Station Explorer for X-ray Timing and Navigation Technology
Architecture Overview

Monther A. Hasouneh
for the SEXTANT team

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Outline

- X-ray pulsar Navigation (XNAV)
  - Background
  - Concept
- Missions
  - NICER Science
  - SEXTANT tech demo
- Architecture
  - NICER XTI
  - Flight software
  - Ground system
  - Ground testbed and end-to-end simulation
- Future activity
Pulsars were discovered in 1967 and immediately recognized as a tool for Galactic navigation.

Millisecond pulsars (MSPs)
- Rival atomic clocks as time-keepers on long time scales (>year)
- Pulse phase and Doppler can be precisely measured
- Provides GPS-like nav & time throughout solar system and beyond
- MSPs are distributed throughout the Galaxy

Pioneer Plaque: Flown on the Pioneer 10&11 Spacecraft
X-ray pulsar navigation (XNAV)

- These are the radio light curves, X-ray curves maybe different.
- This slide borrowed with permission from Neil Ashby’s presentation on XNAV at NIST Metrology Seminar June 7, 2012. Content drawn from public website: http://www.jb.man.ac.uk/pulsar/Education/Sounds/sounds.html
XNAV concept

GPS

\[ |x_1 - x| = c(t - t_1) \]
\[ |x_2 - x| = c(t - t_2) \]

XNAV

\[ \hat{n}_1 \cdot x = c(t_1 - t) \]
\[ \hat{n}_2 \cdot x = c(t_2 - t) \]

Folded photon arrival times (photon counts)

Folded Light Curve for PSR−J0534+2200

You are here...

X-ray photons

NICER XTI

Nasa GSFC

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

You are here...
Neutron star Interior Composition Explorer (NICER) Mission

- NICER
  - SMD competitively selected purely on science
  - Launch in August 2016 on Space-X Dragon
  - 18 Month mission on Express Logistics Carrier (ELC) 2
  - X-ray (0.2–12 keV) concentrator optics and silicon-drift detectors; GPS position and 300 ns absolute time tagging

- SEXTANT — Station Explorer for X-Ray Timing and Navigation Technology
  - STMD funded technology enhancement to use NICER
  - Demonstrate X-ray pulsar navigation (XNAV), enable other applications
  - Only enhanced flight software on NICER, same hardware
Neutron star Interior Composition Explorer (NICER) Mission

- Address NASA and National Academy of Sciences strategic questions
  - **Resolve** the nature of *ultra-dense* matter at the threshold of collapse to a black hole
  - **Structure**—Reveal the nature of matter in the interiors of neutron stars
  - **Dynamics**—Uncover the physics responsible for the dynamic behavior of neutron stars
  - **Energetics**—Determine how energy is extracted from neutron stars
- NICER offers a fundamental investigation of extremes in gravity, material density, and electromagnetic fields
Demonstrate GPS-like autonomous position determination (absolute) anywhere in the Solar System using X-ray observations of Millisecond Pulsars (MSPs)
- Provide 1st real-time, on-orbit demo of XNAV concept
- Determine practical limitations of Pulsar Navigation

Other benefits
- Evaluate the use of pulsars as part of a more universal time standard
- Potentially demonstrate the use of X-rays in communication (XCOM)
NICER X-ray Timing Instrument

- 56 co-aligned X-ray concentrator optics and associated Silicon Drift Detectors (SDDs) in Focal Plane Modules (FPMs)
- 7 Measurement/Power Units
- The FPMs detect X-rays arriving from the concentrators
- MPUs time-tag and packetize photon events
- < 300 nsec absolute time resolution
- > 2000 cm² effective area
- Moderate (CCD-like) energy resolution

Stowed, deploying, and observing
Flight Software

SEXTANT flight software architecture diagram
The ground system maintains the pulsar catalog
- incorporates data from radio telescopes, other X-ray telescopes, and the NICER XTI, once operational
- provide current timing models, or ephemerides, and pulse profile templates to meet SEXTANT navigation needs

The ground system is also responsible for performance monitoring and telemetry collection for post-processing purposes
Provides **end-to-end simulation capability** for evaluation of XNAV performance for arbitrary mission concepts specifying

- Mission design parameters
- X-ray optics/detector models
- Pulsar models/catalogs and observation schedules
- Photon processing and orbit determination algorithms

Leverages NASA Goddard GN&C engineering and X-ray detector lab technologies

Offers three *simulation modes* with varying levels of fidelity

Standardized interfaces defined to foster collaboration
Ground testbed end-to-end simulation flow

Three modes of simulation.
(no HWIL) shortcut the measurement process to allow faster-than-real-time simulations
**Goddard XNAV Lab Testbed (GXLT)**

**Control program**
Loads different scenarios (receiver orbits, pulsar observation schedule, etc.) for testing

**MXS driver**
Firmware + Software simulates receiver dynamics and drives MXS hardware
Photon simulation

Matlab simulation of photon arrival process

Modulated X-ray source modulating signal and photon arrivals
Future Activity

- Ground activity
  - Broad improvements to modeling fidelity
  - Extensive algorithm testing
- Flight activity
  - SEXTANT engineering-unit hardware integration
  - Flight software development & integration
  - Payload integration & test
  - On-orbit demonstration (baseline) and experimentation
Backup slides
GXLT components

GSFC’s General Mission Analysis Tool: Scenario-definition-> Spacecraft ephem.

XNAV meas model (DDG - Delay Doppler Gen.): Spacecraft ephem. -> Pulsar pulse phase truth

Modulated X-ray source and driver: Pulsar pulse truth -> X-rays with correct inst. rate

Silicon drift detectors/and time stamping electronics: X-ray photons time-stamped to < 300ns (UTC)

Algorithms for batch processing photons to extract phase and Doppler measurements

Extended Kalman Filters: OD-toolbox and GEONS Fuse Spacecraft dynamic models and pulse phase and Doppler measurements to generate estimated Spacecraft ephem.
Preliminary results: simulation setup

- Scenario modeled on SEXTANT ISS-like LEO orbit
- Observation schedule set to observe three pulsars sequentially, making 10 independent phase/Doppler measurements from each before switching. The cycle of 30 measurements was repeated 4 times, leading to a 16 day simulation

<table>
<thead>
<tr>
<th>Name</th>
<th>PSR B1937+21</th>
<th>PSR B1821-24</th>
<th>PSR J0218+4232</th>
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<tr>
<td>Pulse Frequency ($F_0$)</td>
<td>641.92 Hz</td>
<td>327.40 Hz</td>
<td>430.46 Hz</td>
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<td>Source Photon Arrival Rate ($\alpha$)</td>
<td>0.030 cts/s</td>
<td>0.083 cts/s</td>
<td>0.079 cts/s</td>
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<tr>
<td>Background Photon Arrival Rate ($\beta$)</td>
<td>0.050 cts/s</td>
<td>0.410 cts/s</td>
<td>0.086 cts/s</td>
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<td>Observation Time ($t_{obs}$)</td>
<td>2710 s</td>
<td>1940 s</td>
<td>30010 s</td>
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<tr>
<td>Cramér-Rao Lower Bound (CRLB)</td>
<td>5 $\mu$s</td>
<td>10 $\mu$s</td>
<td>10 $\mu$s</td>
</tr>
</tbody>
</table>

Shape
Preliminary results (nominal rates)

- Expected error level of ~1km achieved after a few orbits (typical conv. time for nav. filters)
- Consistent results obtained for different Modeling Schemes
Preliminary results (100X rates)

- Pulsar rates increased by factor of 100 to reduce sim. time to 4 hours for real-time MS2 hardware
- Results similar to previous case