NICER

Neutron star Interior Composition ExploreR

SEXTANT - Station Explorer for X-ray Timing & Navigation Technology

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Outline

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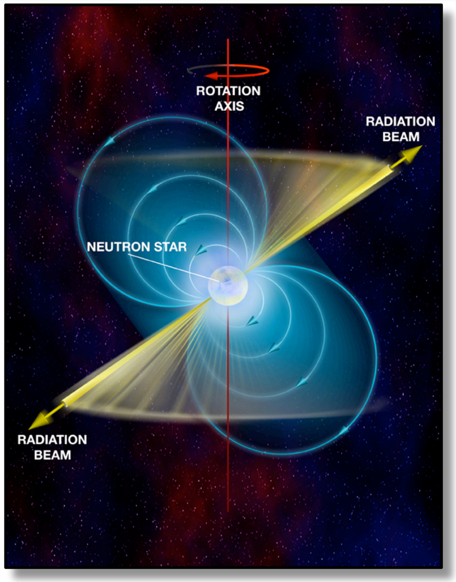
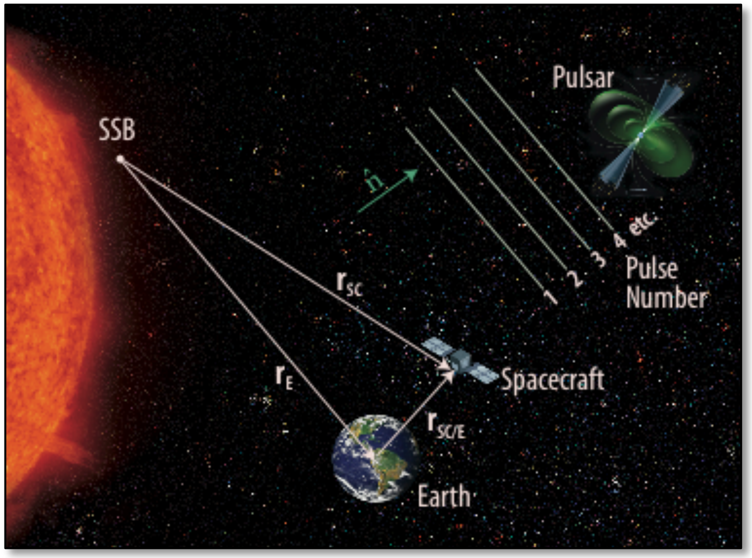
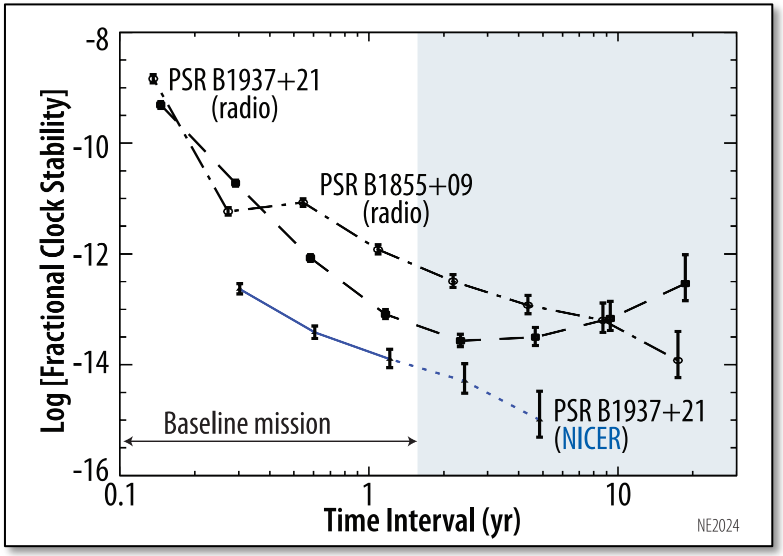
X-ray Navigation – XNAV

- Millisecond Pulsar X-ray Navigation
  - Pulsars are neutron stars that appear to pulsate across the electromagnetic spectrum, but are bright enough in X-rays to enable XNAV instrumentation & solutions
  - Some millisecond pulsars (MSPs) rival atomic clocks in long-term timing stability
  - Pulse phase or time of arrival deviations can update spacecraft dynamics model along line of sight
  - Observing multiple MSPs can yield 3D orbit data
  - GPS-like positioning & timing throughout solar system & beyond





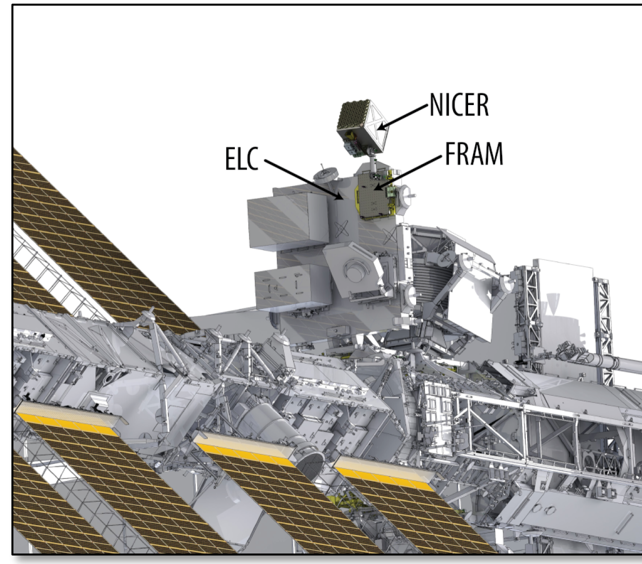


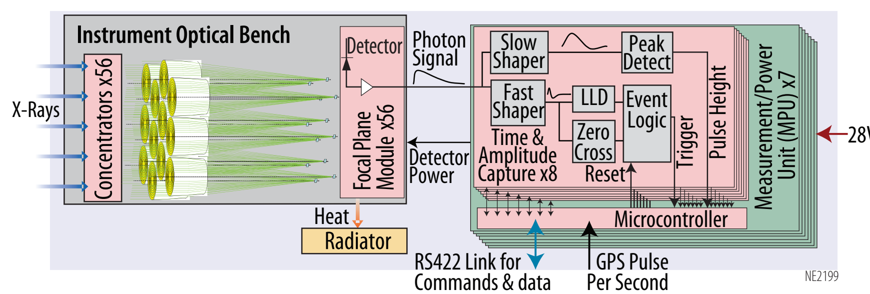
XNAV Development History

- XNAV has rich history beginning with discovery of first radio pulsar
  - Significant body of published research
- Naval Research Laboratory (NRL) (1999-2000)
  - Unconventional Stellar Aspect (USA) Experiment
- DARPA XNAV Project (2005-2006)
  - Ball Aerospace collaborated with Microcosm Inc.
  - Algorithms, Infrastructure
  - Detector and Pulsar modeling studies (NRL)
  - Modulated X-ray Source (MXS) developed, Gendreau
- DARPA XTIM (2009-2012) continuation DARPA XNAV, led by Lockheed with Ball Aerospace
  - Used Large Area Collimated Detector
- NASA SBIRs with Microcosm
- NICER / SEXTANT selection 04/2013
  - SEXTANT team deeply involved in prior programs
  - Evolution of XNAV detector ideas shows NICER XTI (concentrating optics/ silicon det) to be practically ideal
- ***Prior work has set the stage for SEXTANT to perform the full onboard XNAV OD***

NICER/SEXTANT Companion Mission

- NICER – Neutron Star Interior Composition ExploreR
  - Fundamental investigation of *ultra-dense* matter: structure, dynamics, & energetics
  - Launch in Oct 2016 on Space-X Dragon
  - 18 Month mission on Express Logistics Carrier (ELC)
  - X-ray Timing Instrument (XTI)
    - X-ray (0.2–12 keV) concentrator (single-bounce) optics and silicon-drift detectors
    - High precision time tagging (300 ns absolute)
    - Large effective area (>1800 cm^2)
    - X-ray detectors with high quantum efficiency and spectral resolution
- SEXTANT – XNAV Flight Demo
  - STMD/GCDP funded technology enhancement
  - 1st demo of real-time, on-board pulsar XNAV
  - Leverage NICER Hardware with enhanced flight XNAV software

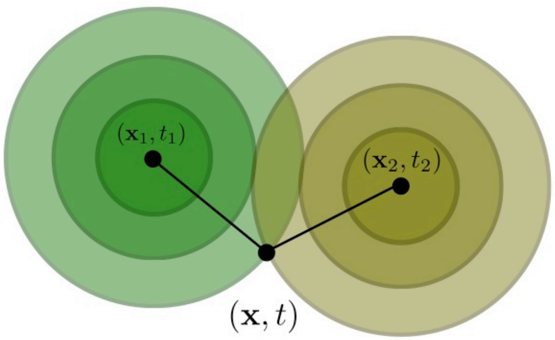




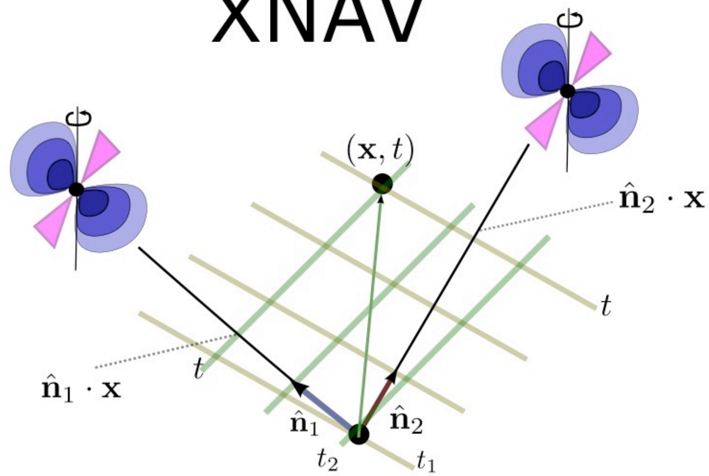
Block diagram of NICER XTI

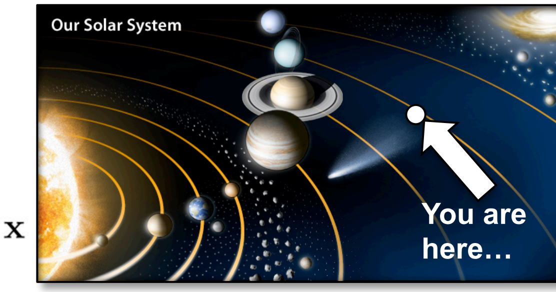
XNAV Demonstration Concept

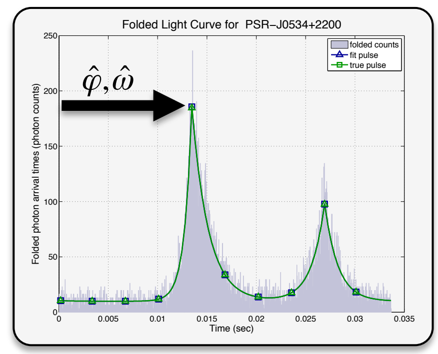
GPS

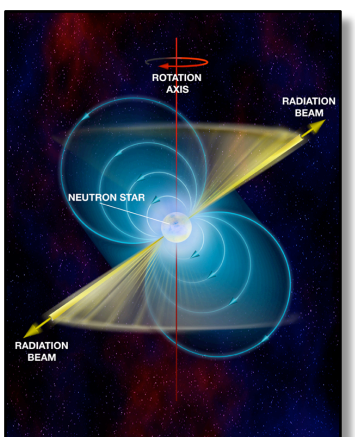


XNAV

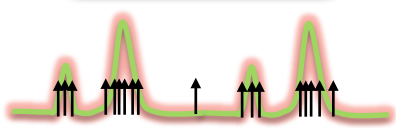




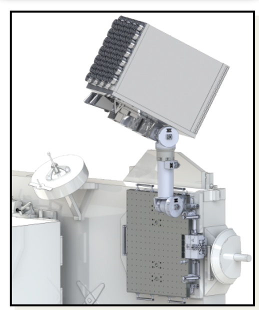




X-ray photons



NICER Instrument

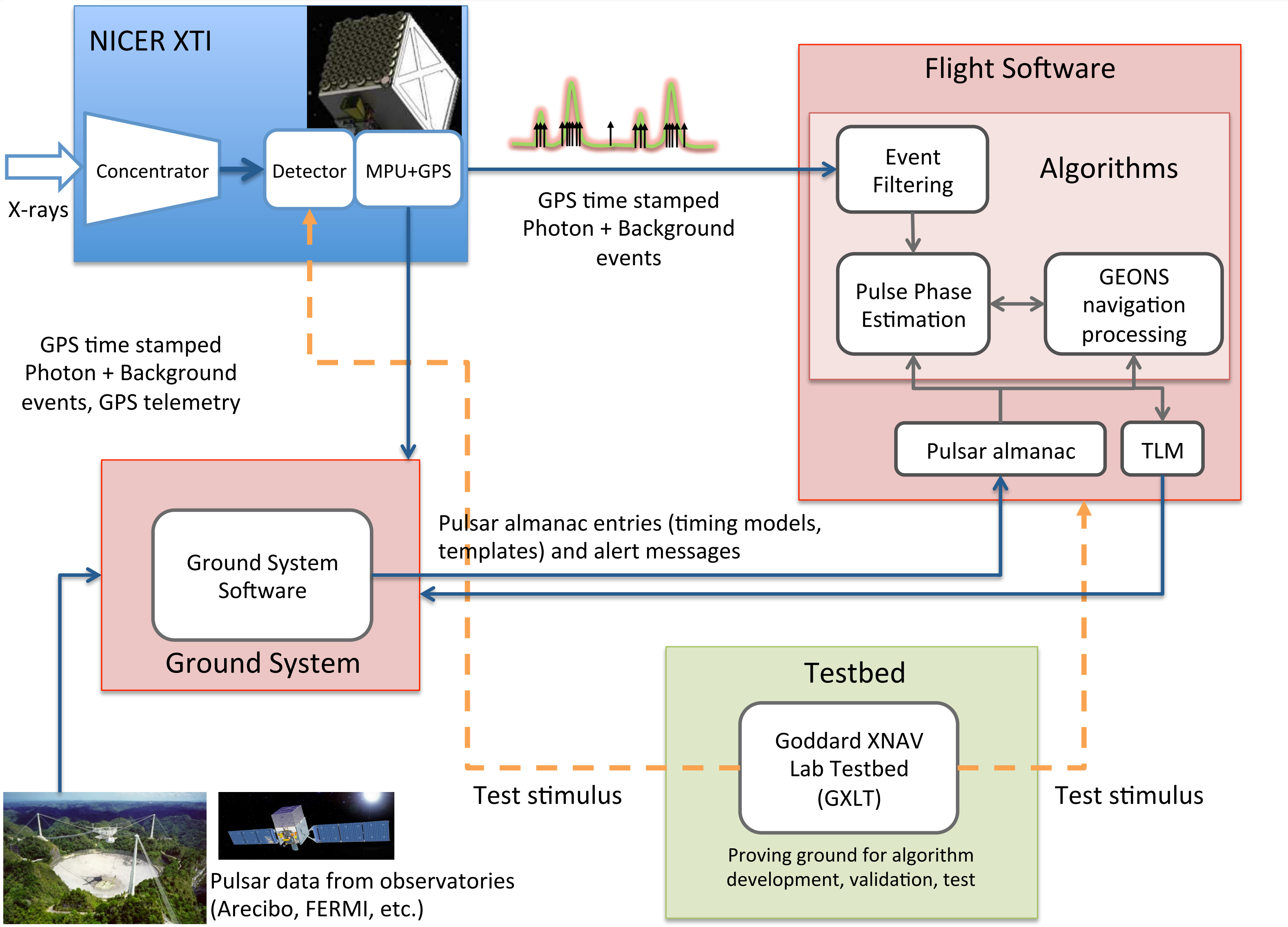


SEXTANT algorithms

SEXTANT Demonstration Objective

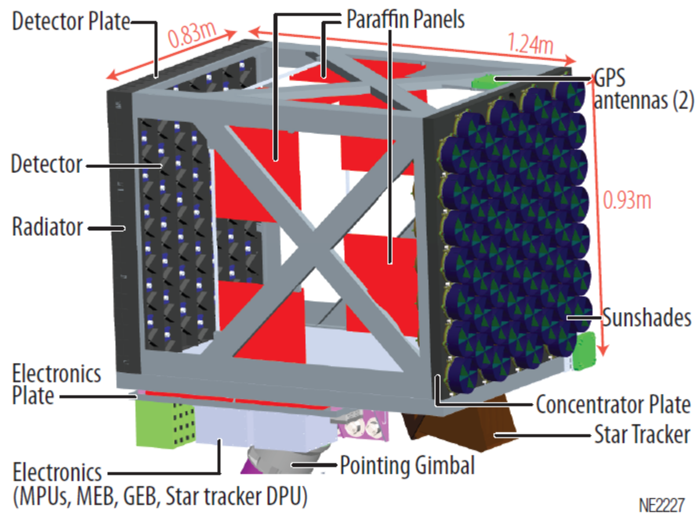
- **SEXTANT Primary Objective**
  Provide first demonstration of real-time, on-board X-ray Pulsar Navigation
  - *Primary Objective: 10 km orbit determination accuracy, worst direction, 2 weeks*
  - Implement a fully functional XNAV system in a challenging ISS/LEO orbit; NICER compatible
  - Advance XNAV technologies
- **Secondary Objectives**
  - Repeat XNAV demo with new NICER data & new MSP discoveries
  - Validate & enhance the unique Goddard XNAV Lab Testbed (GXLT)
  - Use SEXTANT data & GXLT to study real-world XNAV scenarios
  - Evaluate candidate photon processing & navigation algorithms & develop new techniques
  - Study utility of pulsars for time keeping & clock synchronization
- **Planned Experiments**
  - 2-week period observing 3 – 5 pulsars early in the mission (primary)
  - Opportunistic experiments
  - Ground experiments using collected photon data
- **Stretch Objective**
  - *1 km orbit determination accuracy, worst direction, using up to 4 weeks of observations.*

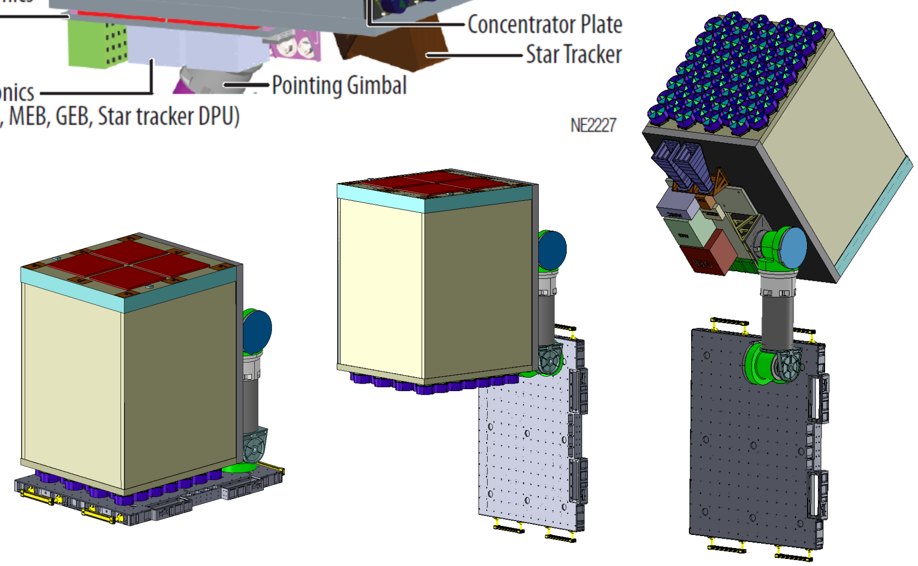
SEXTANT System Architecture



NICER X-ray Timing Instrument (XTI)

- 56 co-aligned X-ray concentrator optics and associated Silicon Drift Detectors (SDDs) in Focal Plane Modules (FPMs)
- 7 Measurement/Power Units (MPUs)
- The FPMs detect X-rays arriving from the concentrators
- MPUs time-tag and packetize photon events
- < 300 nsec absolute time resolution
- > 1800cm^2 effective area
- Moderate (CCD-like) energy resolution

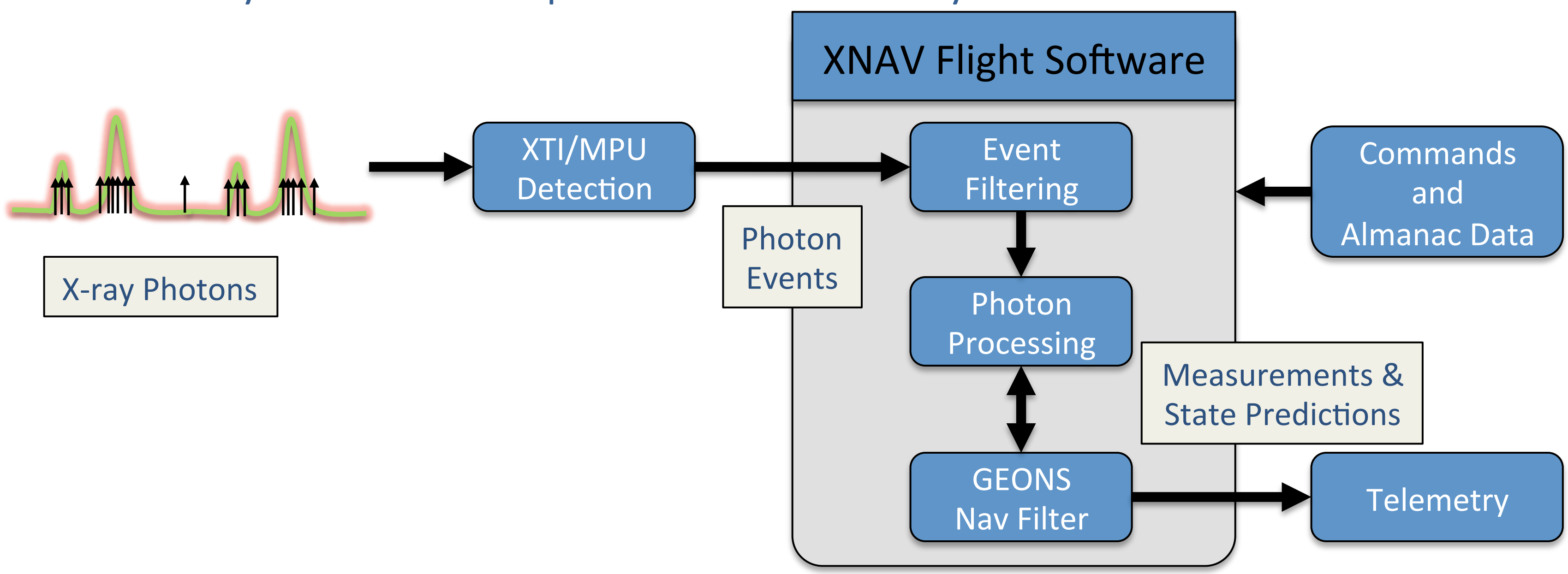




Stowed, deploying, and observing at ELC mounted location on ISS

SEXTANT Flight Software App

- XNAV Flight Software (XFSW) Sequence Flow:
  - XTI detects events from sequential pulsar observations, output via MPU
  - Pre-process filtering of photon events and buffer collection to obtain statistically sufficient observations of a single pulsar
  - Batch process events to extract single measurement of phase, Doppler, count rates
  - Navigation algorithm (GEONS EKF) blends models of S/C dynamics with phase & frequency measurements to update spacecraft state estimate
- Ground system maintains pulsar almanac used by XFSW



Photon Event Arrival Model

- The arrival times of X-ray photons at the detector are modeled as a non-homogeneous Poisson process (NHPP) with quasi-periodic rate function:

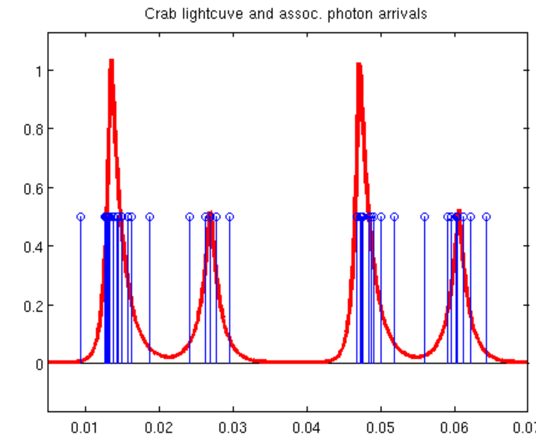
$$\bar{\lambda}(t) = \lambda(\phi(t)) = \beta + \alpha h(\phi(t))$$

  - *h* is the known pulsar *lightcurve*
  - periodic in [0,1) integrating to 1 with minimum value 0
  - *b* is total background rate
  - *a* is the mean signal rate

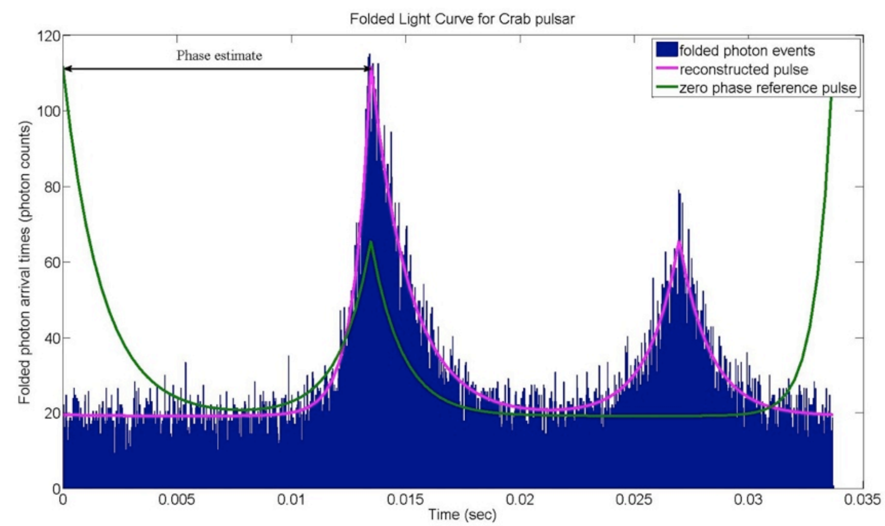
The probability of *k* events arriving in the interval (t_a, t_b) is given by

$$P(k;(t_a,t_b)) = \frac{e^{-(\bar{\Lambda}(t_b)-\bar{\Lambda}(t_a))}(\bar{\Lambda}(t_b)-\bar{\Lambda}(t_a))^k}{k!}$$

$$\bar{\Lambda}(t) = \int_0^t \bar{\lambda}(s)ds$$



Arrival times follow a NHPP



Lightcurve recovery by "pulse folding"

Pulse Phase Arrival Model

- The phase model at the detector is

$$\phi(t) = \phi_0(t - \tau(t))$$

  - ϕ_0 is the phase evolution at a reference observatory (RefObs)
  - provided by the standard pulsar timing software TEMPO2 (see Hobbs et. al., Edwards et. al.)
    - Extremely high fidelity models
    - Provides convenient piecewise polynomial approximations to the full timing model ϕ_0
  - ***τ(t)*** the prop time of the pulse wavefront moving from the detector to the RefObs at speed *c*
    - If the RefObs is *close* to the detector (Geocenter) $\tau(t) = \frac{\vec{x}(t) \cdot \vec{n}}{c}$

    where $\vec{x}(t)$ is the detector coordinates in a frame centered at the RefObs and $\vec{n}$ is the direction to the given pulsar
  - If the RefObs is not so close to the detector (e.g., SSB), parallax and Solar Shapiro delay terms are needed as well
  - SEXTANT's algorithms are based on a Geocentric RefObs but can support SSB RefObs

For a Geocenter RefObs:

$$\begin{aligned}
\phi(t) &= \phi_0\left(t - \frac{\vec{x}(t)\cdot\vec{n}}{c}\right) \\
&= \phi_0\left(t - \frac{\tilde{\vec{x}}(t)\cdot\vec{n}}{c} + \frac{\delta\vec{x}(t)\cdot\vec{n}}{c}\right) \quad (\tilde{\vec{x}}(t) \text{ from filter}) \\
&\simeq \phi_0\left(t - \frac{\tilde{\vec{x}}(t)\cdot\vec{n}}{c}\right) + \dot{\phi}_0\left(t - \frac{\tilde{\vec{x}}(t)\cdot\vec{n}}{c}\right)\frac{\delta\vec{x}(t)\cdot\vec{n}}{c}, \\
&=: \tilde{\phi}(t) + e(t)
\end{aligned}$$

where

$$\delta\vec{x}(t) = \tilde{\vec{x}}(t) - \vec{x}(t)$$

For SEXTANT, we assume

$$e(t) \simeq q + f(t - t_a)$$

(*q* and *f* are constants)

Alternate models are possible but this linear model works well in simulations (with short observation intervals)

ML Pulse Estimation

Pulse Phase Estimation Algorithm

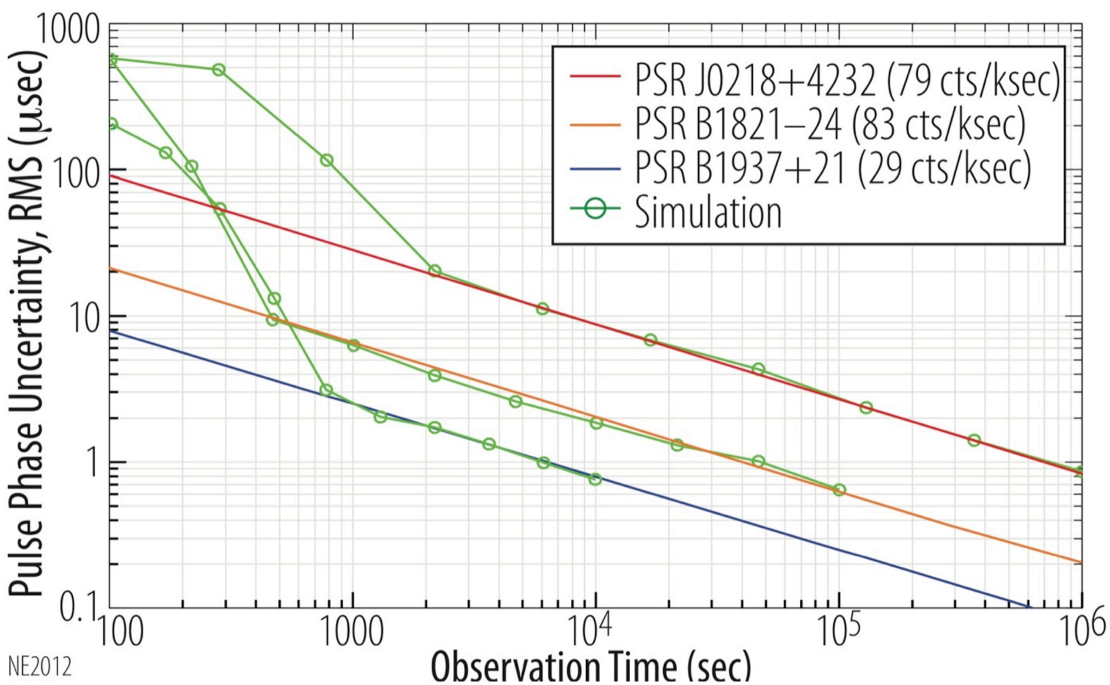
1. Observe arrival times $\{T_k\}_{k=1}^N$ during a fixed interval $[t_a, t_b]$.
2. Determine estimates $(\hat{q}, \hat{f})$ of the parameters (q, f) in the model $e(t) = q + f(t - t_a)$ by maximizing the log-likelihood function with $\{T_k\}_{k=1}^N$

$$L(\hat{\theta}) = \sum_{k=1}^{N} \log \lambda\Big(\tilde{\phi}(T_k) + q + f(T_k - t_a)\Big) - (\alpha + \beta)(t_b - t_a)$$

   with $\theta = (q, f, \alpha, \beta)$.
3. Form phase and frequency estimates $\hat{\phi}(t) = \tilde{\phi}(t) + \hat{q} + \hat{f}(t - t_a)$ and $\dot{\hat{\phi}}(t) = \dot{\tilde{\phi}}(t) + \hat{f}$, respectively.

Phase Estimate Accuracy

- The Cramér–Rao lower bound (CRLB) gives limit of achievable accuracy of any estimator with fully specified statistical model.
- We can compute CRLB for NHPP model assuming α, β known
  - For XNAV the CRLB is smallest for short period, for highly *peaked* pulsars with high SNR
- ML estimators asymptotically (many photons) achieve CRLB
- CRLB useful for
  - performance estimation
  - determining target observation times
- There are other error sources including those associated with model mismatch
  - best you can do with a statistical model



GEONS Navigation Filter

- Goddard Enhanced Onboard Navigation System (GEONS)
  - 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 (and will be used) on Terra, EO-1, GPM, MMS, NICER/SEXTANT
  - Licensed to Orbital, Ball, ITT, Moog/Broad Reach
- SEXTANT team added an XNAV measurement model to GEONS

$$\phi(t) = \phi_0 \left(t - \frac{\vec{x}(t) \cdot \vec{n}}{c} \right) + \nu(t), \quad \text{where } \nu \text{ is noise}$$

connects pulse phase observable with spacecraft state

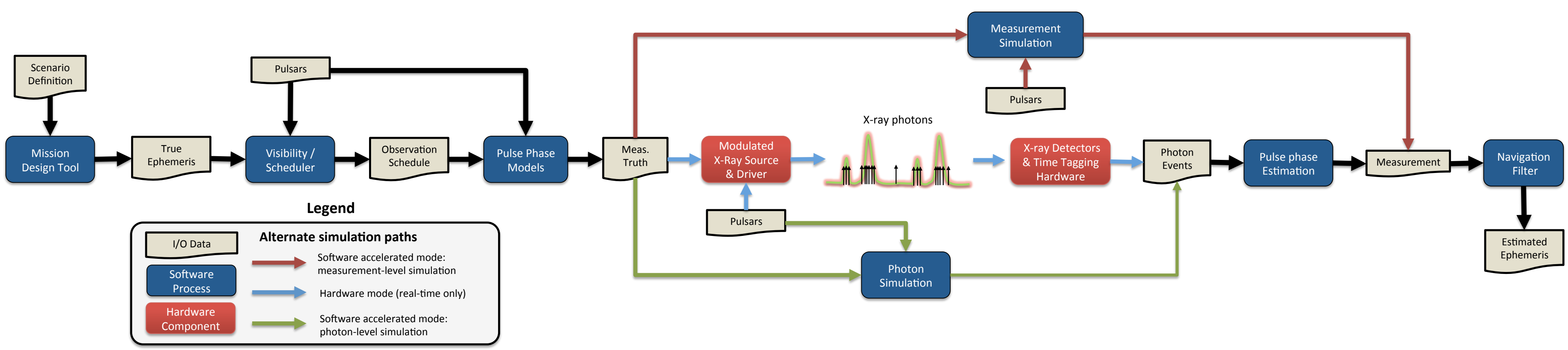
- Differentiate to get a frequency measurement equation

SEXTANT Ground Testbed

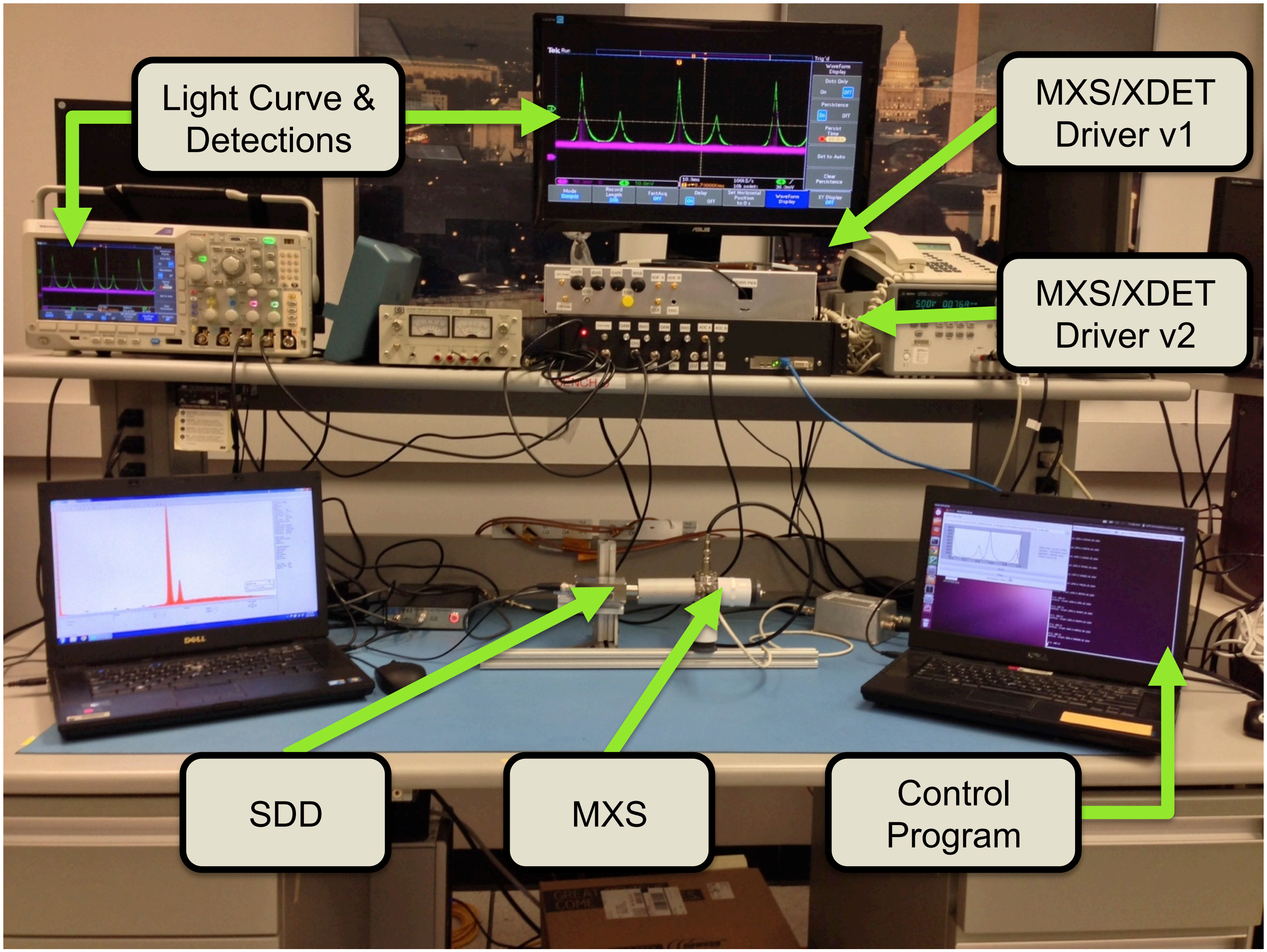
Level 0 simulation
- Software only XNAV measurement simulation
- Useful for long term studies (deep space trajectories, etc)

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
- *Test-as-you-fly*
- Use the Modulated X-ray source (MXS) to generate the photon events
- X-ray detector & electronics time-tag the photon events
- Useful for testing flight hardware

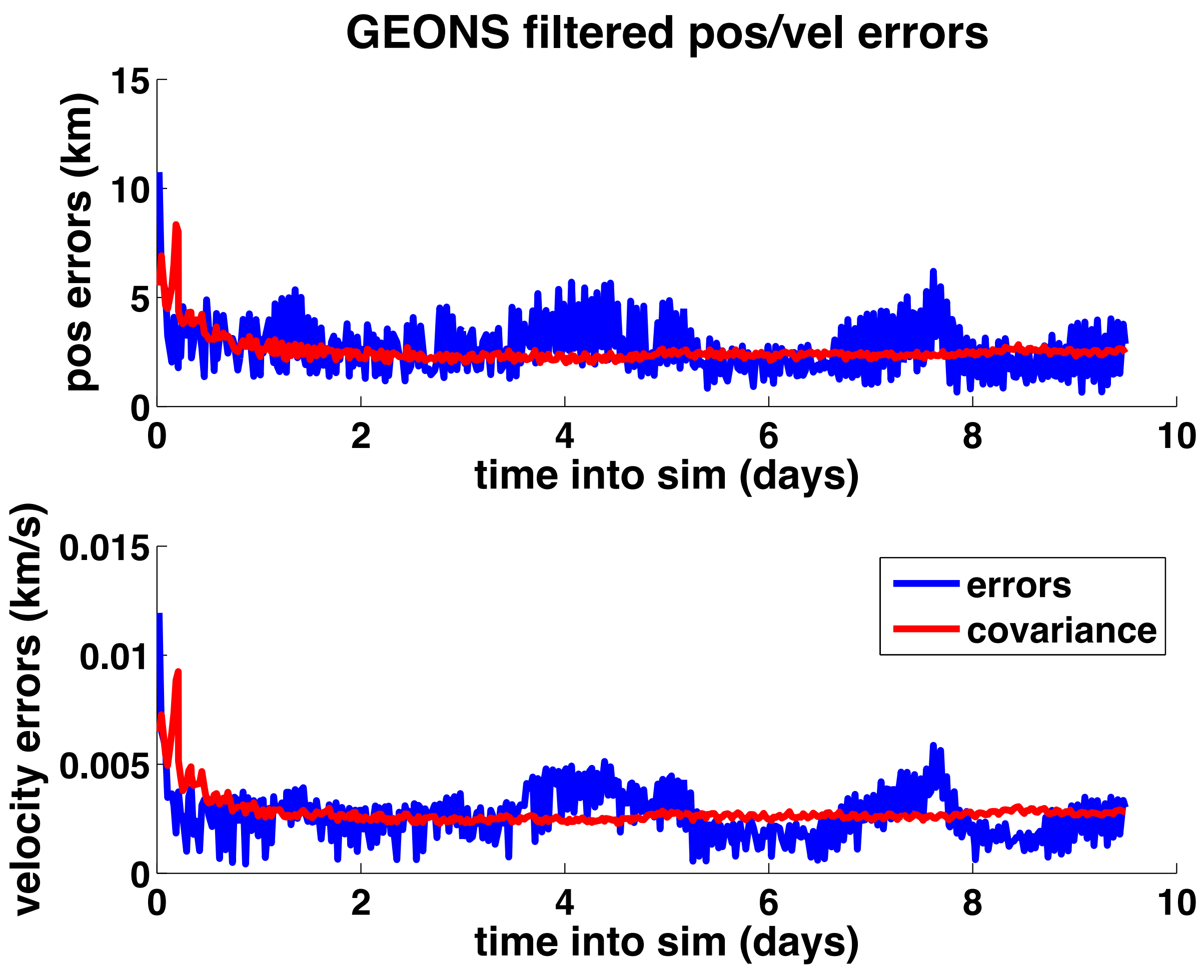


GXLT - Goddard X-ray Laboratory Testbed



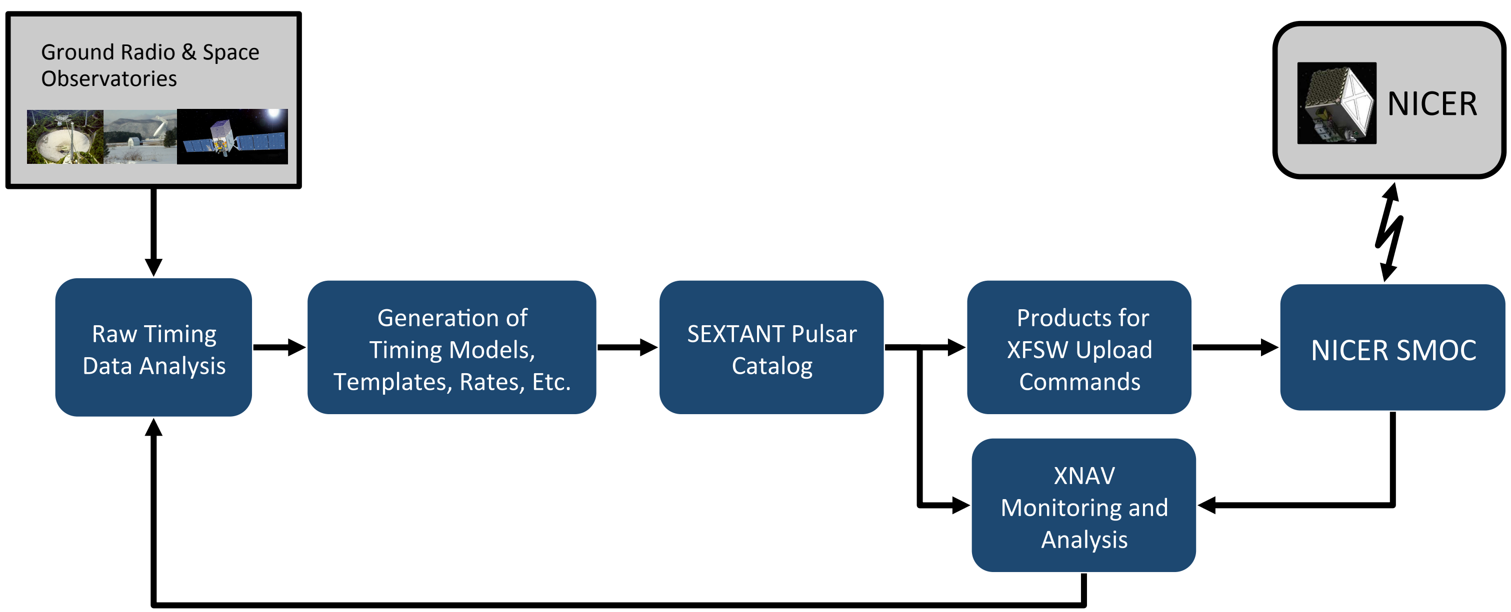
Simulation Results

- Achieving performance levels that meet SEXTANT requirement (10km worst direction after 14 days) with margin.
- Three pulsars: B1937+21,B1821-24, J0218+4232
- Large initial errors added to the state
- Rapid divergence occurs without processing XNAV measurements

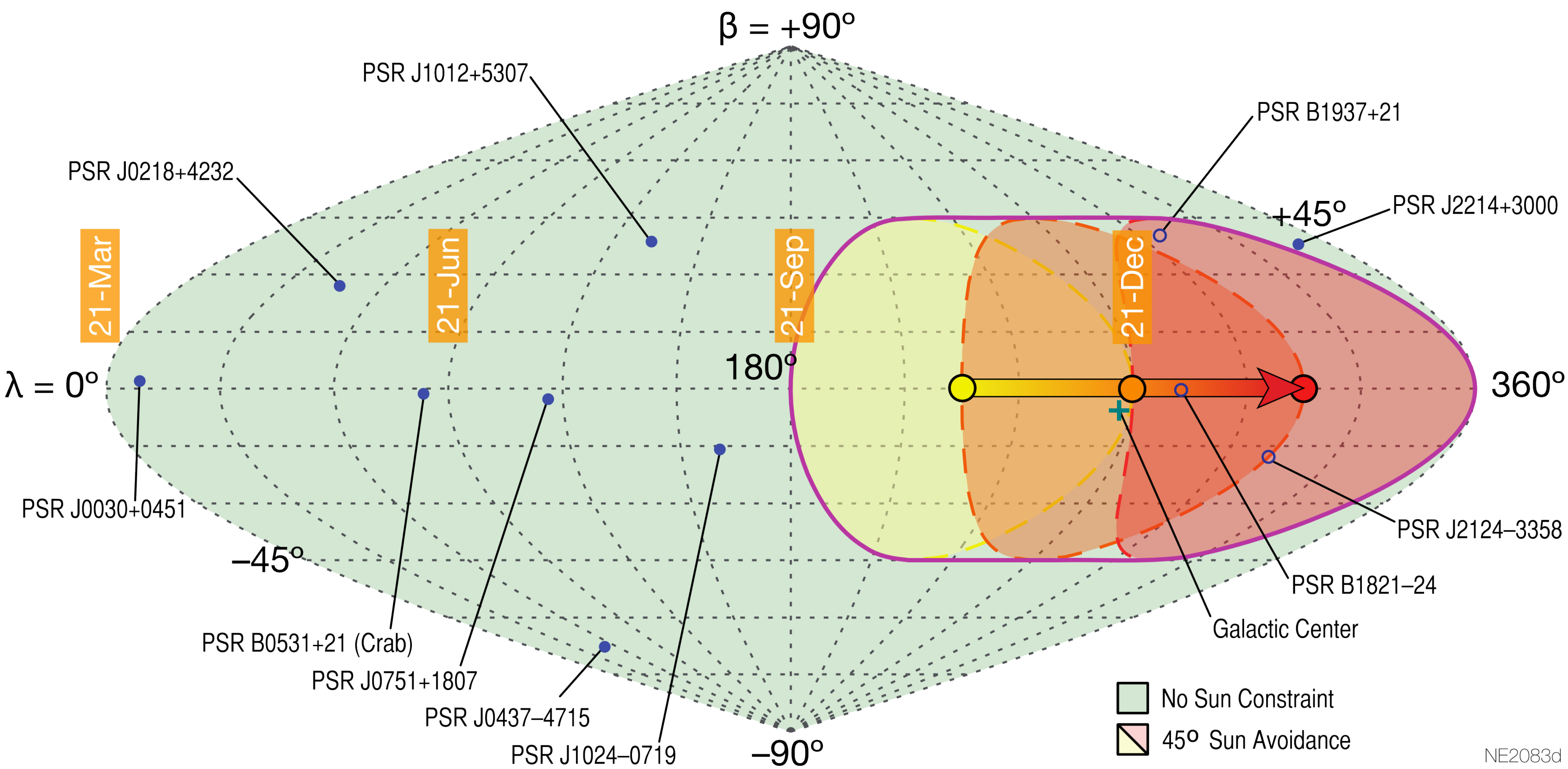


SEXTANT Ground System

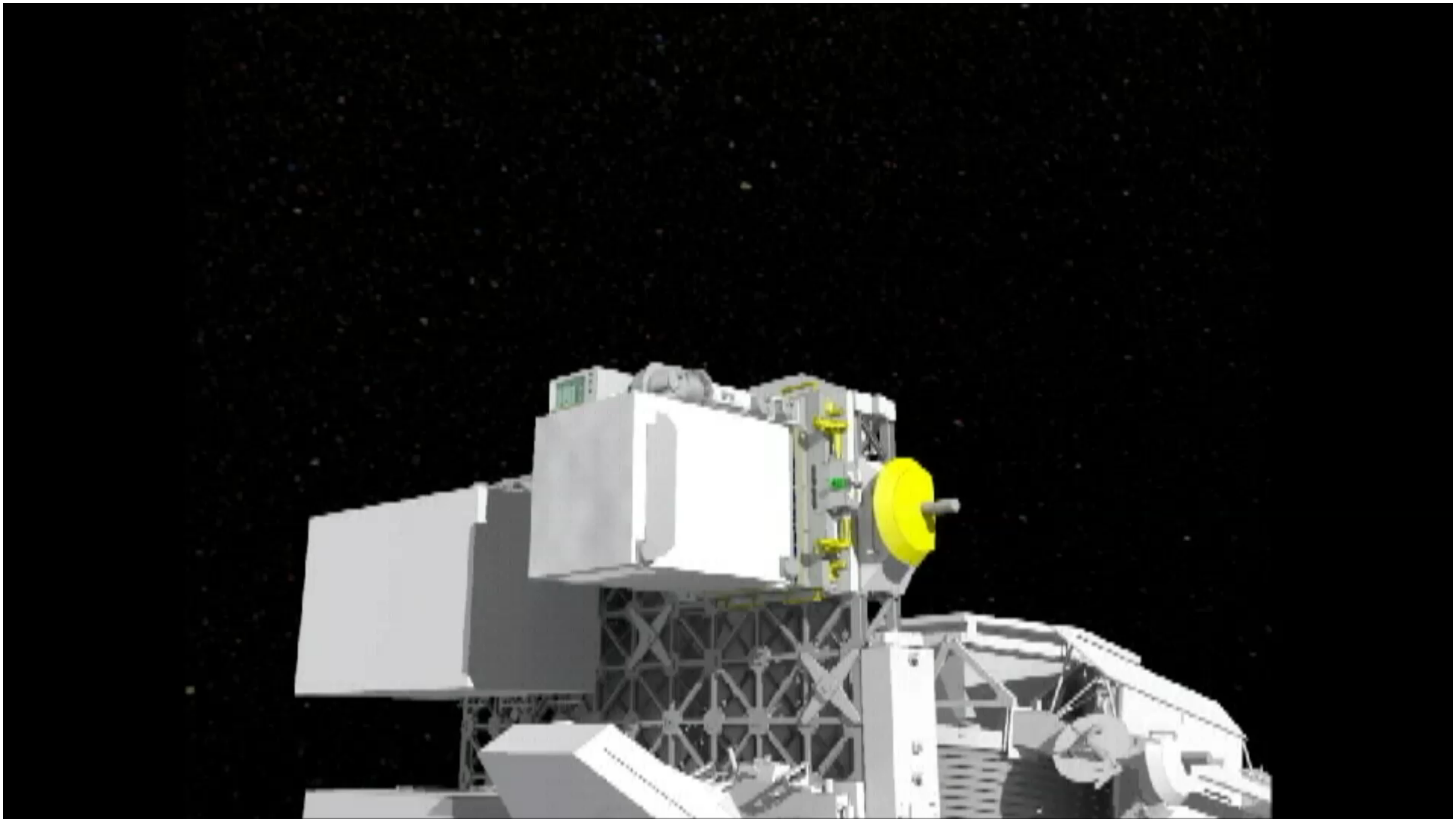
- Generate and maintain the pulsar almanac
  - Timing models
  - Profile templates (light-curves)
  - NICER data after sufficient data collected
- Maintain and update application
  - Pulsar upload tables
- Monitor performance
  - Trending
  - Alerts
- Driven initially with radio observations



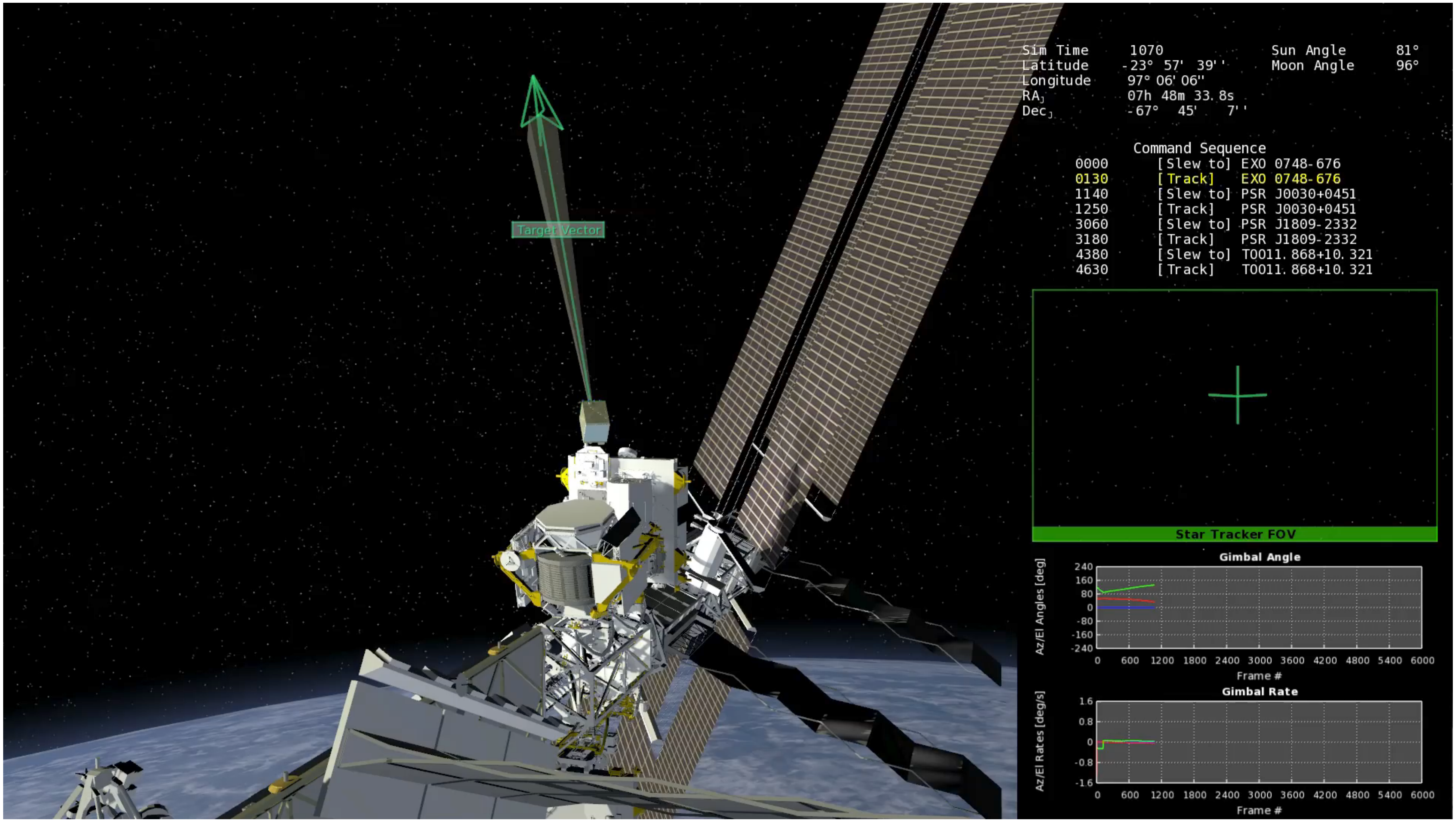
Concept of Operations (1/3)



Concept of Operations (2/3)



Concept of Operations (3/3)



Current Progress

- NICER in Phase C
- Successful review progress
  - SEXTANT Baseline Review Aug 2013
  - NICER PDR Dec 2013
  - SEXTANT CDR-EPR Aug 2014
  - GCD Continuation Review Aug 2014
  - NICER IFSW Aug 2014
  - NICER CDR Sep 2014
- Milestones
  - XFSW Build 0 (internal) Dec 2013
  - XFSW Build 1 Apr 2014
  - XFSW Build 1.1 (clean-up) May 2014
  - IFSW Build 1 integration & testing Jun 2014

Summary & Future Work

- NICER/SEXTANT is an excellent partnership between science and technology (SMD & STMD)
- SEXTANT will be a:
  - First demonstration of real-time, on-board XNAV
  - Significant historical event enabled by ISS
  - Bridge between science, technology & exploration to connect with the public
- Near-term milestones
  - XFSW Build 2 Mar 2015
  - IFSW Build 2 testing
- NICER URL
  - **`http://heasarc.gsfc.nasa.gov/docs/nicer/`**

Backup

SEXTANT in NICER
Flight Software Architecture