New High-Altitude GPS Navigation Results from the Magnetospheric Multiscale Spacecraft and Simulations at Lunar Distances

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Outline

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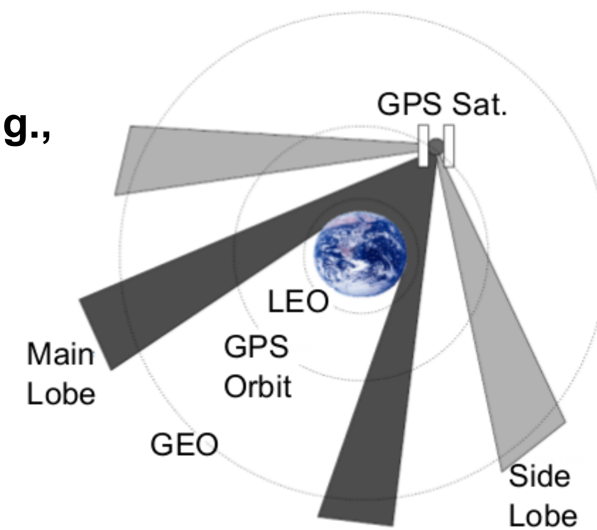
  - High altitude GPS
  - Magnetospheric Multiscale (MMS) Mission
  - GPS Navigation for MMS
    - MMS Mission
    - MMS Navigation system
- **New results from MMS Phase 2B**
- **Simulations at Lunar distance**
  - Calibration on MMS Phase 2B
  - MMS extended mission concept
  - Concept Lunar trajectory
- **Conclusion**

Background on high-altitude (HEO) GPS

- **HEO GPS navigation offers performance and cost improvements, but poses challenges**
  - Sparse mainlobe availability, sidelobes weak, unspecified/uncharacterized, poor geometry, potentially harsher radiation environment.
- **Ongoing research in HEO GPS R&D since 1990's, GSFC among leaders**
  - Numerous simulations studies at GEO, HEO, even Lunar distances
  - GSFC led effort to define/expand GPS Space Service Volume definition and characterize in-situ GPS transmitter antenna patterns (GPS-ACE 2015)
  - Developed Navigator HEO GPS receiver
- **Early on-orbit experiments in late 1990's-early 2000's**
  - AFRL Falcon Gold, TEAMSAT, EQUATOR-S
  - NASA GSFC / AMSAT OSCAR-40, 2000
- **Recent growth in available receivers/applications, e.g.,**
  - GD Monarch flying on USG SBIRS (GEO) (~2011-2012)
  - Surrey Satellite SGR-GEO experiment on GIOVE-A (2013)
  - Airbus/Astrium MosiacGNSS and LION GNSS Rx for HEO
  - Moog-Broad Reach Navigator (AFRL ANGELS 2015, EAGLE 2017)
  - RUAG Podrix to fly on ESA Proba-3 (2018)
  - *General Dynamics' Viceroy-4 flying GOES-16 at GEO (2017)*
  - ***NASA GSFC Navigator GPS flying HEO MMS since 3/2015***

High-altitude GPS

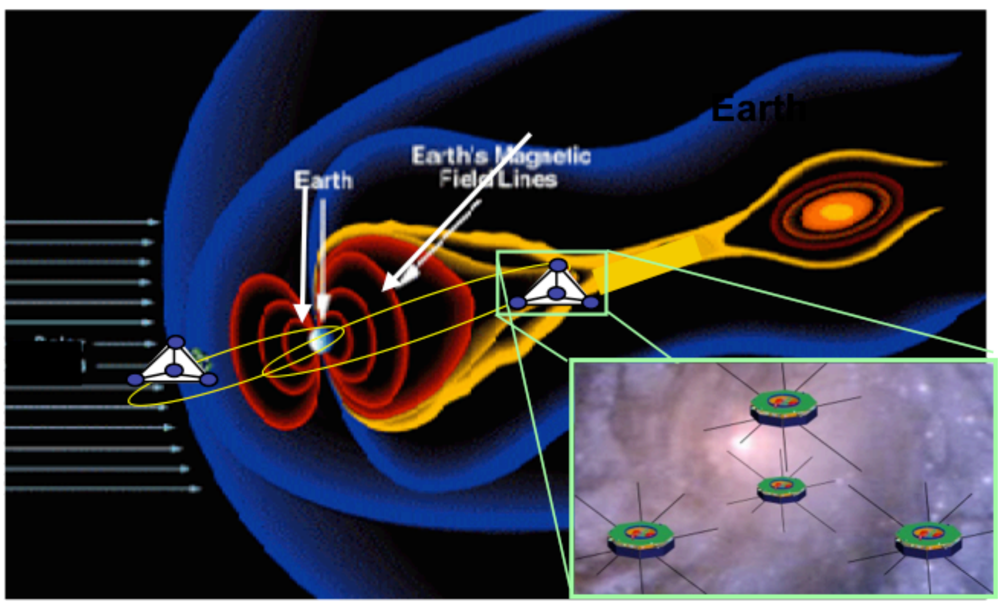


- ***<u>MMS set records for highest (and fastest) GPS receiver operations to date</u>***

Magnetospheric Multiscale Mission (MMS)

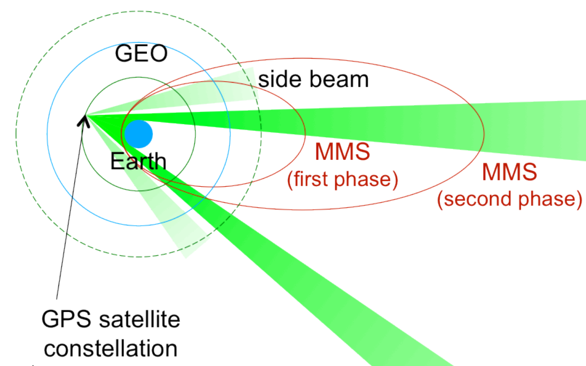
- **Discover the fundamental plasma physics process of reconnection in the Earth's magnetosphere.**
- **Coordinated measurements from tetrahedral formation of four spacecraft with scale sizes from 400km to 7km**
- **Flying in two highly elliptic orbits in two mission phases**
  - Phase 1 1.2x12 R_E (magnetopause)
  - Phase 2B 1.2x25 R_E (magnetotail)

(For reference GEO ~6.5 R_E, Moon ~60 R_E)



MMS Navigation System

- **MMS Navigation system consists of Navigator GPS receiver, with Ultra-stable crystal oscillator and Goddard Enhanced Onboard Navigation Software (GEONS)**
- **Navigator-GPS**
  - Product of NASA Goddard project to build high-altitude GPS receiver (~2001)
  - Rad-hard C/A code receiver, with fast unaided weak signal acq (<25dB-Hz)
  - Heritage on STS-125 Relative Navigation Sensor Experiment (2009), Global Precipitation Measurement Mission (GPM, 2014-), Tech incorporated into Honeywell Orion GPS - demo on EFT-1 of fast-acq for rapid recovery from blackout (Dec 2014)
- **GEONS**
  - UD-factorized Extended Kalman Filter, $4^{th}/8^{th}$ order RK integrator, realistic process noise models. High-fidelity dynamics and many measurement models available.
  - Development dates back to 1980's on Cosmic Origins Background Explorer (COBE).
  - Flying on Terra, GPM, NICER, SEXTANT, MMS, planned on Restore-L, possible WFIRST.
- **MMS-GEONS**
  - Estimate absolute pos/vel, clock bias, rate & accel, integrator step 10s
  - 13x13 geopotential, sun, moon point mass, SRP, drag
  - Process L1 C/A GPS undifferenced pseudorange at 30s rate
  - Accelerometer data at 10s during maneuver



- **MMS Navigation main challenges**
  - Sparse, weak, poorly characterized signal signal environment, poor geometry
  - Spacecraft spin stabilized at 3RPM; obstructions on top and bottom of spacecraft drove to four antennas around perimeter, receiver implements handoff tracking technique antenna-to-antenna every 5s

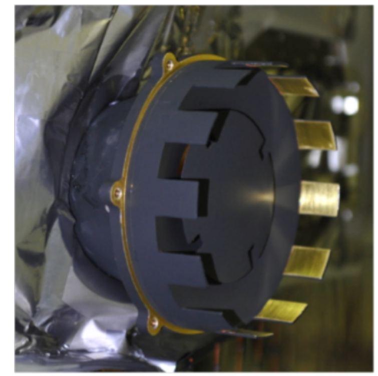
MMS Navigator GPS hardware

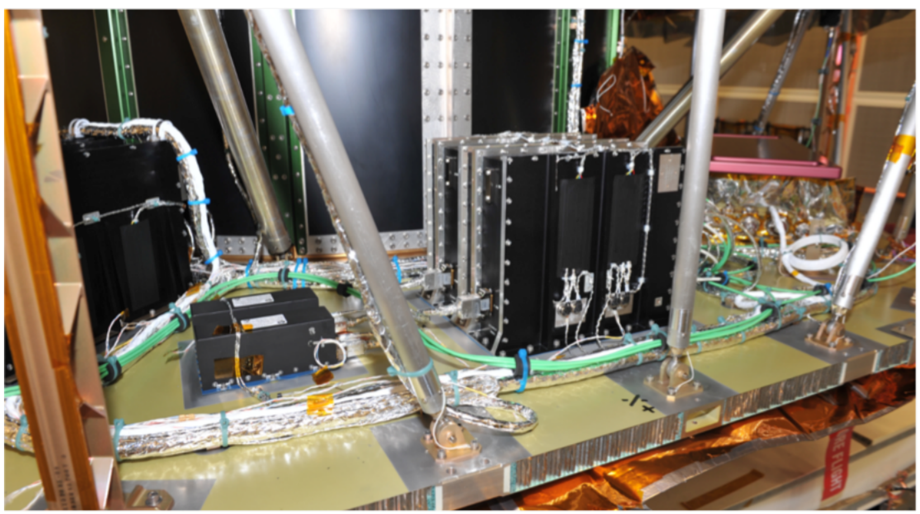
- **GPS hardware all developed and tested at GSFC. Altogether, 8 electronics boxes, 8 USOs, 32 antennas and front ends**

Ultra Stable Osc.

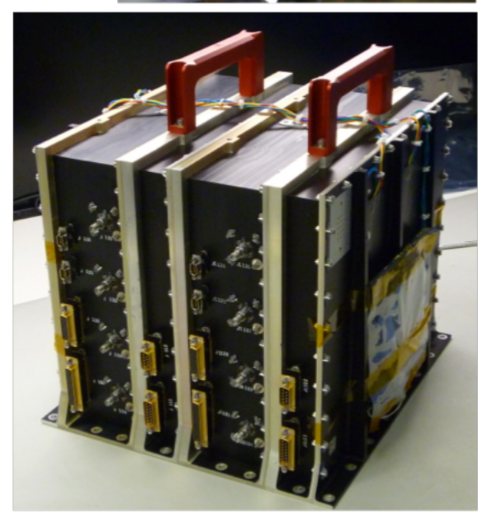
Front end electronics assembly

GPS antenna





Receiver and USO on spacecraft deck

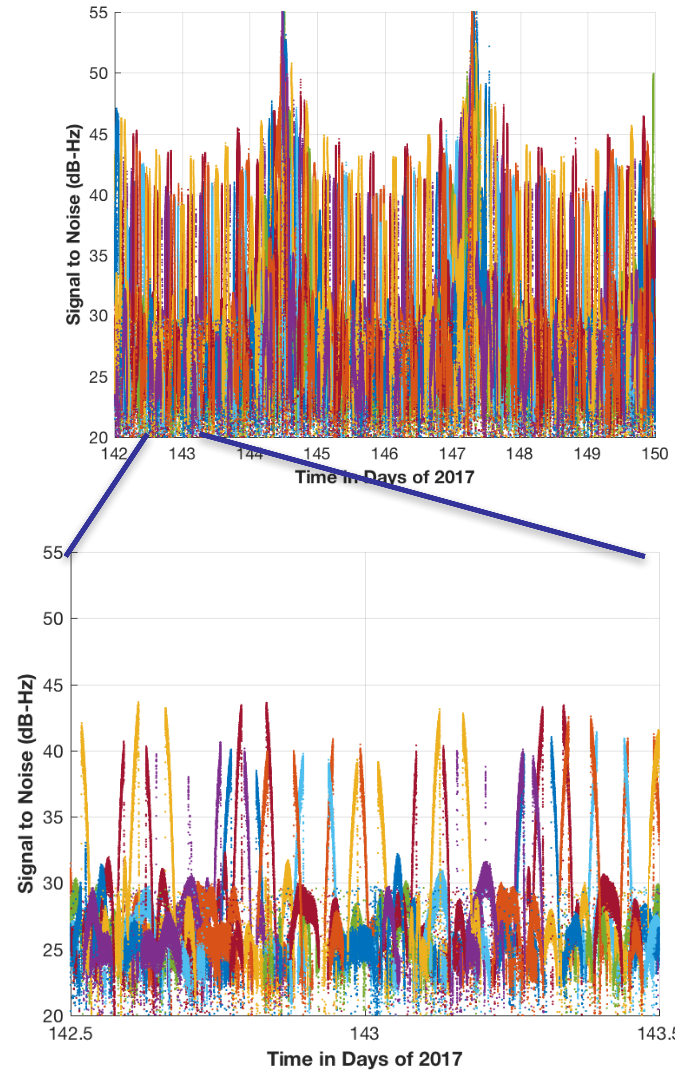


Redundant receiver electronics

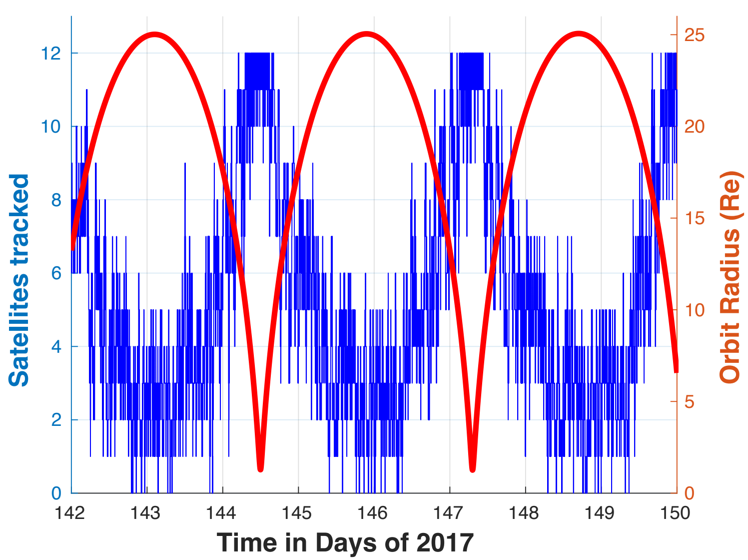
On-orbit Phase 2B results: signal tracking

- **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**

C/N_0 vs. time, near apogee

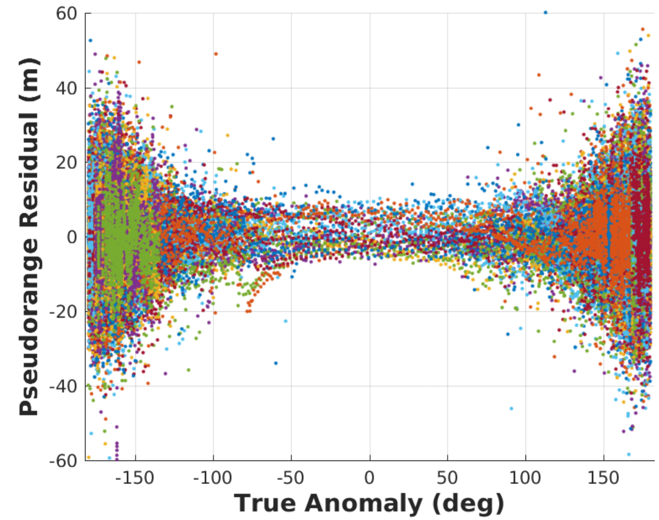


Signals tracked

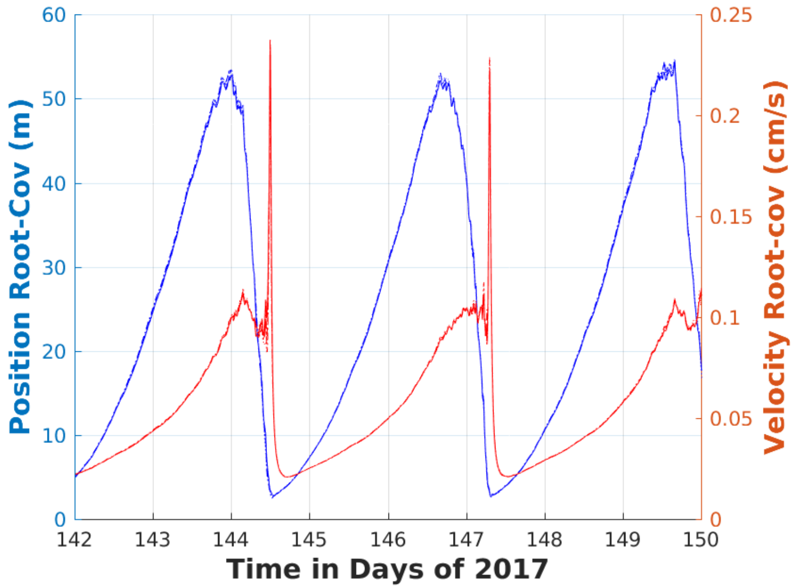


On-orbit Phase 2B results: measurement and navigation performance

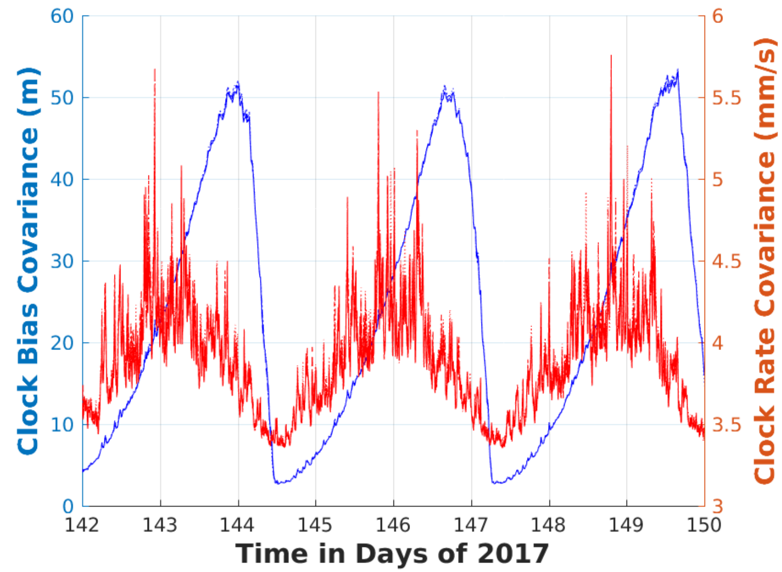
- **GEONS filter RSS 1-sigma formal errors reach maximum of ~50m and briefly 5mm/s (typically <1mm/s)**
- **Measurement residuals are zero mean, of expected variation <10m 1-sigma.**
  - Suggests sidelobe measurements are of high quality.



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

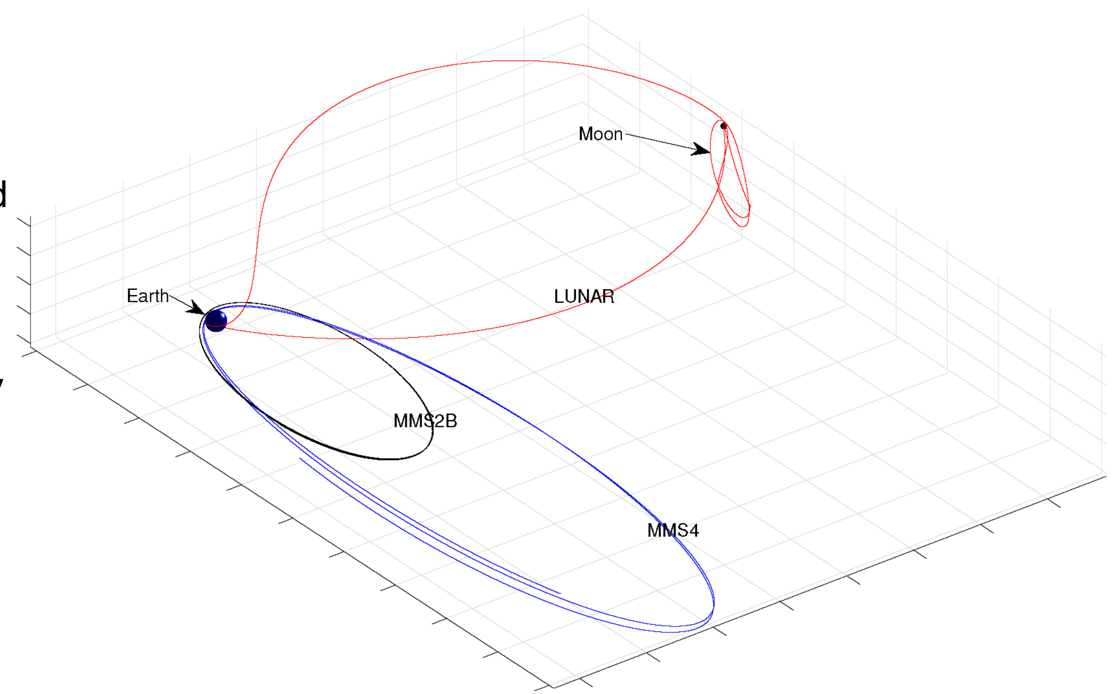


Filter formal clock errors (1σ root cov)



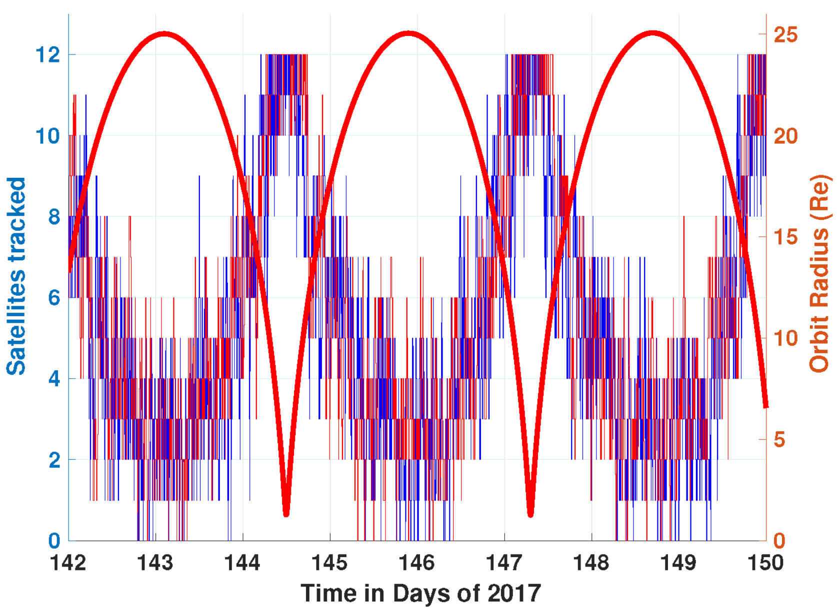
Simulations

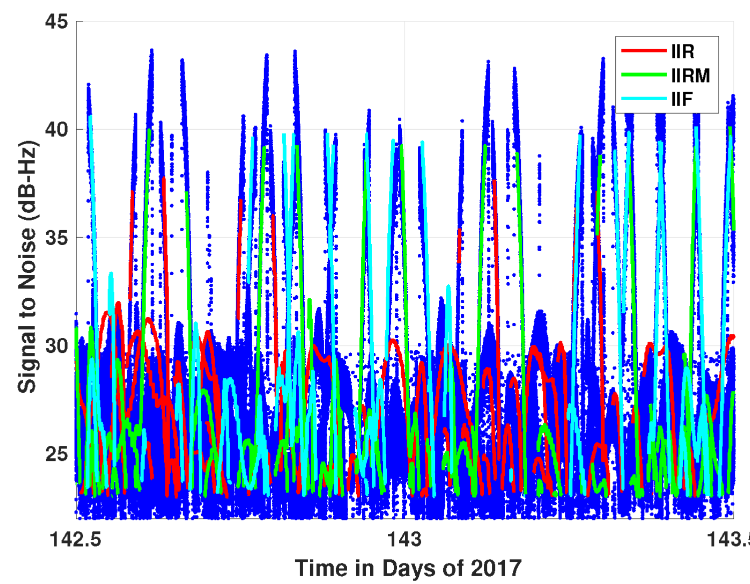
- **Wanted to "get a feel for" performance of MMS Navigation system in:**
  1. A concept MMS extended mission orbit with apogee raised to 60 RE
  2. A concept Lunar trajectory
- **Ran "quick" GEONS ground simulations using new flexible MATLAB based GEONS simulation architecture using GEONS-*Datagen* GPS data simulation**
  - Very similar approach to MMS preflight analysis, but with link models recalibrated based on on-orbit observations in Phase 2B
    - Model MMS GPS receiver performance
    - Run GEONS FSW as configured for MMS
  - Simulation used higher order dynamics than filter, but included some simplifications
    - None or impulsive burns
    - No SRP or drag
  - Ran one case for each trajectory considered
    - Examined visibility, tracking performance, filter formal and actual errors



MMS2B calibration

- Propagated initial state from flight data, same period as flight data plots
- Used GEONS-Datagen, with representative GPS Block IIR and IIRM 2D transmit antenna patterns obtained from www.gps.gov, to simulate signals (used IIRM for IIF also)
- Compared signals tracked and C/N_0 simulated vs. flight and adjusted receiver loss and GPS transmit power slightly per-block to line up
- Ran filter, looked at performance and compared to flight results (signals tracked, C/N0 arcs, filter formal errors)
- Obtained a close *qualitative* match for all metrics
  - Did not model GPS transmitter yaw: sidelobe arcs don't match exactly
  - Randomness in acquisition model prevents exact match

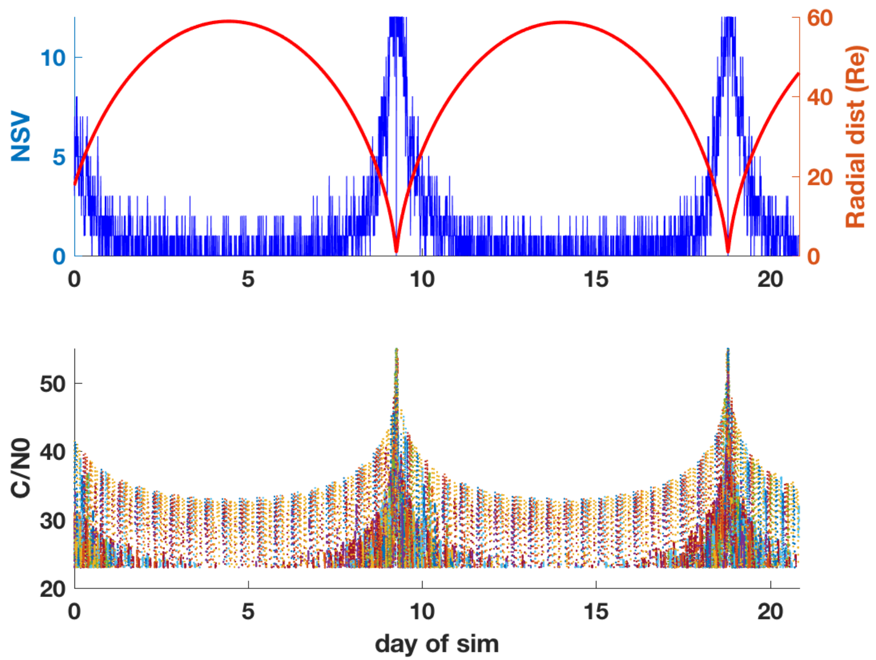




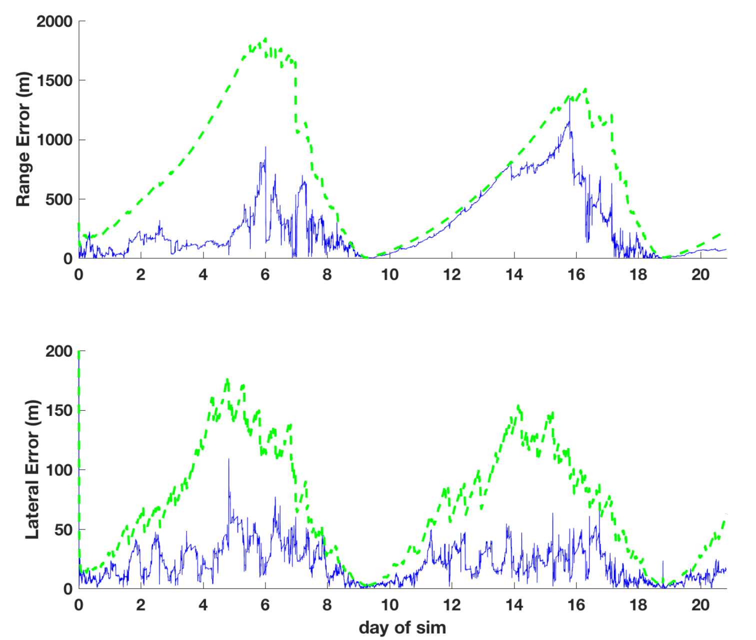
Concept MMS extended mission performance

- **How will MMS-Nav perform if they raise apogee to 60 RE in extended mission?**
- **Propagated MMS4 initial state for 20+ days using "truth dynamics," no maneuvers**
- **Use identical GEONS-Datagen configuration as in calibration, and similar filter config**
  - plus some extra process noise near perigee
- **Split errors in range/lateral direction**
  - Range/clock errors become highly correlated and dominate total position error, performance limited by clock instability.

Signals tracked and radial dist (top); C/N_0 (bottom)



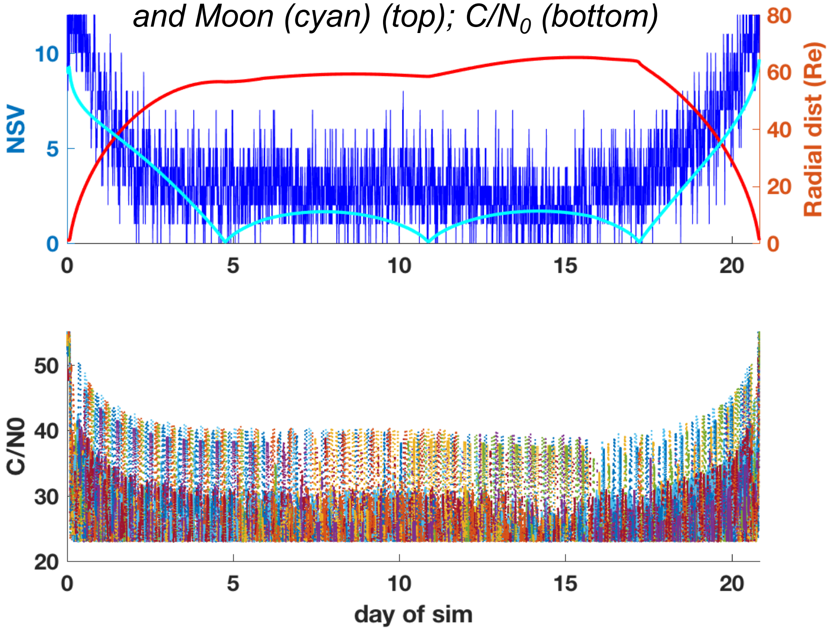
Filter position formal (3σ) and actual errors



Concept Lunar mission

- **How will MMS-Nav perform if used on a conceptual Lunar mission with 14dBi high-gain?**
  - GSFC internal research project aims to develop such an antenna
- **Used concept Lunar trajectory:**
  - LEO->translunar->Lunar (libration) orbit->return
- **Use identical GEONS-Datagen configuration as in calibration, and similar filter config:**
  - extra process noise near moon
  - high-gain switched on at 12RE
- **Visibility similar to MMS2B, as high-gain makes up for additional path loss**
- **Again, range/clock-bias errors dominate**
  - With atomic clock, or, e.g., periodic 2-way range/Doppler, could reduce range errors to meas. noise level

Signals tracked and radial dist to Earth (red) and Moon (cyan) (top); C/N_0 (bottom)



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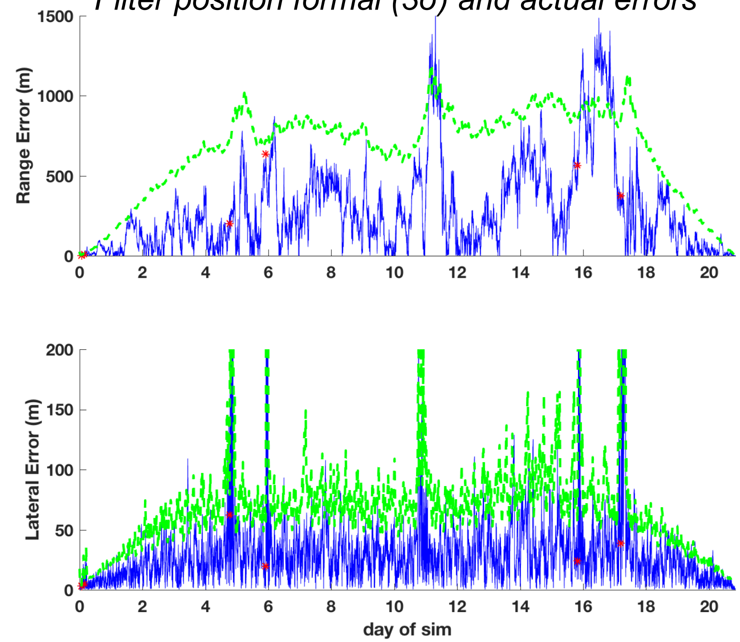

Conclusion

- **High altitude GPS is now a proven technology that can reduce operations costs and even enable missions like MMS (and GOES-16 now)**
  - Applications and receiver availability expanding rapidly
- **MMS currently in Phase 2B orbit at 25Re (40% to moon) navigating onboard with GPS using GSFC-Navigator receiver + GEONS filter software**
  - *Highest (and fastest) operational use of GPS (already was case in Phase 1)*
  - Onboard navigation significantly out-performing requirements
  - Signal visibility throughout Phase 1 and even Phase 2B orbit is excellent
  - Sidelobe signals appear to be of "navigation quality"
- **Conducted simulations to predict MMS-nav system performance on two concept trajectories reaching Lunar distances**
  - Receiver should continue to perform very well for MMS extended mission
  - MMS-nav system with high-gain could offer strong onboard navigation performance for future Lunar exploration or habitation missions
- **High-altitude GPS navigation performance will only get better with new GNSS systems, signals, and receiver tech, but we believe useful onboard GPS navigation at Lunar distances is achievable *now* using *currently available signals* and *flight proven* receiver technology**