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

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Outline

- X-ray Pulsar Navigation Concept & Background
- Neutron-star Interior Composition Explorer (NICER) mission
- Station Explorer for X-ray Timing & Navigation Technology (SEXTANT) demonstration
- SEXTANT architecture overview
- Review previously demonstrated primary goal
- Recent Experimental Results
  - Navigating with the Crab pulsar
  - Estimating clock bias and rate
- Conclusions & Future Work

X-ray Pulsar Navigation (XNAV)

- Millisecond pulsars (MSPs): rapidly rotating neutron stars that pulsate across electromagnetic spectrum
- Some MSPs rival atomic clock stability at long time-scales
  - Predict pulse arrival phase with great accuracy at any reference point in the Solar System via pulsar timing model on a spacecraft
  - Compare observed phase to prediction for navigation information
- Why X-rays?
  - Many stable MSPs conveniently detectable in (soft) X-ray band
  - X-rays immune to interstellar dispersion thought to limit radio pulsar timing models
  - Highly directional compact detectors possible
- **Main Challenge: *MSPs are very faint!***
  - *Except Crab (PSR J0534+2200)*
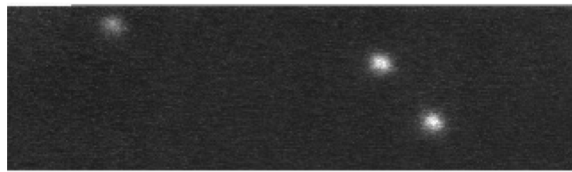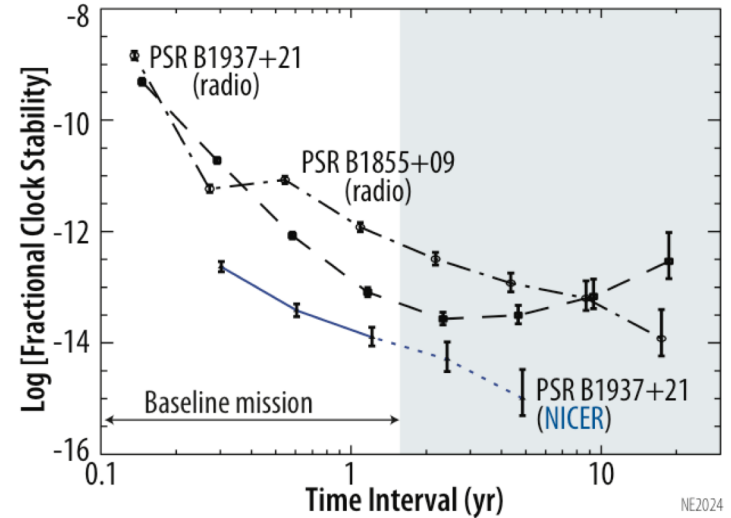
Crab Pulsar (1/3 speed), Cambridge University, Lucky Image Group

Folded Light Curve for PSR–J0534+2200
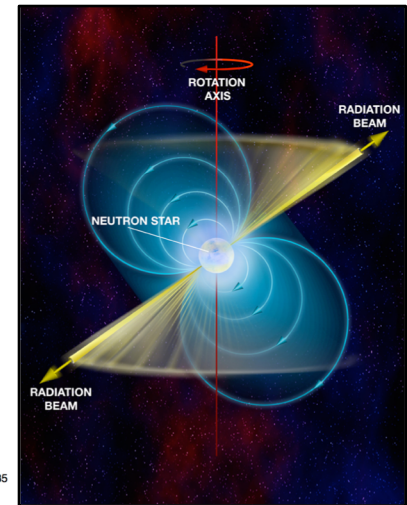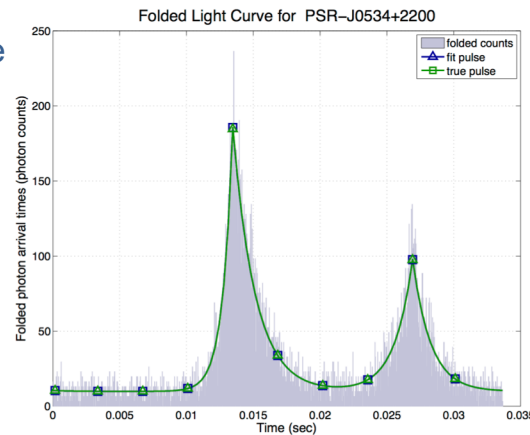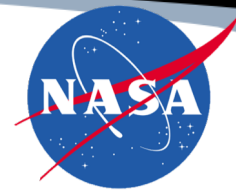
X-ray pulsar Navigation (XNAV)

Applications

- Autonomous navigation and timing of uniform quality throughout the Solar System
  - Enabling technology for very deep space missions
  - Backup autonomous navigation for crewed missions
  - Augment Deep Space Network (DSN) or optical navigation techniques
  - Highly available, onboard navigation during periods of limited or no Earth contact, e.g., behind Sun

History

- Pulsars discovered in 1967, 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
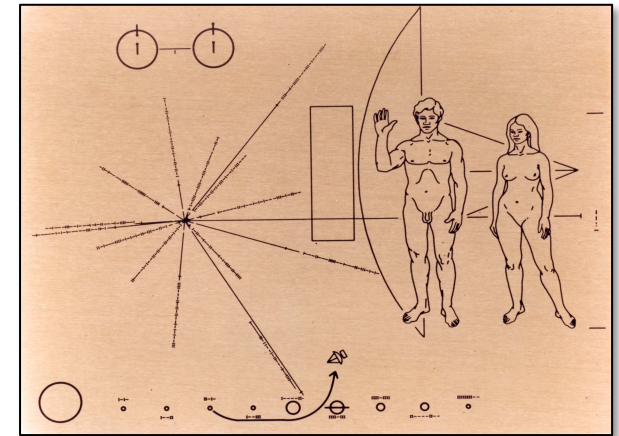
Pioneer plaque (Pioneer 10,11 1972-73) with Pulsar periods and relative distances to our Sun

Neutron-star Interior Composition Explorer (NICER)

- Launched June 3, 2017 on Space-X CRS-11 to ISS with 18 month nominal mission
  - Additional 6 month Guest Observer program
- X-ray Timing Instrument (XTI) provides unprecedented combination of time resolution, energy resolution, & sensitivity
- Fundamental investigation of ultra-dense matter: structure, dynamics, & energetics
- Determine 4 neutron star radii within 5%, an order of magnitude better than known today
- *NICER's combination of low-background, large area, precise timing, scalability, & low-cost is nearly ideal for XNAV demonstration*

pts: 2018-04-20 02:21:38 UTC
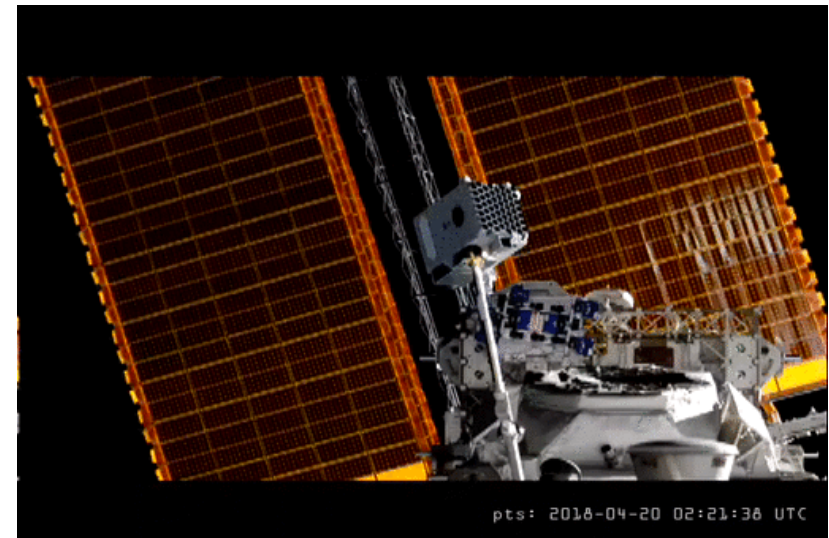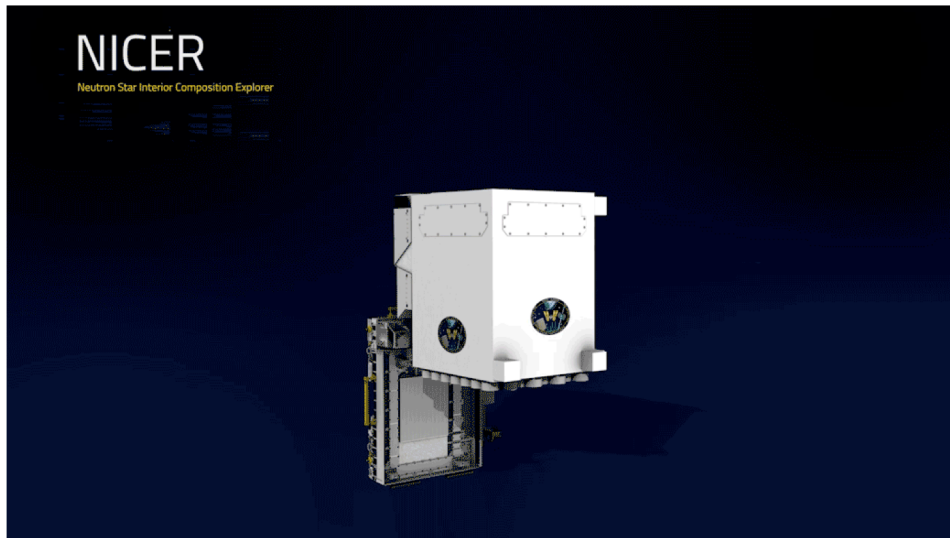
NASA Space Tech Mission Directorate Game Changing Development funded technology enhancement to NICER
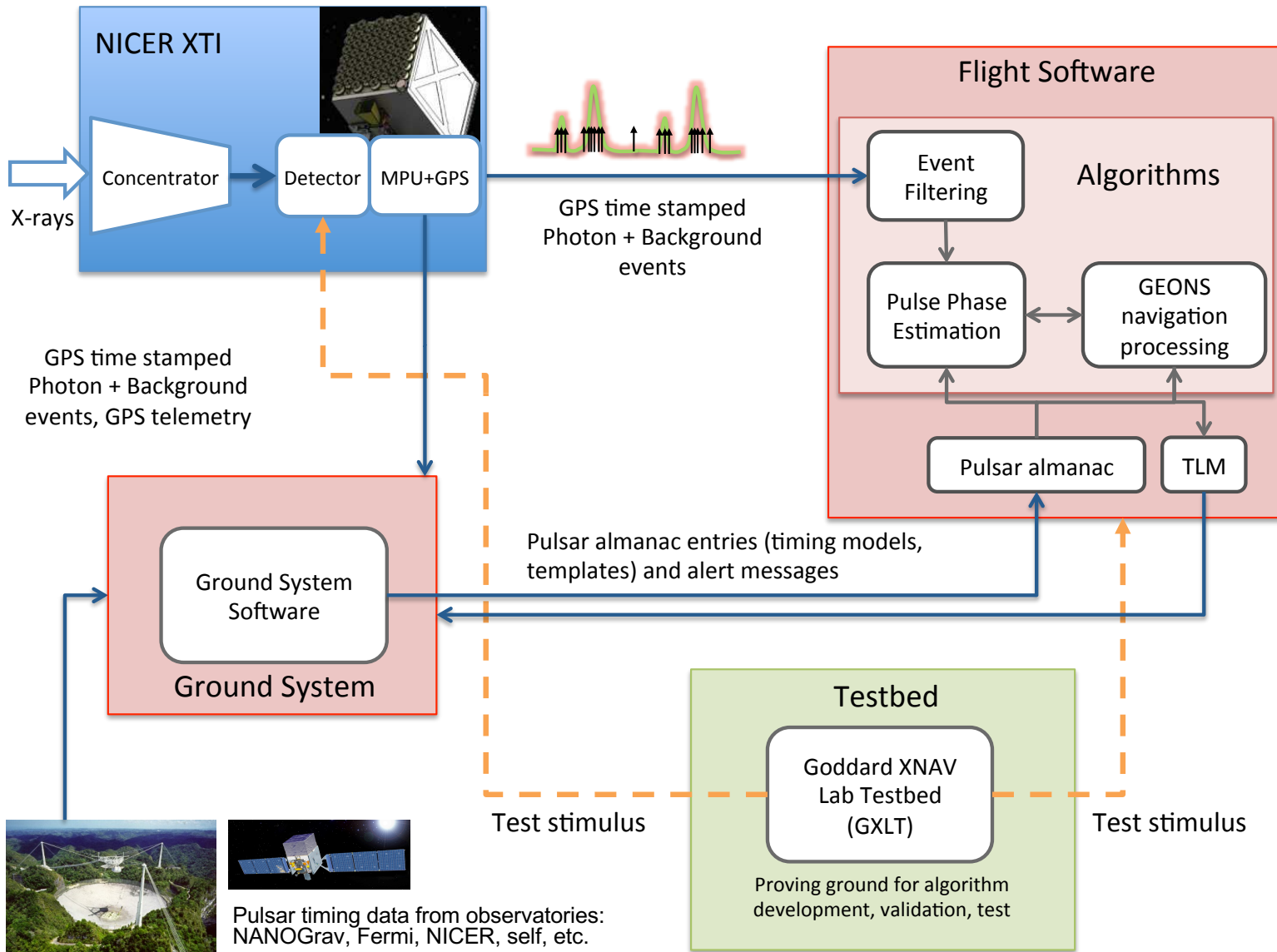
SEXTANT Primary Objective: *Provide first demonstration of real-time, on-board X-ray Pulsar Navigation*

- Implement fully functional XNAV system in a challenging ISS Low Earth Orbit
- Meet 10 km (1 km stretch) performance goal
- Advance core XNAV technologies
- Validate SEXTANT XNAV laboratory testbed (XLT)
- Technology infusion
- In the first 6 months of operation, SEXTANT made great progress toward mission objectives:
  - Completed initial calibration activities
  - Completed multiple successful ground and flight experiments that have met its 10 km performance goal
  - Successfully demonstrated primary objective in Nov 2018, during 2-day experiment
    - See Mitchell et al., *SEXTANT X-Ray Pulsar Navigation Demonstration: Initial On-Orbit Results*, AAS Guidance & Control Conference, 2018, `https://go.usa.gov/xQXc8`
- Here we present some additional results beyond the 2-day experiment
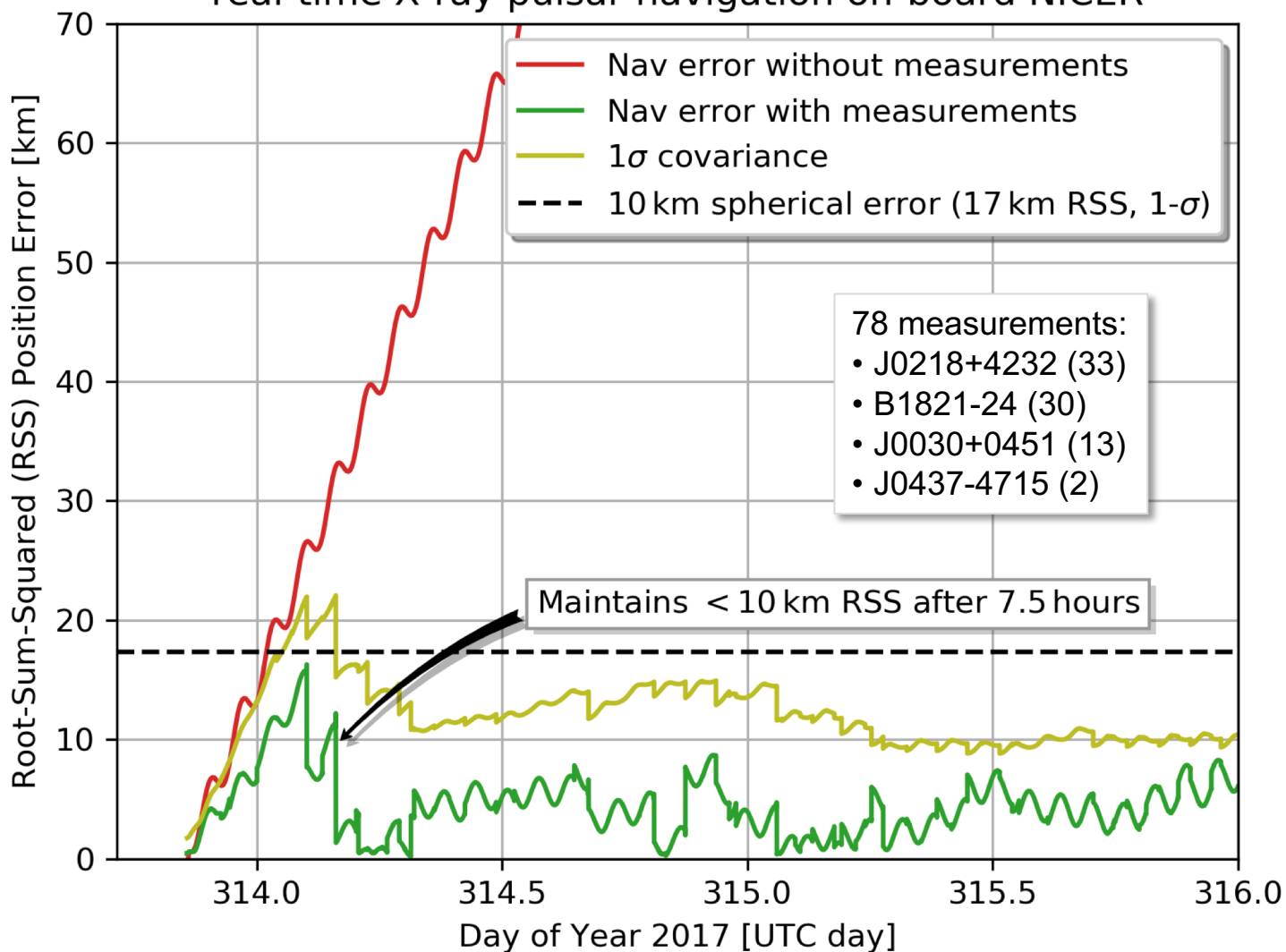 - Crab pulsar XNAV measurement experiment
  - Time estimation bias experiment

SEXTANT System Architecture

NICER XTI

X-rays → Concentrator → Detector → MPU+GPS

GPS time stamped Photon + Background events

GPS time stamped Photon + Background events, GPS telemetry

Flight Software

Algorithms

Event Filtering

Pulse Phase Estimation ↔ GEONS navigation processing

Pulsar almanac

TLM

Ground System Software

Ground System

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

Testbed

Goddard XNAV Lab Testbed (GXLT)

Proving ground for algorithm development, validation, test

Test stimulus

Test stimulus

Pulsar timing data from observatories: NANOGrav, Fermi, NICER, self, etc.

SEXTANT successfully demonstrates fully autonomous, real-time X-ray pulsar navigation on-board NICER

Legend:
- Nav error without measurements
- Nav error with measurements
- 1σ covariance
- 10 km spherical error (17 km RSS, 1-σ)

78 measurements:
- J0218+4232 (33)
- B1821-24 (30)
- J0030+0451 (13)
- J0437-4715 (2)

Maintains < 10 km RSS after 7.5 hours

Y-axis: Root-Sum-Squared (RSS) Position Error [km]

X-axis: Day of Year 2017 [UTC day]

Crab Pulsar (PSR B0531+21)

- Compared to other SEXTANT MSPs, Crab pulsar allows equivalent navigation performance using less observation time, or allows capability for smaller X-ray instruments
  - Crab pulsar flux rates >3 orders of magnitude higher than other SEXTANT MSPs
- Crab requires frequent ground updates (or onboard timing noise estimation) for onboard XNAV
  - Rotationally unstable, so timing model prediction limited to few days (months or years for stable MSPs)
- Alternately, Crab timing model can be accurately determined after-the-fact for use in a post-processing mode

Image by Chandra X-ray Observatory
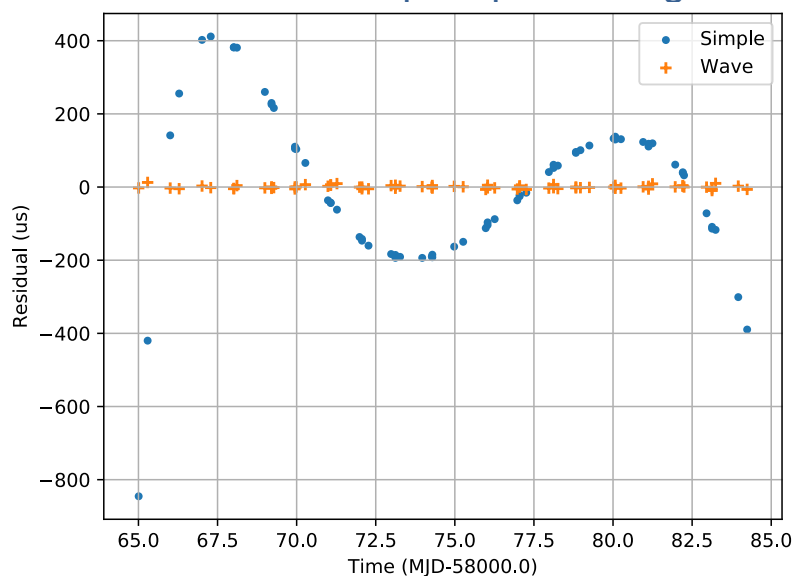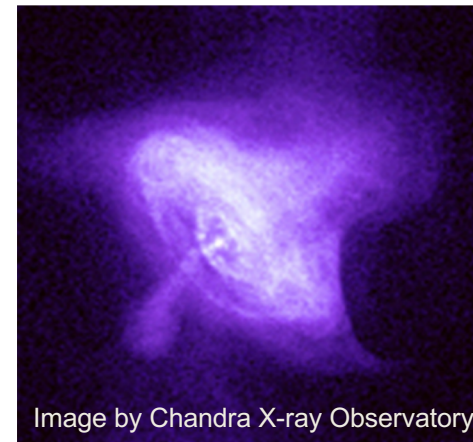
Timing model residuals, pre/post sinusoidal correction fit
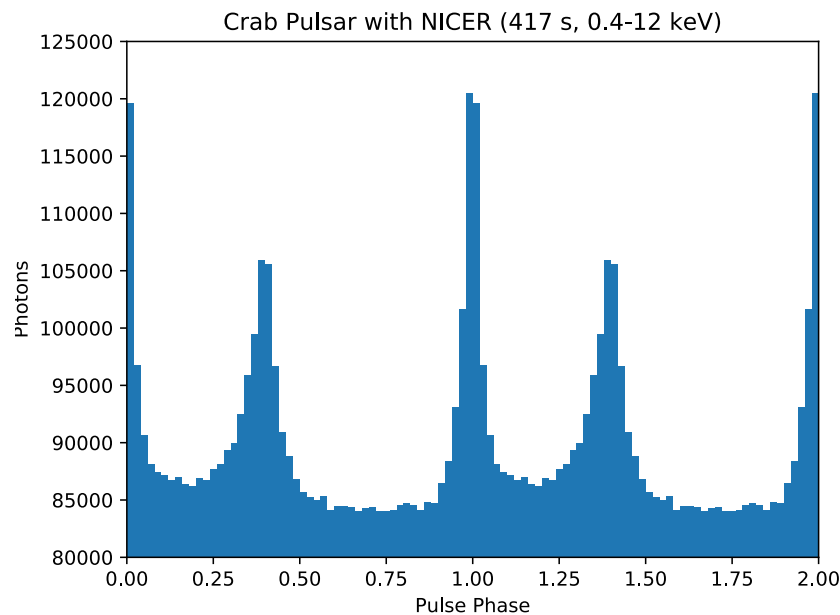
Crab light curve obtained with 417 s NICER observation

- 2017 days-of-year 318–322 SEXTANT conducted 1st ground experiment using pulsar B0531+21 (Crab)
  - Initialized with degraded GPS state that propagates to >100 km RSS error in few hours
  - Recorded data replayed through ground version of flight software, no clock bias/rate estimation
  - Measurement count: B0531+21 (1119), J0030+0451 (31), J0218+4232 (40)

Errors reduced by XNAV processing to well under 10 km RSS rapidly & maintained for 3 days

XNAV Position Error Compared to GPS

Observing schedule

Crab pulsar observations
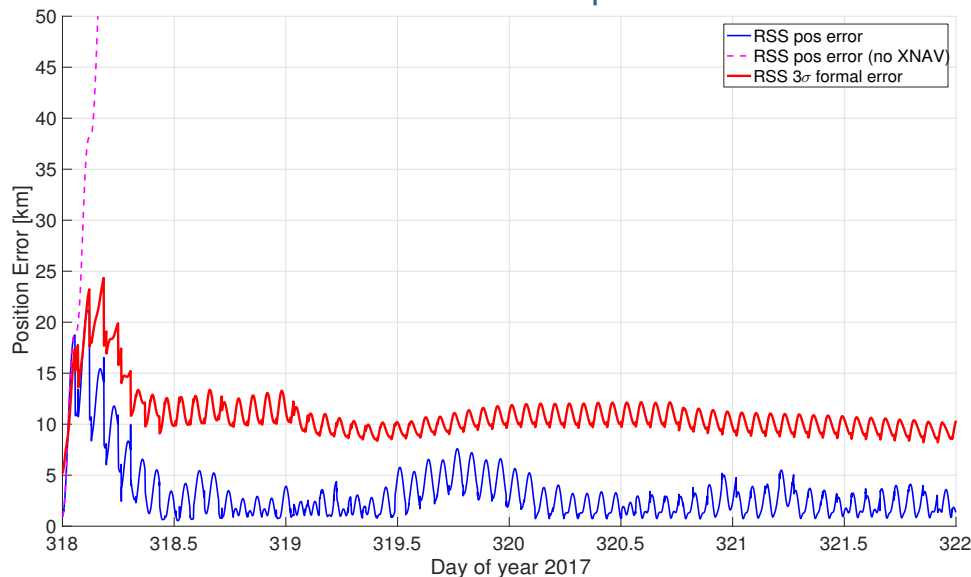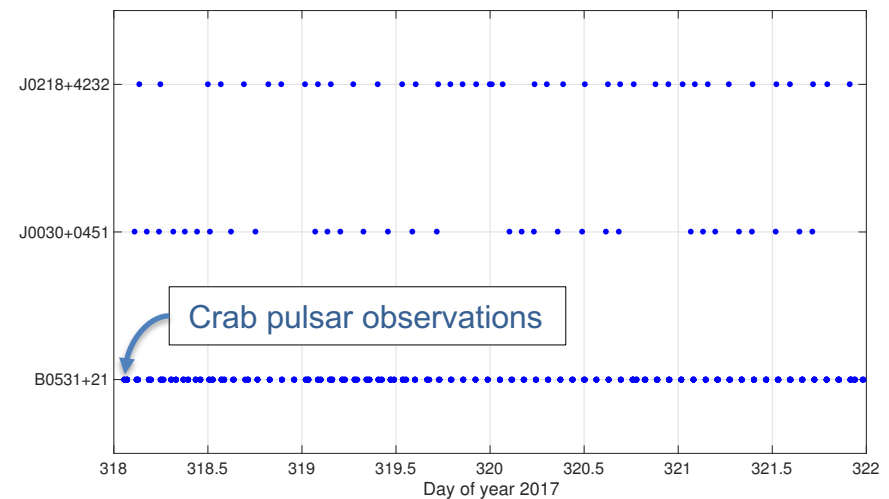
Time estimation experiment

- *Tested SEXTANT flight software to navigate & simultaneously estimate clock bias and rate*
- Used strong MSP schedule with PSR B1937+21 from 2017 days-of-year 260–264.5
- Used same data for previously reported SEXTANT ground experiment
- Developed augmented navigation filter XNAV measurement model with clock bias & rate estimation
- Simulated clock error trajectories from model of moderate-cost Frequency Electronics, Inc. (FEI) ultra-stable crystal oscillators (USOs) used on NASA's Magnetospheric MultiScale (MMS) mission
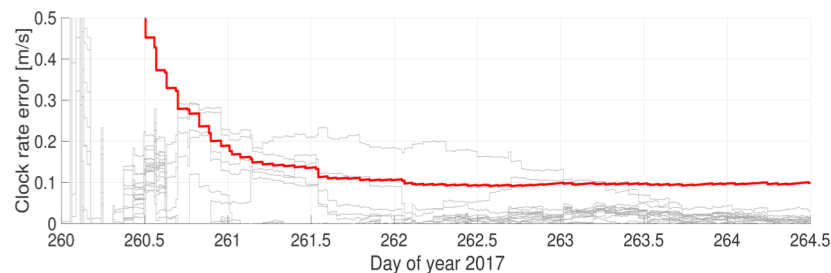- Added clock errors to NICER GPS-timestamped X-ray photon event data
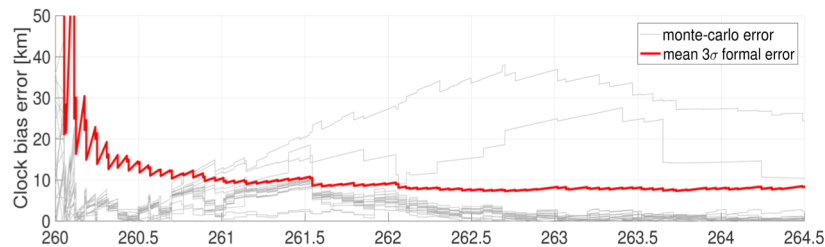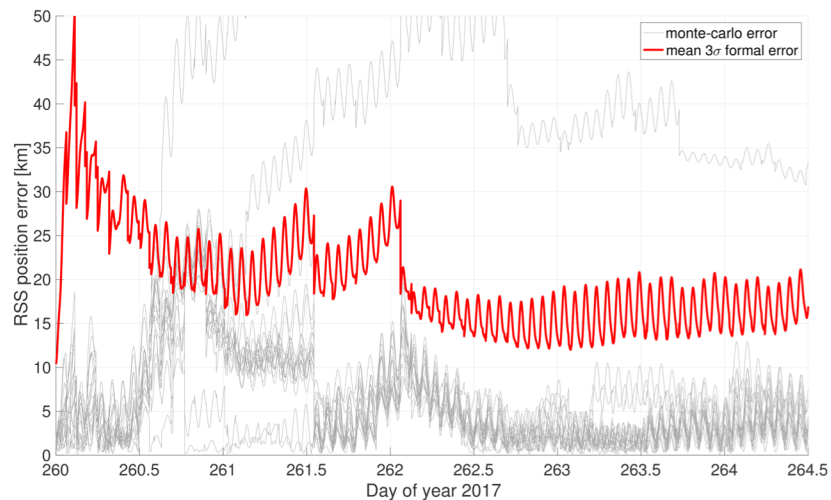

FEI USOs used on MMS
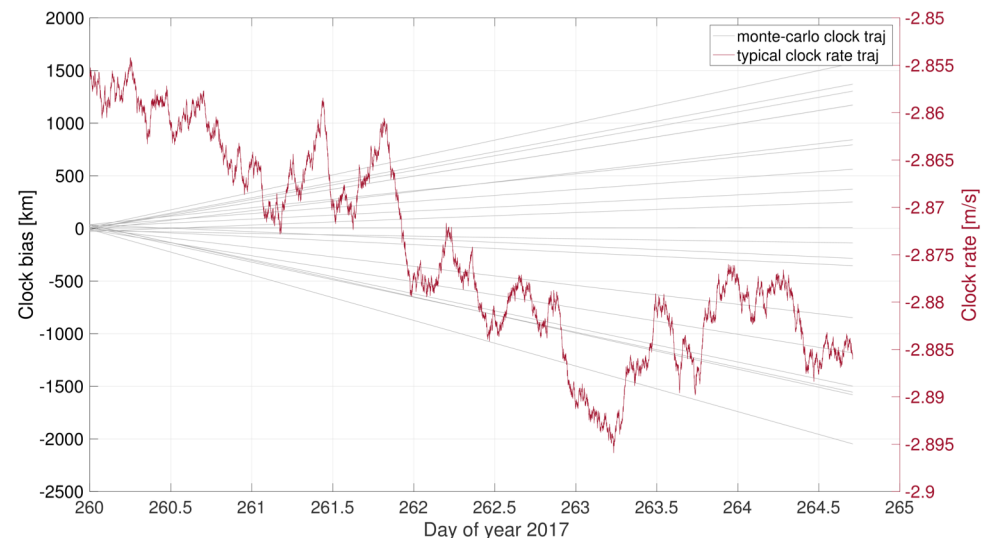
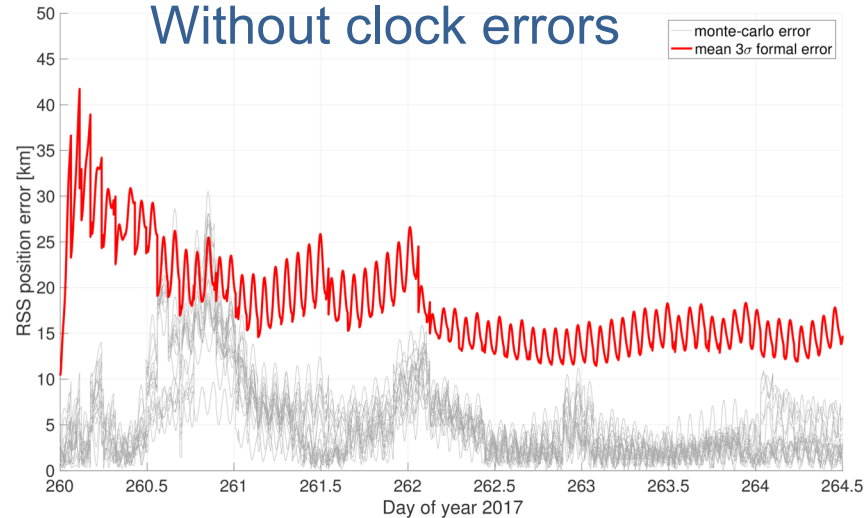Simulated ultra-stable crystal oscillator clock error trajectories

With clock errors


Without clock errors

- Methodology: Replay NICER X-ray data with 40 trials through SEXTANT flight software
  - Randomized initial state errors, additive clock errors (20 trials)
  - Randomized initial state errors, no clock errors, no estimate clock states (20 trials)
- Result: Clock is accurately estimated with similar navigation performance
  - Specific cases have an increased chance of divergence
  - Preliminary results, will investigate larger trial set in future

Conclusions

- XNAV is an enabling technology for autonomous deep space navigation & a complement to alternate techniques
- NASA's NICER is the first mission dedicated to the study of pulsars
    - NICER instrument is a superb sensor for XNAV demonstration
- SEXTANT is an attached technology demonstration for first onboard, real-time XNAV use
    - Also advance key XNAV technology components
- SEXTANT has *already* demonstrated feasibility of autonomous in-space XNAV through multiple successful ground and flight experiments meeting 10 km performance goal

- In this paper, we present additional results obtained using NICER/SEXTANT flight telemetry:
    - Successfully processed unique high flux, but rotationally unstable, Crab pulsar
        - Potentially significant benefit for missions needing high-cadence measurements or with small X-ray instrument
    - Successfully estimated position, velocity AND local clock bias and rate estimation possible with moderate-cost/performance spacecraft oscillator
        - **atomic clock *not necessary***
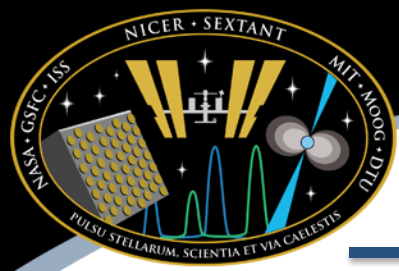
SEXTANT Future Work

- Continue XNAV experiments
  - Flight & Ground experiments
  - Dedicated time for SEXTANT focused observing schedule
- Test & tune current algorithms and develop new ones
- Use SEXTANT XNAV testbed to simulate future applications including deep space trajectories & modeling of reduced size instruments
- Pursue technology infusion opportunities