Space Navigation using X-ray Pulsar Observations

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X-ray Navigation (XNAV)

• X-ray Pulsars as Guide Stars
• Brief History of XNAV
• X-ray Pulsars for Position Determination
• X-ray Pulsars as Precision Time References
• Attitude Determination Using X-ray Sources
• XNAV Demonstration Missions
• Acknowledgements
XNAV Sources: X-ray Pulsars

• The principal celestial sources considered are X-ray pulsars
  – Rotation-powered Pulsars (RPSR)
  – Accretion-powered milli-Second Pulsars (MSP)

• Alternate sources are also being explored
Pulsars provide stable frequency standards

Variance of millisecond pulsars (most precise astronomical clocks) is comparable to that of atomic clocks


X-ray Guide Stars

- Very different from the “visible” sky
- Nearly all sources extended or variable
XNAV – A Brief History

- **1967**: Bell J. & Hewish A. Successful discovery of radio pulsar
- **1974**: Downs, G.S. from NASA/JPL outlines concept, “Interplanetary Navigation Using Pulsating Radio Sources”
- **1981**: Chester & Butman also from NASA, “Navigation Using X-ray Pulsars”
- **1988**: Wallace K. from U.K. use of radio stars for navigational systems
- **1988**: Kent Wood of NRL proposes the Unconventional Stellar Aspect (USA) experiment to DoD (Operated May 1999-Nov 2000)
- **1996**: Hanson, J.E. Stanford Ph.D. dissertation “Principles of X-ray Navigation”
- **2004**: ESA Advanced Concepts Team ARIADNA pulsar navigation study
- **2005-2006**: DARPA XNAV Phase I Program
- **2006-Present**: NASA Supports XNAV development through series of SBIR’s with Microcosm/CrossTrac/ASTER
- **2010 – DARPA White Paper on XTIM Concept and Applications**
- **2010 – DARPA begins instrument development for XTIM demonstration mission**
- **2011 – SEXTANT Selected for Phase A study with strong support from NASA/OCT**
**XNAV Concept**

- Pulsar signals can be used as a natural navigation reference
- They provide an oscillating signal with long-term stability comparable to atomic clocks
- XNAV concept essentially computes a range from the SSB to a spacecraft along the direction from the SSB to the pulsar
- Concept uses range and range-rate for accurate position and velocity solutions
  - However, line of sight attitude measurements from these sources also available
  - So, occultation and pulsar-elevation measurements also possible
- There are many algorithmic analogies between XNAV and GNSS systems
XNAV Instrument

- With stored accurate source timing models and sufficient collection time and detector area, pulsar signals can be filtered to produce accurate range, range-rate, and potentially time estimates for spacecraft in Earth orbit or interplanetary space.
- X-ray emitting pulsar signals are faint, noisy, and not tagged with time or ECI position of origin.
- Potential Applications
  - Autonomous Spacecraft Navigation
  - DSN Augmentation
  - Clock Synchronization
XNAV Performance: B1821-24

\[ f(t, t_0) = h_1 e^{-\frac{(t-t_1)}{2w_1^2}} + h_2 e^{-\frac{(t-t_2)}{2w_2^2}} + c \]

- Histogram of B1821-24 pulse provided by Paul Ray (NRL)
- Double gaussian pulse model fit to simulated data
- Derivatives calculated analytically
- Integrals evaluated numerically

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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<tbody>
<tr>
<td>Pulse Period</td>
<td>3.05</td>
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<tr>
<td>Avg Pulsar Flux</td>
<td>$6.04 \cdot 10^{-4}$ ph·cm$^{-2}$·sec$^{-2}$</td>
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<tr>
<td>Pulse Fraction</td>
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<td>Bin Size</td>
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<td>Diffuse X-ray Bkgnd Flux</td>
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<td>Net Cosmic Ray Bkgnd Flux</td>
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<tr>
<td>Detector Bkgnd Rate</td>
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</tbody>
</table>

ph·sec$^{-2}$
Predicted Performance: B1821-24
XNAV Applications

- Earth-Sun L2 Point
  - Autonomous navigation and orbit maintenance
- Outer Planets and Deep Solar System
  - Accuracy (normal to line of sight) could augment DSN at distances > Jupiter
- Planetary Approaches and Orbits
  - Improve autonomy and reduce operations cost and DSN load
- Formation Flying and Relative Navigation
  - Can use aperiodic sources as well
- GPS Augmentation and Backup
X-ray Pulsars as a “Universal” Time Reference

• Globally distributed time reference
  – Does not require line-of-sight between reference spacecraft to synchronize time

• Long duration stable absolute reference
  – Used in conjunction with local atomic clock

• “Short” duration stable relative reference
  – Allows sources like Crab to be used
XTIM Applications

• Numerous potential applications for XTIM
  – Provision of accurate time to a system of users
  – Support for secure communications
  – Verification/validation of new clock technologies
  – Enhanced observation techniques
    • e.g. Distributed RF Communications
  – Enhanced studies of variable celestial sources
  – Stability monitoring of existing time standards
  – Reliability and integrity of secure communications
    • e.g. financial data transfer
X-ray Attitude Determination

Precision X-ray Star Camera

- Small diffraction limit due to short X-ray wavelength
- Milli-arcsecond capable
- Potential for small package

X-ray Star Scanner

- Arcminute level attitude determination
- For use with spin stabilized spacecraft
- CubeSat compatible
XSS Concept

- Simple X-ray detector with collimator limits field of view
- As spacecraft spins, a series of pulses are created
- Each corresponds to the position of a star
- Attitude solution generated from unique pattern
XNAV Technology Demonstrations

**XNAV Demonstration SEXTANT (GSFC)**
- Will demonstrate XNAV position determination on Space Station
- Currently in technology development phase

**XTIM Demonstration XTIM Instrument (DARPA)**
- Will demonstrate concept of “locking” to an X-ray pulsar
- Instrument CDR in early 2012
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