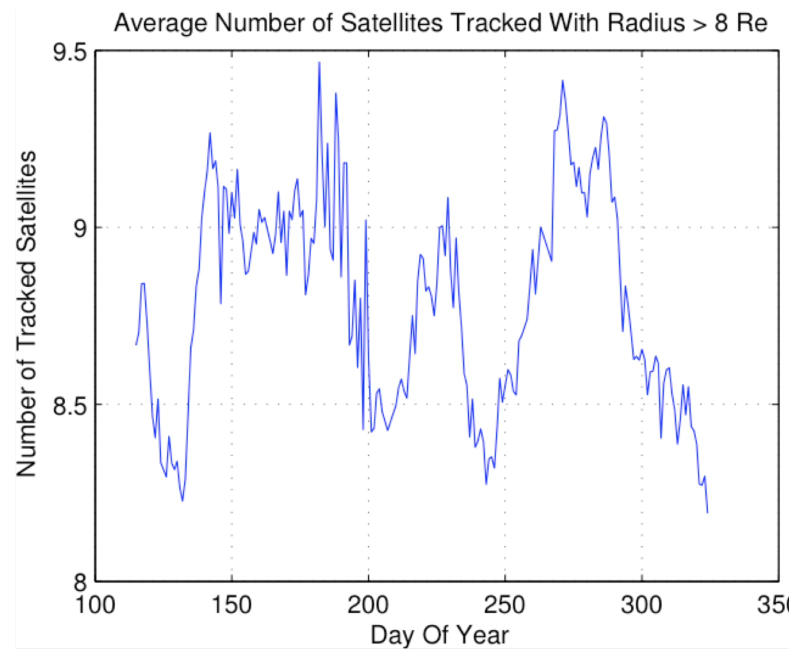
- Once powered, receiver began acquiring weak signals and forming point solutions
- Long term trend shows average of >8 signals tracked above $8R_E$
- Above GPS constellation, vast majority of these are sidelobe signals
- Visibility exceeded preflight expectations

Signal to noise vs. time



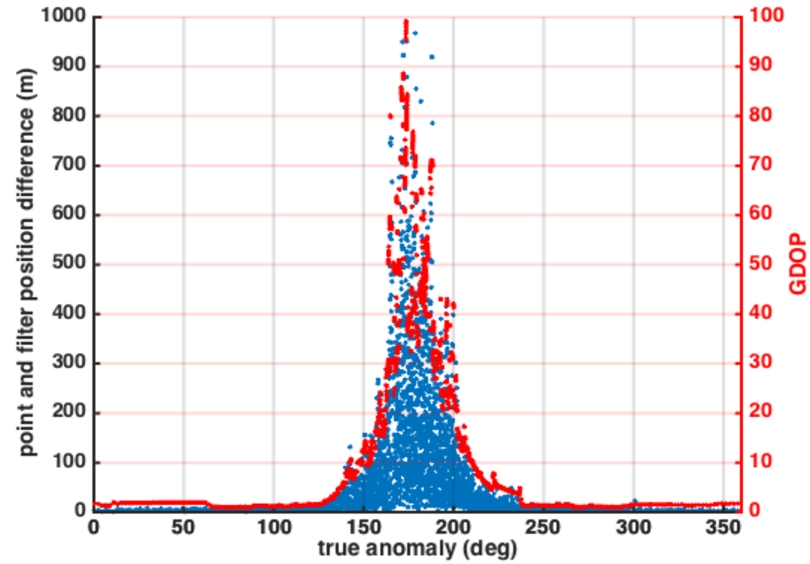
Signals tracked during first few orbits

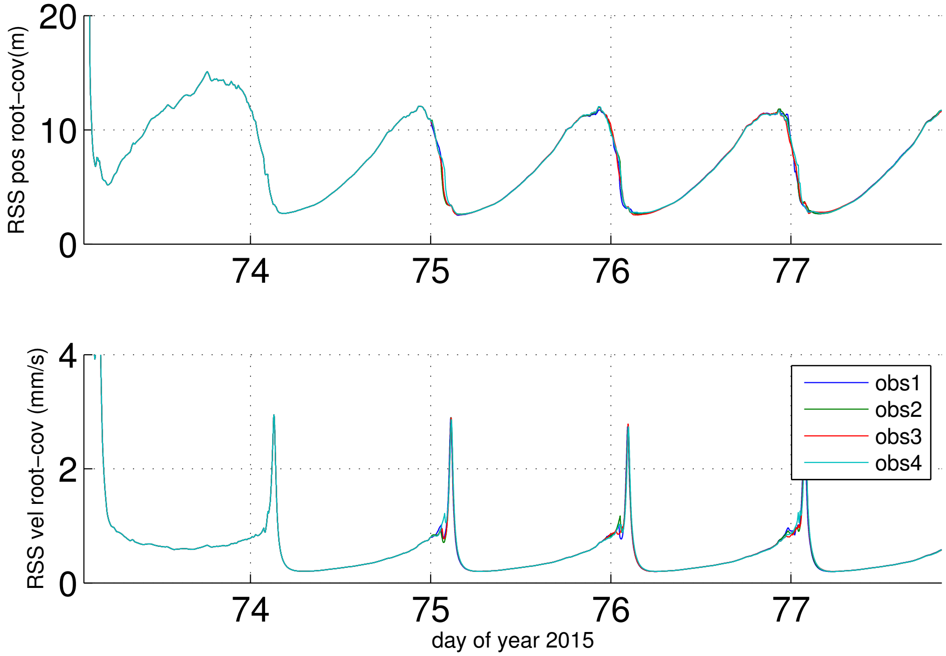


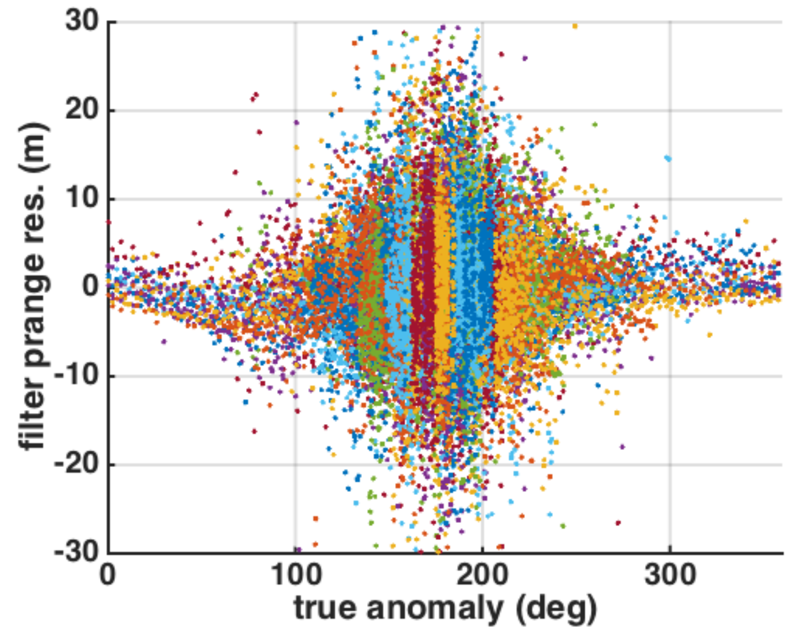


Phase 1 Results: Measurement and Navigation Performance

- GEONS filter RSS 1-sigma formal errors reach maximum of 12m and 3mm/s (typically <1mm/s)
- Although geometry becomes seriously degraded at apogee, point solutions almost continuously available
- Measurement residuals are zero mean, of expected variation. Suggests sidelobe measurements are of high quality.







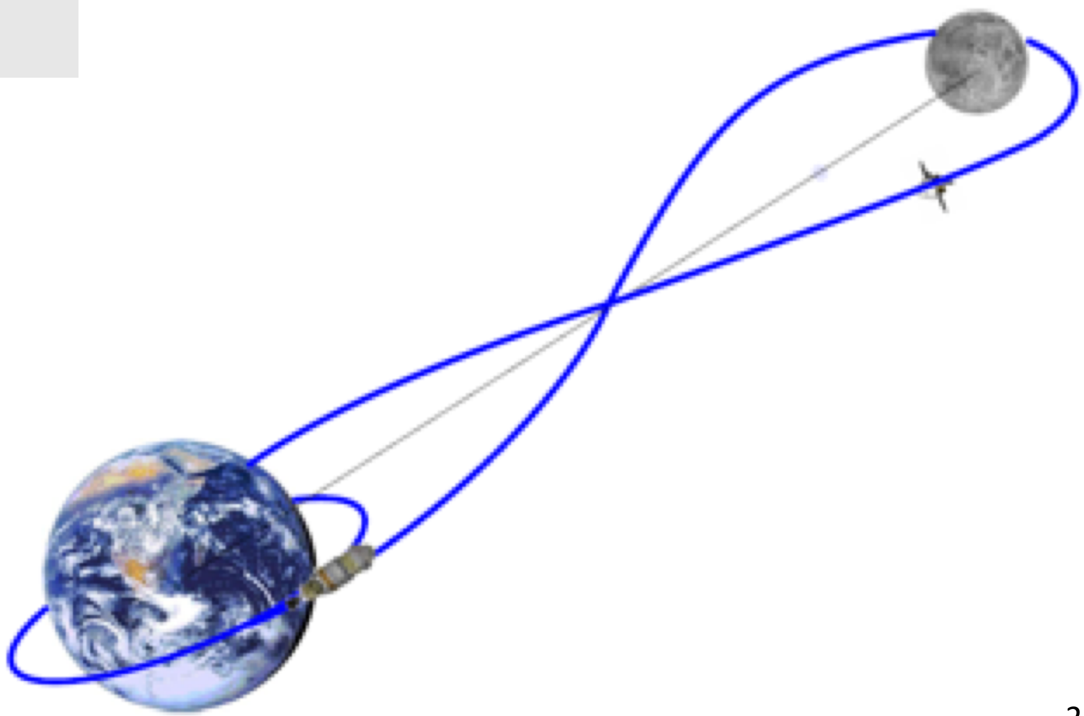
Phase 3 Lunar Case

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)

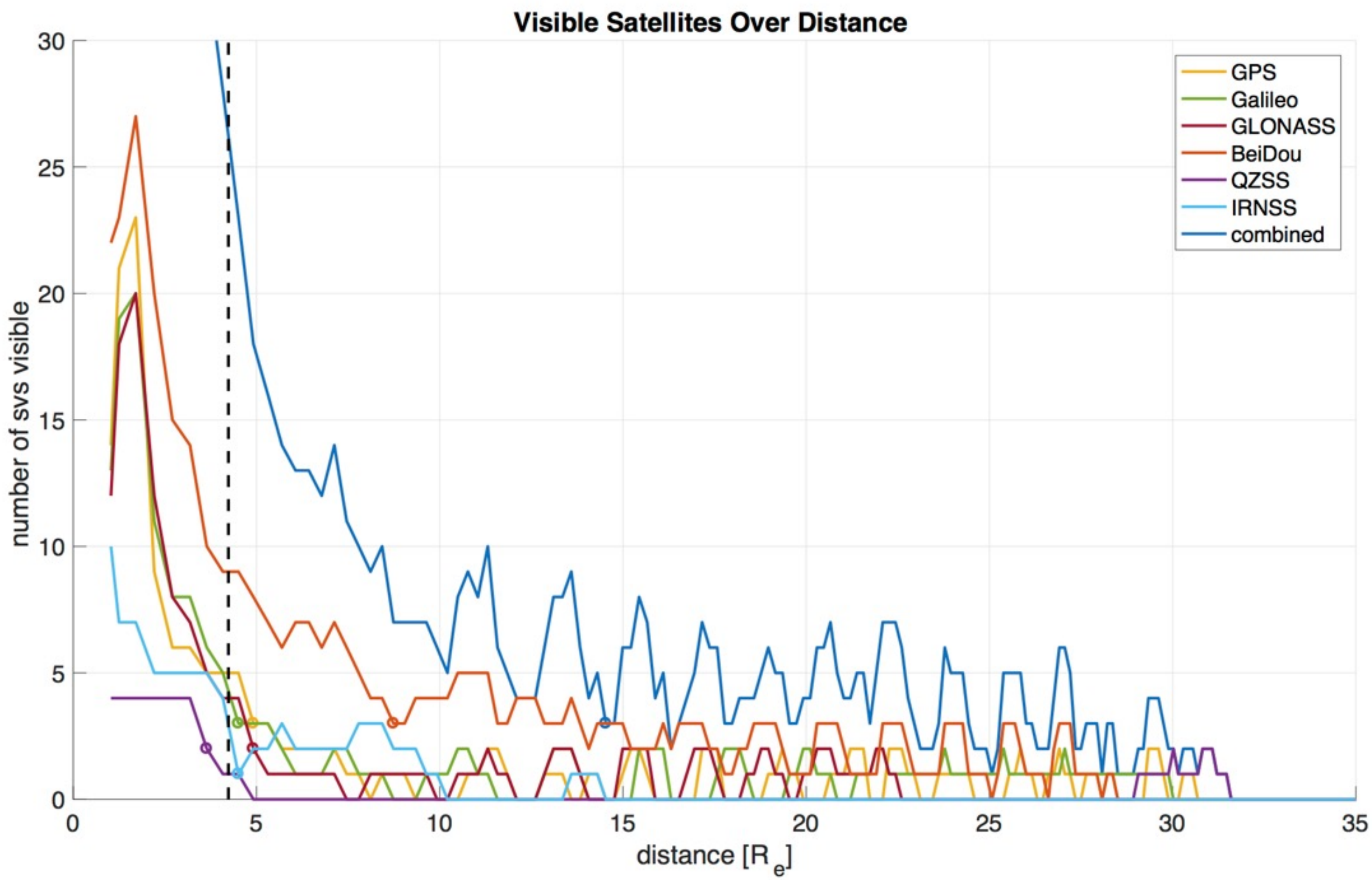
Status:

- NASA is lead for lunar case
- Specification complete
- NASA/ESA have completed implementation
- ESA comparing results



Phase 3 Lunar Case Results

- Metrics (same as HEO and GEO cases):
  - C/N_0, SV visibility over time/distance, Position Dilution of Precision (PDOP)



C/N_0 Over Distance