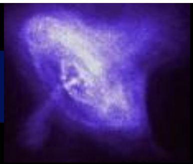

Predicted Performance of an X-ray Navigation System For Future Deep Space and Lunar Missions

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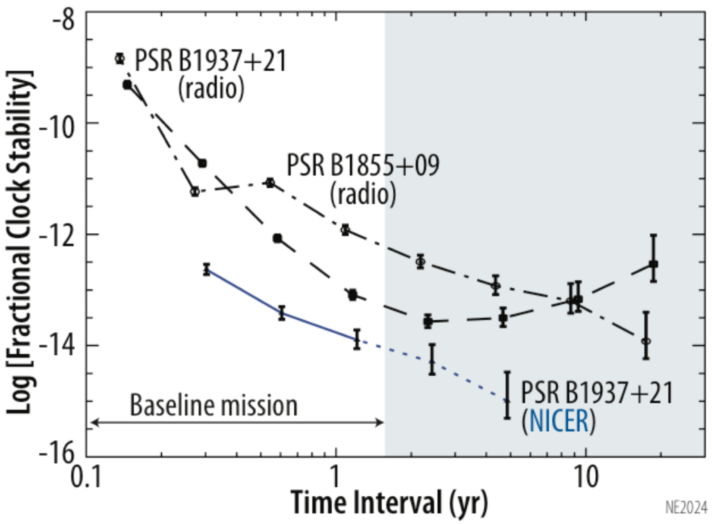
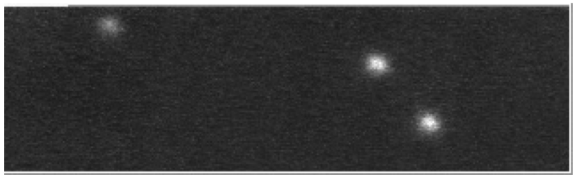
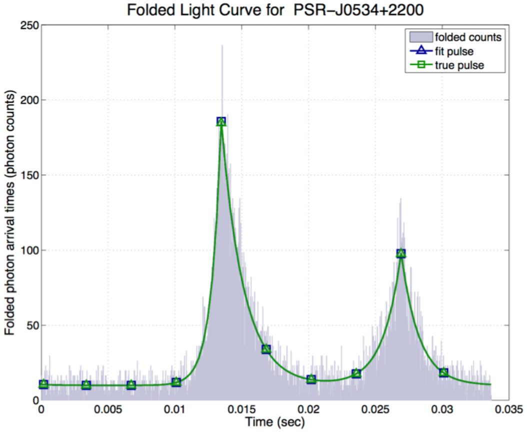
X-ray Pulsar Navigation (XNAV)

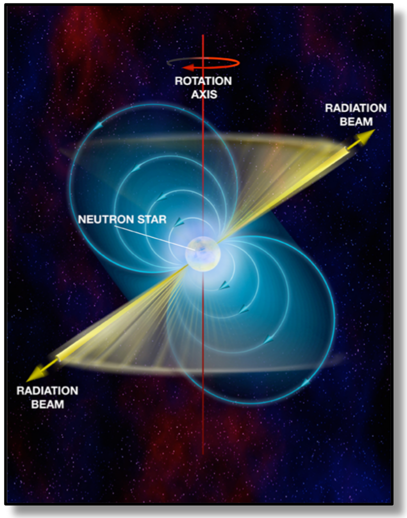
- Millisecond pulsars (MSPs): rapidly rotating neutron stars that pulsate across electromagnetic spectrum
- Some MSPs rival atomic clock stability at long time-scales
  - Predict pulse arrival phase with great accuracy at any reference point in the Solar System via pulsar timing model on a spacecraft
  - Compare observed phase to prediction for navigation information
- Why X-rays?
  - Many stable MSPs conveniently detectable in (soft) X-ray band
  - X-rays immune to interstellar dispersion thought to limit radio pulsar timing models
  - Highly directional compact detectors possible
- **Main Challenge: *MSPs are very faint!***





Crab Pulsar (1/3 speed), Cambridge University, Lucky Image Group





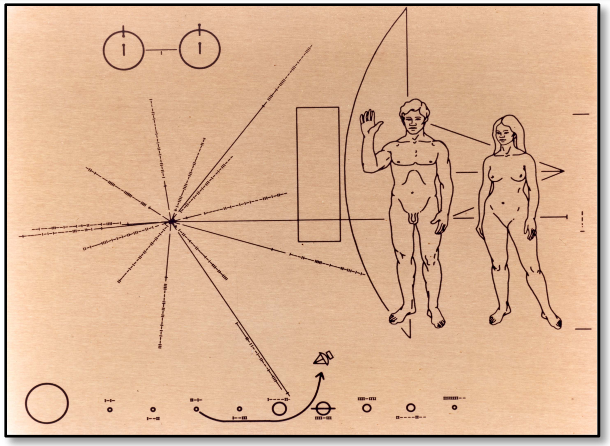
X-ray Pulsar Navigation (XNAV)

Applications

- XNAV can provide autonomous navigation and timing that is of uniform quality throughout the solar system
  - Is 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

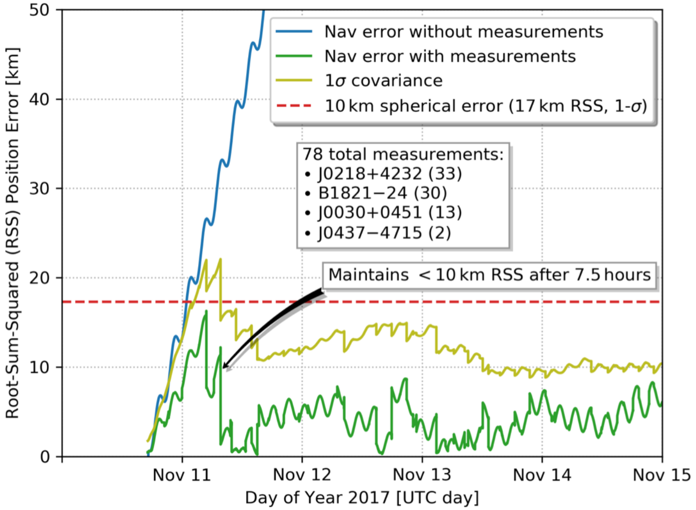
History

- 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)
- Significant body of research (international interest, academic research, several Ph.D. dissertations, etc.)
- ***NICER/SEXTANT successfully demonstrates real-time, onboard, autonomous XNAV*** **(Nov 2017)**



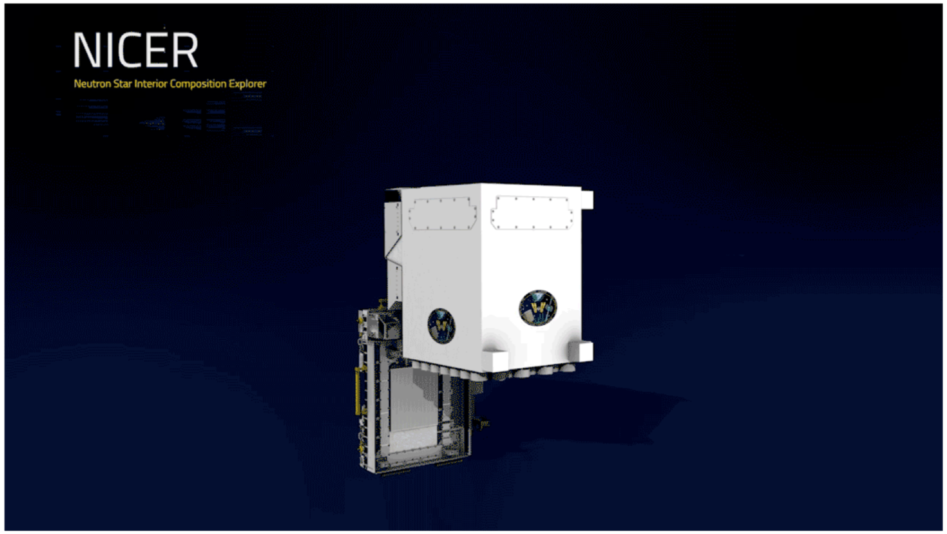
Pioneer plaque (Pioneer 10,11 1972-73) with pulsar periods and relative distances to our Sun

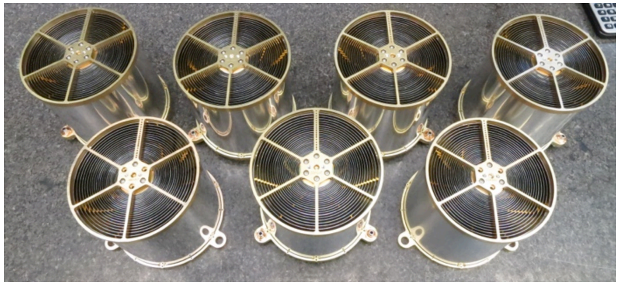
SEXTANT Experiment 1 successfully demonstrates fully autonomous, real-time X-ray pulsar navigation on-board NICER

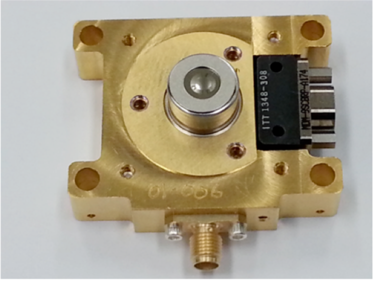


NICER/SEXTANT Overview

- Launched on June 3, 2017 on Space-X CRS-11 to ISS
- Neutron-star Interior Composition Explorer (NICER)
  - Fundamental investigation of ultra-dense matter: structure, dynamics, & energetics
  - Nearly ideal XNAV detector combination: low-background, large effective collecting area, precise timing, scalability, and low-cost
  - Assembly of 56 X-ray concentrators and detectors, ~1800 cm^2 effective collecting area in soft X-ray band
  - Scalable design, e.g., reduce to 1,4,10, etc. concentrators
- SEXTANT – Successful demonstration results reported in Mitchell (2018) and Winternitz (2018)

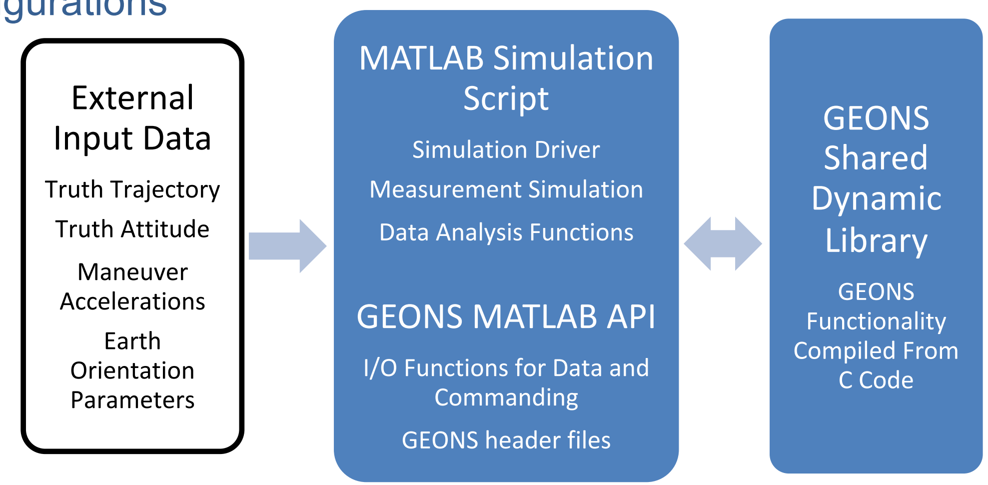




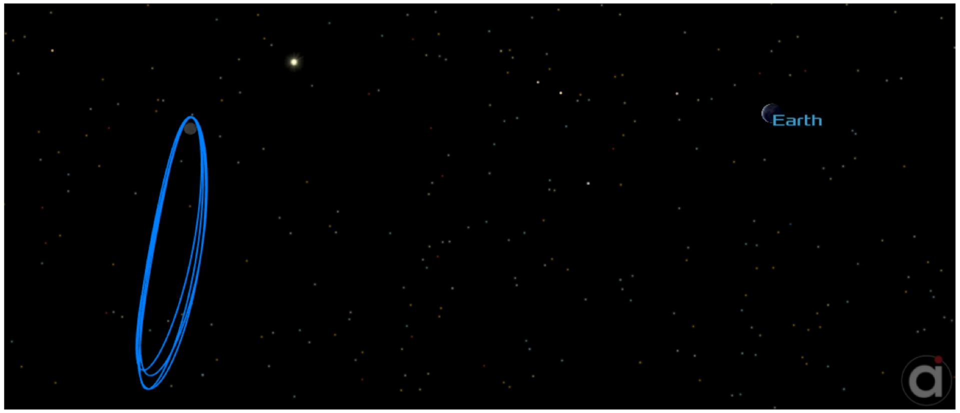


Simulation Setup

- NICER/SEXTANT focused primarily on LEO/ISS orbit and required ground support systems
- NICER/SEXTANT XNAV Flight Software (XFSW) consists of two main components
  - Event/measurement processing
  - Goddard Enhanced Onboard Navigation System (GEONS) navigation filter (EKF)
- GEONS Ground MATLAB Simulation (GGMS)
  - General tool for running GEONS simulations from convenient MATLAB wrapper
  - Includes NICER/SEXTANT flight software XNAV measurement models
- This work examines performance of XNAV vs. 2-way ground tracking from Deep Space Network (DSN) for 3 scenarios beyond LEO
  - Measurements are simulated and processed by GEONS/GGMS
  - Focus on top 5 XNAV pulsar configurations that provides good geometry
  - Assume perfect clock
  - Conduct single run(s), not Monte Carlo



Gateway Simulation



***Candidate orbit for NASA's proposed Gateway is a* Near-Rectilinear Halo Orbit (NRHO)**

NRHO:

- 1800 km x 68,000 km
- Period of 6.5 days

Ground navigation:

- 2-way range and Doppler alternating from Goldstone, Madrid, and Canberra
- Limit to 8 hrs of tracking per day
- Use DSN level of accuracy

Simulation details:

- Run for 45+ days
- Trade number of XNAV concentrators (56, 10, 4, and 1)

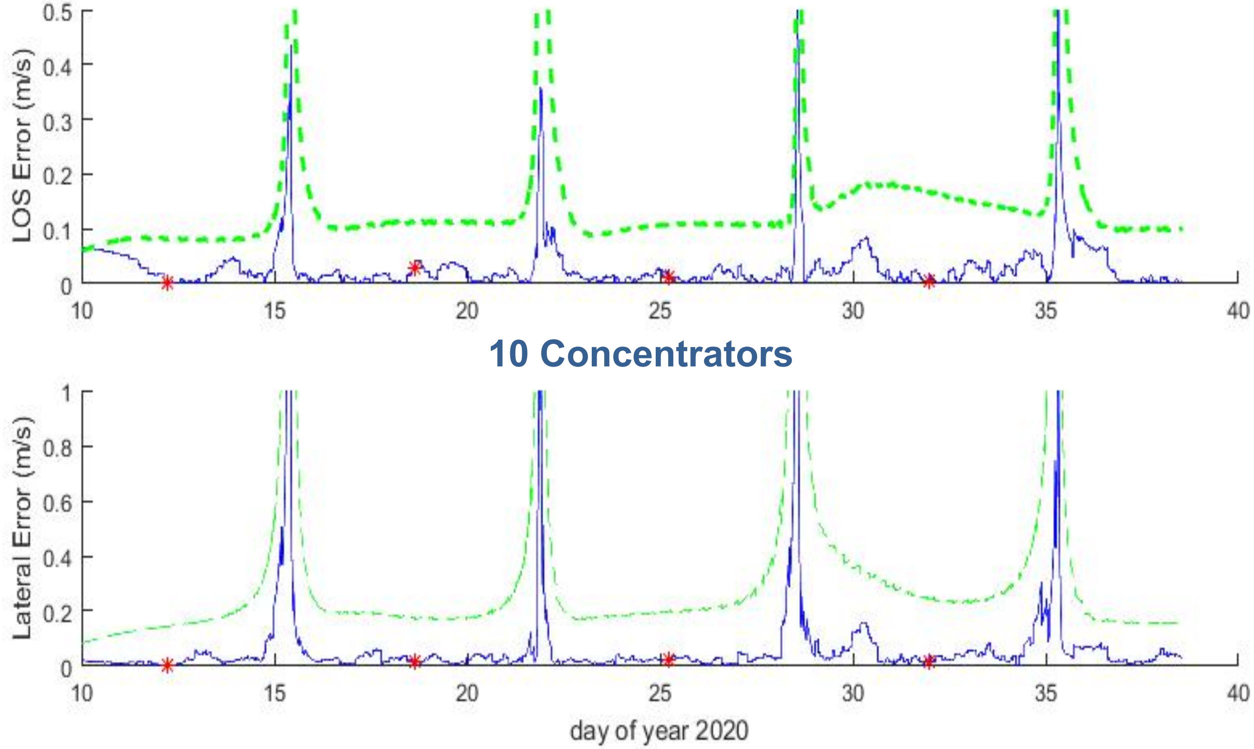
Notes:

- Two classes of operations: *crewed* vs. *un-crewed*
- Un-crewed operations are quiescent and similar to a robotic spacecraft
- Crewed operations involve significant increase in perturbations due to more out-gassing (waste, CO_2, etc.)

Gateway Results (Uncrewed)

- Performance promising for backup applications
- Large integration times to formulate measurements (> 13 min)
- Velocity spikes at periapsis due to combination of rapidly changing dynamics and large integration times

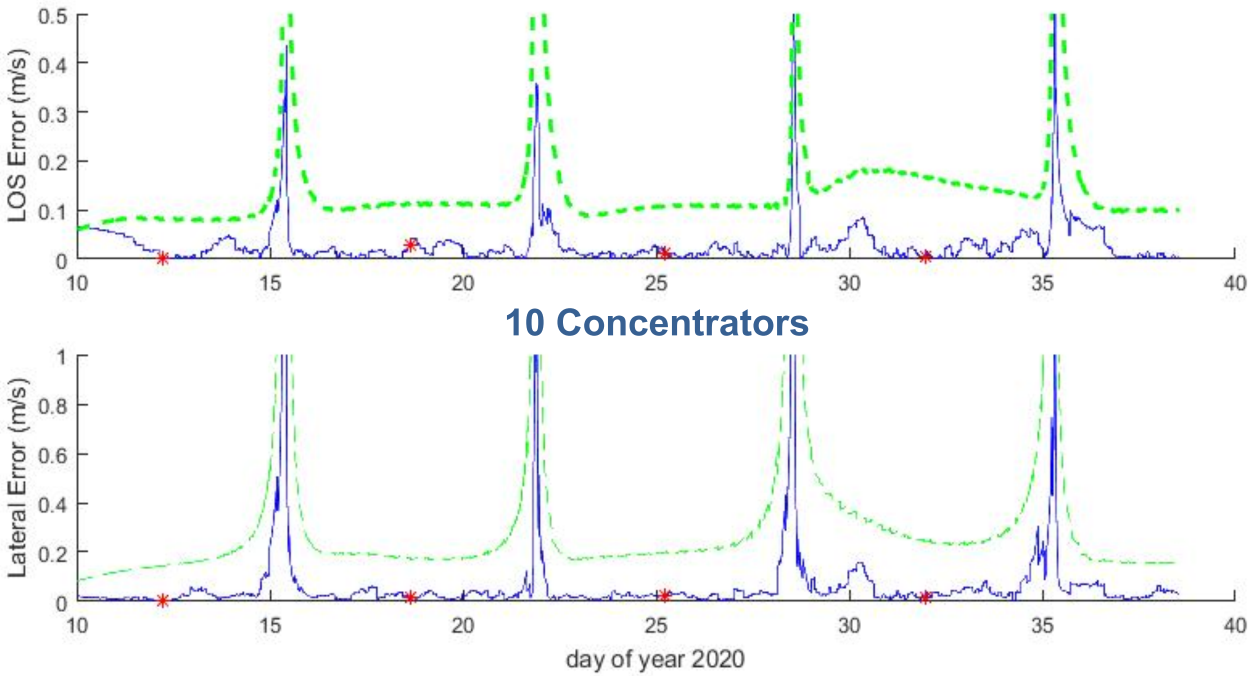
Steady State Statistics		
	RMS Position Error (km)	RMS Velocity Error (m/s)
DSN	0.157	0.0035
XNAV 56 Concentrators	3.5	0.1331
XNAV 10 Concentrators	5.3	0.1631
XNAV 4 Concentrators	9.1	0.4101
XNAV 1 Concentrators	9.2	0.5814



Gateway Results (Crewed)

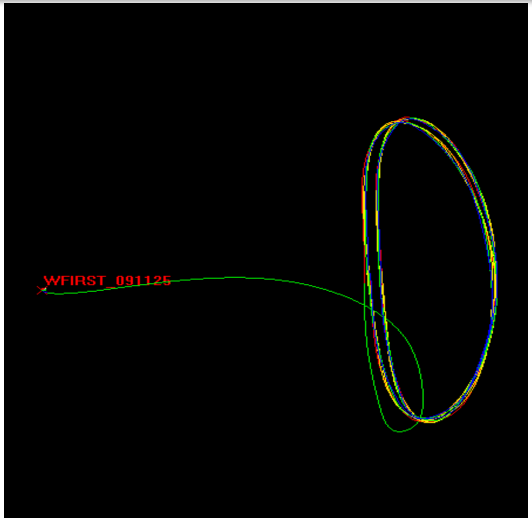
- Performance degraded as compared to un-crewed
- Large velocity spikes at periapsis still present
- At XNAV level of performance additional disturbances have only minor effect

Steady State Statistics		
	RMS Position Error (km)	RMS Velocity Error (m/s)
DSN	2.73	0.052
XNAV 56 Concentrators	6.32	0.177
XNAV 10 Concentrators	7.89	0.275
XNAV 4 Concentrators	11.91	0.465
XNAV 1 Concentrators	16.45	0.977



WFIRST Simulation

Proposed mission in halo orbit about Sun-Earth L2 common for telescope missions



Sun-Earth L2:

- 1.6 million km *y*-axis in Rotating Libration Point (RLP) frame
- Period of 6 months

Ground navigation:

- 2-way range and Doppler from White Sands and Canberra
- 1 hr of range per station contact
- Use DSN level of accuracy

Simulation details:

- Run for 1 year
- Trade number of XNAV concentrators (56,10, 4, and 1)

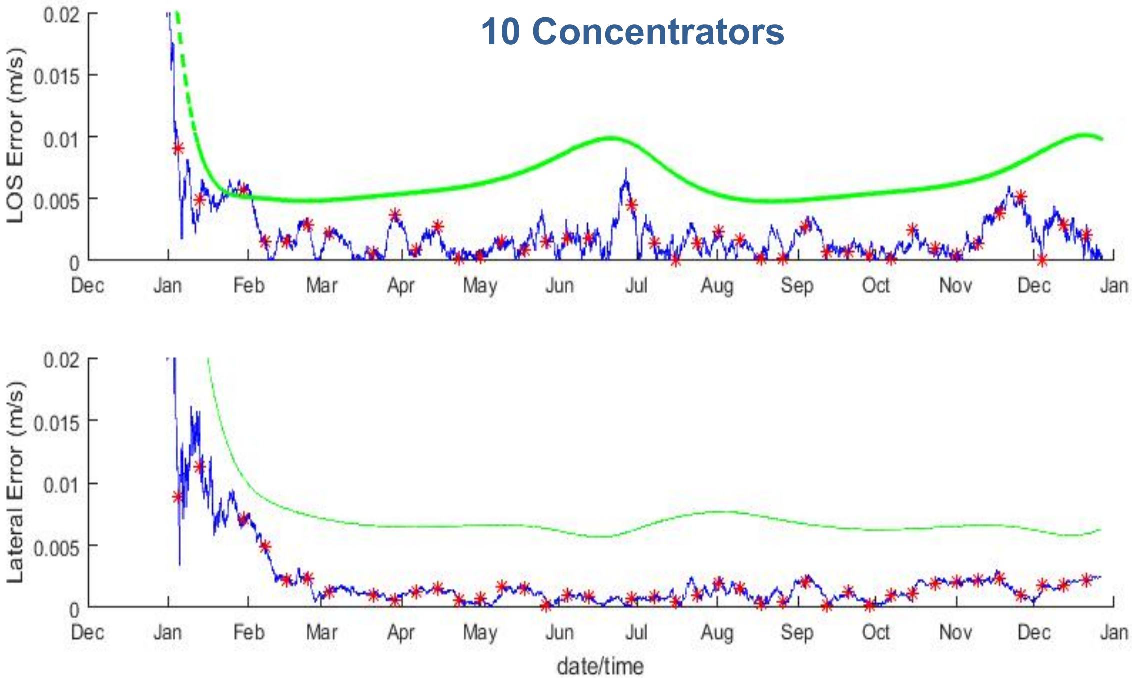
Notes:

- Demanding bandwidth requirements limit the amount of available ranging in favor of download of scientific data
- Station keeping maneuvers required every 4 weeks
- Momentum unloads required weekly

WFIRST Results

- No velocity spikes as dynamics through perigee are more benign than for Gateway
- Possible semi-annual variation likely due to pulsar geometry changes relative to orbit
- The 56 or 10 concentrator configuration exhibits performance acceptable for primary navigation

Steady State Statistics		
	RMS Position Error (km)	RMS Velocity Error (m/s)
DSN	1.5	0.0005
XNAV 56 Concentrators	1.7	0.0016
XNAV 10 Concentrators	3.4	0.0024
XNAV 4 Concentrators	4.5	0.0034
XNAV 1 Concentrators	7.2	0.0046



New Horizons Simulation

Robotic probe on a Solar System escape trajectory

Escape Trajectory:

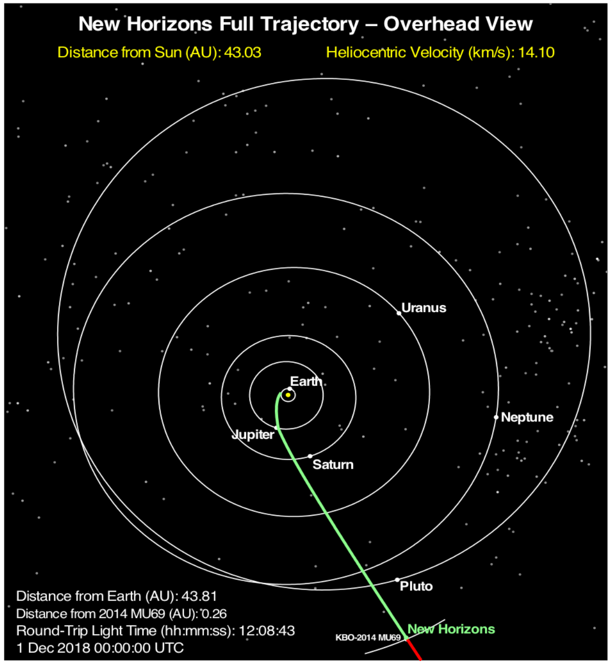
- Interested in swath near Saturn orbit crossing
- Spacecraft in hibernation mode

Ground navigation:

- 2-way range and Doppler from Goldstone, Madrid, and Canberra
- Use all available contacts
- Use as reported transponder accuracies

Simulation details:

- Run for 30 days
- Trade number of XNAV concentrators (56,10, 4, and 1)



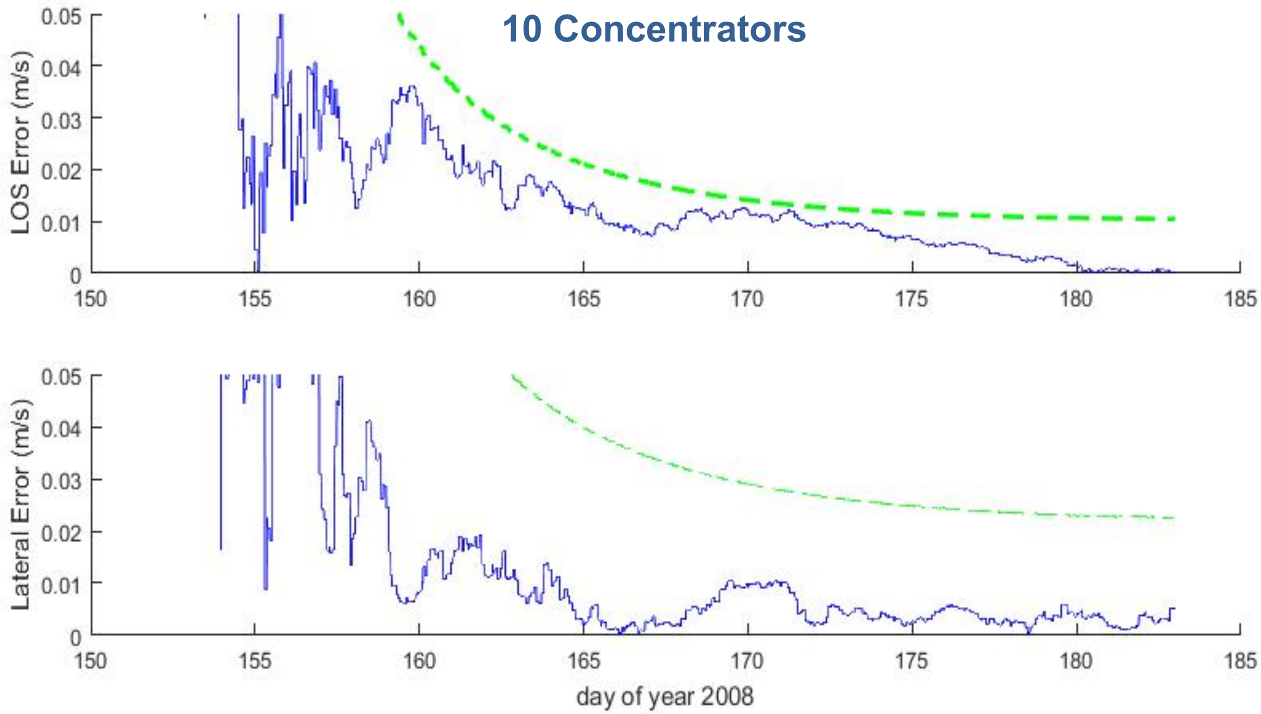
Notes:

- Although New Horizon's navigation plan includes combination of 3-way, 2-way, ΔDOR, and optical we only use 2-way
- Overlapping 2-way is equivalent to 3-way but ***NOT*** ΔDOR and optical

New Horizons Results

- Lack of ΔDOR skews the reported DSN results
- XNAV exhibits excellent performance for this profile
- The linear trajectory is insensitive to long integration times to generate measurements

Steady State Statistics		
	RMS Position Error (km)	RMS Velocity Error (m/s)
DSN	66.76	0.0508
XNAV 56 Concentrators	2.67	0.0038
XNAV 10 Concentrators	6.63	0.0090
XNAV 4 Concentrators	5.72	0.0111
XNAV 1 Concentrators	18.98	0.0125



Conclusions & Future Work

- Demonstrated the potential performance of XNAV for three mission profiles
  - Gateway: suitable for backup navigation capability
    - Matures support for Deep Space Transport backup navigation
  - WFIRST: potentially suitable for primary navigation capability in Sun-Earth L2
  - New Horizons: potentially suitable for primary navigation capability in deep space
- Illustrated sensitivities in XNAV performance
  - Geometric dependence vs. integration time
  - Number of concentrators traded vs. performance
- Future work includes:
  - Further refinement of simulation models based on NICER/SEXTANT results
  - Inclusion of limitations such as solar / planetary occultations
  - Analysis of XNAV performance against other navigation techniques such as ΔDOR
  - Monte Carlo or linear covariance analysis to produce statistically robust performance predictions