SEXTANT X-ray Pulsar Navigation Demonstration: Flight System and Test Results

Presented by Luke Winternitz


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Outline

• X-ray pulsar Navigation (XNAV)
• NICER Mission
• SEXTANT Overview
• SEXTANT System Architecture
  – Flight software and algorithms
  – SEXTANT ground system
  – SEXTANT ground testbed
• Ground test results
• Summary
• Millisecond pulsars (MSPs) are rapidly rotating neutron stars that appear to pulsate across the electromagnetic spectrum
• Some millisecond pulsars (MSPs) have long-term timing stability that rivals that of atomic clocks
• An orbit model of a spacecraft observing an MSP can be autonomously adjusted to account for departures of measured pulse phase from predictions
• XNAV could be an enabling technology for deep space navigation and an important augmentation to DSN

History
• Pulsars were discovered in 1967 and immediately recognized as a tool for Galactic navigation
• 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.)
• SEXTANT builds on previous work to perform the first in-space, real-time demonstration and validation of XNAV
NICER
- Fundamental investigation of ultra-dense matter: structure, dynamics, & energetics
- Will determine the radii of neutron stars to 5%, an order of magnitude better than known today
- Launch in January 2017 (TBR) on Space-X Dragon
- 18 Month mission on ISS Express Logistics Carrier

X-ray Timing Instrument (XTI)
- An unprecedented combination of time resolution, energy resolution, and sensitivity
- X-ray (0.2–12 keV) concentrator (single-bounce) optics and silicon-drift detectors
- High precision time tagging (100 ns RMS)
- Low background (<0.4 cts/sec)
- Large effective area (>1800 cm^2)
- X-ray detectors with high quantum efficiency and spectral resolution

NICER’s XTI is extremely well suited for SEXTANT’s XNAV Demo
Station Explorer for X-ray Timing and Navigation Technology (SEXTANT)

NASA Space Tech Mission Directorate Game-Changing Division funded technology enhancement to NICER

SEXTANT Primary Objective: Provide first demonstration of real-time, on-board X-ray Pulsar Navigation
• Implement a fully functional XNAV system in a challenging ISS/LEO orbit; NICER compatible
• Advance core XNAV technologies

Key Performance Parameter
• Achieve 10 km orbit determination accuracy, worst direction, using up to 2 weeks of observations.

Stretch Goal
• Achieve 1 km orbit determination accuracy, worst direction, using up to 4 weeks of observations.

Planned Experiments
• Two 2-4 week periods observing 3 – 5 pulsars
• Opportunistic on-orbit experiments
• Ground experiments using collected photon data

Other objectives
• Validate and enhance the unique Goddard XNAV lab testbed (GXLT)
• Use SEXTANT data and GXLT to study real-world XNAV scenarios and evaluate alternative XNAV algorithms
• Study utility of pulsars for time keeping and clock synchronization
• Expand the catalog of XNAV-worthy MSPs
SEXTANT System Architecture

NICER XTI

Concentrator → Detector → MPU+GPS

Ground System Software

Ground System

Flight Software

Event Filtering

Pulse Phase Estimation

GEONS navigation processing

Pulsar almanac

TLM

Algorithms

GPS time stamped Photon + Background events

GPS time stamped Photon + Background events, GPS telemetry

Pulsar almanac entries (timing models, templates) and alert messages

Testbed

Goddard XNAV Lab Testbed (GXLT)

Test stimulus

Proving ground for algorithm development, validation, test

Test stimulus

Pulsar data from observatories (Arecibo, FERMI, etc.)

X-rays
System Architecture

- NICER X-Ray Timing Instrument (XTI)
  - XTI detects events from sequential pulsar observations, output via MPU
  - Essentially ideal instrument for XNAV: high signal-to-noise, large collecting area, precise timing, scalable
- Flight Software
  - A GSFC Core Flight System (CFS) “App” running in the NICER Instrument Flight Software
  - Implements SEXTANT XFSW algorithms
  - Interfaces to the SEXTANT Ground System through command/telemetry link
- Ground System
  - Maintains pulsar almanac
  - Generates XFSW configuration table
  - Generate optimized observation schedule
  - Monitors performance
  - Generates SEXTANT commands
- Goddard XNAV Lab Testbed (GXLT)
  - Developed to provide test-as-you-fly system for SEXTANT algorithm development, XFSW test, and requirements verification.
SEXTANT Flight Software

- XNAV Flight Software is single application hosted by NICER Instrument Flight Software
- Pre-processes and buffers photon events from XTI
  - Filter out background
  - Attach phase and frequency prediction
- Batch Process blocks of photons to obtain Maximum Likelihood phase and frequency estimates based on NHPP arrival model
- Filter Blends models of spacecraft dynamics with phase & frequency estimates in GEONS to maintain spacecraft state estimate
GEONS Navigation Filter

- Flight-proven, Award-winning, NPR 7150.2 Compliant UD-Factorized Extended Kalman Filter
- Estimate multiple spacecraft absolute and/or relative states
- Enables data fusion and regime independence
- Earth, Moon, LPOs, Deep Space
- GPS, TDRSS, DSN/USN/GN, Crosslink, Celestial Object, Accelerometer, and XNAV measurements.
- Used on Terra, EO-1, GPM, MMS, NICER/SEXTANT
- Licensed to Orbital, Ball, ITT, Moog/Broad Reach
- SEXTANT team has added XNAV phase/frequency measurement model and other enhancements
SEXTANT Ground System Flow

NRL
- Radio and X-ray observations
  - Model fitting
  - Pulsar Almanac
    - Timing models
    - Templates
    - Count rates
    - Spectra

SEXTANT
- SEXTANT Scheduler and manual tuning
  - Proposed Schedule and app config
    - Build config
      - Configuration Table
        - EOPs
          - Verification

  - NICER Visibility
  - Pulsar Visibility
  - NICER Scheduler
    - Candidate Navigation Schedule
      - Upload to NICER

Legend
- I/O Data
- Process
- Process w/ decision

NICER SMOC
A simulation environment for evaluating and predicting the performance of the SEXTANT XNAV system

Level 0 simulation
- Simulated measurements (no photon processing)
- Useful for long term studies (deep space trajectories, etc.)

Level 1 simulation
- Software only photon event simulation
- Photon processing algorithm implemented for measurement generation
- Primary mode of development for SEXTANT

Level 2 simulation
- Hardware-in-the-loop simulation
- Use the Modulated X-ray source (MXS) to generate the photon events
- X-ray detector and electronics time-tag the photon events
- Provides “test-as-you-fly” mode

Legend
- I/O Data
- Software Process
- Hardware Component
- Alternate simulation paths
  - Software accelerated mode: measurement-level simulation
  - Hardware mode (realtime only)
  - Software accelerated mode: photon-level simulation
Pulsar Simulator

MXS control electronics

- Modulated X-ray source (MXS) allows precise control of X-ray intensity and timing
- Can be driven to precisely emulate MSP pulse shape, frequency, and phase as seen by spacecraft in orbit or in deep space

Detected X-rays follow drive current
NICER EM Single-Timing-Chain

ASIST Station
MXS
X-ray Detector (FPM)
MPU
MEB EM2
Payload XNAV Test Configuration
• Each XFSW build is subjected to a comprehensive multi-stage build verification test plan
  – **Baseline performance** established in GXLT level 1 simulation
  – **Multiple intermediate tests** where simulated photons are fed back through XFSW on PC and NICER electronics
  – **Hardware system test** on NICER electronics (EM timing-chain or payload) stimulated by GXLT (level-2) pulsar simulator
Baseline Test Results for XFSW v2.1.0

- Standard 5-day test using software simulated events in GXLT level-1 simulation

- Red is 3-sigma formal error
- Blue is actual error
- Baseline performance meets target accuracy

- Phase residuals (in cycles) consistent with predicted variance
• Successful 12hr XNAV demonstrates onboard processing of pulsar modulated X-rays through full NICER flight instrument timing chain.

• Red is 3-sigma formal error
• Blue is actual error
• Performance meets target accuracy

• Phase residuals (in cycles) consistent with predicted variance
Summary

• XNAV could be an enabling technology for deep space navigation and an important augmentation to DSN

• NASA’s NICER will place an X-ray timing instrument with an unprecedented combination of time resolution, energy resolution, and sensitivity on the ISS in January 2017 and will measure the radius of neutron stars to 5%, an order of magnitude improvement

• SEXTANT is an attached technology demonstration that will
  – Provide the first on-orbit demonstration of XNAV on-board and in real-time
  – Implement a fully functional XNAV system in a challenging ISS/LEO orbit targeting 1-10km orbit determination accuracy
  – Advance core XNAV technologies hardware and software

• The SEXTANT flight system is mature and has been verified in a unique hardware-in-the-loop, test-as-you-fly testbed: the GXLT