

# ***X-ray Pulsar Navigation (XNAV) for Deep-Space Autonomous Applications***

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# Outline

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- **X-ray Pulsar Navigation (XNAV) Concept**
- **Science mission (NICER) & tech demo (SEXTANT)**
  - Description & objectives
- **SEXTANT system architecture overview**
- **Test-as-you-fly support hardware**
  - Table-top pulsar simulator
  - Modulated X-ray Source (MXS)
- **Current hardware-in-the-loop test results**
- **Current & Future Work**



# X-ray Navigation (XNAV) Concept

- **Precise timing enables navigation**

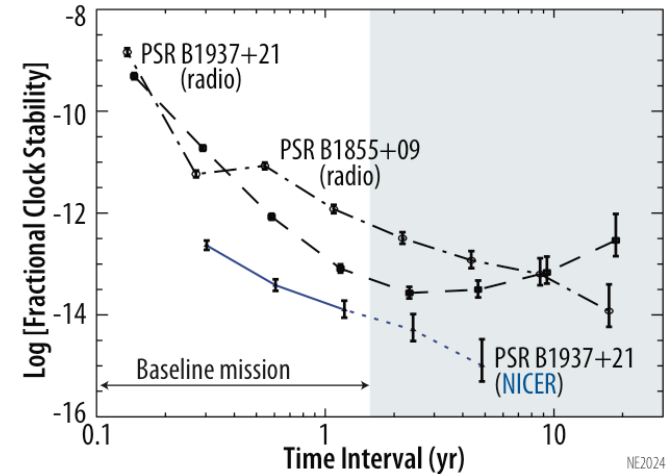
- Pulsars: rapidly spinning neutron stars
- Millisecond pulsars (MSPs)
  - rival atomic clocks as time-keepers
  - accuracy & stability
- Enable *galaxy-wide* positioning / time-base
  - GPS-like navigation capability throughout solar system
  - Sequential target observation for 3D state

- **Measurement**

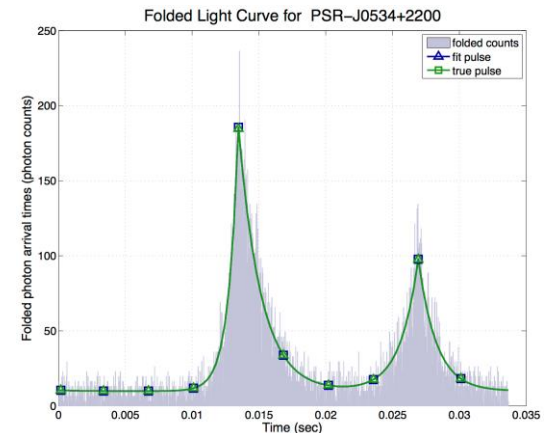
- Time tag X-ray photons
- Pulse arrival time, i.e., pulsar *pseudo-range*
- Stitch sequence together for autonomous navigation solution

- **Utility**

- Outer planet and beyond exploration
- Independent navigation for manned missions
- Navigation on opposite side of the Sun
- Asteroid orbit charting
- Complement / Augment Deep Space Network (DSN)
- Pulsars for (independent) time keeping



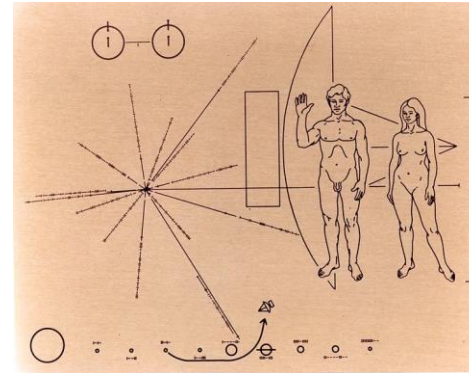
**Crab Pulsar (1/3 speed), Cambridge University, Lucky Image Group**





# 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
  - Used Large Area Collimated Detector
- NASA SBIRs with Microcosm
- NICER / SEXTANT selection 4/2013
  - 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 on-board XNAV OD***





# SEXTANT Technology Demonstration

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

- Funded by STMD Game Changing Development (GCD)

### 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

### Key Performance Parameter (KPP)

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

### Stretch Objective

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

### Planned Experiments

- 2-4 week period observing 3 – 5 pulsars early in the mission, models derived from radio telescope data
- 2-4 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



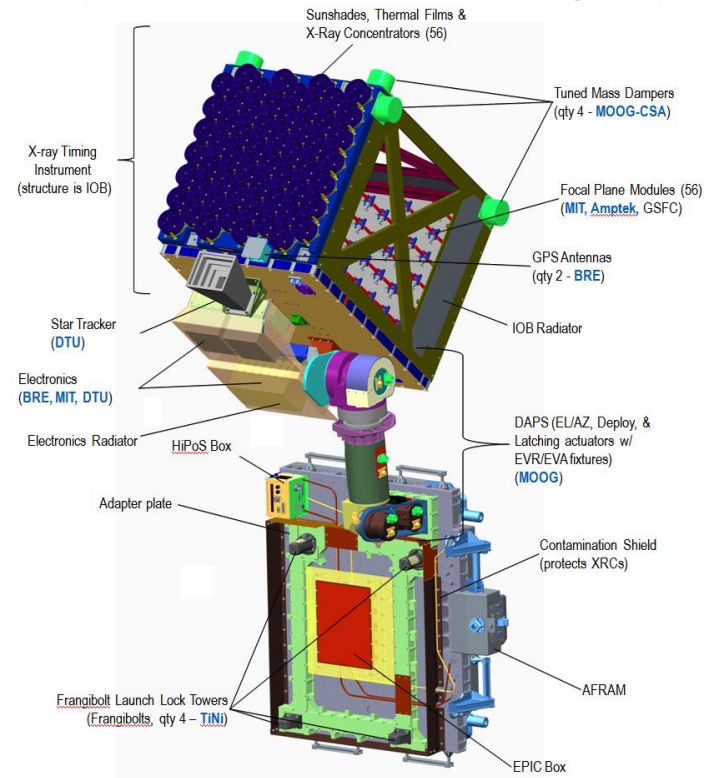
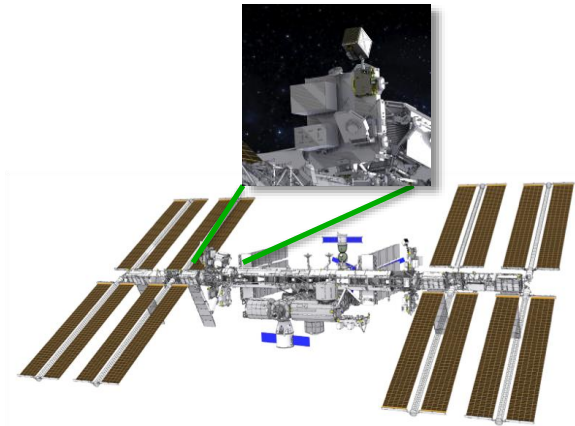
### Other objectives

- Validate and enhance the unique Goddard XNAV Laboratory Testbed
- 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
- Identify technology infusion path for practical sensor: HEOMD, SMD



# NICER: An Astrophysics Mission of Opportunity on the International Space Station (ISS)

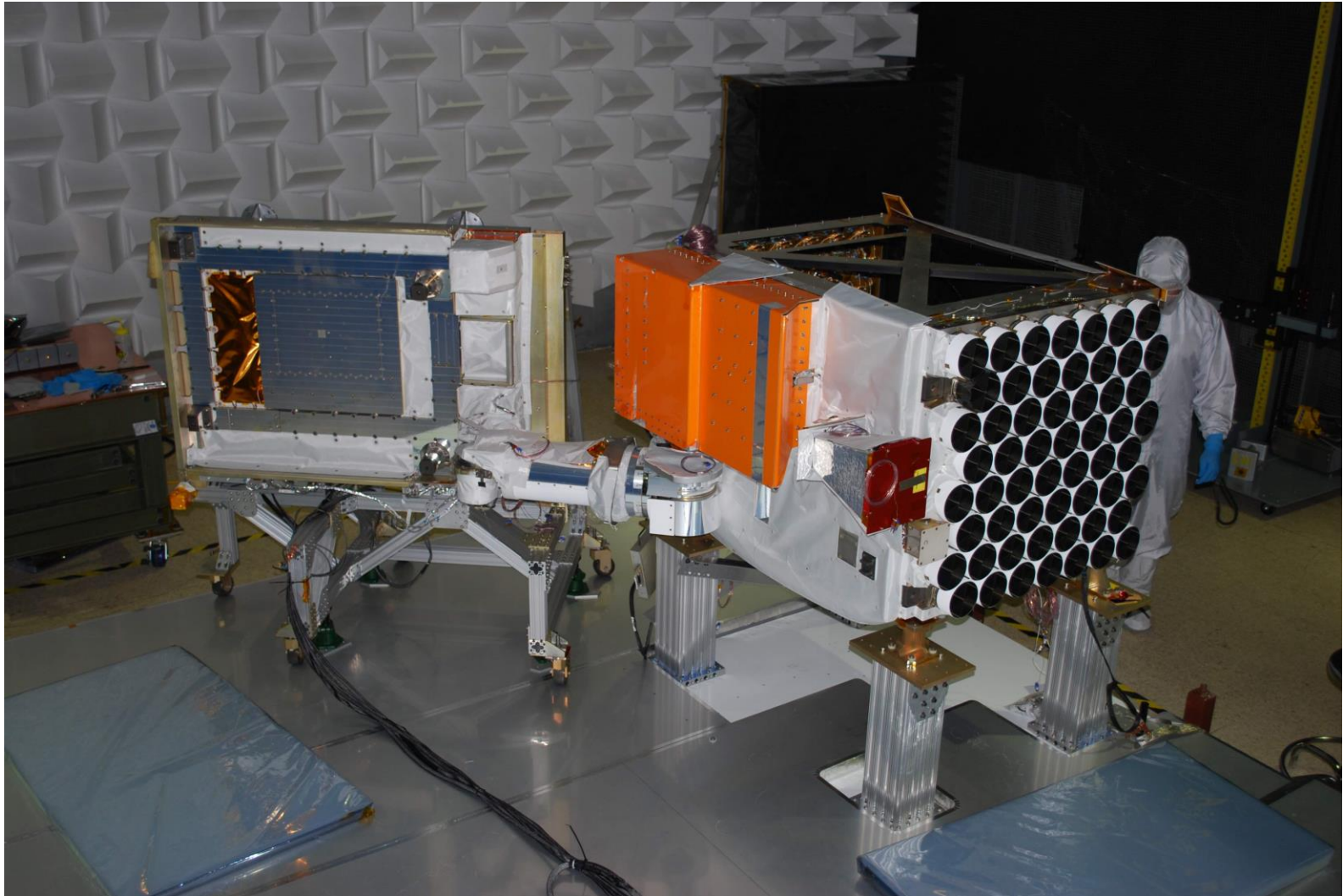
- Neutron-star Interior Composition Explorer (NICER)
- Science: *Understanding ultra-dense matter* through observations of neutron stars in the soft X-ray band
- Launch: NET April 2017, SpaceX-11 resupply
- Platform: ISS EXPRESS Logistics Carrier (ELC), with active pointing over nearly a full hemisphere
- Duration: 18+6 = 24 months, includes 6 month Guest Observer program
- Instrument: X-ray (0.2–12 keV) *concentrator* optics and silicon-drift detectors. GPS position & absolute time reference
- Status:
  - Arrived @ KSC, Jun 2016
  - Aliveness testing until launch





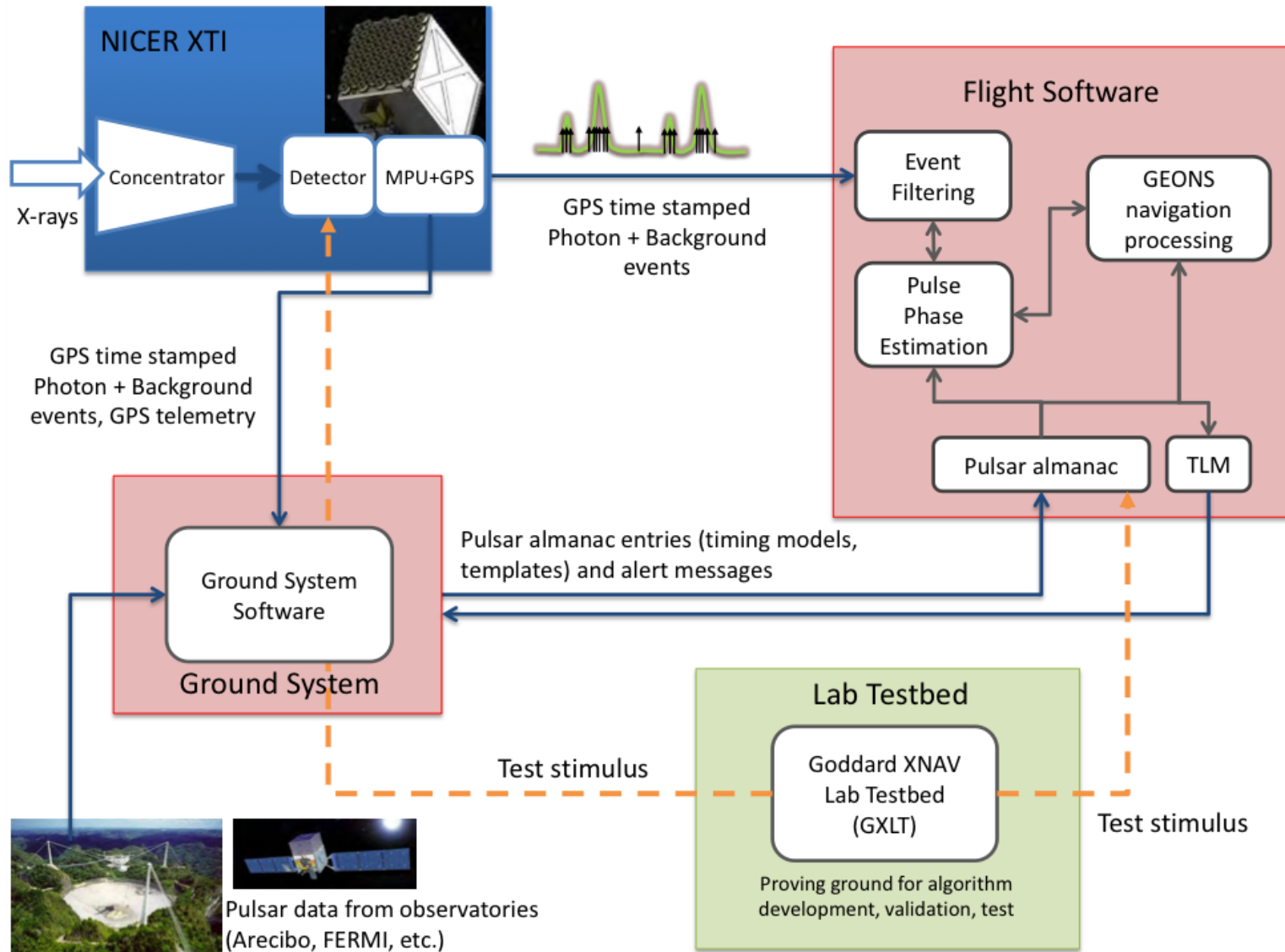
# NICER Payload in Deployed Configuration

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# System Architecture Diagram

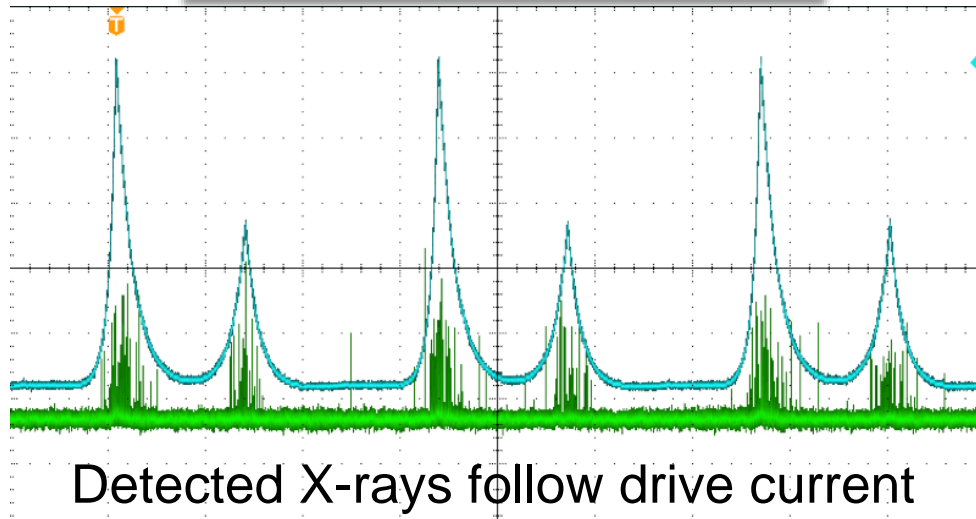
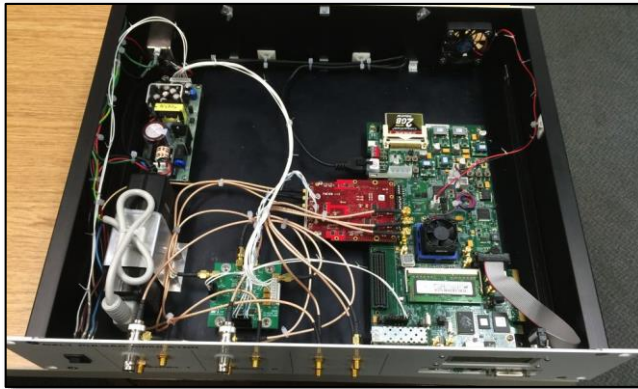






# Table-Top Pulsar Simulator

## MXS control electronics



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

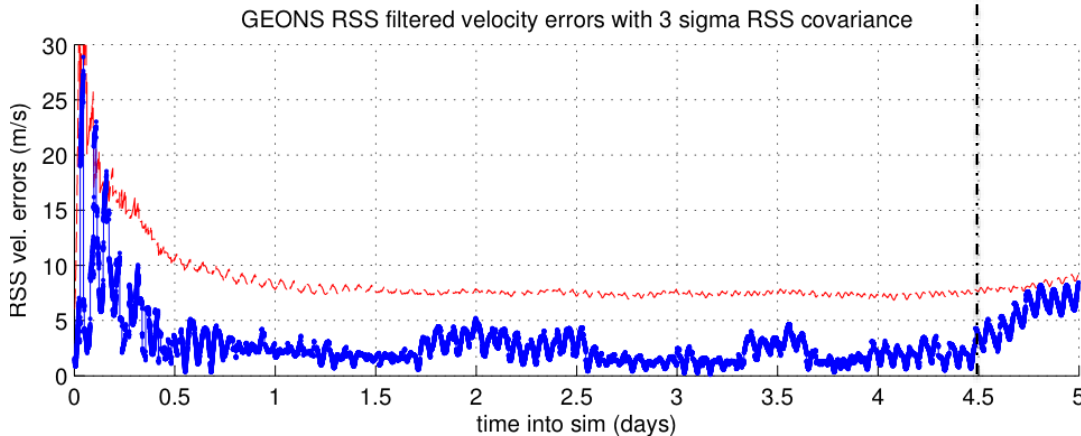
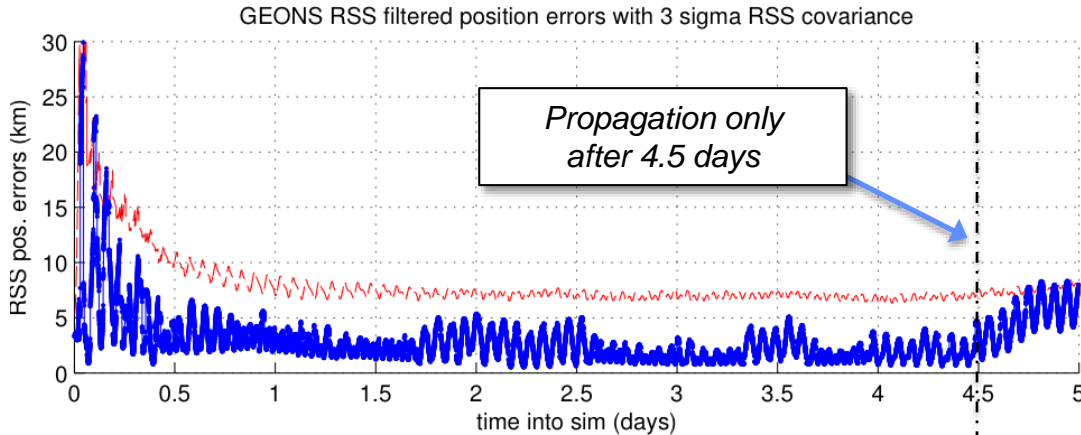


Modulated X-ray source (MXS)



# Baseline Test Results for XFSW v2.1.4

- **Standard 5-day test using software simulated events in XLT**



- Red upper bound is  $3\sigma$  formal error
- Blue is actual error
- Baseline performance meets target accuracy
  - $< 10$  km RSS error after 0.5 days
  - $< 5$  km RSS error after 4 days



# Current & Future Work

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- **Prepare for launch and operations**
  - Currently Not Earlier Than 2017-04-09
- **Infuse XNAV Laboratory Testbed into other labs**
- **Future mission studies**
  - Considering effects of including XNAV capability for future missions in a number of orbit regimes
- **Practical sensor development**
- **Identify mission infusion**