An Introduction to High-Altitude Space Use of GNSS (For Timing People)

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Timing Subcommittee
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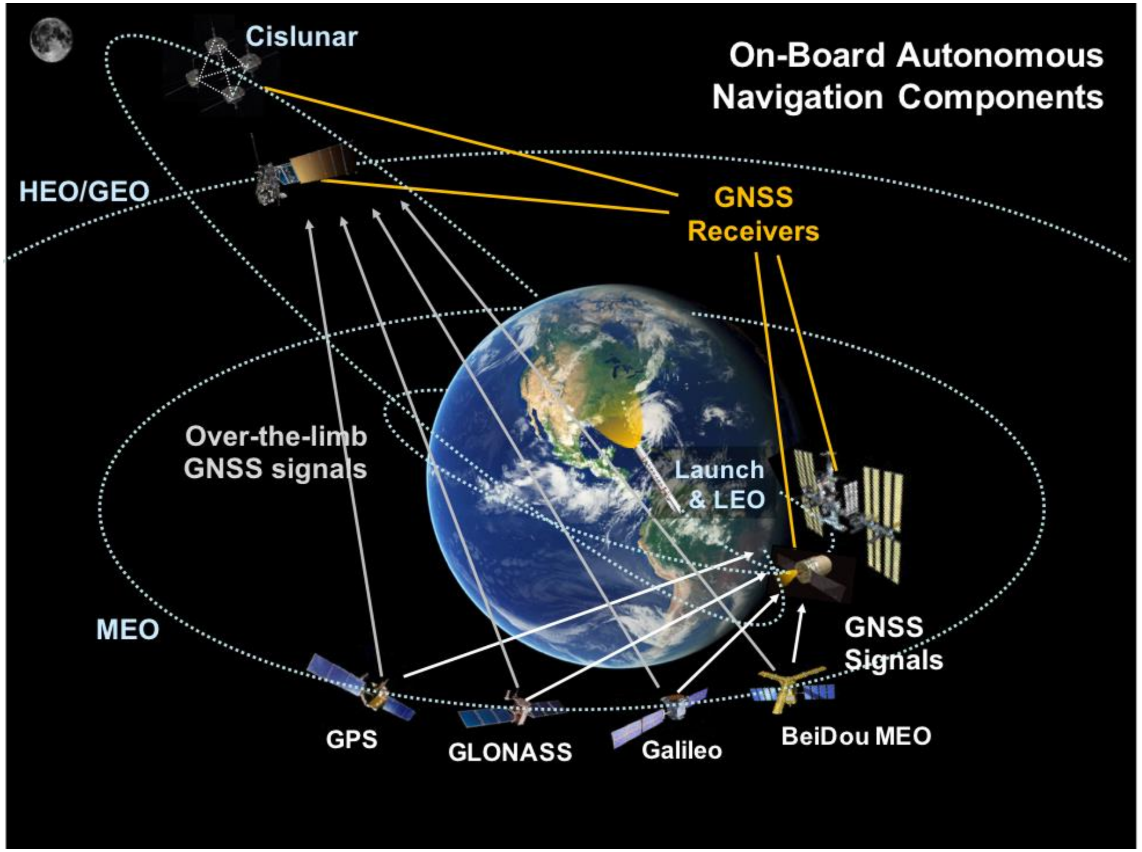
Space Uses of Global Navigation Satellite Systems (GNSS)

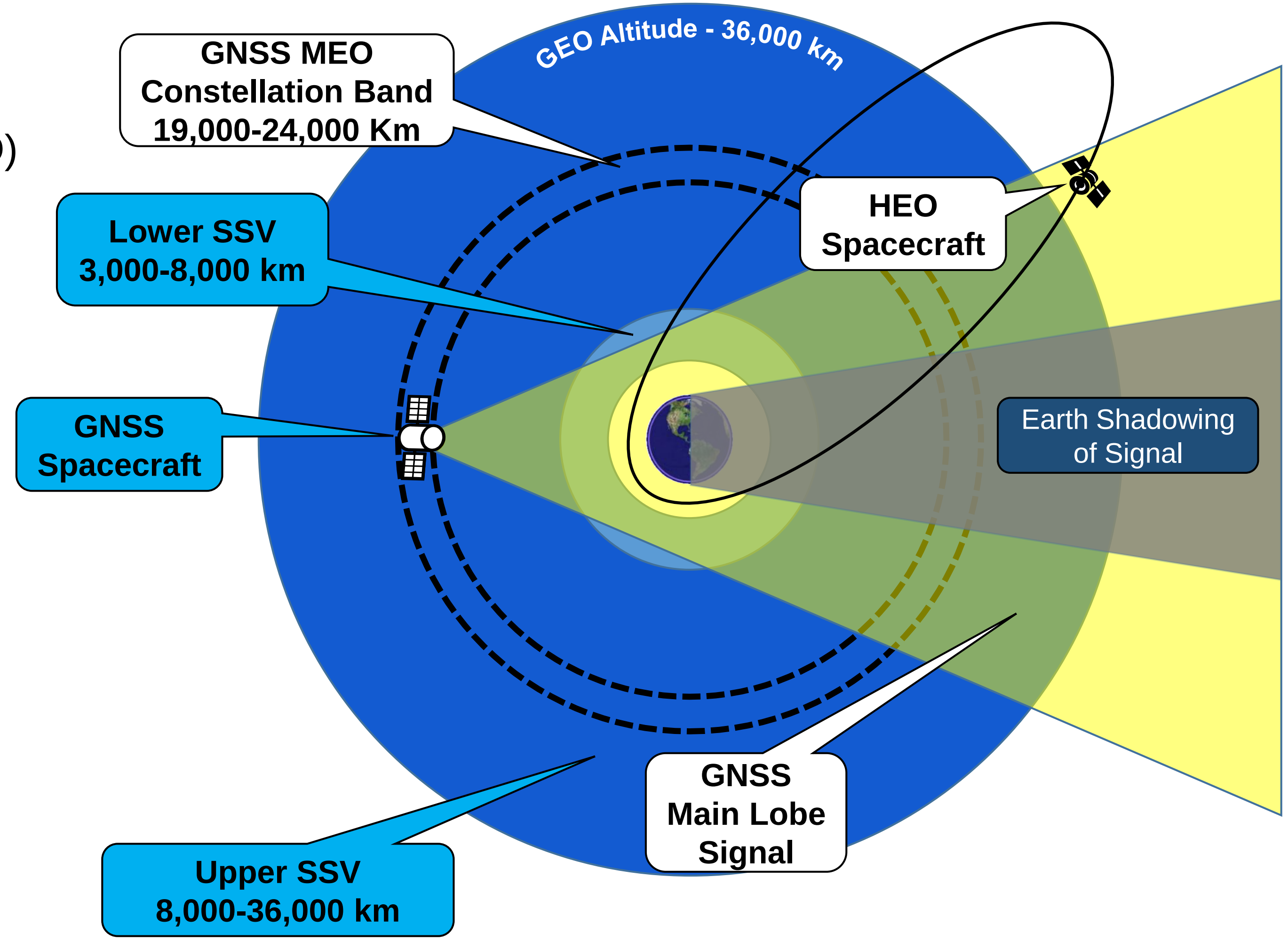
- **Real-time On-Board Navigation**: Precision formation flying, rendezvous & docking, station-keeping, Geosynchronous Orbit (GEO) satellite servicing
- **Earth Sciences**: GNSS as a measurement for atmospheric and ionospheric sciences, geodesy, and geodynamics
- **Launch Vehicle Range Operations**: Automated launch vehicle flight termination; providing safety net during launch failures & enabling higher cadence launch facility use
- **Attitude Determination**: Some missions, such as the International Space Station (ISS) are equipped to use GPS/GNSS to meet their attitude determination requirements
- **Time Synchronization: Support precise time-tagging of science observations and synchronization of on-board clocks**



Reception of High-Altitude GNSS Signals

- **Terrestrial Service Volume (TSV)**:
  - altitude ≤3,000 km
  - Covers terrestrial and low Earth orbit (LEO) users
- **Space Service Volume (SSV):**
  - **Lower SSV**: altitude 3,000–8,000 km
  - **Upper SSV**: altitude 8,000–36,000 km
  - Covers users near to and above GNSS constellations

- Signal coverage in the Upper SSV is achieved primarily via:
  - GNSS **main lobe "spillover"** signals
  - GNSS **side lobe** signals (not shown)

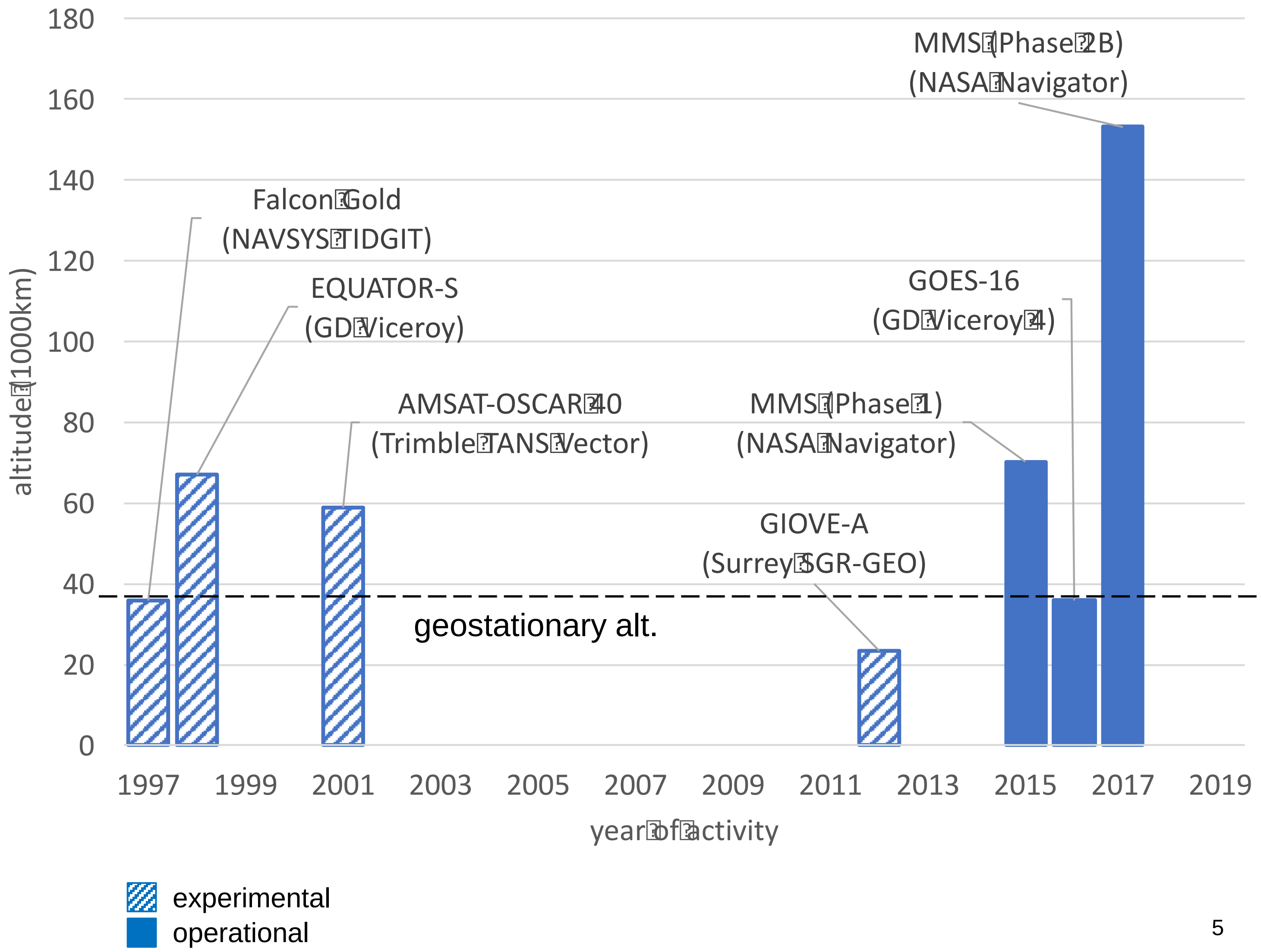


Operational Challenges

Regime	Altitude Range (km)	Challenges & Observations (Compared to previous scenario)	Mitigations	Operational Status
Terrestrial Service Volume	≤3,000	Acquisition & Tracking: Higher Doppler, faster signal rise/set; accurate ephemeris upload required; signal strength & availability comparable to Earth use	Development of space receivers; fast acquisition algorithm eliminates ephemeris upload	Extensive Operational use
Lower SSV	3,000–8,000	More GPS/GNSS signals available; highest observed Doppler (HEO spacecraft)	Max signals require omni antennas; receiver algorithms must track higher Doppler	Operational (US & foreign)
Upper SSV	8,000–36,000	Earth obscuration significantly reduces main lobe signal availability; frequent ops w/ <4 signals; periods of no signals; weak signal strength due to long signal paths	Navigation filter/fusion algorithms (e.g. GEONS) enable nav w/ <4 signals and flywheeling through outages; use of signal side lobes and/or other GNSS constellations; higher gained antennas, weak signal receivers	Operational (US & foreign)
Beyond the SSV	36,000–360,000+	Even weaker signals & worse signal geometry	Use higher gain, small footprint antenna; accept geometric performance degradation or augment with signals of opportunity to improve	Operational to 150,000 km (MMS), Orion Lunar perf. experiment

A History of High-Altitude GPS Users

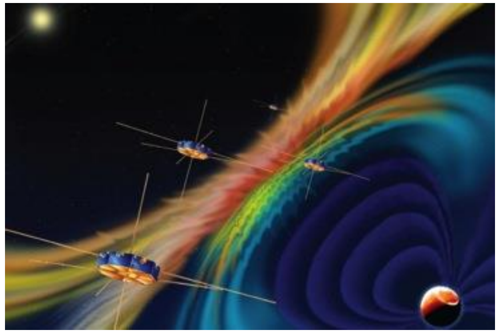
- **1990s**: Early flight experiments demonstrated basic feasibility – ***Equator-S***, ***Falcon Gold***
- **2000**: Reliable GPS orbit determination demonstrated at GEO employing a bent pipe architecture and ground-based receiver (Kronman 2000)
- **2001**: ***AMSAT OSCAR-40*** mapped GPS main and sidelobe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



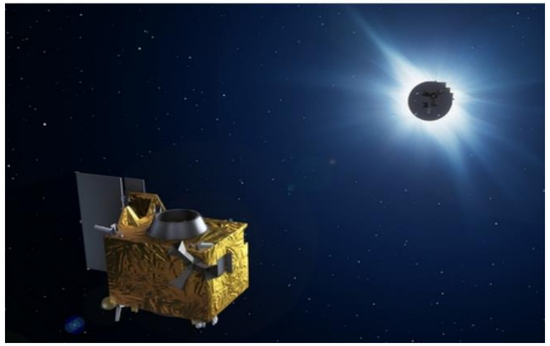
The Promise of using GNSS in the Space Service Volume

- GPS timing **reduces need for expensive on-board clocks** (from: $100sK-1M to: $15K–50K)
- Significantly **improves real-time navigation performance** (from: km-class to: meter-class)
- Supports **quick trajectory maneuver recovery** (from: 5-10 hours to: minutes)
- 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 Orbit (GEO) missions,** including:

Earth Weather Prediction using Advanced Weather Satellites

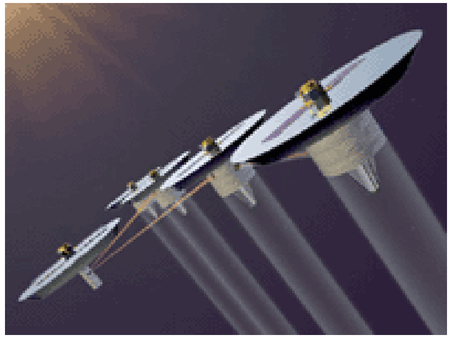


Space Weather Observations

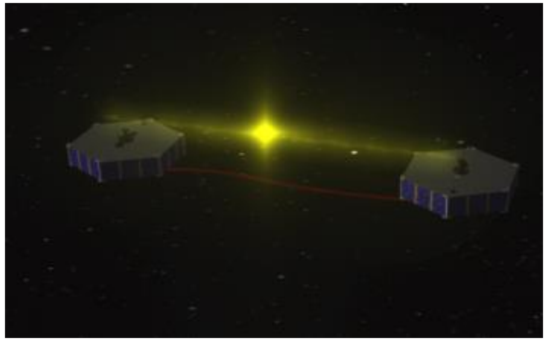


Precise Relative Positioning

Launch Vehicle Upper Stages & Beyond-GEO applications



Formation Flying, Space Situational Awareness (SSA), Proximity Operations

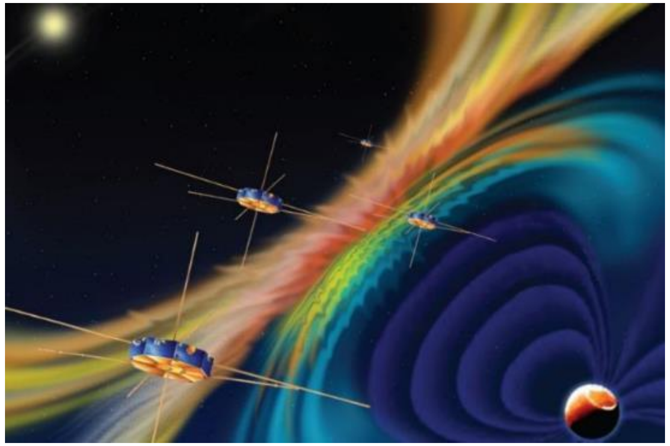


Precise Position Knowledge & Control at GEO

Using GPS above the GPS Constellation: NASA GSFC MMS Mission

Magnetospheric Multi-Scale (MMS)

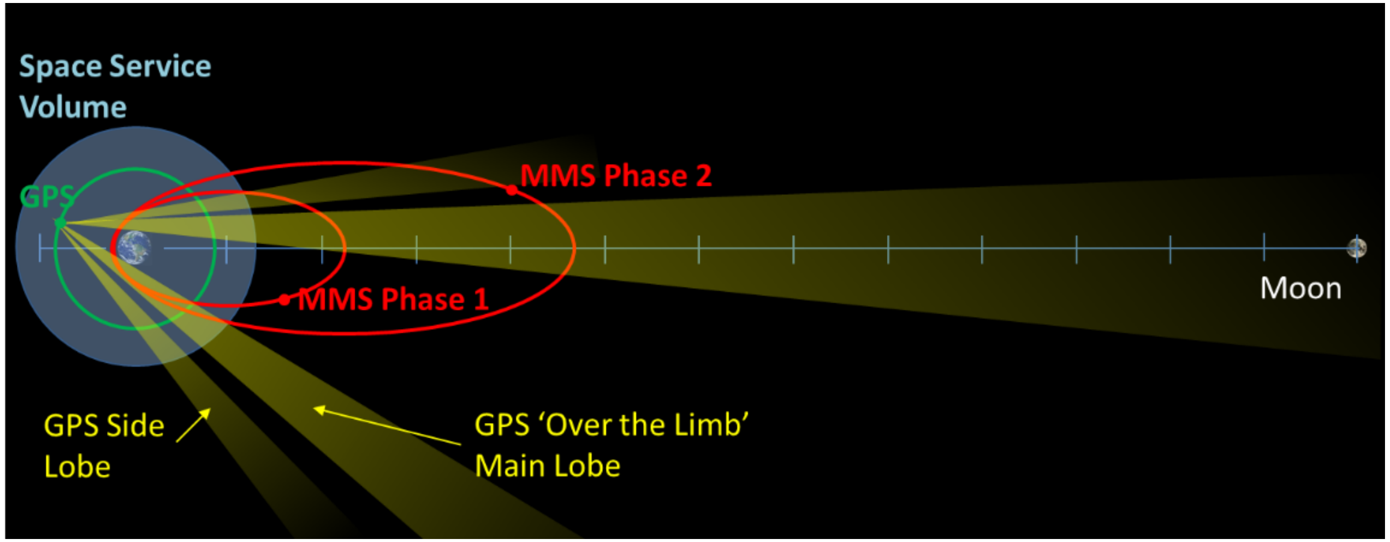
- Launched March 12, 2015
- Four spacecraft form a tetrahedron near apogee for performing magnetospheric science measurements (space weather)
- Four spacecraft in highly eccentric orbits
  - **Phase 1**: 1.2 x 12 Earth Radii (Re) Orbit (7,600 km x 76,000 km)
  - **Phase 2**: Extends apogee to 25 Re (~150,000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



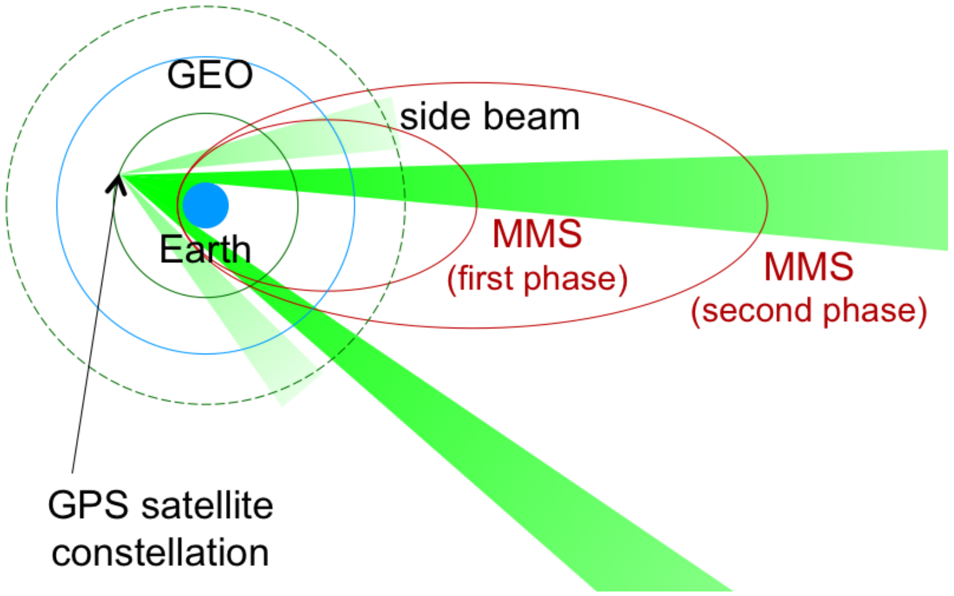
National Aeronautics and Space Administration

MMS Navigator GPS 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 Guiness world record for the highest-ever reception of signals and onboard navigation solutions by an operational GPS receiver in space
- At the lowest point of the MMS orbit Navigator set Guiness world for fastest operational GPS receiver in space, at velocities over 35,000 km/h



MMS Navigation & Clock



- **MMS baselined Goddard's high-altitude Navigator GPS receiver + GEONS Orbit Determination (OD) filter software as sole means of navigation (mid 2000's)**
  - Original design included crosslink, later descoped
  - In order to meet requirements without crosslink, a USO would be needed.
- **Main challenge:** Sparse, weak, poorly characterized signal 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.) is a key component that supports filter propagation
- **USO was specified to meet 100µs holdover over 65 hours under all environmental conditions**
  - Eventually the timing requirement was relaxed to 325us due to spare margin.

- Specific requirements were developed based on a simulation of the ability of the GEONS filter to estimate the USO behavior, and resulted in around a **5e-11 stability requirement (at 65hrs)** over all enveloping environmental conditions.

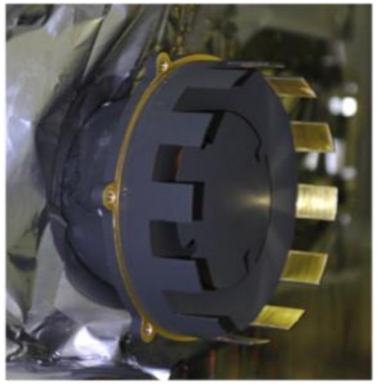
MMS Navigator GPS hardware

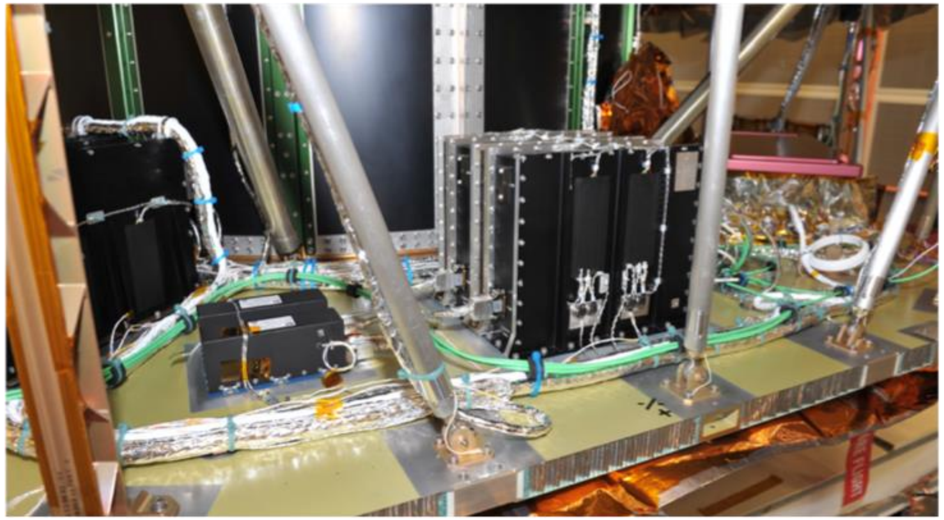
GPS hardware all developed and tested at GSFC. Altogether, 8 electronics boxes, 8 USOs, 32 antennas and front ends

Ultra Stable Osc.

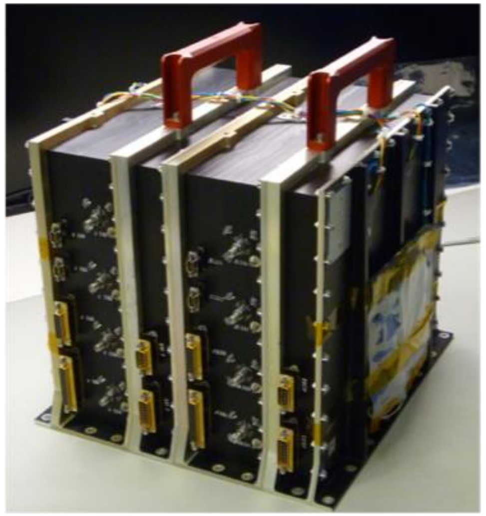
Front end electronics assembly

GPS antenna



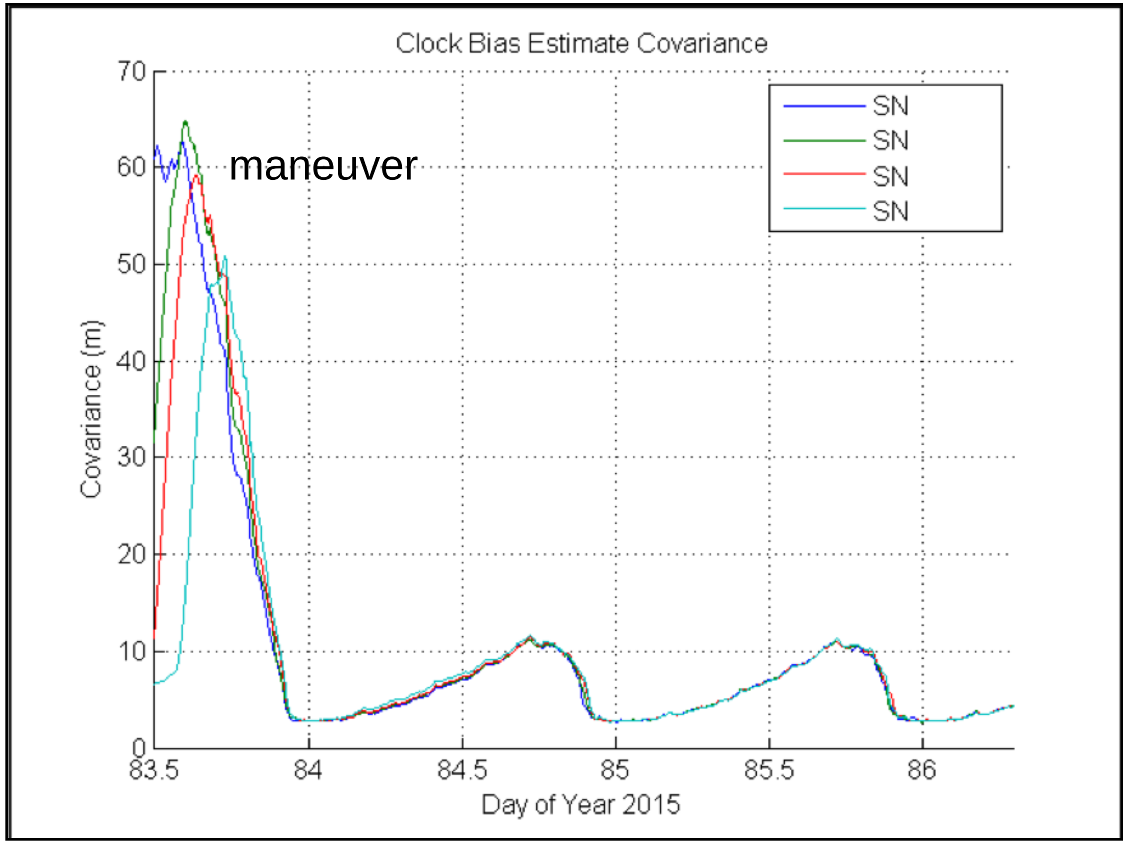


Receiver and USO on spacecraft deck

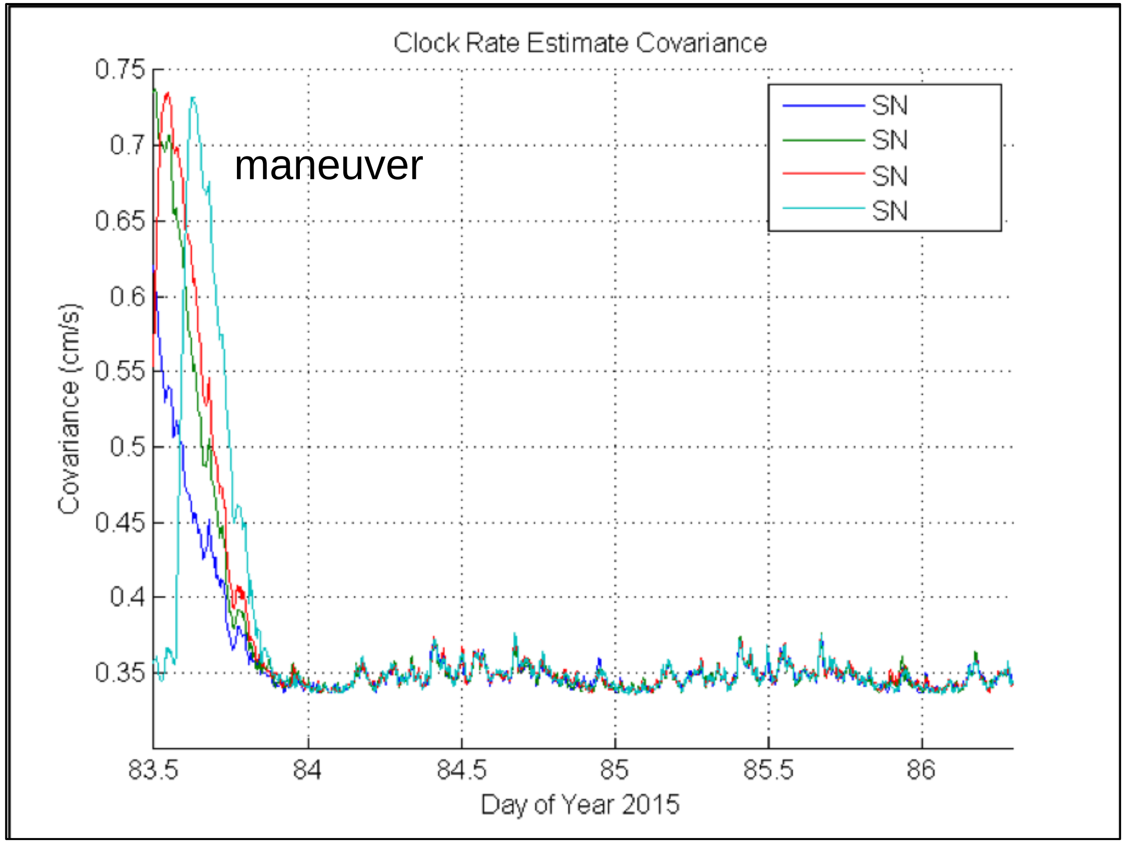


Redundant receiver electronics

On-orbit Phase 1 results: Clock Performance



- Filter is able to estimate clock bias to within 15m (or about 50ns)
- Rapid clock reconvergence after maneuvers

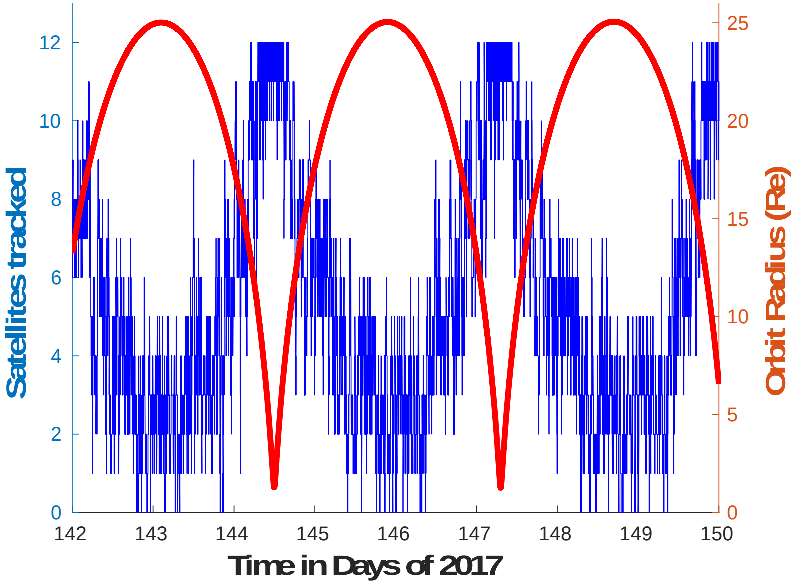


- Filter is able to estimate clock rate to within 4mm/s or about 1e-11 fractional frequency
- Precise estimation across all oscillators

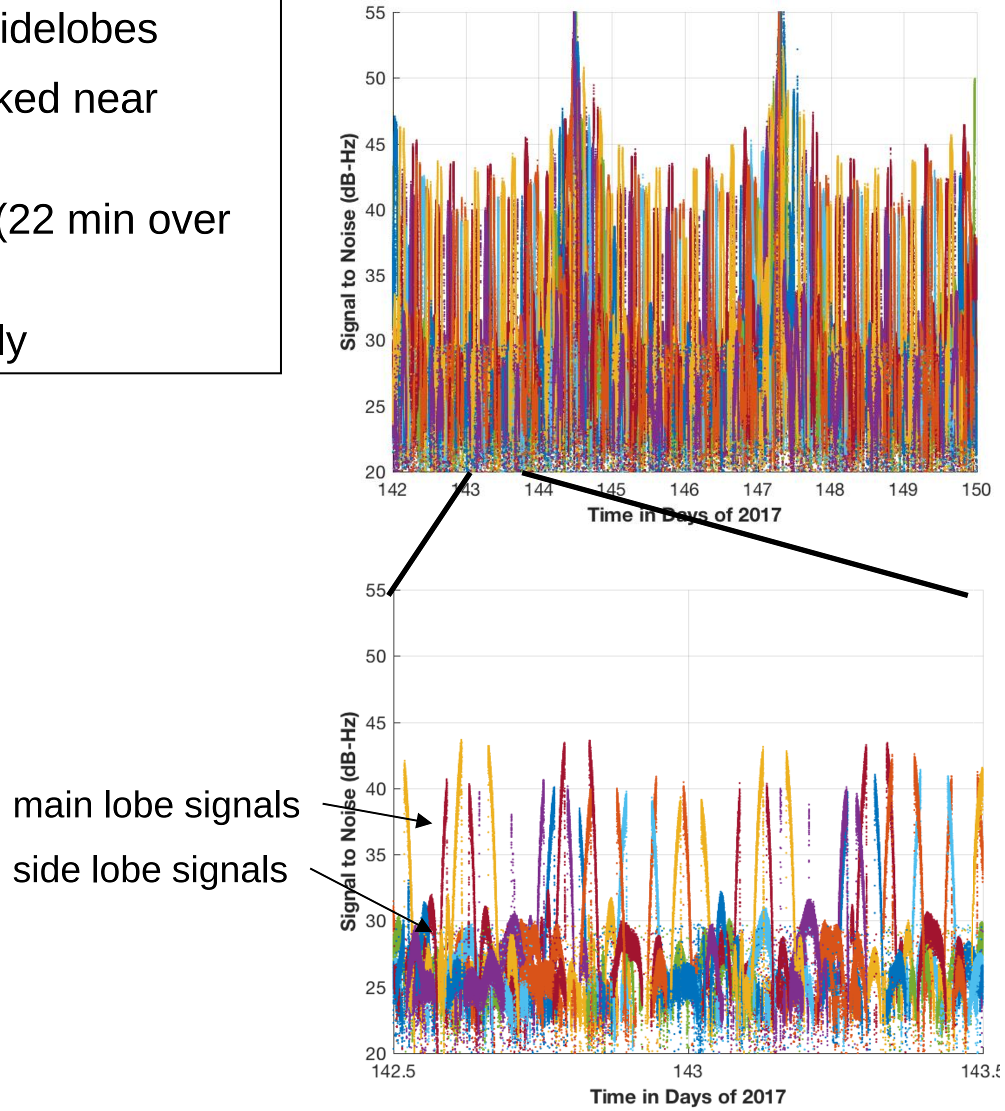
On-orbit Phase 2B results: signal tracking

- Consider 8-day period early in Phase 2B (150k km apogee)
- Above GPS constellation, majority of signals are sidelobes
- Long term trend shows average of ~3 signals tracked near apogee, with up to 8 observed.
  - Cumulative outage over sample orbit: 0.5% (22 min over 67-hour orbit); average duration: 2.8 min
- Visibility exceeds preflight expectations significantly

Signals tracked



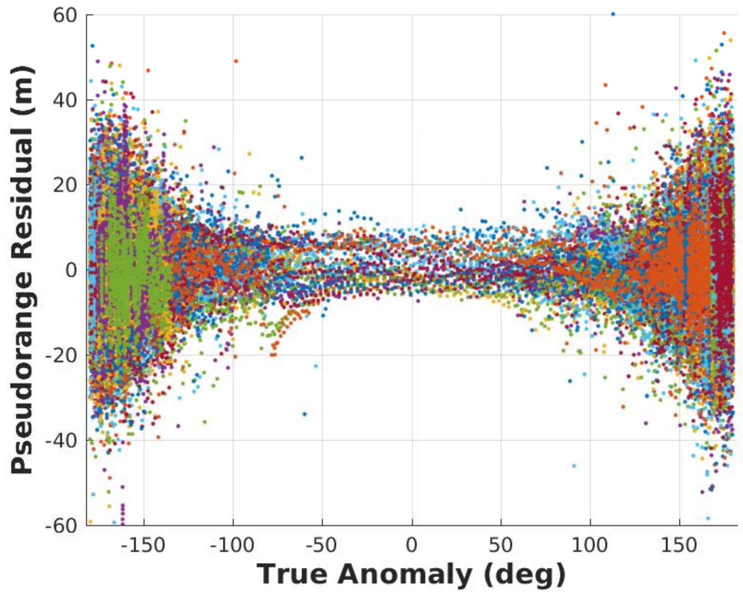
C/N_0 vs. time, near apogee



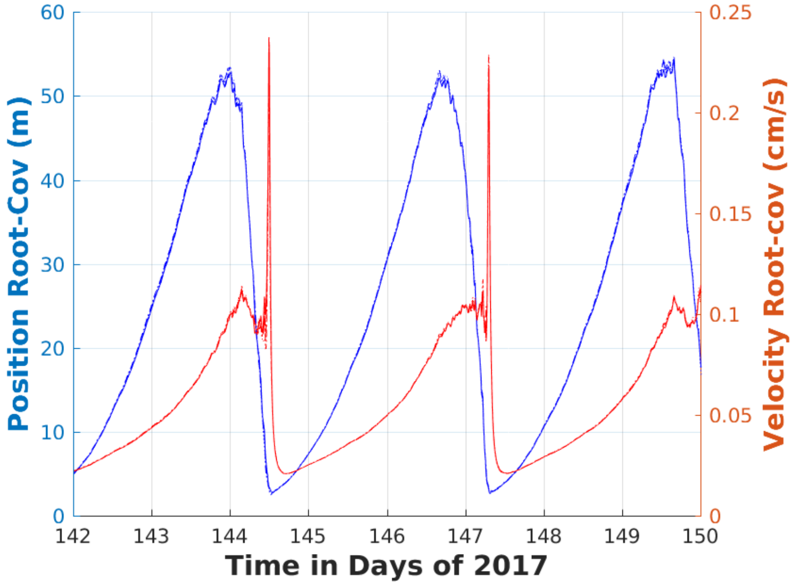
On-orbit Phase 2B results: measurement/nav performance

- GEONS filter RSS 1-sigma formal errors reach maximum of ~50m and briefly 5mm/s (typically <1mm/s)
- As apogee increases, range and clock errors become highly correlated; seen in pos/clock covariances below
  - 50m corresponds to 167ns clock bias

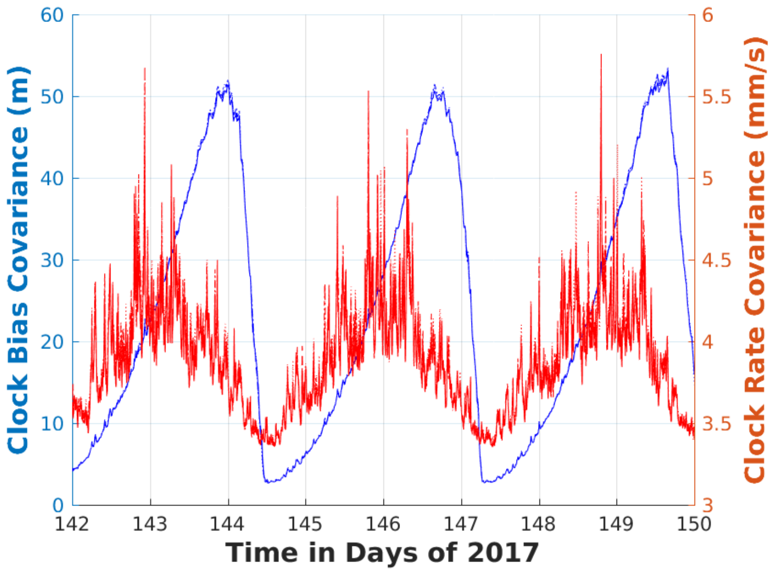
Pseudorange residuals



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



Filter formal clock errors (1σ root cov)

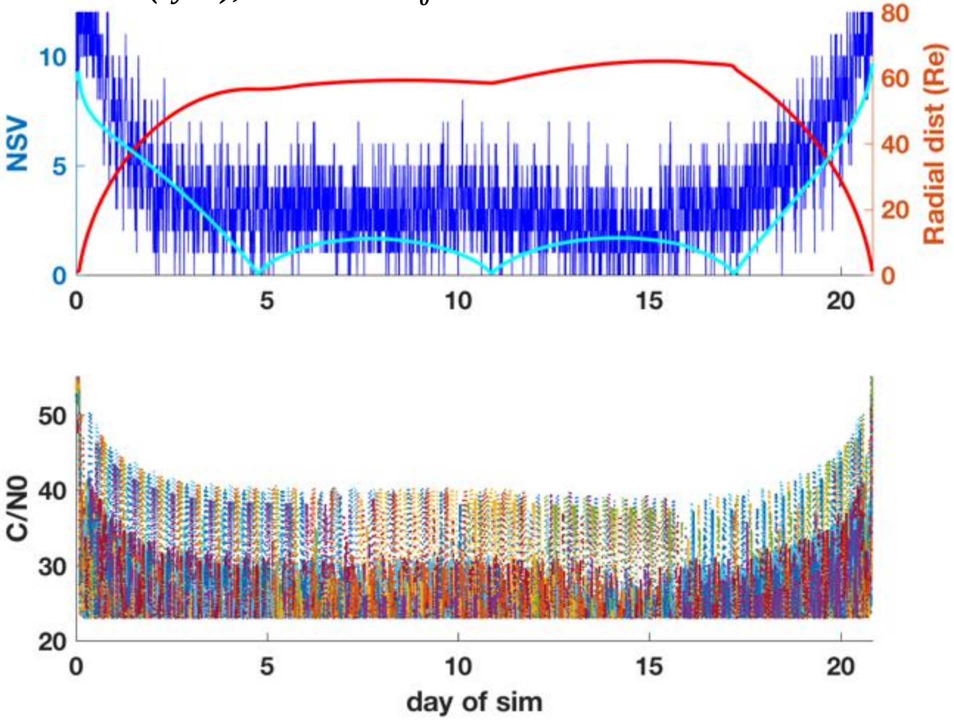


Measurement residuals (above) are zero mean, of expected variation <10m 1-sigma. Suggests sidelobe measurements are of high quality.

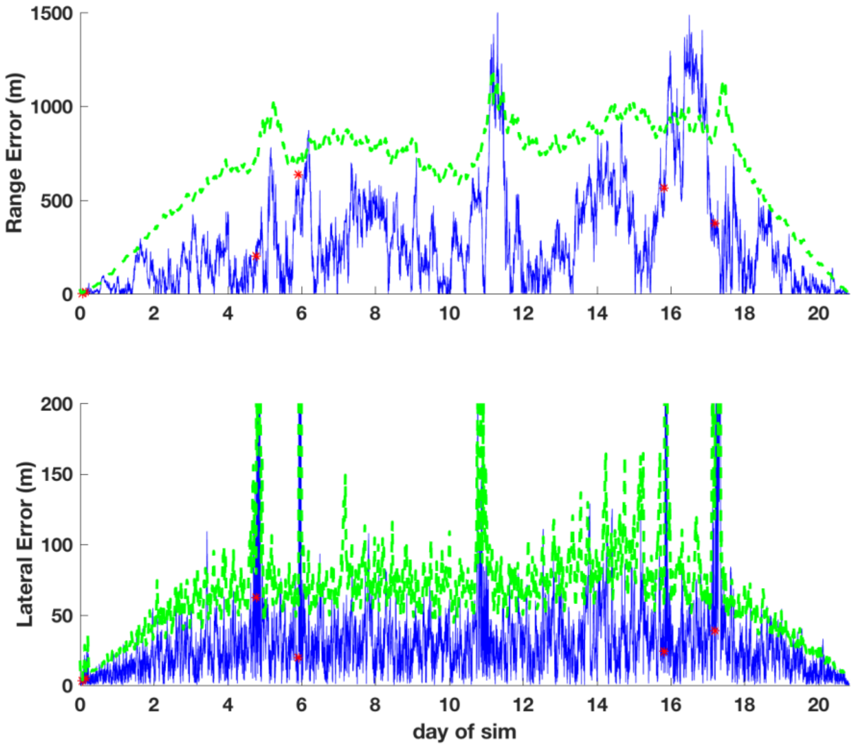
MMS study: Concept Lunar mission

- **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 GEONS filter.**
- **Visibility similar to MMS2B, as high-gain makes up for additional path loss**
  - Avg visibility: ~3 SVs; C/N0 peaks > 40dB-Hz (main lobes) or > 30 dB-Hz (side lobes)
- **Range/clock-bias errors dominate – order of 1-2 km (3–7 μs); lateral errors 100-200 m**
  - With atomic clock, or, e.g., periodic 2-way range/Doppler, could decorrelate and reduce range errors to meas. noise level
  - Additional (independent) measurement source breaks range/clock bias ambiguity

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



Filter position formal (3σ) and actual errors



Next Steps: Multi-GNSS

International Committee on Global Navigation Satellite Systems

- **Multi-GNSS usage at high altitude promises to widely expand the availability of GNSS signals for navigation and timing.**
- Efforts through the UN International Committee on GNSS (ICG) seek to establish and develop the **combined Multi-GNSS SSV.**
- Efforts underway include:
  - **SSV Booklet Development**
    - » Documents and publishes SSV performance metrics for each individual constellation
    - » Includes internationally coordinated SSV analyses and simulations
    - » Communicates assumptions & analysis results
    - » Supports international space user characterization of PNT performance in SSV
    - » Booklet final draft distributed to ICG and providers for final approval; planned publication: Nov 2018
  - **Companion SSV Outreach Video** being produced by NASA on behalf of ICG
  - **Coordinated Outreach Initiative** to communicate capabilities of SSV to future SSV users
  - **ICG-approved Recommendation to examine use of GNSS SSV for exploration activities in cis-Lunar space**

Conclusions

- **High-altitude space use of GNSS is an emerging operational capability**
    - Latest operational examples include: GOES-16, MMS
    - Applications extend both to navigation and timing
- **Signal availability is key to both timing and navigation**; nearly-continuous availability of signals enables benefits for time synchronization, clock bias estimation, maneuver recovery, etc.
- **MMS on-orbit performance exceeds requirements and expectations**; predictions show that good performance may be extendable to lunar distance.
    - Breaking the range & clock bias ambiguity will be key to increased performance at increasingly high altitudes
    - High-quality clock OR periodic independent range measurement are potential solutions
- **Future performance increases** will be achieved via advanced receivers and the move to multi-GNSS. This is enabled by work via the UN International Committee on GNSS (ICG).
- For more:
    - Attend “The Navigation of Satellites” session, Thursday PM at ION GNSS+
    - See References, next chart

References

- **MMS**
  - Winternitz, Luke B., et al., “Global Positioning System Navigation Above 76,000 km for NASA's Magnetospheric Multiscale Mission,” https://ntrs.nasa.gov/search.jsp?R=20160011975
  - Winternitz, Luke B., et al., “New High-Altitude GPS Navigation Results from the Magnetospheric Multiscale Spacecraft and Simulations at Lunar Distances,” https://ntrs.nasa.gov/search.jsp?R=20170009487

- **GOES-16**
  - Chapel, J., et al., “In-Flight Guidance, Navigation, and Control Performance Results for the GOES-16 Spacecraft,” GNC 2017: 10th International ESA Conference on Guidance, Navigation & Control Systems, Salzburg, Austria, May 2017
  - Concha, M., et al., “Performance Characterization of GOES-R On-Orbit GPS Based Navigation Solution,” AAS Guidance and Control Conference 2017, Feb 2017, Breckenridge, CO, AAS Paper 17-138
  - Winkler, A., et al., “GPS Receiver OnOrbit Performance for the GOES-R Spacecraft,” GNC 2017: 10th International ESA Conference on Guidance, Navigation & Control Systems, Salzburg, Austria, May 2017

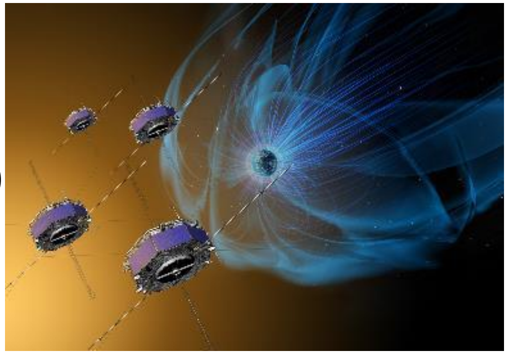
- **General**
  - Ashman, Benjamin W., et al., “Exploring the Limits of High Altitude GPS for Future Lunar Missions,”, https://ntrs.nasa.gov/search.jsp?R=20180001247
  - Ashman, Benjamin W., et al., “GPS Operations in High Earth Orbit: Recent Experiences and Future Opportunities,” https://ntrs.nasa.gov/search.jsp?R=20180003360

BACKUP

U.S. Initiatives & Contributions to Develop & Grow a High-Altitude GNSS Capability for Space Users

Operational Users

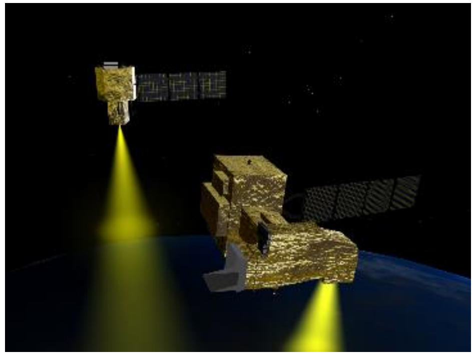
- MMS
- GOES-R, S, T, U
- EM-1 (Lunar enroute)
- Satellite Servicing



Operational Use Demonstrates Future Need

Space Flight Experiments

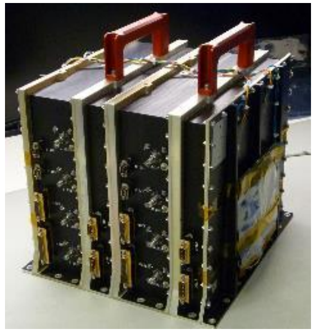
- Falcon Gold
- EO-1
- AO-40
- GPS ACE
- EM-1 (Lunar vicinity)



Breakthroughs in Understanding; Supports Policy Changes; Enables Operational Missions

SSV Receivers, Software & Algorithms

- GEONS (SW)
- GSFC Navigator
- General Dynamics
- Navigator commercial variants (Moog, Honeywell)



Develop & Nurture Robust GNSS Pipeline

SSV Policy & Specifications

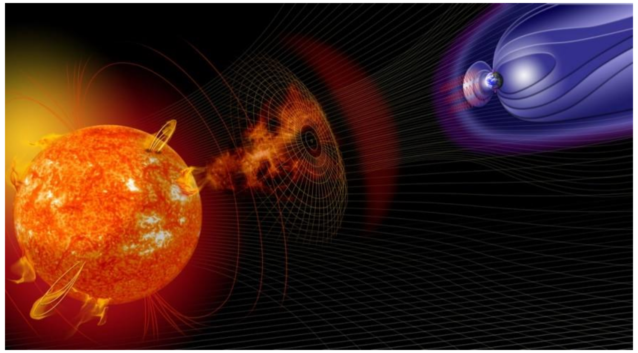
- SSV definition (GPS IIF)
- SSV specification (GPS II
- ICG Multi-GNSS SSV common definitions & analyses

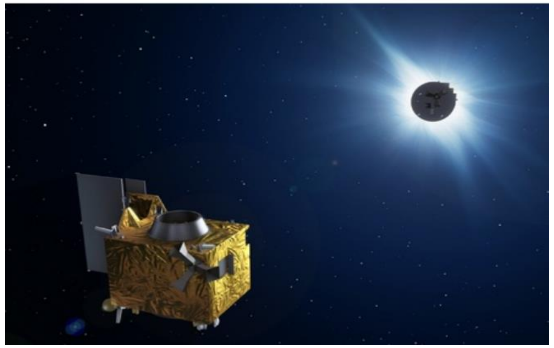
Operational Guarantees Through Definition & Specification

The Promise of using GNSS beyond the Space Service Volume

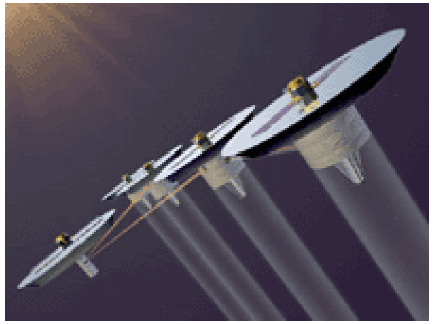
- GPS timing **reduces need for expensive on-board clocks** (from: $100sK-1M to: $15K–50K)
- **Supports real-time navigation performance** (from: no real time to: km or ten meter-class)
- Supports **quick trajectory maneuver recovery** (from: 5-10 hours to: minutes)
- **Near-continuous navigation signals reduces DSN navigation support**
- **Increased satellite autonomy & robotic operations**, lowering ops costs (savings up to $500-750K/year)
- Supports vehicle autonomy, new/enhanced capabilities and better performance for Cis-Lunar & Gateway **mission scenarios,** including:

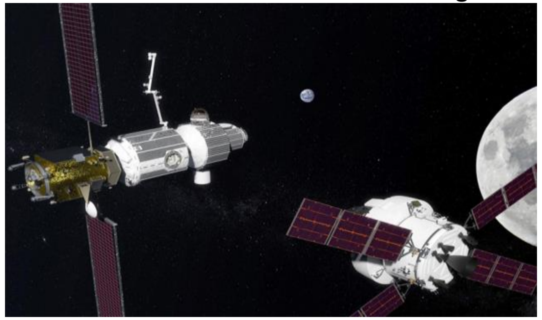

Earth Observations beyond GEO


Space Weather Observations


Precise Relative Positioning


Launch Vehicle Upper Stages & Cislunar applications


Formation Flying, Space Situational Awareness, Proximity Ops


Lunar Orbiting Platform-Gateway Human & Robotic Space Applications

Some key USO derived requirements

- Hadamard deviation

    1 second ………. 1E-11

    30 seconds ……. 2E-12

    6 hours …………. 7.07E-12

    24 hours ……….. 1.41E-11

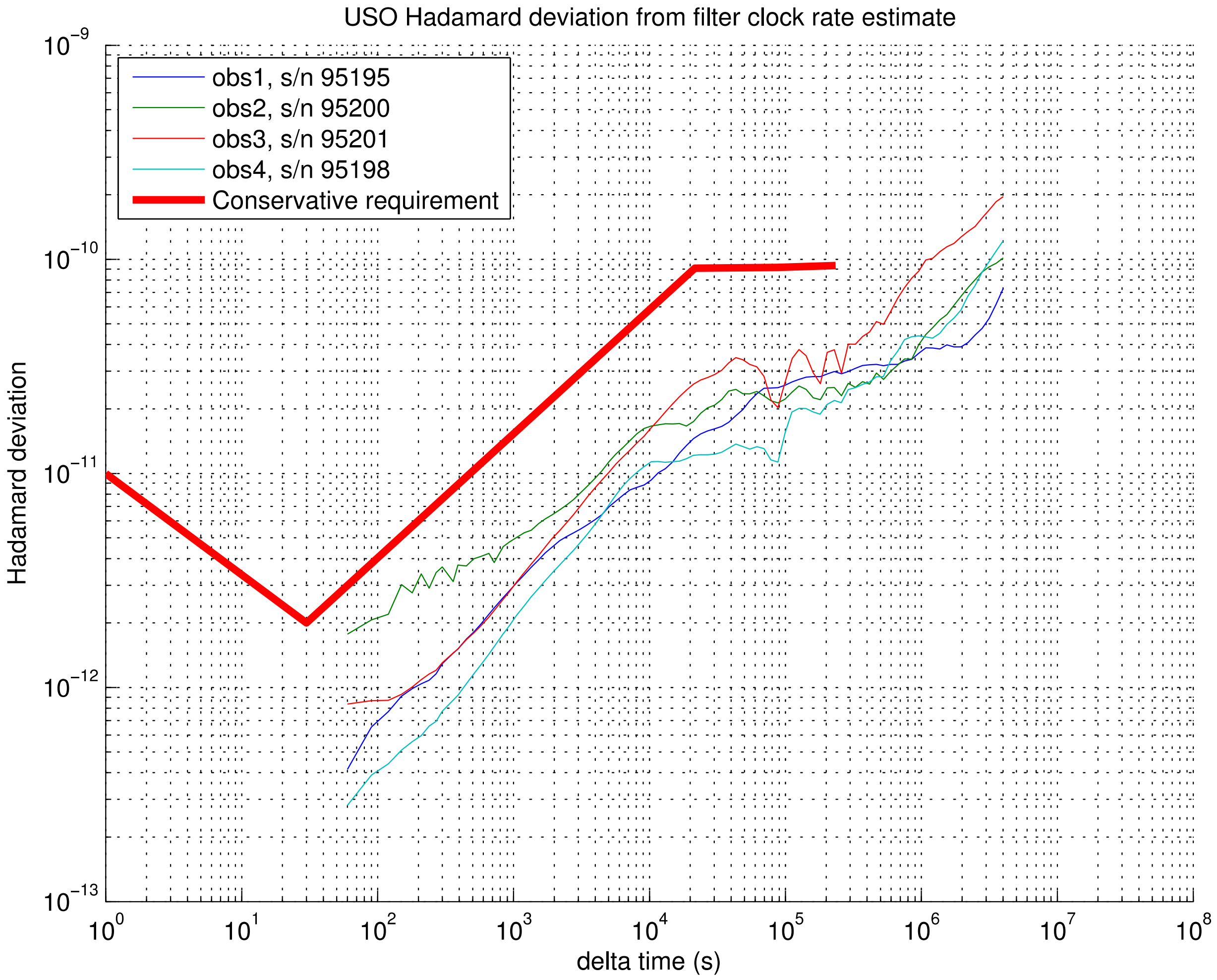
    65 hours ……….. 2.32E-11

- The USO frequency stability vs. incremental temperature change shall be within 3.0E-11 per degree C, across the proto-flight temperature range.
- The USO frequency stability vs. magnetic field intensity shall be within ± 1E-11 for magnetic field intensities of ± 0.5 Oersted.
- USO frequency aging after 30 days within ± 5E-11/day.
- Other requirements covered stability over comprehensive environmental effects: acceleration, pressure, aging, supply voltage, impedance, etc.

Total USO Hadamard deviation

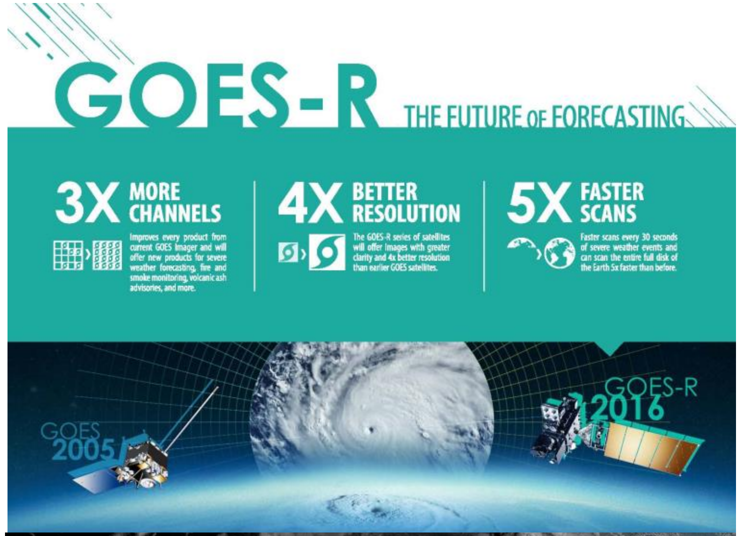
- Measured through filter clock rate estimate.
- Requirement line shown is lab Hadamard deviation requirement with 3C temp change and 0.5T magnetics stability req. RSS'd in for intervals >6hrs

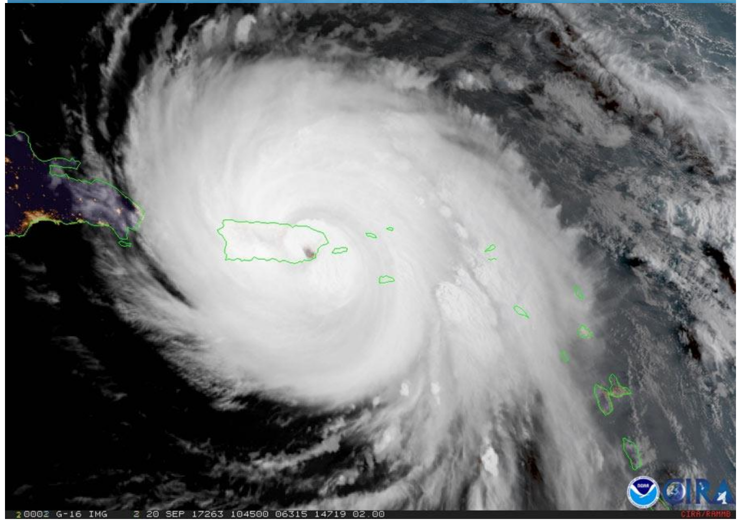
  Covers rough expected environment change over those periods



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: March 1 2018
- 15 year life, series operational through mid-2030s
- Employs GPS at GEO to meet stringent navigation requirements
- Relies on beyond-spec GPS sidelobe signals to increase SSV performance
- Collaboration with the USAF (GPS) and ICG (GNSS) expected to ensure similar or better SSV performance in the future
- NOAA also identifies **EUMETSAT (EU) and Himawari (Japan) weather satellites** as reliant on increased GNSS signal availability in the SSV

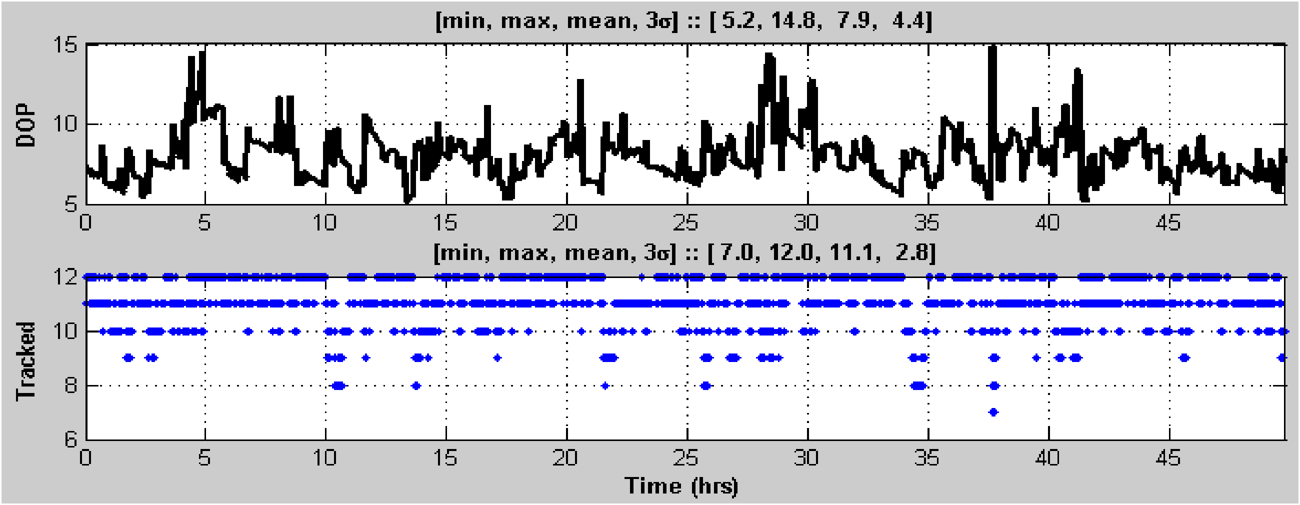




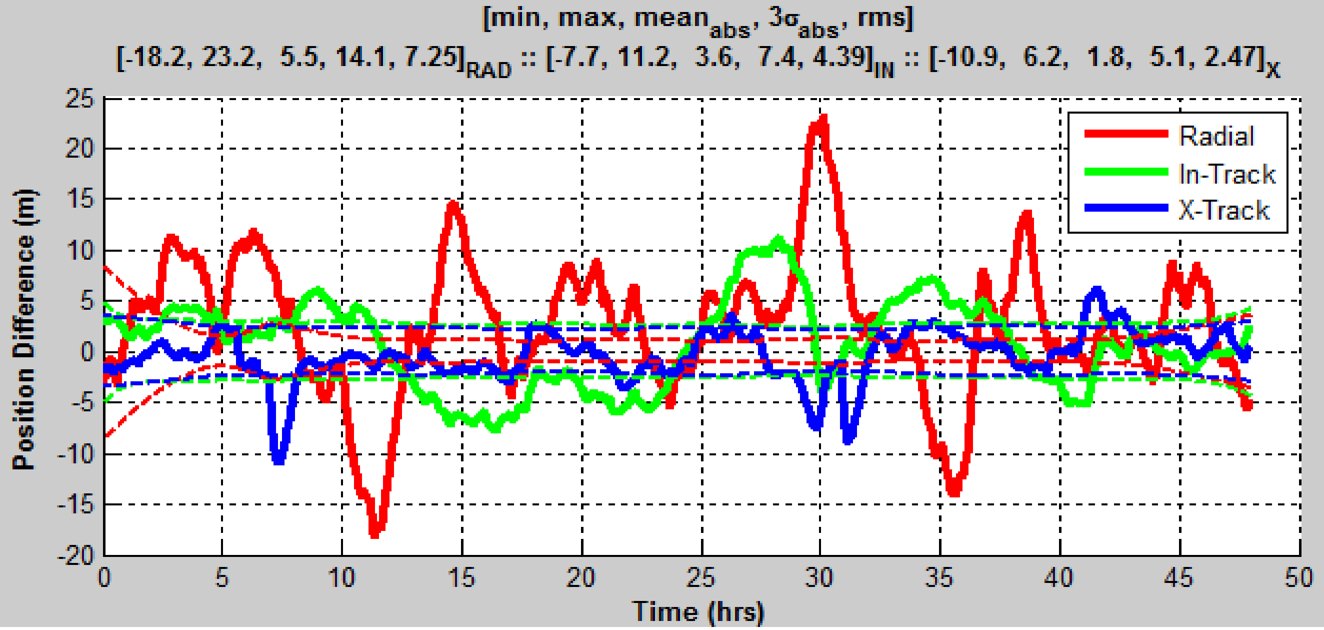
GOES-16 Image of Hurricane Maria Making Landfall over Puerto Rico

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 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



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.