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

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Outline

• 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

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

**Folded Light Curve for PSR J0534+2200**
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
Table-Top Pulsar Simulator

MXS control electronics

- 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

Detected X-rays follow drive current

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

• 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