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
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**

<table>
<thead>
<tr>
<th>Concentrators</th>
<th>RMS Position Error (km)</th>
<th>RMS Velocity Error (m/s)</th>
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<tr>
<td>DSN</td>
<td>0.157</td>
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<tr>
<td>XNAV 56</td>
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<td>XNAV 10</td>
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<tr>
<td>XNAV 4</td>
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<td>XNAV 1</td>
<td>9.2</td>
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</table>
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.

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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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<td>XNAV 1 Concentrators</td>
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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 ΔDOR
  – Monte Carlo or linear covariance analysis to produce statistically robust performance predictions