Autonomous navigation above the GNSS constellations and beyond:

GPS navigation for the Magnetospheric Multiscale Mission and SEXTANT Pulsar navigation demonstration

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Scientific and Fundamental Aspects of GNSS / Galileo

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Outline

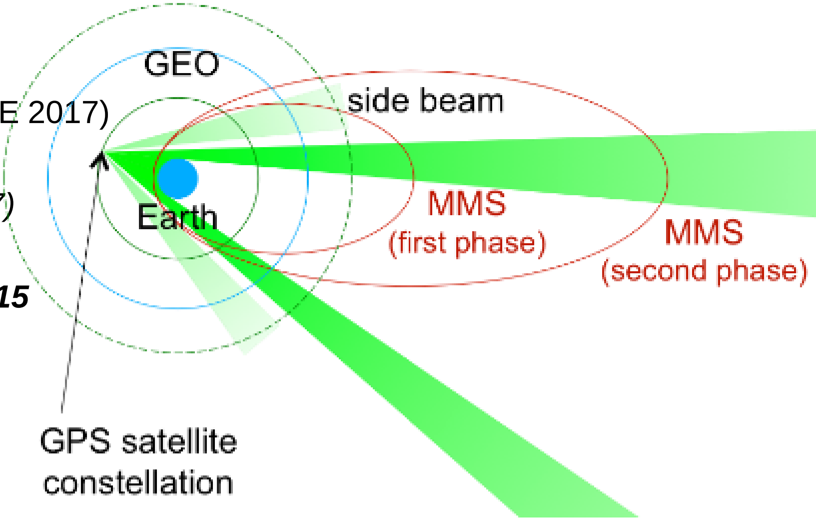
- **Part I: High altitude GPS Navigation for MMS**
  - High altitude GPS Navigation background and history
  - High altitude GPS Nav efforts at NASA
  - Magnetospheric Multiscale (MMS) Mission
    - Results from MMS Phase 1
    - New results from MMS Phase 2B
    - Performance projections at Lunar distances

- **Part II: Station Explorer for X-ray Timing and Navigation (SEXTANT)**
  - X-ray Pulsar Navigation (XNAV) background and history
  - NICER Mission and SEXTANT tech demo
  - SEXTANT XNAV system design
  - Performance predictions and early results

Background on high-altitude (HEO) GPS

- **HEO GPS navigation offers performance and cost improvements, but poses challenges**
  - Sparse mainlobe availability, sidelobes are weak, unspecified/uncharacterized, poor geometry, potentially harsher radiation environment.
- **Ongoing research in HEO GPS since 1990's, GSFC among leaders**
  - Simulations, protection, characterization of signals in the GPS Space Service Volume, receiver development (Navigator)
- **Early on-orbit experiments in late 1990's-early 2000's**
  - 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)*
  - *SmallGEO satellite (2017)*
  - ***NASA GSFC Navigator GPS flying HEO MMS since 3/2015***

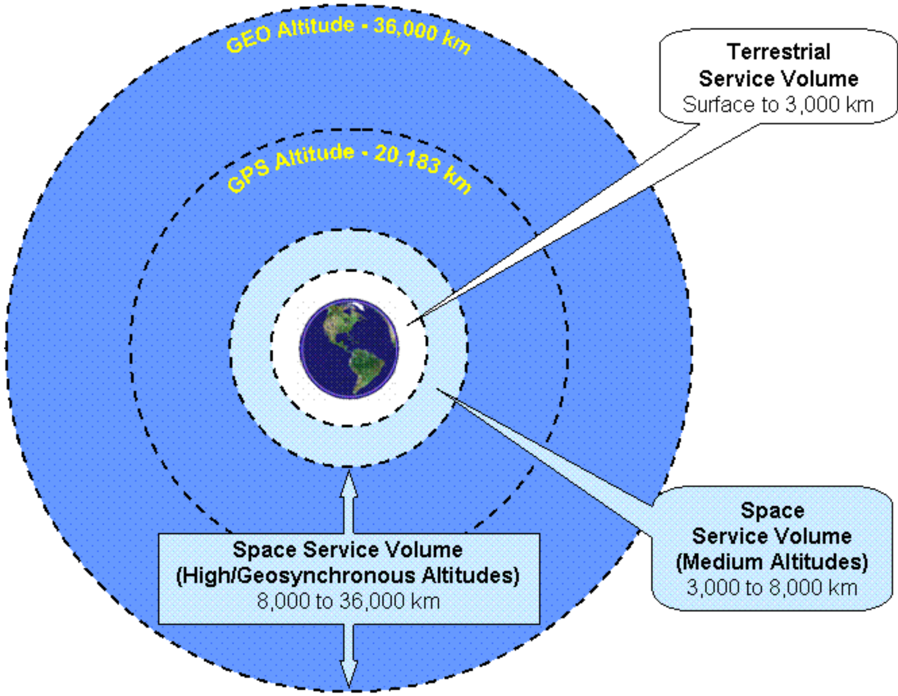
High-altitude GPS



MMS set records for highest (and fastest) GPS receiver operations to date

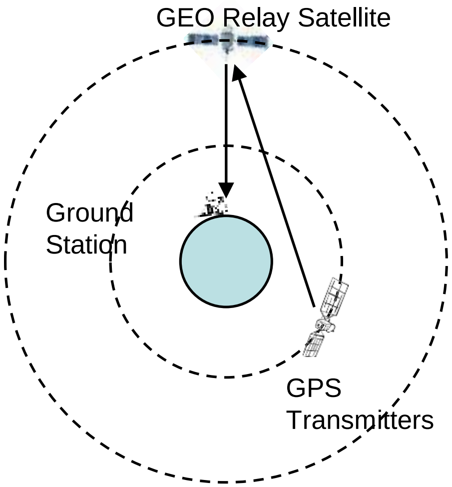
Space Service Volume (SSV) and Signal Characterization

- **GSFC has led the effort to define the Space Service Volume for Space users beyond LEO**
- **Working to continue to develop SSV along two lines**
  - Extend GPS SSV requirements to capture emerging users
  - Define interoperable multi-GNSS SSV with foreign providers.
- **Characterization of signals:**
  - Public release of Lockheed Martin data on GPS Block IIR & IIR(M) antenna patterns on www.gps.gov (2015)
    - Quantifies antenna characteristics, including main & side lobe gain, enabling improved simulation
  - On-orbit experience with MMS,GOES-16, GPS-ACE

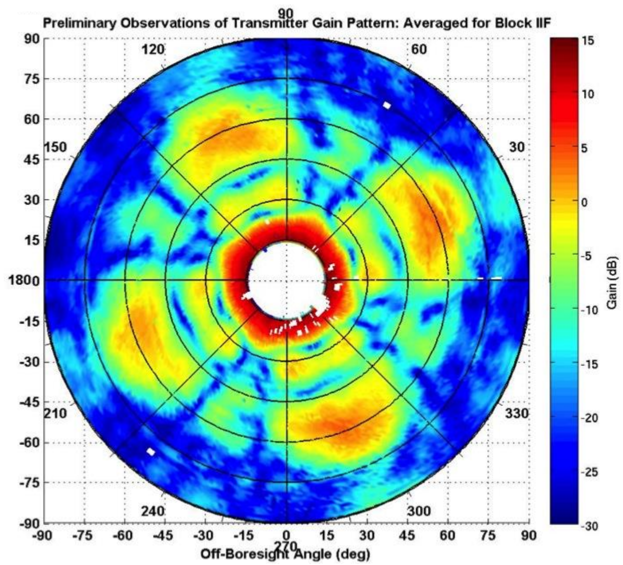


ACE: GPS Antenna Characterization Experiment (Aerospace Corp. and NASA/GSFC)

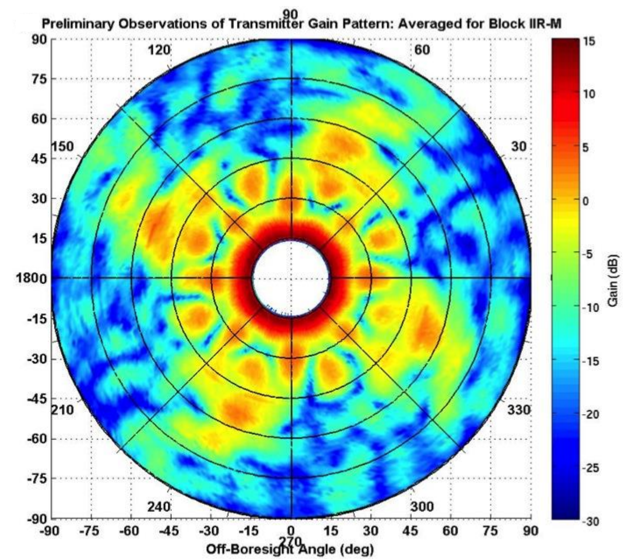
- **Goal: Characterize GPS transmitter patterns in sidelobes: Improve transmit models for HEO, verify requirements for signals in GPS SSV.**
- **Method: Process "bent-pipe" GPS signals received by GEO vehicle and transmitted to ground site using**
- **Results:**
  - **Unprecedented new knowledge of complete "as-flown" GPS transmit antenna patterns including side lobes**
  - **Initial pseudorange accuracy characterization indicates**
  - **Realtime navigation experiment at GEO**



In-Flight Measurement Average from IIF SVs



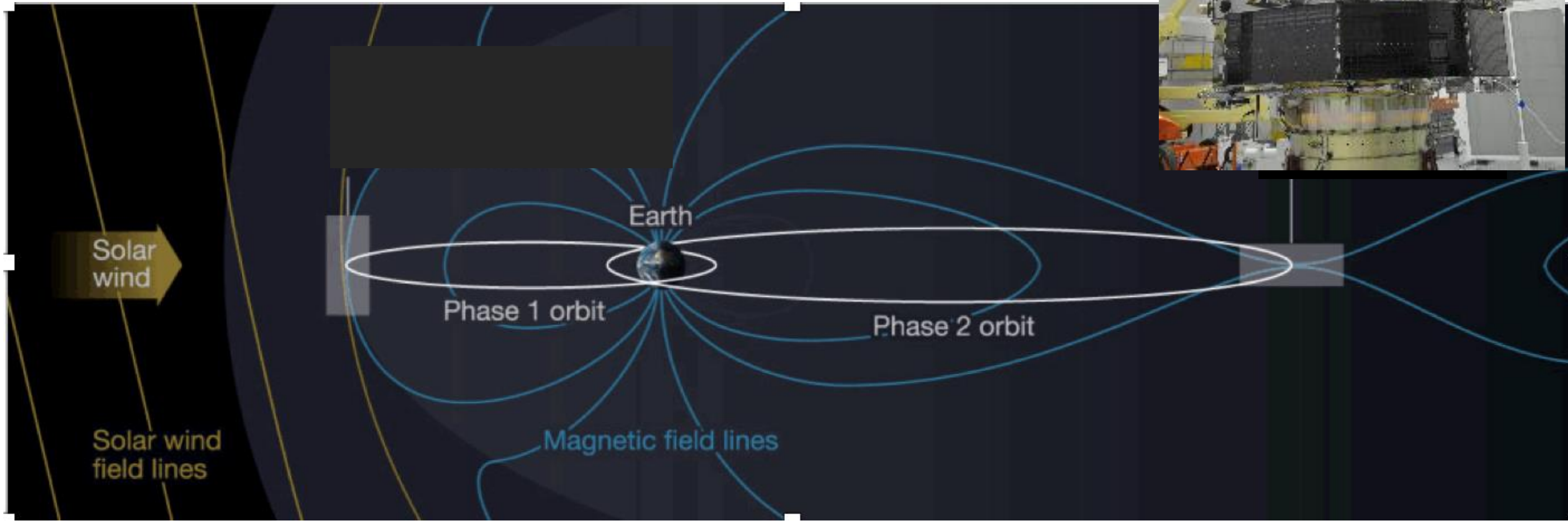
In-Flight Measurement Average from IIR-M* SVs



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)

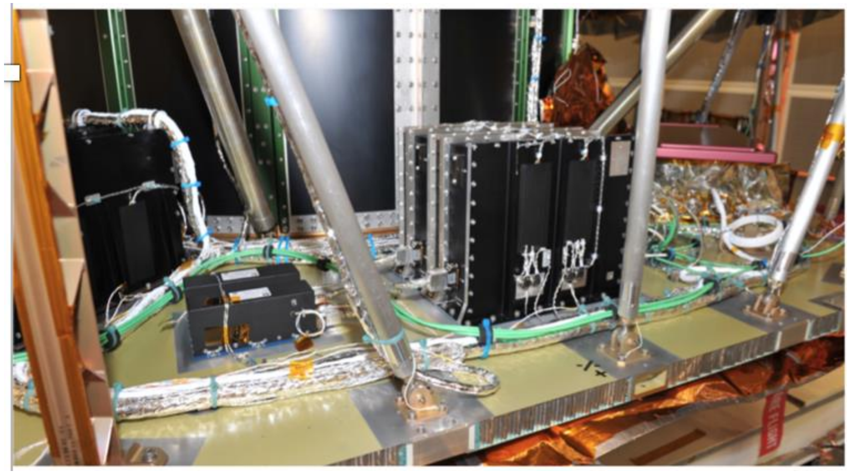


E. Conant, N. Kaloterakis and M. Twombly, "Look Inside the Tools NASA Uses to Study Space Weather," National Geographic, 10 10 2015. [Online]. Available: http://news.nationalgeographic.com/2015/10/151010-datapoints-look-inside-the-tools-nasa-uses-to-study-space-weather/.

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 high-altitude receiver**
  - Rad-hard, C/A code receiver, with fast,weak signal acq (<25dB-Hz), ultra stable crystal oscillator
  - 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, 4th/8th order RK integrator, realistic process noise models. High-fidelity dynamics and many measurement models available.
  - Heritage dating back to 1980’s, now flying Terra (2000), GPM(2014), MMS(2015), NICER/SEXTANT (2017), planned on missions for 2020’s.
  - Process GPS pseudorange for MMS

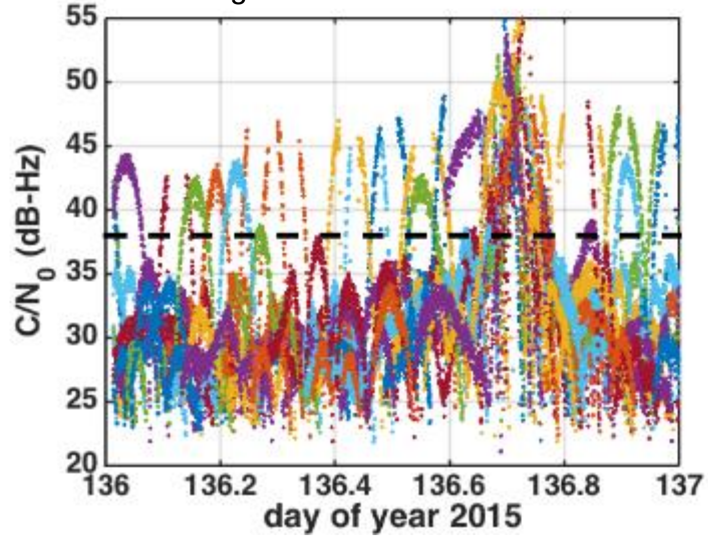
- **MMS Navigation main challenges**
  - Very high-altitude
  - Spin stabilized at 3RPM; four antennas around perimeter, receiver implements handoff tracking technique antenna-to-antenna every 5s



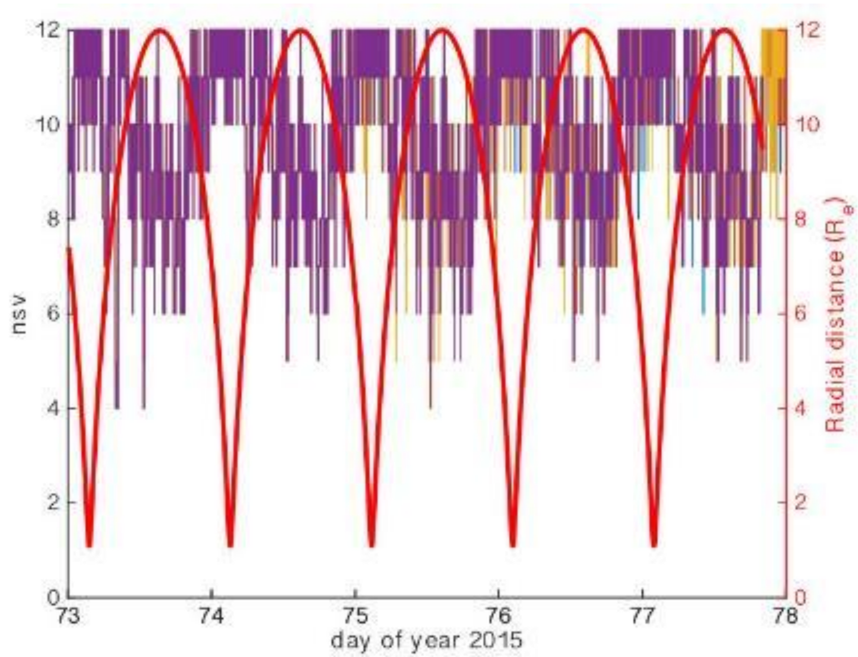
Phase 1 Performance: signal tracking

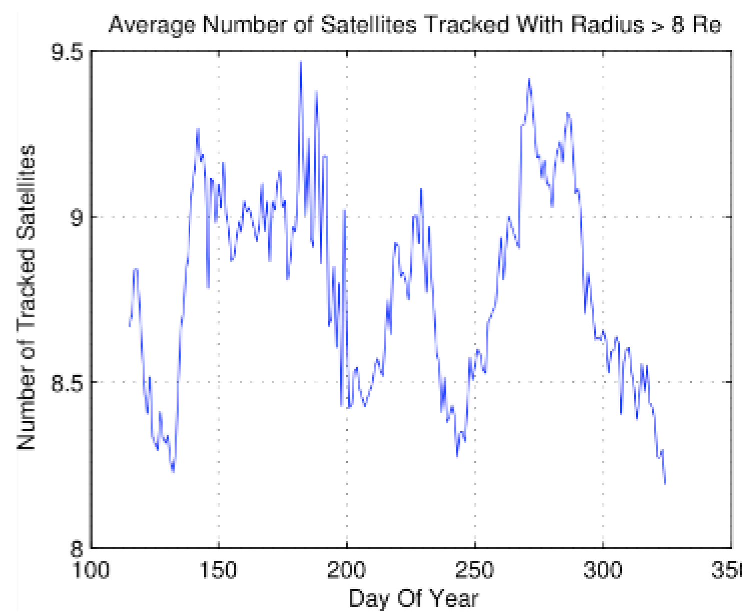
- Once powered, receiver began acquiring weak signals and forming point solutions
- Long term trend shows average of >8 signals tracked above $8R_E$
- Above GPS constellation, vast majority of these are sidelobe signals
- Visibility exceeded preflight expectations

Signal to noise vs. time



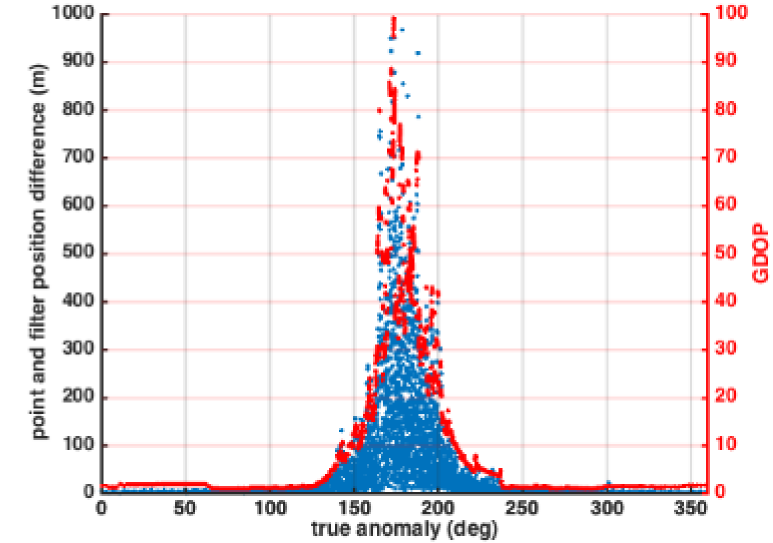
Signals tracked during first few orbits

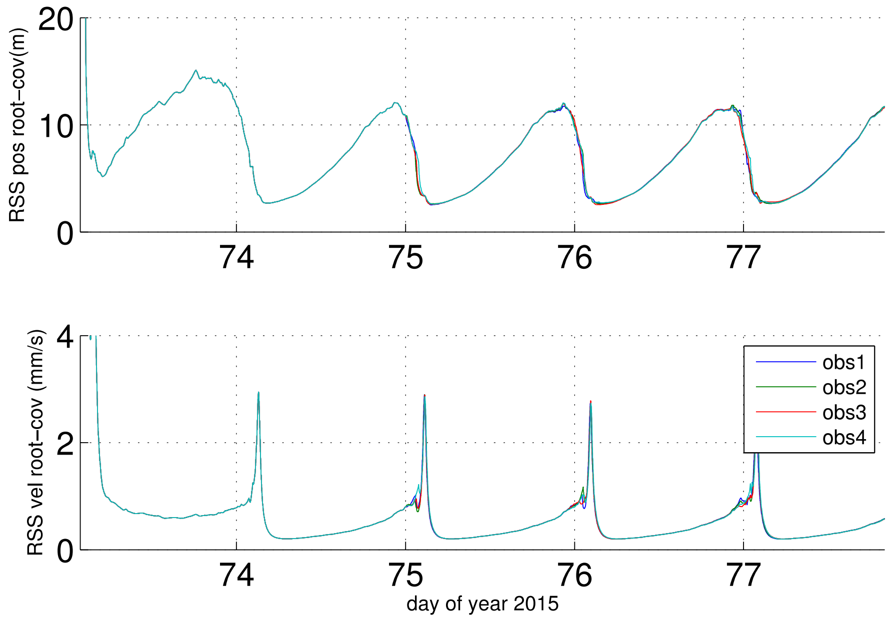


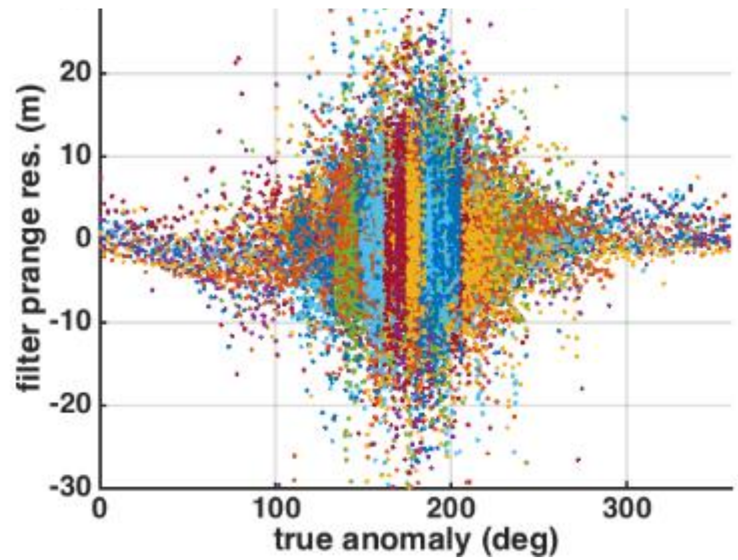


Phase 1 results: measurement and navigation performance

- **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.**





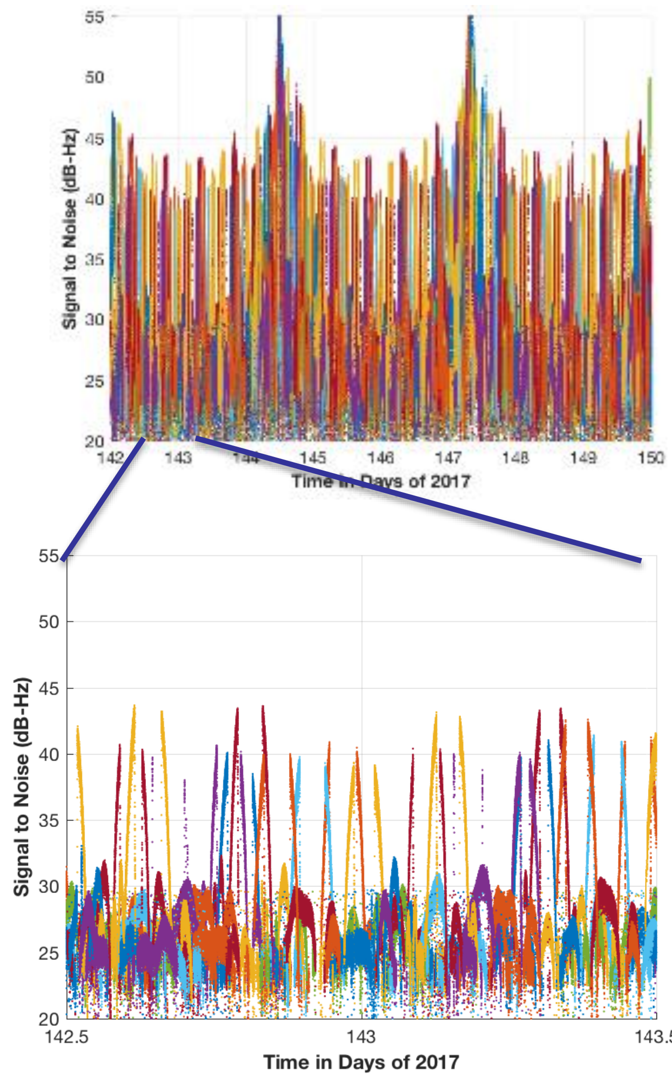


On-orbit Phase 2B results: signal tracking

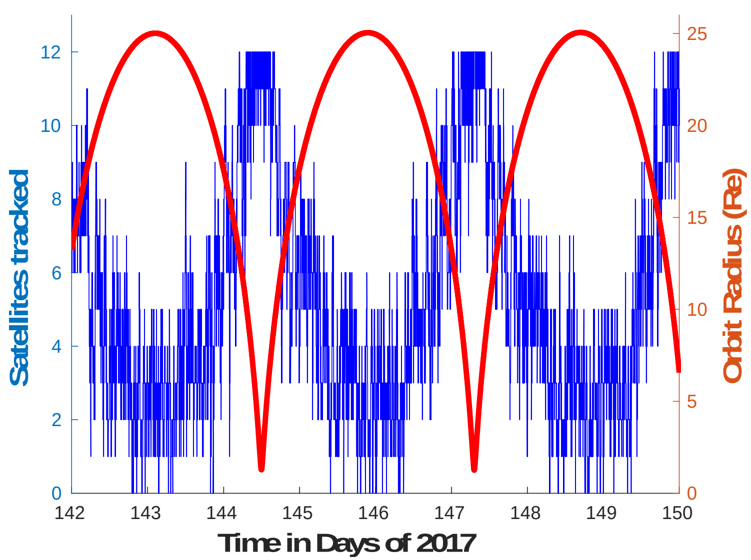
Goddard Space Flight Center

- **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

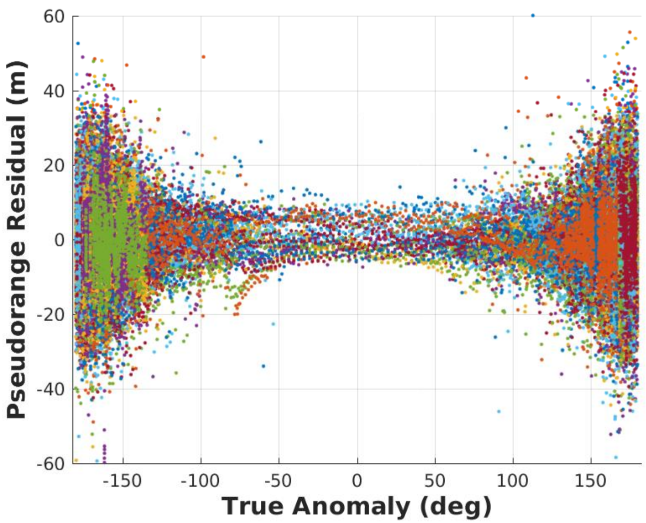


Signals tracked

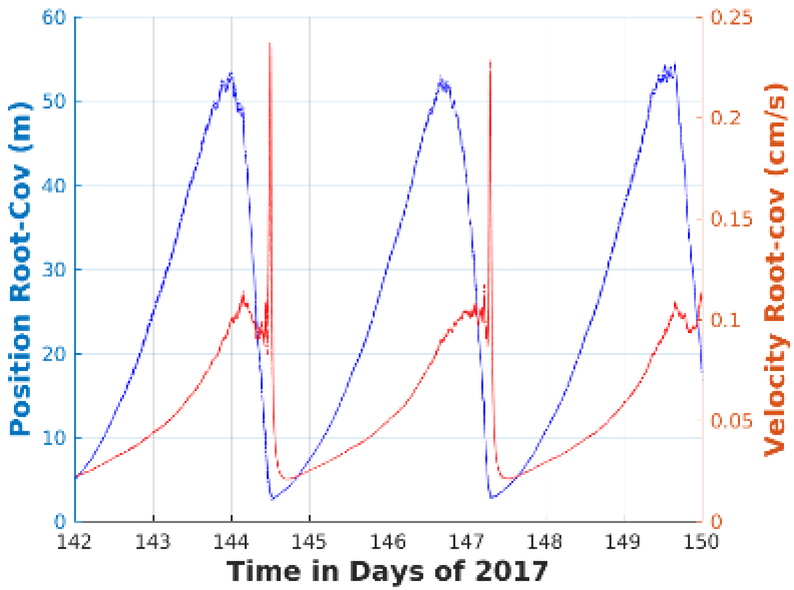


On-orbit Phase 2B results: measurement and navigation performance

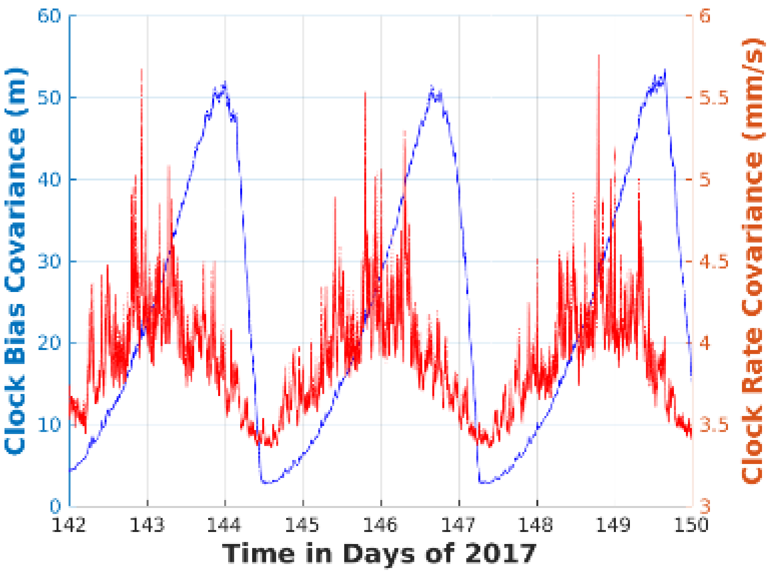
- **GEONS filter RSS 1-sigma formal errors reach maximum of ~50m and briefly 5mm/s (typically <1mm/s)**
- **Measurement residuals are zero mean, of expected variation <10m 1-sigma.**
  - Suggests sidelobe measurements are of high quality.



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

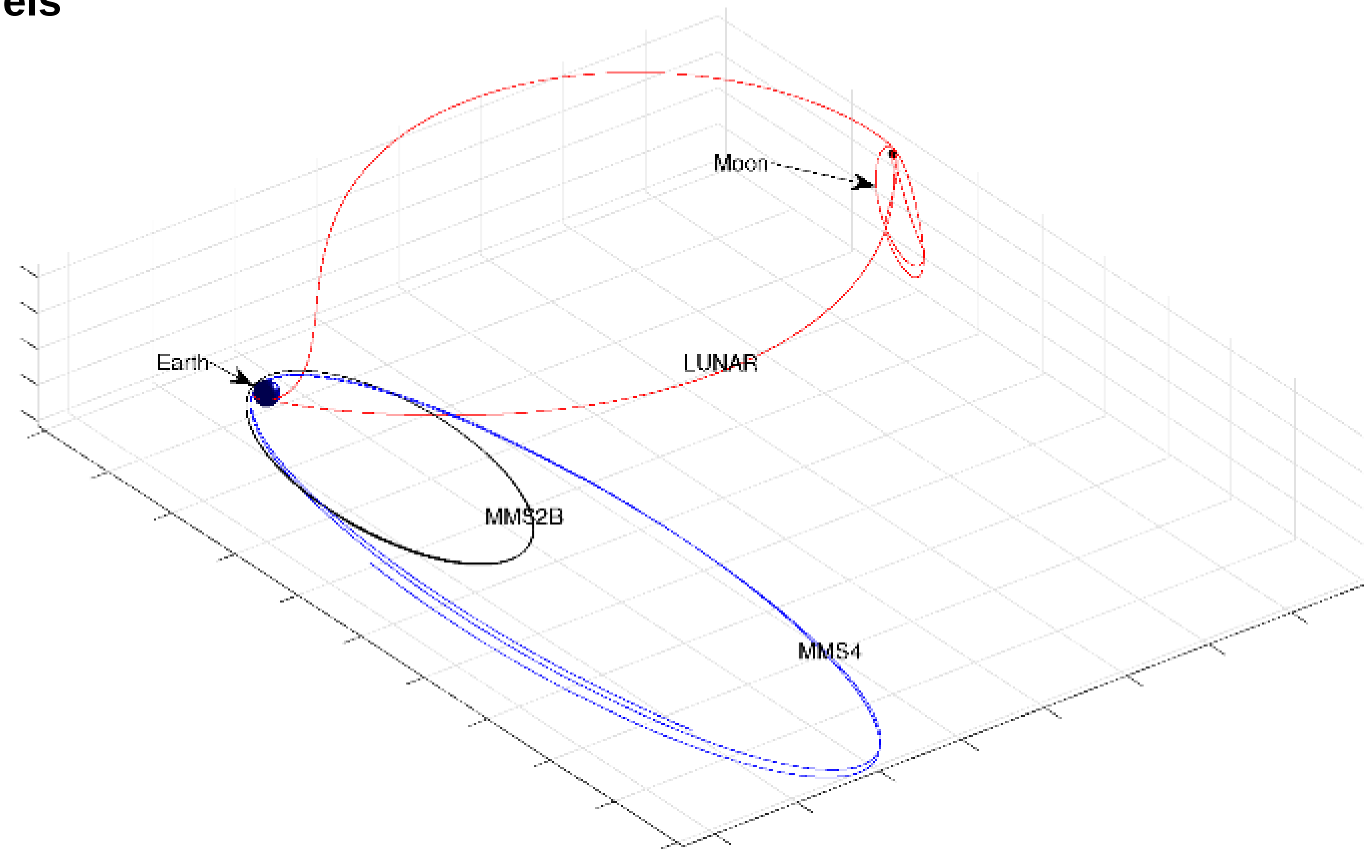


Filter formal clock errors (1σ root cov)



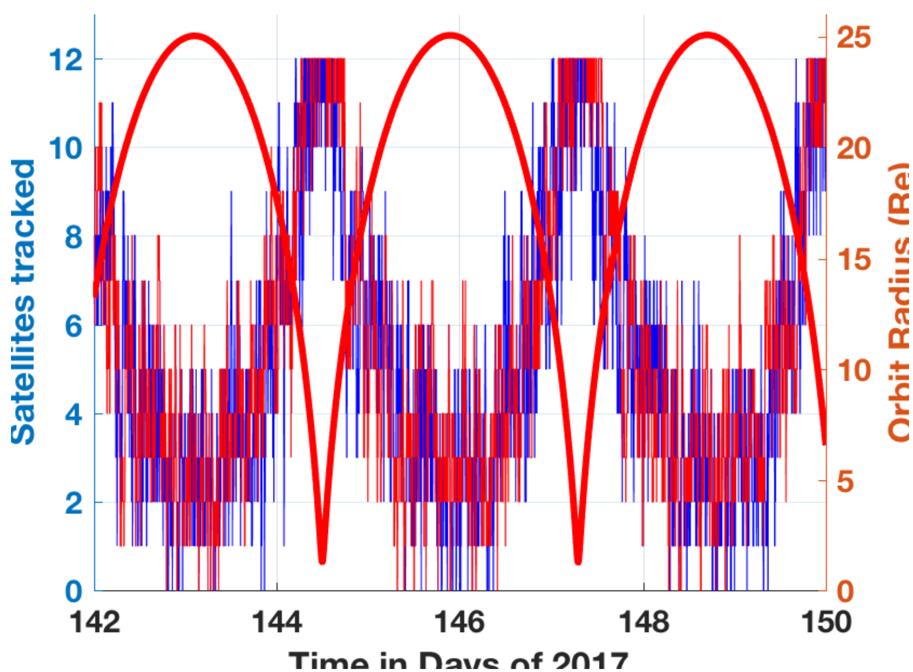
GEONS simulations at lunar distances

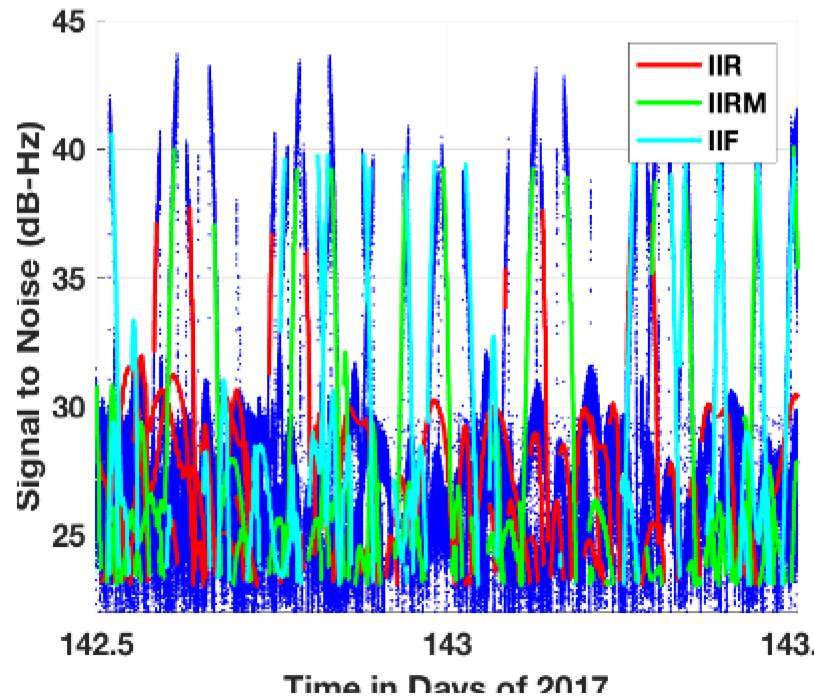
- **Ran GEONS ground simulations to "get a feel for" performance of MMS-Navigation system in:**
  1. A concept MMS extended mission orbit with apogee raised to 60 RE
  2. A concept Lunar trajectory – using high-gain receive antenna
- **First though, use MMS2B flight data to recalibrate GPS measurement simulation models**



Ground simulation recalibration using MMS2B on-orbit data

- Propagated initial state from flight data, same period as flight data plots
- Used GEONS/Datagen, with representative GPS Block IIR and IIRM transmit ant. pats
- Compared signals tracked and C/N_0 simulated vs. flight; adjusted receiver loss and GPS transmit power per-block to line up
- Obtained a close *qualitative* match between simulated and observed signals

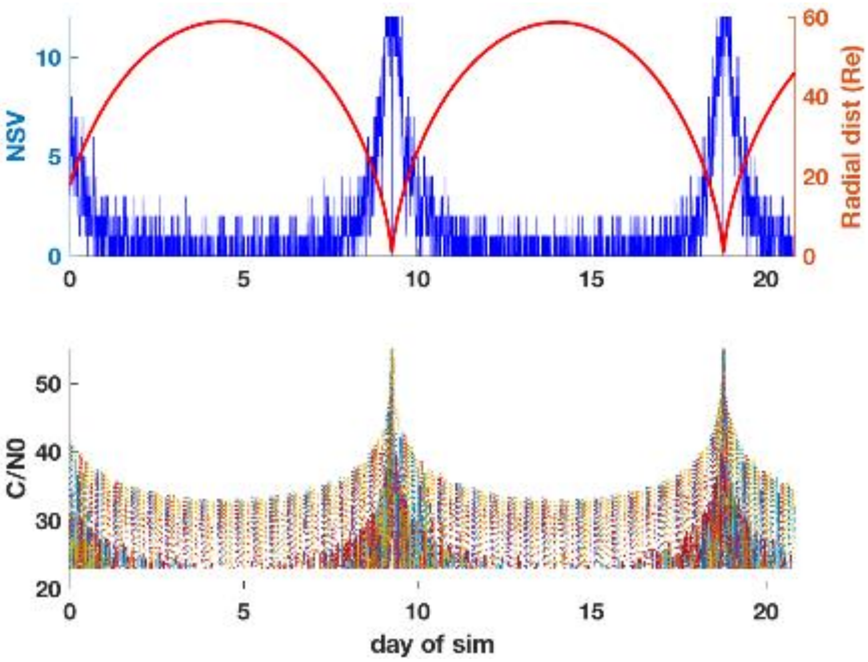




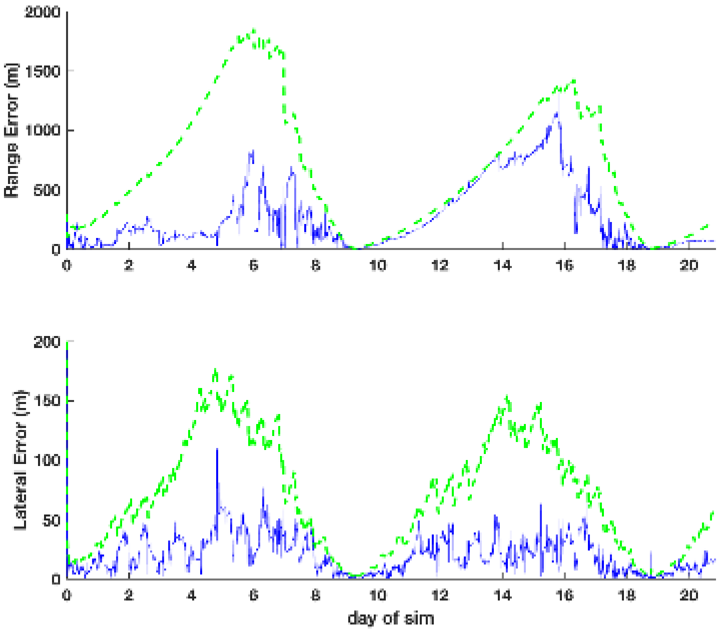
Concept MMS extended mission performance

- **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, range knowledge limited by clock instability.

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

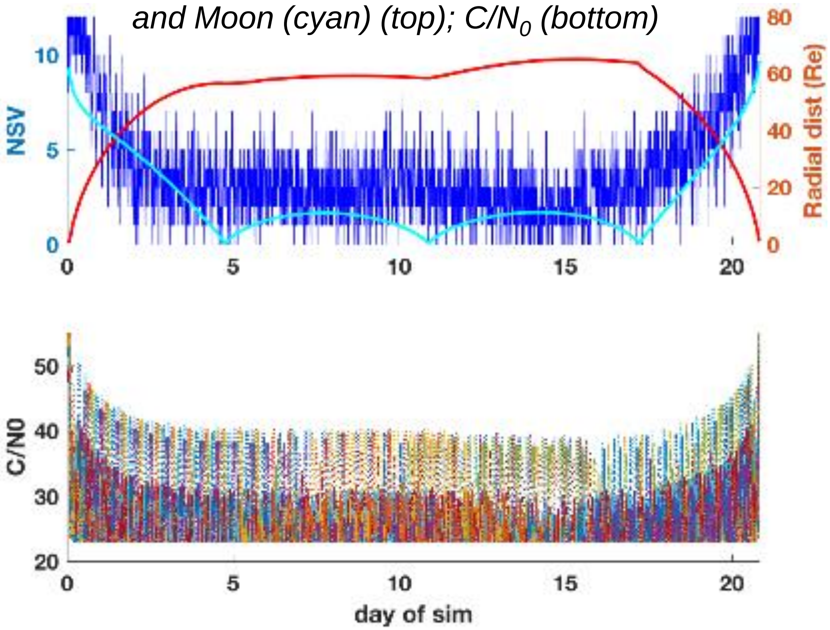


Filter position formal (3σ) and actual errors

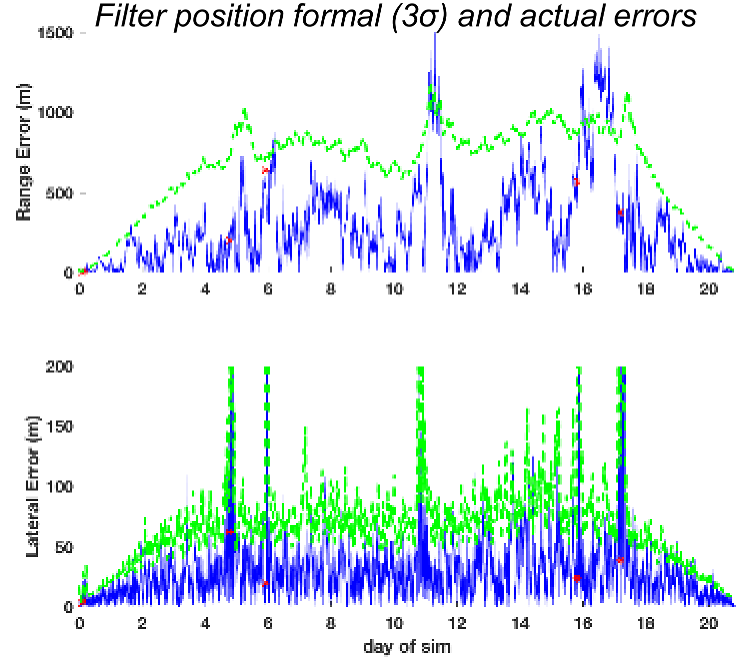


Concept Lunar mission

- **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)



Filter position formal (3σ) and actual errors

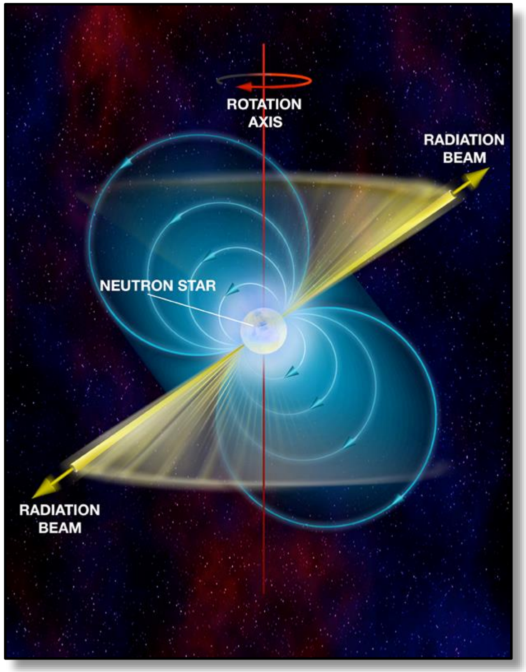
Conclusion and bridge to part II

- **High altitude GNSS navigation is now a proven technology that can reduce operations costs and enable missions like MMS**
  - Applications and receiver availability expanding rapidly
- **MMS currently in Phase 2B orbit with apogee 40% to Moon**
  - *Highest (and fastest) operational use of GPS*
  - Onboard navigation significantly out-performing requirements and preflight expectations.
- **Simulations suggest strong onboard GPS navigation at or somewhat beyond Lunar distances is achievable *now* using *currently available signals* and *flight proven* receiver technology**

- **Far from the Earth, an autonomous onboard navigation technique, analogous to GNSS, but largely free from the geometry and signal degradation limitations of GNSS, is in the midst of its first on-orbit demonstration in NASA's NICER/SEXTANT project…**

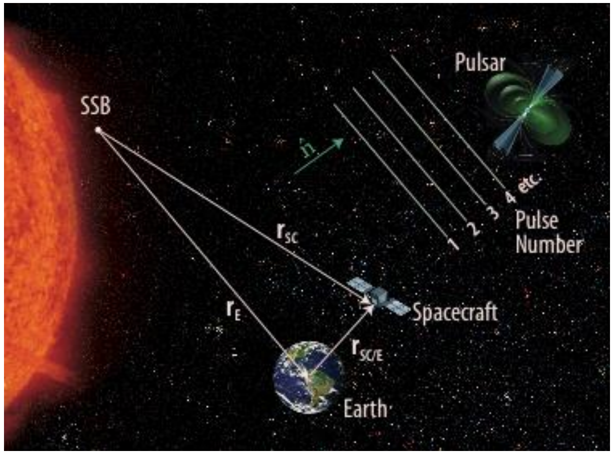
X-ray pulsar navigation (XNAV)

- **Millisecond pulsars (MSPs) are rapidly rotating neutron stars that appear to pulsate across the electromagnetic spectrum**
- **Some MSPs have long-term timing stability that rivals that of atomic clocks**
  - Pulse arrival phase can be predicted with great accuracy at any reference point in the Solar System through use of a pulsar timing model on a spacecraft
  - Comparing observed phase to predictions gives information that may be used in a navigation process



- **Why X-rays?**
  - Some stable MSPs have "strong" X-ray emissions
  - X-ray are immune to interstellar dispersion effects thought to limit radio pulsar timing models
  - Highly directional compact detectors possible

- **Main Challenge: *MSPs are very faint!***

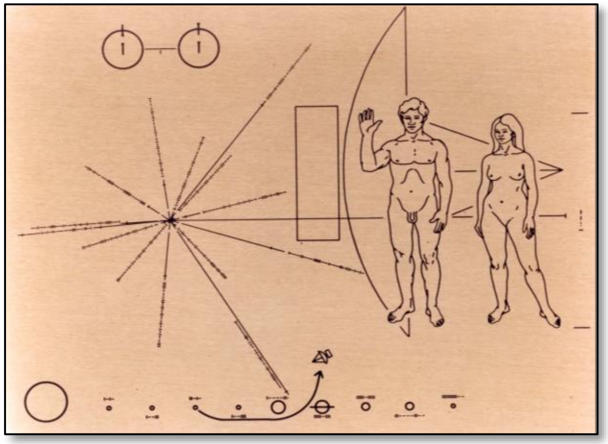


X-ray pulsar Navigation (XNAV)

Applications

- **XNAV can provide autonomous navigation and timing that of uniform quality throughout the solar system**
  - Enabling technology for very deep space missions
  - Backup autonomous navigation for manned space flight
  - Complementary to DSN or op-nav techniques
  - Autonomous navigation behind the Sun

Pioneer plaque (Pioneer 10,11 1972-73) with Pulsar periods and relative distances to our Sun



History

- **Pulsars were discovered in 1967 and immediately recognized as a potential tool for Galactic navigation**
- **US Naval Research Laboratory (NRL) (1999-2000)**
  - Unconventional Stellar Aspect (USA) Experiment
- **DARPA XNAV, XTIM Projects (2005-2006, 2009-2012)**
- **Significant body of research (international interest, academic research, several Ph.D. dissertations, etc.)**

- ***NICER/SEXTANT (2013 selection, 2017 launch) builds on previous work to perform the first in-space, real-time demonstration and validation of XNAV***

Neutron Star interior Composition ExploreR (NICER)

- Launched in June 3, 2017 on Space-X CRS-11 to ISS
- Installed X-ray Timing Instrument to ELC-3: *An unprecedented combination of time resolution, energy resolution, and sensitivity*
- Fundamental investigation of *ultra-dense* matter: structure, dynamics, & energetics
- Will determine the radii of neutron stars to 5%, an order of magnitude better than known today
- 18 Month mission on ISS Express Logistics Carrier
- **NICER XTI's Combination of low-background, large area, precise timing, scalability, and low-cost makes it nearly ideal for XNAV**

Station Explorer for X-ray Timing and Navigation Technology (SEXTANT)

NASA Space Tech Mission Directorate Game-Changing Division funded technology enhancement to NICER

SEXTANT Primary Objective: *Provide first demonstration of real-time, on-board X-ray Pulsar Navigation*

- Implement fully functional XNAV system in a challenging ISS/LEO orbit
- Advance core XNAV technologies

Performance target

- 10 km (1km stretch) accuracy, worst direction in 2 weeks

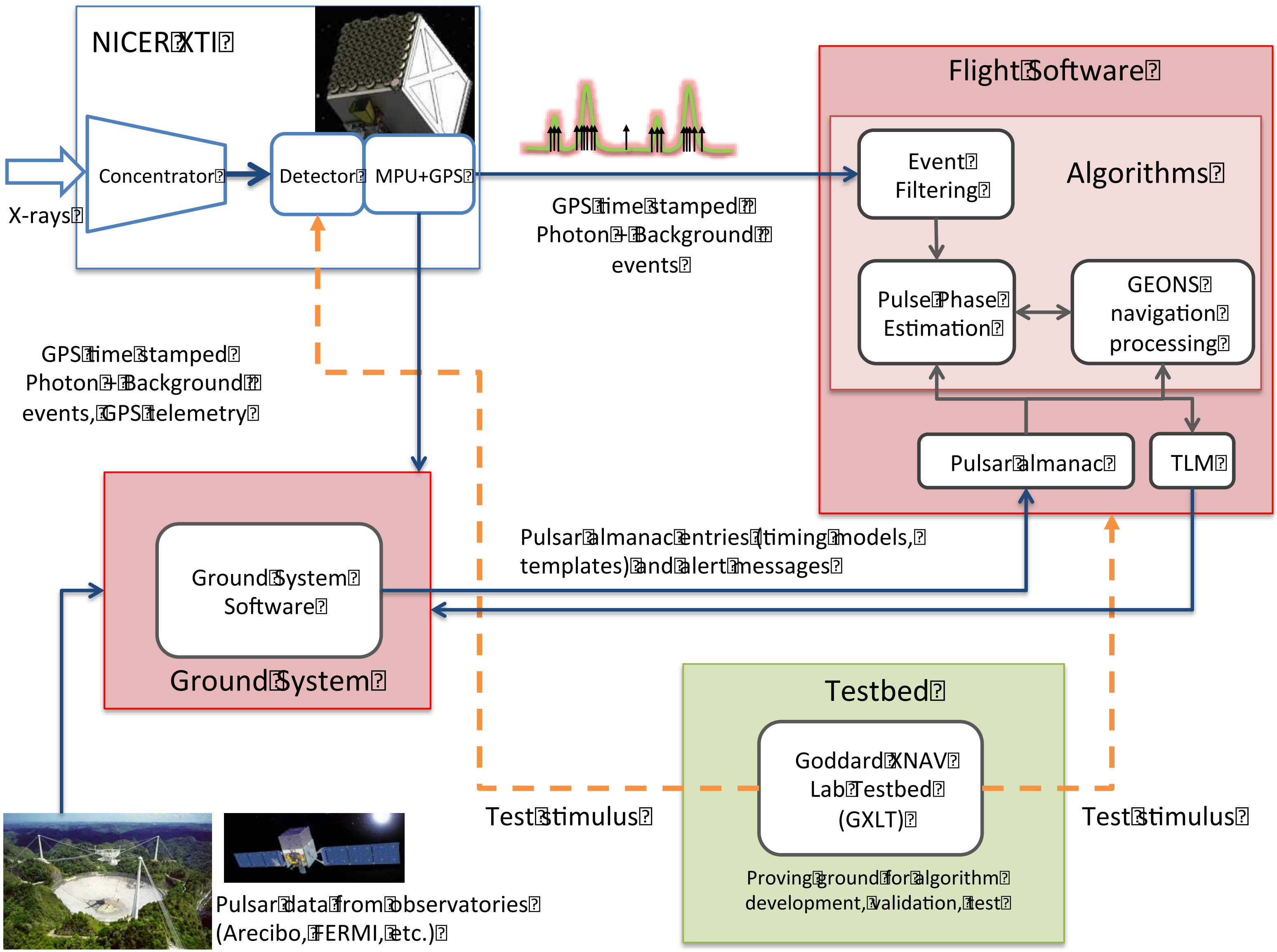
Planned Experiments

- Two 2 week periods where SEXTANT controls pointing schedule
- Opportunistic on-orbit experiments
- Ground experiments using collected photon data

Other objectives

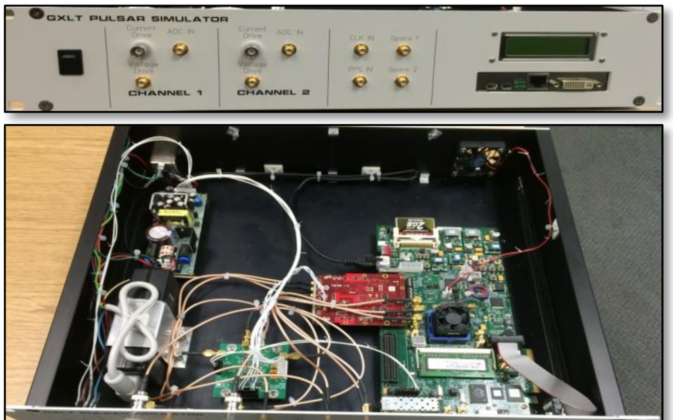
- Validate and enhance the SEXTANT ground testbed
- Use SEXTANT ground testbed to study "real-world" XNAV scenarios and evaluate alternative algorithms
- Study utility of pulsars for time keeping and clock synchronization
- Expand the catalog of XNAV Pulsars

SEXTANT System Architecture



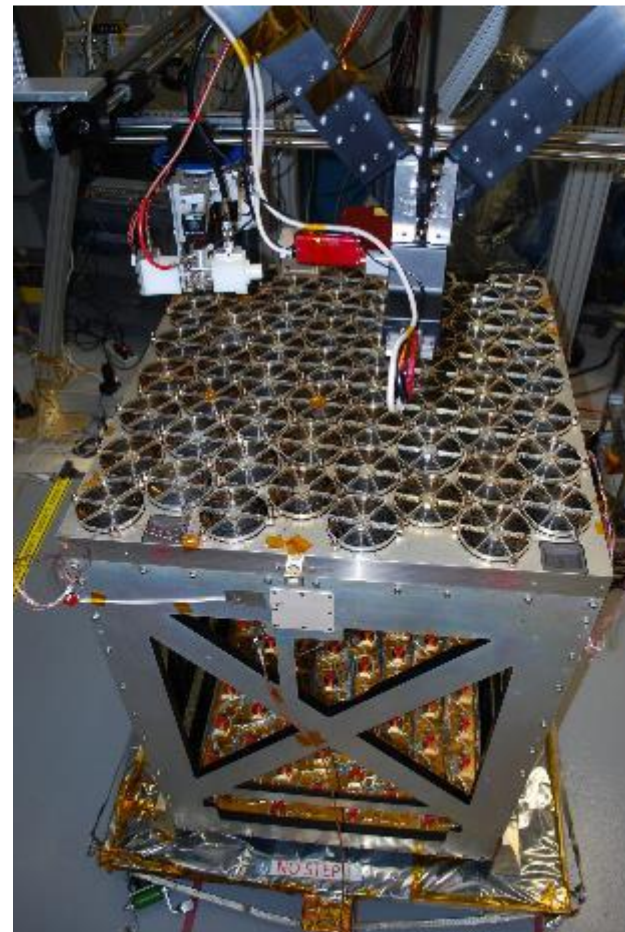
Test-as-you-fly XNAV simulation ground validation

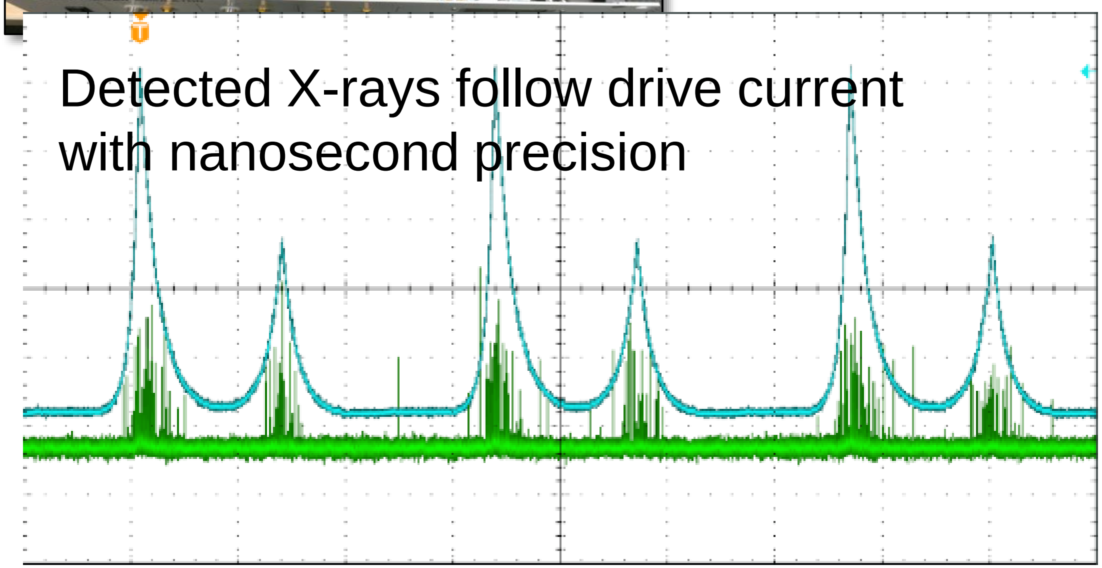
MXS control electronics



Modulated X-ray source (MXS)

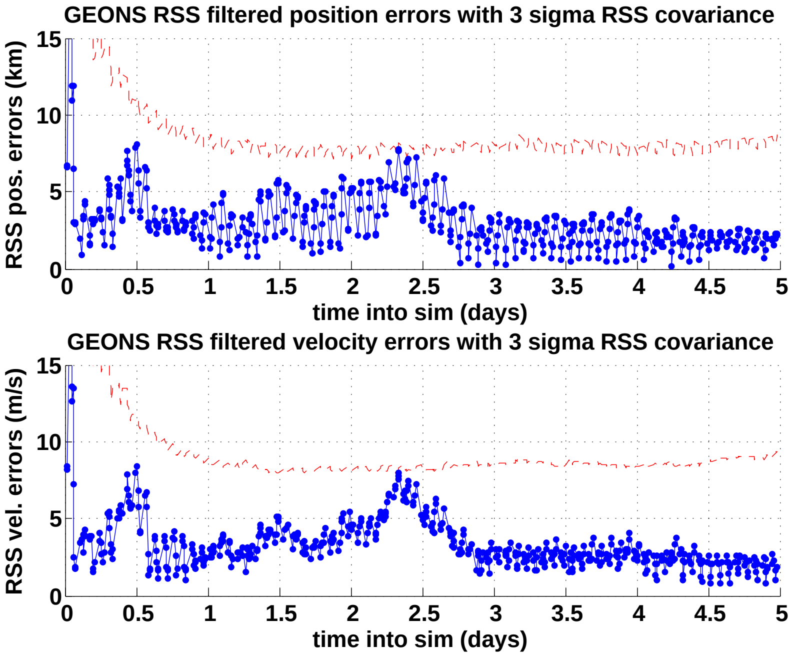
Payload with MXS stimulating each detector

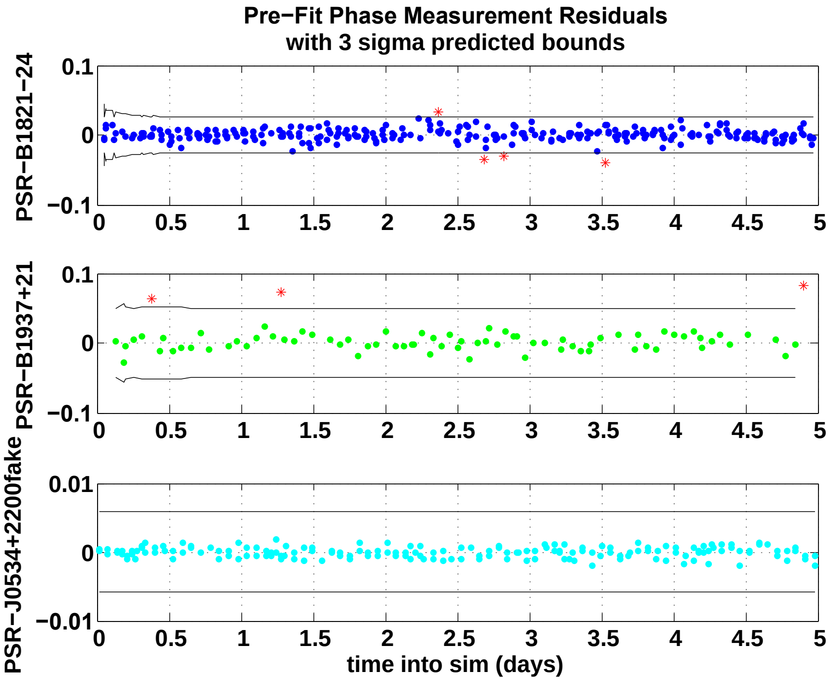




Preflight "baseline" simulation results

- **Standard 5-day test using software simulated events in GXLT level-1 simulation**





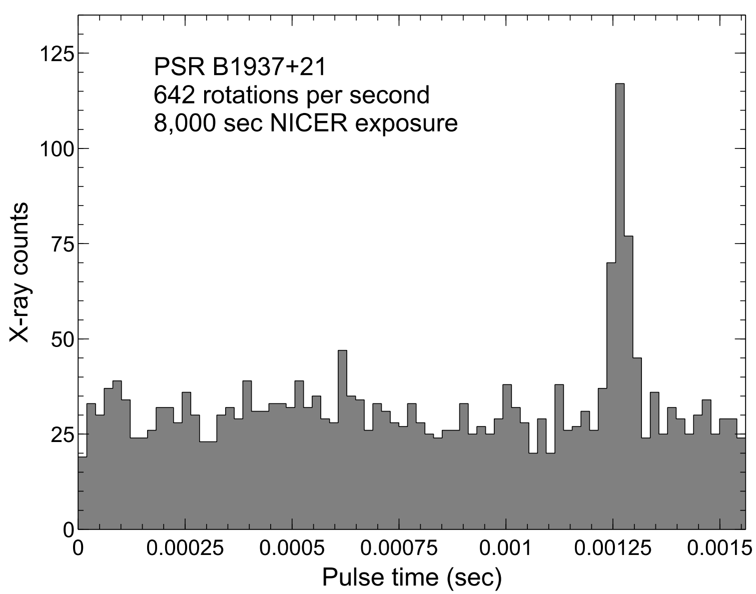
- Red is 3-sigma formal error
- Blue is actual error
- Baseline performance meets target accuracy

- Phase residuals (in cycles) consistent with predicted variance

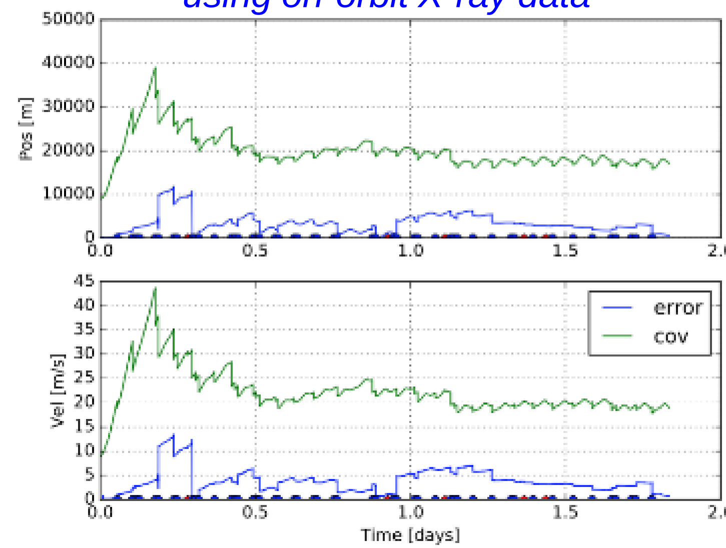
Early on-board results

- **NICER launched June 3, 2017, successfully completed commissioning and is producing fantastic science already**
- **SEXTANT team is making steady progress toward stated goals**
  - Conducted baseline, and refined pulsar model calibration
  - Refining tools for XNAV post-processing, and observation scheduling
  - Developing refinements to XNAV FSW for future update
  - Running opportunistic ground and on-orbit navigation experiments when NICER schedule supports (includes sufficient XNAV target observations)
  - Preparing for official on-board experiments

Early detection of PSR B1937+21



Promising 2-day XNAV ground experiment using on-orbit X-ray data



XNAV summary

- **XNAV could be an enabling technology for autonomous deep space navigation and a complement to alternate (DSN and op-nav) techniques.**
- **NASA's NICER is the first mission dedicated to the study of pulsars. Its timing instrument on the ISS provides an unprecedented combination of time resolution, energy resolution, and sensitivity, and provides a nearly ideal sensor for an XNAV demonstration.**
- **SEXTANT is an attached technology demonstration that will**
  - Provide the first on-orbit demonstration of XNAV on-board and in real-time
  - Implement a fully functional XNAV system in a challenging ISS/LEO orbit targeting 1-10km orbit determination accuracy
  - Advance core XNAV technologies hardware and software
- **The SEXTANT flight system was verified in a unique hardware-in-the-loop, test-as-you-fly testbed and is now operating on the ISS and is making steady progress toward its stated goals.**

Credits and a few references

- **Credit to MMS Navigator GPS development team and MMS flight dynamics team**
- **Credit to NICER and SEXTANT development teams**
- **References (MMS)**
  - *New High Altitude GPS Navigation Results from the Magnetospheric Multiscale Spacecraft and simulations at Lunar Distances*; Winternitz, Luke B.; Bamford, William A.; Price, Samuel R.; Proceedings of ION GNSS+ 2017;
  - *Global Positioning System Navigation Above 76,000 km for NASA's Magnetospheric Multiscale Mission*; Winternitz, Luke B.; Bamford, William A.; Price, Samuel R.; Carpenter, J. Russell; Long, Anne C.; Farahmand, Mitra, NAVIGATION, Summer 2017;
- **References (NICER/SEXTANT)**
  - *SEXTANT X-Ray Pulsar Navigation Demonstration: Flight System and Test Results*;Winternitz, Luke M. B.; Mitchell, Jason W.; Hassouneh, Munther A.; Valdez, Jennifer E.; Price, Samuel R.; Semper, Sean R.; Yu, Wayne H.; Ray, Paul S.; Wood, Kent S.; Arzoumanian, Zaven; Gendreau, Keith C. IEEE Aerospace Conference 2016;
  - *X-ray Pulsar Navigation Algorithms and Testbed for SEXTANT;* Winternitz, Luke M. B.; Hasouneh, Monther A.; Mitchell, Jason W.; Valdez, Jennifer E.; Price, Samuel R.; Semper, Sean R.; Yu, Wayne H.; Ray, Paul S.; Wood, Kent S.; Arzoumanian, Zaven; Gendreau, Keith C.; IEEE Aerospace Conference 2015;
- **All available at https://ntrs.nasa.gov**

Thank you.