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

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for the SEXTANT team

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Outline

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- Missions
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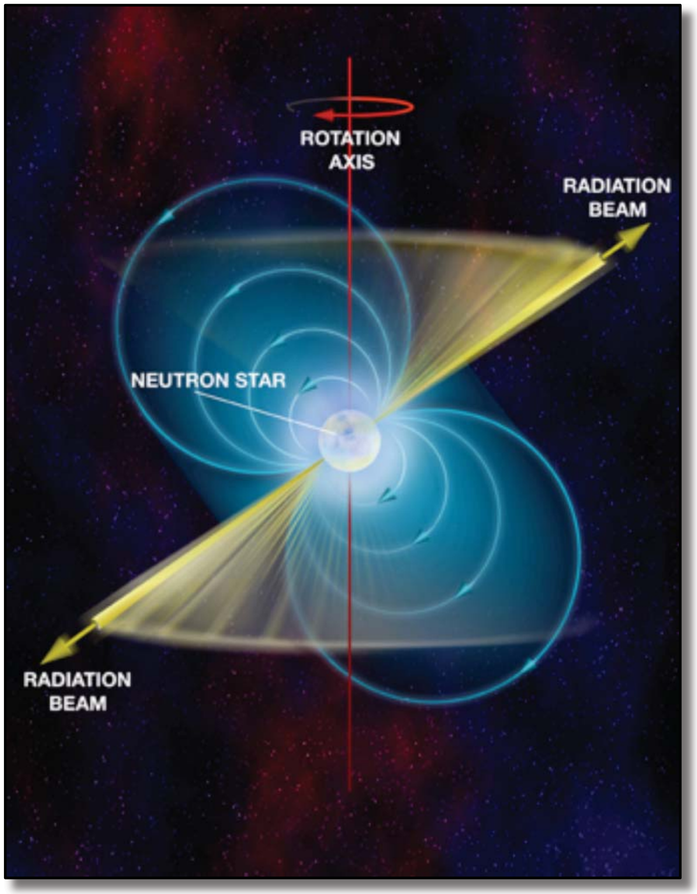
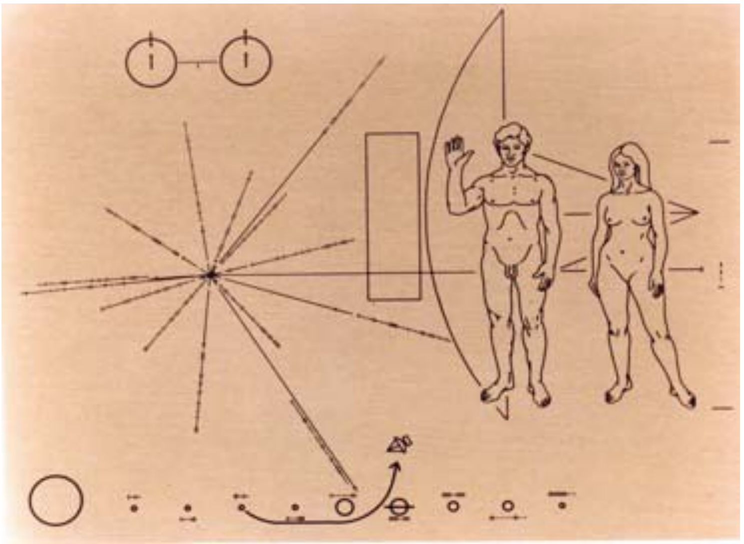
  - SEXTANT tech demo
- Architecture
  - NICER XTI
  - Flight software
  - Ground system
  - Ground testbed and end-to-end simulation
- Future activity



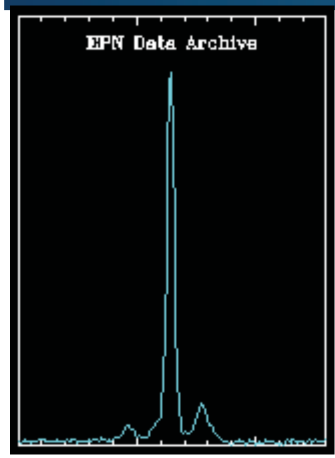
X-ray pulsar navigation (XNAV)

- 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)



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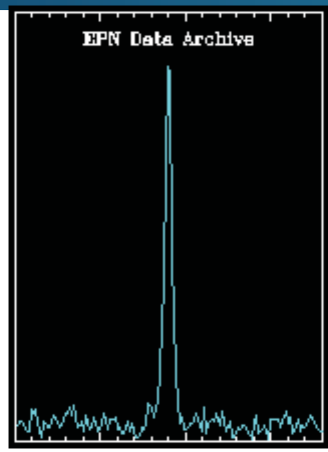
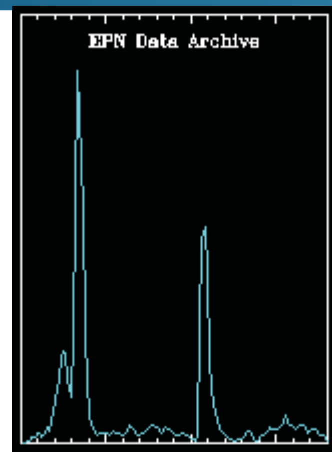
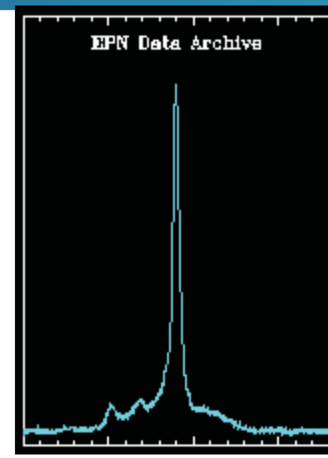


Vela



Crab



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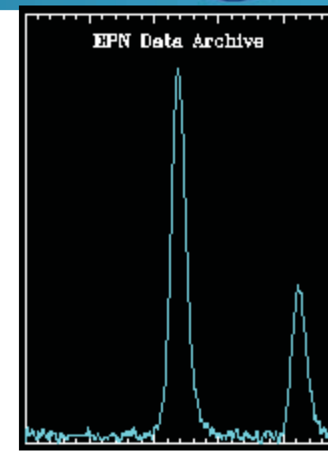
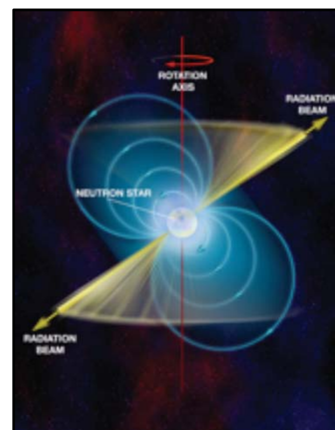


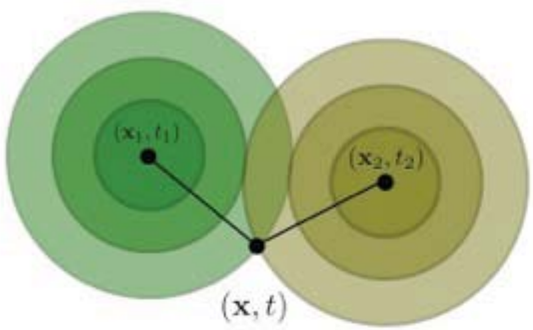
B1937

- 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



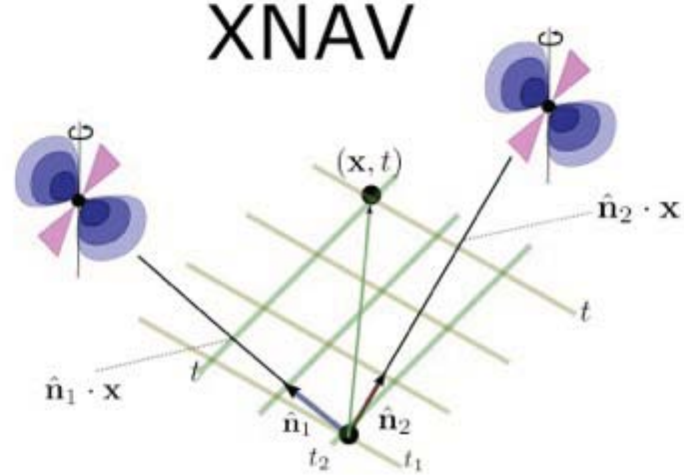
XNAV concept

GPS

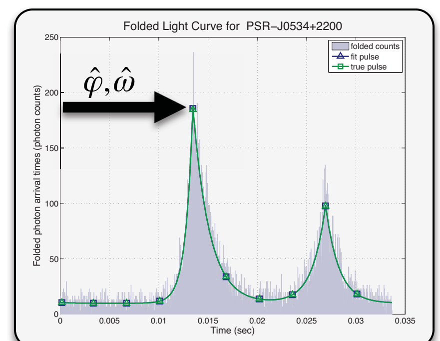


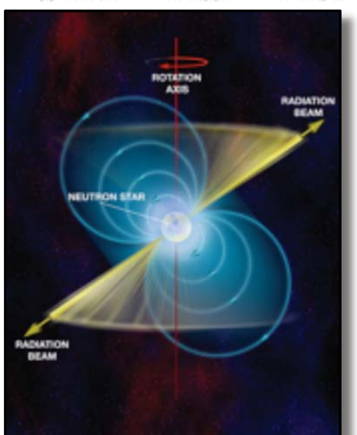
$$\|\mathbf{x}_1 - \mathbf{x}\| = c(t - t_1)$$
$$\|\mathbf{x}_2 - \mathbf{x}\| = c(t - t_2)$$

XNAV

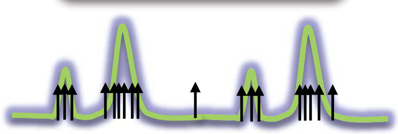


$$\hat{\mathbf{n}}_1 \cdot \mathbf{x} = c(t_1 - t)$$
$$\hat{\mathbf{n}}_2 \cdot \mathbf{x} = c(t_2 - t)$$





X-ray photons

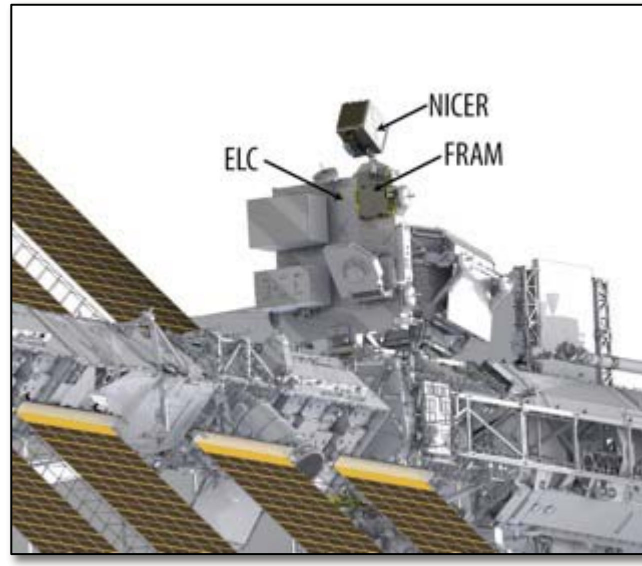


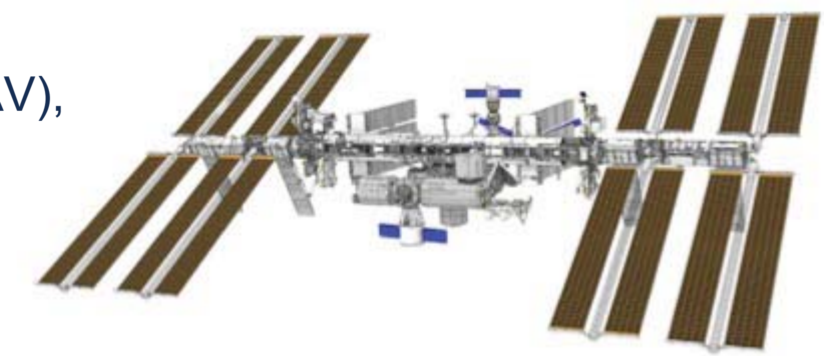
NICER XTI

SEXTANT algorithms

Neutron star Interior Composition Explorer (NICER) Mission

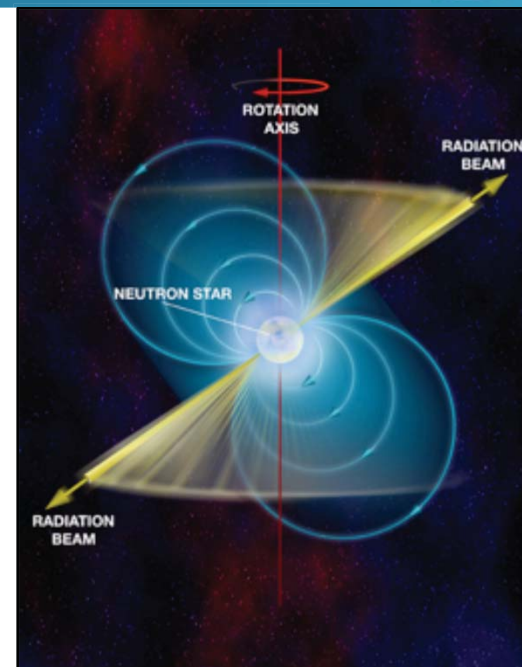
- NICER
  - SMD competitively selected purely on science
  - Launch in August 2016 on Space-X Dragon
  - 18 Month mission on Express Logistics Carrier (ELC) 2
  - X-ray (0.2–12 keV) *concentrator optics* and silicon-drift detectors; GPS position and 300 ns absolute time tagging
- SEXTANT — Station Explorer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





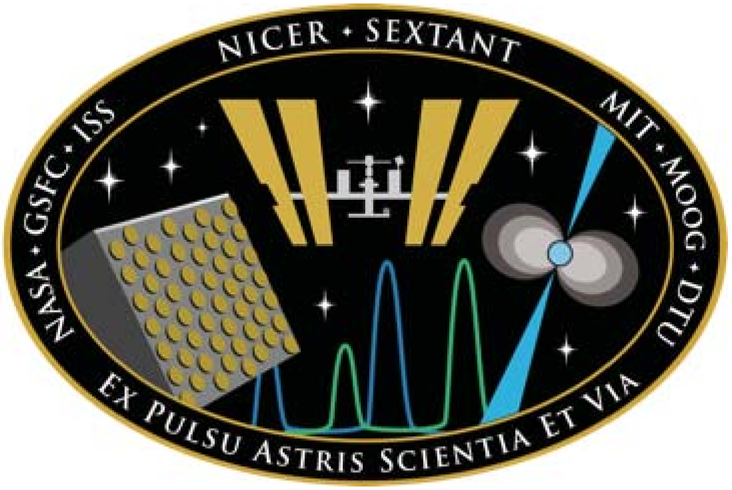
Neutron star Interior Composition Explorer (NICER) Mission

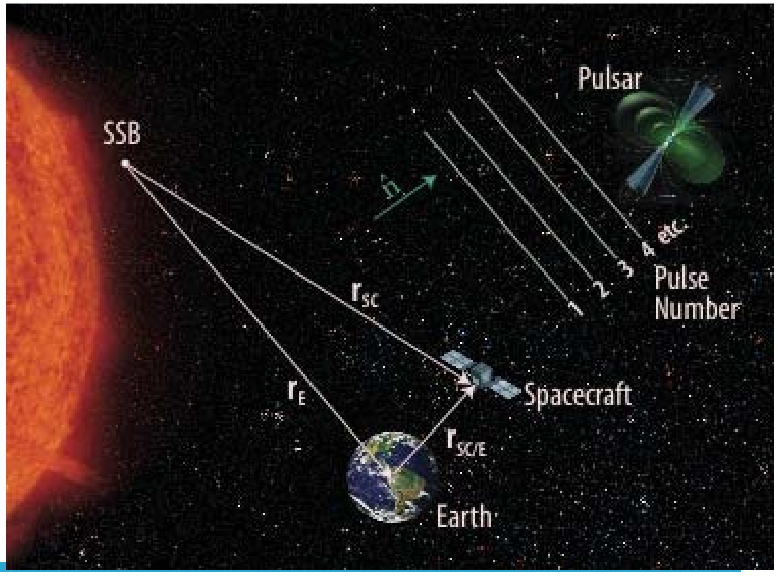
- Address NASA and National Academy of Sciences strategic questions
  - Resolve the nature of *ultra-dense* matter at the threshold of collapse to a black hole
  - **Structure**—Reveal the nature of matter in the interiors of neutron stars
  - **Dynamics**—Uncover the physics responsible for the dynamic 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



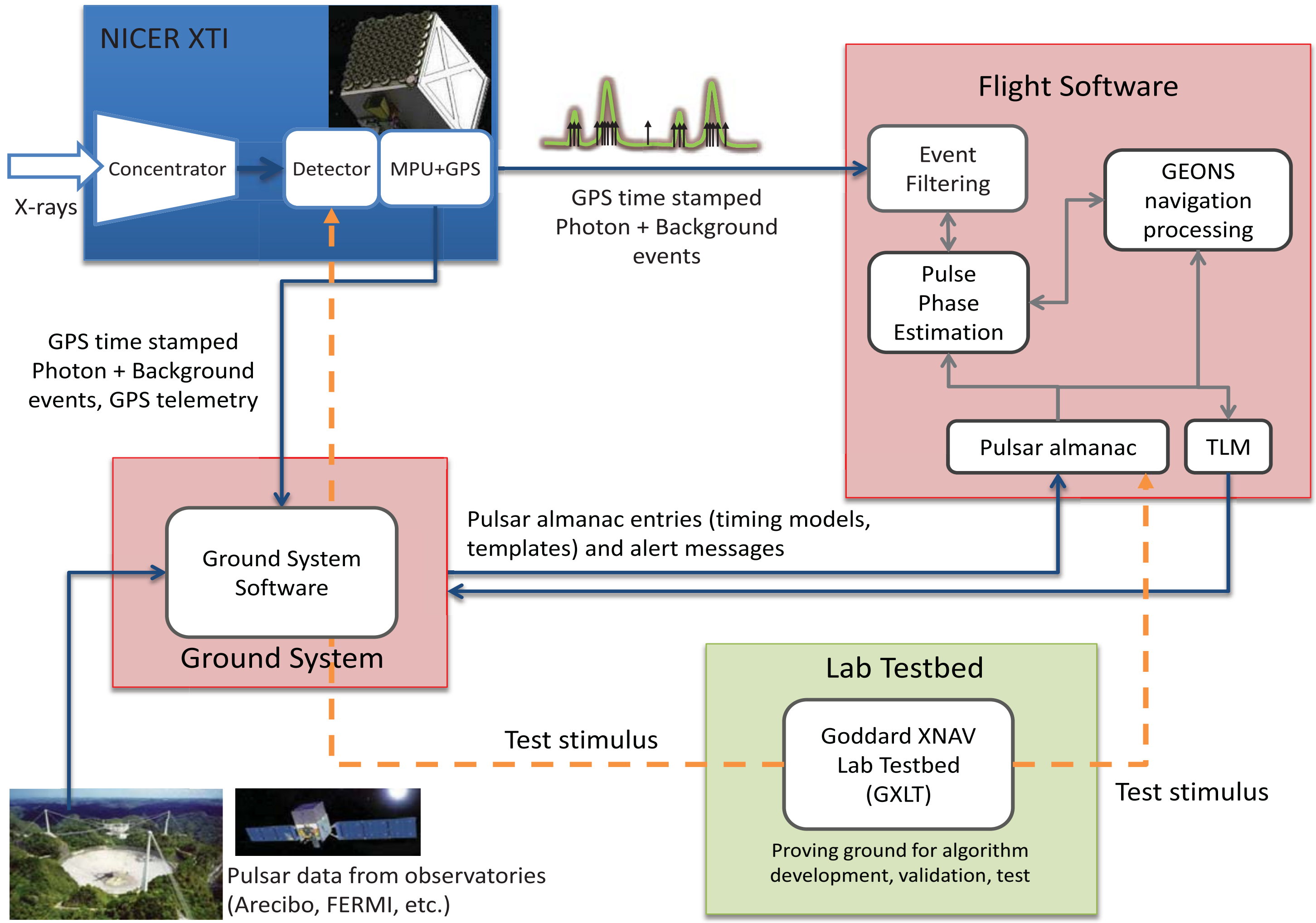
Station Explorer for X-Ray Timing and Navigation Technology (SEXTANT) Demo

- 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)



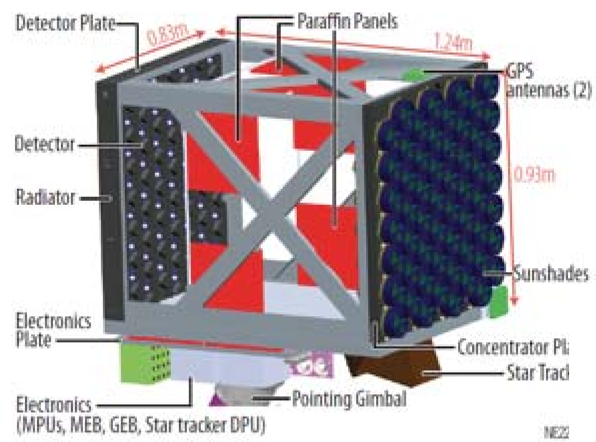


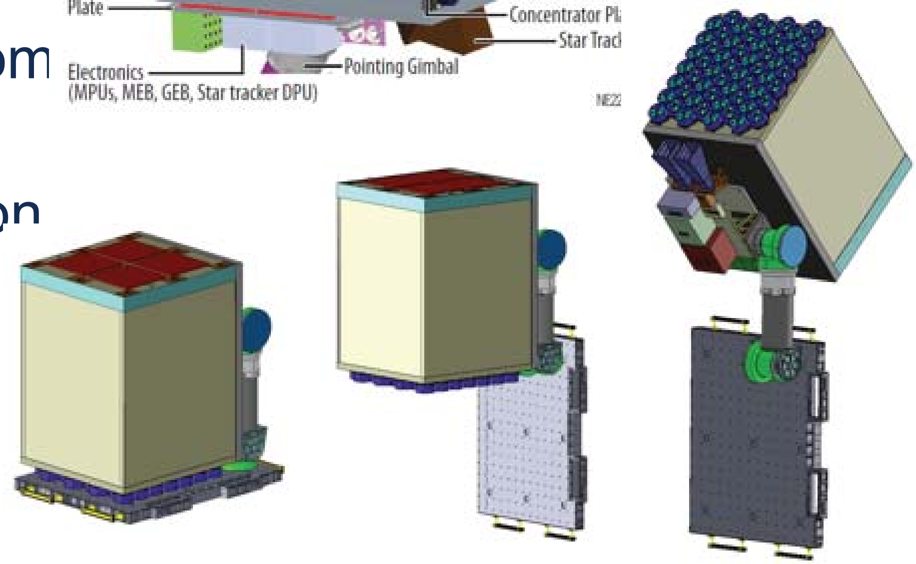
SEXTANT System Architecture



NICER X-ray Timing Instrument

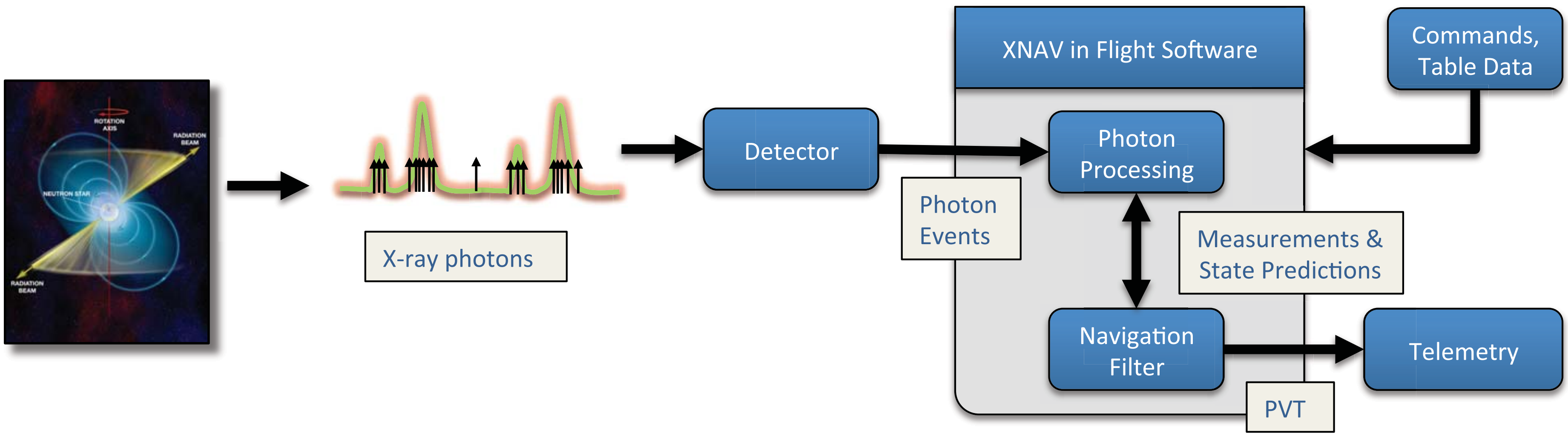
- 56 co-aligned X-ray concentrator optics and associated Silicon Drift Detectors (SDDs) in Focal Plane Modules (FPMs)
- 7 Measurement/Power Units
- The FPMs detect X-rays arriving from the concentrators
- MPUs time-tag and packetize photon events
- < 300 nsec absolute time resolution
- > 2000 cm^2 effective area
- Moderate (CCD-like) energy resolution





Stowed, deploying, and observing

Flight Software



SEXTANT flight software architecture diagram

Ground System

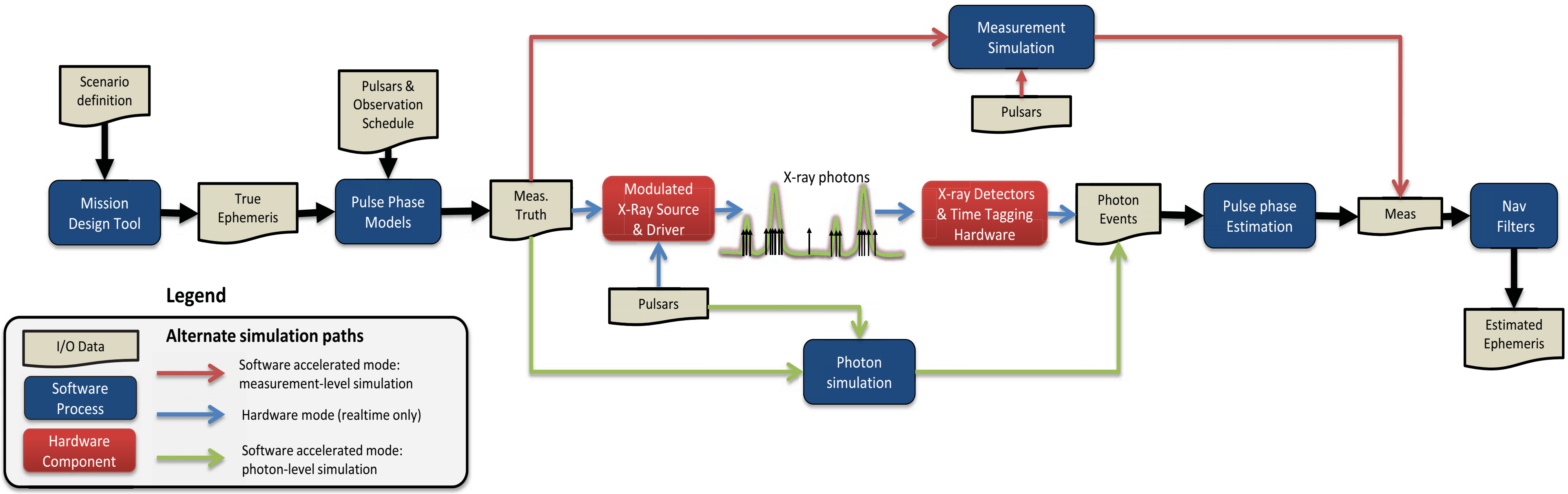
- The ground system maintains the pulsar catalog
  - incorporates data from radio telescopes, other X- ray telescopes, and the NICER XTI, once operational
  - provide current timing models, or ephemerides, and pulse profile templates to meet SEXTANT navigation needs

- The ground system is also responsible for performance monitoring and telemetry collection for post-processing purposes

Ground Testbed

- 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



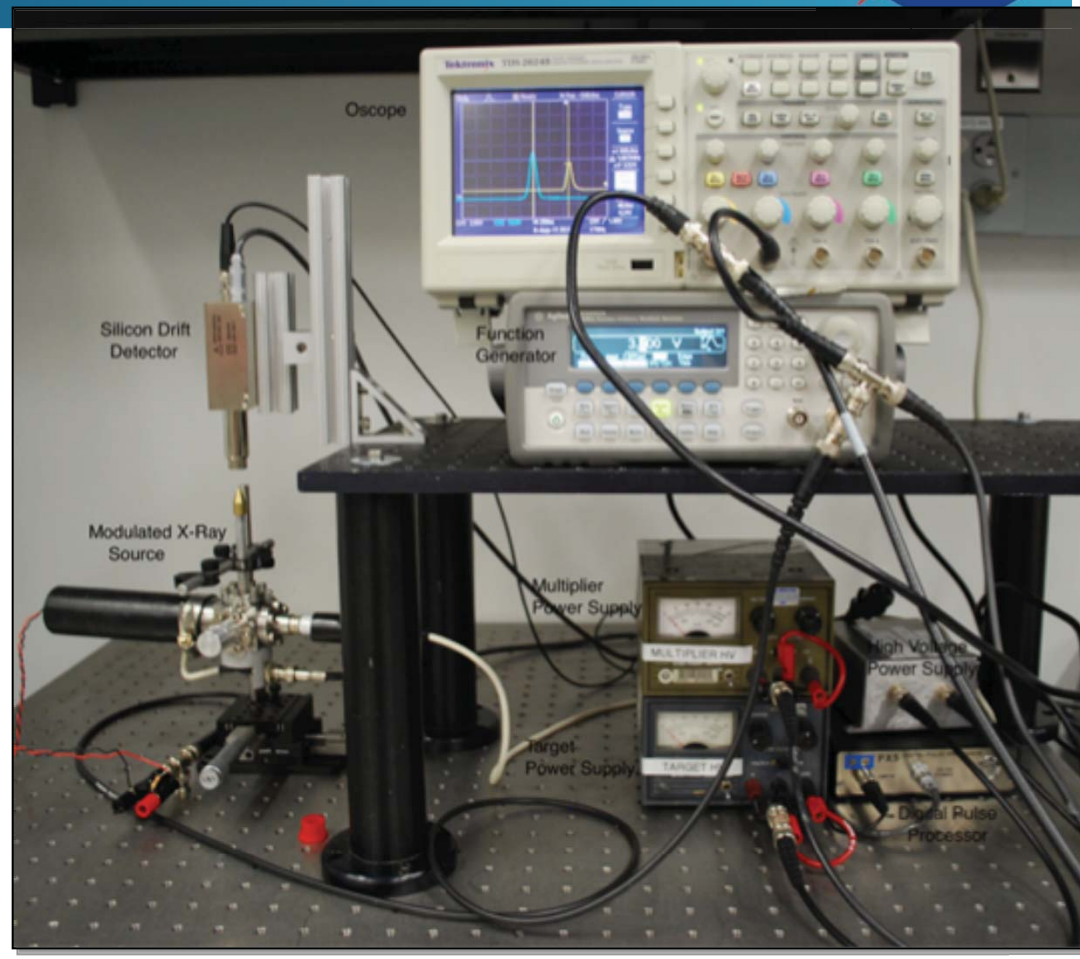
Three modes of simulation.
(no HWIL) shortcut the measurement process to allow faster-than-real-time simulations

GXLT hardware testbed

Goddard XNAV Lab Testbed (GXLT)

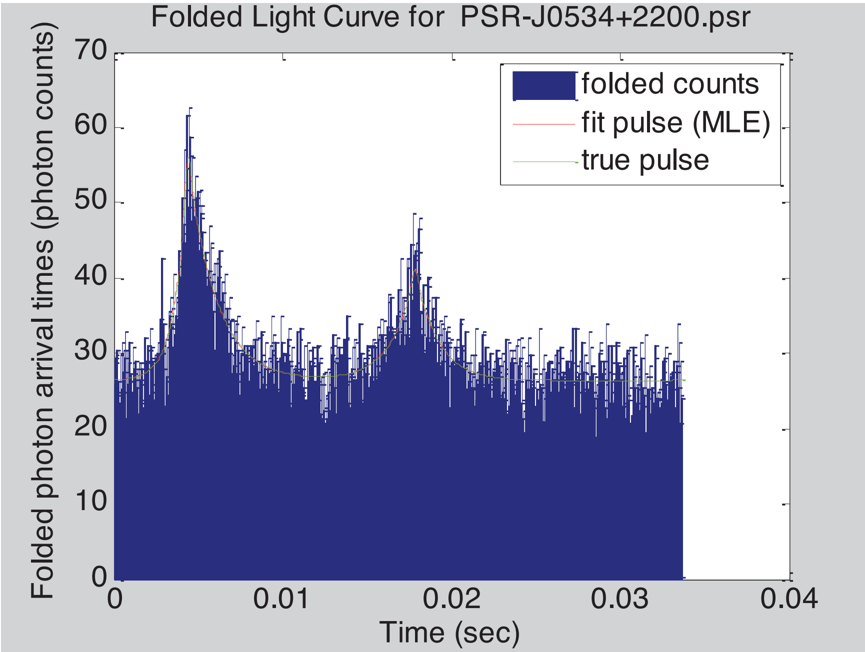
Control program
Loads different scenarios (receiver orbits, pulsar observation schedule, etc.) for testing

MXS driver
Firmware + Software simulates receiver dynamics and drives MXS hardware

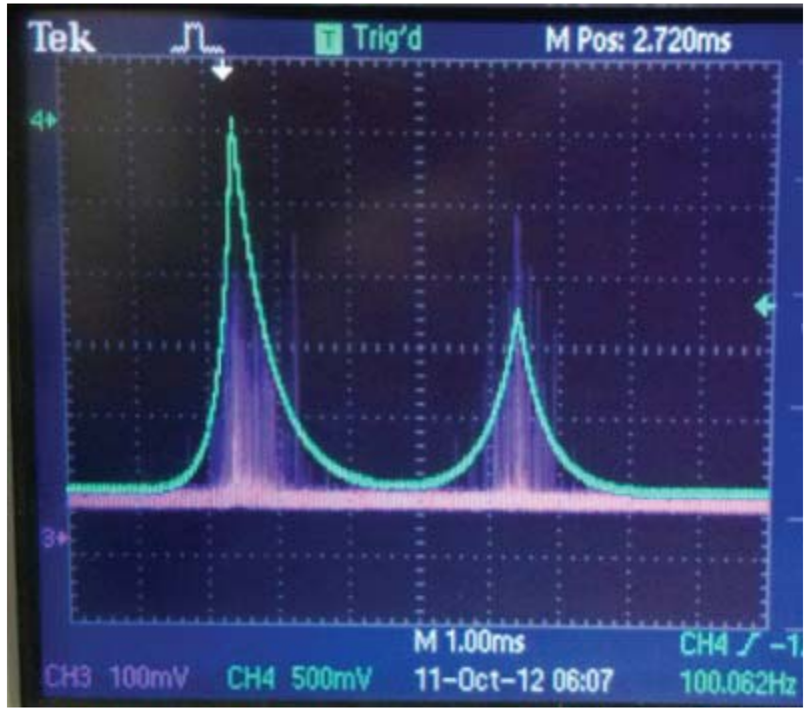


Modulated X-ray Source (MXS) and Silicon Drift Detector (SDD)

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

Mission Design Tool

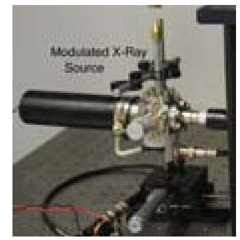
GSFC's General Mission Analysis Tool:
Scenario-definition-> Spacecraft ephem.

Pulse Phase Models

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

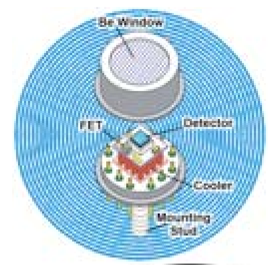
Modulated X-Ray Source & Driver

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



Photon Detector and Time Tagging

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



Pulse phase Estimation

Algorithms for batch processing photons to extract phase and Doppler measurements

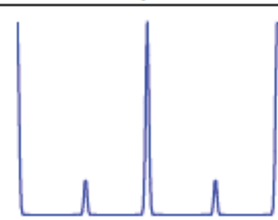
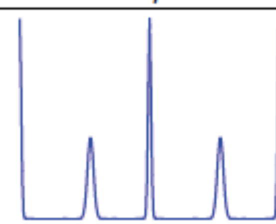
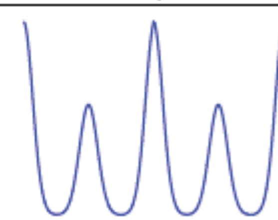
Navigation Filters

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

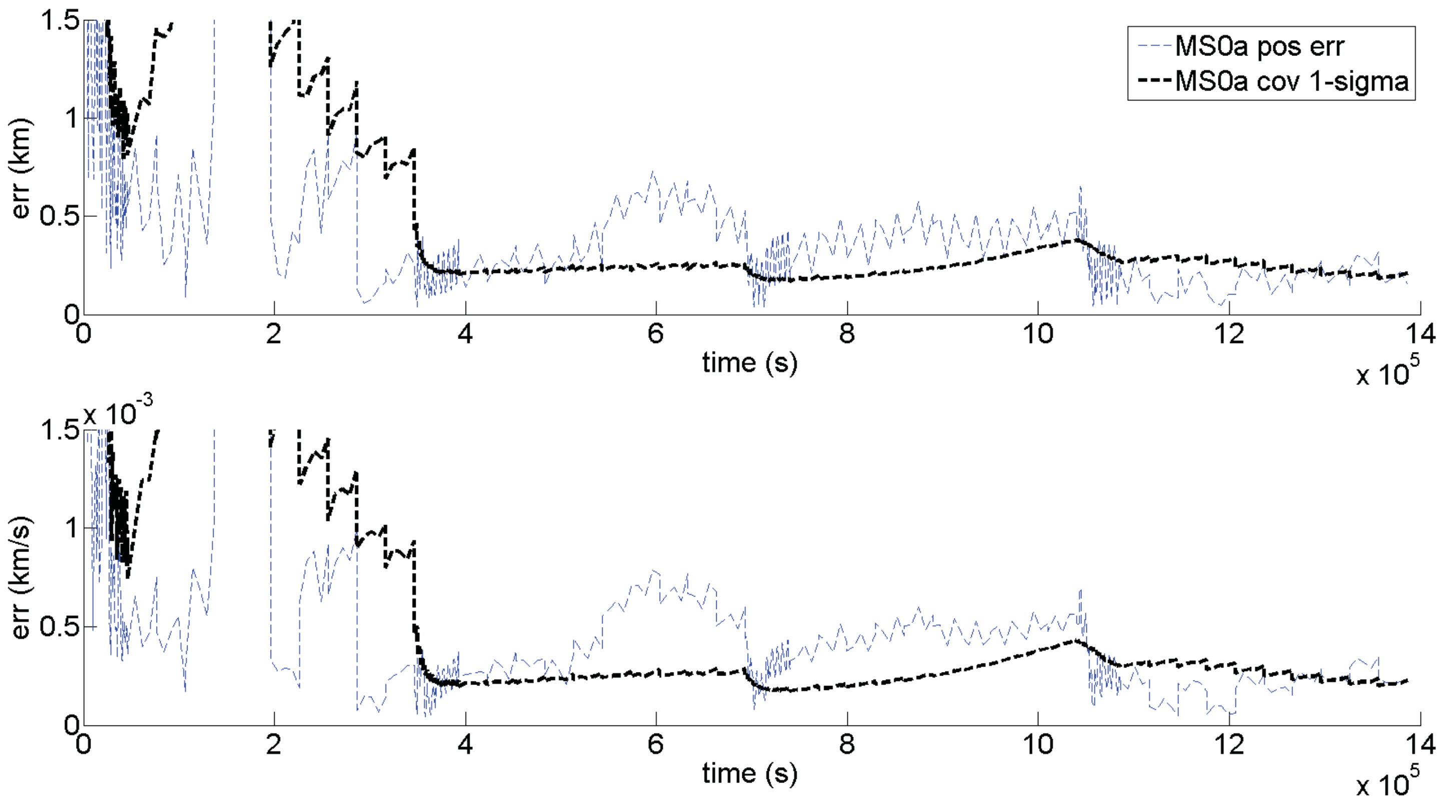
ODTBX

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

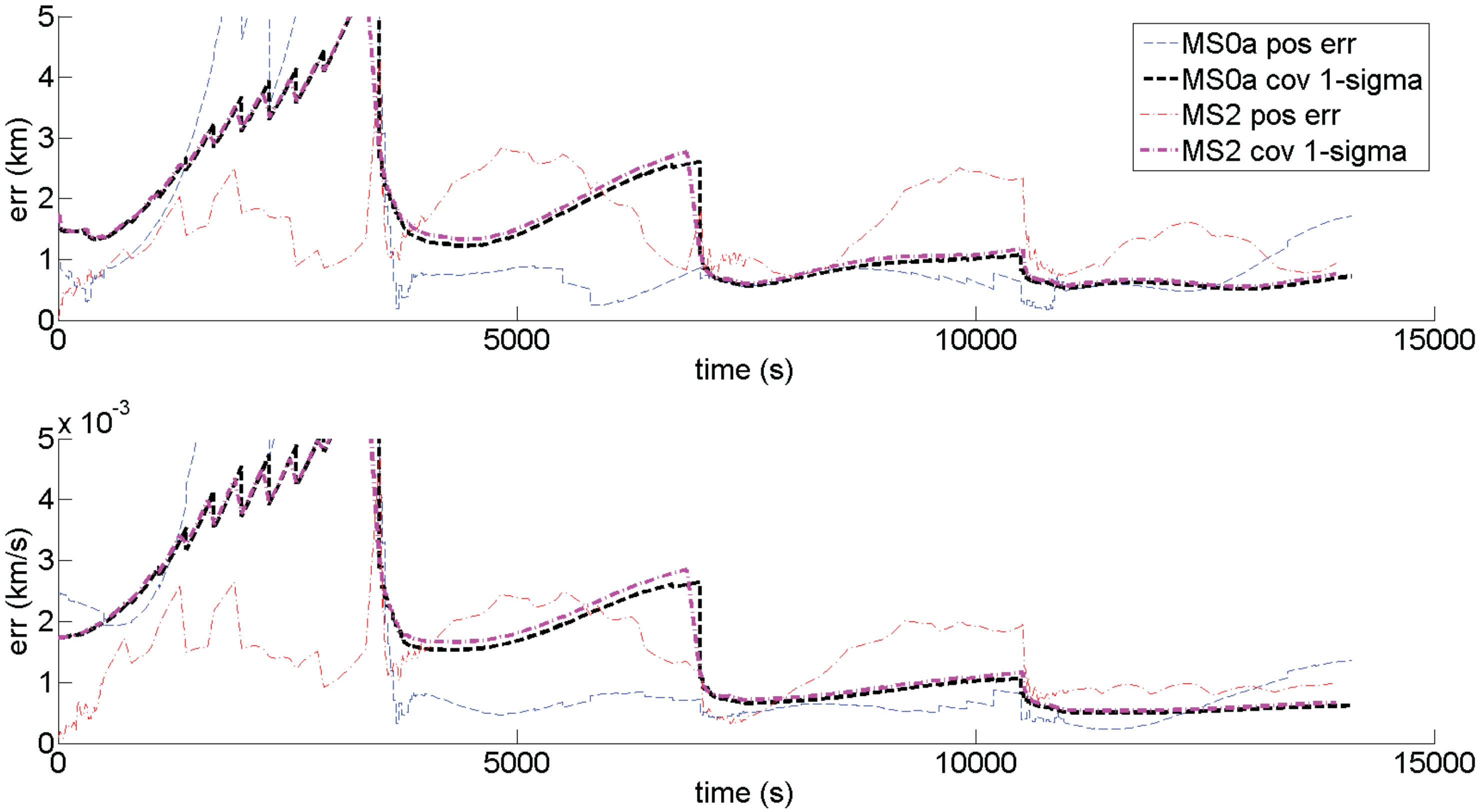
Name	PSR B1937+21	PSR B1821-24	PSR J0218+4232
Pulse Frequency (F_0)	641.92 Hz	327.40 Hz	430.46 Hz
Source Photon Arrival Rate (α)	0.030 cts/s	0.083 cts/s	0.079 cts/s
Background Photon Arrival Rate (β)	0.050 cts/s	0.410 cts/s	0.086 cts/s
Observation Time (t_{obs})	2710 s	1940 s	30010 s
Cramér-Rao Lower Bound (CRLB)	5 μs	10 μs	10 μs
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