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Space Navigation using X-ray Pulsar Observations

J. Hanson, CrossTrac Engineering, Inc
(408)898-0376
hanson@netwiz.net

X-ray Navigation (XNAV)

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- 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

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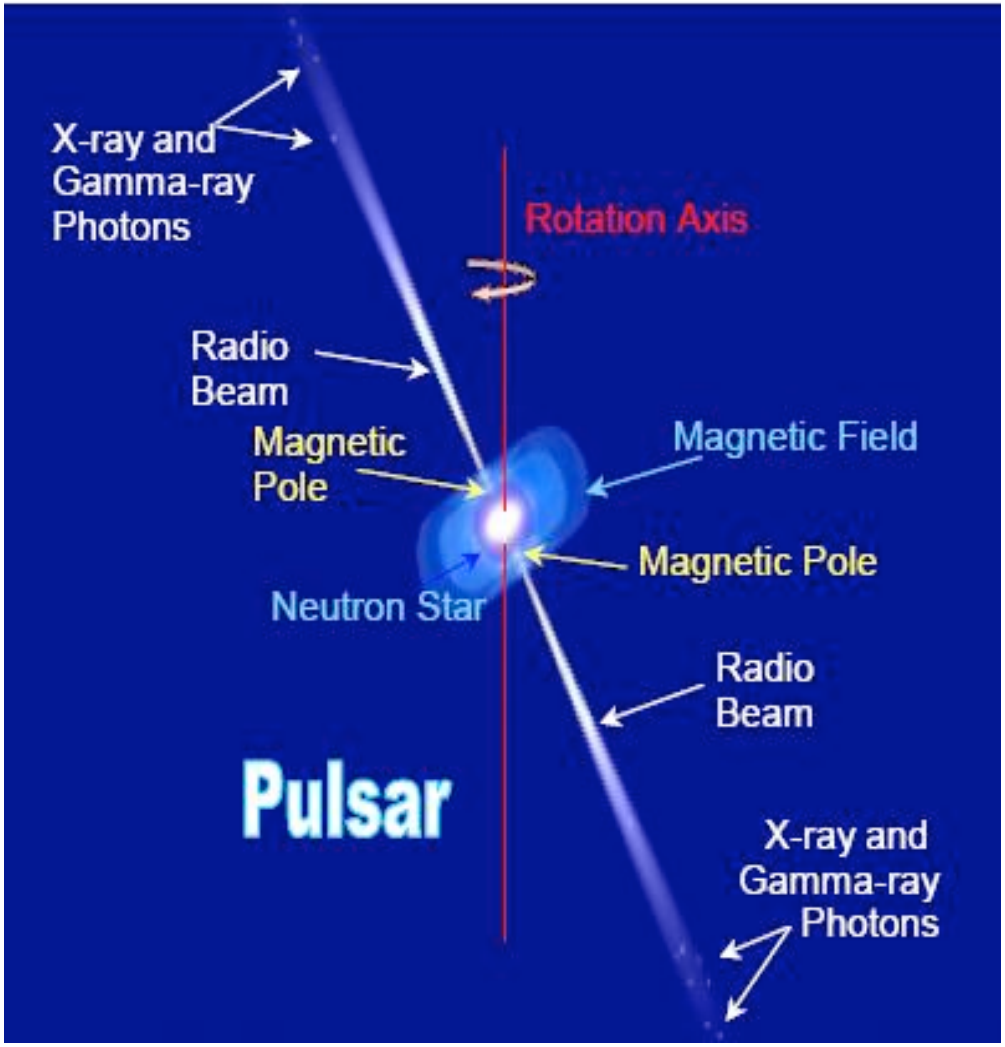
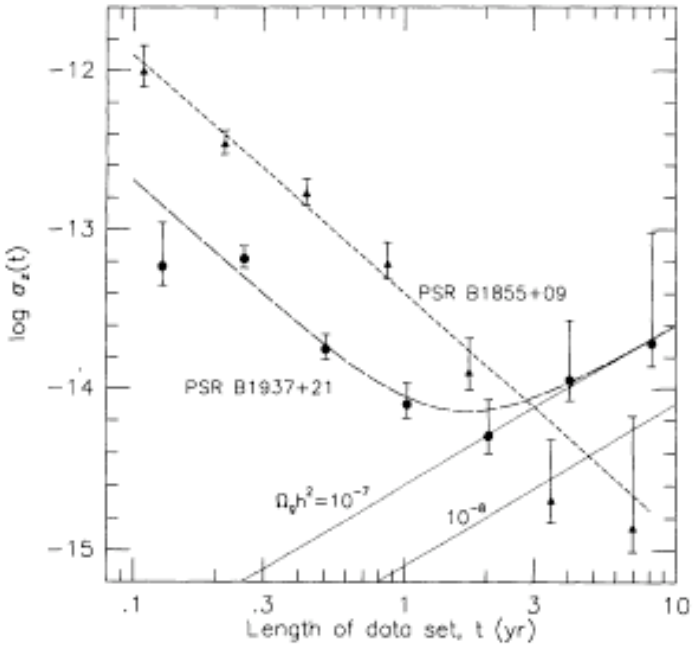
XNAV Sources: X-ray Pulsars

- 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



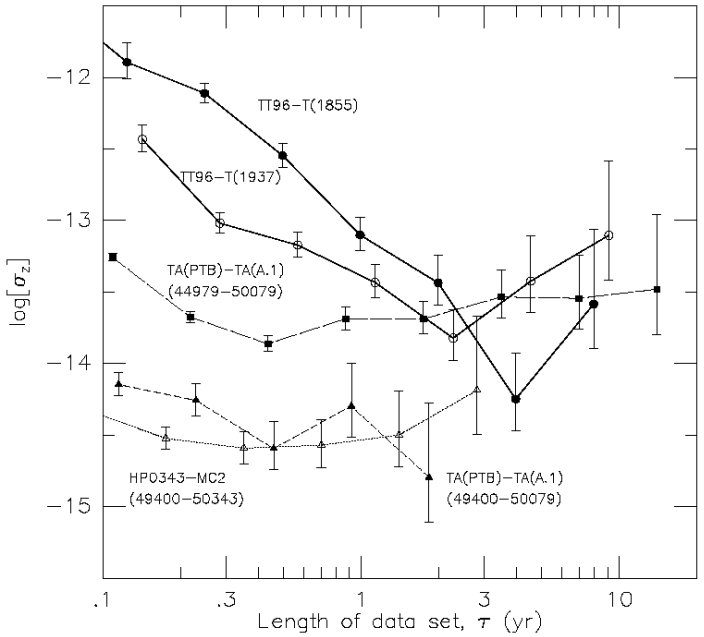
XNAV Sources:
MSPs as Celestial Atomic Clocks

Pulsars



Kaspi, Taylor, & Ryba, ApJ, 1994

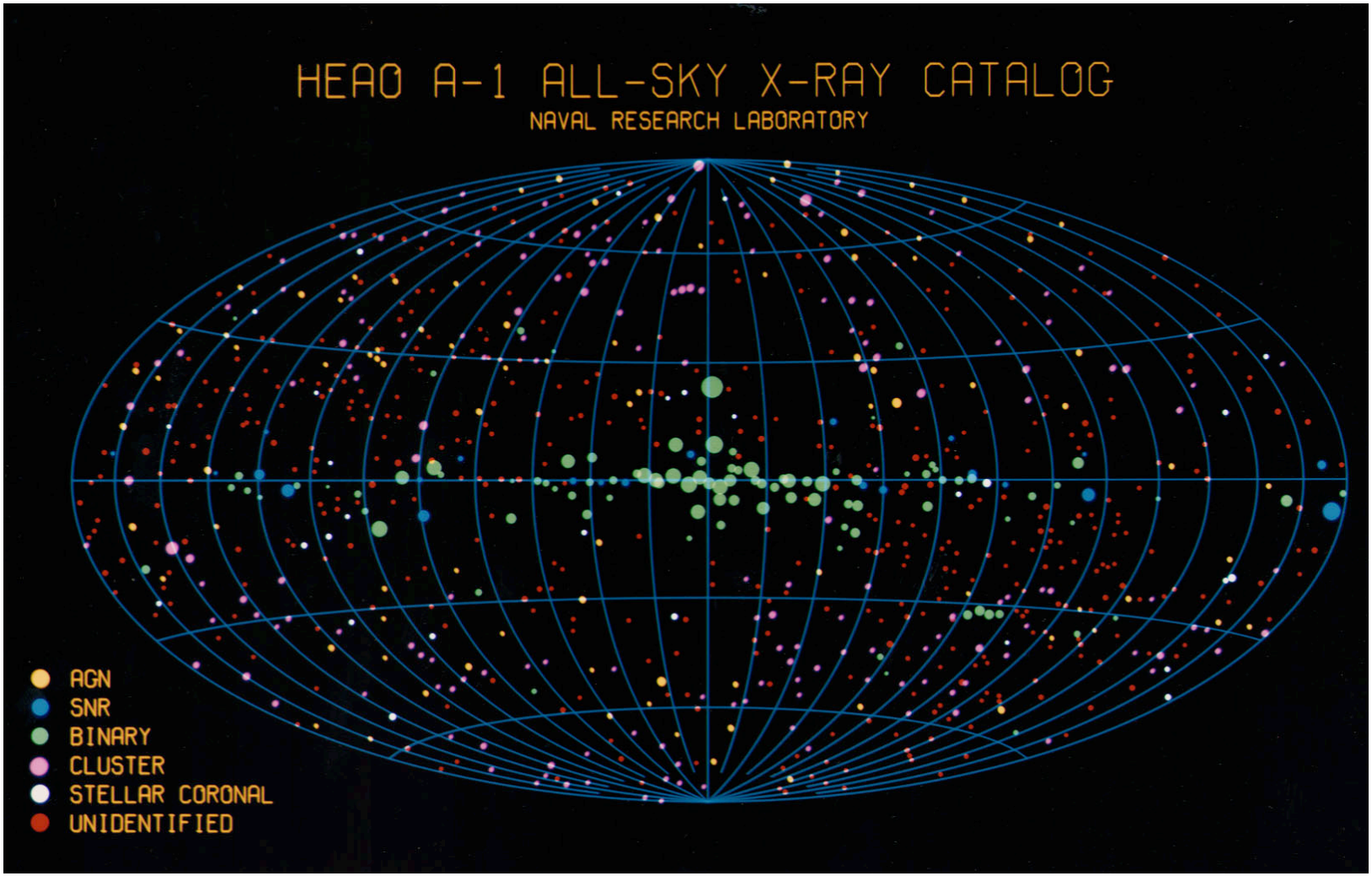
Atomic Clocks



Matsakis, Taylor, Eubanks, A&A, 1997

- Pulsars provide stable frequency standards
- Variance of millisecond pulsars (most precise astronomical clocks) is comparable to that of atomic clocks

X-ray Guide Stars

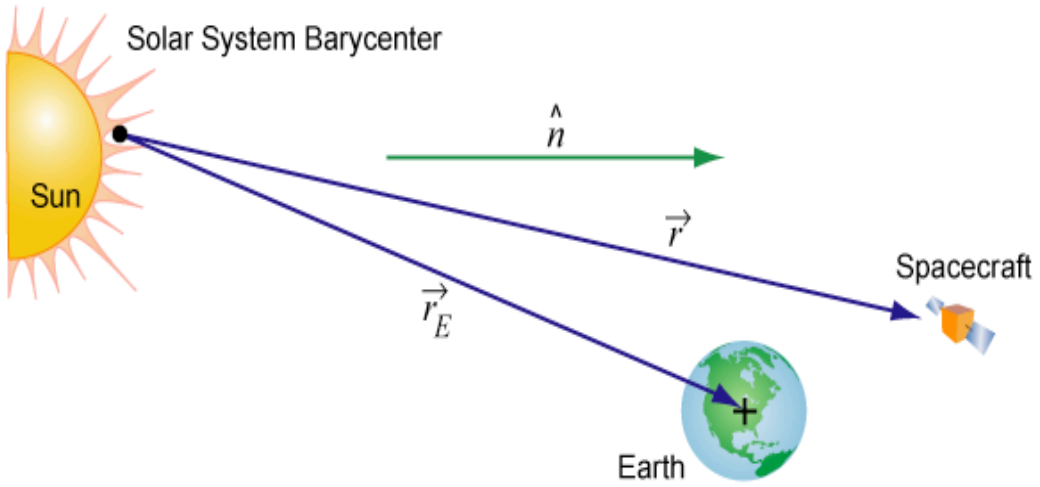


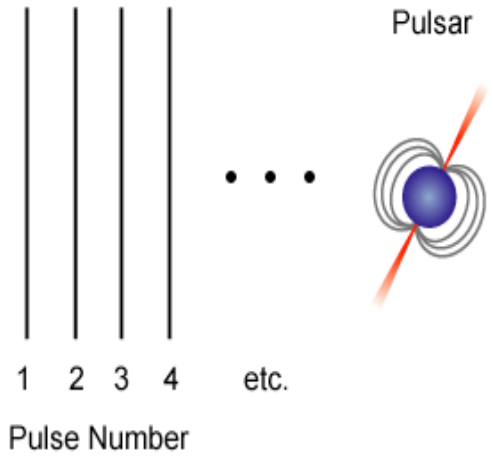
- Very different from the “visible” sky
- Nearly all sources extended or variable

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: Sheikh, S.I. UMD Ph.D. dissertation "The Use of Variable X-ray Sources for Spacecraft Navigation"
- 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

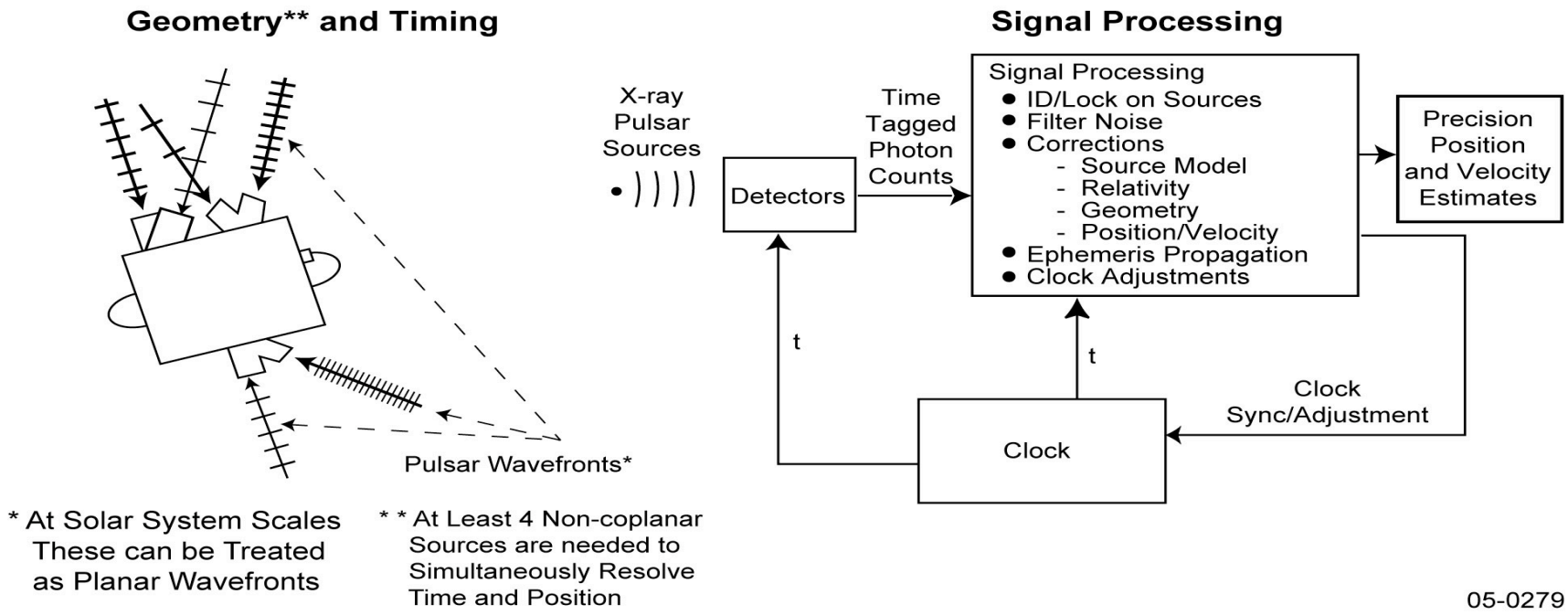
XNAV Concept





- 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

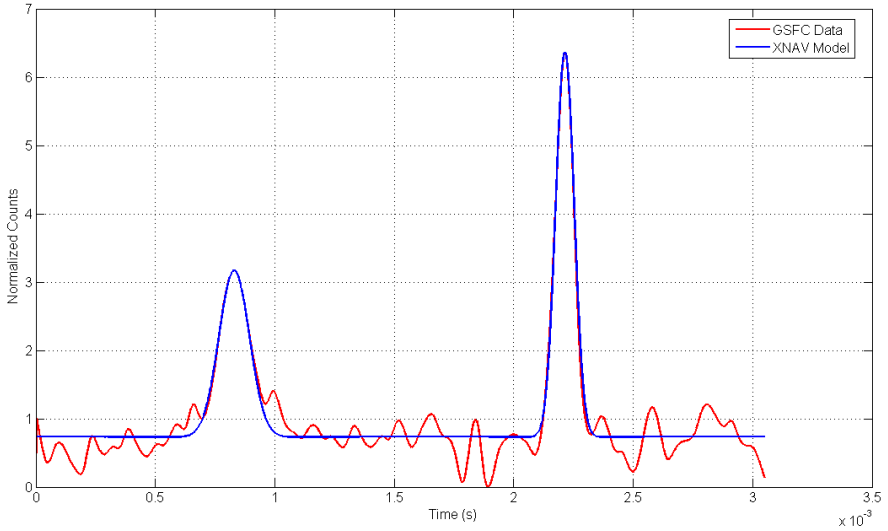
XNAV Instrument



- 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

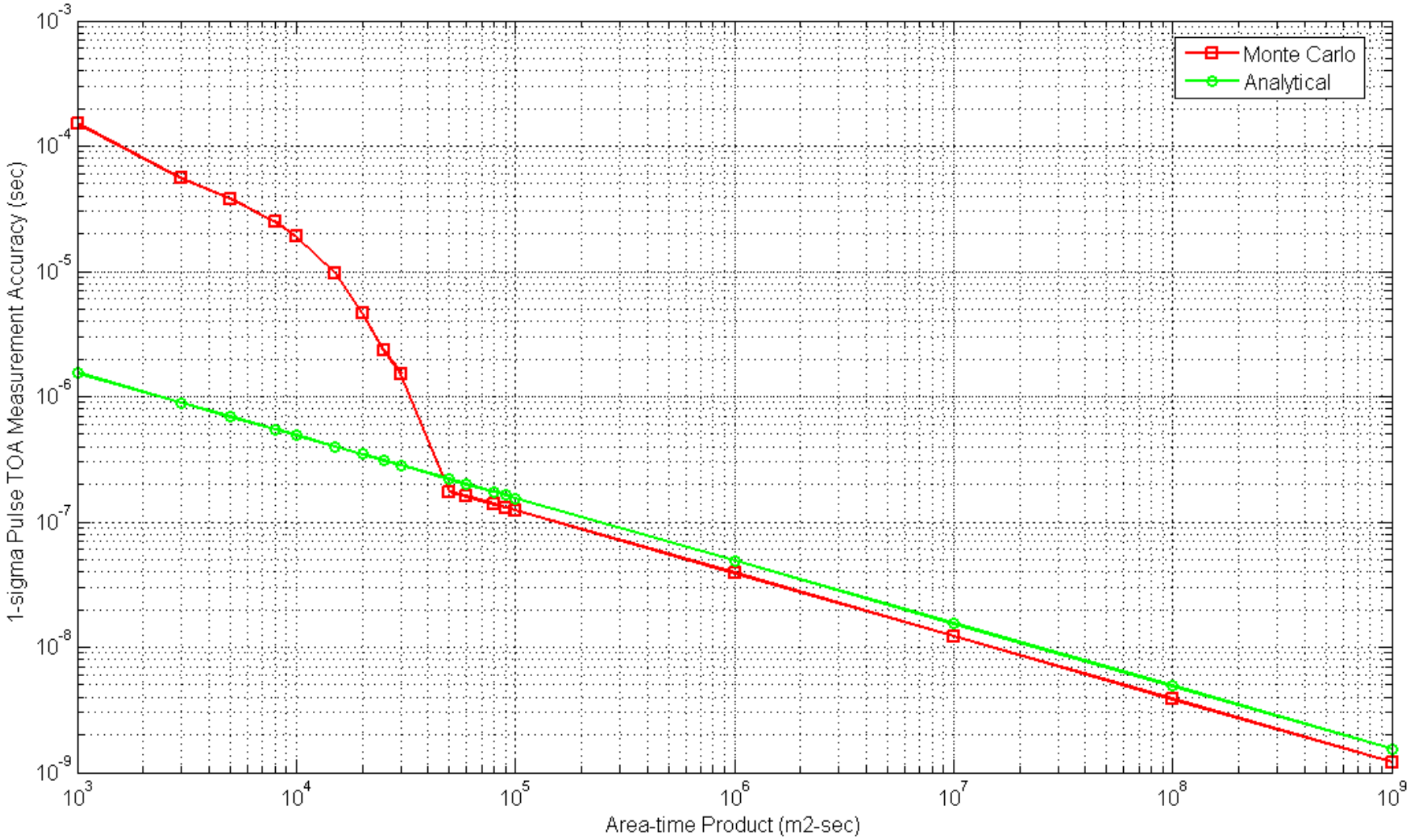
$$f(t_i, t_0) = h_1 e^{-\frac{(t-\tau_1)}{2w_1^2}} + h_2 e^{-\frac{(t-\tau_2)}{2w_2^2}} + c$$



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

Pulse Period	3.05	msec
Avg Pulsar Flux	$6.04 \cdot 10^{-4}$	ph·cm^{-2}·sec^{-2}
Pulse Fraction	0.98	
Bin Size	0.1	μsec
Diffuse X-ray Bkgnd Flux	0.1	ph·cm^{-2}·sec^{-2}
Net Cosmic Ray Bkgnd Flux	5	ph·cm^{-2}·sec^{-2}
Detector Bkgnd Rate	0.1	ph·sec^{-2}

Predicted Performance: B1821-24



XNAV Applications

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- 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

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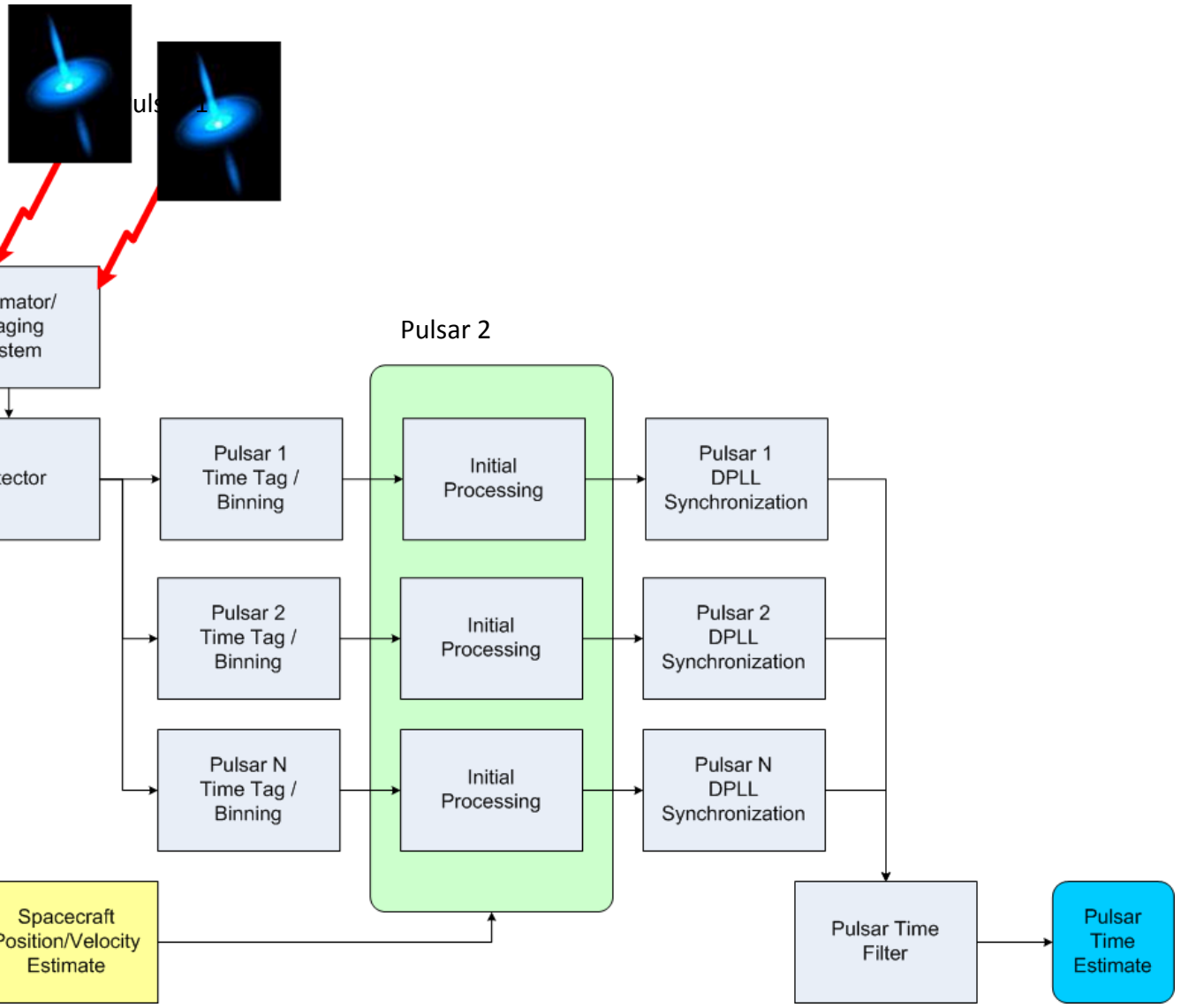
XTIM Concept



X-ray Pulsars as a "Universal" Time Reference

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- 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

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XTIM Applications

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- 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

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X-ray Attitude Determination

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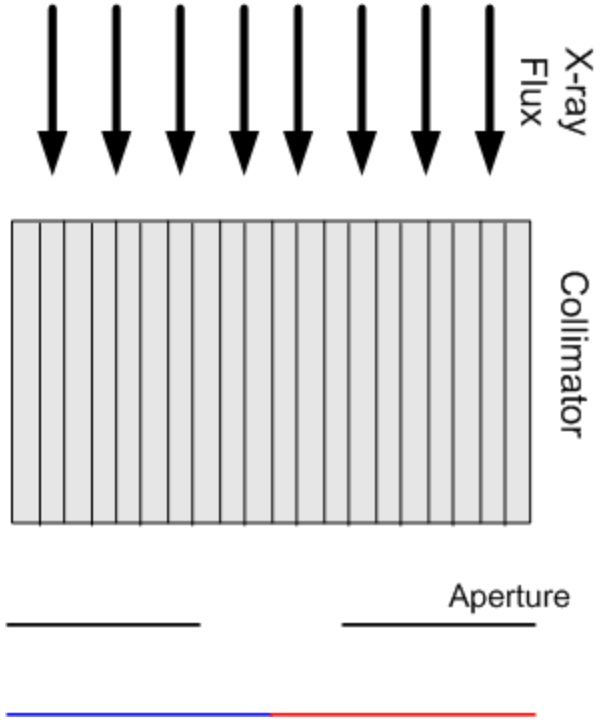
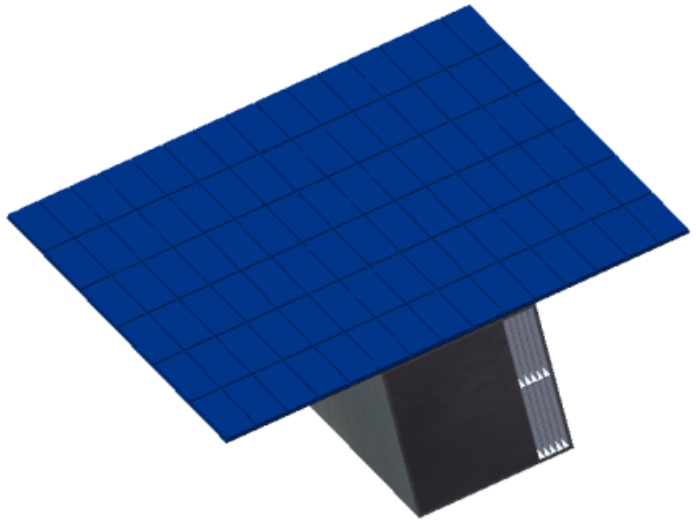
Precision X-ray Star Camera

- 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



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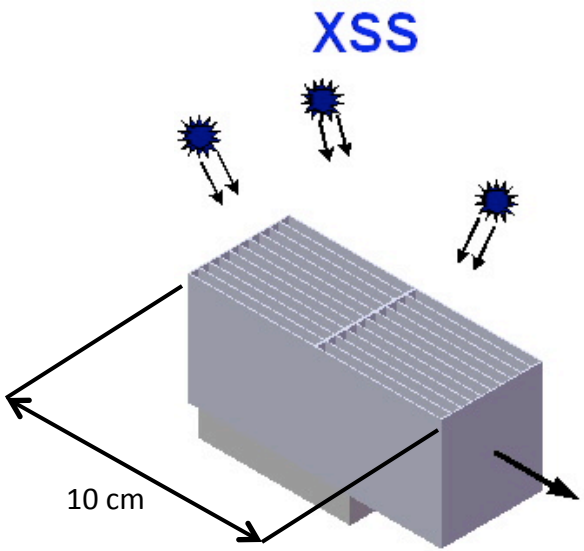
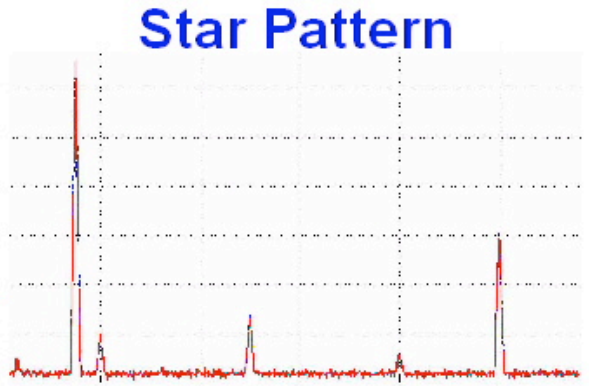
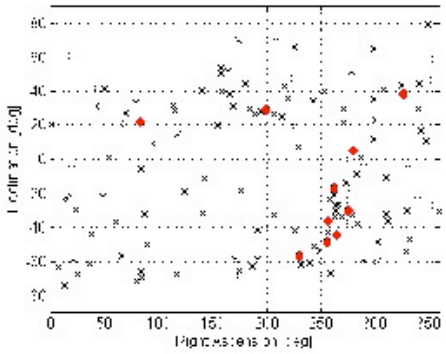
XSS Concept







- 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

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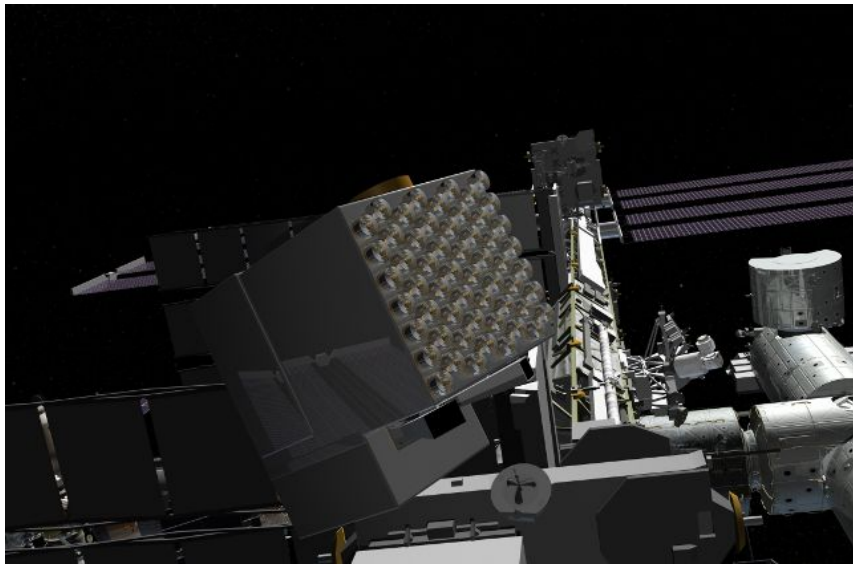
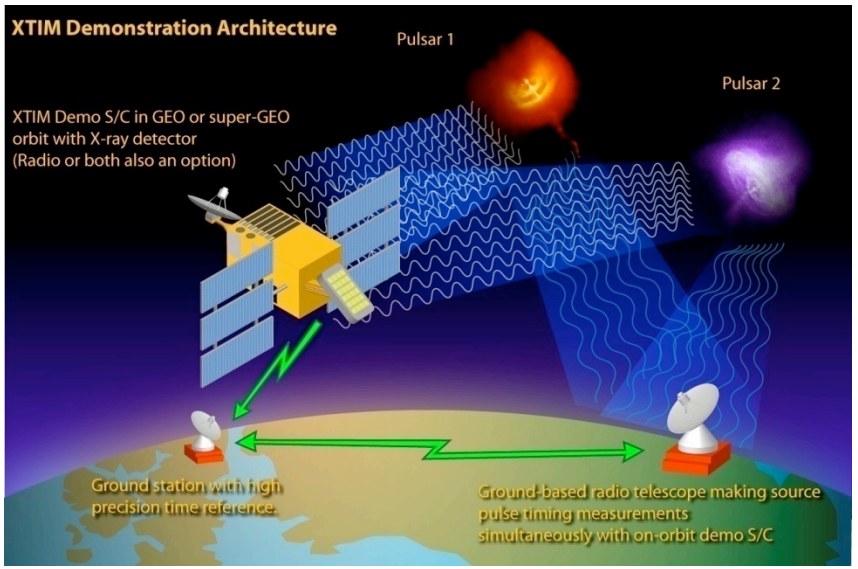
XNAV Demonstration
SEXTANT (GSFC)

- 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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