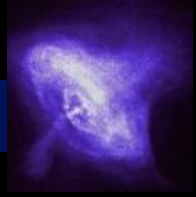


SEXTANT X-Ray Pulsar Navigation Demonstration: Initial On-orbit Results

Jason W. Mitchell†, Luke B. Winternitz†, Munther A. Hassouneh†,
Samuel R. Price†, Sean R. Semper †, Wayne H. Yu†, Paul S. Ray‡,
Michael T. Wolff‡, Matthew Kerr‡, Kent S. Wood#, Zaven Arzoumanian†,
Keith C. Gendreau†, Lucas Guillemot §, Ismael Cognard§, Paul Demorest¶

† *NASA Goddard Space Flight Center*

‡*Naval Research Laboratory*

#*Praxis, Inc.*

§*Laboratoire de Physique et Chimie de l'Environnement et de l'Espace*

¶*National Radio Astronomy Observatory*

American Astronautical Society
41st Annual Guidance and Control Conference

Beaver Run Resort, Breckenridge, CO
February 7, 2018

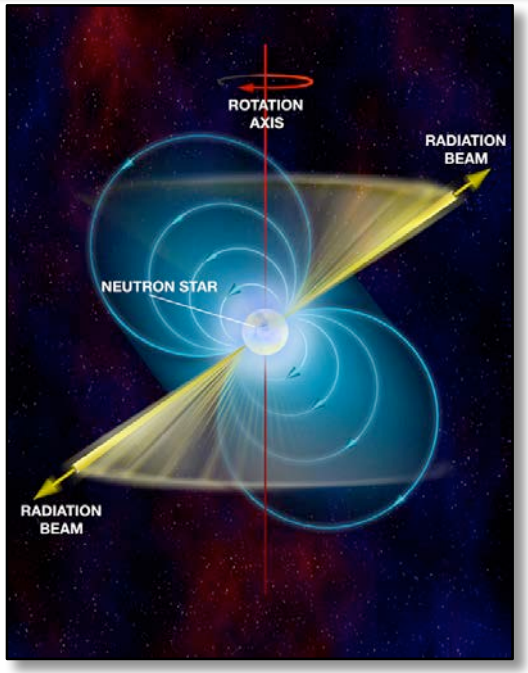
X-ray pulsar navigation (XNAV)

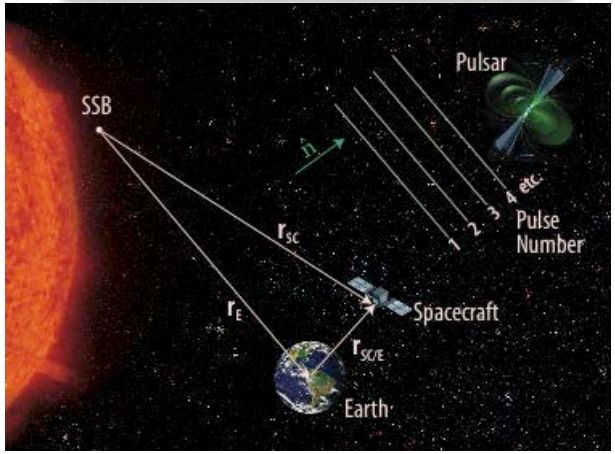
- Millisecond pulsars (MSPs) are rapidly rotating neutron stars that appear to pulsate across the electromagnetic spectrum

- Some MSPs have long-term timing stability that rivals that of atomic clocks
  - Pulse arrival phase can be predicted with great accuracy at any reference point in the Solar System through use of a pulsar timing model on a spacecraft
  - Comparing observed phase to predictions gives information that may be used for navigation

- Why X-rays?
  - Some stable MSPs have conveniently detectable X-ray emissions
  - X-ray are immune to interstellar dispersion effects thought to limit radio pulsar timing models
  - Highly directional compact detectors possible

- **Main Challenge: *MSPs are very faint!***





X-ray pulsar Navigation (XNAV)

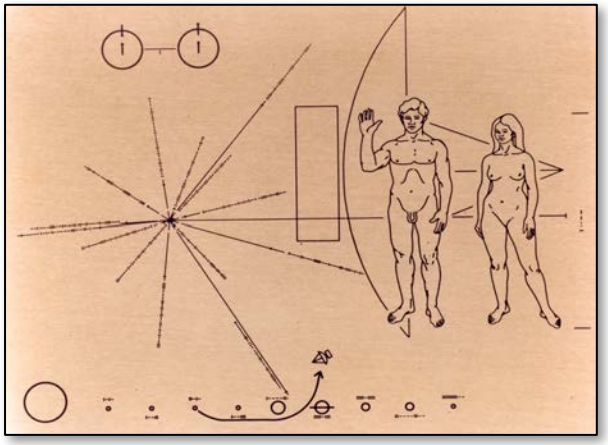
Applications

- XNAV can provide autonomous navigation and timing that is of uniform quality throughout the solar system
  - Enabling technology for very deep space missions
  - Backup autonomous navigation for crewed space flight
  - Augments Deep Space Network (DSN) or op-nav techniques
  - Autonomous navigation while occulted, e.g., behind Sun

History

- Pulsars were discovered in 1967 and immediately recognized as a potential tool for Galactic navigation
- US 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.)

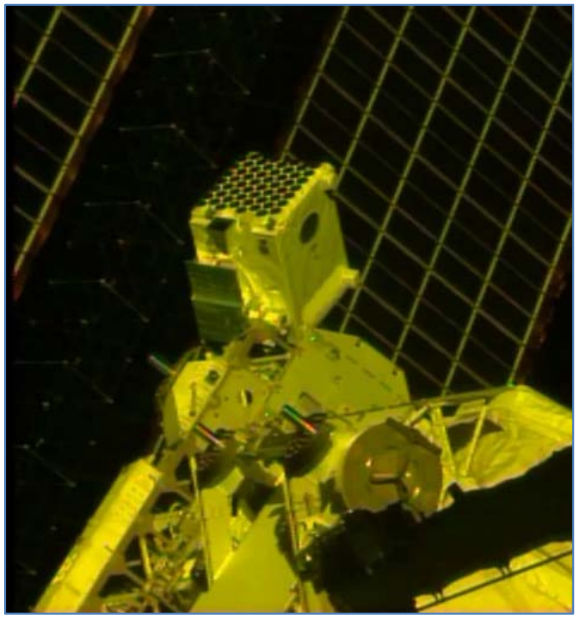
- *NICER/SEXTANT (2013 selection, 2017 launch) builds on previous work to perform the first in-space, real-time demonstration and validation of XNAV*



Pioneer plaque (Pioneer 10,11 1972-73) with Pulsar periods and relative distances to our Sun

Neutron-star Interior Composition Explorer (NICER)

- Launched on June 3, 2017 on Space-X CRS-11 to ISS with 18 month nominal mission
- Installed X-ray Timing Instrument to Express Logistics Carrier (ELC) 2: An unprecedented combination of time resolution, energy resolution, and sensitivity
- 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
- **NICER XTI's Combination of low-background, large area, precise timing, scalability, and low-cost makes it nearly ideal for XNAV**



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

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

SEXTANT Primary Objective: *Provide first demonstration of real-time, on-board X-ray Pulsar Navigation*

- Implement fully functional XNAV system in a challenging ISS/LEO orbit
- Advance core XNAV technologies

Performance target

- 10 km (1km stretch) accuracy, worst direction in 2 weeks

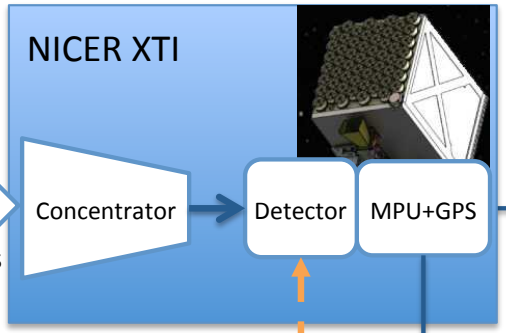
Planned Experiments

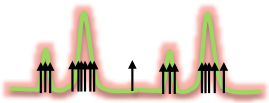
- Two 2 week periods where SEXTANT controls pointing schedule
- Opportunistic on-orbit experiments
- Ground experiments using collected photon data

Other objectives

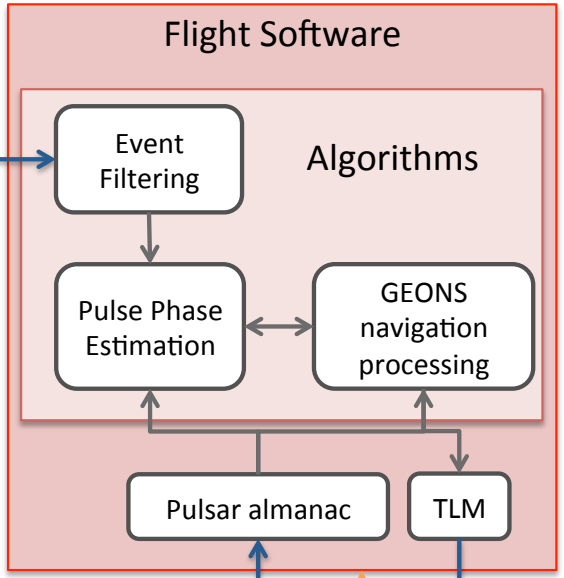
- Validate and enhance the SEXTANT ground testbed
- Use SEXTANT ground testbed to study “real-world” XNAV scenarios and evaluate alternative algorithms
- Study utility of pulsars for time keeping and clock synchronization
- Expand the catalog of XNAV Pulsars

SEXTANT System Architecture

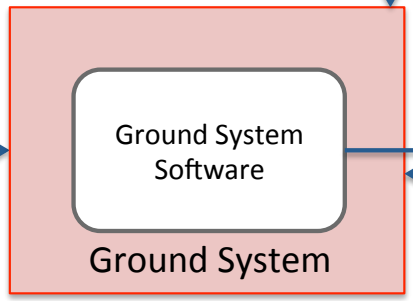




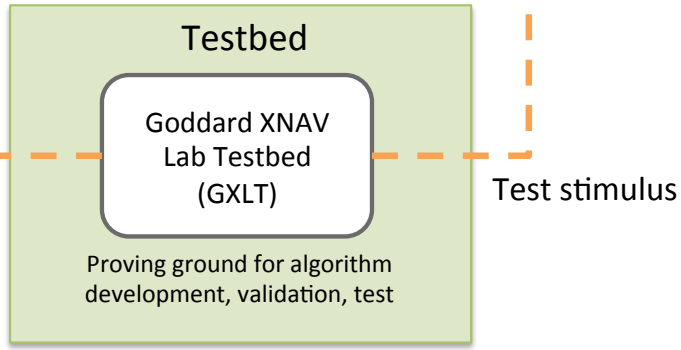
GPS time stamped
Photon + Background
events



GPS time stamped
Photon + Background
events, GPS telemetry



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



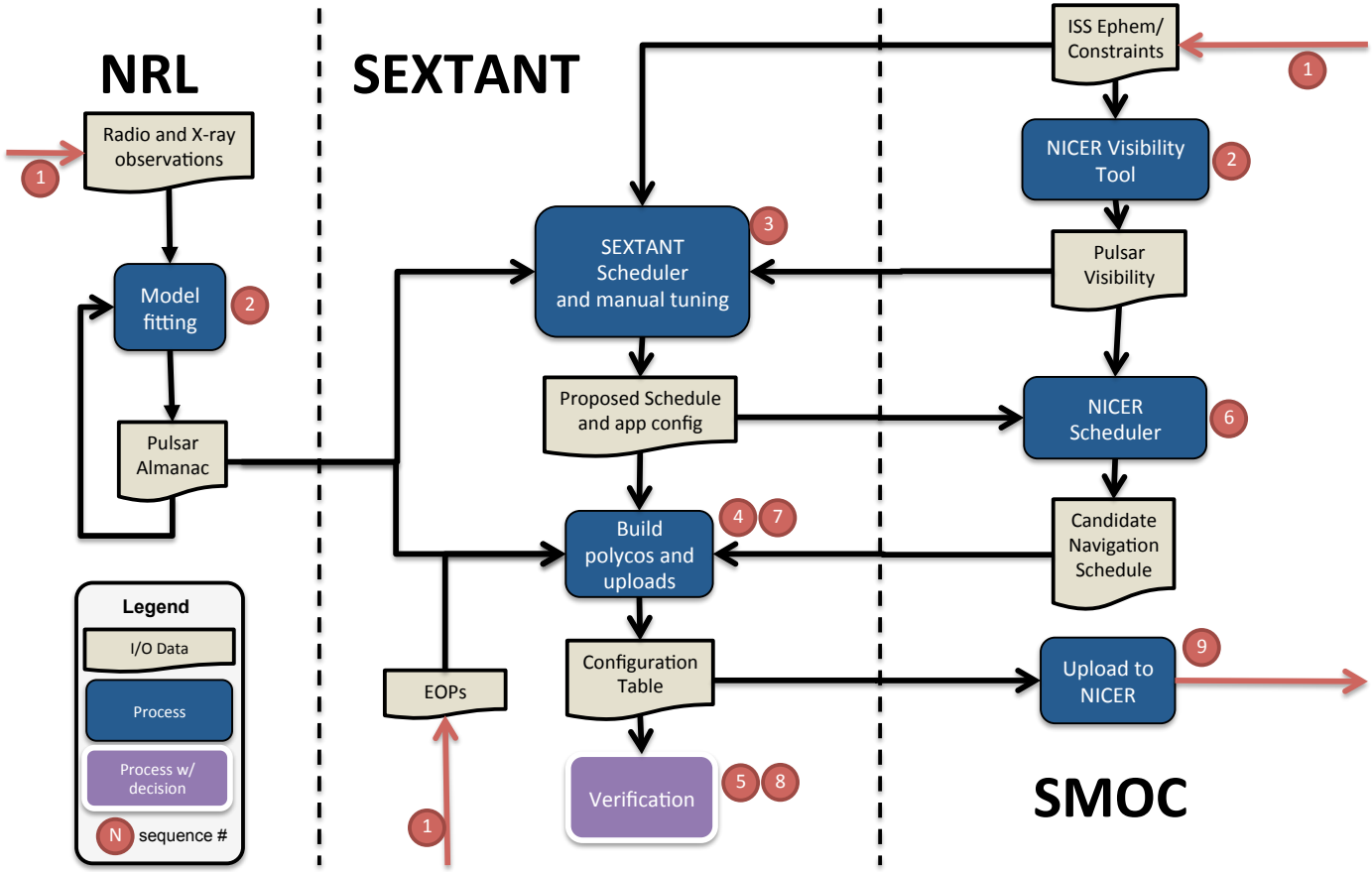
Test stimulus

Test stimulus

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

SEXTANT Operations flow

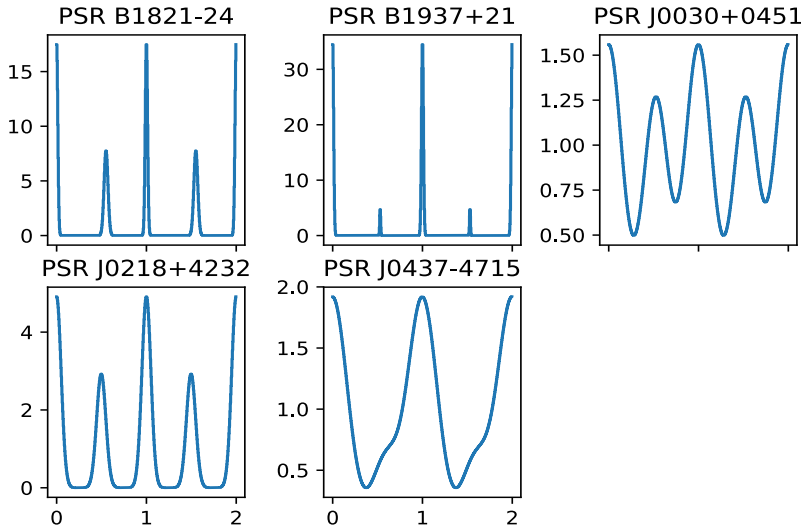
- Pulsar almanac (timing models, templates, count rates) generated by NRL team members
- SEXTANT team generates candidate navigation optimized schedules, iterating with NICER schedulers
- Then verifies schedule performance in simulation, where it tunes XNAV app, and uploads a XNAV FSW configuration table and schedule



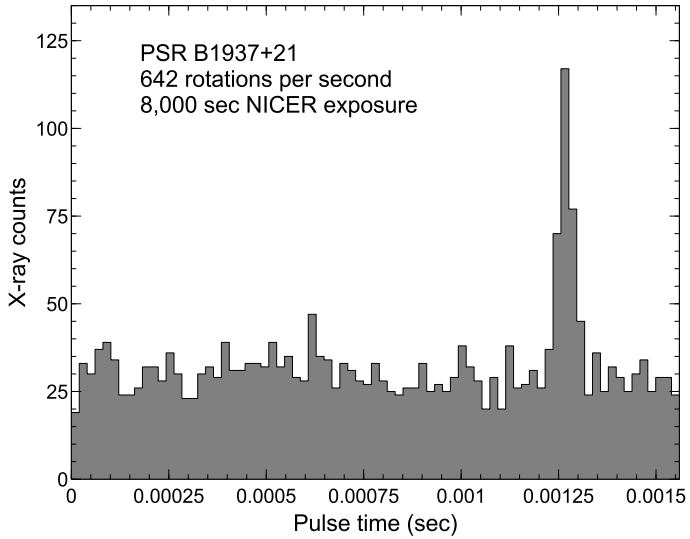
Calibration: Pulsar models

- Pulsar timing models for initial operations based on data from ground based radio observatories, optionally incorporating NICER data.
- Pulse templates, count rates and, X-ray to radio phase offset, determined from NICER data after sufficient observation time on each target was obtained.

Pulse templates

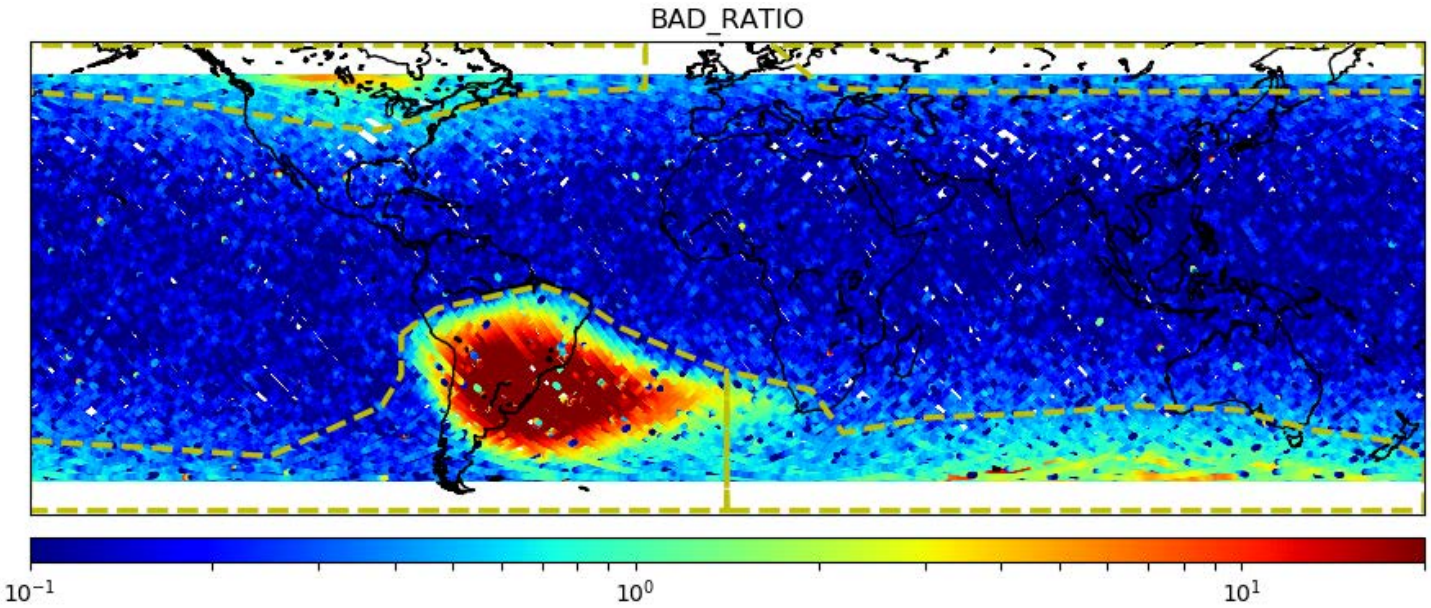


Early detection of PSR B1937+21



Calibration: Instrument

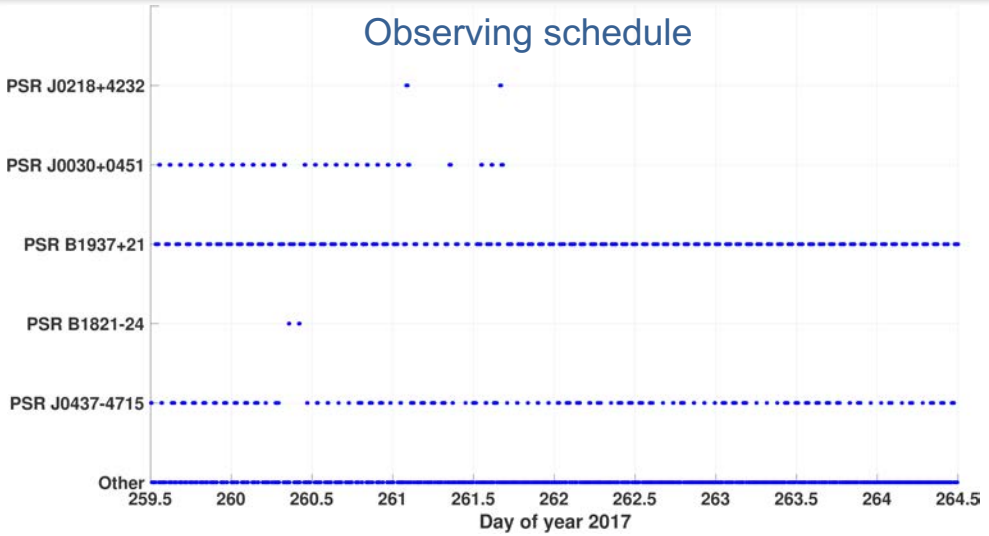
- Proper filtering of background events is key to obtaining best instrument and XNAV performance. NICER/SEXTANT team put fort extensive effort to optimize for science and XNAV.
  - Energy cuts per source have been optimized for science and XNAV
  - Polar regions and SAA maps refined using flight data
- Learning to work with/around nuances of instrument took time

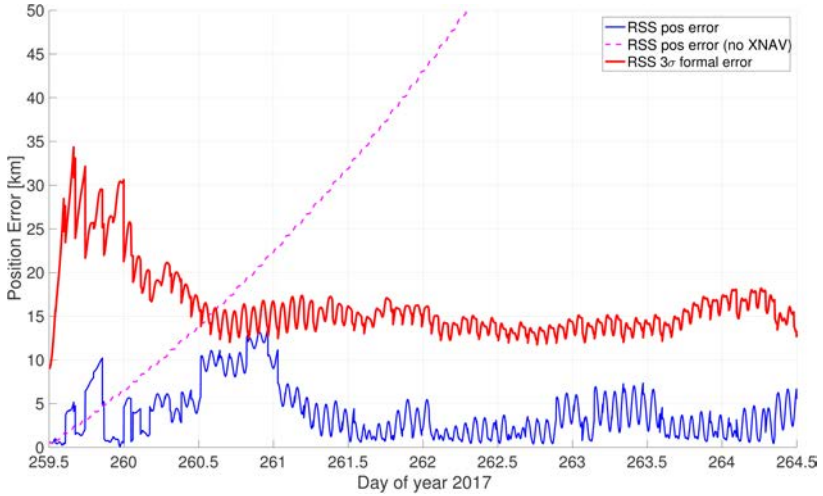


Map of high background regions

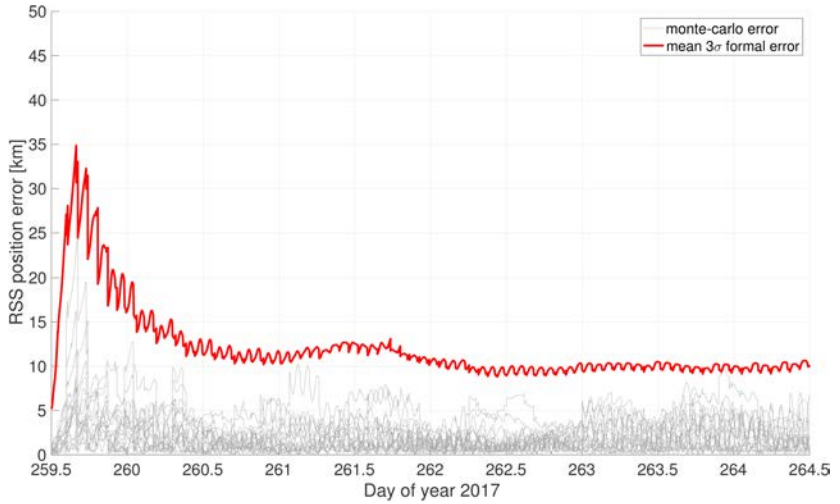
Ground experiment

- Between 2017 day of year 259.5-264.5 SEXTANT conducted its best ground experiment *replaying* NICER photons through ground version of SEXTANT Flight Software application
- Strong MSP schedule including significant time on *Tier 1* PSR B1937+21
- Initialized with degraded GPS state that propagates to more than 100km error over experiment period
- Errors reduced by XNAV processing to under 10km RSS rapidly and maintained at this level for 5 days
- SEXTANT end-to-end simulation predicted performance consistent with obtained result, a step toward validating its predictive capability





SEXTANT ground replay performance

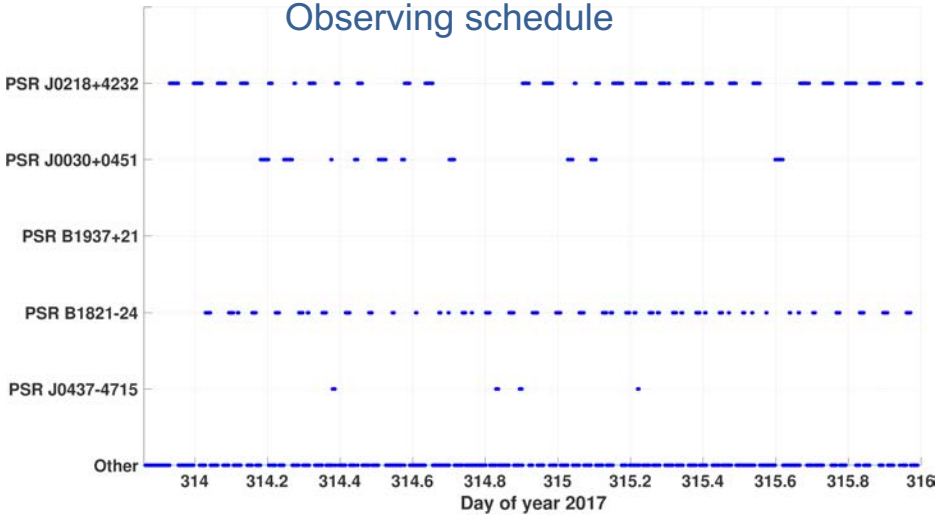


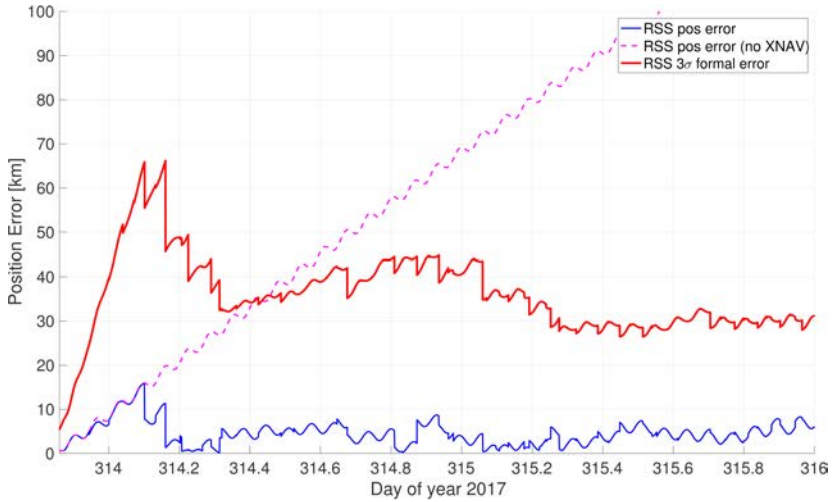
Simulation performance prediction

Flight experiment

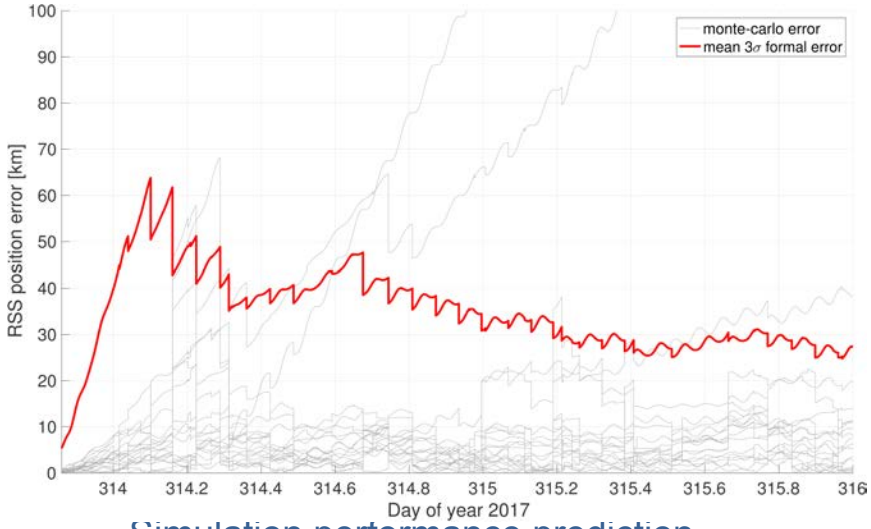
- **Between 2017 day of year 314 to 316 SEXTANT conducted its first *realtime, onboard* experiment**
- **Good (but not ideal) MSP schedule including significant time on *Tier 1* PSR B1821-24**
- **Initialized with degraded GPS state that propagates to more than 100km error**
- **Errors reduced by XNAV processing to under 10km RSS rapidly and maintained at this level for 2 days**
- **SEXTANT end-to-end simulation results predicted performance consistent with obtained result although a few cases diverged**

Observing schedule





SEXTANT onboard performance



Simulation performance prediction

Conclusions and Future Work

- XNAV could be an enabling technology for autonomous deep space navigation and a complement to alternate techniques
- NASA's NICER is the first mission dedicated to the study of pulsars. Its instrument is a superb sensor for an XNAV demonstration
- SEXTANT is an attached technology mission with the goal of making first demo of XNAV in space, and of advancing key XNAV technology
- In the first 6 months of operation SEXTANT has made great progress toward mission objectives:
  - Completed initial calibration activities
  - Ran multiple successful ground and flight experiments that have met its 10 km performance goal
- In 2018 and beyond, SEXTANT will
  - Continue to run XNAV experiments including dedicated time where SEXTANT will dictate NICER pointing schedule
  - Evaluate navigation utility of any newly discovered MSPs
  - Test and tune current algorithms and develop new ones
  - Use SEXTANT XNAV testbed to simulate future applications including deep space trajectories and modeling of reduced size instruments
  - Pursue technology infusion opportunities