A High-Fidelity Performance and Sensitivity Analysis of X-ray Pulsar Navigation in Near-Earth and Cislunar Orbits

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Outline

- X-ray Pulsar Navigation (XNAV) Background
- Simulation Architecture and Assumptions
- Navigation and Sensitivity Analysis
- Conclusions
- Future Work

X-ray Pulsar Navigation (XNAV) Background

- **Millisecond pulsars (MSPs) are rapidly rotating neutron stars that appear to pulsate across the electromagnetic spectrum.**
- **Some MSPs have atomic-clock like long-term timing stability**
  - 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 for navigation
  - Some stable MSPs emit in X-ray band, X-rays immune to interstellar dispersion effects thought to limit radio pulsar timing models, Highly directional compact detectors possible
  - XNAV Main Challenge: MSPs are very faint!
- **Applications**
  - XNAV can provide autonomous navigation and timing that is of uniform quality throughout the solar system
  - Possible enabling technology for very deep space missions
  - Provides backup autonomous navigation for crewed missions
  - Augments Deep Space Network (DSN) or op-nav techniques
  - Allows autonomous navigation while occulted, e.g., behind 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)
  - Durable academic/international research interest and activity

- **NICER/SEXTANT built on previous work to perform the first in-space, real-time demonstration and validation of XNAV in 2017**

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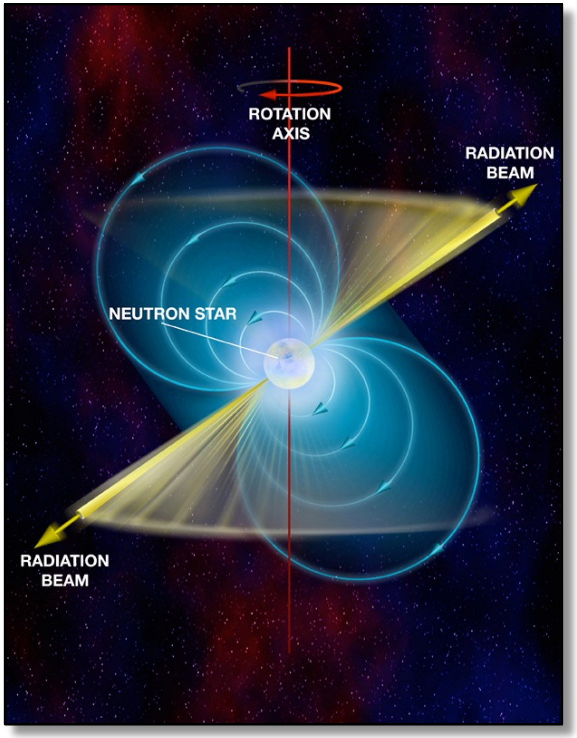
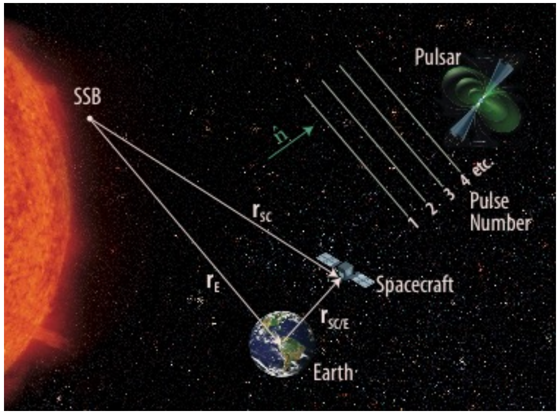
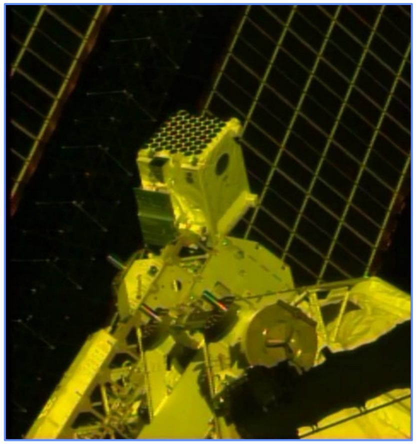




NICER/SEXTANT

- **NICER Neutron Star Interior Composition Explorer**
  - NICER Launched on June 3, 2017 on Space-X CRS-11 to ISS with 18 month nominal mission
  - Fundamental investigation of ultra-dense matter: structure, dynamics, & energetics, determine the radii of neutron stars to 5%, an order of magnitude better than known today
- **NICER X-ray Timing Instrument (XTI) 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 (SEXTANT)**
  - NASA Space Tech Mission Directorate Game Changing Development funded technology enhancement to NICER
  - 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
  - Provide ~10 km level navigation



NICER on ISS

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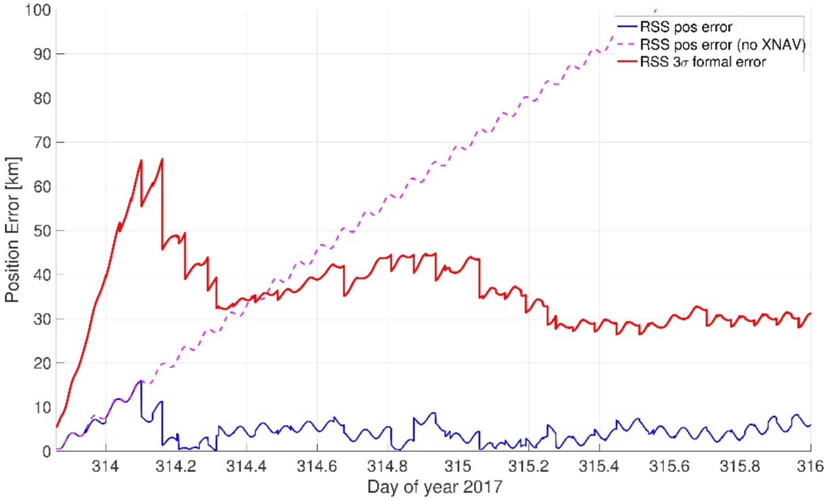
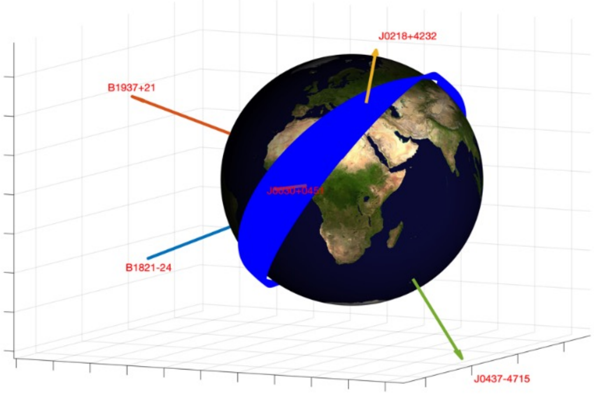
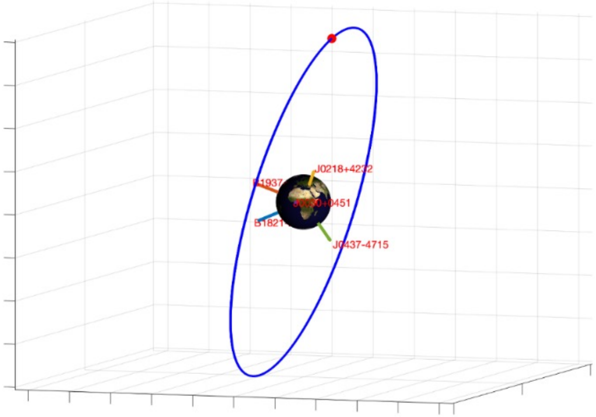


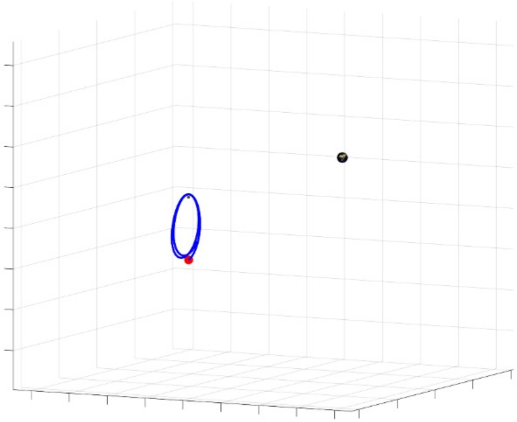
SEXTANT onboard performance

New XNAV Simulation Overview

- **Developed general simulation tool to study XNAV system performance in arbitrary scenarios**
  - Leveraged SEXTANT experience, flight software, and simulation tools
  - Added XNAV capability to the actively developed GEONS Ground MATLAB Simulation (GGMS) tool: XNAV-Enhanced GGMS=XGMS
  - The XGMS follows basic approach of SEXTANT, but incorporates numerous enhancements developed as part of this project
- **Used XGMS to study three specific cases – each challenging for different reason**
  - ISS-like LEO at 400 km altitude, 55° deg inclination
  - Highly Inclined Geosynchonous Orbit (HI-GEO) 75° inclination
  - Lunar Gateway-like NRHO





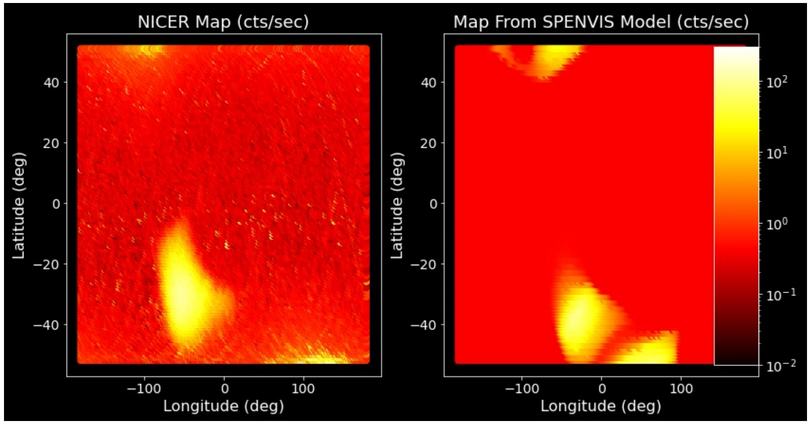


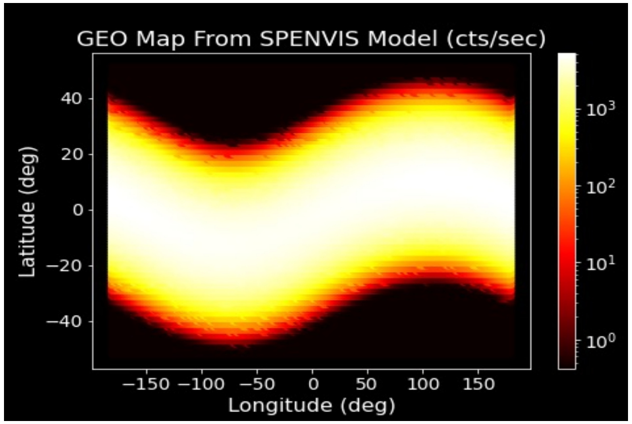
Key XGMS Features/Enhancements

- **Overall simulation architecture based on GGMS tool with high-fidelity XNAV simulation enhancements**
  - Leverages years of work on general dynamic simulation environment using GEONS
  - XNAV simulation/processing follows and enhances SEXTANT approach
  - Enables simulation of local clock behavior and future data fusion studies, e.g., XNAV+DSN, XNAV+GPS, etc.
- **Photon processing algorithms**
  - Numerous algorithmic enhancements exploring ideas that arose from SEXTANT experience
- **Event simulation**
  - On-the-fly event simulation generation, using efficient and accurate method for simulating Non-Homogenous Poisson Process (NHPP) and TEMPO2 [REF 15] based timing models following SEXTANT
- **Visibility and scheduler enhancements**
  - On-demand visibility analysis integrated into GEONS
  - Periodic, on-demand, replanning of observation schedule using multiple algorithms that obey visibility constraints and optimize metrics relevant to navigation
- **Uses latest GEONS v3.0 navigation filter software with XNAV model enhancements**
- **Particle background radiation models (details on next slide)**

Particle Background Radiation Modeling

- **Custom particle maps developed for LEO, GEO, and NRHO orbits**
  - Provides predicted particle induced background count rate along trajectory
  - Based on data from the Space Environment, Effects, and Education System (SPENVIS) [REF 9] fit to NICER on-orbit count rate LEO data then projected to GEO and NRHO
  - Particle populations vary in different regimes
    - LEO - Trapped electrons and protons esp. around South Atlantic Anomaly (SAA) and polar horns
    - GEO - Dense trapped electrons and protons in radiation belts; settles to low level outside
    - NRHO - Constant solar wind and galactic cosmic rays; Neglect transient solar flare events; Similar total rates to LEO (away from SAA and polar horns)
- **Predictions appear plausible, but significant uncertainty remains**
  - GEO prediction depends strongly on minimum “cutoff” energy threshold. Developed maps with different thresholds that give 10x variation in peak count rate
  - Refinements left to future work
    - Analysis of particle interactions with detector and optimization of detector/shielding, etc.
    - Correlation with additional on-orbit data sets





Simulation Setup/Assumptions

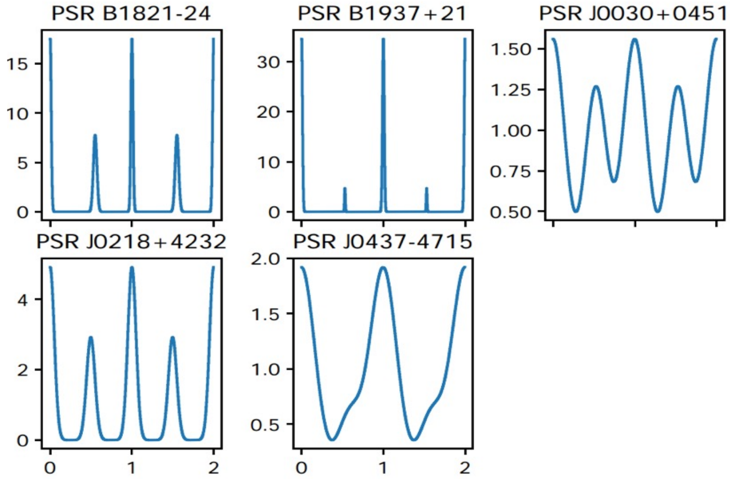
- **Baseline NICER-like detector with 56-concentrators**
- **Baseline RAFS local oscillator**
- **SEXTANT post-flight updated pulsar almanac with five key MSPs, fixed observation times per pulsar, tuned for each case**
- **Particle background models**
  - NICER-data based particle map for LEO
  - Optimistic GEO particle SPENVIS-based particle background maps for HI-GEO
  - Constant SPENVIS-based Galactic Cosmic Flux (GCF) map for NRHO
- **Visibility constraints:**
  - Sun <45º baseline
  - Earth<30º, Moon <15º, Planets <1º
  - Particle rate < 0.8 counts/s
- **Baseline simulations start October 1 running up to 39 days, giving good visibility to MSPs**

- **Truth trajectory simulated in GEONS using high-fidelity dynamic models and used for XNAV measurement simulation; GEONS filter uses lower-fidelity dynamic models to simulate modeling errors**

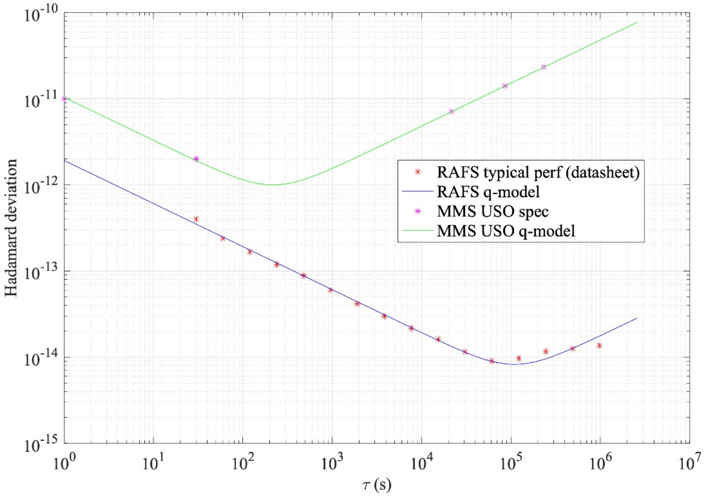
- **Basic initialization with 1-10km level error for baseline cases**
- **Ground-based initialization including DSN tracking passes at the start of the simulation used for detector size sensitivity studies**

- **Monte-Carlo simulations performed for the three baseline scenarios and to evaluate sensitivity to**
  - Local clock quality
  - Detector size
  - GEO inclination

- **All simulations use 70 Monte-Carlo trials varying initial errors, clock errors, X-ray processes, disturbances, and spacecraft constant perturbations**



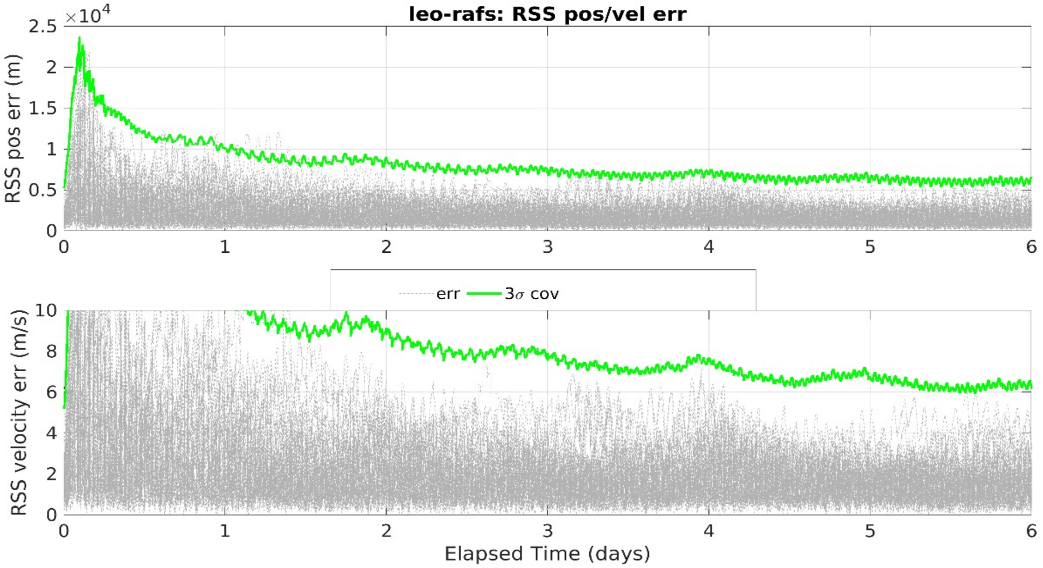
Pulse shapes of the five MSPs used in this analysis. Reproduced from [REF 3].

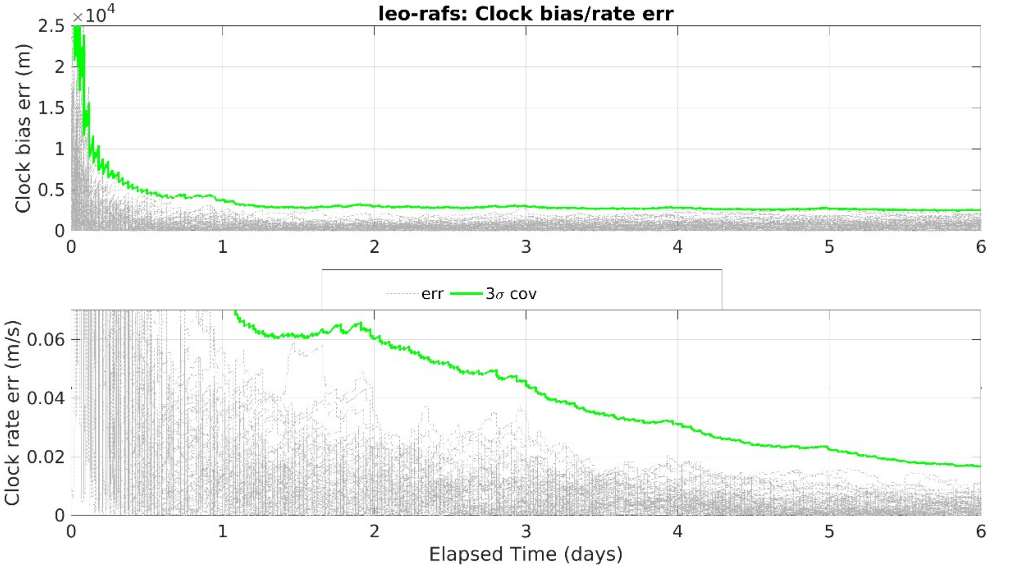


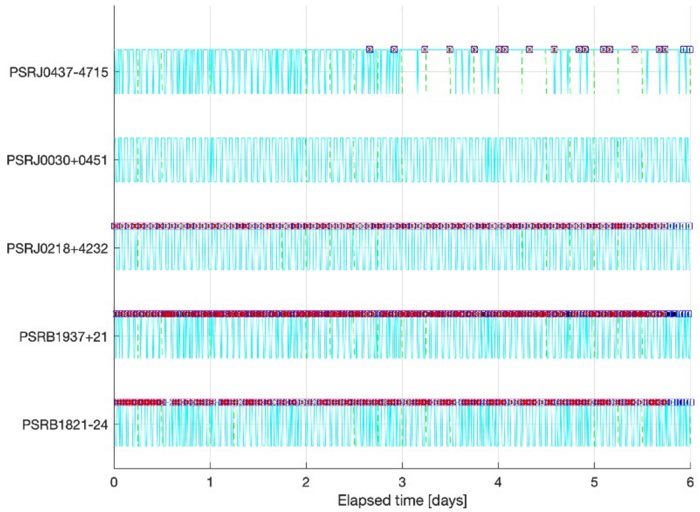
Master Oscillator Stability

LEO Baseline Performance

- Results consistent with SEXTANT simulations and on-board results
- Steady-state RSS position and velocity accuracy of 10 km and 10 m/s
- Time and frequency accuracy of 3 km and 0.02 m/s with RAFS



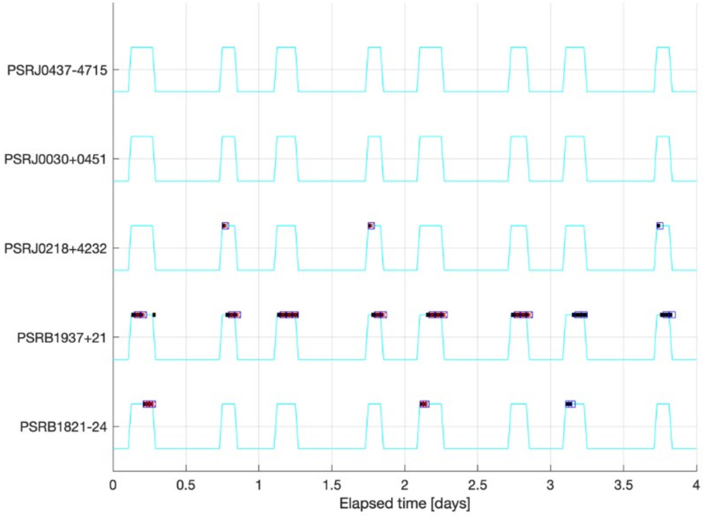




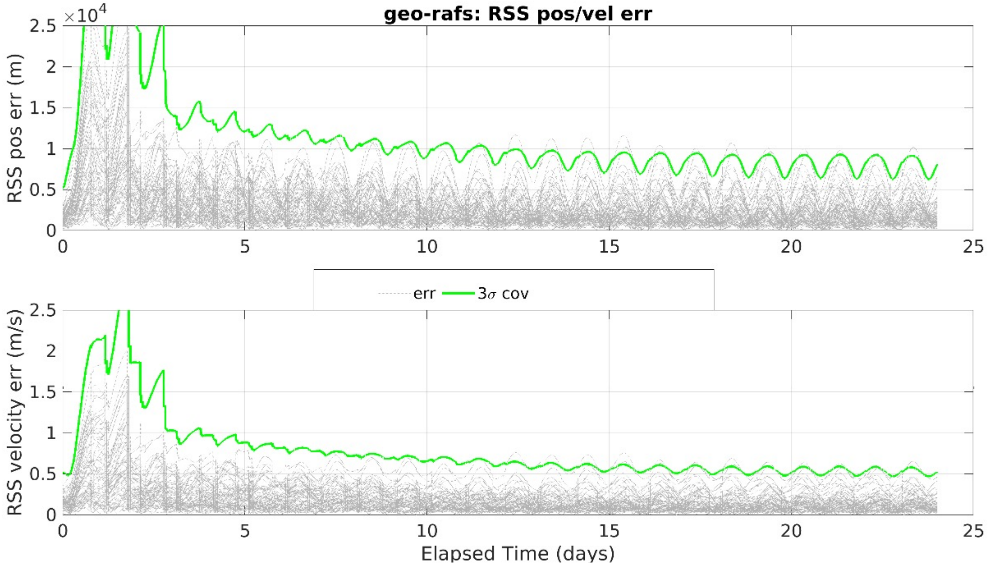
Visibility showing regular Earth occultations (~16/day) for an example run. Marks indicate measurements.

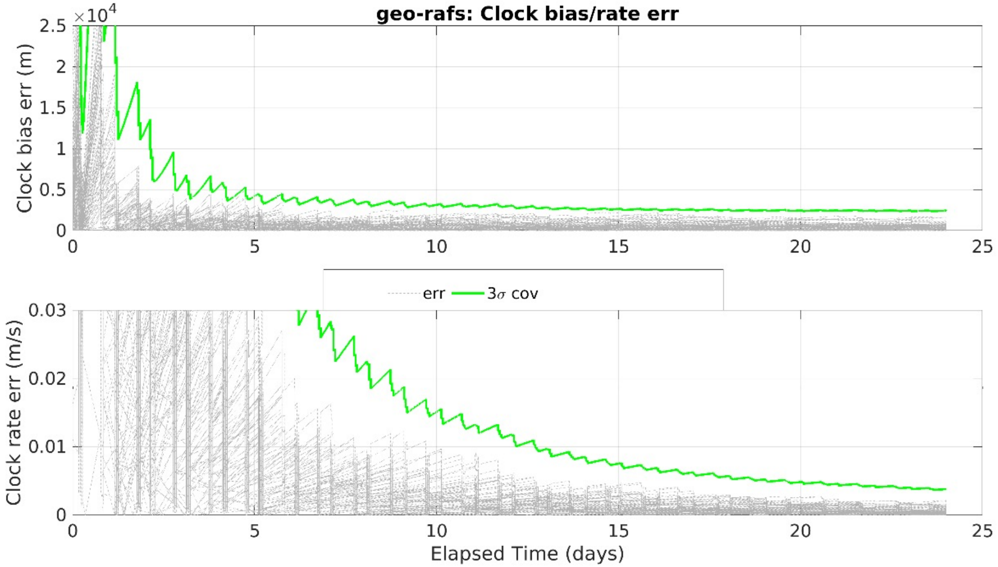
HI-GEO Baseline Performance

- HI-GEO trajectory spends a significant fraction of time outside of the radiation belts
- Steady-state RSS position and velocity accuracy of 10 km and 1 m/s
- Time and frequency accuracy of 2 km and 0.005 m/s with RAFS



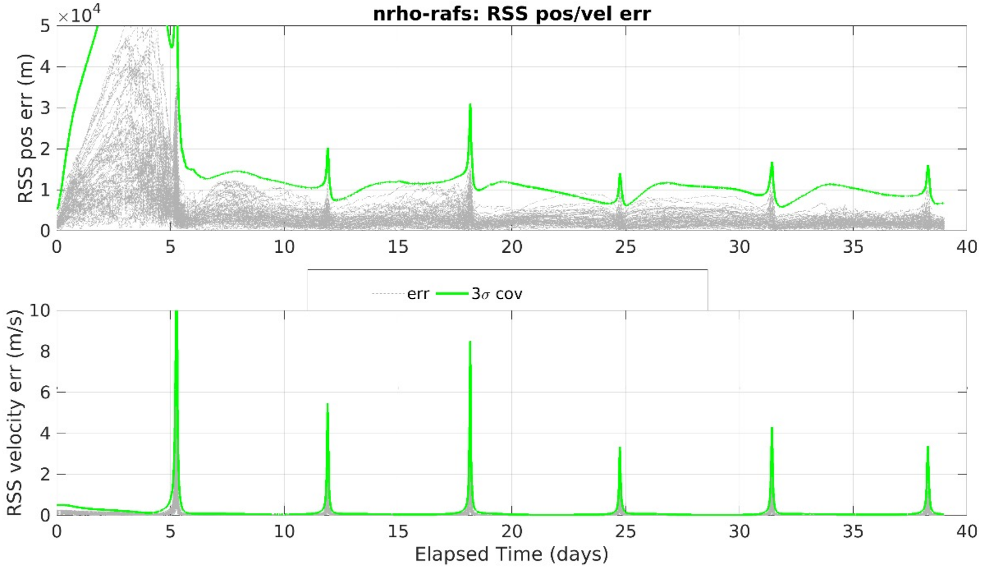
HI-GEO visibility with observations and measurement times showing the periodic loss of visibility when passing through radiation belts

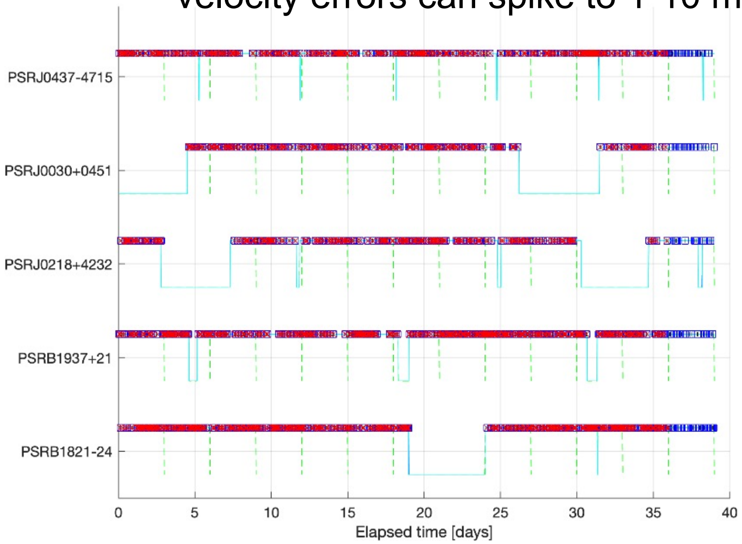




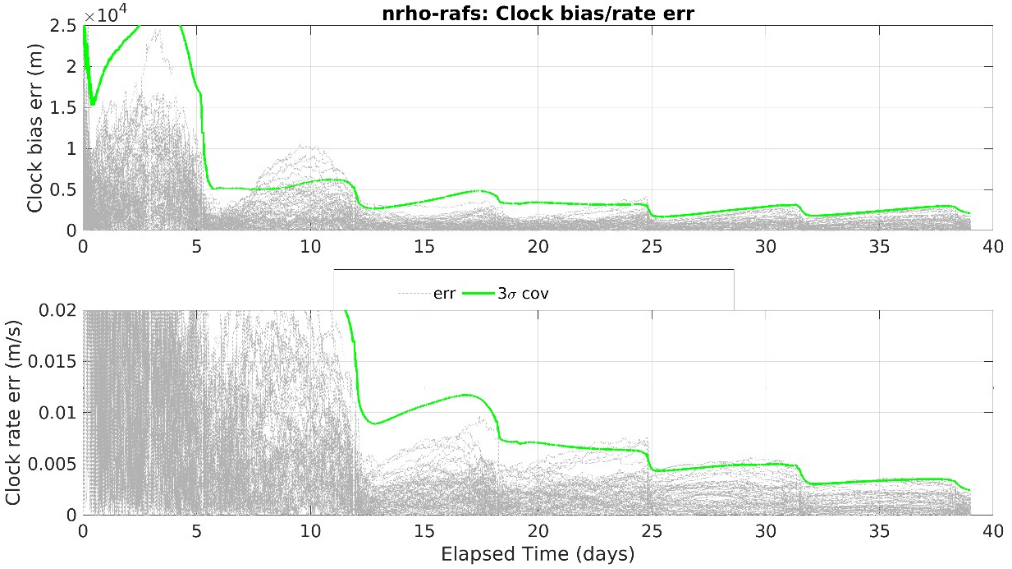
NRHO Baseline Performance

- Provides much longer continuous visibility to XNAV pulsars than either the LEO or HI-GEO cases
- Performance varies greatly between the (brief) perilune and (long) apolune regions:
    - At apolune, 10 km position and 5 cm/s velocity accuracy can be expected
    - At perilune, due to high dynamics, velocity errors can spike to 1-10 m/s





Visibility over the NRHO run (high=visible). Marks on the lines show measurement times.



Sensitivity Analysis

- **Local Clock**
  - Compared Rubidium Atomic Frequency Standard (RAFS) vs. less stable “Ultra-Stable crystal Oscillator” (USO)
  - In all cases, timing much better with the RAFS vs. USO
  - However steady-state position and velocity performance was less sensitive to the clock
  - Details:
    - LEO: steady-state position, velocity, and clock bias errors are similar, but clock bias rate errors are 2.5x larger with the USO
    - HI-GEO: steady-state position and velocity errors are similar, but steady-state clock bias errors increase by 50% and clock bias rate errors are 15x larger with the USO
    - NRHO apolune: steady-state position and velocity errors increase by 30% increase, 2x larger clock bias errors, and 8x larger clock bias rate errors with the USO
    - NRHO perilune: steady-state position errors increase by 30% increase, 50% increase in velocity and clock bias errors, and 8x larger clock bias rate errors with the USO
- **Detector size**
  - Doubled detector size successively from 1/8th, to ¼, ½, baseline (56 concentrators), and 2x baseline
  - Observation time was scaled in proportion to maintain a constant expected number of photons in each batch
  - As expected, navigation performance is always better with a larger detector
  - HI-GEO, NRHO: Performance is stable down to ¼ size detector
  - LEO: Performance is stable only down to ½ size detector due to higher dynamics/shorter continuous observation arcs
- **GEO inclination**
  - Orbit inclination varied from 45° to 90° in steps of 5°
  - As expected, navigation performance improves as inclination increases from 65° to 90°
  - Performance is unstable in sims with incl.<65°, where high particle background rates reduce visibility

Conclusions

- **Developed XGMS - a highly capable, high-fidelity tool for studying XNAV scenarios and sensitivities to parameter variations**
  - An XNAV-focused extension of the GEONS Ground MATLAB Simulation (GGMS) building on algorithms/software/experience from SEXTANT

- **Studied XNAV-based nav and timing for three challenging scenarios**
  - ISS-like LEO, Highly Inclined GEO (HI-GEO), and Lunar-Gateway-like NRHO
  - Baseline NICER-like detector with RAFS and Oct. 1 start for up to 39 days
  - Sensitivity to clock, detector size, and GEO inclination

- **ISS-like LEO case**
  - Challenging due to the high dynamics and regular Earth occultations, limiting continuous observation arcs
  - Results consistent with SEXTANT simulations and on-board results
  - Reliable RSS position and velocity accuracy of 10 km and 10 m/s
  - Time and frequency accuracy of 3 km and 0.02 m/s are achieved with RAFS

Conclusions (cont'd)

- **GEO case**
  - *Under our detector and background modeling assumptions, due to high particle background radiation levels, equatorial and low inclination Geosynchronous orbits (GEO) below about 40º are not expected to be practical candidates for application of XNAV.*
  - Assuming MSP observations made only in regions of low to moderate particle background, analysis suggests reasonably good XNAV performance is possible at higher inclination
  - Showed in Highly Inclined GEO (HI-GEO) at 75º Navigation to <10 km and 1 m/s possible

- **Lunar Gateway-like NRHO case**
  - Longer continuous visibility to XNAV pulsars than either the LEO or HI-GEO
  - Performance varies greatly between the (brief) perilune and (long) apolune regions; perilune dynamics can be destabilizing to navigation
  - At apolune, 10 km position, and quite accurate 5 cm/s velocity can be expected
  - At perilune, due to high dynamics, velocity errors can spike to 1-10 m/s

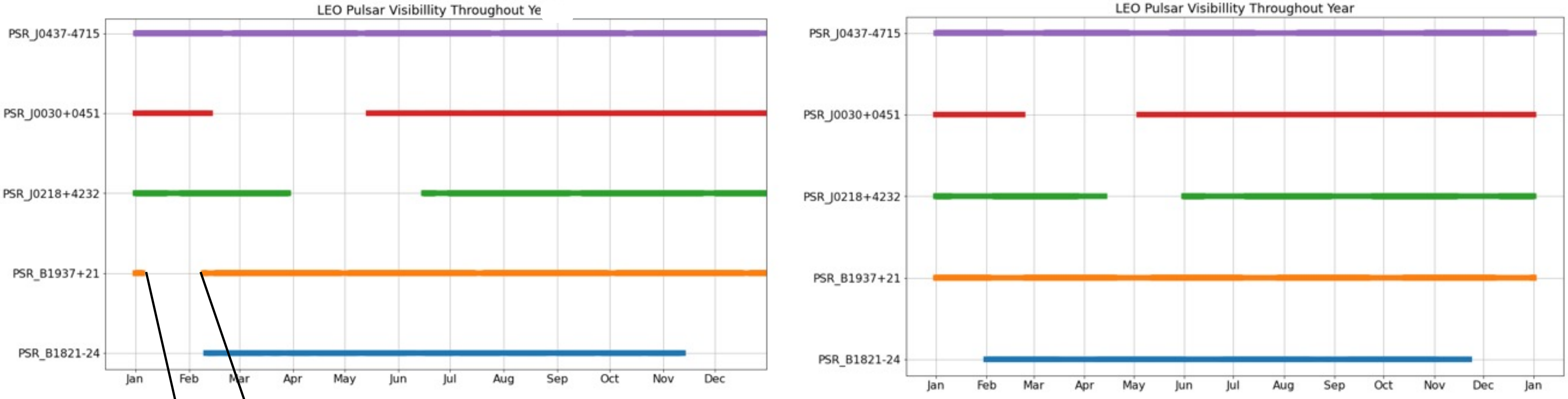
- **Sensitivity analyses**
  - **Local Clock:** Timing much better with the RAFS vs. USO, but steady-state position and velocity performance was similar.
  - **Detector size:** Detectors of ¼ size for NRHO and HI-GEO and ½ size for LEO can support stable, but reduced performance; Marginal benefit from 2x times detector size

Future Work

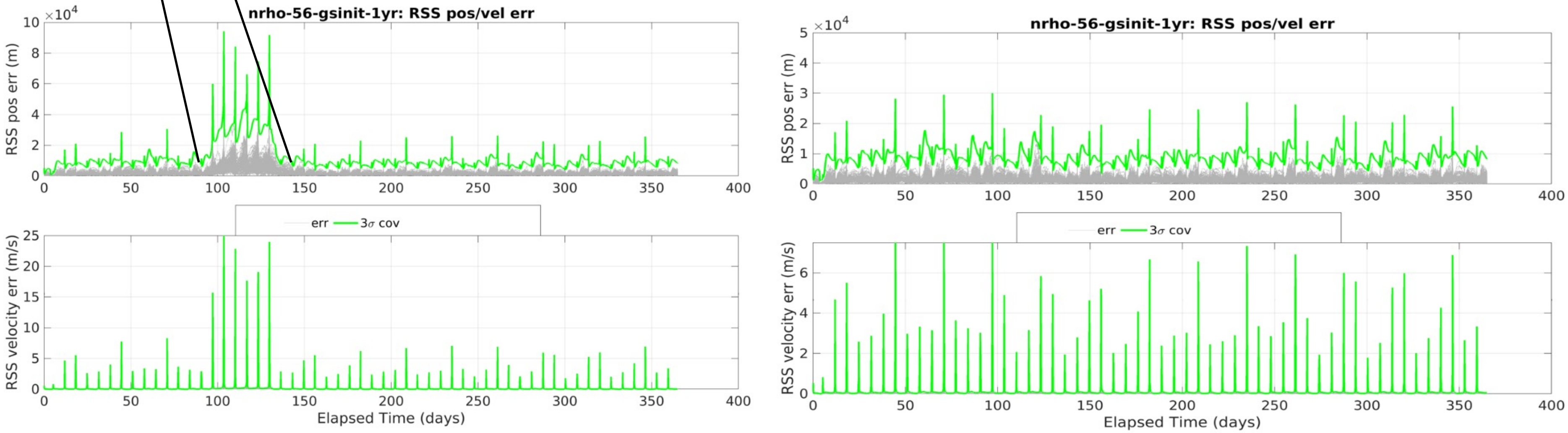
- **Study additional cases**
  - Other Lunar orbits, Earth-Sun Lagrange point missions, Earth-Mars transit, Asteroid Belt missions, and other deep space trajectories, etc.
  - These may better highlight unique strengths of XNAV?
- **Investigate sensitivity and impact of initialization error, initialization strategies**
  - Find tolerable structure and magnitude of initialization error
  - Is cold start possible?
- **Enhance particle background models and study background sensitivity**
  - Correlate/adjust models with other on-orbit data
  - Develop fully general background maps
- **Optimize MSP target observation times**
  - Find best observation time for each pulsar for each scenario
  - Determine observation times dynamically?
- **Integration of unique high-flux Crab pulsar in simulation and processing**
  - Follow and enhance SEXTANT approach to Crab processing
  - Possible to mitigate Crab timing instability in processing?
- **Detector concepts, miniaturization, and optimization**
  - Develop practical concepts for specific applications, optimize detector for XNAV, study background mitigation techniques
- **Operation in regions of high background**
  - Possible to use combo of techniques above to operate in noisy environments like GEO?
- **Investigate sensitivity to annual pulsar visibility variation**
  - See next slide

Impact of Annual Visibility on NRHO Performance

- **Loss of top two pulsars in Jan/Feb mitigated by relaxed Sun pointing constraint**



Annual visibility of five key XNAV MSPs with sun keep-out-zone (KOZ) of 45º (left) and 35º (right)



References

1. *Mitchell, J. W., et al., “SEXTANT - Station Explorer for X-ray Timing and Navigation Technology.” AIAA Guidance, Navigation, and Control Conference. Kissimmee, FL.*
2. *Arzoumanian, Z, Gendreau, K. C., et al., "The Neutron Star Interior Composition Explorer (NICER): Mission Definition," Proc. SPIE 9144, Space Telescopes and Instrumentation 2014: Ultraviolet to Gamma Ray, 914420 (29 July 2014); https://doi.org/10.1117/12.2056811*
3. *Mitchell, J. W., et al., “SEXTANT X-ray Pulsar Navigation Demonstration: Initial On-Orbit Results”, Annual American Astronautical Society (AAS) Guidance and Control Conference 2018, Breckenridge, CO.*
4. *Winternitz, L. M. B., et al., “SEXTANT X-ray Pulsar Navigation Demonstration: Additional On-Orbit Results”, International Conference on Space Operations 2018. Marseille, France.*
5. *Winternitz, L. M. B, et al. "X-ray Pulsar Navigation Algorithms and Testbed for SEXTANT”, IEEE Aerospace Conference, Big Sky, MT, March 2015.*
6. *Winternitz, L. M. B, et al. "SEXTANT X-Ray Pulsar Navigation Demonstration: Flight System and Test Results”, IEEE Aerospace Conference, Big Sky, MT, March 2016.*
7. *https://www.spenvis.oma.be/*
8. *Vette, J. I., The AE-8 Trapped Electron Model Environment, NSSDC/WDC-A-R&S 91-24, 1991a.*
9. *Sawyer, D. M., and Vette, J. I., AP-8 Trapped Proton Environment for Solar Maximum and Solar Minimum, NSSDC/WDC-A-R&S 76-06, 1976.*
10. *Golshan, A.R, and S. I. Sheikh, S. I., On pulse phase estimation and tracking of variable celestial X-ray sources. In Proceedings of the 63rd Annual Meeting of The Institute of Navigation, pages 413{422, Cambridge, MA, April 2007. Institute of Navigation.*
11. *Ashby, N. and Golshan, A. R., Minimum uncertainties in position and velocity determination using X-ray photons from millisecond pulsars. In Institute of Navigation National Technical Meeting, 2008.*
12. *Emadzadeh, A. A., and Speyer, J. L., Navigation in Space by X-ray pulsars. Springer, 2011.*
13. *Hobbs, G. B., Edwards, R. T., Manchester, R. N., TEMPO2, a new pulsar-timing package – I. An overview, Monthly Notices of the Royal Astronomical Society, Volume 369, Issue 2, June 2006, Pages 655–672, https://doi.org/10.1111/j.1365-2966.2006.10302.x*
14. *Bar-David, I. Communication under the Poisson Regime. Information Theory, IEEE Transactions on, 15(1):31{37, Jan 1969.*
15. *Steven T. Hutsell, et al., “Operational Use of the Hadamard Variance in GPS”, Proceedings of the 28th Annual Precise Time and Time Interval Systems and Applications Meeting/Proceedings of the Institute of Navigation GNSS+, pages 201–214, December 1996*
16. *Spectratime RAFS datasheet, https://www.spectratime.com/uploads/documents/ispace/iSpace_RAFS_Spec.pdf*
17. *Okajima, T., et al.,The Performance of NICER flight x-ray concentrator. Proc. SPIE 9905, Space Telescopes and Instrumentation 2016: Ultraviolet to Gamma Ray, 99051H (22 July 2016).*
18. *https://naif.jpl.nasa.gov/pub/naif/misc/MORE_PROJECTS/DSG/*