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

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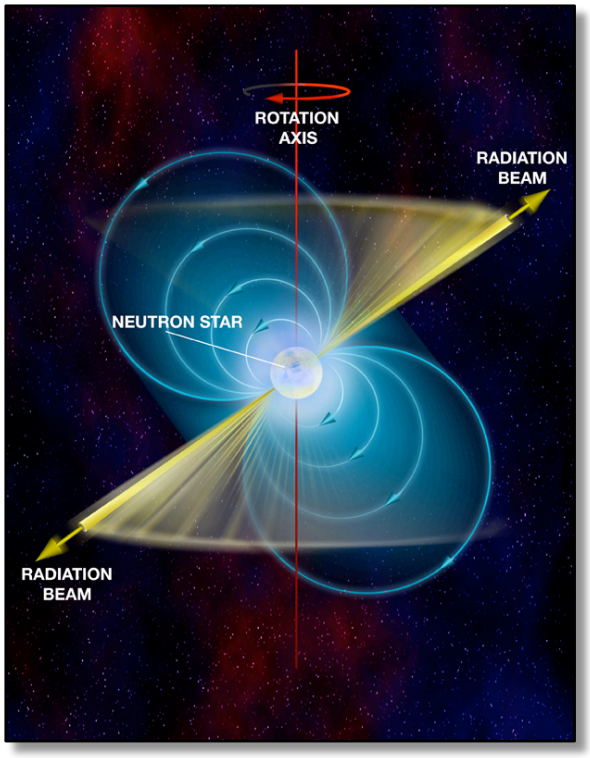
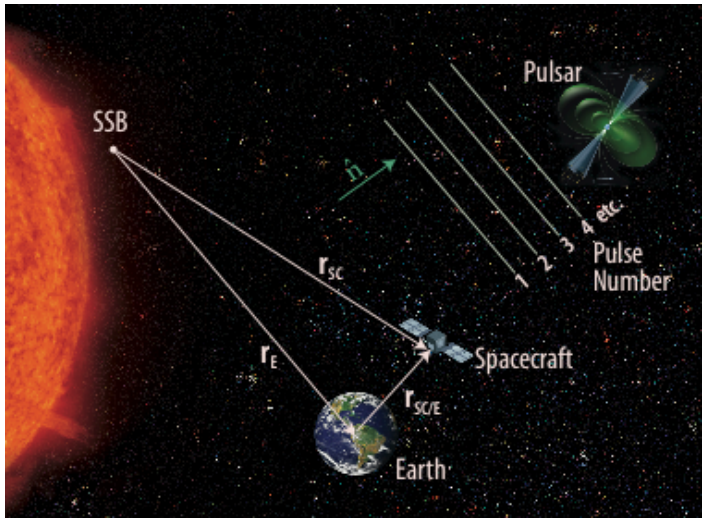
- NICER Mission
- SEXTANT Overview
- SEXTANT System Architecture
  - Flight software and algorithms
  - SEXTANT ground system
  - SEXTANT ground testbed
- Ground test results
- Summary



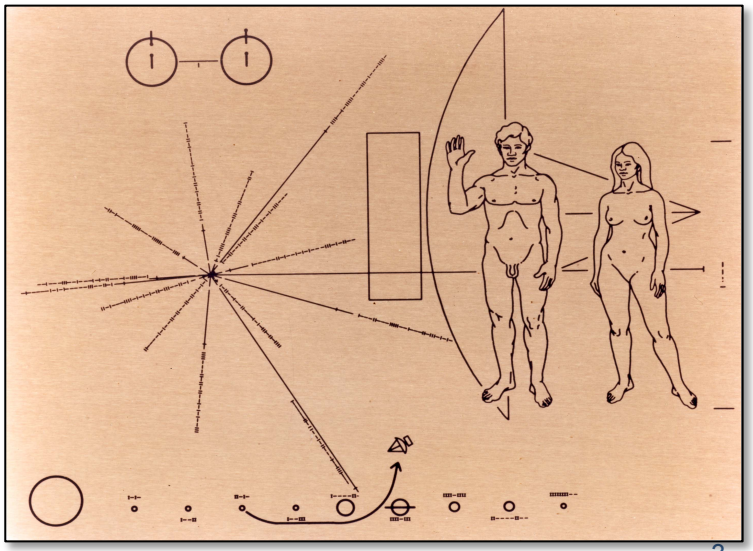
X-ray pulsar Navigation (XNAV)

- 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

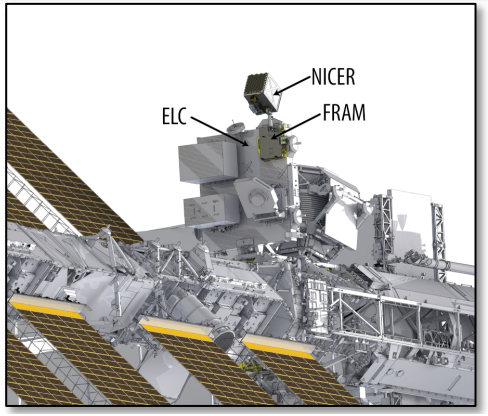


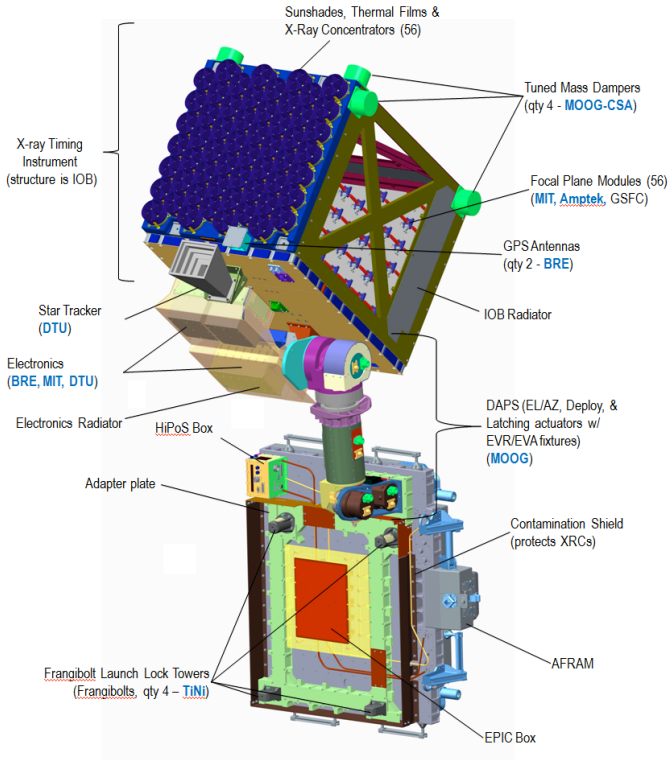
Neutron-star Interior Composition Explorer (NICER)

- 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.

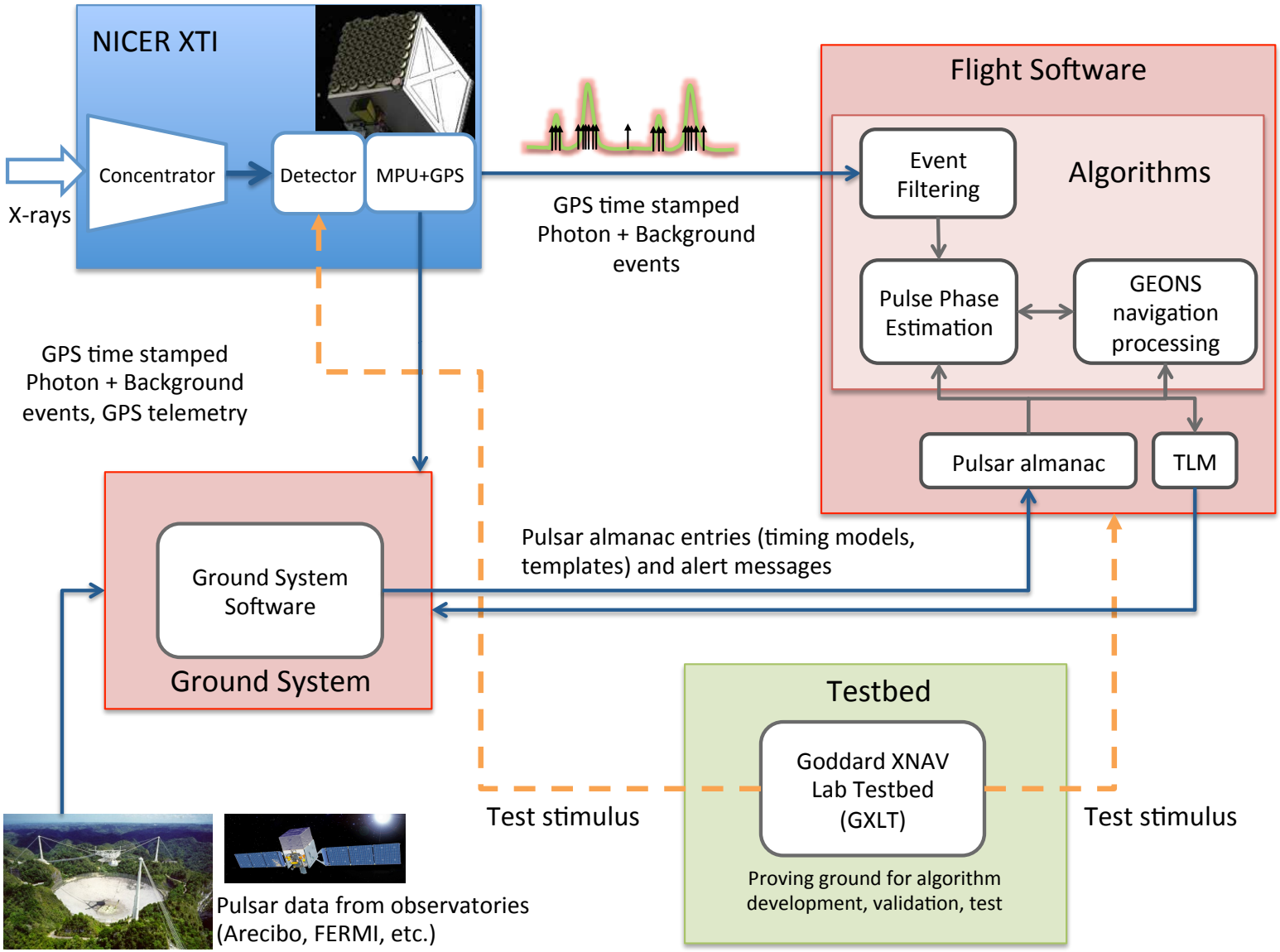
Planned Experiments

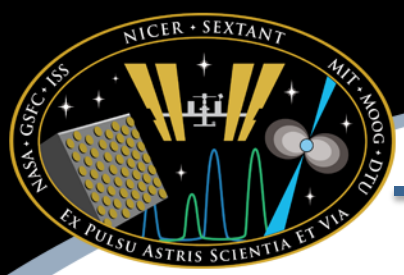
- Two 2-4 week periods observing 3 – 5 pulsars
- Opportunistic on-orbit experiments
- Ground experiments using collected photon data

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

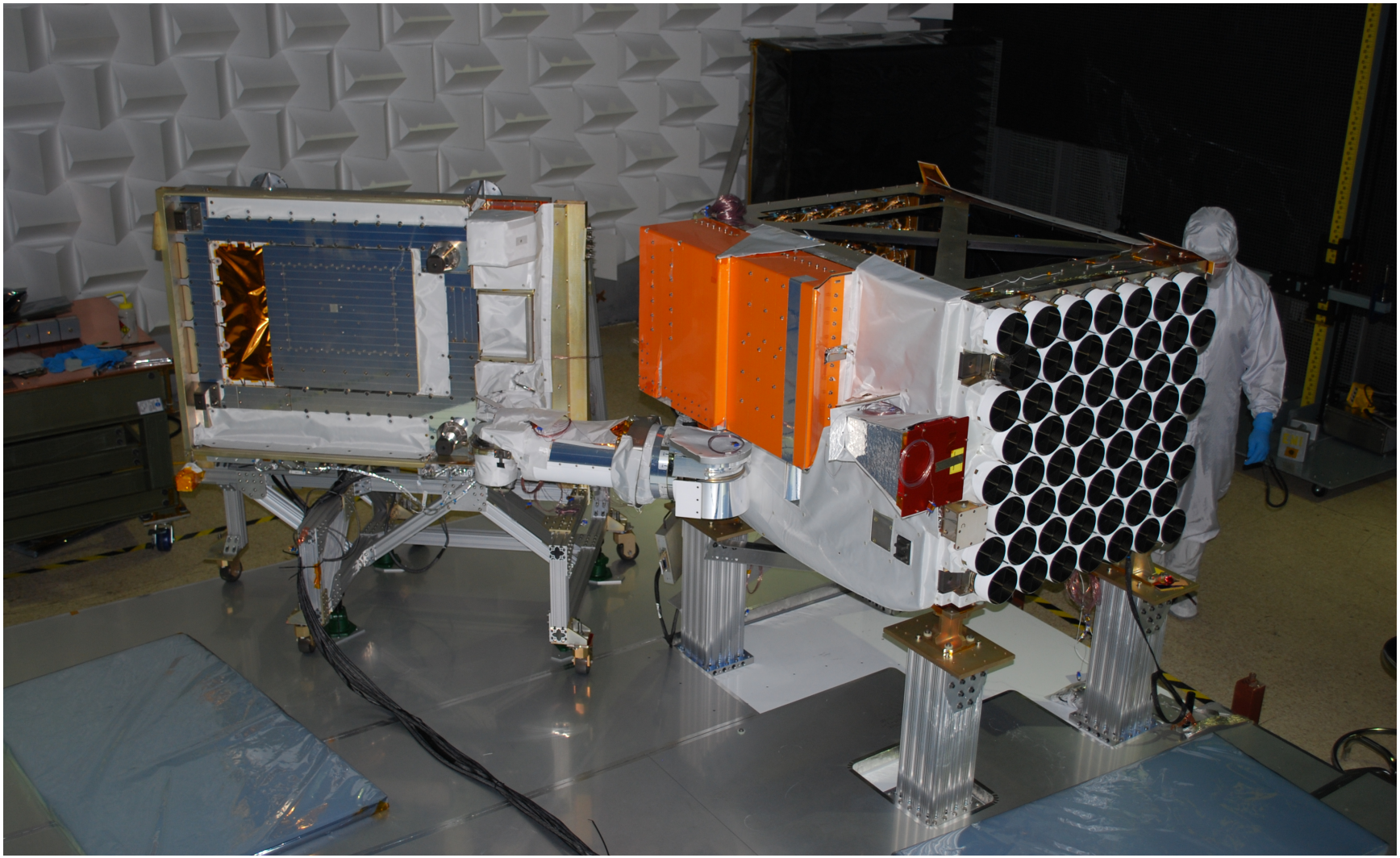




System Architecture

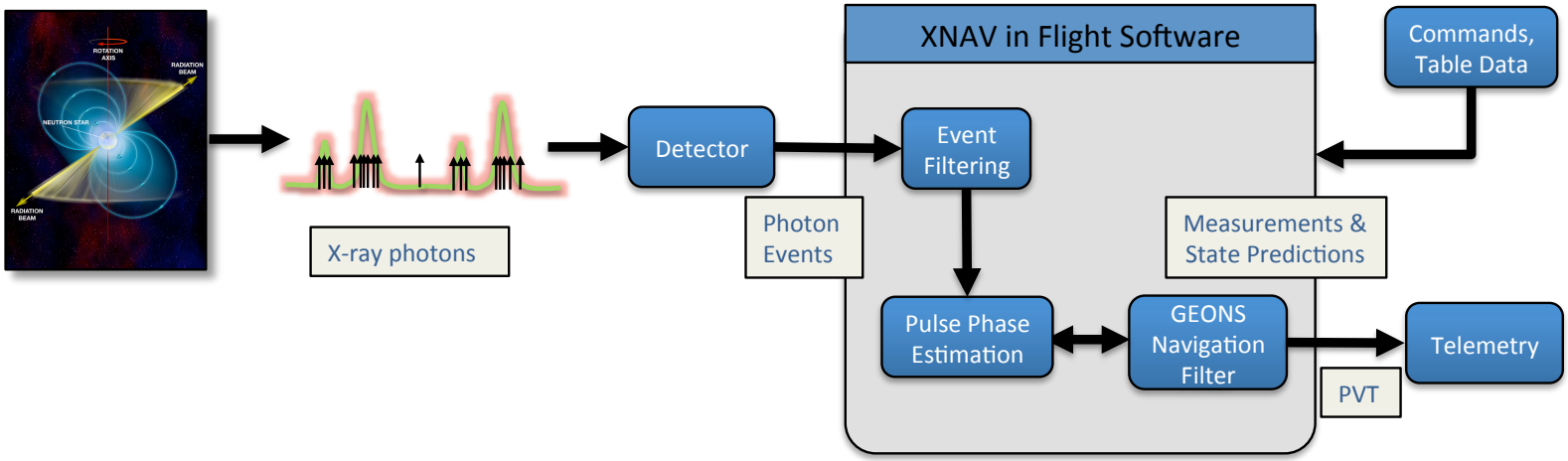
- NICER X-Ray Timing Instrument (XTI)
  - XTI detects events from sequential pulsar observations, output via MPU
  - Essentially ideal instrument for XNAV: high signal-to-noise, large collecting area, precise timing, scalable
- Flight Software
  - A GSFC Core Flight System (CFS) “App” running in the 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.

NICER Payload in Deployed Configuration



SEXTANT Flight Software

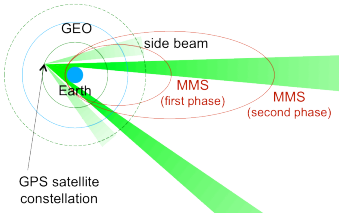
- XNAV Flight Software is single application hosted by NICER Instrument Flight Software
- Pre-processes and buffers photon events from XTI
  - Filter out background
  - Attach phase and frequency prediction
- Batch Process blocks of photons to obtain Maximum Likelihood phase and frequency estimates based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



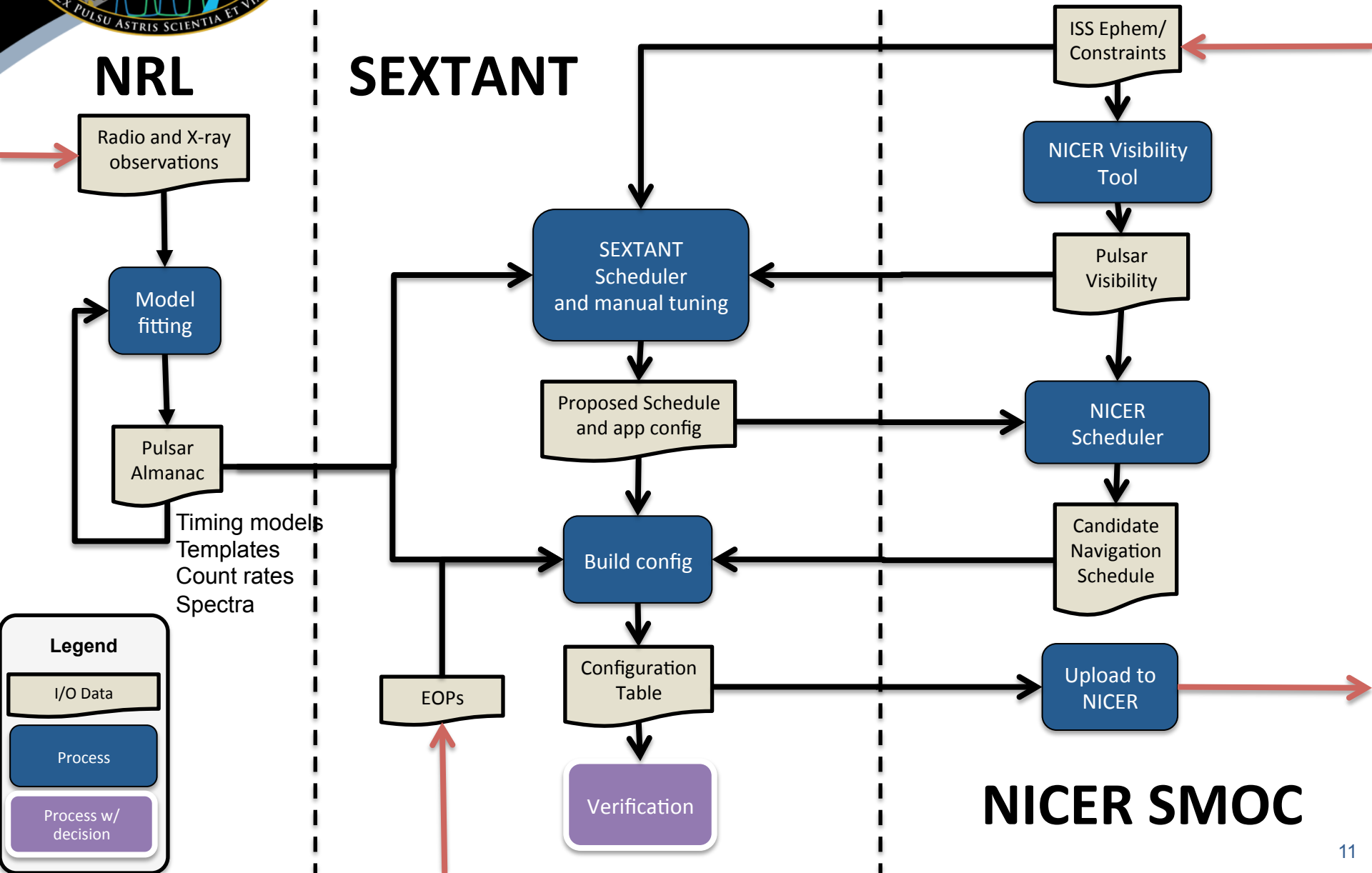
GEONS Navigation Filter

- 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



Goddard XNAV Lab Testbed (GXLT)

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

Level 0 simulation

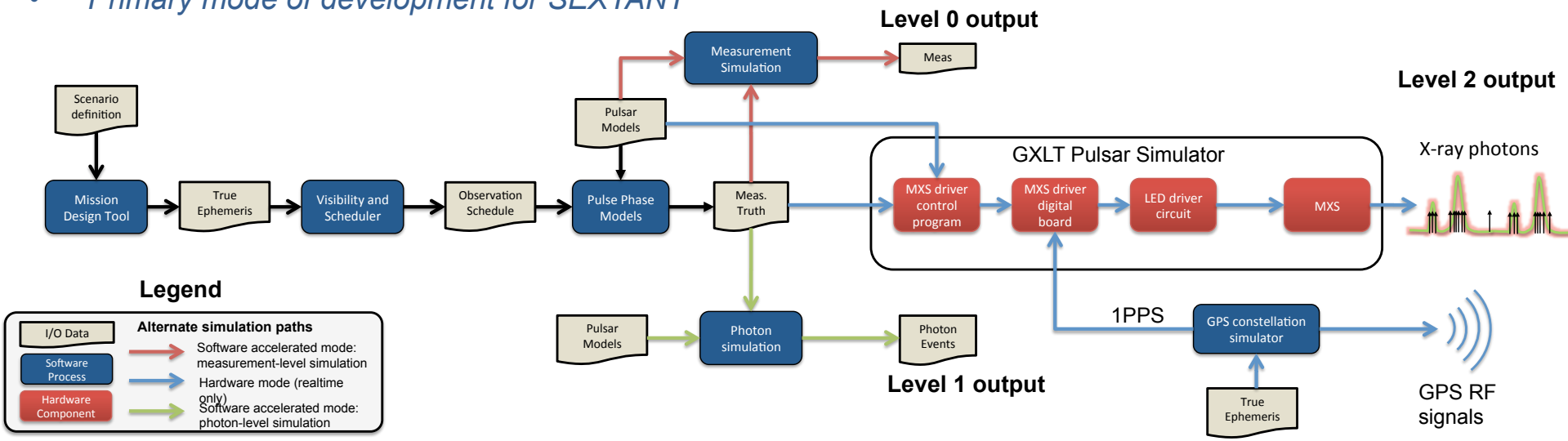
- Simulated measurements (no photon processing)
- Useful for long term studies (deep space trajectories, etc.)

Level 1 simulation

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

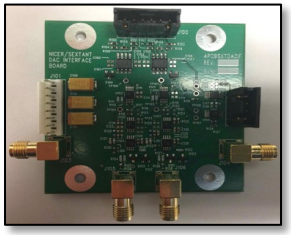
Level 2 simulation

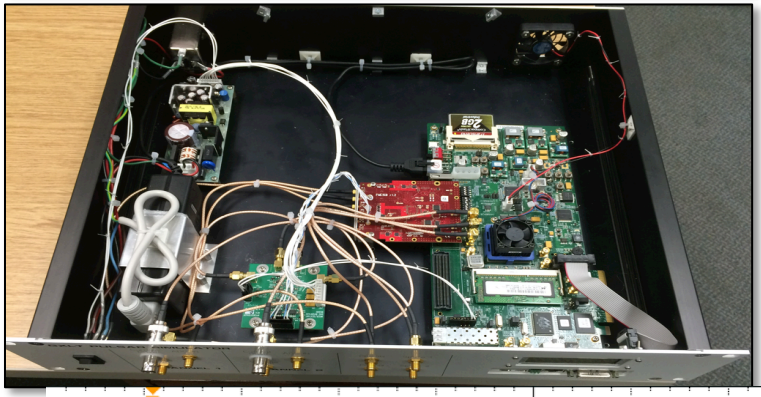
- Hardware-in-the-loop simulation
- Use the Modulated X-ray source (MXS) to generate the photon events
- X-ray detector and electronics time-tag the photon events
- Provides "test-as-you-fly" mode

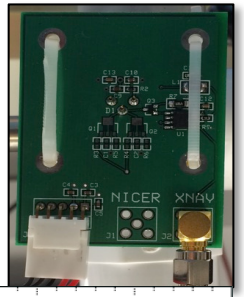


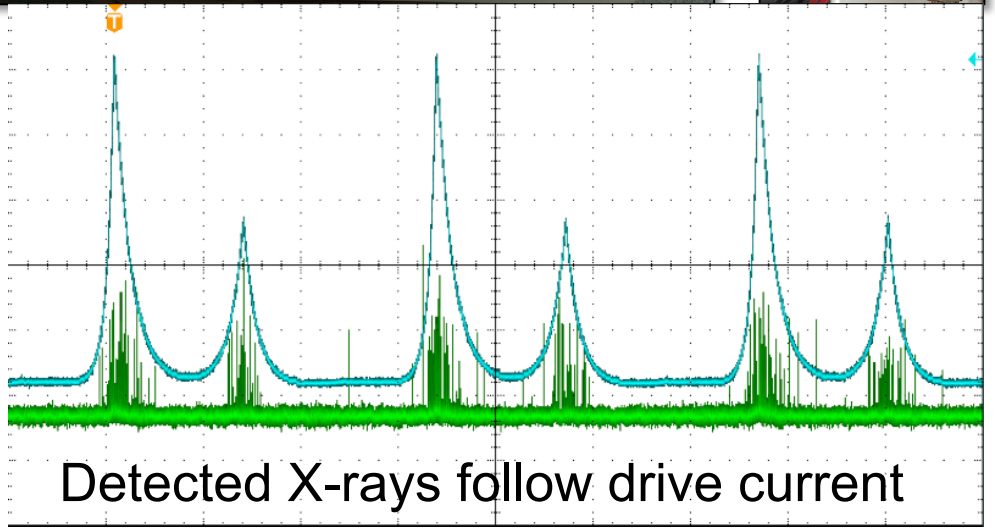
Pulsar Simulator

MXS control electronics







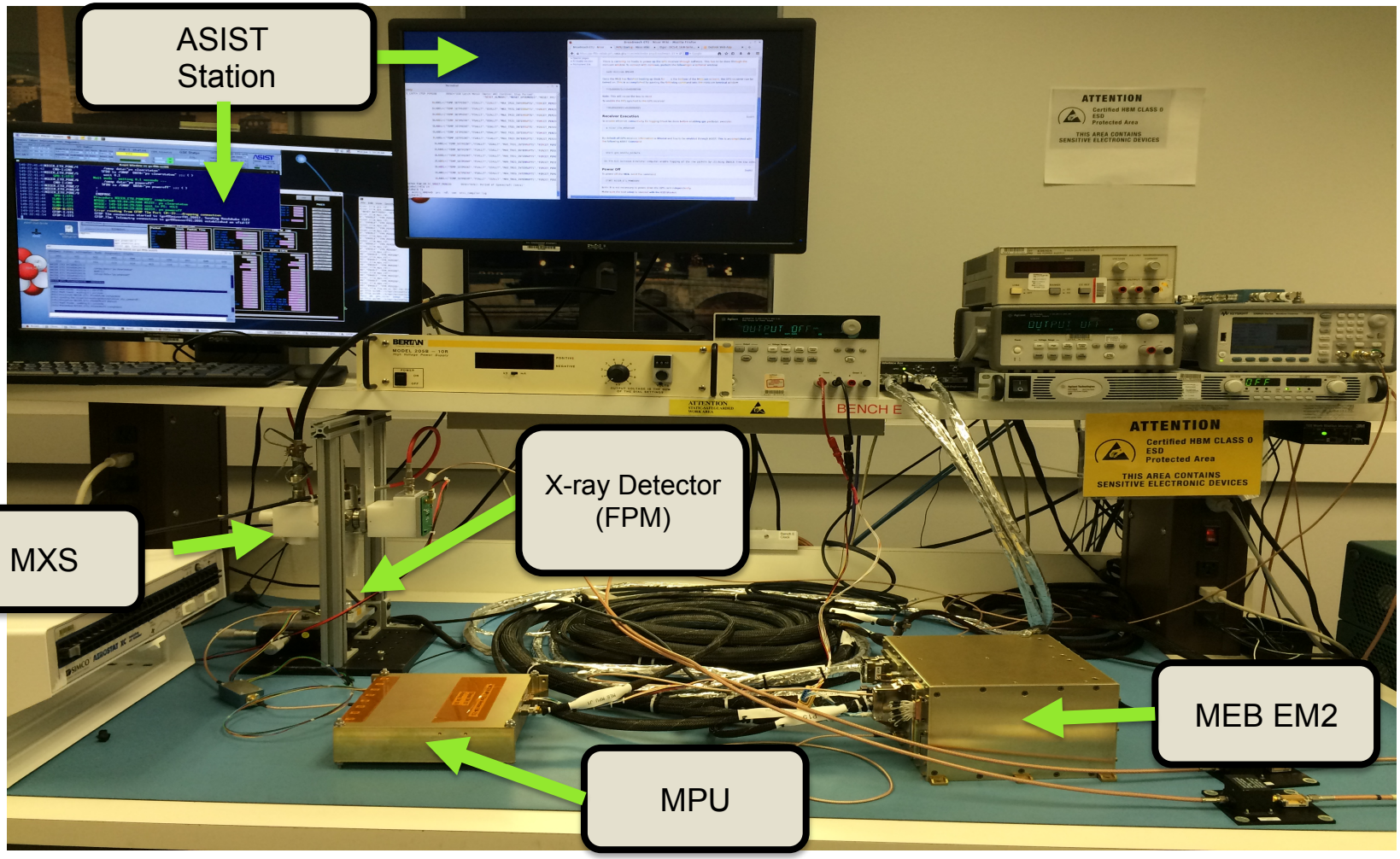


Detected X-rays follow drive current

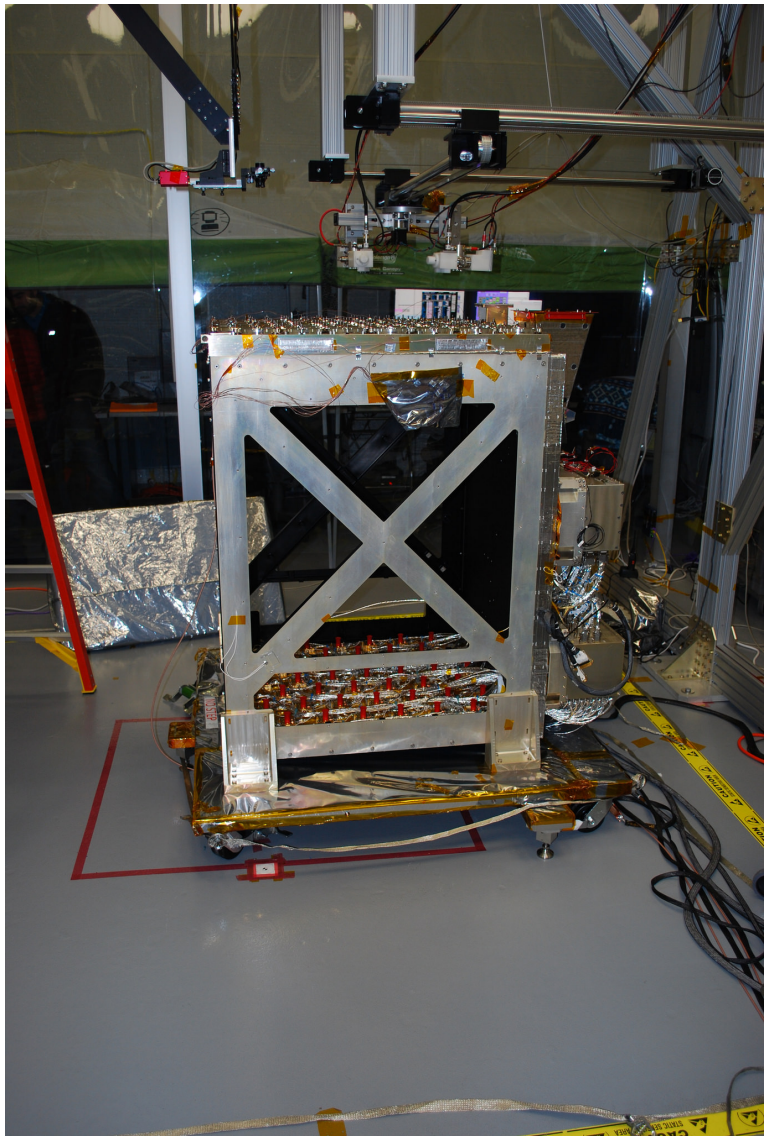
- Modulated X-ray source (MXS) allows precise control of X-ray intensity and timing
- Can be driven to precisely emulate MSP pulse shape, frequency, and phase as seen by spacecraft in orbit or in deep space

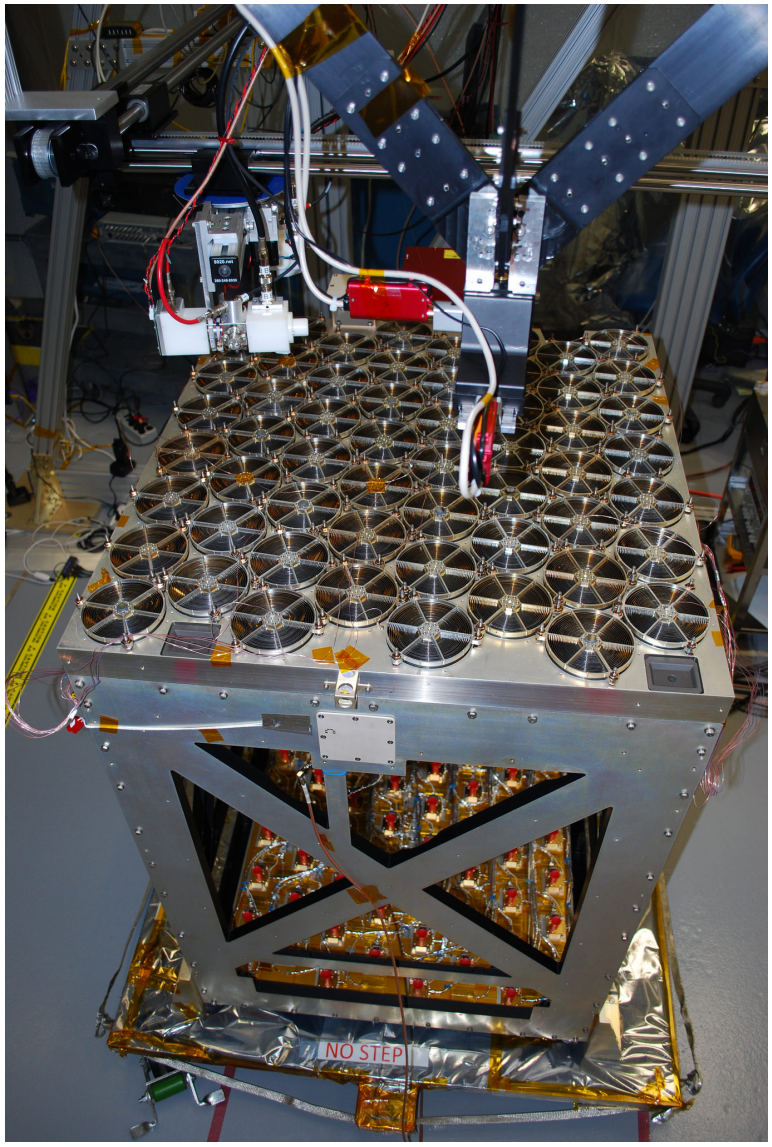
Modulated X-ray source (MXS)

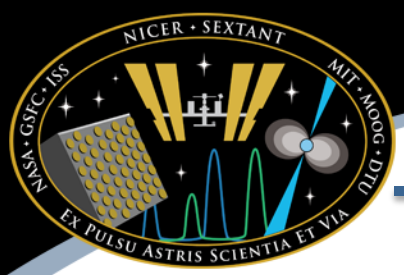
NICER EM Single-Timing-Chain



Payload XNAV Test Configuration





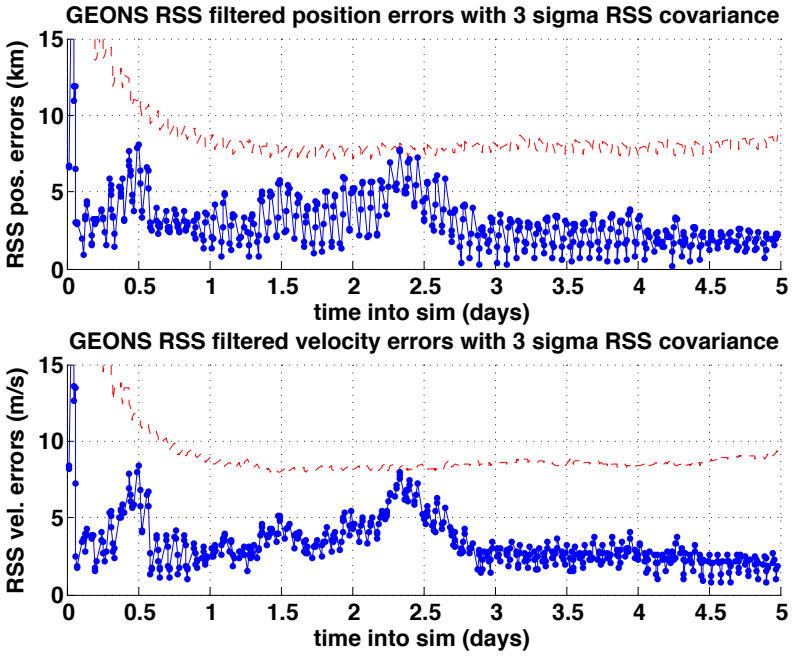


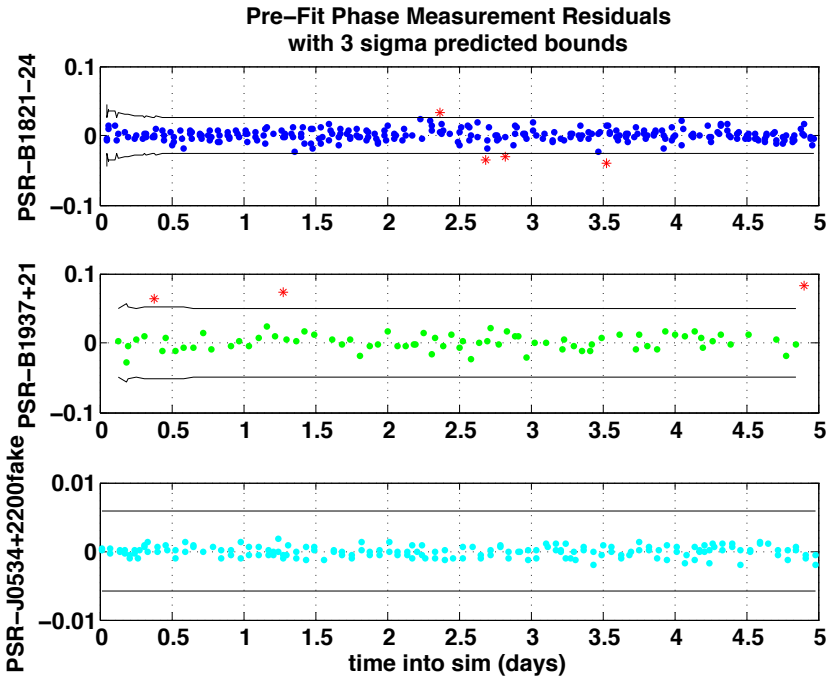
Build Verification Test Plan

- 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**



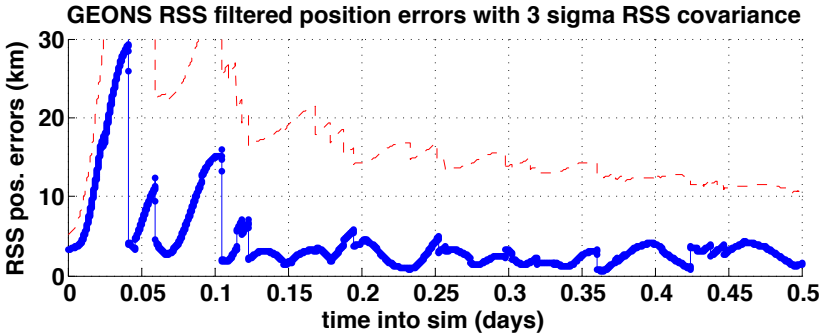


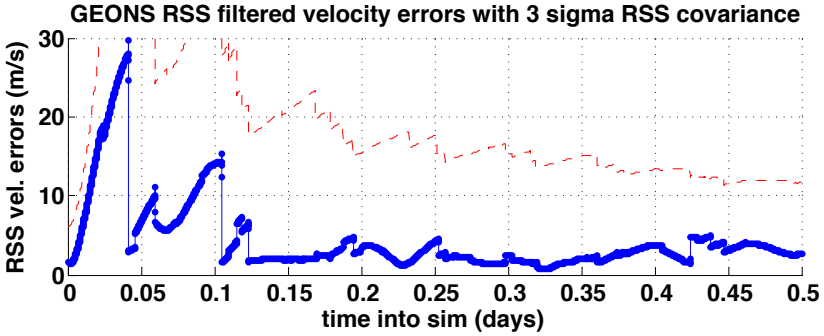
- Red is 3-sigma formal error
- Blue is actual error
- Baseline performance meets target accuracy

- Phase residuals (in cycles) consistent with predicted variance

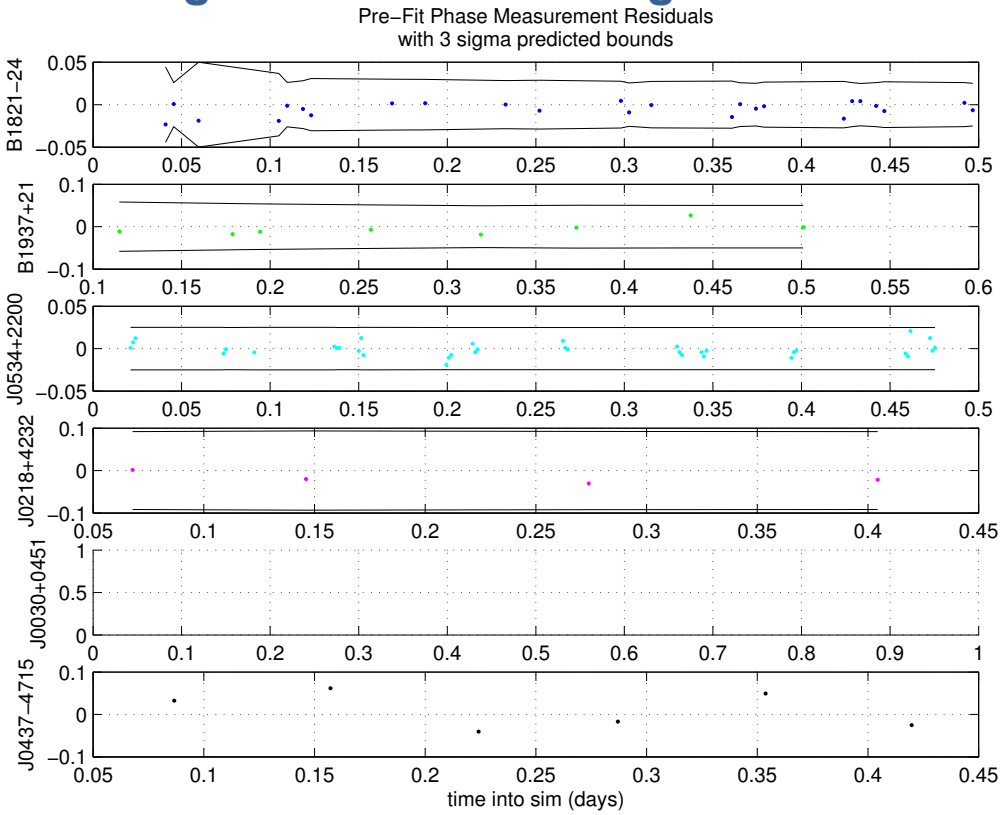
SEXTANT XNAV FSW build 2.1.1 payload level test

- **Successful 12hr XNAV demonstrates onboard processing of pulsar modulated X-rays through full NICER flight instrument timing chain.**

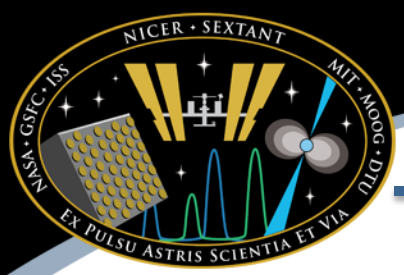




- Red is 3-sigma formal error
- Blue is actual error
- Performance meets target accuracy



- 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