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

Simulation Setup

External Input Data
- Truth Trajectory
- Truth Attitude
- Maneuver Accelerations
- Earth Orientation Parameters

MATLAB Simulation Script
- Simulation Driver
- Measurement Simulation
- Data Analysis Functions

GEONS MATLAB API
- I/O Functions for Data and Commanding
- GEONS header files

GEONS Shared Dynamic Library
- GEONS Functionality Compiled From C Code
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, CO₂, 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

<table>
<thead>
<tr>
<th>Steady State Statistics</th>
<th>RMS Position Error (km)</th>
<th>RMS Velocity Error (m/s)</th>
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10 Concentrators
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

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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

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10 Concentrators
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

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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 \( \Delta \text{DOR} \)
  - Monte Carlo or linear covariance analysis to produce statistically robust performance predictions