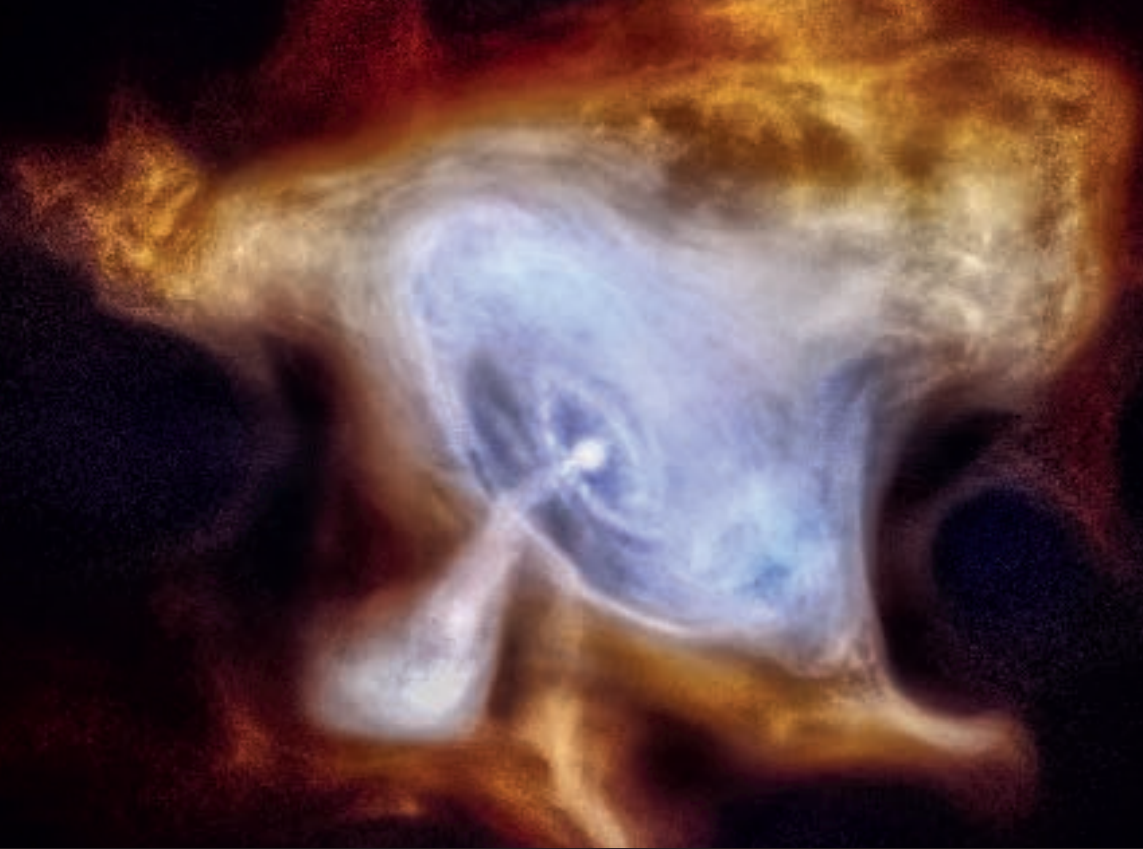
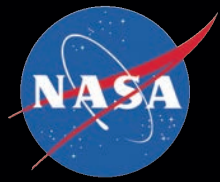




Demonstrating a Galactic Positioning System Using X-ray Emitting Millisecond Pulsars with the NICER/SEXTANT Mission



NASA Engineering & Safety Center Academy Webcast

Jason W. Mitchell, PhD

jason.w.mitchell@nasa.gov

2019-11-18



Outline



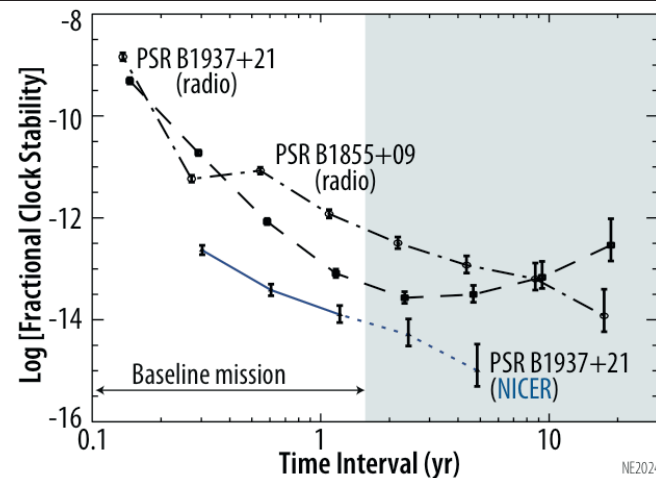
- **Introduction**
- **Instrument and science overview**
- **SEXTANT overview**
- **Testbed capability**
- **Primary navigation results**
- **Estimating time**
- **Timing model (extrapolation) performance**
- **Observing the Crab pulsar**
- **Conclusion**
- **Time-domain X-ray technology roadmap**
- **Additional information**



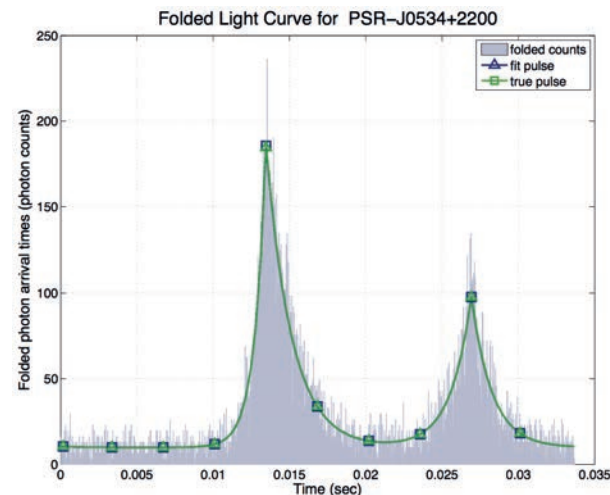
X-ray Pulsar Navigation (XNAV) Concept



- **Precise timing enables navigation**
 - Pulsars: rapidly spinning neutron stars
 - Millisecond pulsars (MSPs)
 - rival atomic clocks as time-keepers
 - accuracy & stability
 - Enable *galaxy-wide* positioning / time-base
 - GPS-like navigation capability throughout solar system
 - Sequential target observation for 3D state
- **Measurement**
 - Time tag X-ray photons, time-series
 - Pulse (light curve) arrival time, i.e., pulsar *pseudo-range*
 - Stitch sequence together for *autonomous navigation solution*
- **Utility**
 - Outer planet and beyond exploration
 - *Independent navigation for crewed missions*
 - Navigation when line of sight occulted, e.g., celestial body
 - Asteroid orbit charting/characterization
 - *Complement / Augment Deep Space Network (DSN)*
 - *Pulsars for (independent) time keeping*
- **Challenge: MSP targets very faint!**
 - Except for Crab pulsar ($>10^4$ brighter)



Crab Pulsar (1/3 speed), Cambridge University, Lucky Image Group

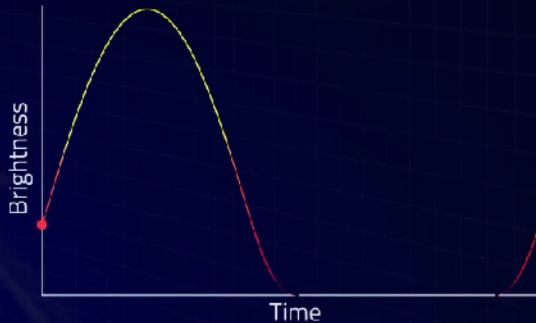
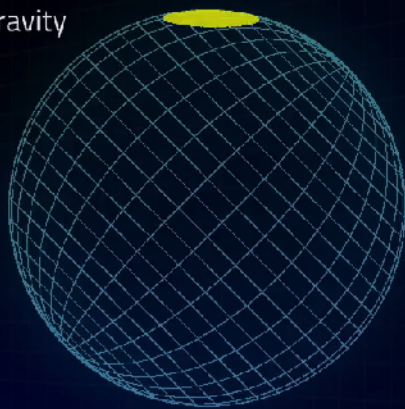




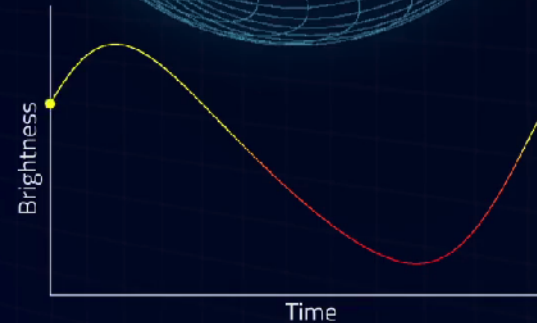
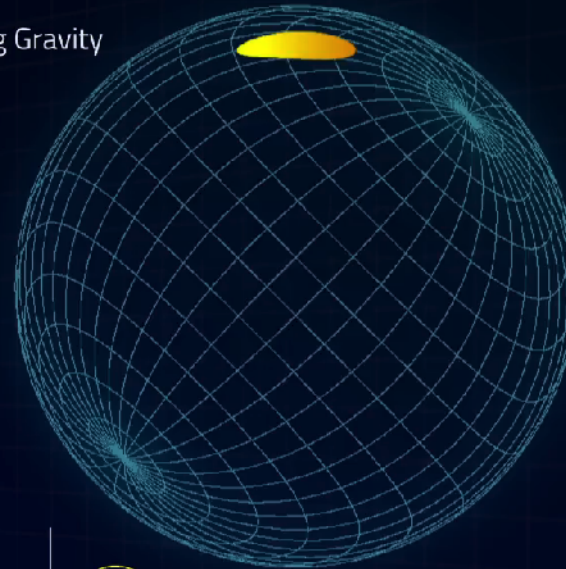
Strong Gravity and Light Curves

Figure credit: Sharon Morsink

No Gravity

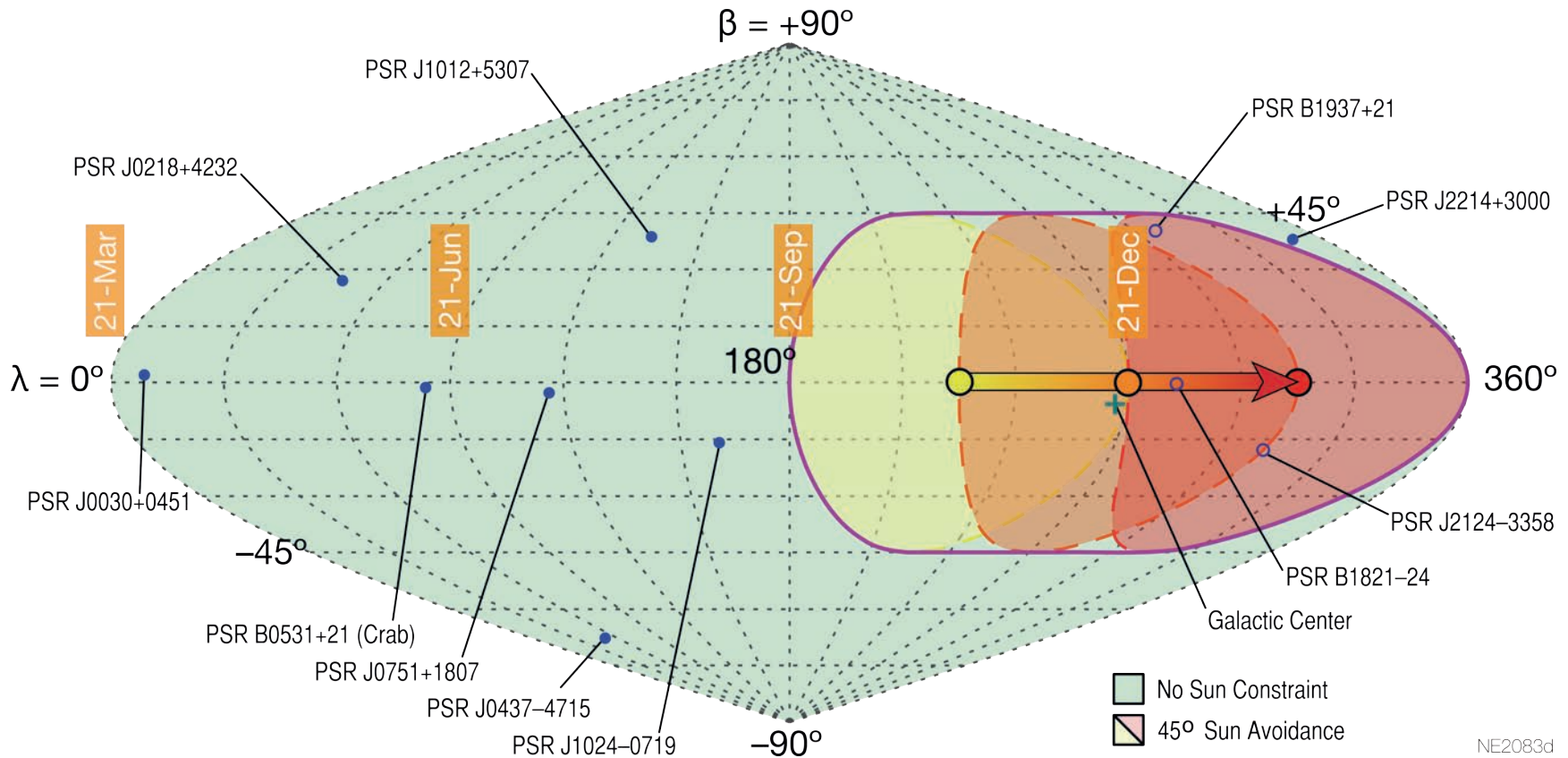


Strong Gravity





Millisecond Pulsar Targets for SEXTANT



NE2083d

- 10 MSP targets of navigation interest, plus Crab pulsar
- Seasonal visibility due to NICER 45° Sun avoidance constraint
- Some combination of MSPs always visible



SEXTANT Technical Objectives



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

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

- Implement a fully functional XNAV system in a challenging ISS/LEO orbit
- Advance core XNAV technologies
- Non-interfering subsystem of NICER

GCD Key Performance Parameter (KPP)

- Achieve better than 10 km orbit determination accuracy, any direction, using up to 2 weeks of observations

GCD Stretch Objective

- Achieve 1 km orbit determination accuracy, any direction, using up to 4 weeks of observations

Experiments (completed)

- **NE1:** ≤ 2 week period observing 3–5 pulsars early in the mission, models derived from radio telescope data
- **NE2:** ≤ 2 week period observing 3–5 pulsars later in the mission, models derived from NICER data
- Opportunistic on-orbit experiments
- Ground experiments using collected photon data

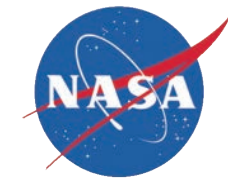


Other objectives

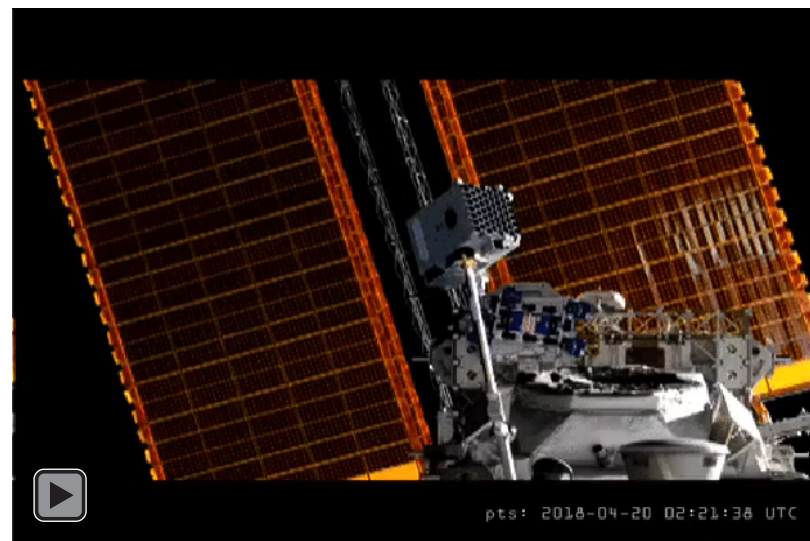
- Validate and enhance the unique Goddard XNAV Laboratory Testbed (XLT)
- Use SEXTANT data and XLT to study real-world XNAV scenarios
- Evaluate alternative photon processing and navigation algorithms and develop new techniques
- Study utility of pulsars for time keeping and clock synchronization
- Technology infusion path for practical sensor: HEOMD, SMD



NICER: X-ray Timing Instrument on ISS



- Neutron-star Interior Composition Explorer (NICER)
- Science: *Understanding ultra-dense matter* through observations of neutron stars in the soft X-ray band
- Launch: 2017-06-03, SpaceX-11 resupply
- Platform: ISS ExPRESS Logistics Carrier (ELC), with active pointing over nearly a full hemisphere
- Duration: 18+6 = 24 months (nominal), includes 6 month Guest Observer program; on-orbit for ~27 months
- Instrument: X-ray (0.2–12 keV) *concentrator* optics and silicon-drift detectors. GPS position & absolute time reference (GSFC Navigator design)
- Enhancements:
 - Guest Investigator/Observer program
 - Demonstration of pulsar-based spacecraft navigation (SEXTANT)
- Status:
 - Nominal science operations since 2017-07-18 (DOY 198)
 - First public release of data began early 2018
 - *Recently approved for 3 year extension*
- ***NICER's combination of low-background, large area, precise timing, scalability, & low-cost is nearly ideal for XNAV demonstration***

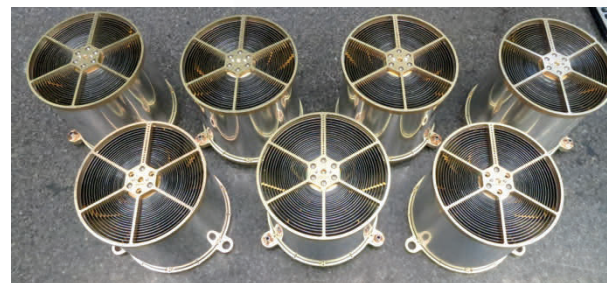
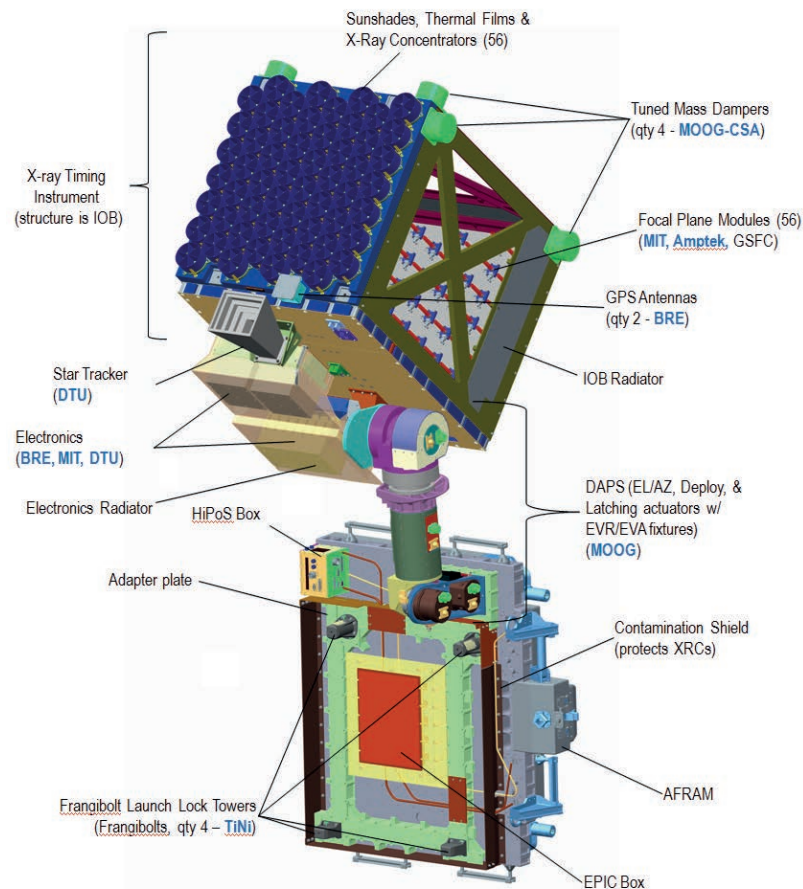




NICER Instrument Overview



- **X-ray Timing Instrument (XTI)**
 - Assembly of 56 X-ray concentrators and detectors, *52 working on-orbit*
 - Detects individual X-ray photons, returns energy and time of arrival
 - Held together in the Instrument Optical Bench
- **Thermal system**
 - Maintains thermal-mechanical alignment
- **Pointing System**
 - Composed of high-heritage components
 - Allows the XTI to track pulsars
 - Slews XTI between targets
- **C&DH**
 - Digital interface to ISS for commands, data
 - Supports pointing system
 - Reusable Core Flight Software from GSFC
- **Flight Releasable Attachment Mechanism**
 - Electrical & mechanical interface to ISS and transfer vehicle
 - Provided by ISS program

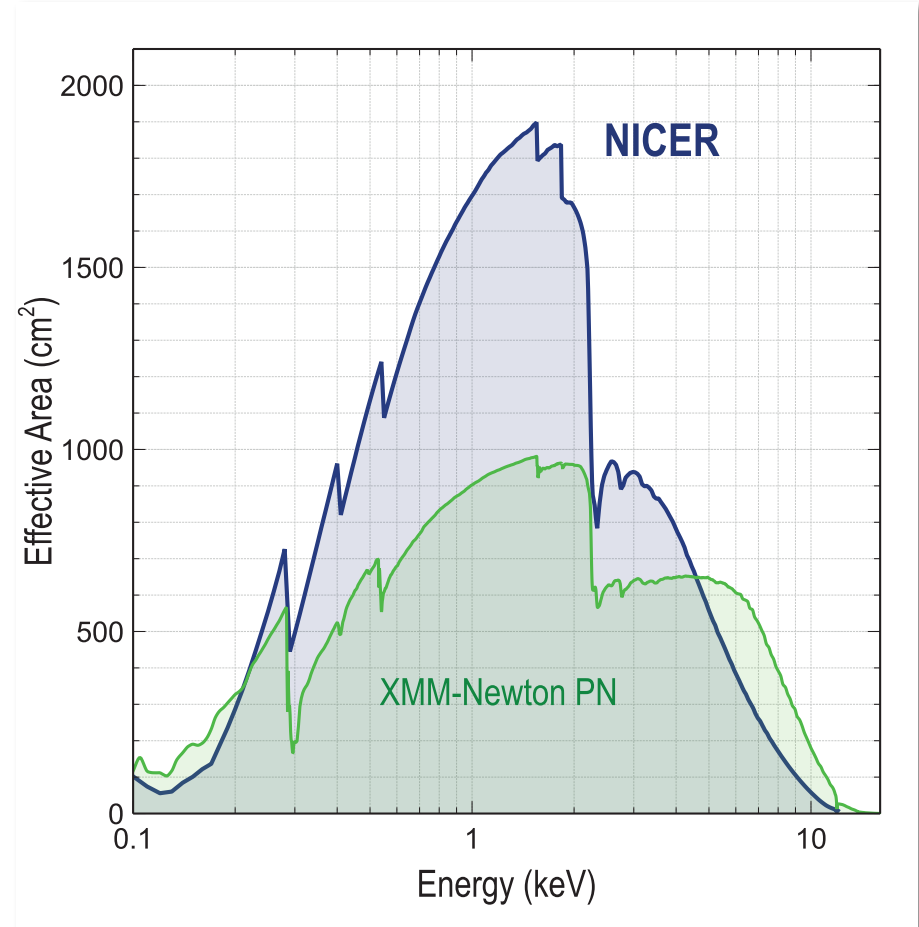




NICER Instrument Capabilities

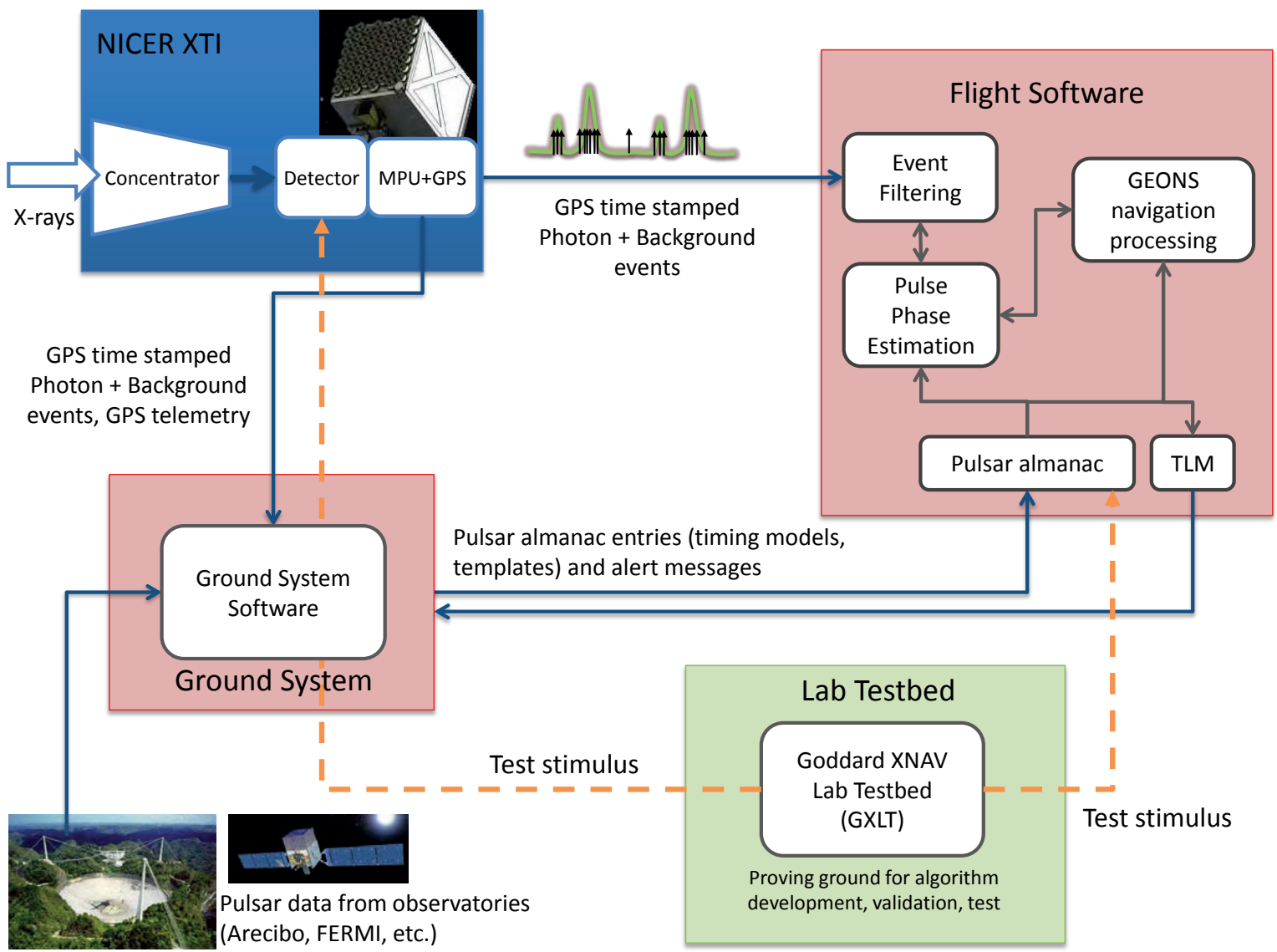


- **Spectral band: 0.2–12 keV**
 - Well matched to neutron stars
 - Overlaps RXTE and XMM-Newton
- **Timing resolution: 100 nsec RMS absolute**
 - 50x better than RXTE
 - ~1000x better than XMM-Newton
- **Energy resolution: 2.5% @ 6 keV**
 - 10x better than RXTE
- **Angular resolution: 6 arcmin (non-imaging)**
 - 10x better than RXTE
- **Sensitivity, 5σ : 5.3×10^{-14} erg/s/cm²**
 - 0.5–10 keV in 10 ksec (Crab-like spectrum)
 - 20x better than RXTE
 - 3x better than XMM-Newton's timing capability





System Architecture Diagram





Goddard XNAV Laboratory Testbed (XLT)



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

Level 0 simulation

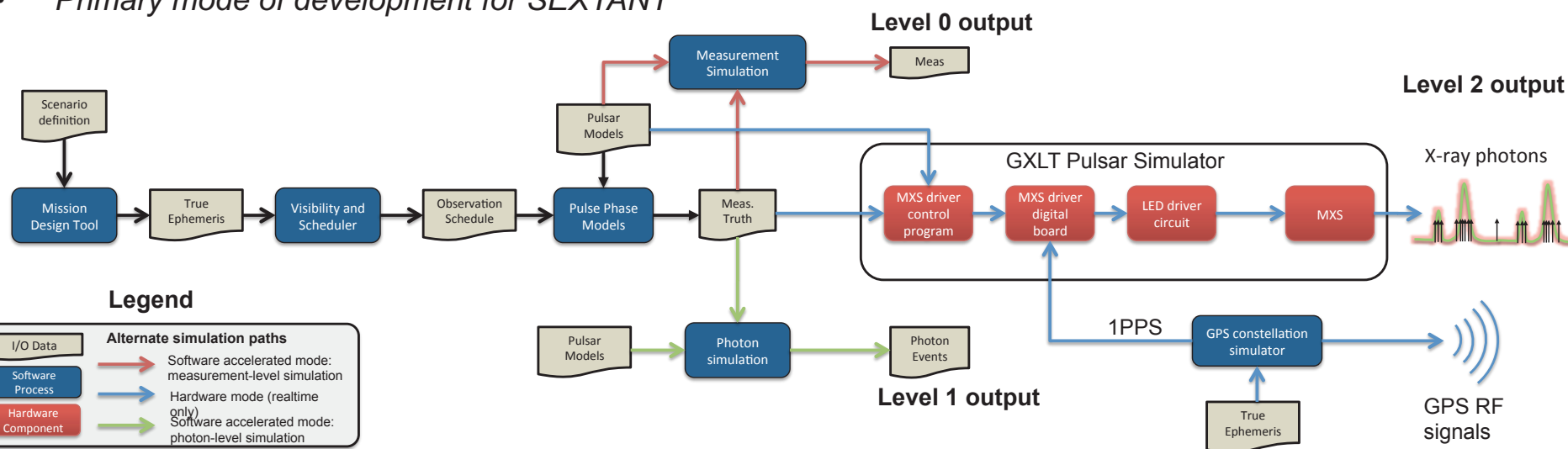
- Simulated measurements (no photon processing)
- Useful for long term studies (deep space trajectories, etc.)

Level 1 simulation

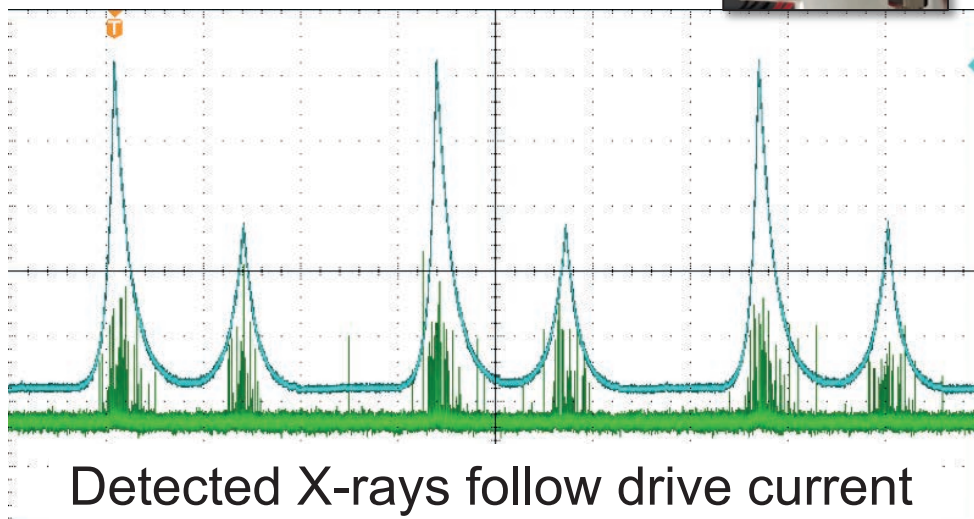
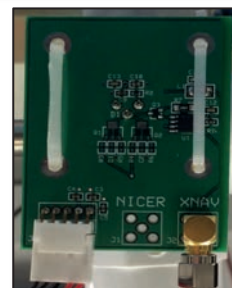
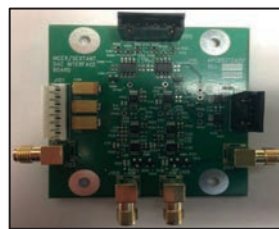
- Software only photon event simulation
- Photon processing algorithm implemented for measurement generation
- *Primary mode of development for SEXTANT*

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



MXS control electronics, 6 Total



Detected X-rays follow drive current

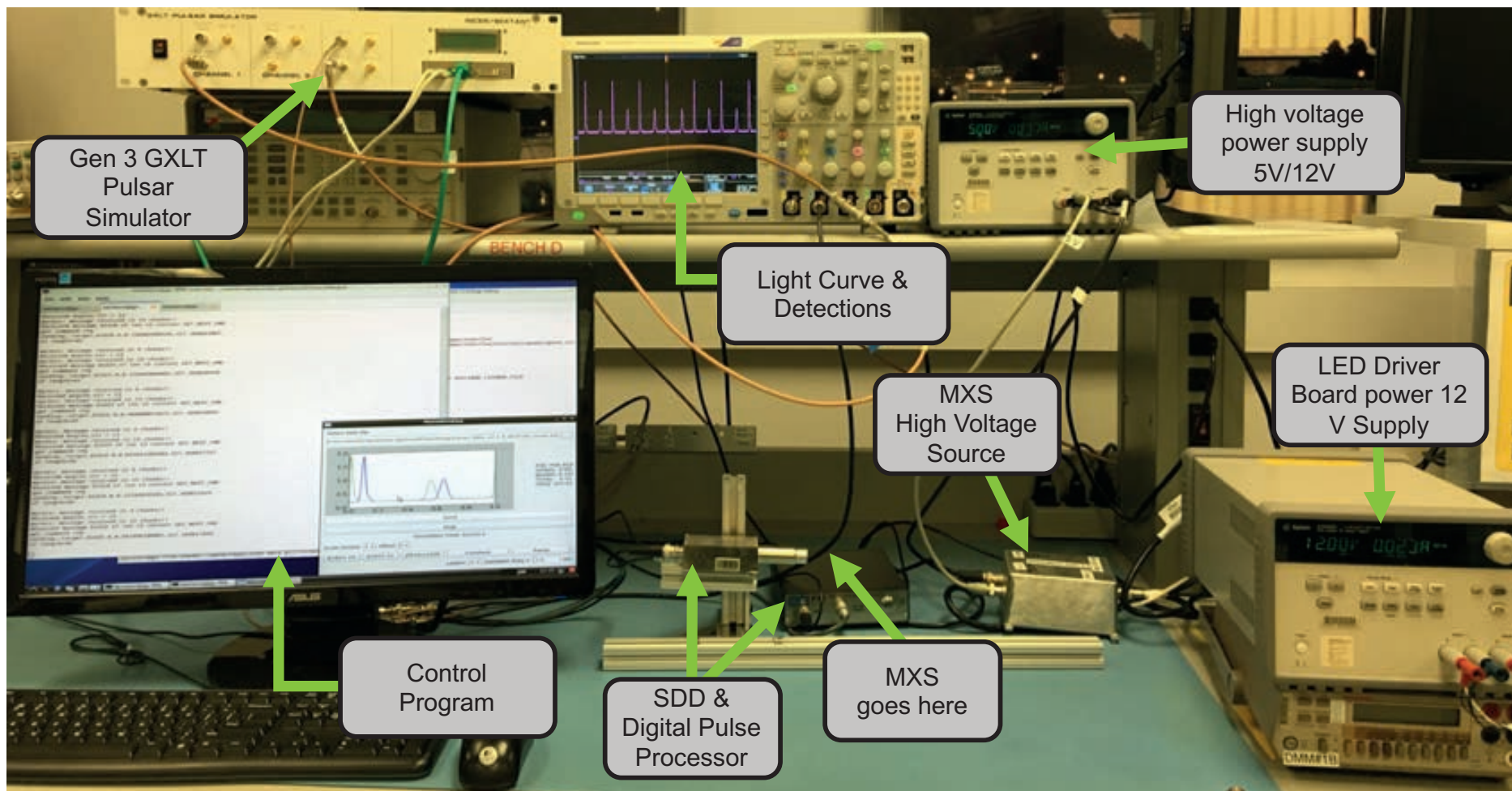
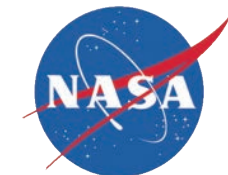
- Modulated X-ray source (MXS) allows precise control of X-ray intensity and timing
- Can be driven to precisely emulate MSP pulse shape, frequency, and phase as seen by spacecraft in orbit or in deep space



Modulated X-ray source (MXS)



NICER EM Single-Timing-Chain (1/2)

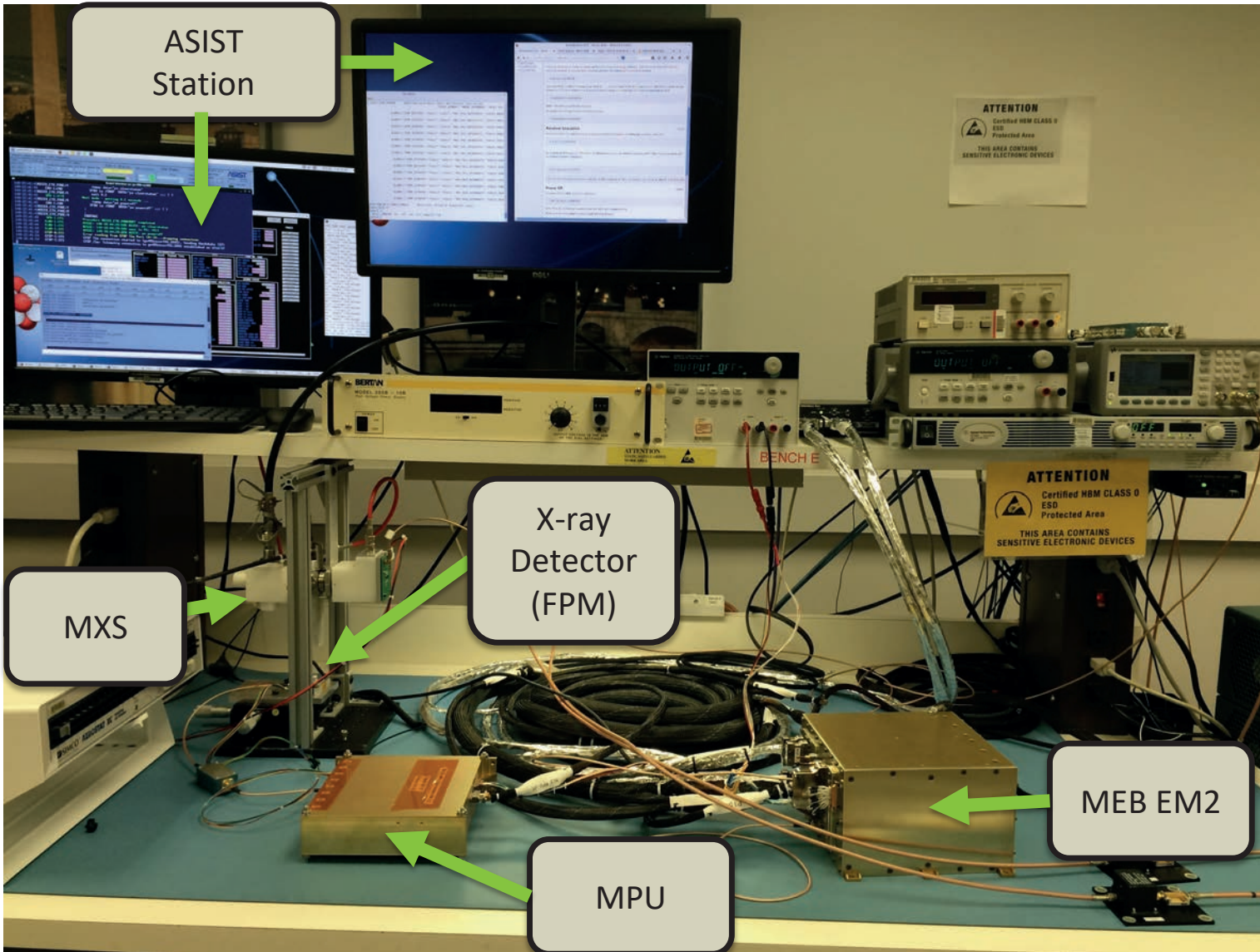


- MXS – Modulated X-ray Source
- MPU – Measurement/Power Unit (Timing electronic package)
- SDD – Silicon Drift Detector
- FPM – Focal Plane Module (SDD w/ pre-amp)
- LED – Light Emitting Diode

- MEB – Main Electronic Box (Flight processor and GPS cards)
- EM2 – Engineering Model #2
- ASIST – Advanced Spacecraft Integration and System Testing Software (Command/telemetry processing ground software)
- GXLT – Goddard XNAV Laboratory Testbed

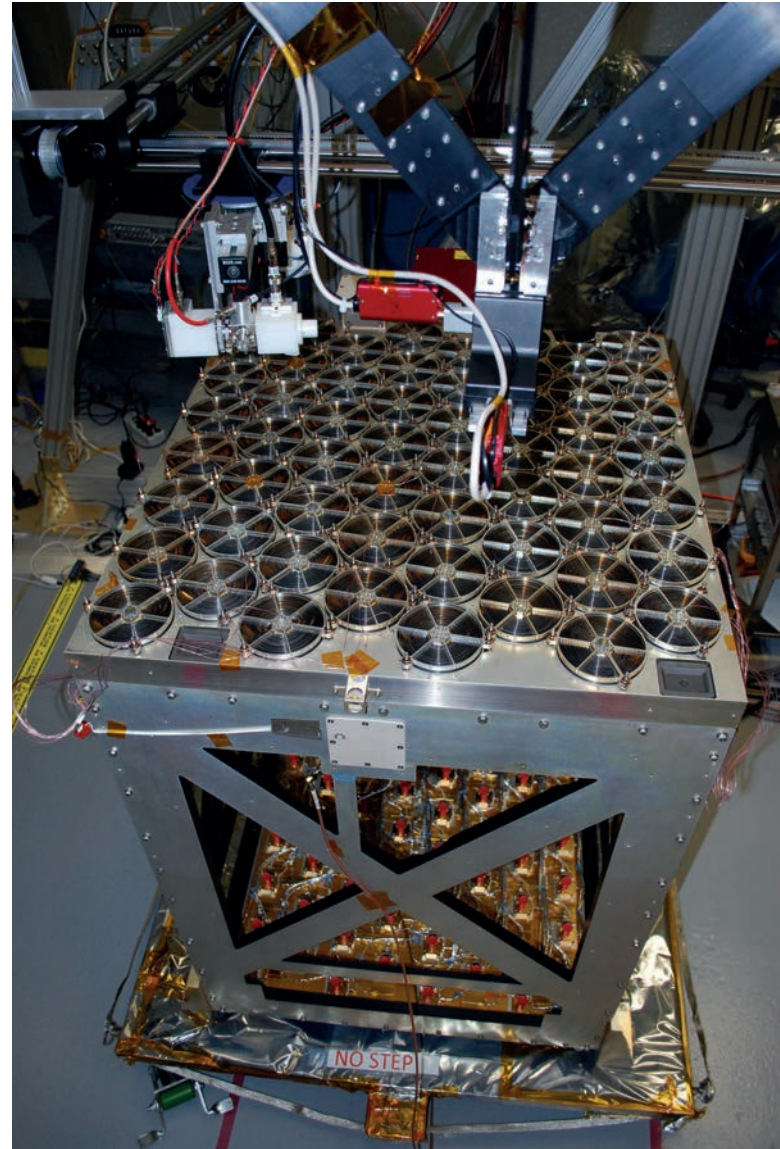
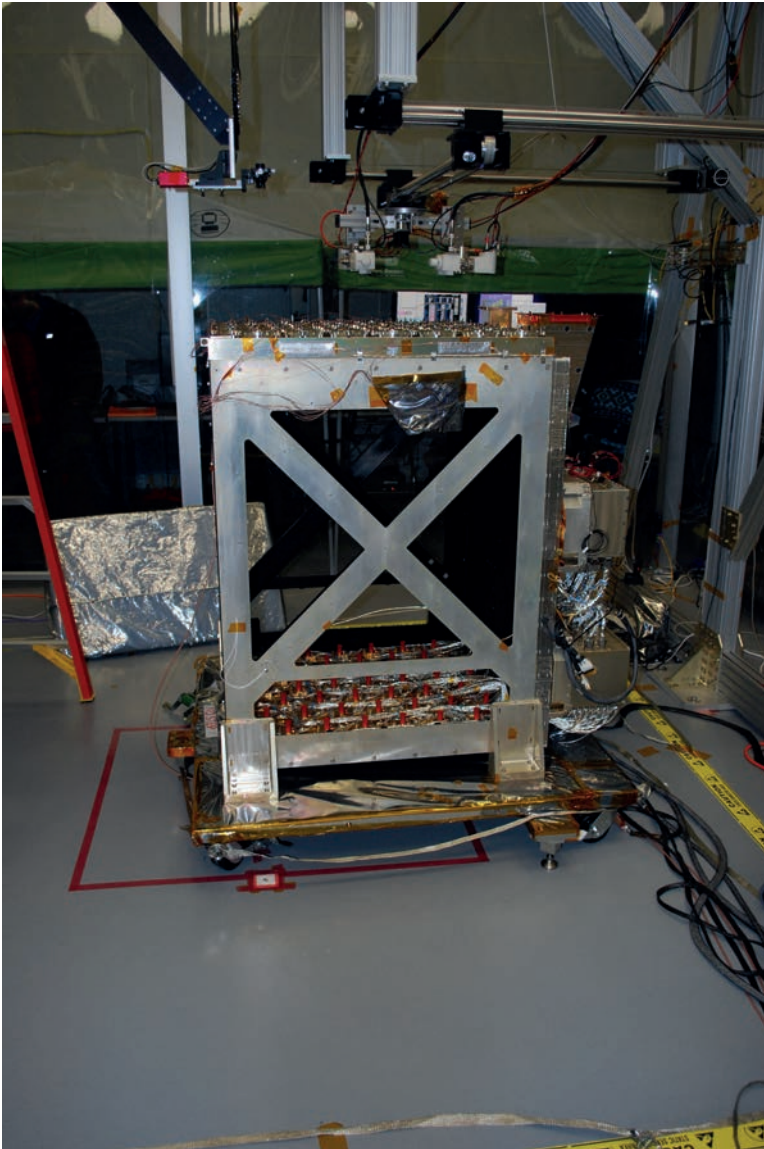


NICER EM Single-Timing-Chain (2/2)



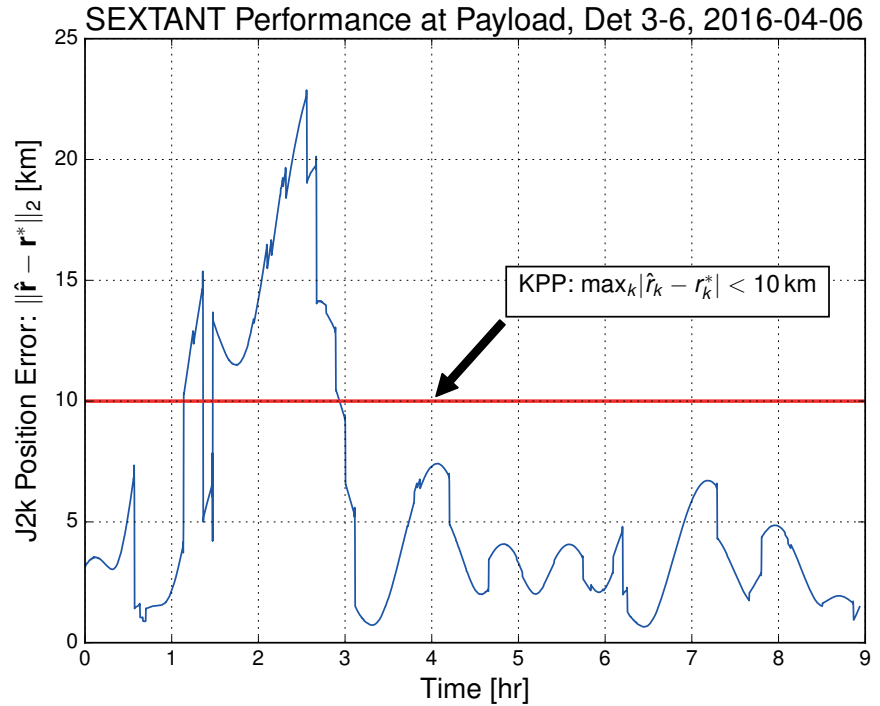
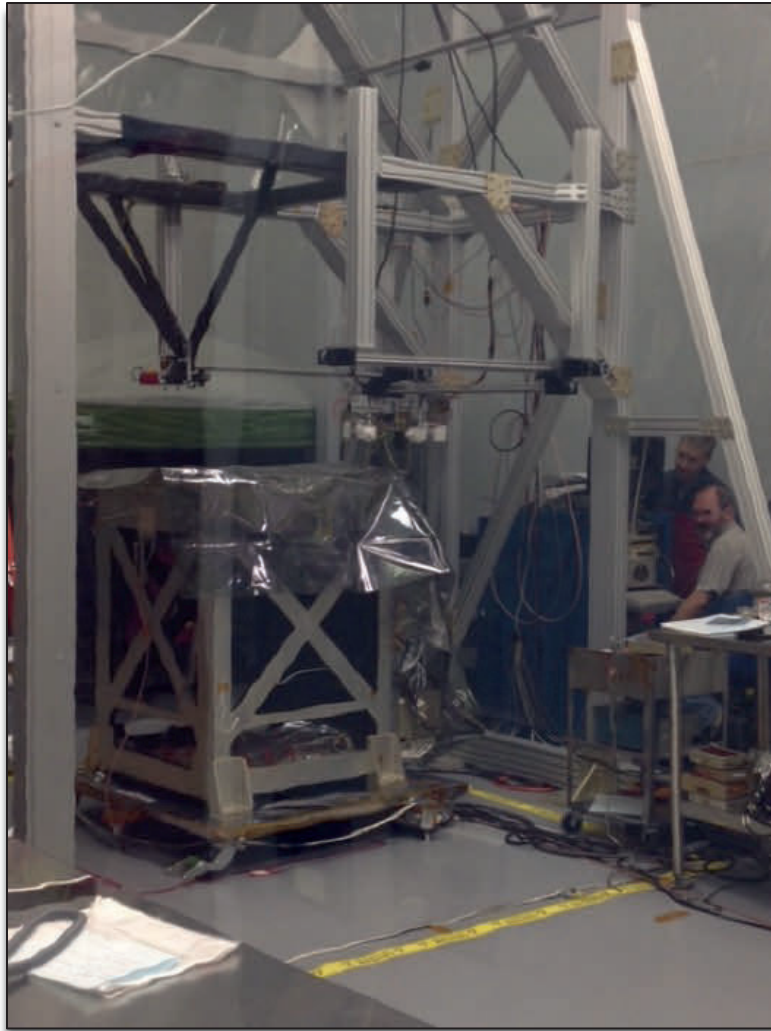


Payload XNAV Test Configuration (FY16)





Post-Environmental CPT: XTI Timing & XNAV Testing (FY16)



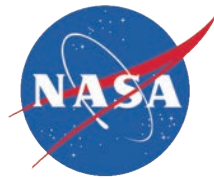


Dragon Separation





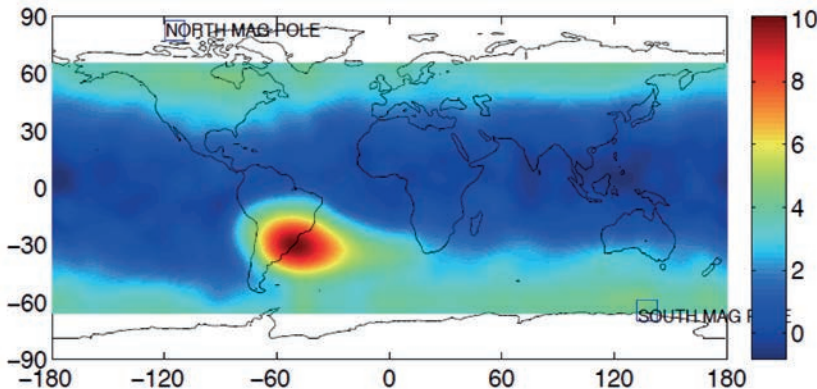
Plans Are Worthless, Planning Is Everything



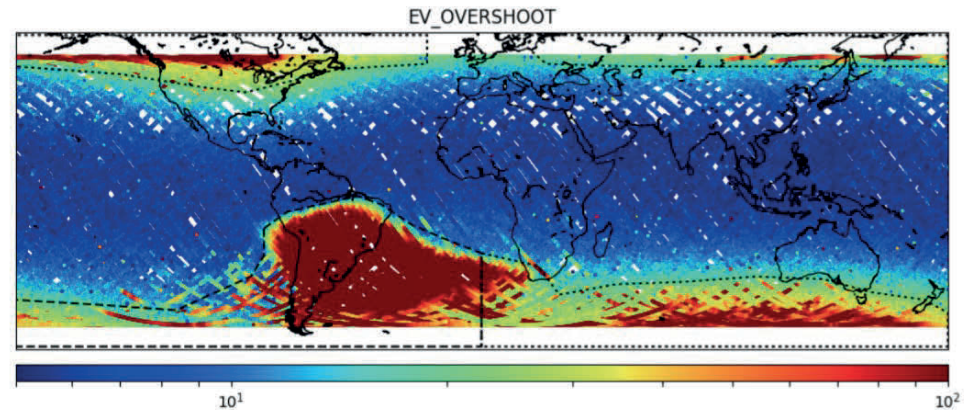
- Instrument on-orbit particle background
- Proper event filtering is key to obtaining best performance
- **NICER/SEXTANT team worked to optimize for science & XNAV**

- Energy cuts per source have been optimized for science and XNAV
- Stray light can trigger undesirable events
 - Mitigations determined and implemented, not on-orbit
 - Could significantly increase low-energy events
- Polar regions and SAA maps refined using flight data, updated on-orbit

Preflight background map



NICER “overshoot” map

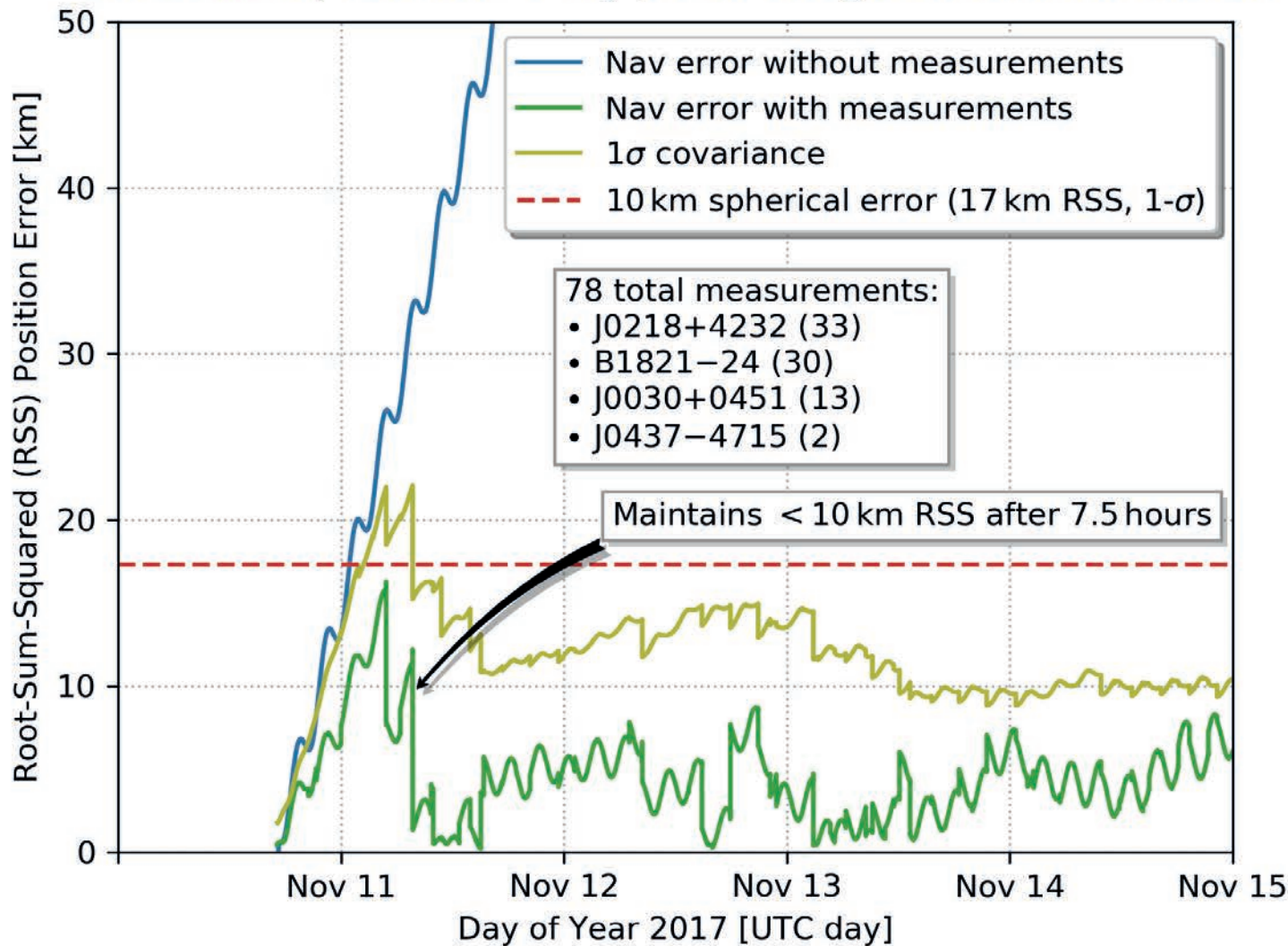




Successful Veteran's Day Weekend (2017) Experiment (NE1) Definitively Demonstrated Feasibility on-Orbit

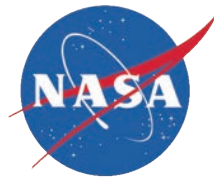


SEXTANT Experiment 1 successfully demonstrates fully autonomous, real-time X-ray pulsar navigation on-board NICER

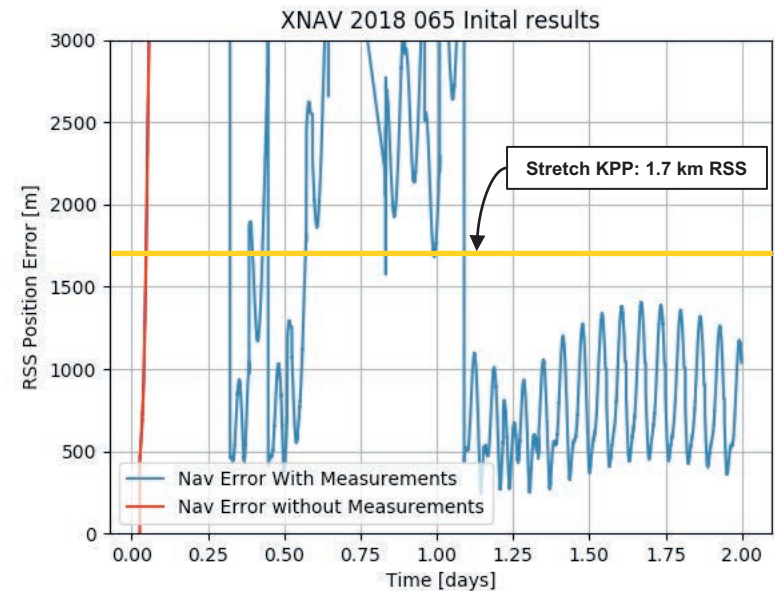
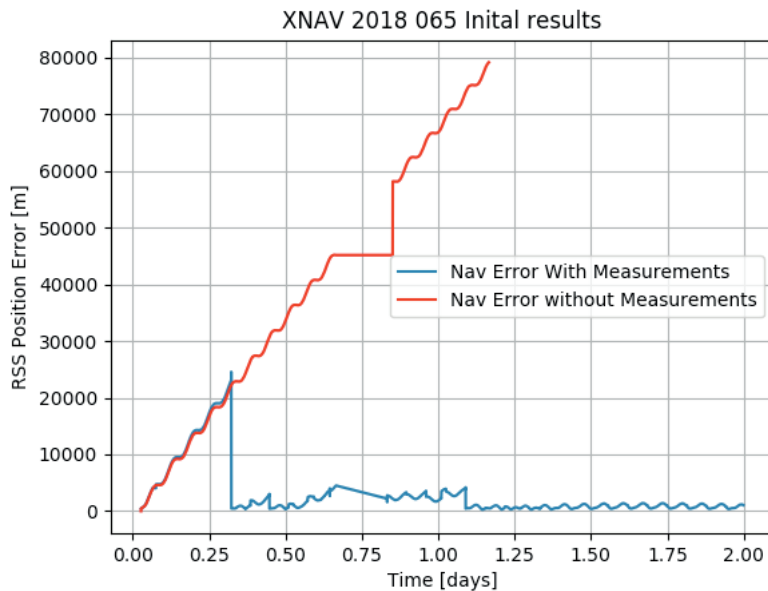




Ad-Hoc Observation Schedule Approaches 1 km Error (RSS)

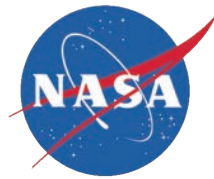


- 2018 DOY 65 (03/06) in *opportunistic mode* observing only B1937+21 for ~16.6 ksec, i.e., *not a nav schedule*
- Obtained 19 measurements
- Mean error < 1 km during DOY 66 (03/07)
- RSS error < 1.7 km RSS (stretch KPP) for nearly 1 day

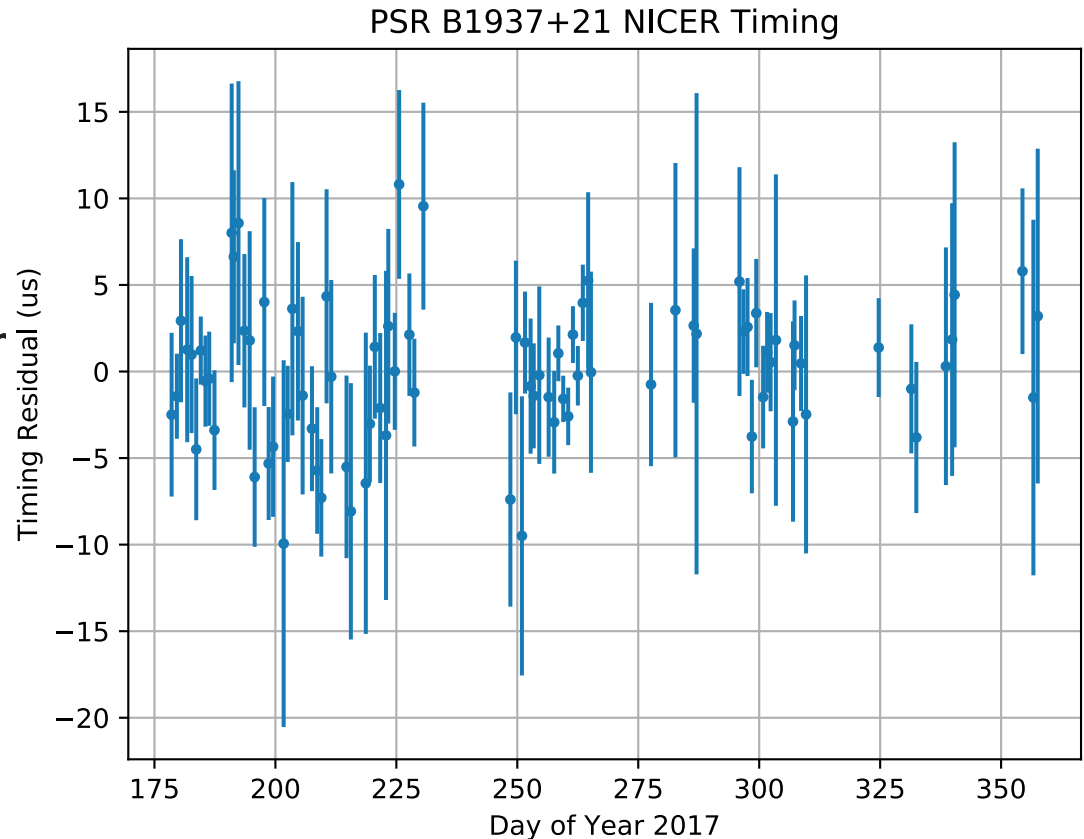




NE2: Example NICER Timing Residuals for B1937+21



- Initial timing model constructed from terrestrial radio data through 2017 DOY 48
- Residuals are difference of measured time-of-arrivals to model
- $<11 \mu\text{s}$ (3.3 km) error for 300 day extrapolation
- Daily time on target varies due to visibility constraints
- Expect improved performance w/ models derived from NICER-only X-ray data
- Timing group currently very active

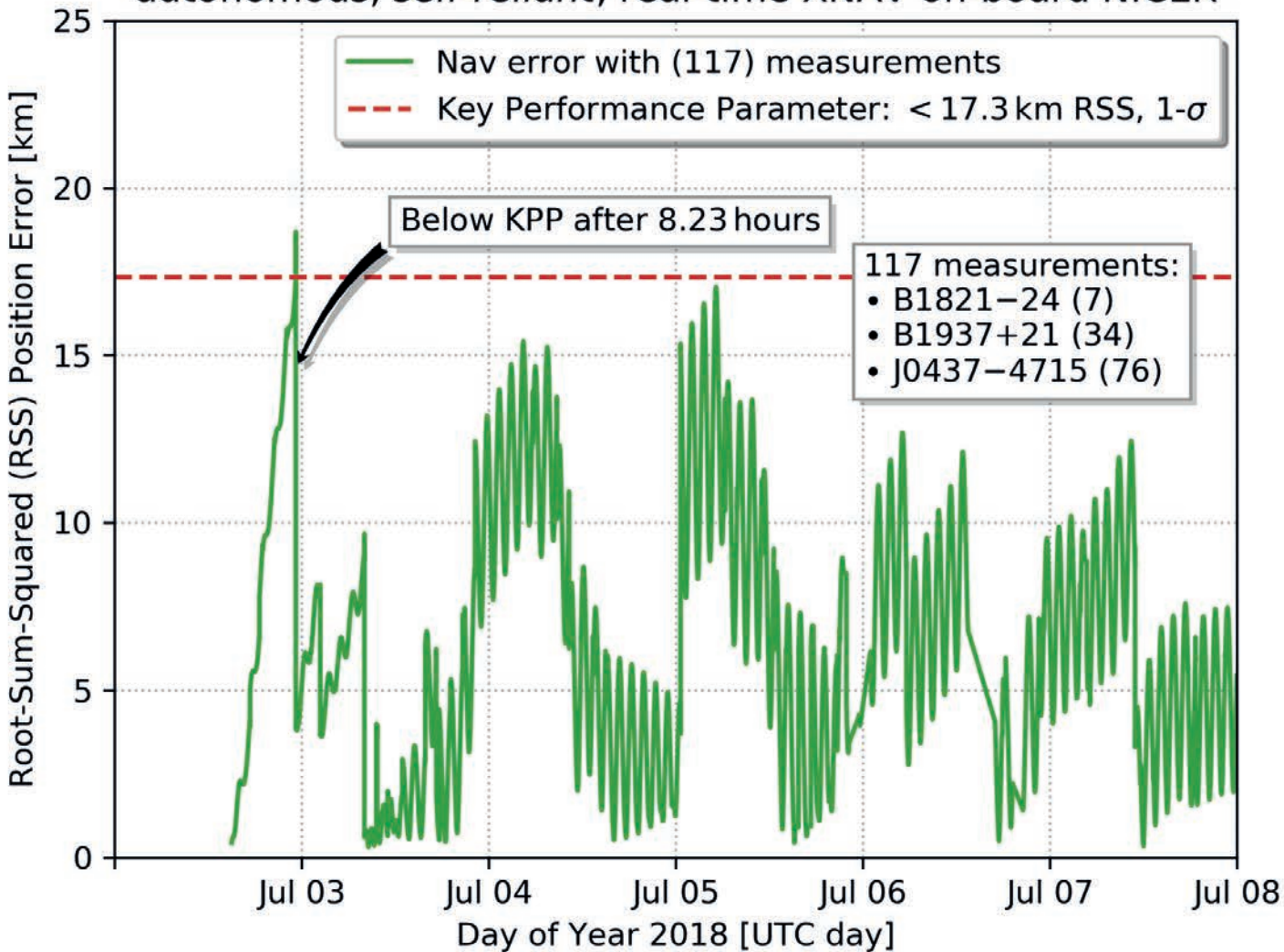




Successful Independence Day Week (2018) Experiment (NE2) Demonstrated Self-Reliance



SEXTANT Experiment 2 successfully demonstrates fully autonomous, *self-reliant*, real-time XNAV on-board NICER





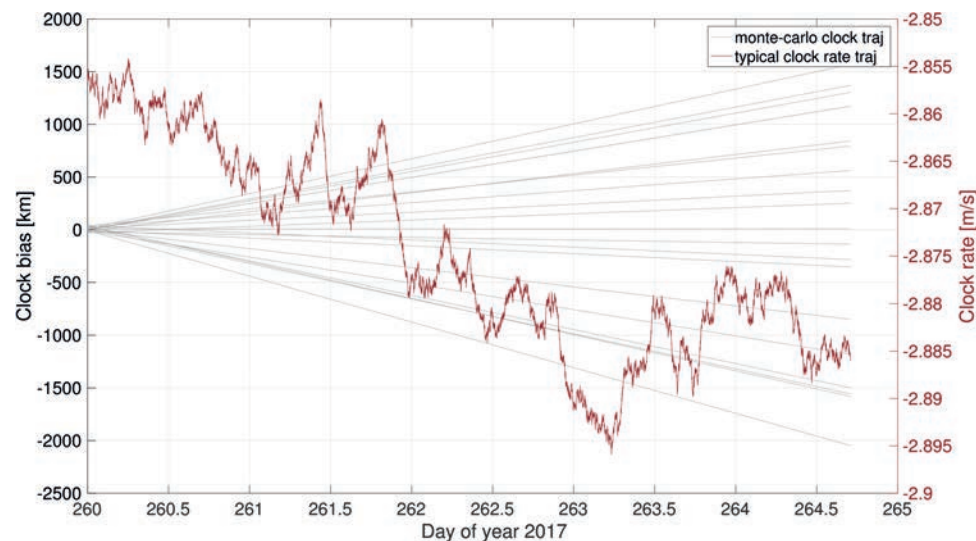
Extending Capability: Time Estimation



- 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



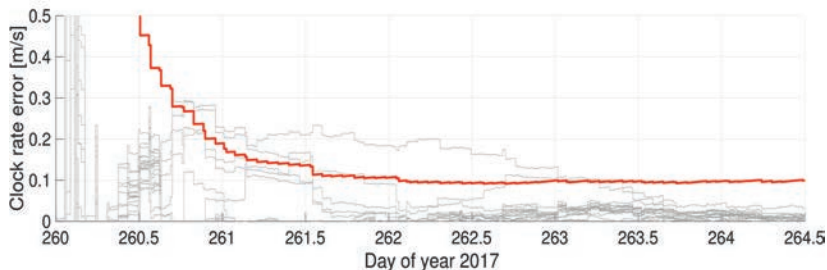
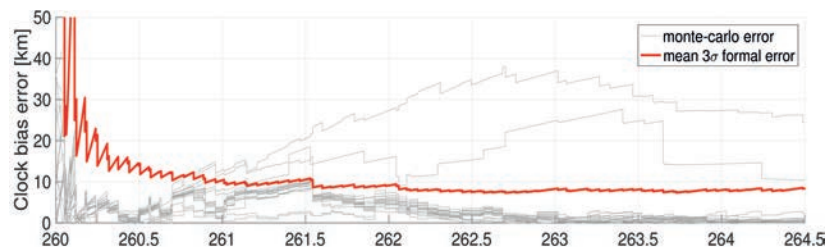
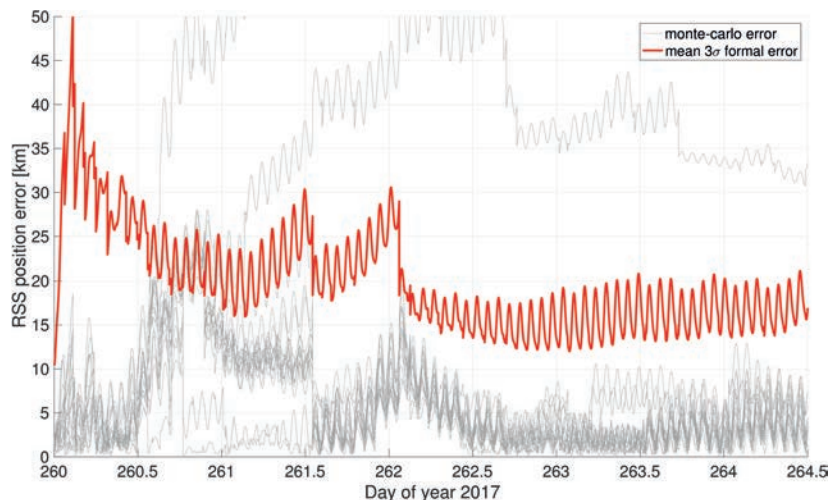
Simulated ultra-stable crystal oscillator clock error trajectories



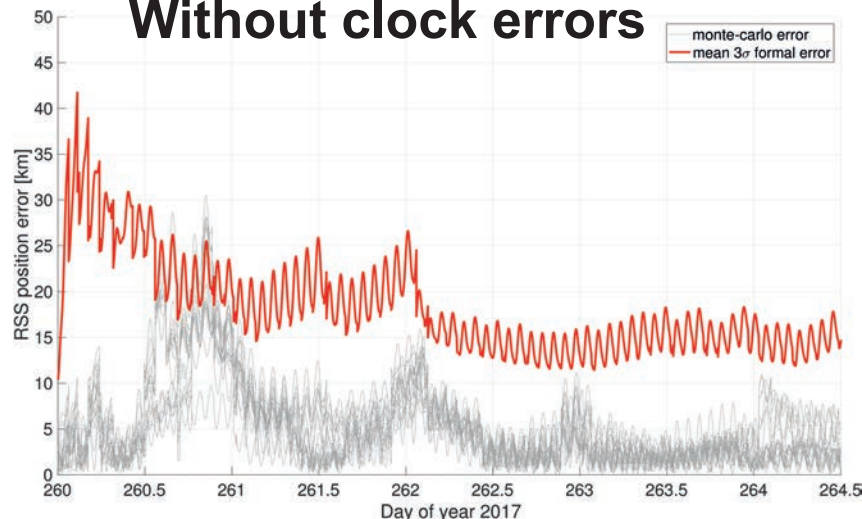
Extending Capability: Time Estimation Ground Performance



With clock errors



Without clock errors



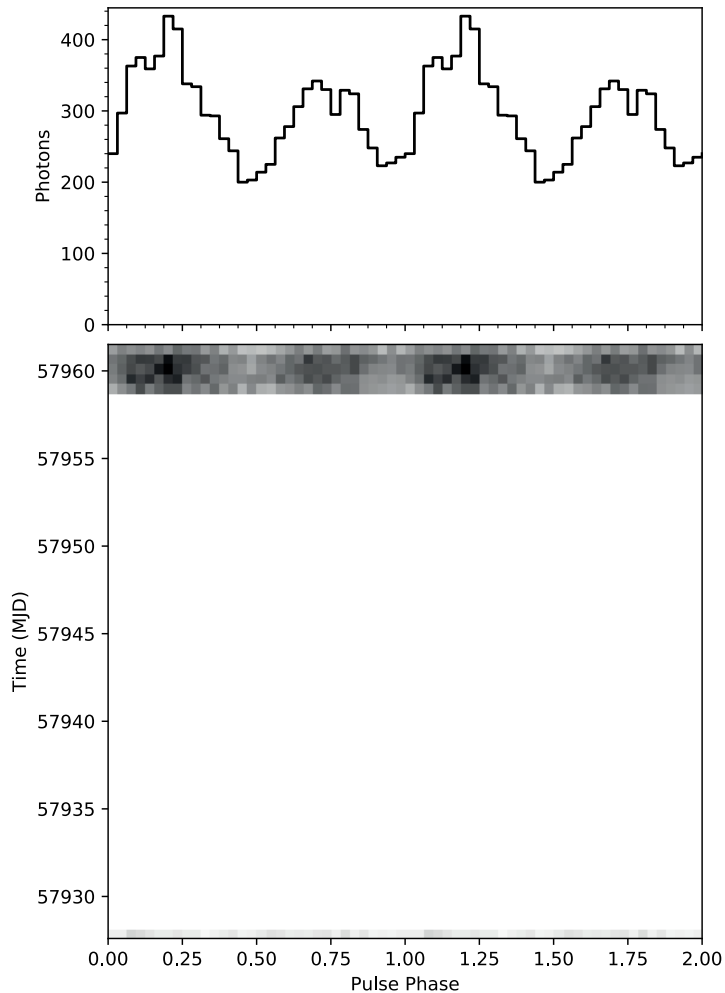
- **Methodology: Replay NICER X-ray data with 40 trials through SEXTANT flight software**
 - Randomized initial state errors, additive clock errors (20 trials)
 - Randomized initial state errors, no clock errors, no estimate clock states (20 trials)
- **Result: Clock is accurately estimated with similar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



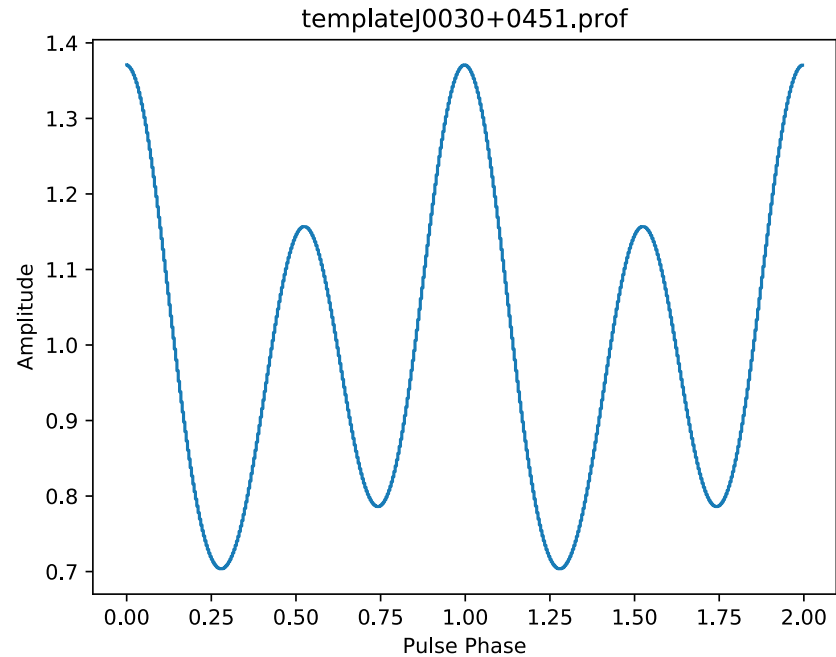
Pulsar Timing Models: Pulse Profile Template, J0030+0451



Phaseogram 0.4 to 2.1 keV



Constructed Analytical Template (2 cycles)

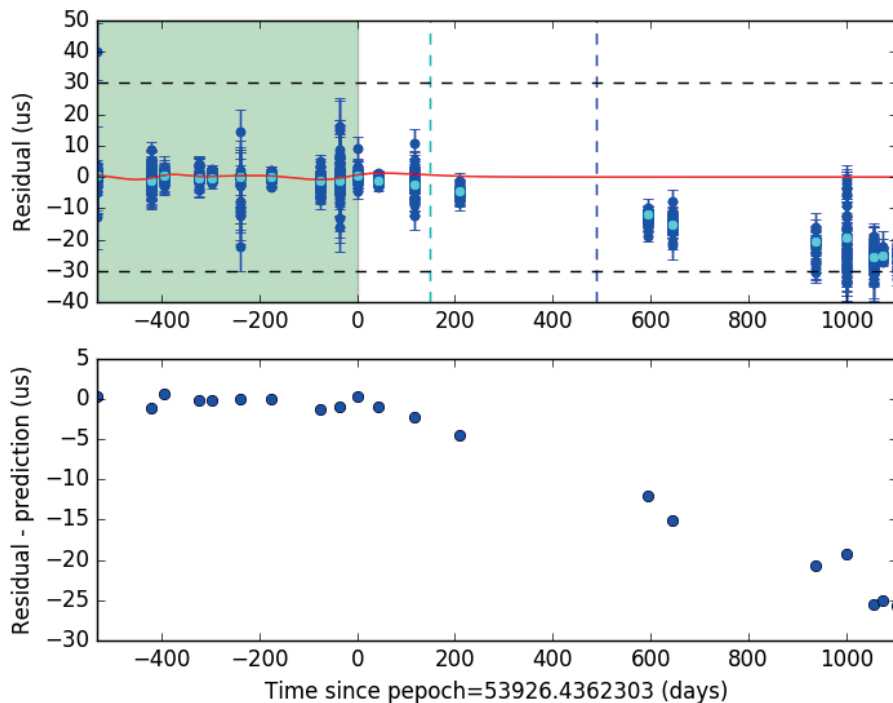




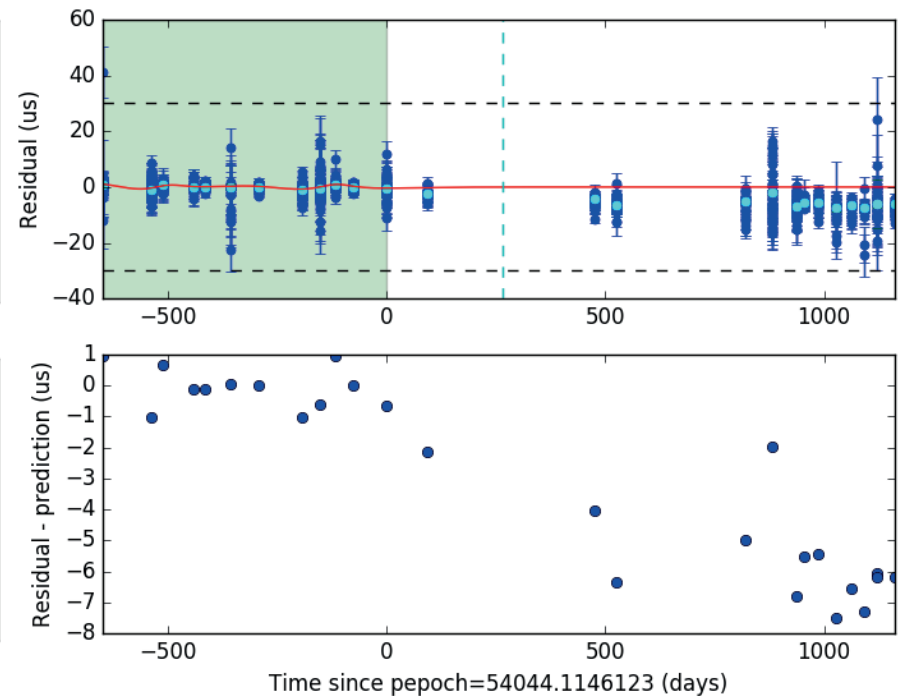
Pulsar Timing Models: Extrapolation Model, J0030+0451



- Time of Arrival (TOA) data set sourced from NANOGrav 11 yr data release
- Training interval (green) of 1.5 yrs (left) starting 2006-07-10 and 2 yrs (right) starting 2006-11-05
- Vertical dashed line show first deviation of $3 \mu\text{s}$ (cyan), $10 \mu\text{s}$ (blue)



$\sim 30 \mu\text{s}$ (9 km) error @ ~ 3 yrs



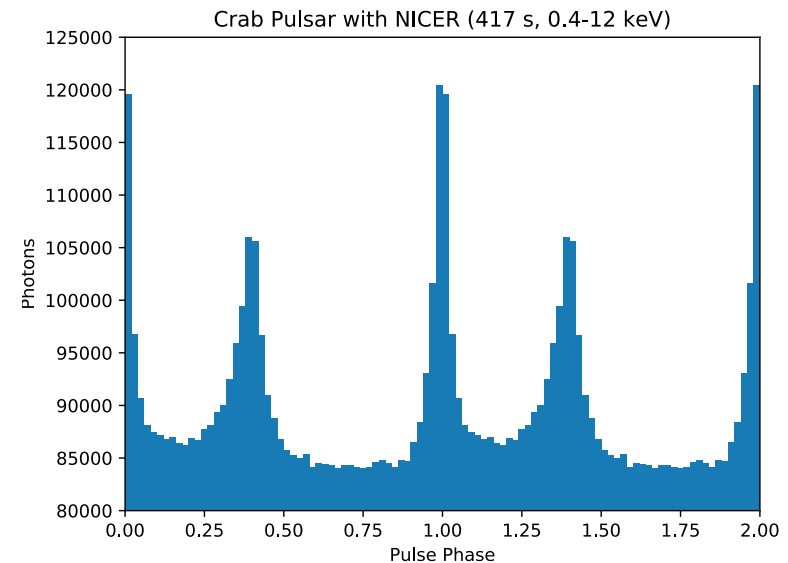
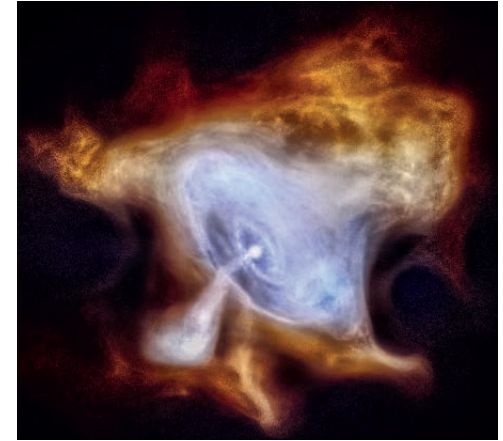
$\sim 8 \mu\text{s}$ (2.5 km) error @ ~ 3 yrs



Benefits of Using Crab Pulsar (B0531+21)



- **Crab pulsar flux $>10^4$ higher than other SEXTANT MSPs**
 - Provides faster measurements (100s of sec)
 - Allows
 - Equivalent navigation performance using less observation time, or
 - Smaller X-ray instruments
- **Crab requires frequent ground updates (or onboard timing noise estimation) for onboard XNAV**
 - Crab is young, noisy timer
 - Timing model prediction limited to few days
 - Compare to months or years for stable MSPs
- **For ground experiment, can accurately determine *a posteriori* model in a *replay* mode**



Crab light curve obtained with 417 s NICER observation

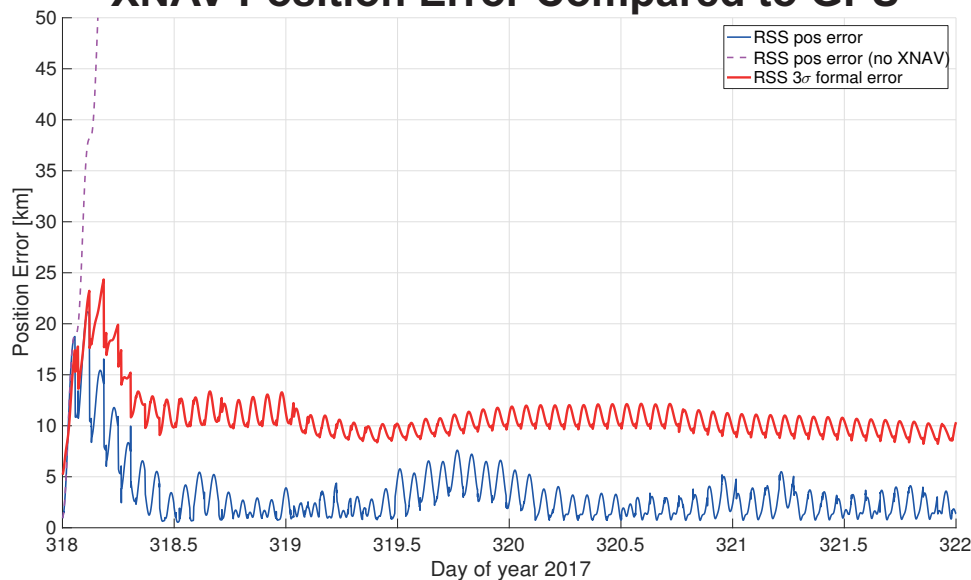


Navigating with Crab Pulsar

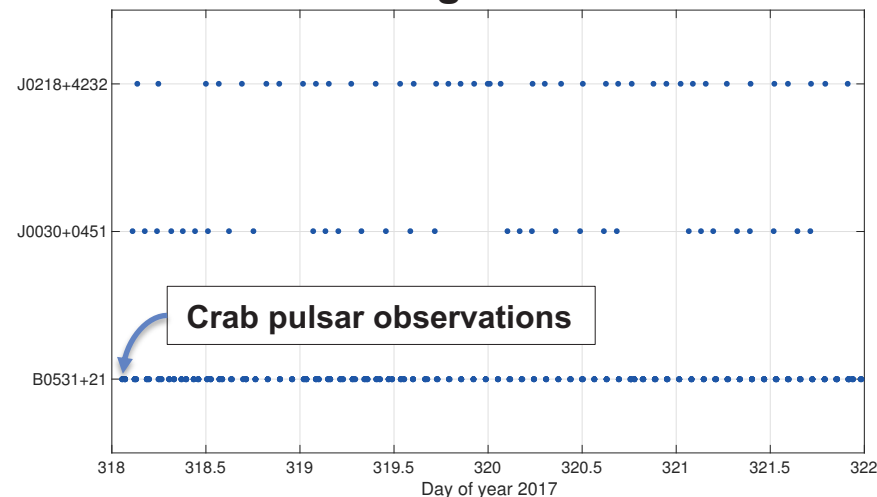
- **2017 days-of-year 318–322 SEXTANT conducted 1st ground experiment using pulsar B0531+21 (Crab)**
 - Initialized with degraded GPS state that propagates to >100 km RSS error in few hours
 - Recorded data replayed through ground version of flight software, no clock bias/rate estimation
 - Measurement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





Conclusion



- **X-ray Pulsar Navigation (XNAV) works!**
 - Hardware design is scalable
 - Flight software is cFS-based (core Flight Software)
 - Leverages heritage GEONS navigation filter (also cFS app)
 - Timing implications beyond navigation
 - Instrument is also X-ray astrophysics instrument
 - Suitable for very deep space (interstellar) missions
 - Excellent backup navigation and time for crewed missions
- **Performance can be quite good!**
 - Trade between (effective) collecting area and observation time
 - Tune for desired goal
- **SEXTANT project officially closed out Dec 2018**
 - Continuing current infusion activities
 - Focused primarily on JSC iPAS facility and Gateway demo
- **NICER Principal Investigator (PI): Keith Gendreau, PhD**
 - keith.c.gendreau@nasa.gov



Time-Domain X-ray Technology: Common Thread for Many Objectives



Diffraction
Limited Soft X-
ray Optics

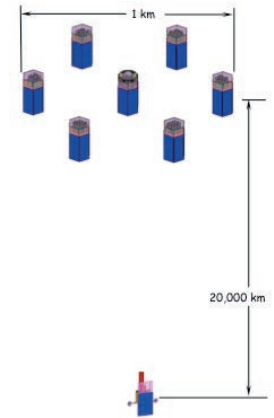


X-ray Beacons for
Relative Navigation

10 μ s X-ray Star Tracker

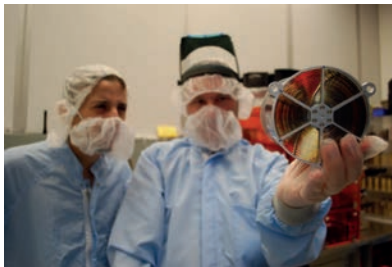
Black Hole Imager

Modulated
X-ray Source
(MXS)



Calibration

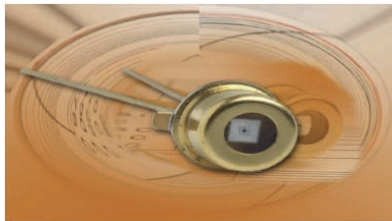
Low Cost
Optics



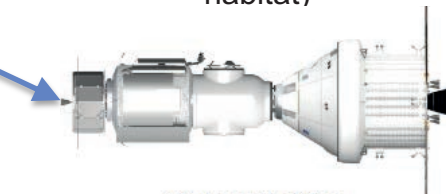
XCOM Demo(s)
2019+ (STP-H6)

Practical XNAV sensor
(HEOMD/AES Cis-lunar
habitat)

Silicon
Detectors



NICER/SEXTANT:
Pulsar Navigation
Demonstration
(2017–2019)



Establish Pulsar Based
Universal Time Reference



ADDITIONAL INFORMATION

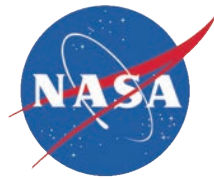


Publications (1/6)

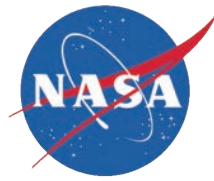
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A Table-Top Pulsar Emulator Demonstration



Goddard XNAV Laboratory
Testbed (GXLT)

Demonstration Video