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

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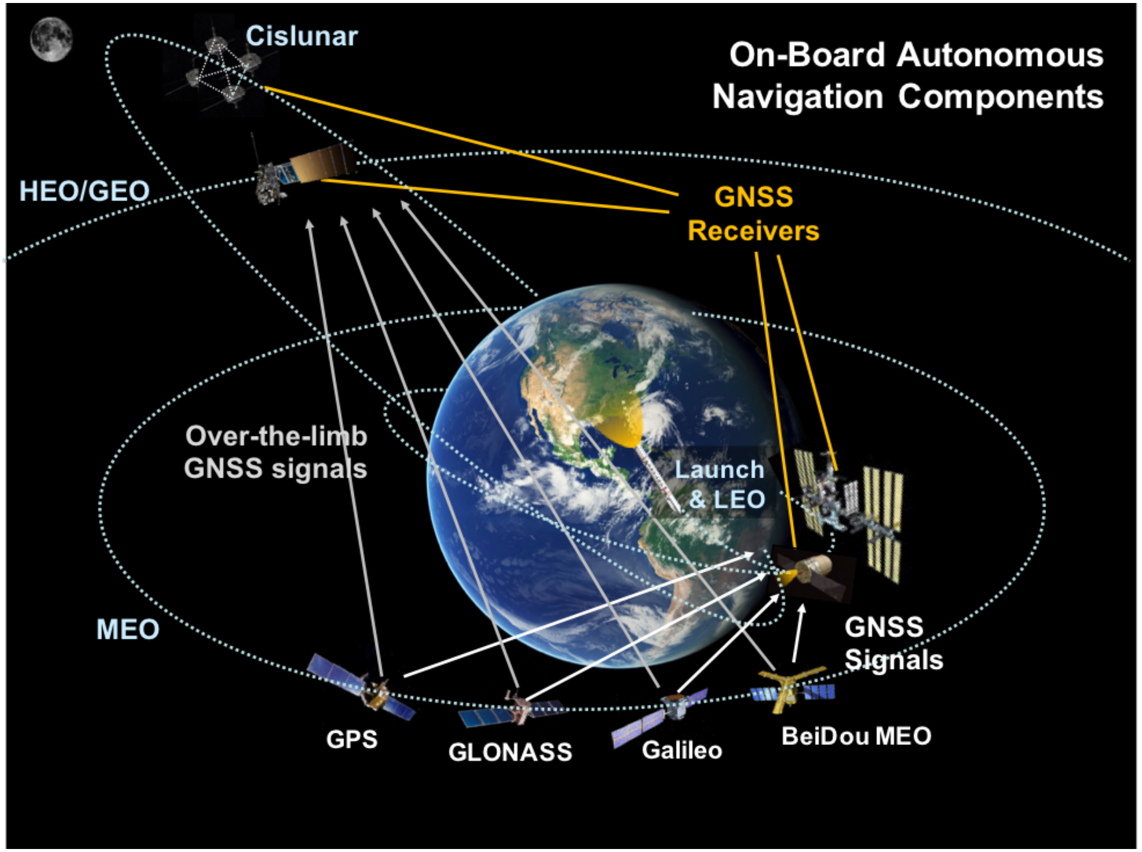
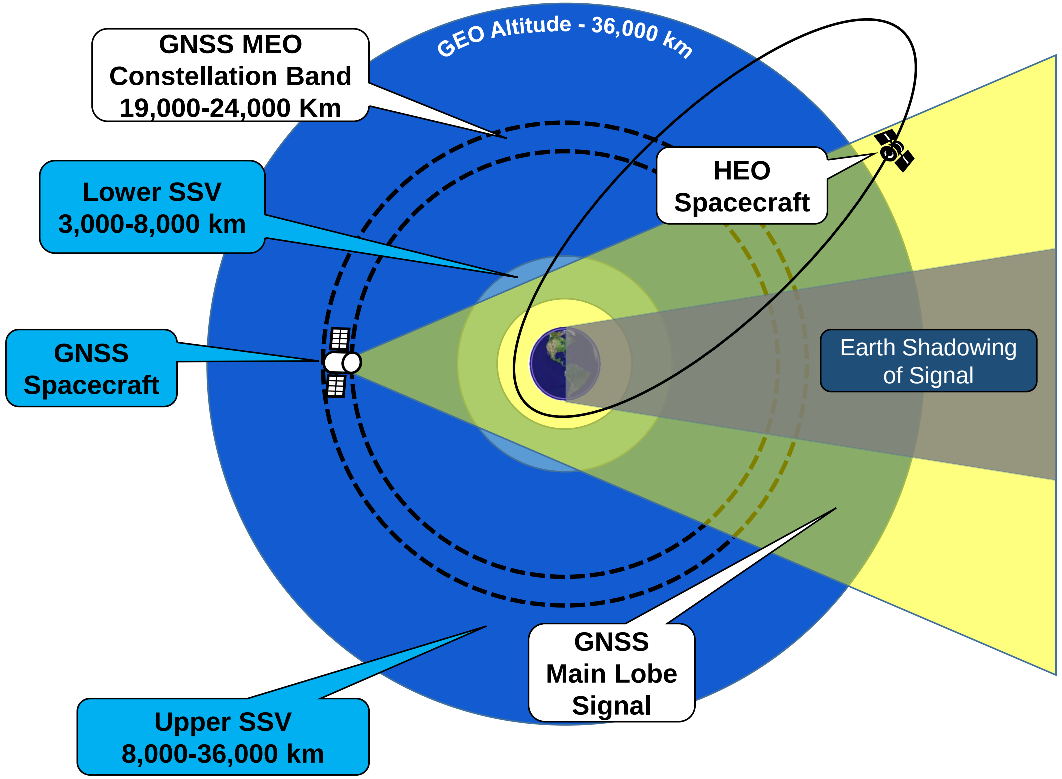
Space Uses of Global Navigation Satellite Systems (GNSS)

- **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**



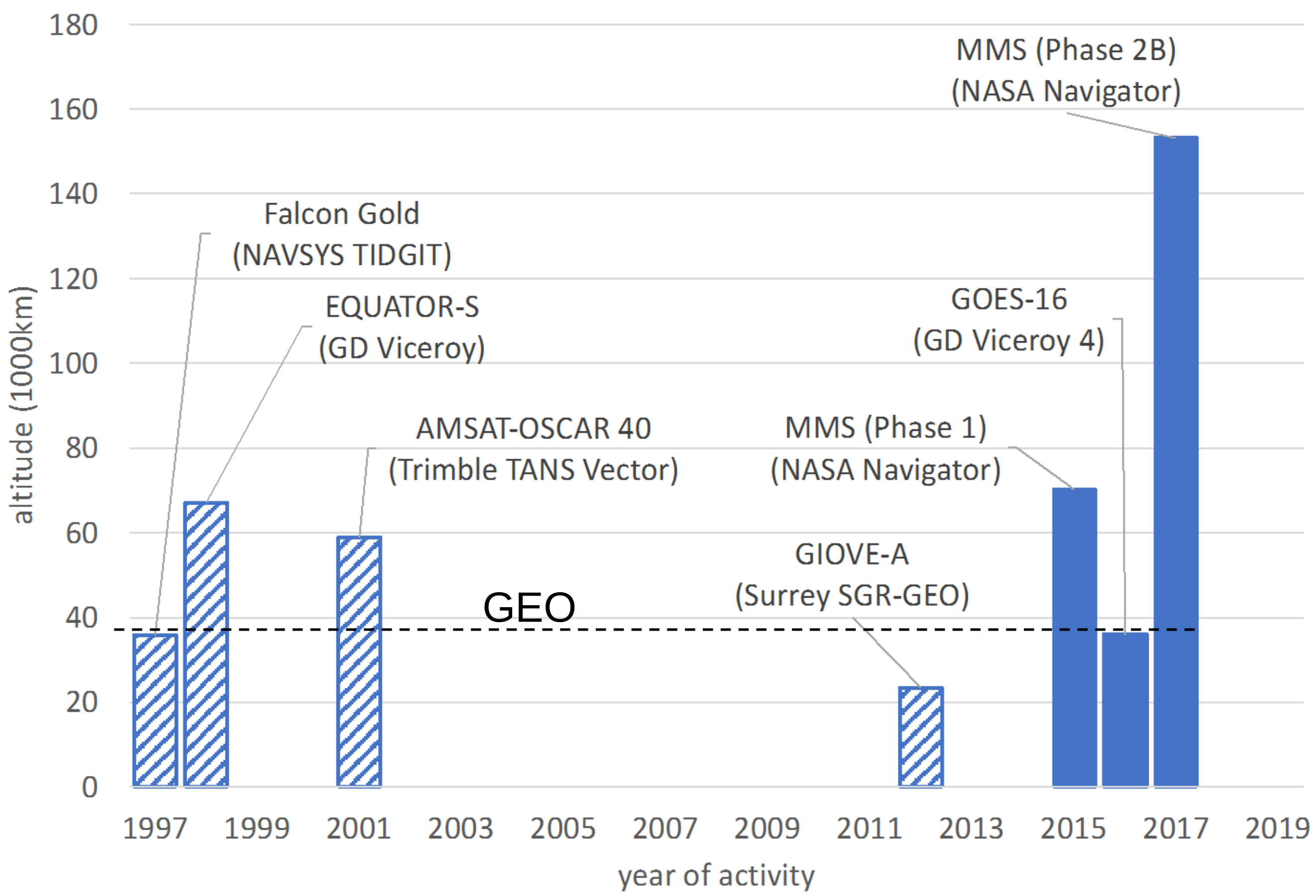
Reception of High-Altitude GNSS Signals

- 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



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 and recently 150,000 km
- **2016**: GOES-16 employed GPS operationally at GEO



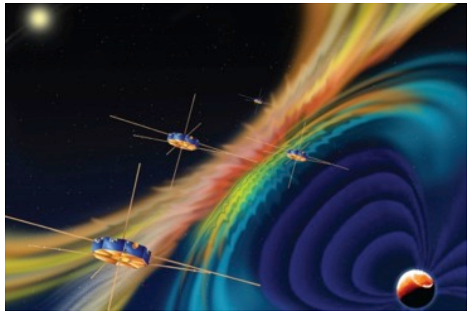
Operational Challenges

Ops Scenario	Altitude Range (km)	Challenges & Observations (Compared to previous scenario)	Mitigations	Operational Status
Terrestrial Service Volume	100- 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
SSV Medium Altitudes	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)
SSV High-GEO Altitudes	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	Nav-Orbit Filter/Fusion algorithms (e.g. GEONS) enables ops w/ <4 signals and flywheel through 0 signal ops; 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

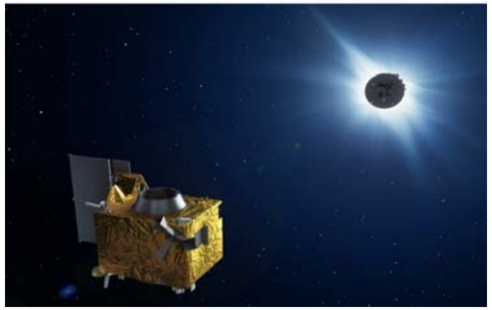
The Promise of using GNSS inside the Space Service Volume

- 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

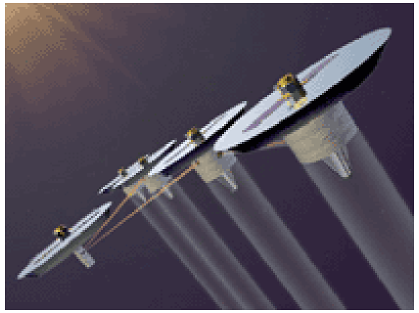


Space Weather Observations

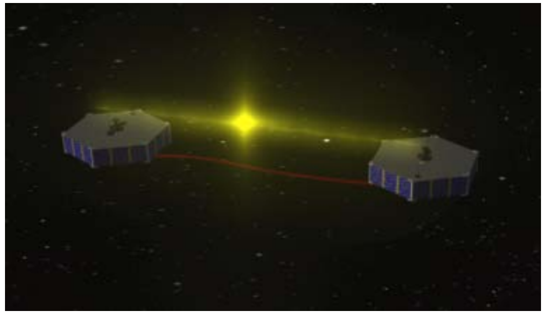


Precise Relative Positioning

Launch Vehicle Upper Stages & Beyond-GEO applications



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

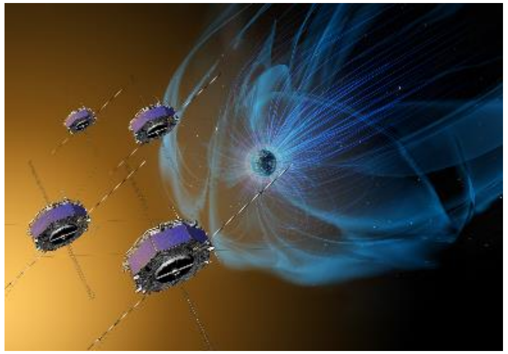


Precise Position Knowledge & Control at GEO

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

Operational Users

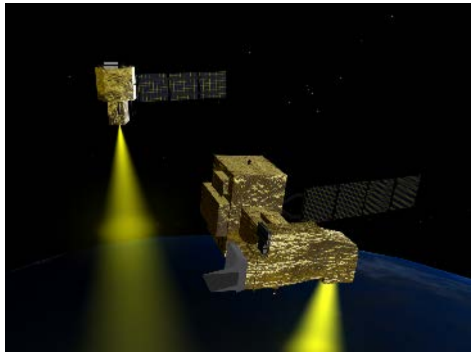
- MMS
- GOES-R, S, T, U
- EM-1 (Lunar enroute)
- Satellite Servicing



Operational Use Demonstrates Future Need

Space Flight Experiments

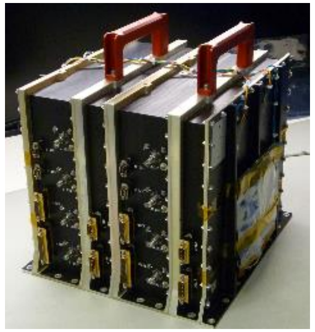
- Falcon Gold
- EO-1
- AO-40
- GPS ACE
- EM-1 (Lunar vicinity)



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

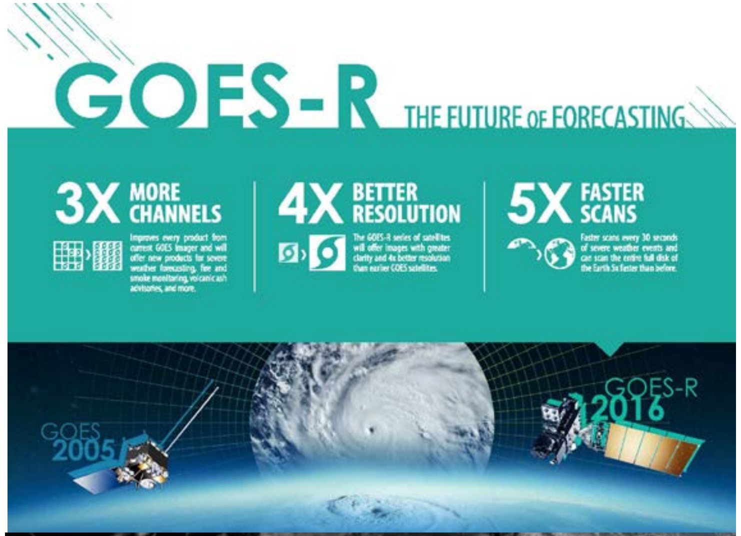
- SSV definition (GPS IIF)
- SSV specification (GPS II
- ICG Multi-GNSS SSV common definitions & analyses

Operational Guarantees Through Definition & Specification

From 1990's to Today, U.S. Provides Leadership & Guidance Enabling Breakthrough, Game-changing Missions through *use of GNSS* ***in the SSV***

GOES-R Series Weather Satellites

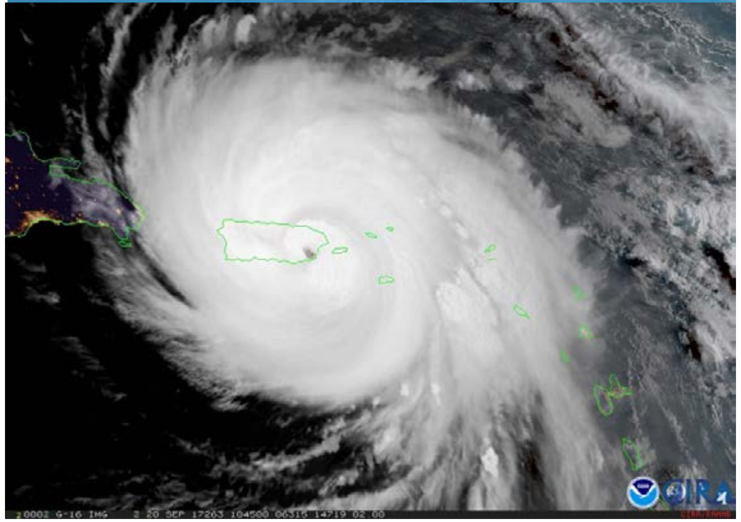
- GOES-R, -S, -T, -U: 4th generation NOAA operational weather satellites
- GOES-R/GOES-16 Launch: 19 Nov 2016; GOES-S/GOES-17 Launch: March 1 2018
- 15 year life, series operational through mid-2030s
- Employs GPS at GEO to meet stringent navigation requirements
- Relies on beyond-spec GPS sidelobe signals 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



Improves every product from current GOES Imager and will offer new products for severe weather forecasting, fire and smoke monitoring, volcanic ash advisories, and more.

The GOES-R series of satellites will offer images with greater clarity and 4x better resolution than earlier GOES satellites.

Faster scans every 30 seconds of severe weather events and can scan the entire full disk of the Earth 5x faster than before.

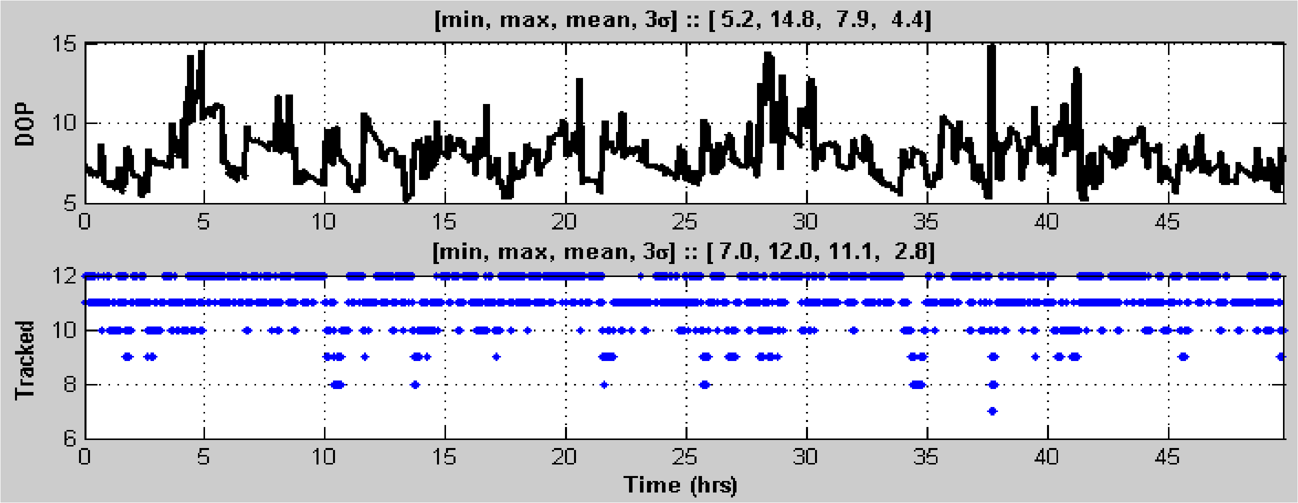


GOES-16 Image of Hurricane Maria Making Landfall over Puerto Rico

GOES-R/GOES-16 In-Flight Performance

GPS Visibility

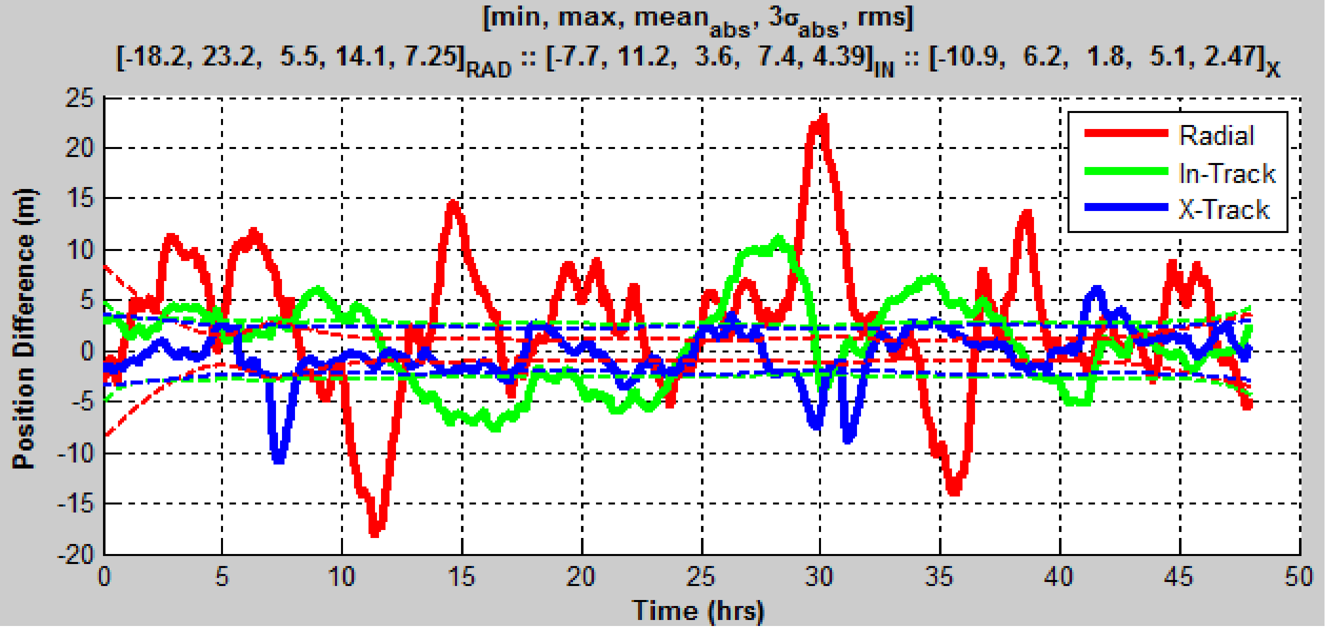
- Minimum SVs visible: 7
- DOP: 5–15
- Major improvement over guaranteed performance spec
  (4+ SVs visible 1% of time)



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.



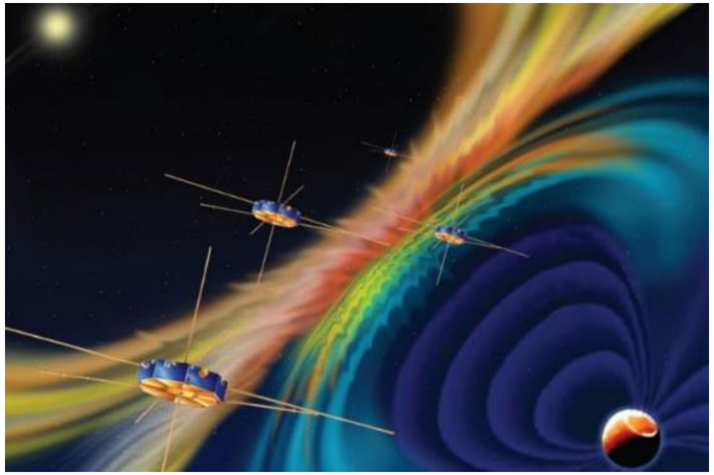
Using GPS above the GPS Constellation: NASA GSFC MMS Mission

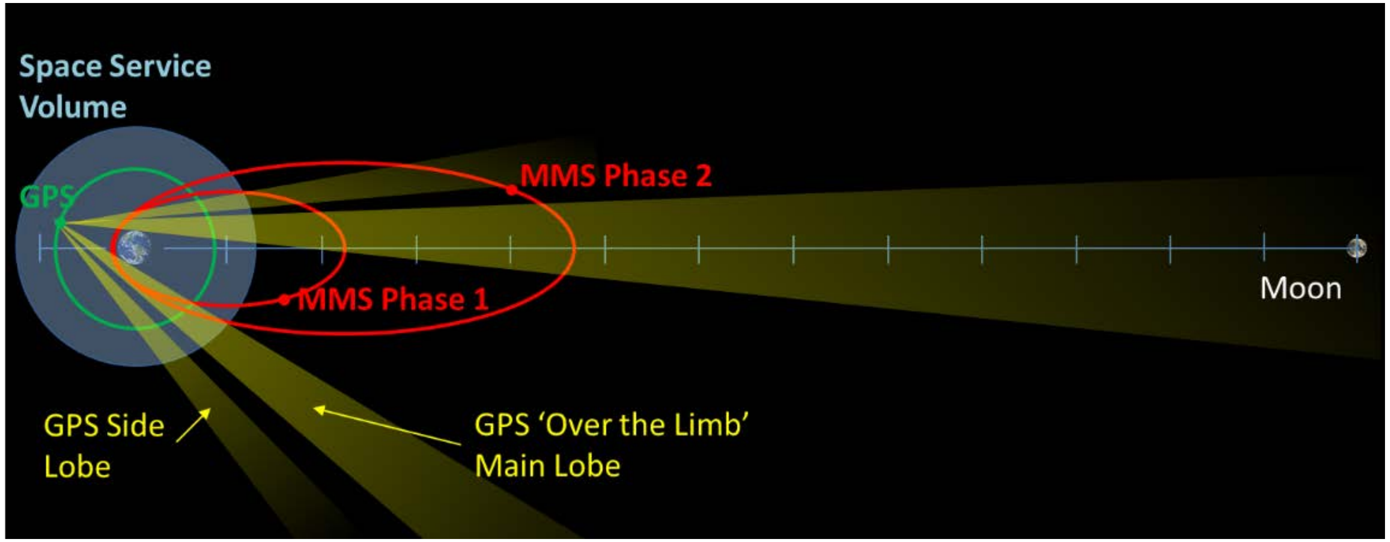
Magnetospheric Multi-Scale (MMS)

- 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!)

MMS Navigator System

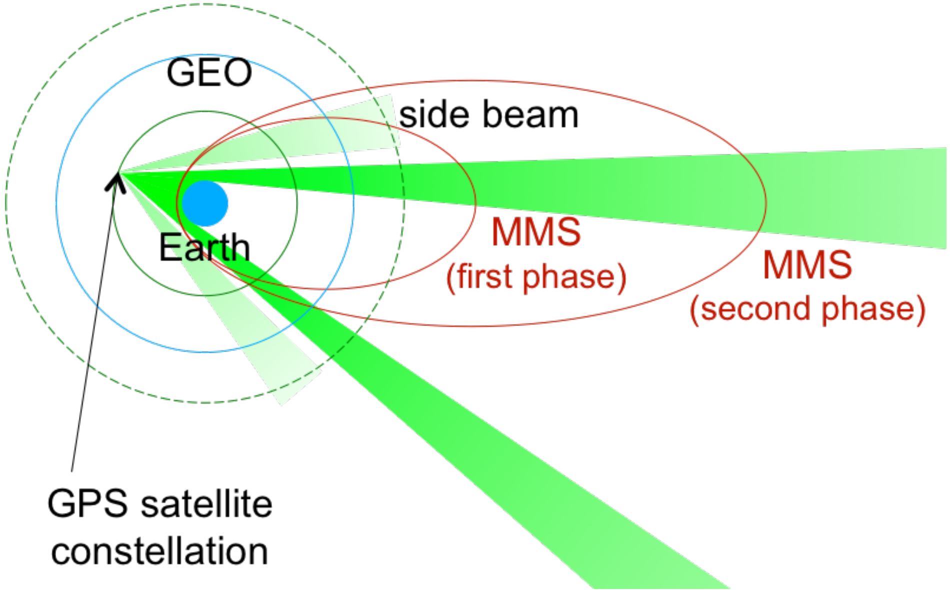
- GPS enables onboard (autonomous) navigation and near autonomous station-keeping
- MMS Navigator system exceeds all expectations
- At the highest point of the MMS orbit Navigator set Guiness world record for the highest-ever reception of signals and onboard navigation solutions by an operational GPS 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

- **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 100us holdover over 65 hours under all environmental conditions*
  - *Driven by operational mode where GPS RF chains would be turned off above 3 Earth radii which is no longer a mode that is planned for use.*
  - *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.*



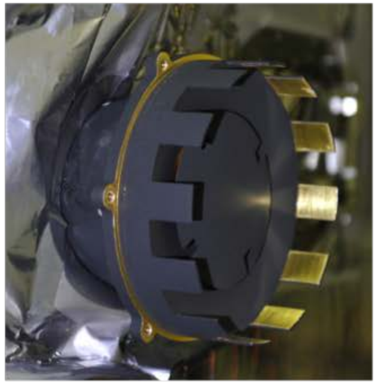
MMS Navigator GPS hardware

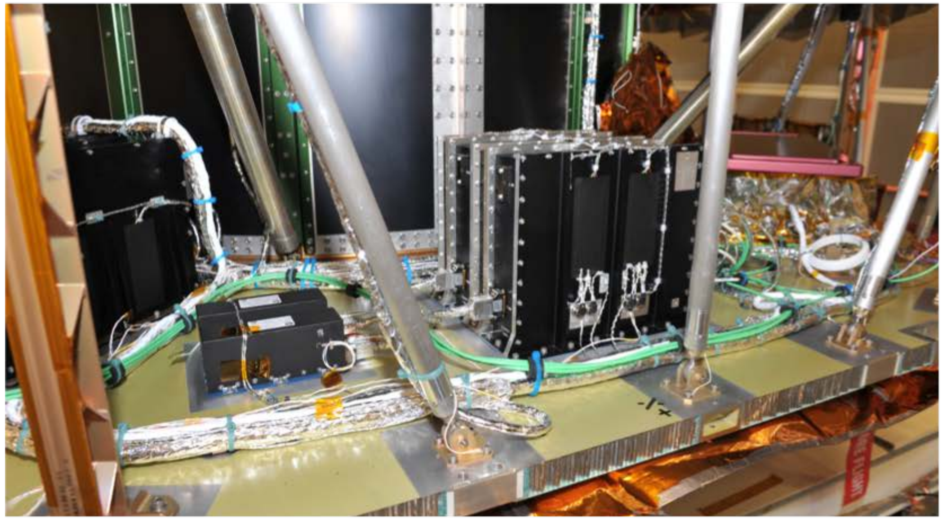
- GPS hardware all developed and tested at GSFC. Altogether, 8 electronics boxes, 8 USOs, 32 antennas and front ends

Ultra Stable Osc.

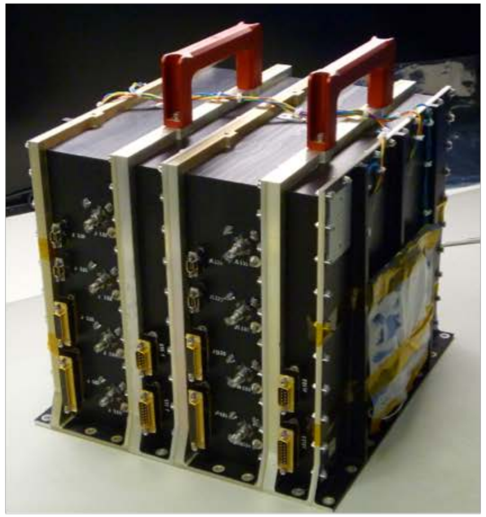
Front end electronics assembly

GPS antenna





Receiver and USO on spacecraft deck

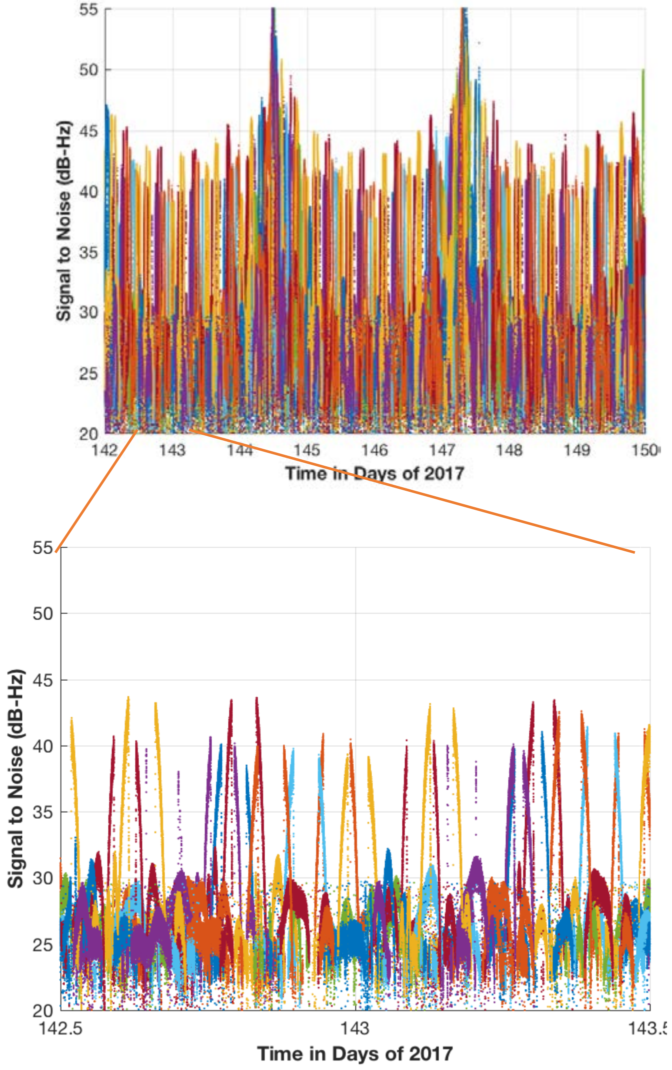


Redundant receiver electronics

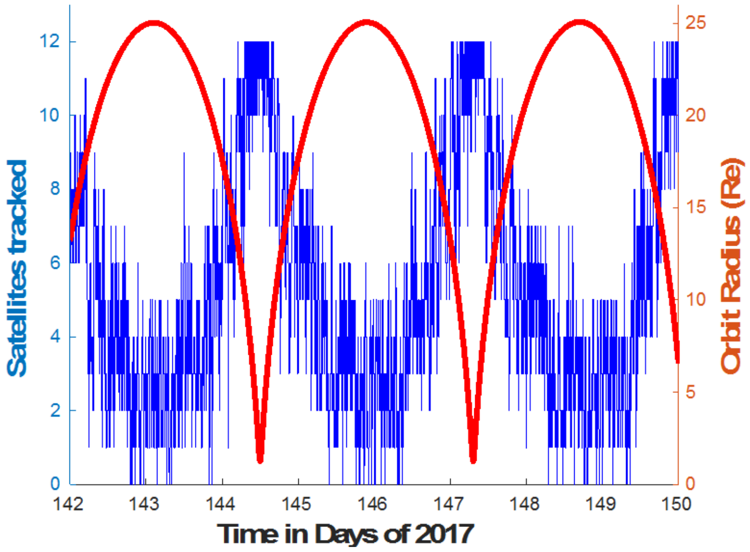
On-orbit Phase 2B results: signal tracking

- 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.
  - Cumulative outage over sample orbit: 0.5% (22 min over 67-hour orbit); average duration: 2.8 min
- Visibility exceeds preflight expectations significantly

C/N_0 vs. time, near apogee

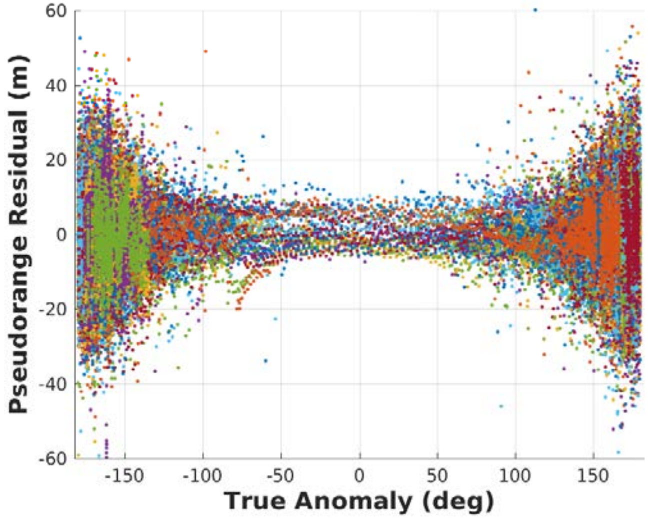


Signals tracked

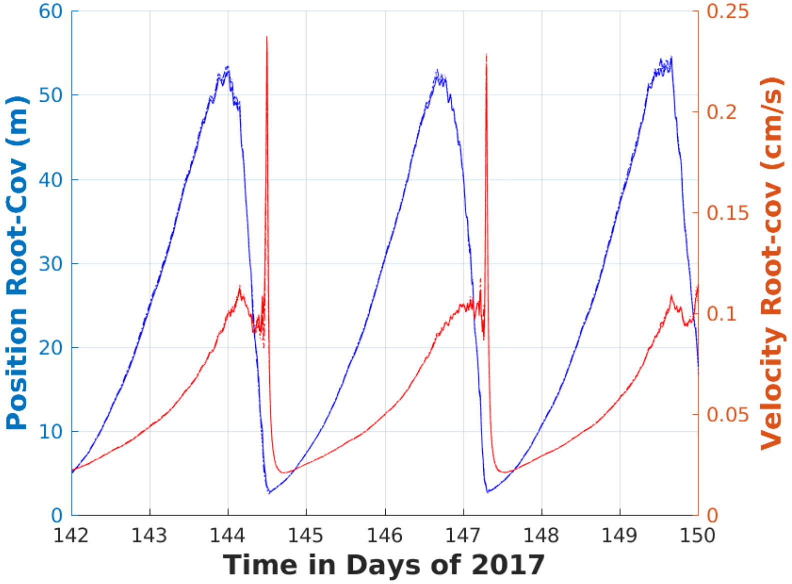


On-orbit Phase 2B results: measurement and navigation performance

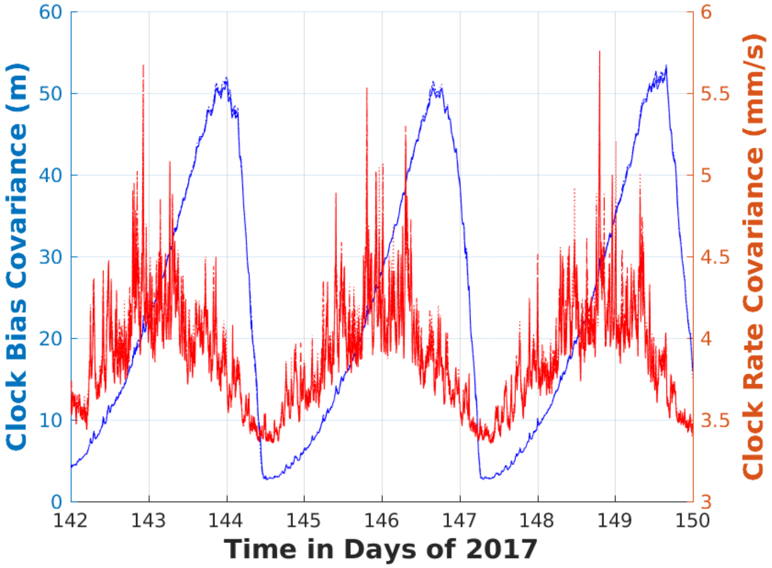
- GEONS filter RSS 1-sigma formal errors reach maximum of ~50m and briefly 5mm/s (typically <1mm/s)
- Measurement residuals are zero mean, of expected variation <10m 1-sigma.
  - Suggests sidelobe measurements are of high quality.
- As apogee increases, range and clock errors become highly correlated; seen in pos/clock covariances below



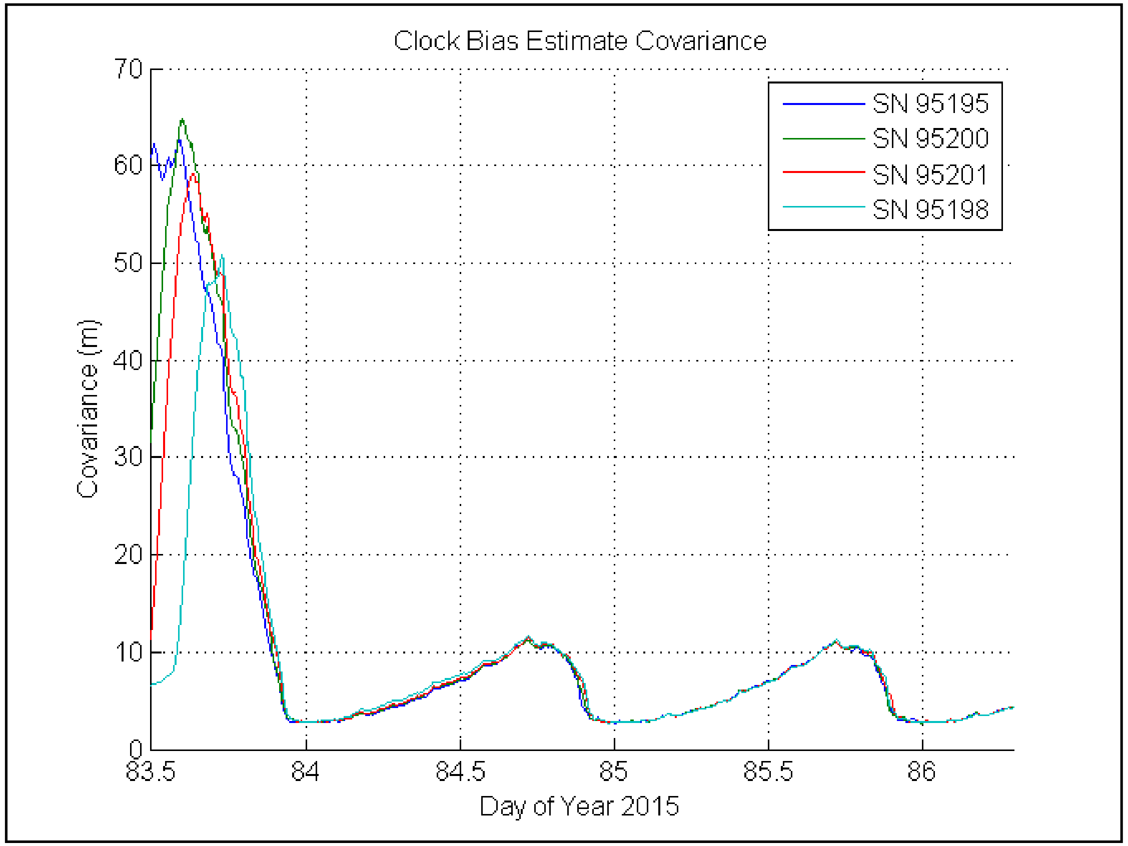
Filter formal pos/vel errors (1σ root cov)

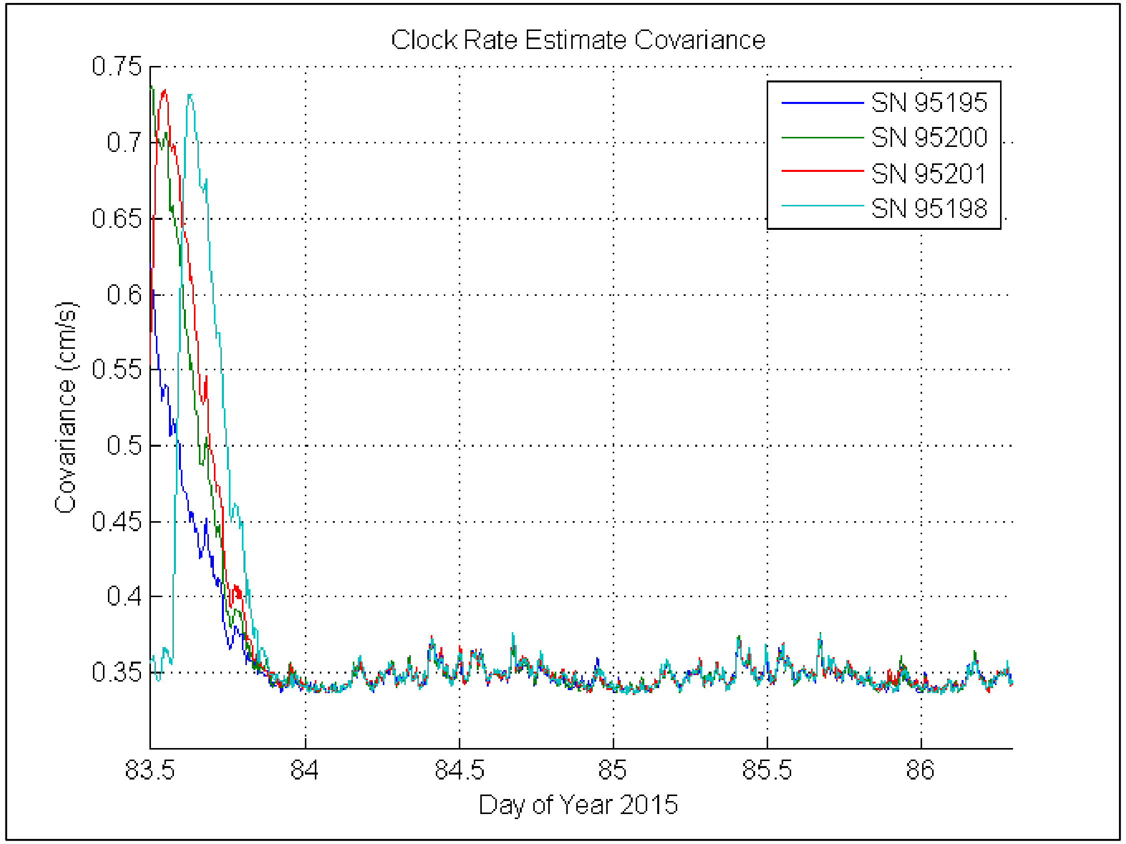


Filter formal clock errors (1σ root cov)



On-Orbit Clock Performance





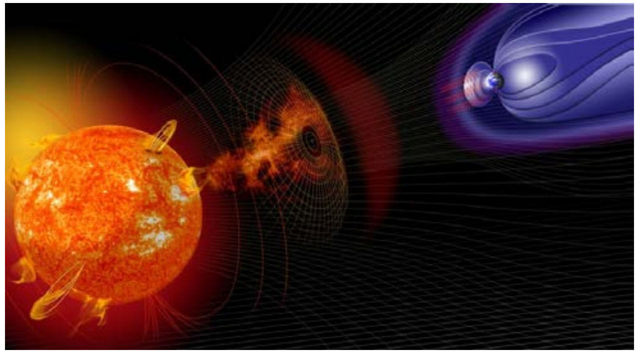
- Filter is able to estimate clock phase to within 15m or about 50ns
- Rapid clock reconvergence after maneuvers

- Filter is able to estimate clock phase to within 0.4cm/s or about 1e-11 fractional frequency
- Precise estimation across all oscillators

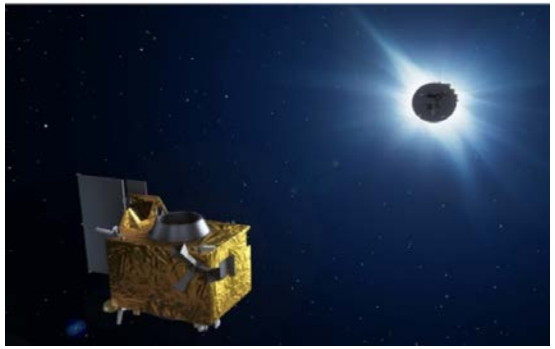
The Promise of using GNSS beyond the Space Service Volume

- 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

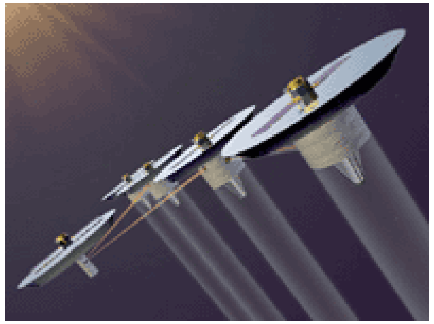


Space Weather Observations

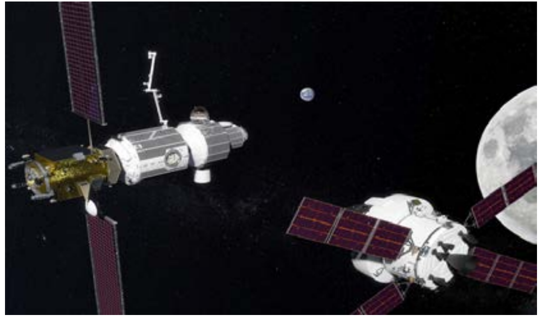


Precise Relative Positioning

Launch Vehicle Upper Stages & Cislunar applications



Formation Flying, Space Situational Awareness, Proximity Ops

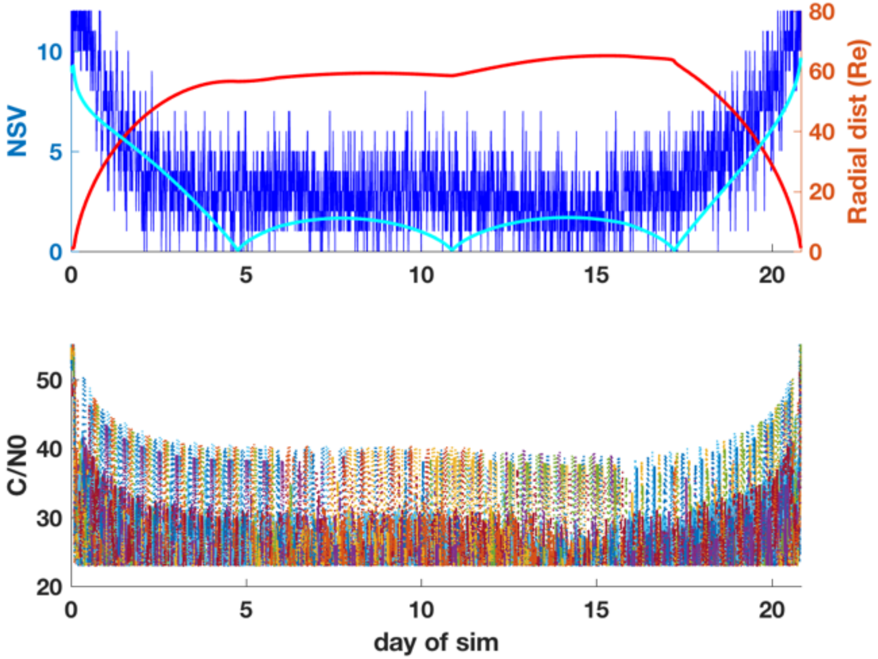


Lunar Orbiting Platform-Gateway Human & Robotic Space Applications

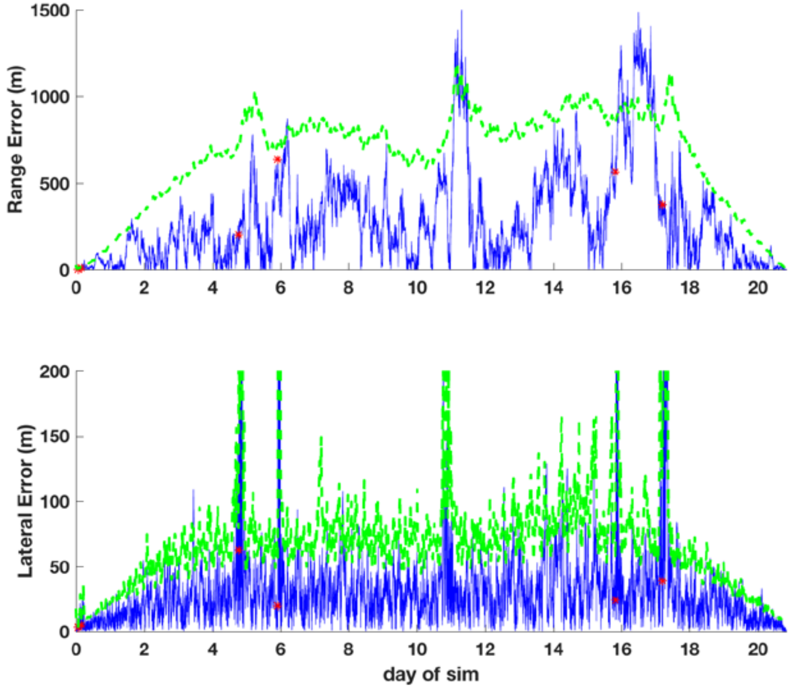
MMS study: Concept Lunar mission

- **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; 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

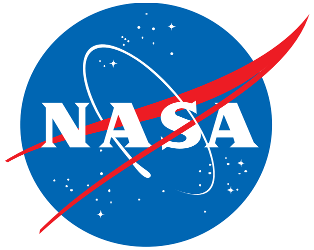


Filter position formal (3σ) and actual errors



Conclusions

- High-altitude space use of GNSS is an emerging operational capability
  - Latest operational demonstrations include: GOES-16, MMS
  - MMS USOs selected to withstand long GNSS signal outages; meeting or exceeding all requirements
- Signal availability is as key to timing as it is to navigation; nearly-continuous availability of signals enables benefits for time synchronization, clock bias estimation, etc.
- Recent predictions show that signal reception of GNSS to lunar distance can be quite good for real-time navigation performance.
  - 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
- Potential applications are far-reaching:
  - Precise time for time-tagging science measurements
  - Payload time signal on Lunar Orbital Platform—Gateway
  - Precise time redistribution in cis-lunar space


NASA

Backup

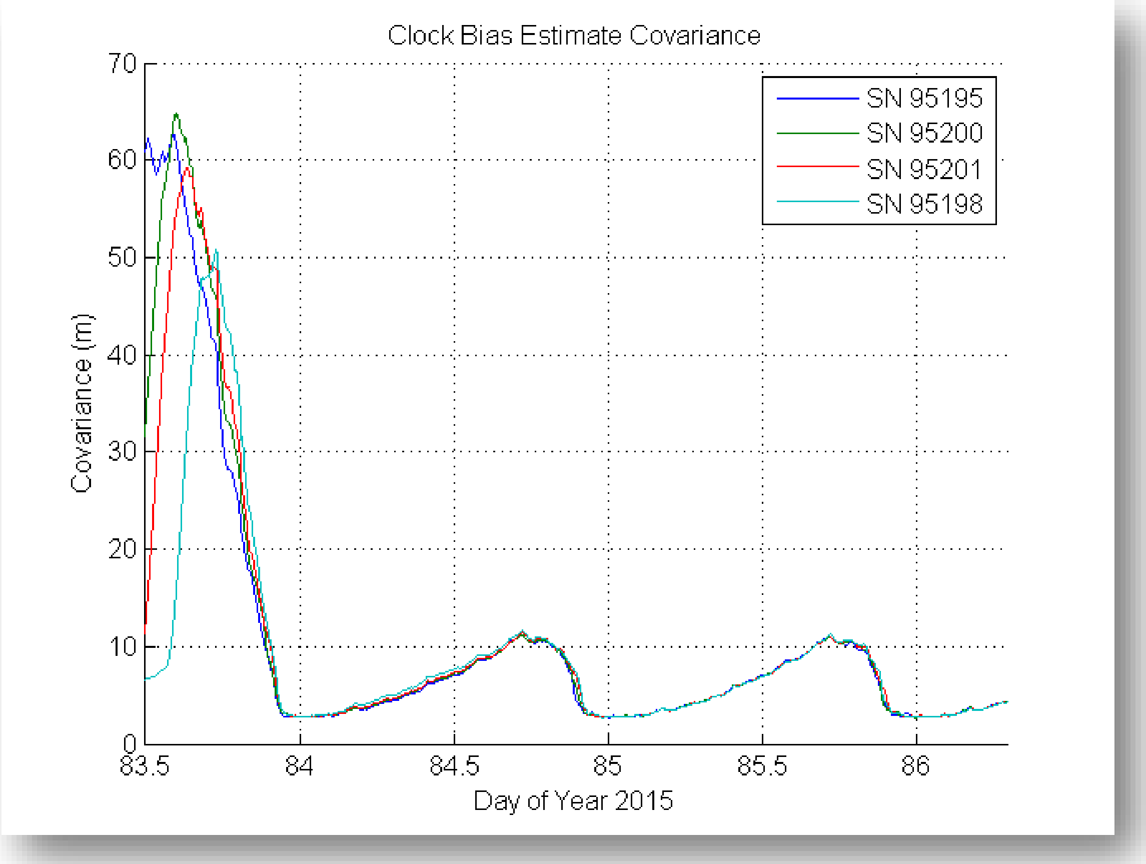
Some key USO derived requirements

- 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.

Clock Bias Estimation

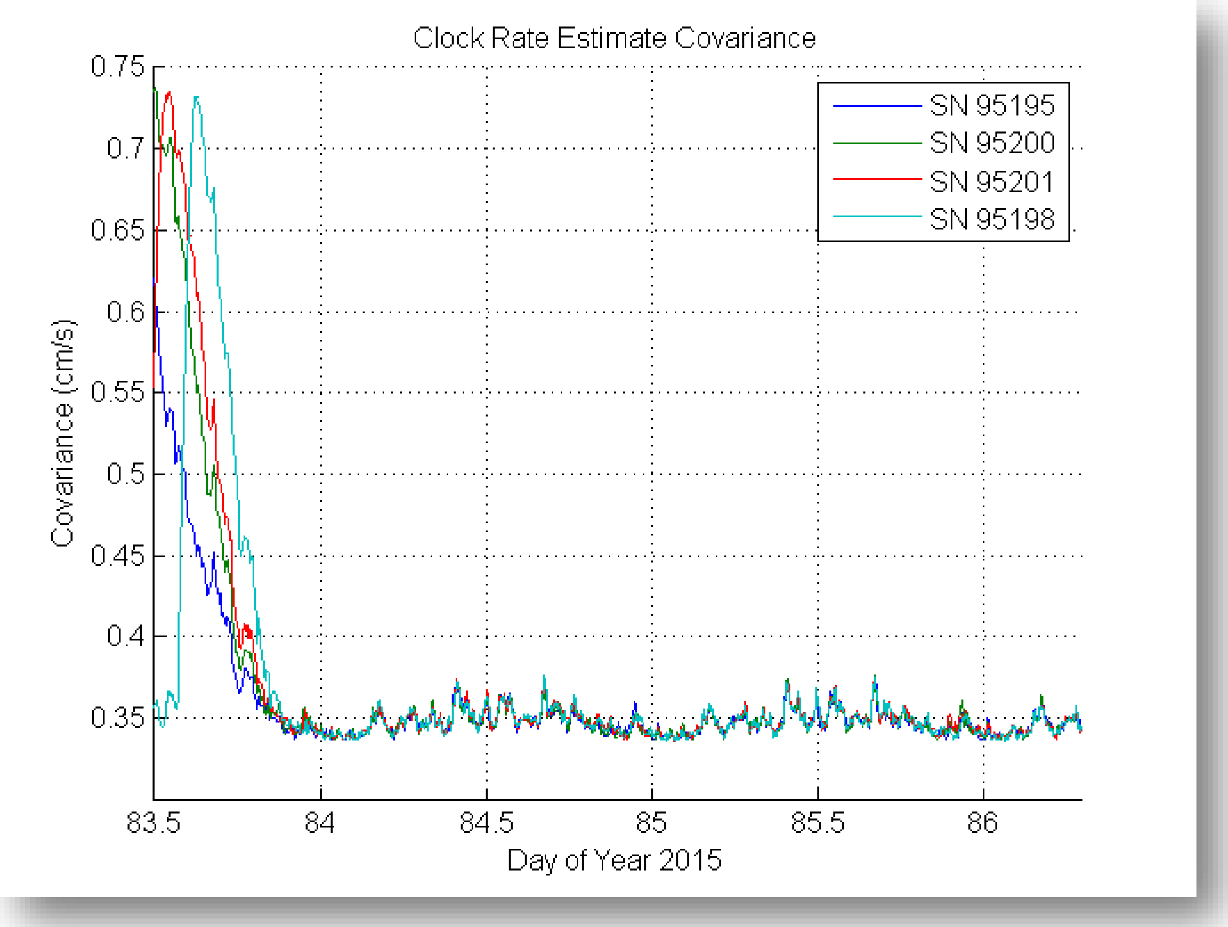
Filter is able to estimate clock phase to within 15m or about 50ns



Rapid clock reconvergence after maneuvers

Clock Rate Estimation

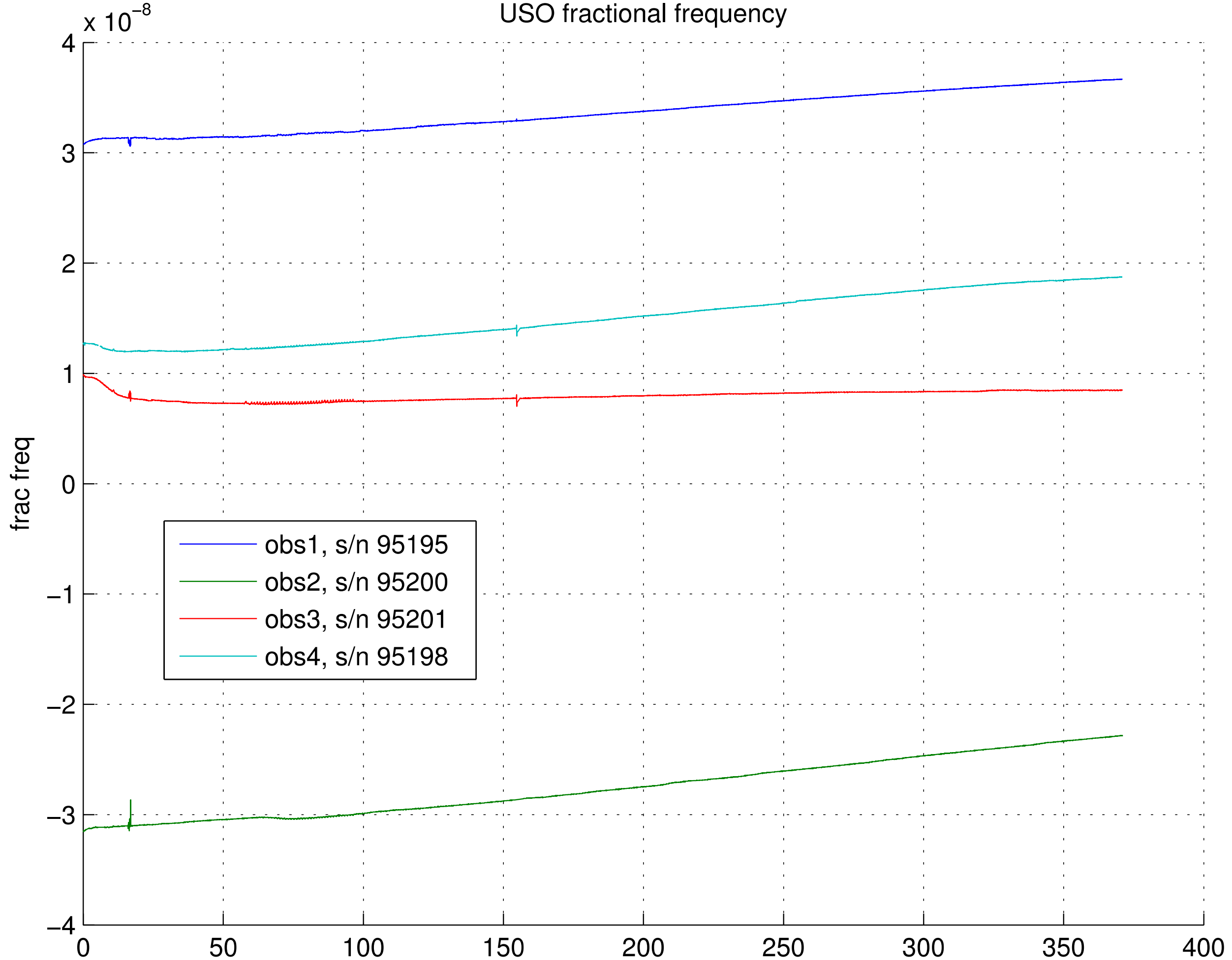
Filter is able to estimate clock phase to within 0.4cm/s or about 1e-11 fractional frequency



Precise estimation across all oscillators

Fractional Frequency Trend

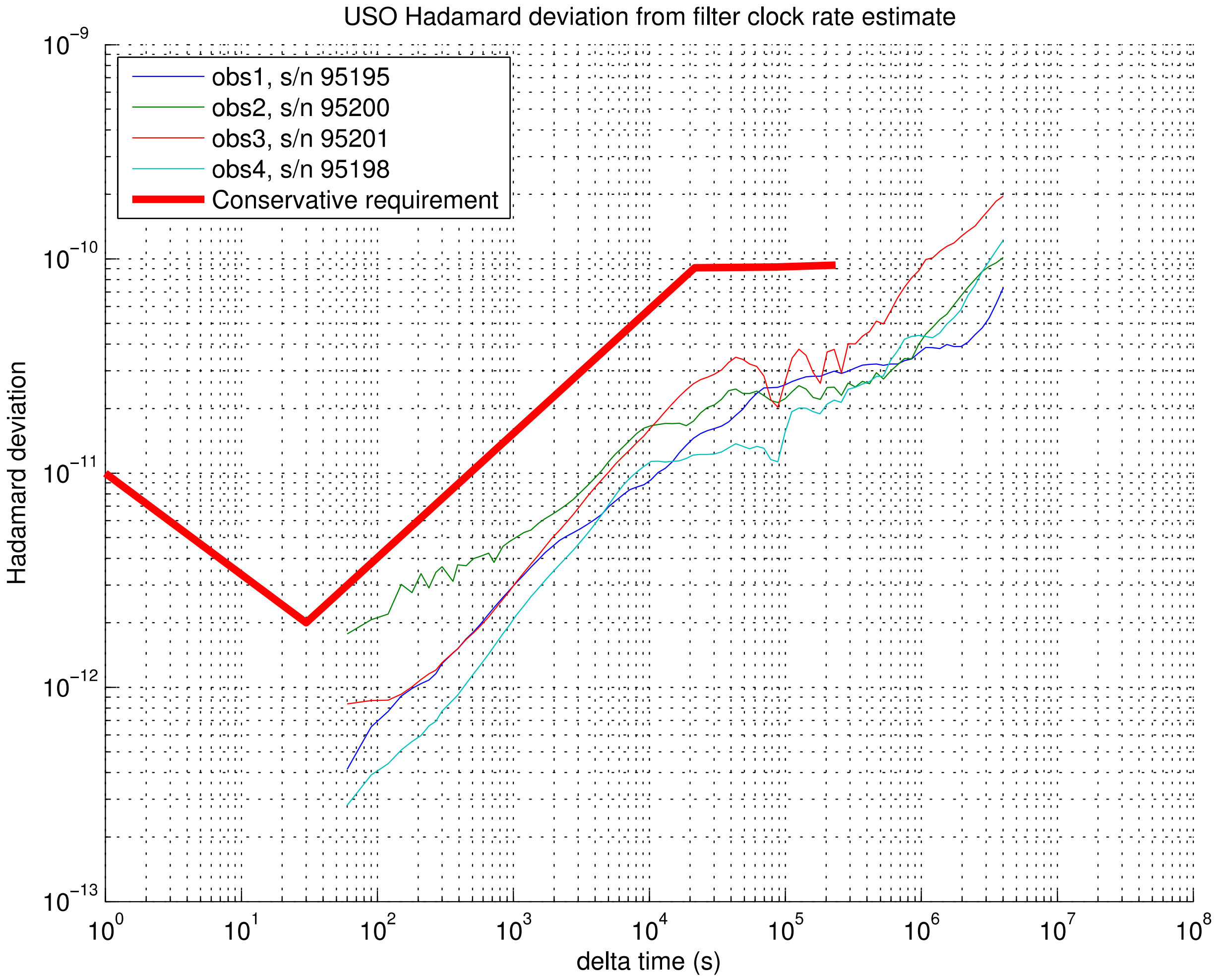
USO freq accuracy requirement of 1e-7 met with margin



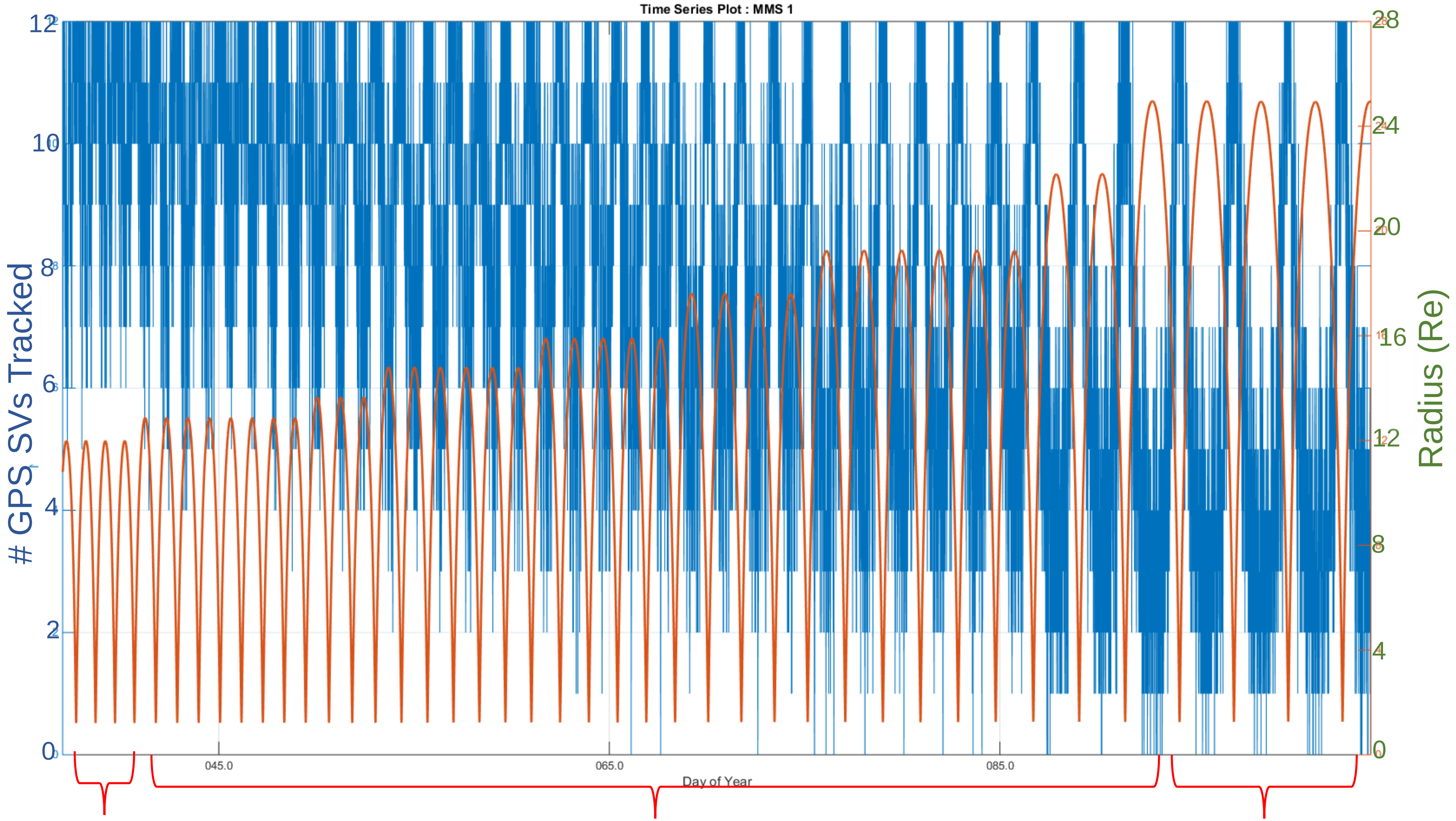
Small glitches correspond to filter resets

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



Signal Tracking Performance During Phase 1 to Phase 2 Apogee Raising (70K km to 150K km)

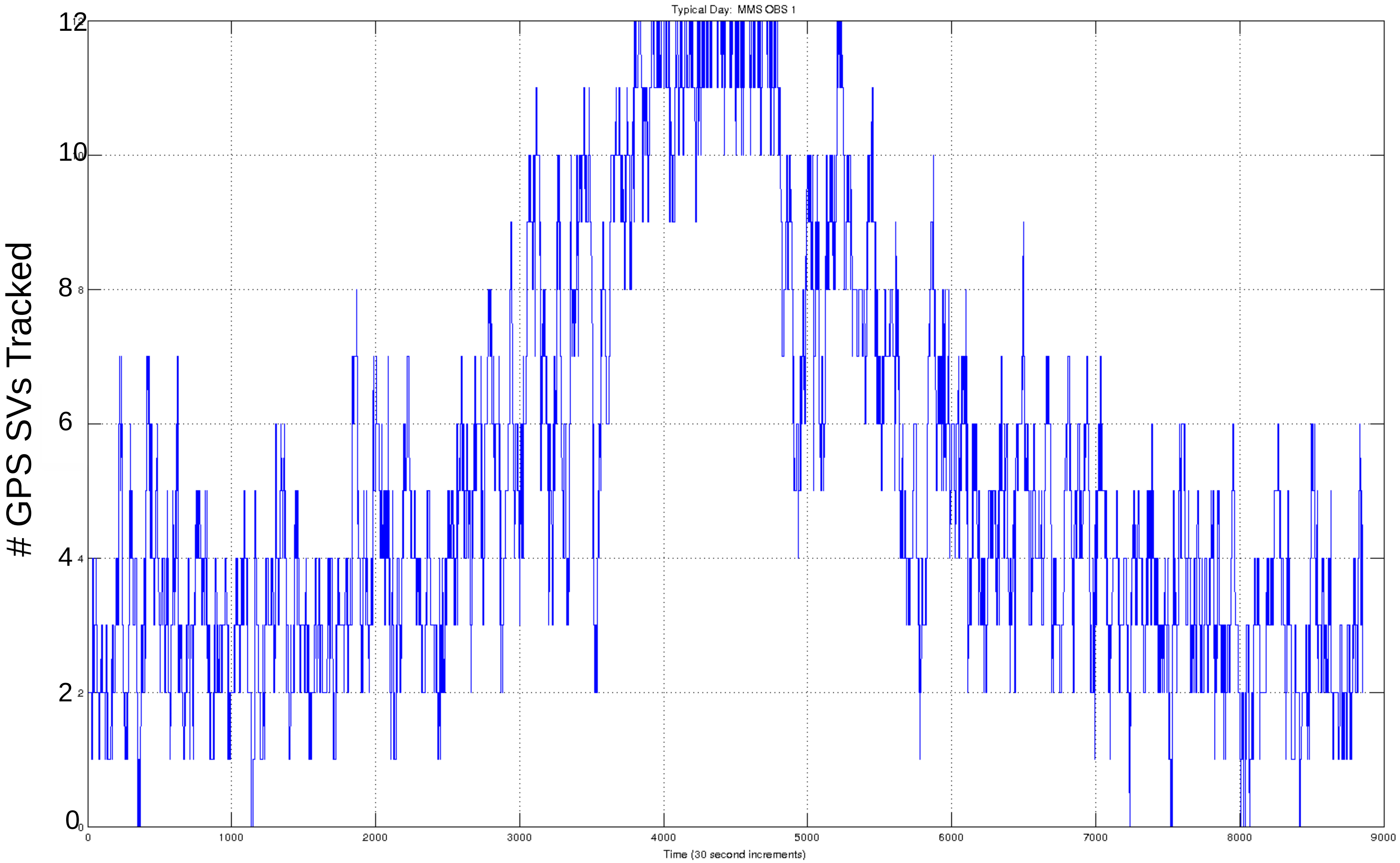


Phase 1
70K km

Orbit Transition

Phase 2
150K km

Signal Tracking Performance
Single Phase 2B Orbit (150K km Apogee)



Average Outage: 2.8 mins; Cumulative outage: 22 min over 67 hour orbit (0.5%)

Note: Actual performance is orbit sensitive