Station Explorer for X-ray Timing and Navigation Technology (SEXTANT): An X-ray Pulsar Navigation and Timing Technology Demonstration

Interstellar Medium Technology Workshop

The Hyatt Place, Washington DC

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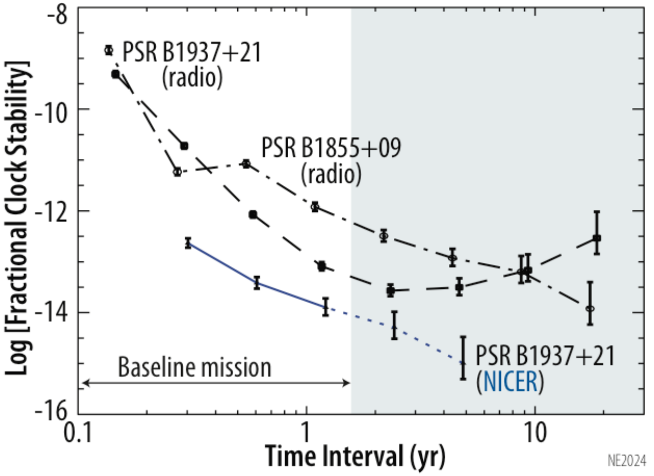
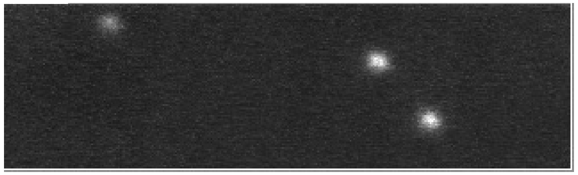
Outline

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

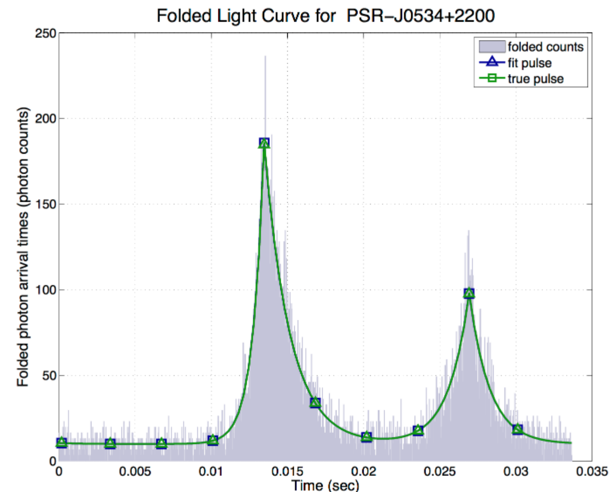
X-ray Pulsar Navigation (XNAV) Concept

- **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)

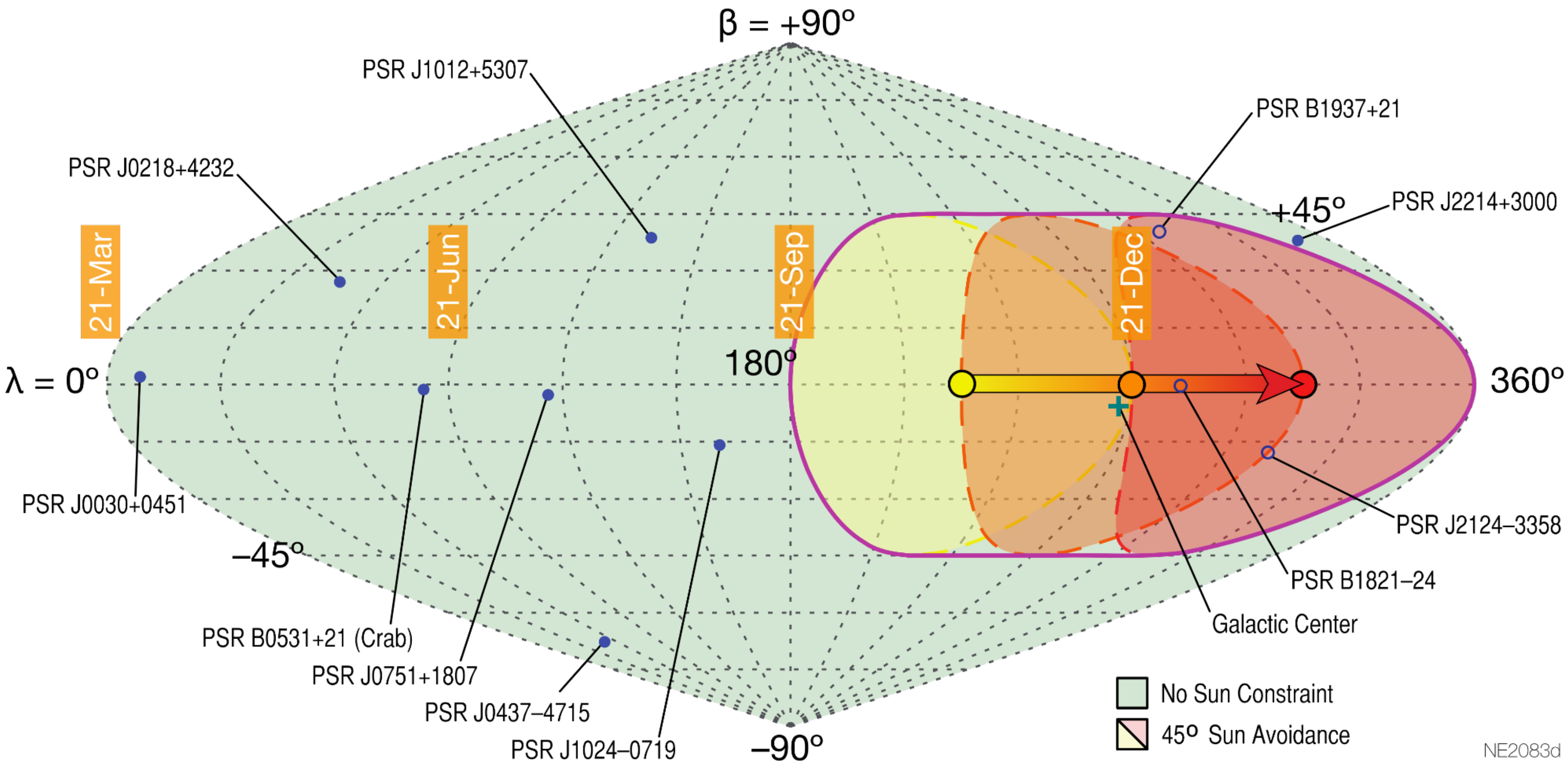




Crab Pulsar (1/3 speed), Cambridge University, Lucky Image Group



Millisecond Pulsar Targets for SEXTANT



- 10 MSP targets of navigation interest, plus Crab pulsar
- Seasonal visibility due to NICER 45º 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)

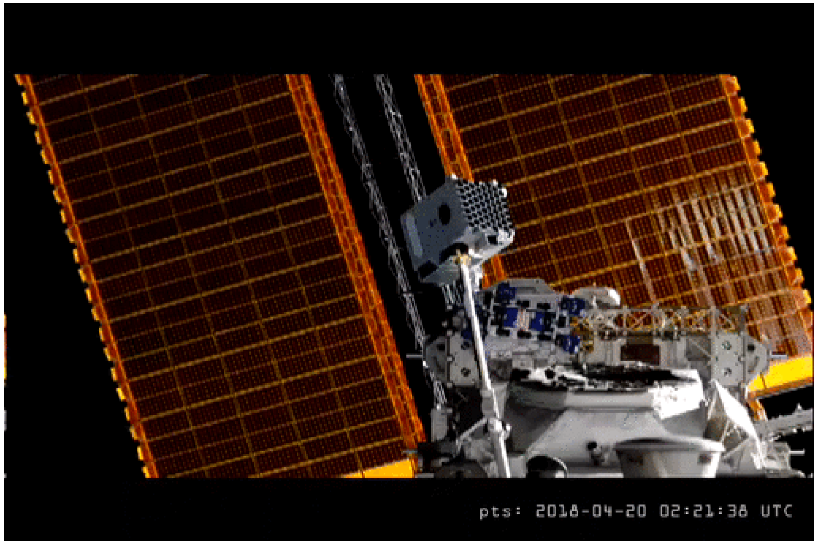
- **NE1:** ≤2 week period observing 3–5 pulsars early in the mission, models derived from radio telescope data
- **NE2:** ≤2 week period observing 3–5 pulsars later in the mission, models derived from NICER data
- Opportunistic on-orbit experiments
- Ground experiments using collected photon data

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

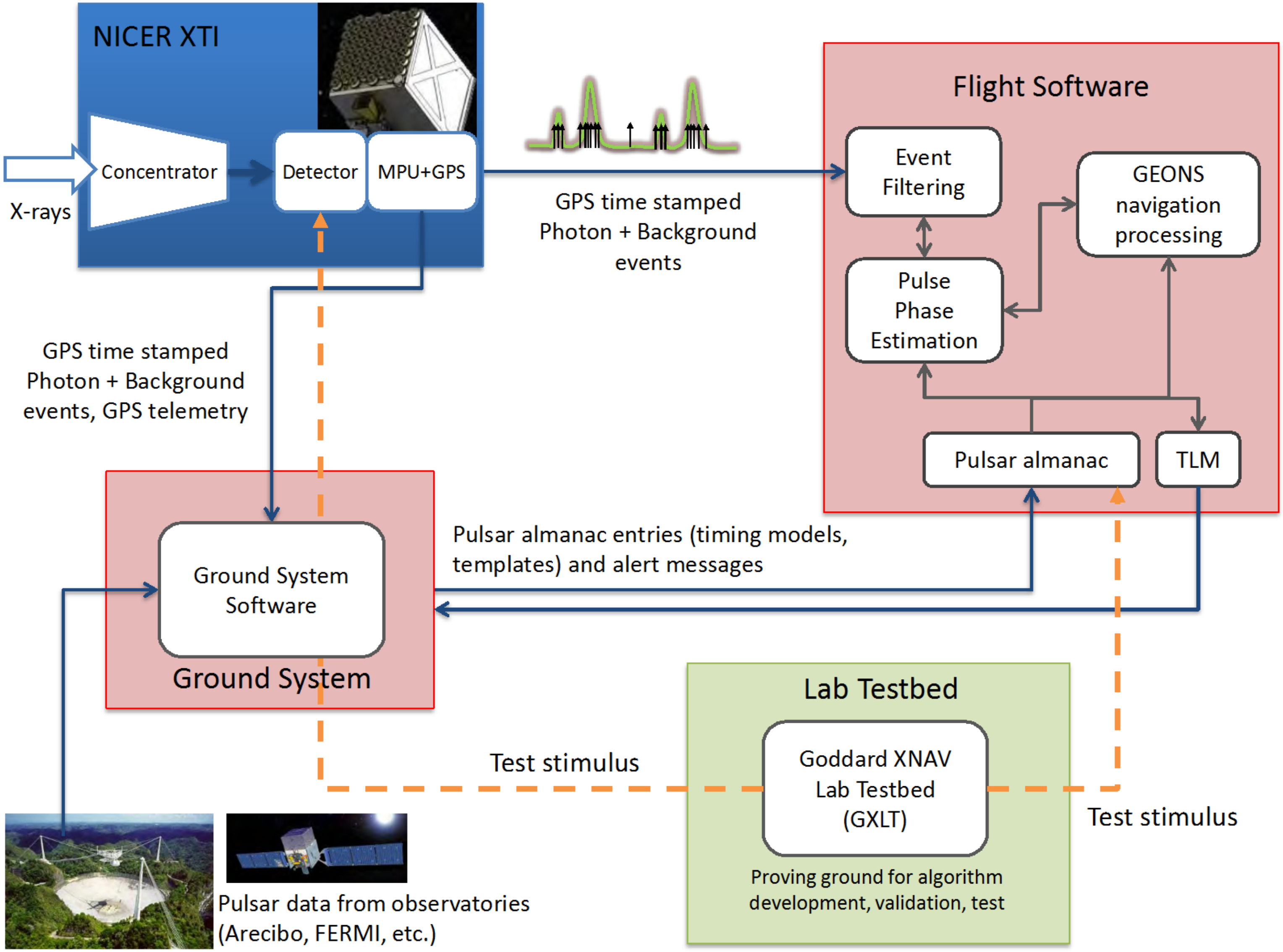
NICER: X-ray Timing Instrument on ISS

- 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***

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

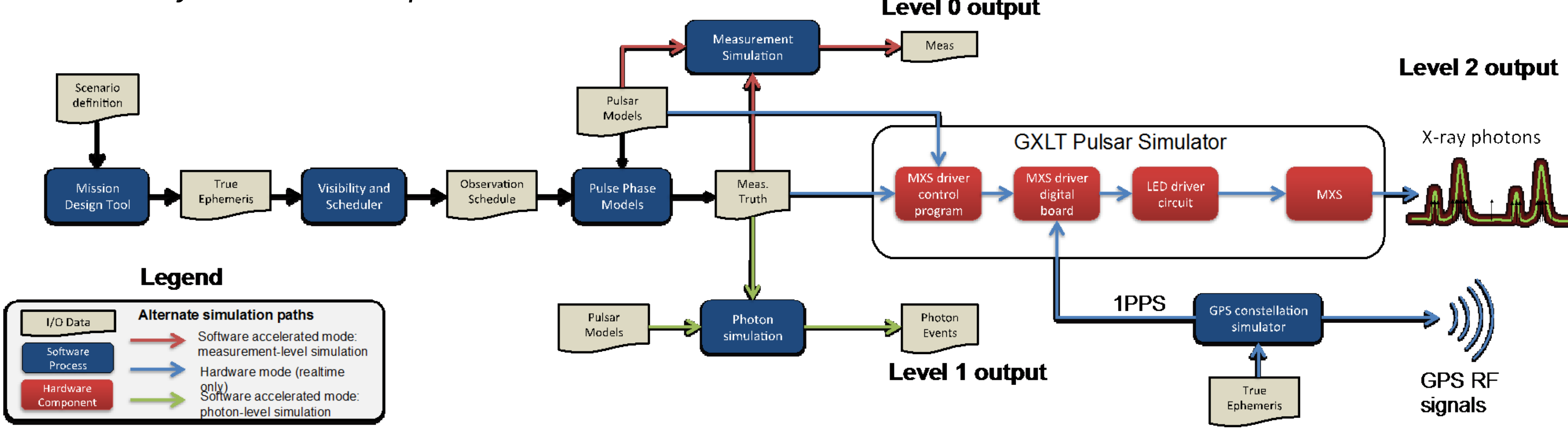
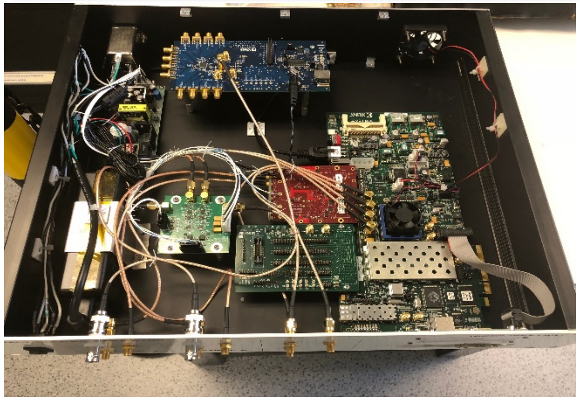
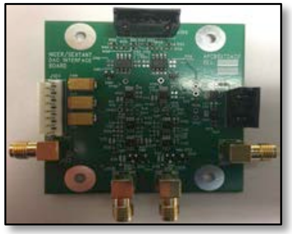
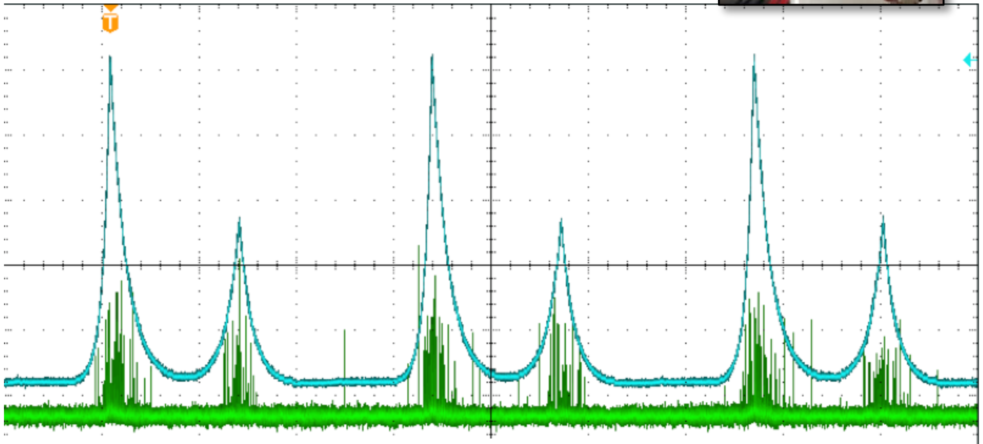


Table-Top Pulsar Simulator, Gen 3

MXS control electronics, 6 Total





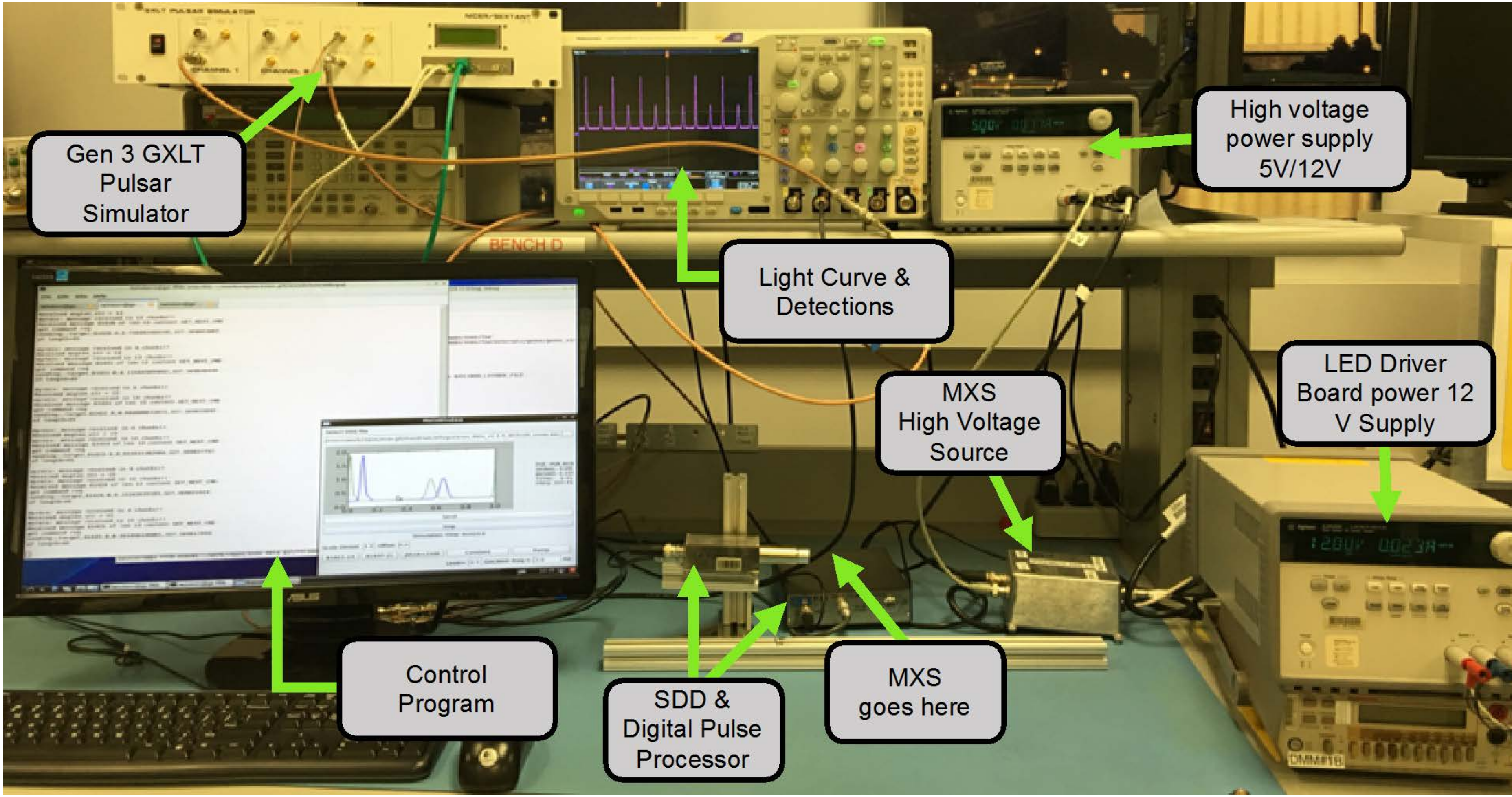


Detected X-rays follow drive current

- 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

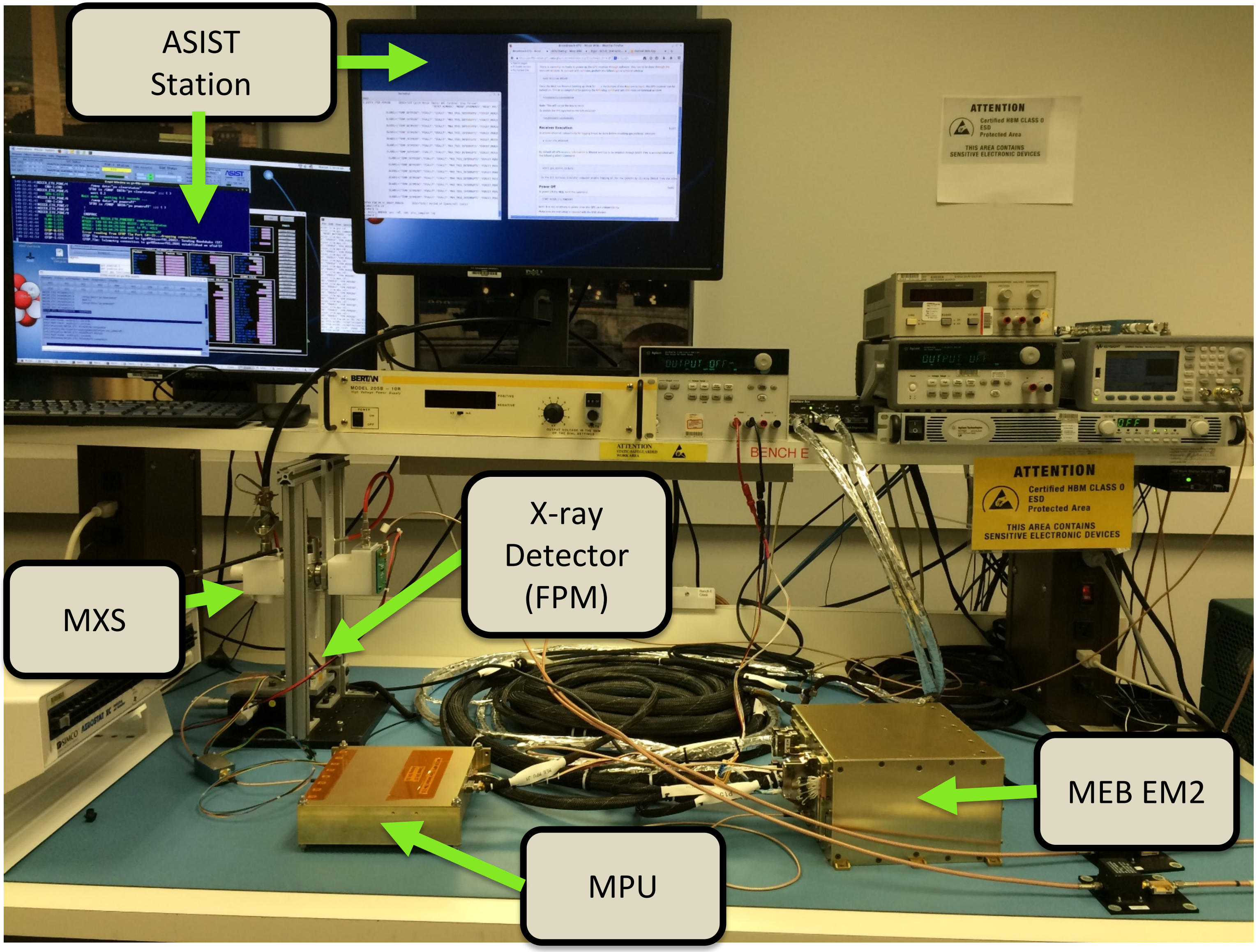
Modulated X-ray source (MXS)

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

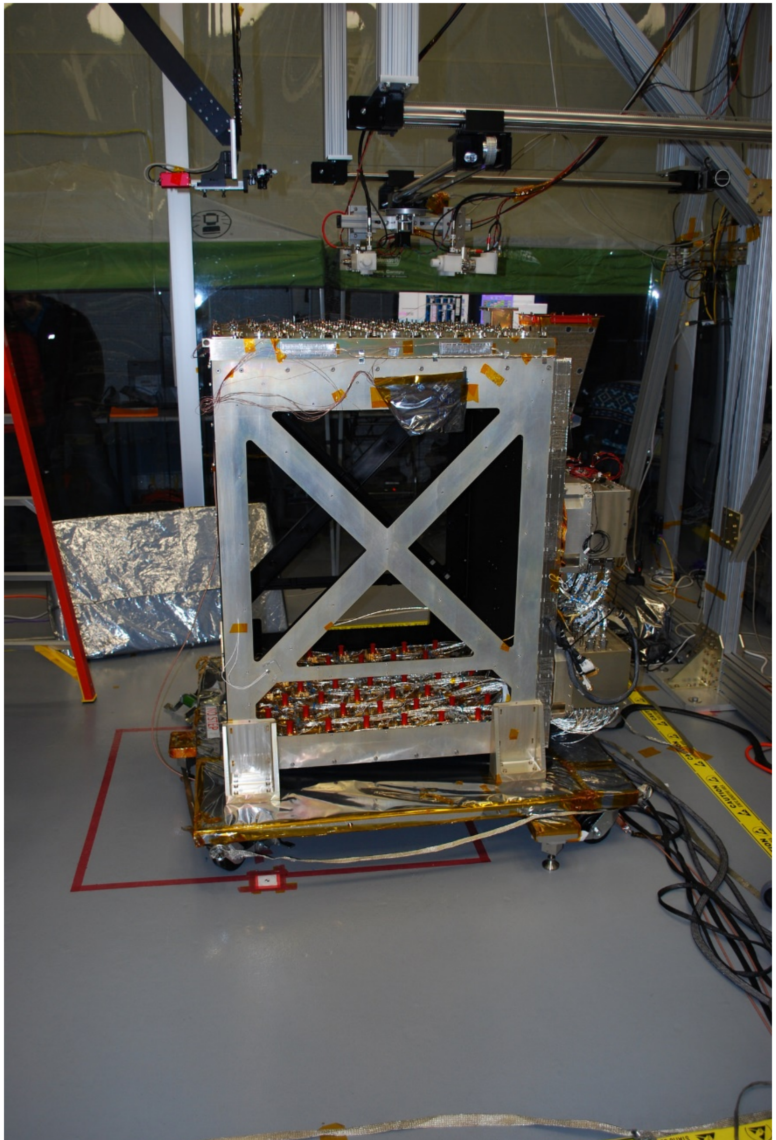


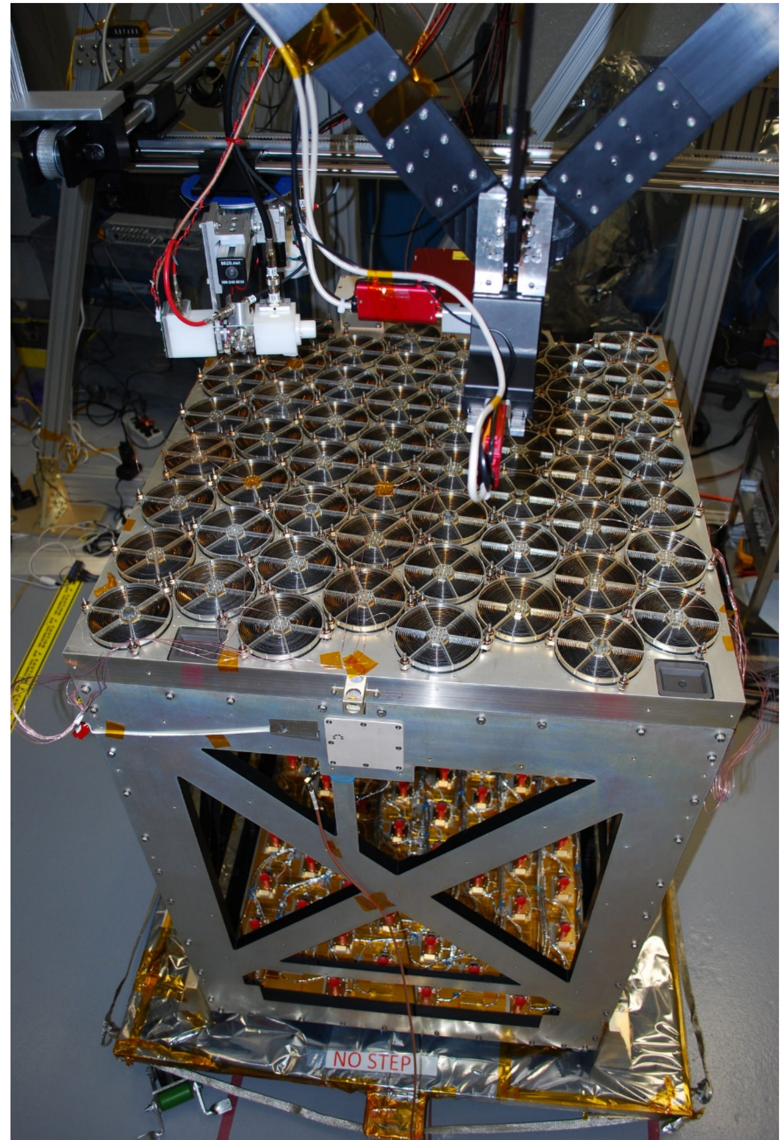
- MXS – Modulated X-ray Source
- MPU – Measurement/Power Unit (Timing electronic package)
- SDD – Silicon Drift Detector
- FPM – Focal Plane Module (SDD w/ pre-amp)
- LED – Light Emitting Diode
- MEB – Main Electronic Box (Flight processor and GPS cards)
- EM2 – Engineering Model #2
- ASIST – Advanced Spacecraft Integration and System Testing Software (Command/telemetry processing ground software)
- GXLT – Goddard XNAV Laboratory Testbed

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

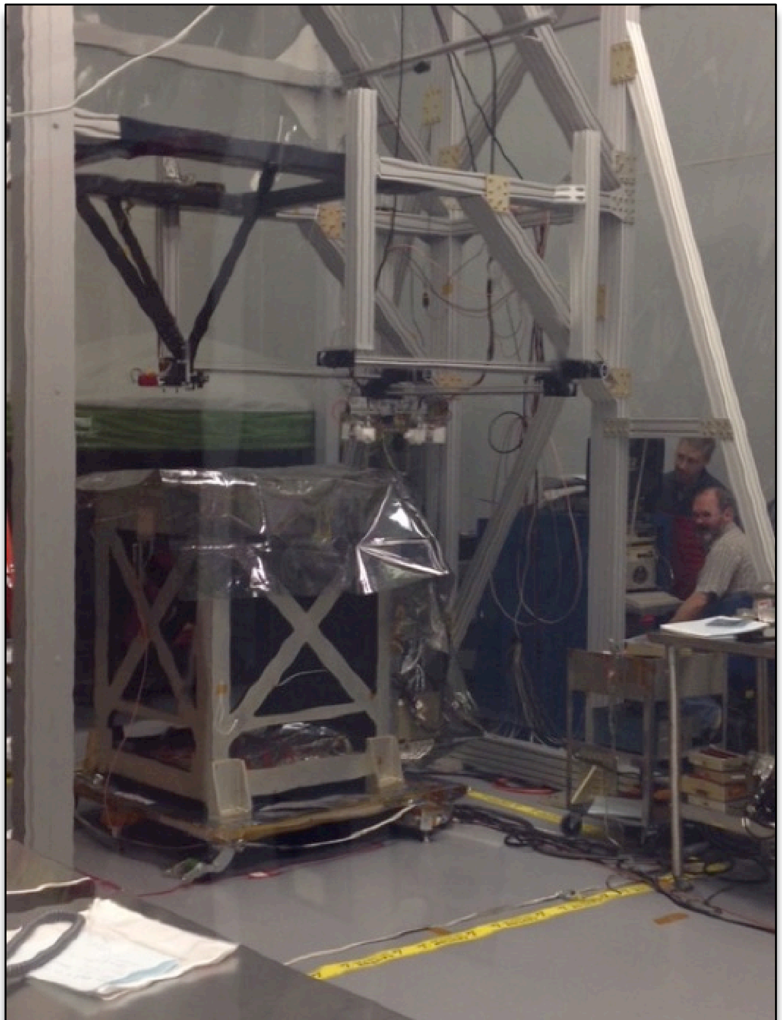


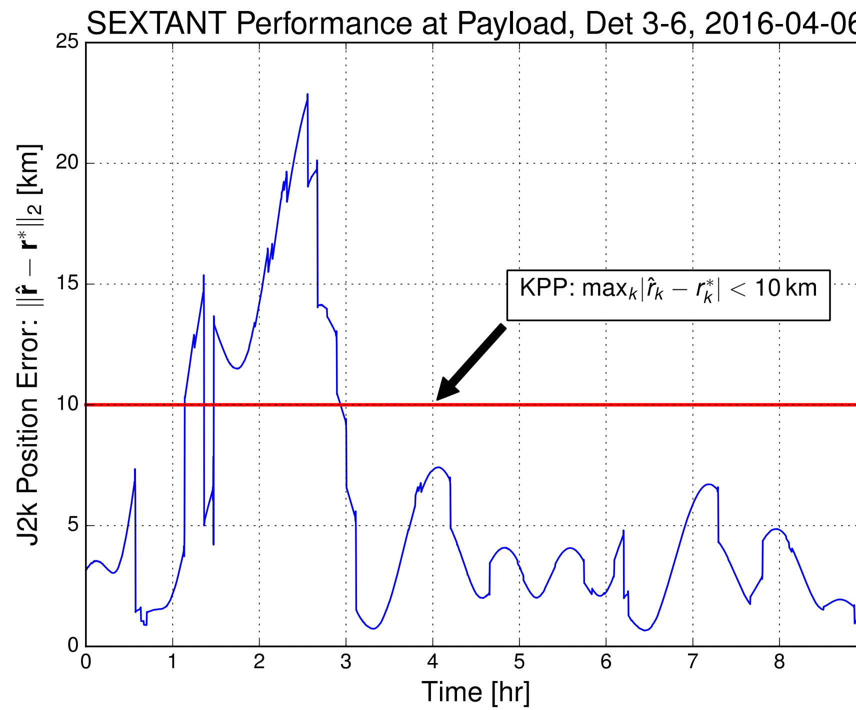
Payload XNAV Test Configuration (FY16)





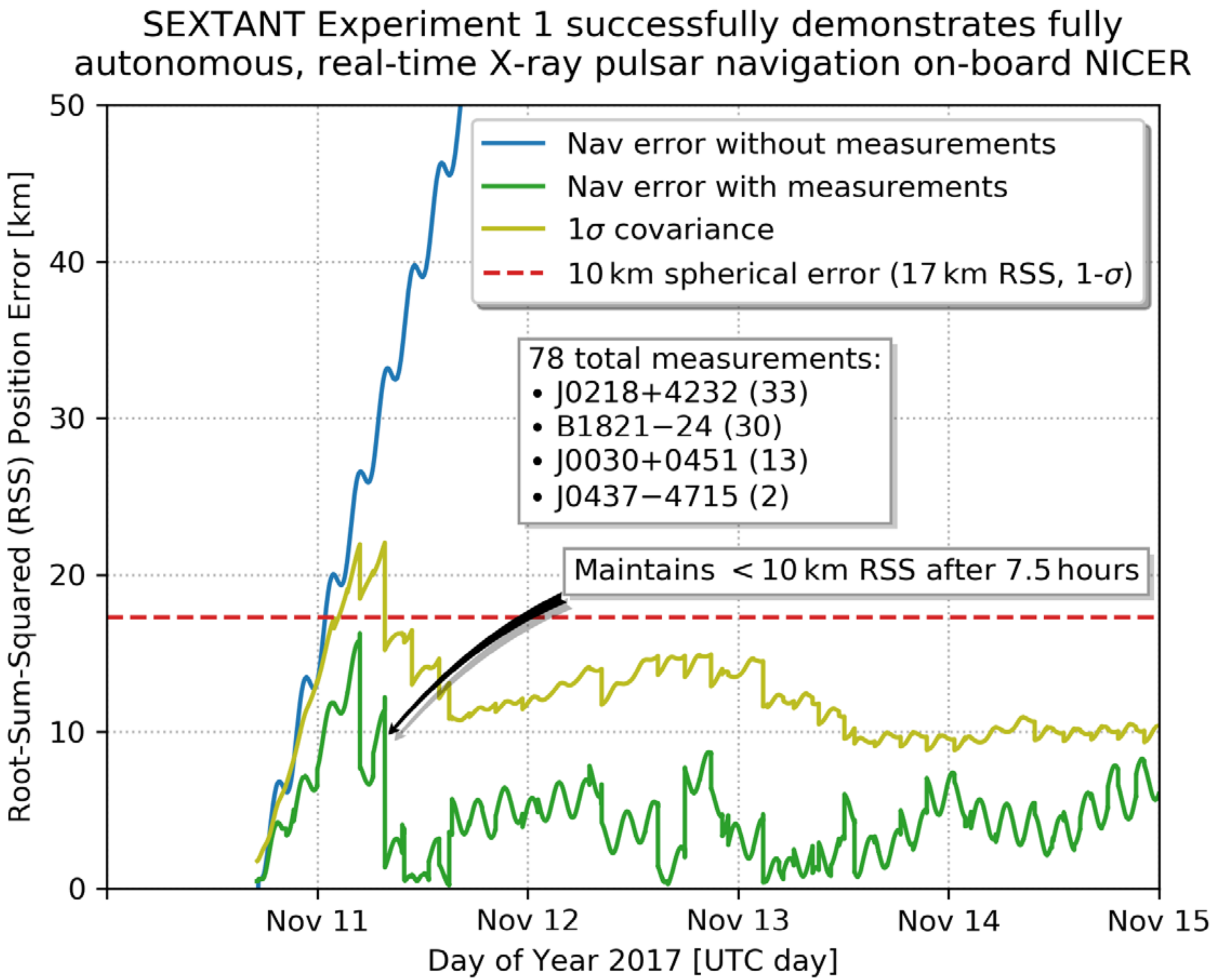
Post-Environmental CPT:
XTI Timing & XNAV Testing (FY16)





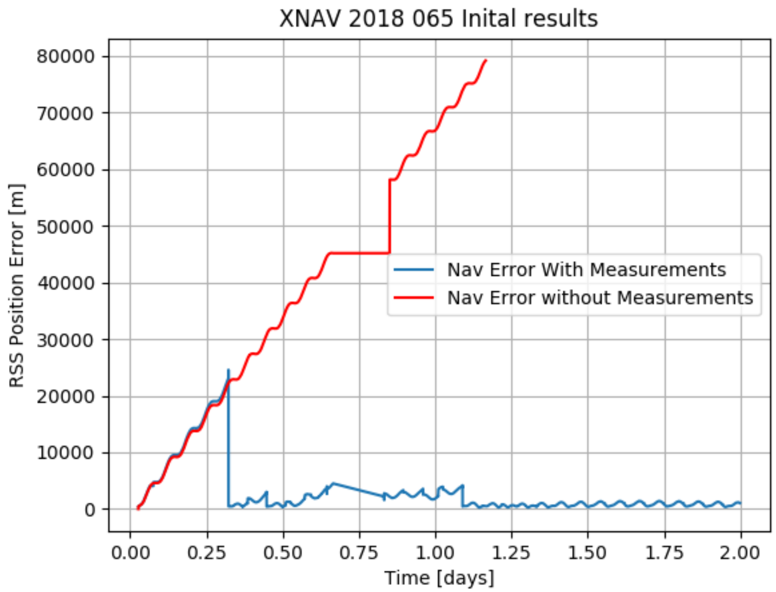
Dragon Separation

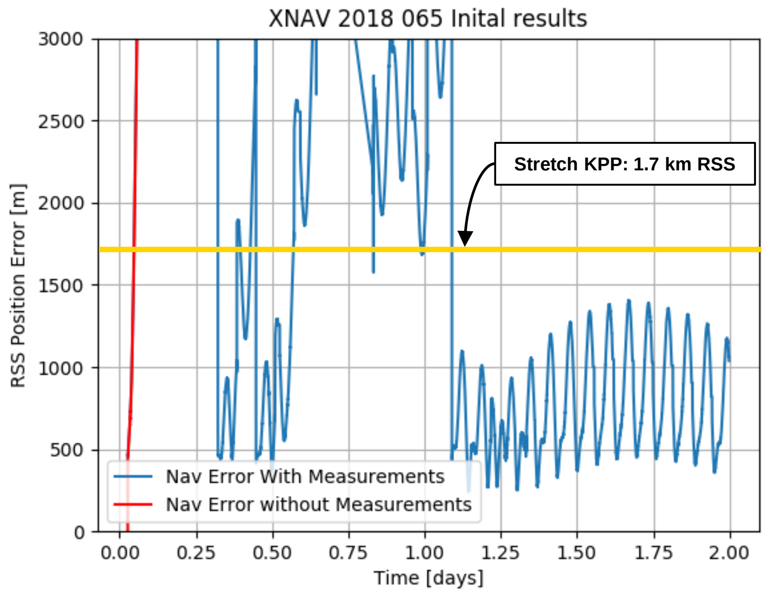
Successful Veteran's Day Weekend (2017) Experiment (NE1) Definitively Demonstrated Feasibility on-Orbit



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

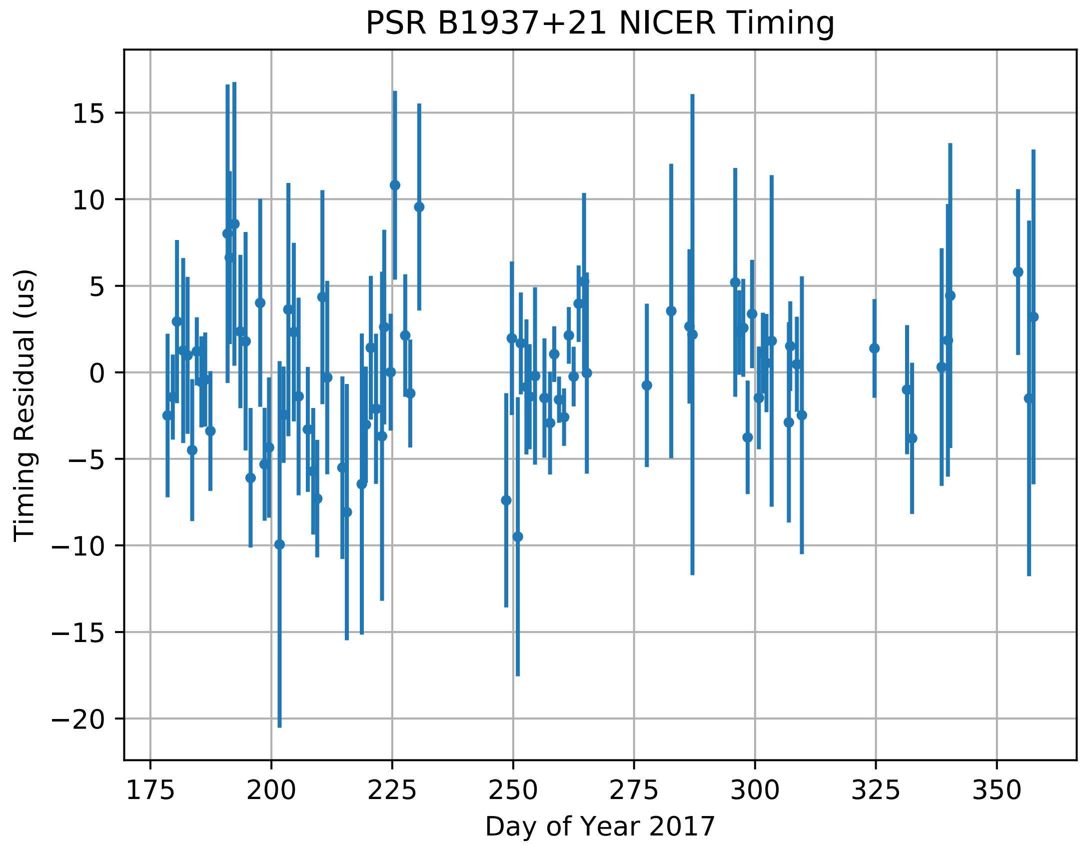
- **2018 DOY 65 (03/06) in *opportunistic mode* observing only B1937+21 for ~16.6 ksec, i.e., *not a nav schedule***
- **Obtained 19 measurements**
- **Mean error < 1 km during DOY 66 (03/07)**
- **RSS error < 1.7 km RSS (stretch KPP) for nearly 1 day**



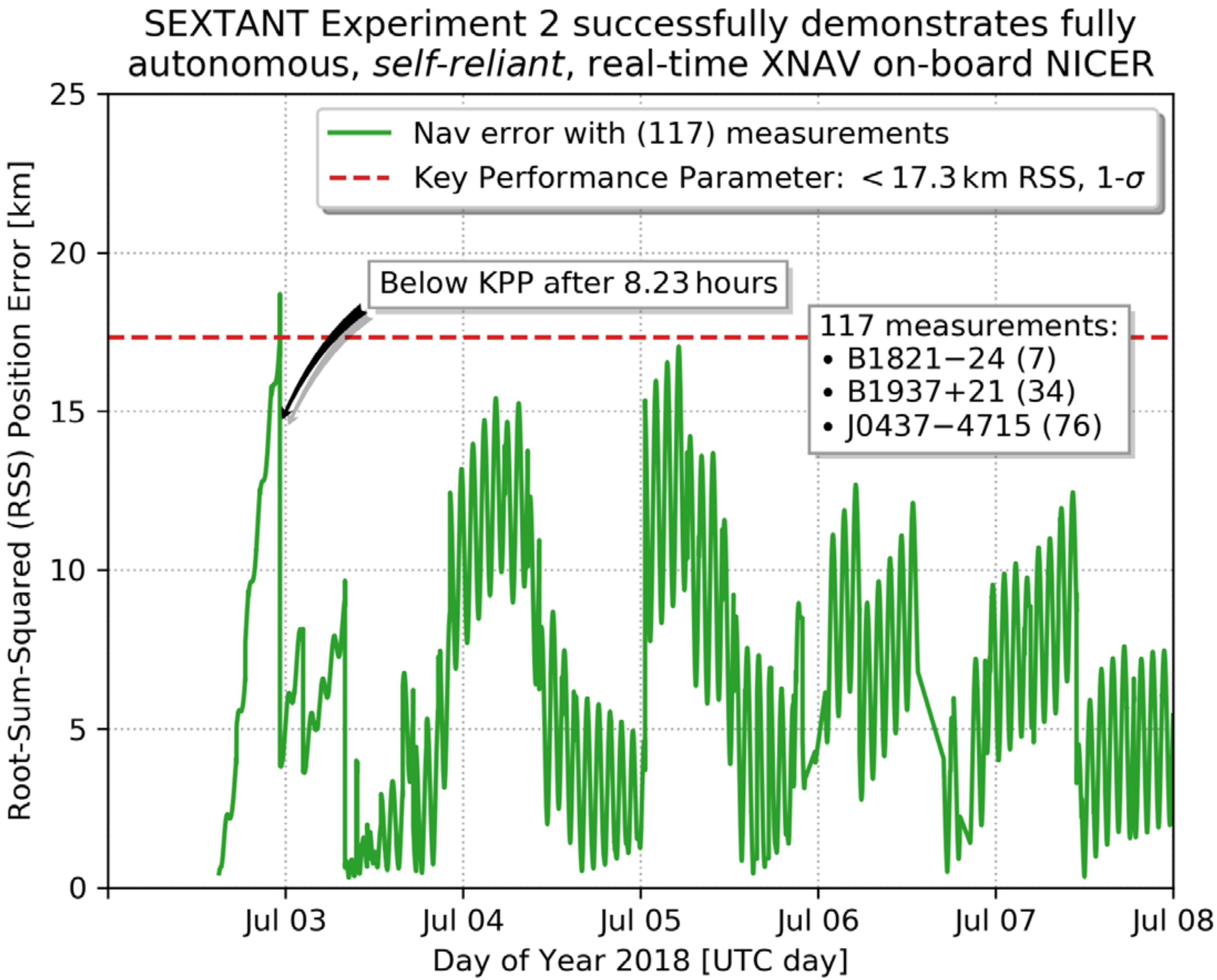


NE2: Example NICER Timing Residuals for B1937+21

- Initial timing model constructed from terrestrial radio data through 2017 DOY 48
- Residuals are difference of measured time-of-arrivals to model
- *<11 μs 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



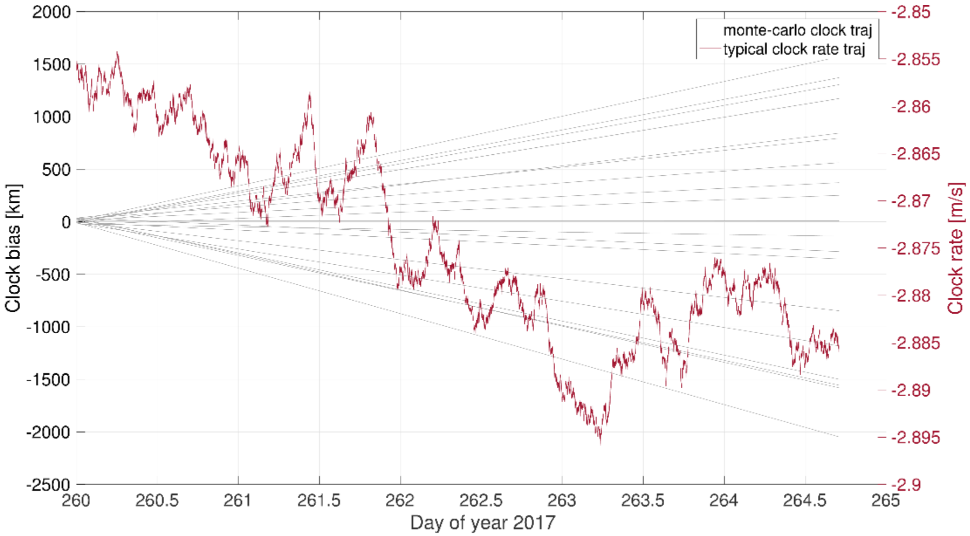
Successful Independence Day Week (2018) Experiment (NE2) Demonstrated Self-Reliance



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**

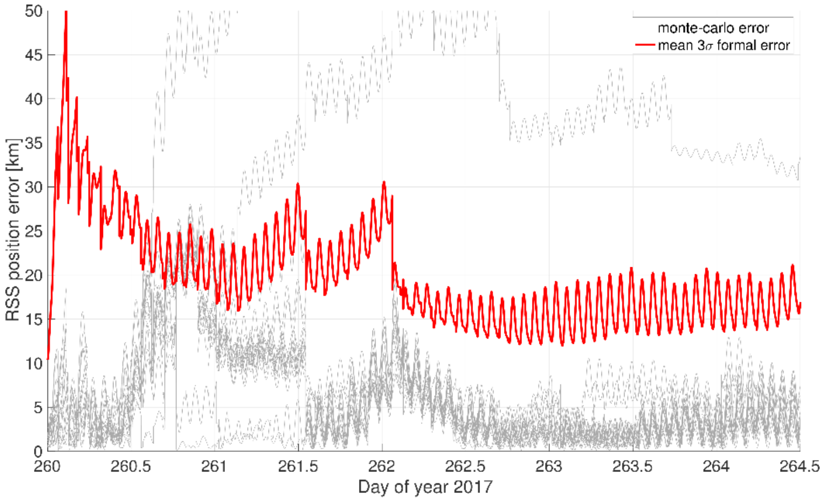
FEI USOs used on MMS

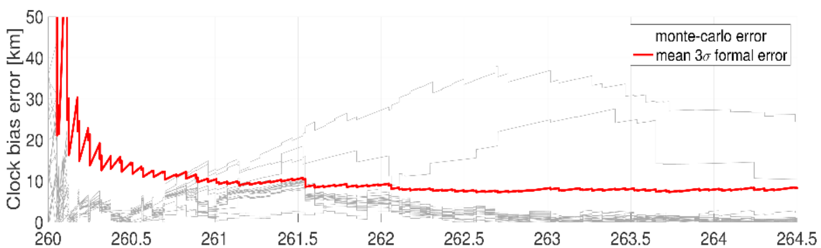


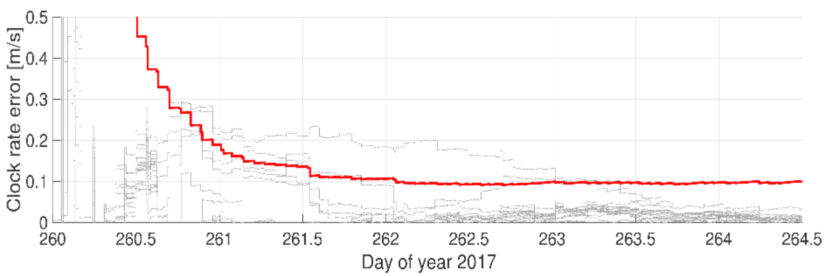
Simulated ultra-stable crystal oscillator clock error trajectories

Extending Capability: Time Estimation Ground Performance

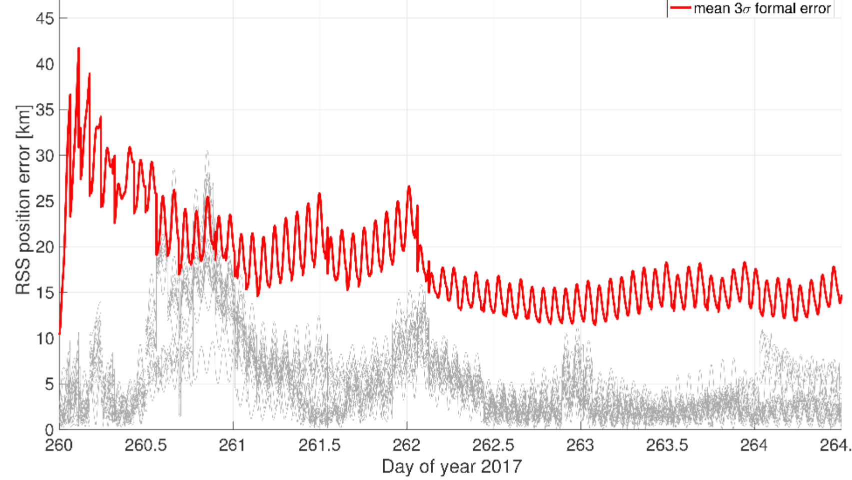
With clock errors







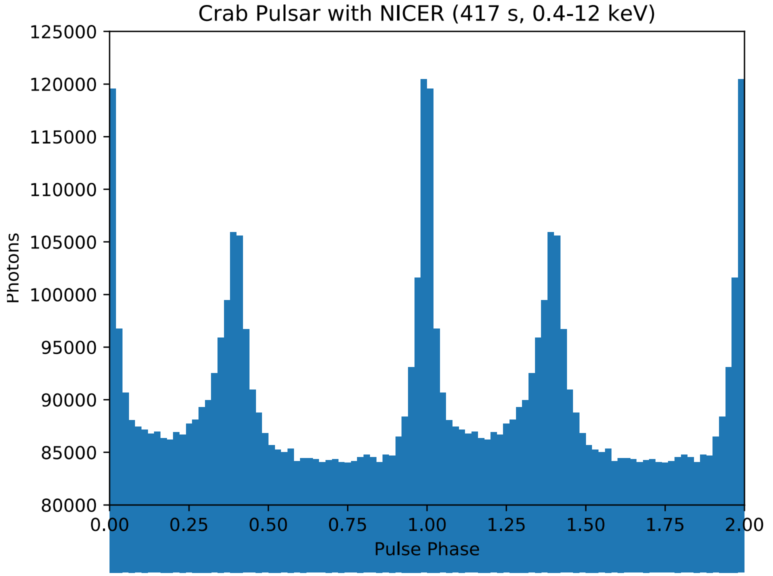
Without clock errors



- **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

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**



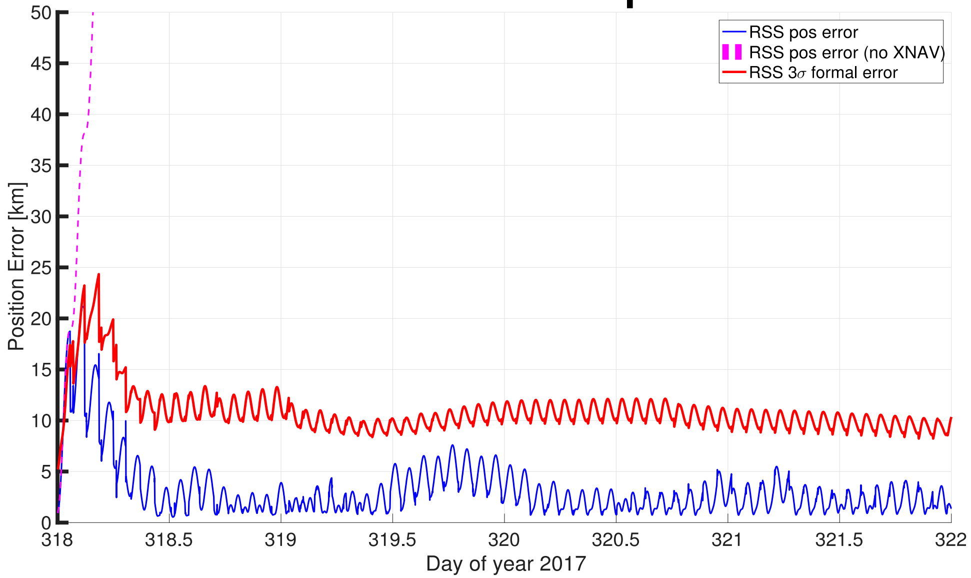
Crab light curve obtained with 417 s NICER observation

Navigating with Crab Pulsar

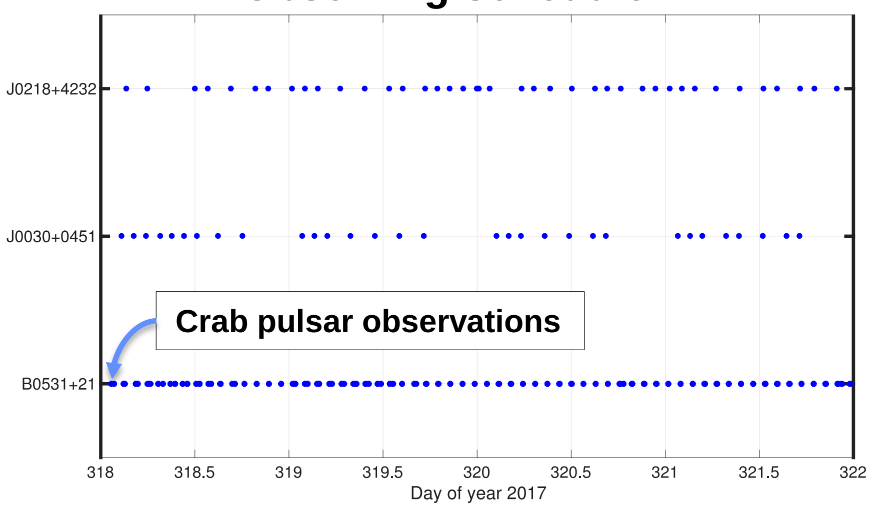
- **2017 days-of-year 318–322 SEXTANT conducted 1st ground experiment using pulsar B0531+21 (Crab)**
  - Initialized with degraded GPS state that propagates to >100 km RSS error in few hours
  - Recorded data replayed through ground version of flight software, no clock bias/rate estimation
  - Measurement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

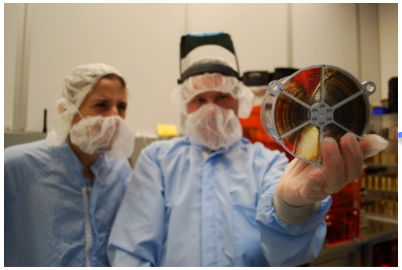
- **X-ray Pulsar Navigation (XNAV) works!**
  - Hardware design is scalable
  - Flight software is cFS-based (core Flight Software)
    - Leverages heritage GEONS navigation filter (also cFS app)
  - Timing implications beyond navigation
  - Instrument is also X-ray astrophysics instrument
- **Performance can be quite good!**
  - Trade between (effective) collecting area and observation time
  - Tune for desired goal
- **Continuing current infusion activities**
  - Focused primarily on JSC iPAS facility and Gateway demo
- **STMD/SMD coordination was high impact!**
- **NICER Principal Investigator (PI): Keith Gendreau, PhD**
  - keith.c.gendreau@nasa.gov

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

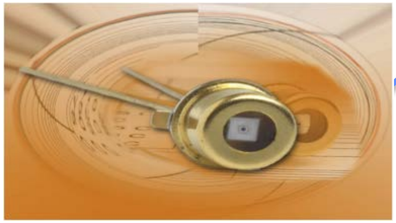
Diffraction Limited Soft X-ray Optics

Modulated X-ray Source (MXS)

Low Cost Optics



Silicon Detectors

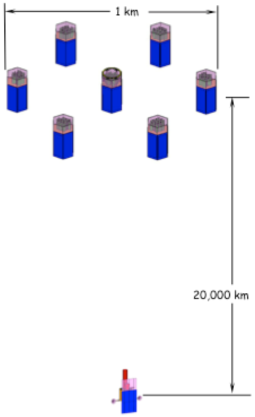


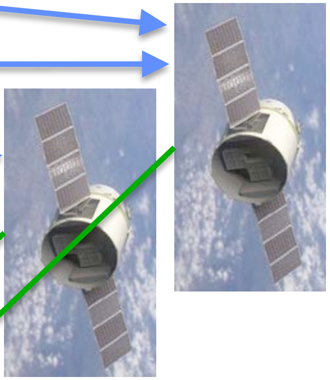
Calibration

X-ray Beacons for Relative Navigation

10 μas X-ray Star Tracker

Black Hole Imager





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

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

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

Establish Pulsar Based Universal Time Reference

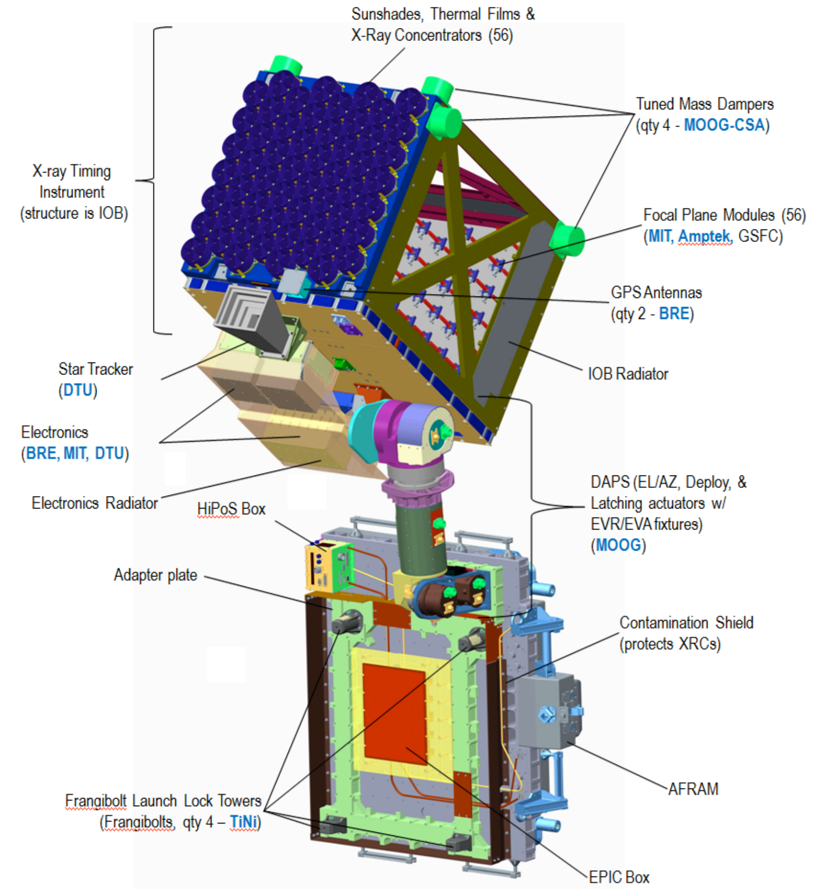
BACKUP

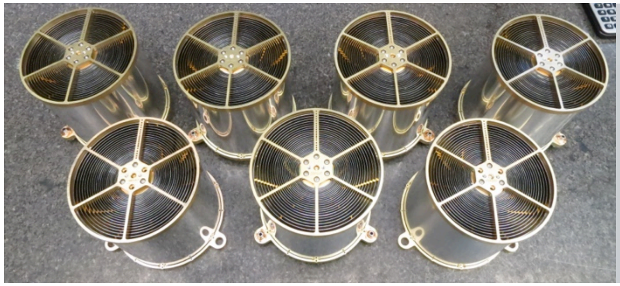
Strong Gravity and Light Curves

Figure credit: Sharon Morsink

NICER Instrument Overview

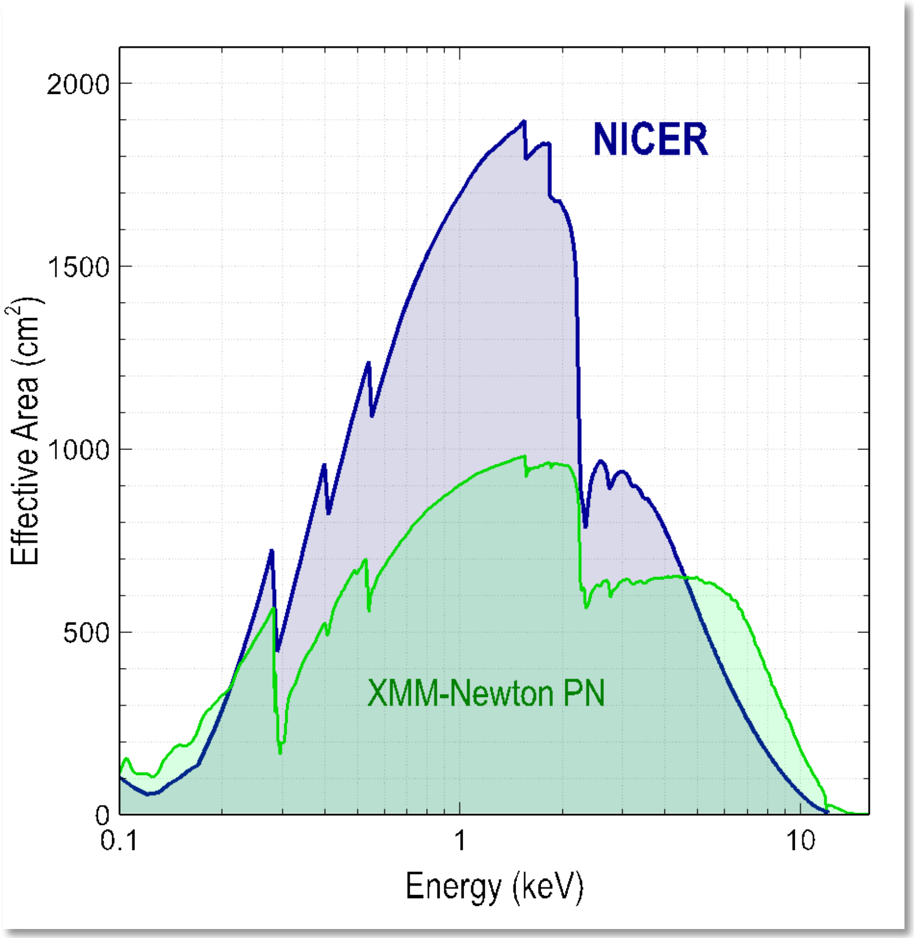
- **X-ray Timing Instrument (XTI)**
  - Assembly of 56 X-ray concentrators and detectors, *52 working on-orbit*
  - Detects individual X-ray photons, returns energy and time of arrival
  - Held together in the Instrument Optical Bench
- **Thermal system**
  - Maintains thermal-mechanical alignment
- **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





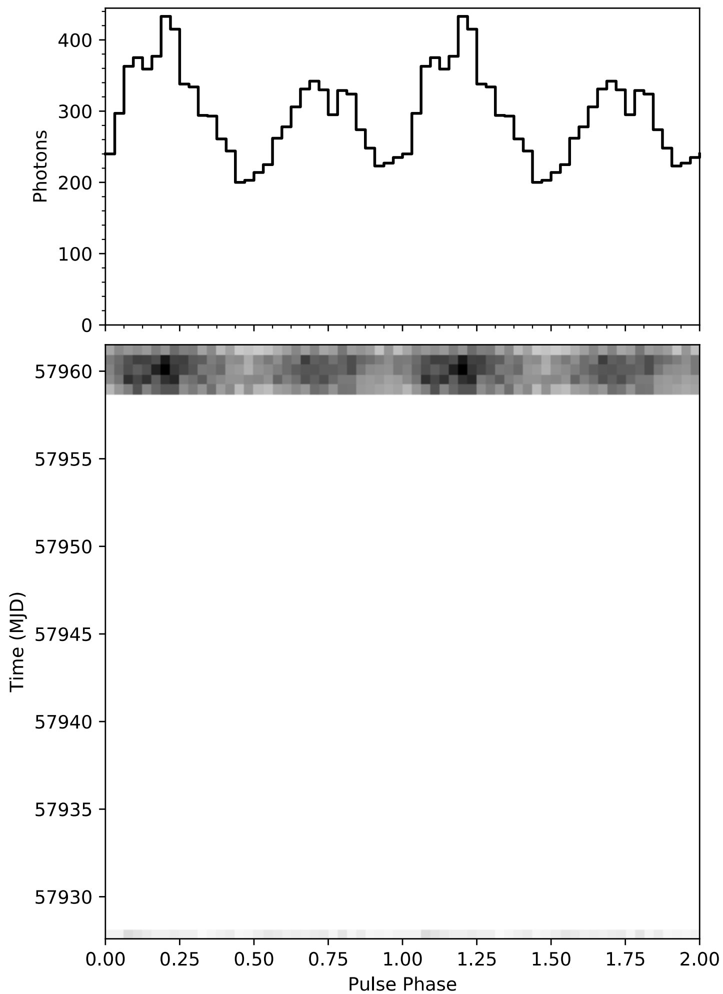
NICER Instrument Capabilities

- **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 x 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

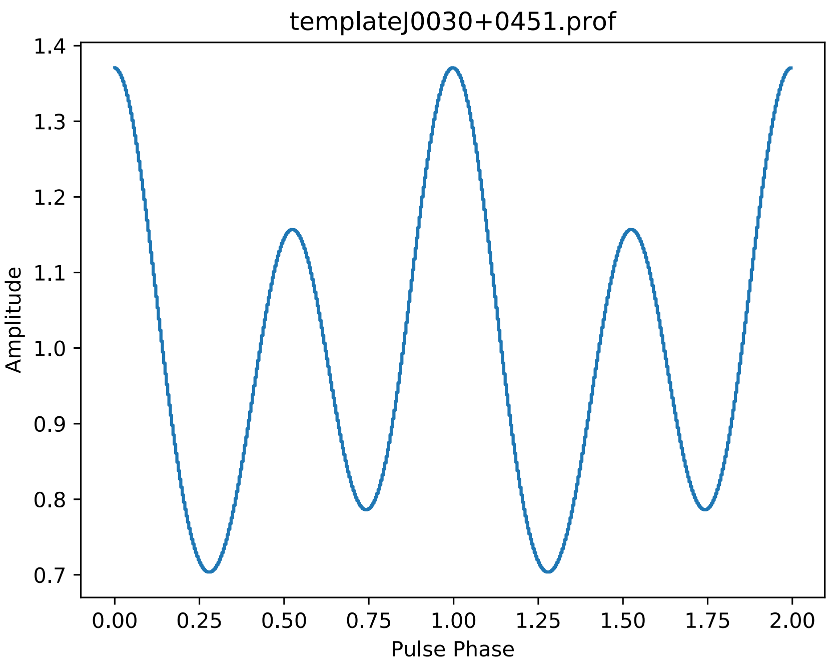


Pulsar Timing Models: Pulse Profile Template, J0030+0451

Phaseogram 0.4 to 2.1 keV

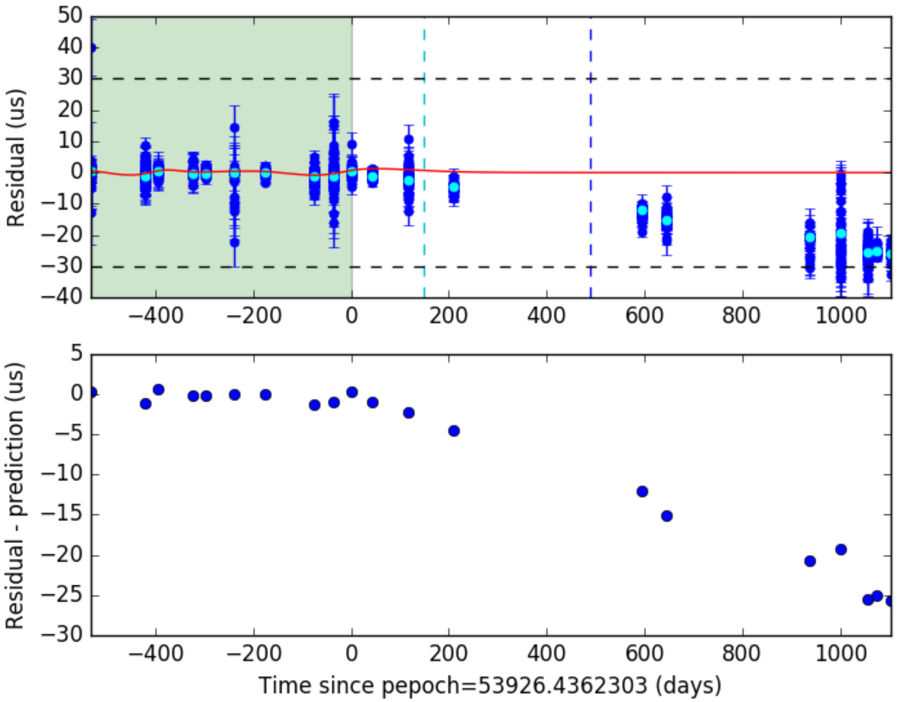


Constructed Analytical Template (2 cycles)

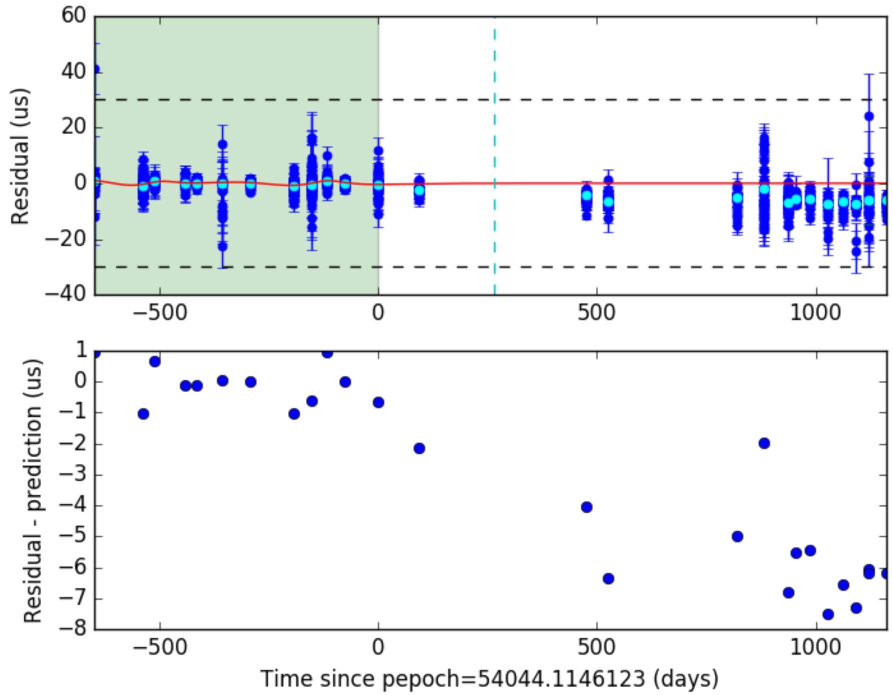


Pulsar Timing Models: Extrapolation Model, J0030+0451

- 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 μs (cyan), 10 μs (blue)



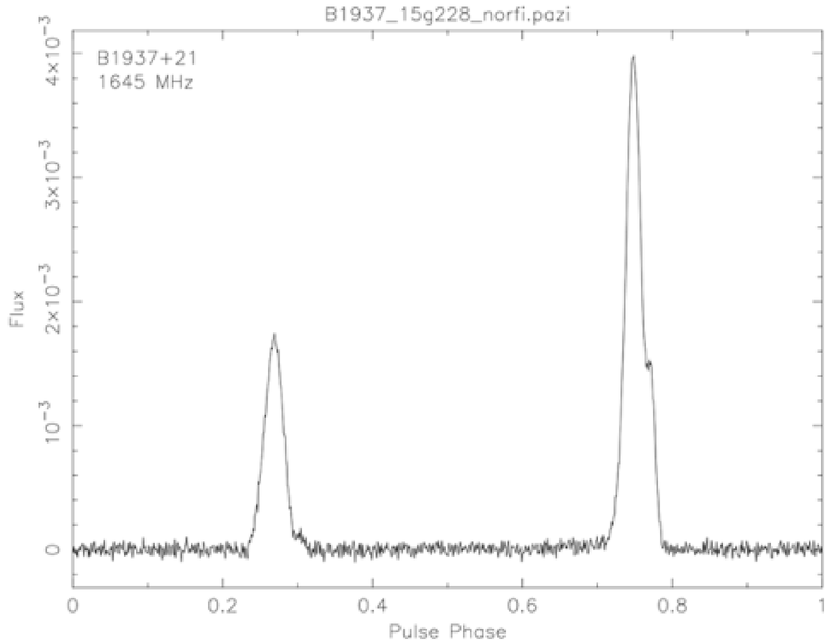
~30 μs (9 km) error @ ~3 yrs



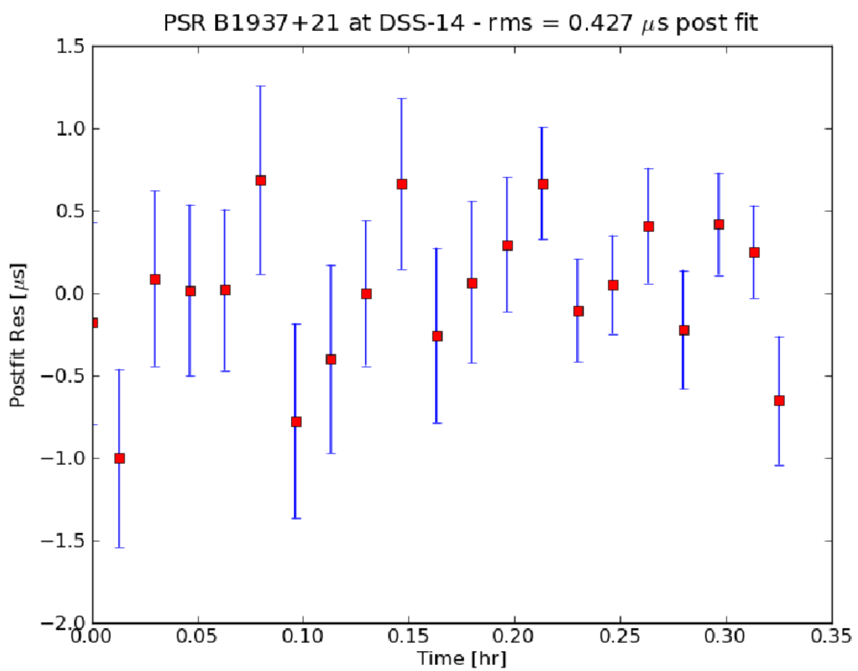
~8 μs (2.5 km) error @ ~3 yrs

NASA Pulsar Timing via DSN

- **PSR B1937+21**
  - Courtesy of Dr. Walid Majid/JPL
  - Sufficient for navigating to ~300 m over short time spans
  - Theoretical lower limit, presumes clock with same or better performance
  - Improved accuracy may be possible
- **All NASA capability**
  - National asset



L-band measurement at Goldstone DSS-14



Timing residuals from model