X-ray NAVigation for Autonomous Position Determination

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National Academies

Panel on Robotics, Communication and Navigation

Dr. Darryll J. Pines

Farvardin Professor and Dean

A. James Clark School of Engineering, University of Maryland

pines@umd.edu

Outline

- Motivation
- What is a Pulsar
- History of X-ray Navigation
- Evolution of a DARPA Program
- XNAV DARPA Program
- Navigation Results from Tracking Pulsars
- Summary/Future thoughts

Motivation

Potential Space Threats

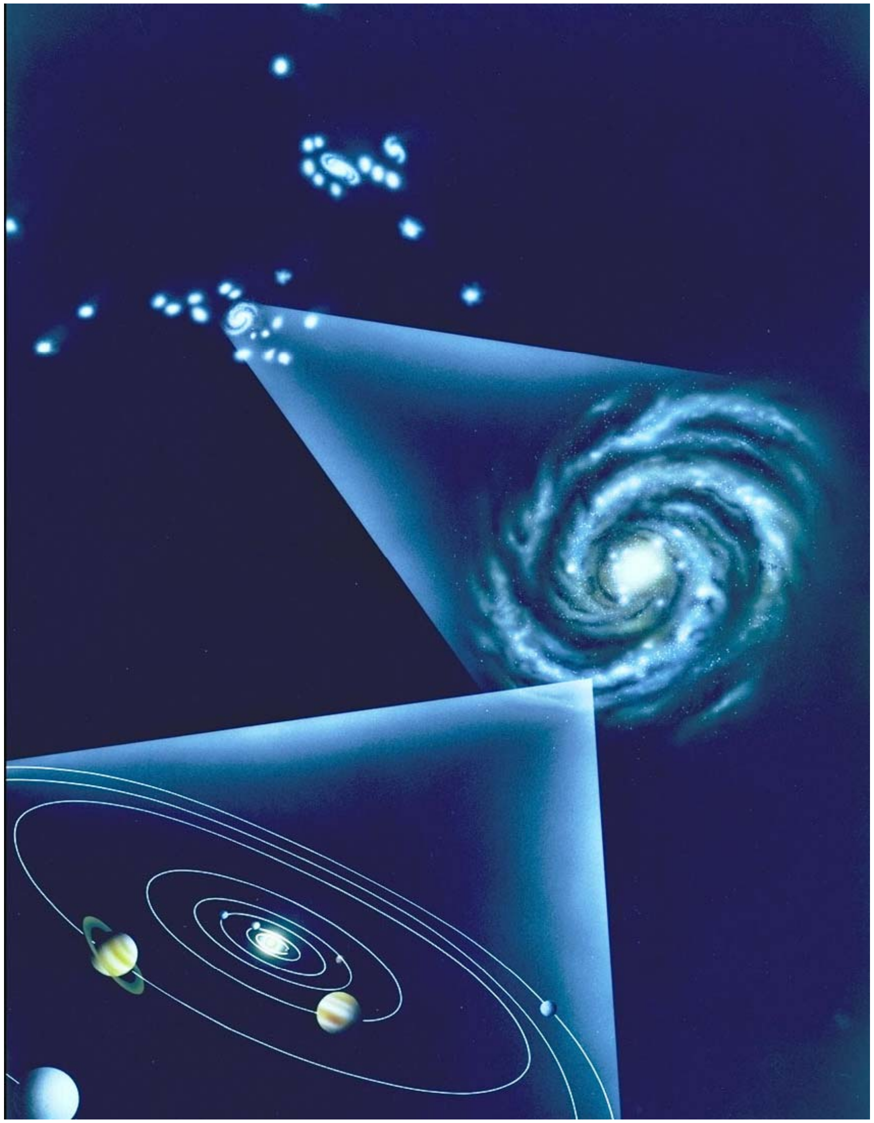
Nuclear Detonation
Directed Energy Beam
Space Interceptor,
Asymmetric threats

- **Reduce Situational Awareness**
- **Impair missile launch detection satellites**
- **Impair satellite communications.**
- **Impair navigation satellites (GPS)**
- **Impair weather satellites**

June, 2003 OSD study recommended "Operationally Responsive Space (ORS)"

A navigation payload to complement or replace the current Global Positioning System (GPS) satellites.

Milky Way Galaxy



•Several Galaxies nearby

•100 Billion Stars in the Milky Way Galaxy

•Solar System originates out of Orion’s Arm

X-ray Pulsars As Navigation Beacons

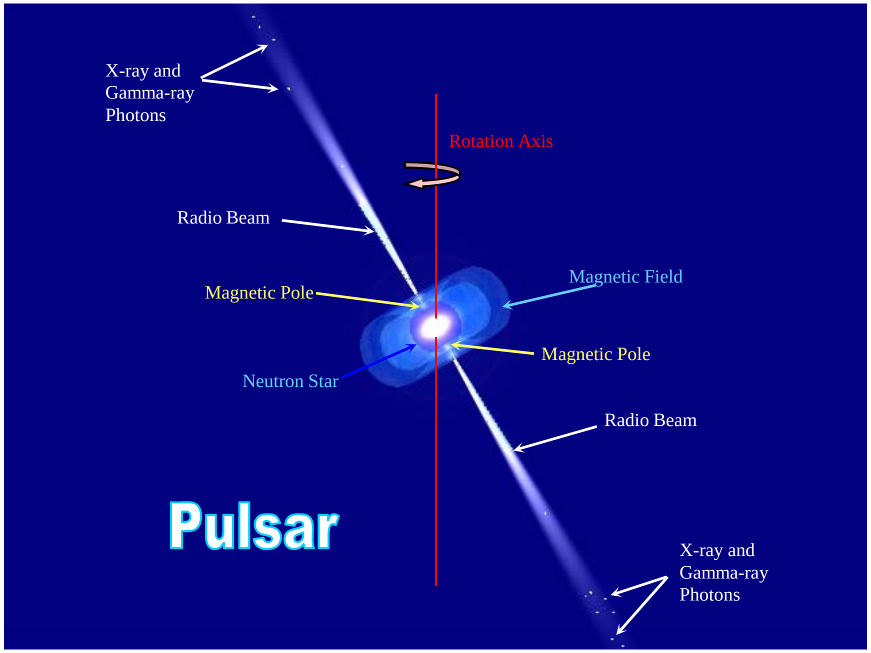
X-ray Pulsars

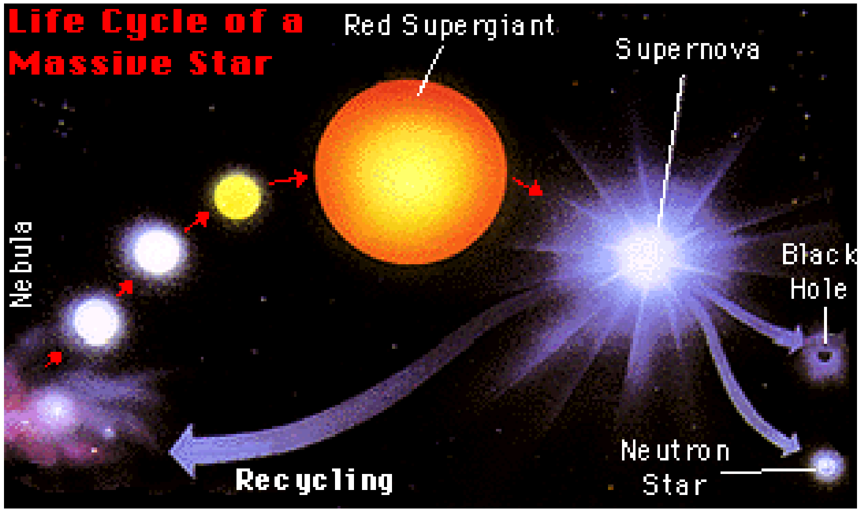
- Intense magnetic fields accelerate charged particles
- X-rays are emitted and can be seen periodically as beams sweep past observers line-of-sight
- Extremely stable - Nature's Galactic "Lighthouses"

Navigation Accuracy

- Governed by pulsar position location accuracy and timing of arrival of photons

$$\Delta t \approx t_b - t_{obs} = \frac{\hat{n} \cdot \Delta\vec{r}}{c}$$

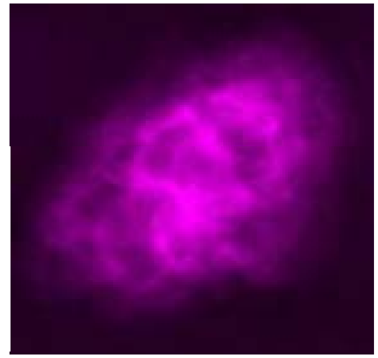




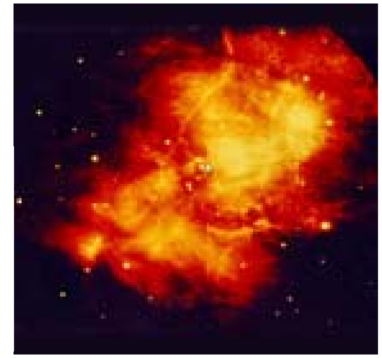
Pulsar Characteristics: Timing Model

X-ray

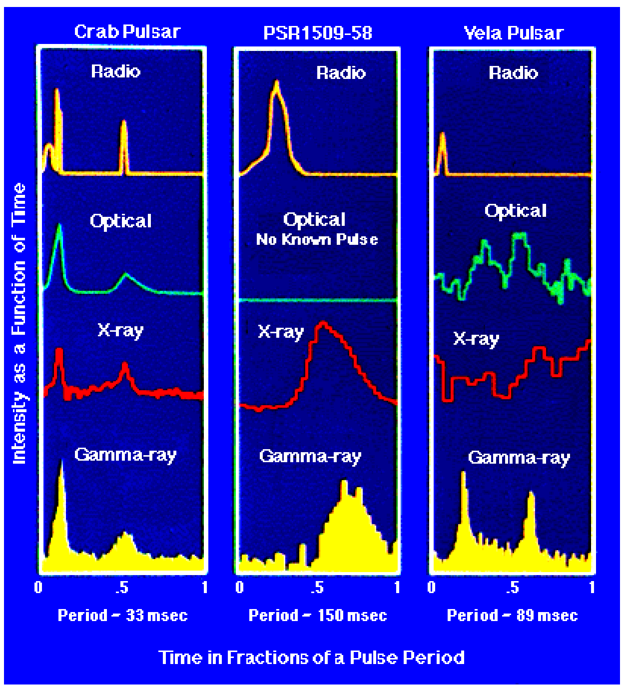
optical

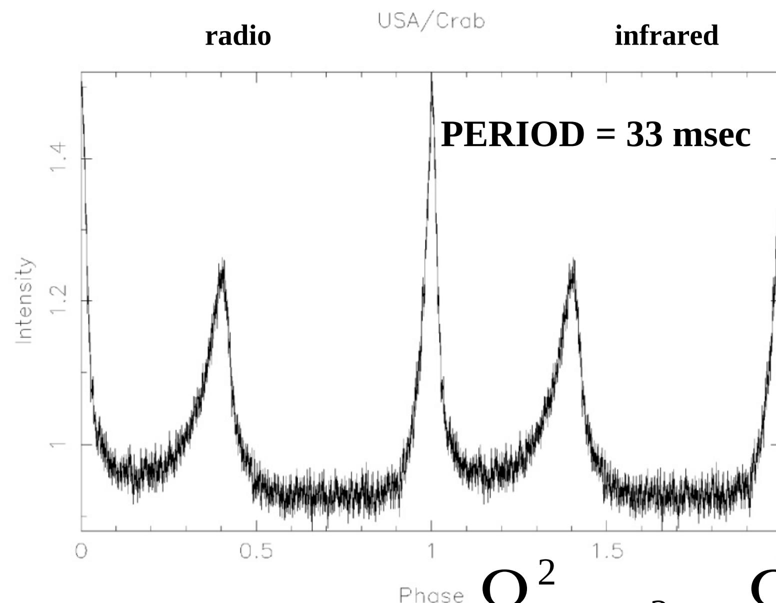


radio



infrared





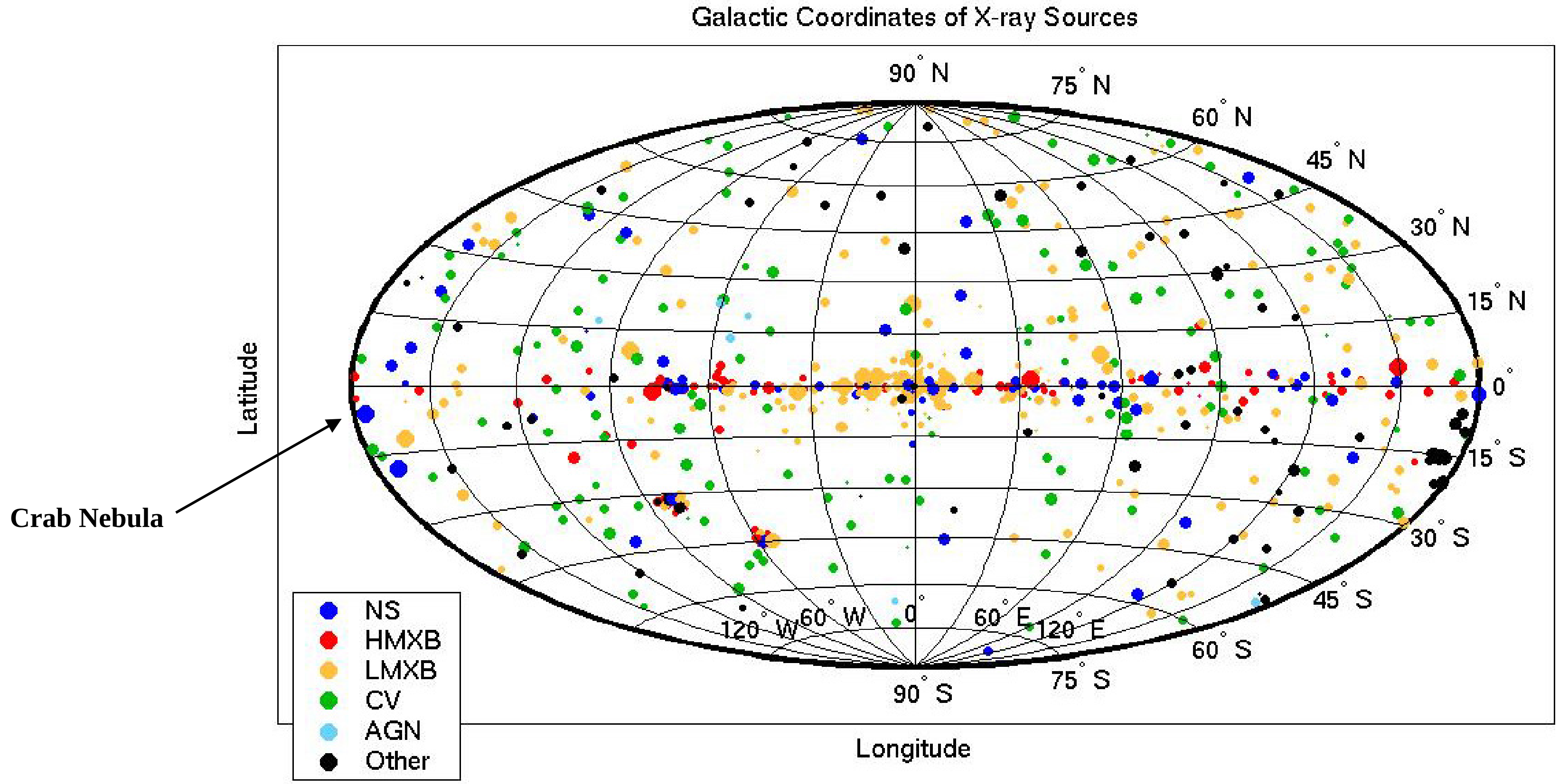
$$N_b = N_o + \Omega \Delta t_b + \frac{\Omega^2}{2} \Delta t_b^2 + \frac{\Omega^3}{6} \Delta t_b^3$$

Number of Pulses Arriving at Barycenter

X-ray Sky

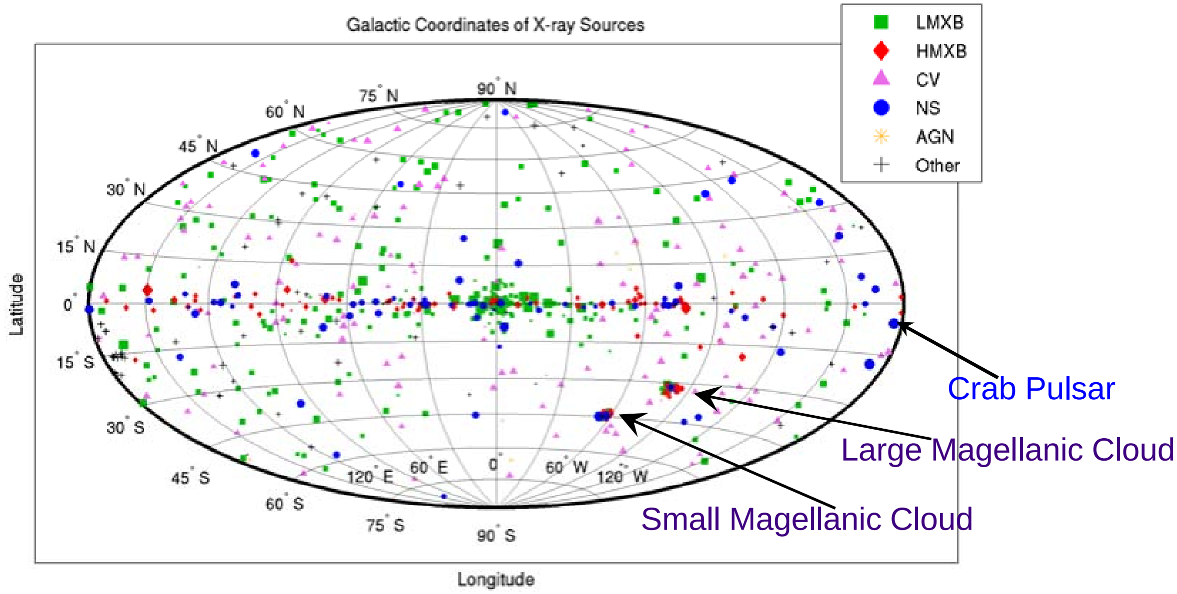
Catalogued by various telescope missions

- *ROSAT* mission catalogued 105,924 X-ray objects
  - ATNF has detected over 1400 radio pulsars
- Working catalogue contains 737 objects

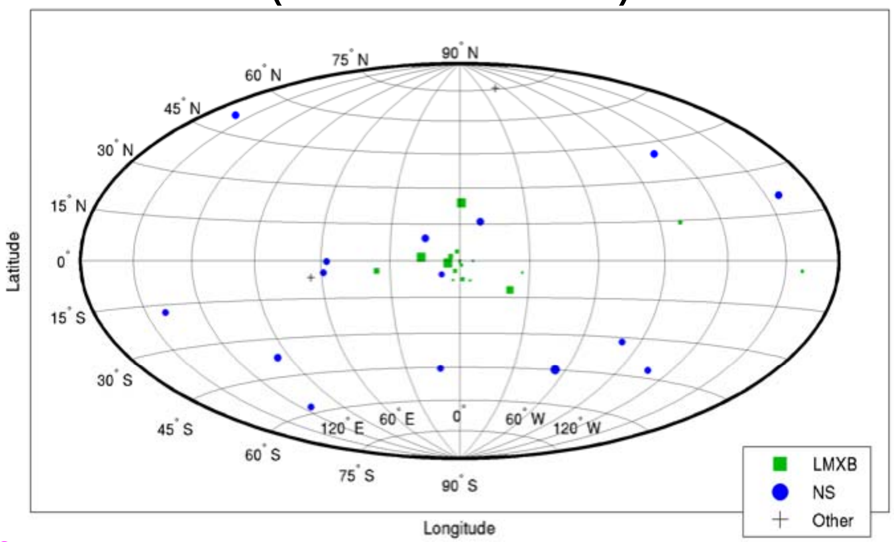


X-ray Source Location Plots

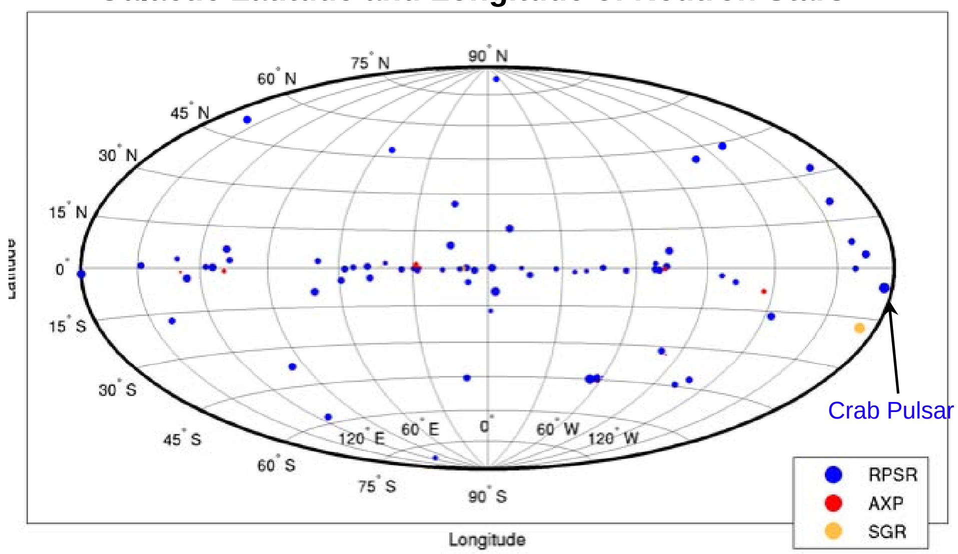
Galactic Latitude and Longitude of X-ray Sources



Galactic Latitude and Longitude of Millisecond Sources (Period < 0.02 seconds)

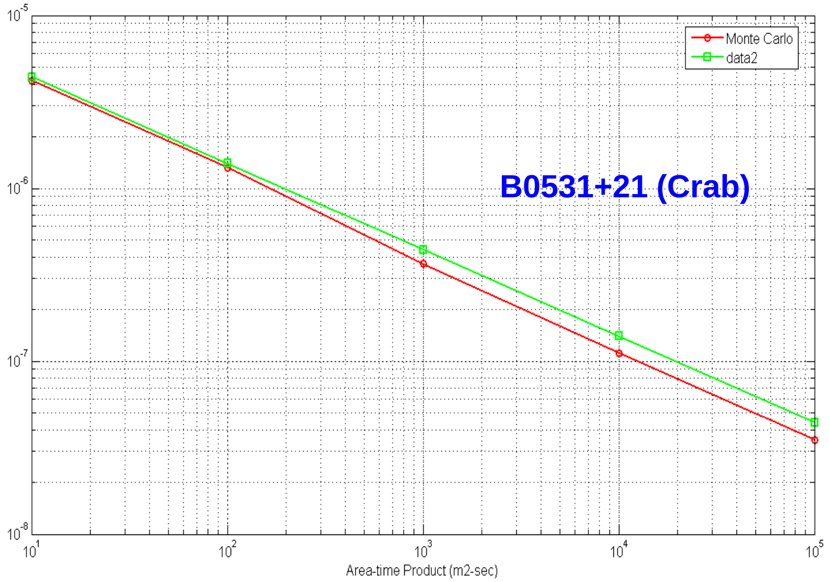


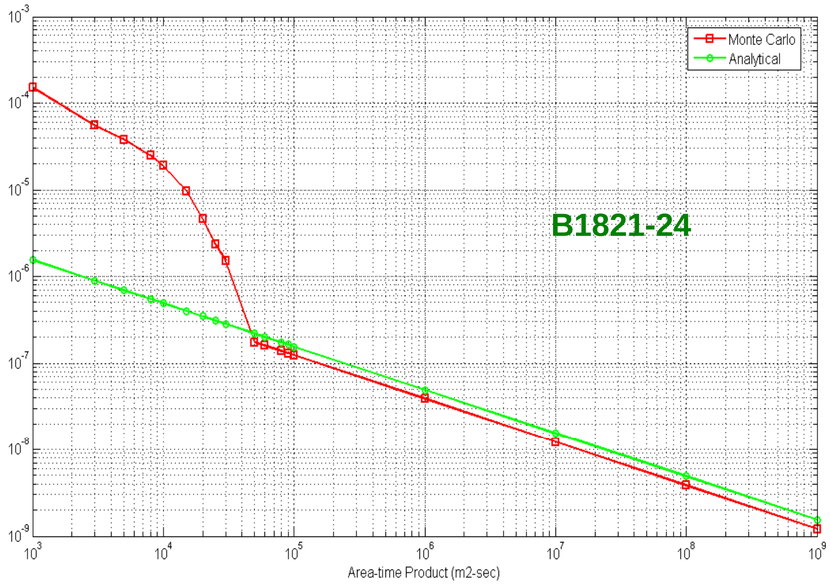
Galactic Latitude and Longitude of Neutron Stars



Pulsar Range Accuracy

TOA Measurement Accuracy versus Observation Time





Assumes constant X-ray background 5 ph/m²/s (2–10 keV)

Analyze photon processing for pulse TOA accuracy
- SNR ratio
- MLE
- Cramer-Rao bound

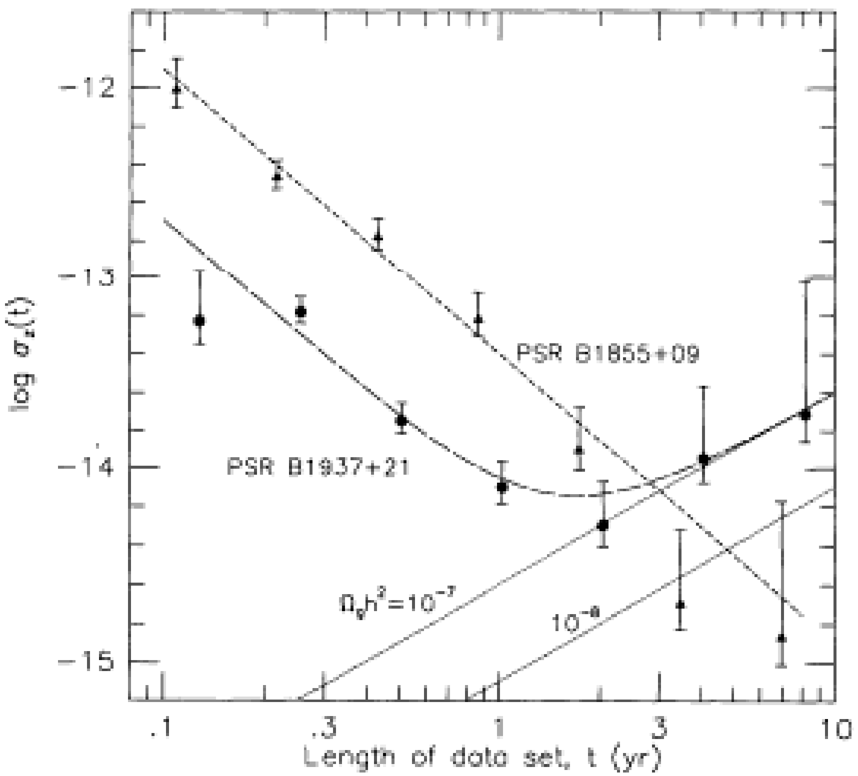
Model pulse shape, flux, pulse fraction, and X-ray background

Absolute Range Method, after 25000 s observation:
- B0531+21: 27 m
- B1821-24: 200 m
- B1937+21: 160 m

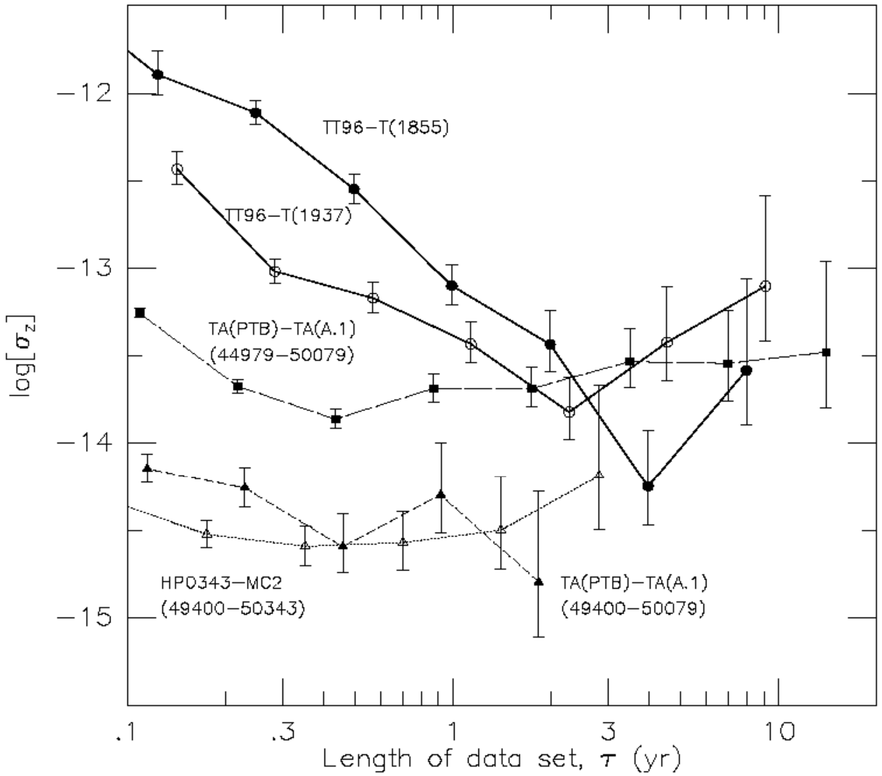
Delta-Phase Range Method, with 100 s phase-locked loop time blocks
- B0531+21: 500 m
- B1821-24: 2000 m (est.)
- B1937+21: 2000 m (est.)

Timekeeping Capability (Calibration of Pulsars)

Pulsars

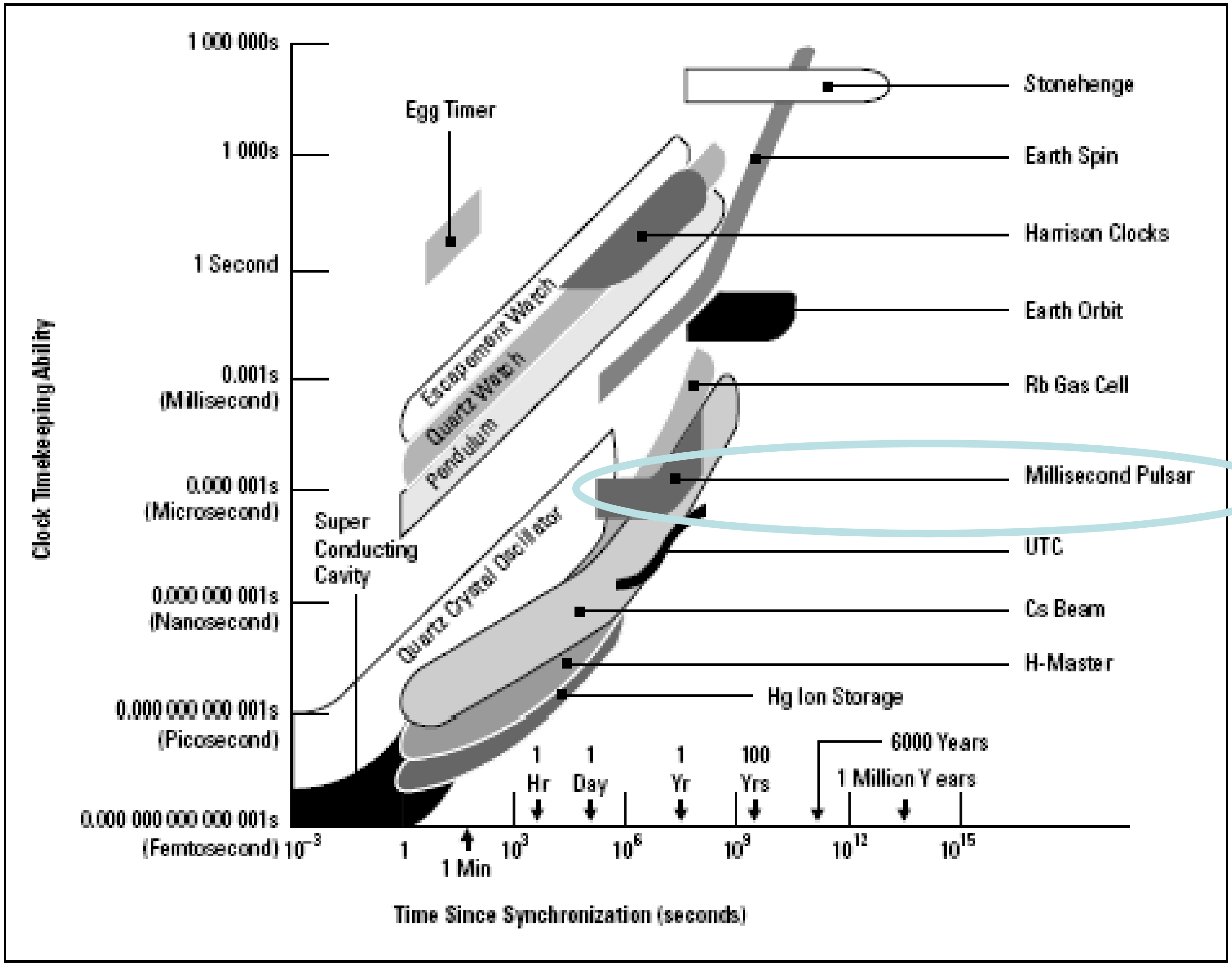


Atomic Clocks



Pulsars provide stable frequency standards.
Variance of millisecond pulsars (most precise astronomical clocks) is comparable to that of atomic clocks.
Pulsars could even be an independent reference standard for GPS

Timekeeping Ability of Different Clocks



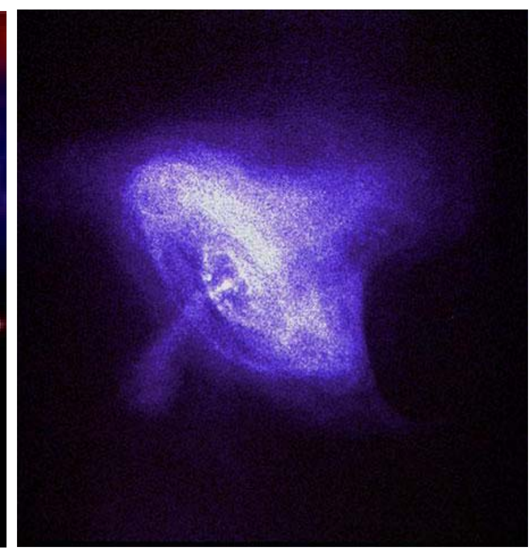
Allan, 97

What is the fundamental timekeeping limit?

History of X-ray Navigation

Historical Contributions to X-ray Navigation

1930's	Various	Theoretical predictions of neutron stars.
1967	A. Hewish & J. Bell	Discovery of radio pulsars
1971	Reichley, Downs & Morris	Described using radio pulsars as clocks
1974	Downs	Radio Pulsars for Interplanetary Navigation
1980	Downs and Reichley	Techniques for measuring arrival times of pulsars
1981	Chester and Butman	Described spacecraft navigation using X-ray pulsars
1988	Wallace	Planned use of radio stars for all weather navigation
1993	Wood	Proposed vehicle attitude and navigation using X-ray pulsars
1996	Hanson	Doctoral thesis on X-ray attitude determination
1999	USA Exp.	Earth orbit vehicle attitude determination using X-ray sources
2005	Sheikh et. Al	Navigation using X-ray sources



Evolution of a Program

X-ray Source **Nav**igation for Autonomous
Position Determination Program

2000: Sheikh takes ENAE 741 class and does a project on Pulsar Navigation

2001: Sheikh starts working on project under Dr. Pines

2002: UMD meets with NRL to discuss X-ray navigation and processing data sets from 1999 USA experiment.

2003: Sheikh processes time of arrival data from USA and gets pretty good navigation results.

2003: Pines interviews at DARPA and starts in October.

2004: Program approved by DARPA Director in February.

2004: Workshop on X-ray Sensors is held in May

2004: BAA released in August

2004: Sheikh wins GNC best paper award

2004: Proposals due in November

2005: Contracts awarded to two teams in May

2005: NASA and other agencies get interested in XNAV

2006: Phase I near completion

2007: Phase II hardware build to be initiated with possible transfer to NASA management

2007: Phase II not funded

2008-11: Elements of program still funded by NASA and DARPA (XTIM, XNAV elements)

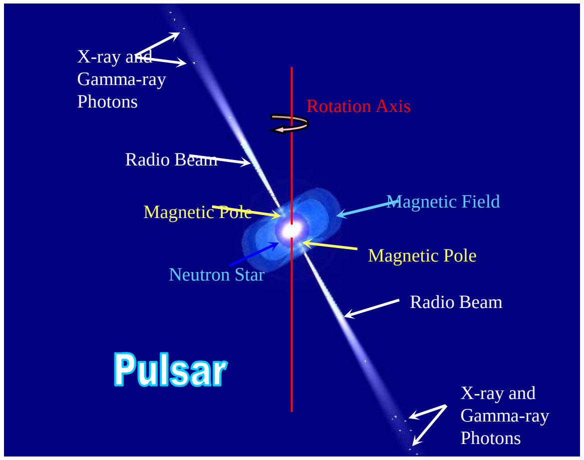
XNAV Program Vision

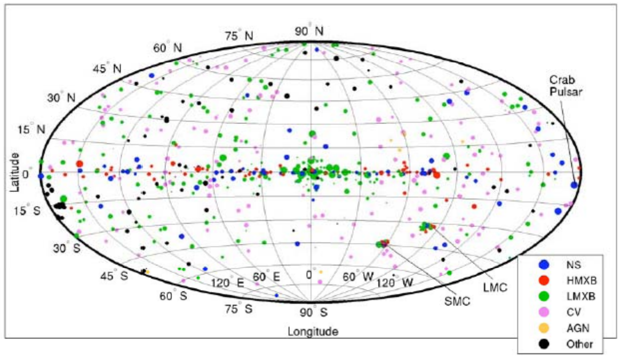
Provide a GPS-free, spacecraft autonomous navigation capability with a position accuracy < 30 m SEP

Provide this capability <u>anywhere</u> in the solar system

- **Develop a revolutionary navigation capability exploiting celestial X-ray sources such as periodic X-ray pulsars for time, position and attitude determination.**
  - **Develop high fidelity catalog of candidate sources.**
  - **Develop new X-ray sensors to meet stringent imaging and timing requirements.**
  - **Develop advanced navigation algorithms incorporating X-ray photon time of arrival data.**

- **System capable of operating in various orbit scenarios:**
  - **LEO, HEO, GEO, Cislunar, Interplanetary**





XNAV Program Description

Motivation: Provides an autonomous navigation capability independent of GPS with < 30m SEP.

Objective: Develop a revolutionary attitude and navigation capability exploiting periodic celestial sources such as pulsar stars, as well as other non-periodic sources in the X-ray band.

Approach: Determine spacecraft time, position, and attitude using X-ray sources.

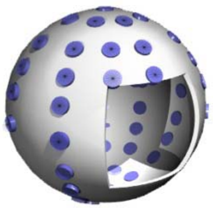
Goals: Determine SEP in space using pulsars as pseudo lighthouses and X-Ray clocks.

Payoffs:

- Autonomous navigation for DoD s/c
- Accurate autonomous natural celestial timing source for military assets
- Provide S/C attitude
- Operational range where GPS is not available (LEO, HEO, GEO, Cislunar, Interplanetary)

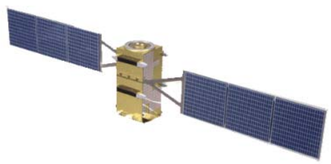
Elements of Operational System

Notional X-Ray Detector System

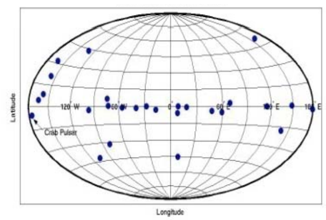


X-ray Imager and Photon Counter

Notional Satellite

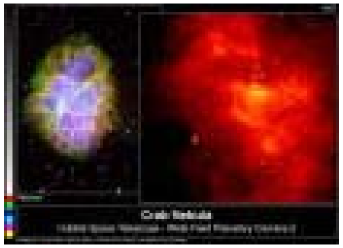


Pulsar Catalogue



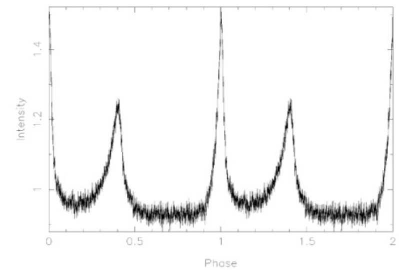
Location and Properties

Pulsar Detection



Crab Nebula

Pulsar Timing Models



Navigation Algorithms $\Delta t_b = \Delta\tau + \frac{\hat{n}\bullet\vec{r}}{c} - \frac{1}{2c\|\vec{D}\|}\left(|\vec{r}|^2 - (\hat{n}\bullet\vec{r})^2\right) + \frac{2GM_{sun}}{c^3}\ln\left|\|\vec{r}\| - (\hat{n}\bullet\vec{r})\right| + \frac{1}{c^2}(\vec{v}\bullet\vec{\rho})$

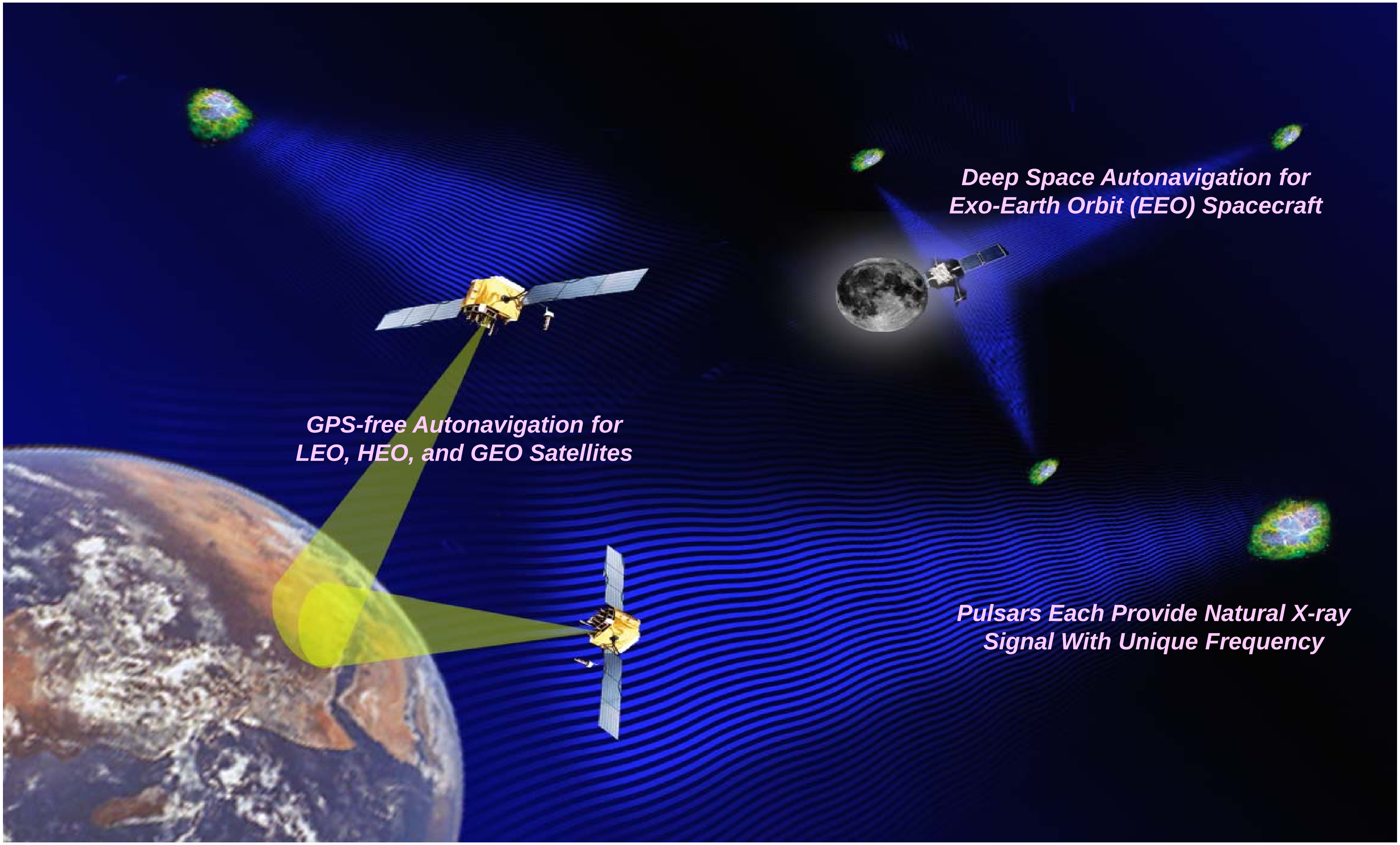
TECHNICAL ISSUES TO BE ADDRESSED

- Determination of Source locations
- Development of Pulsar Timing Models
- Detector design and performance
- Development of Navigation Algorithms
- Evaluation of System Performance
- Evaluation of Terrestial, LEO, GEO, HEO, Interplanetary Applications

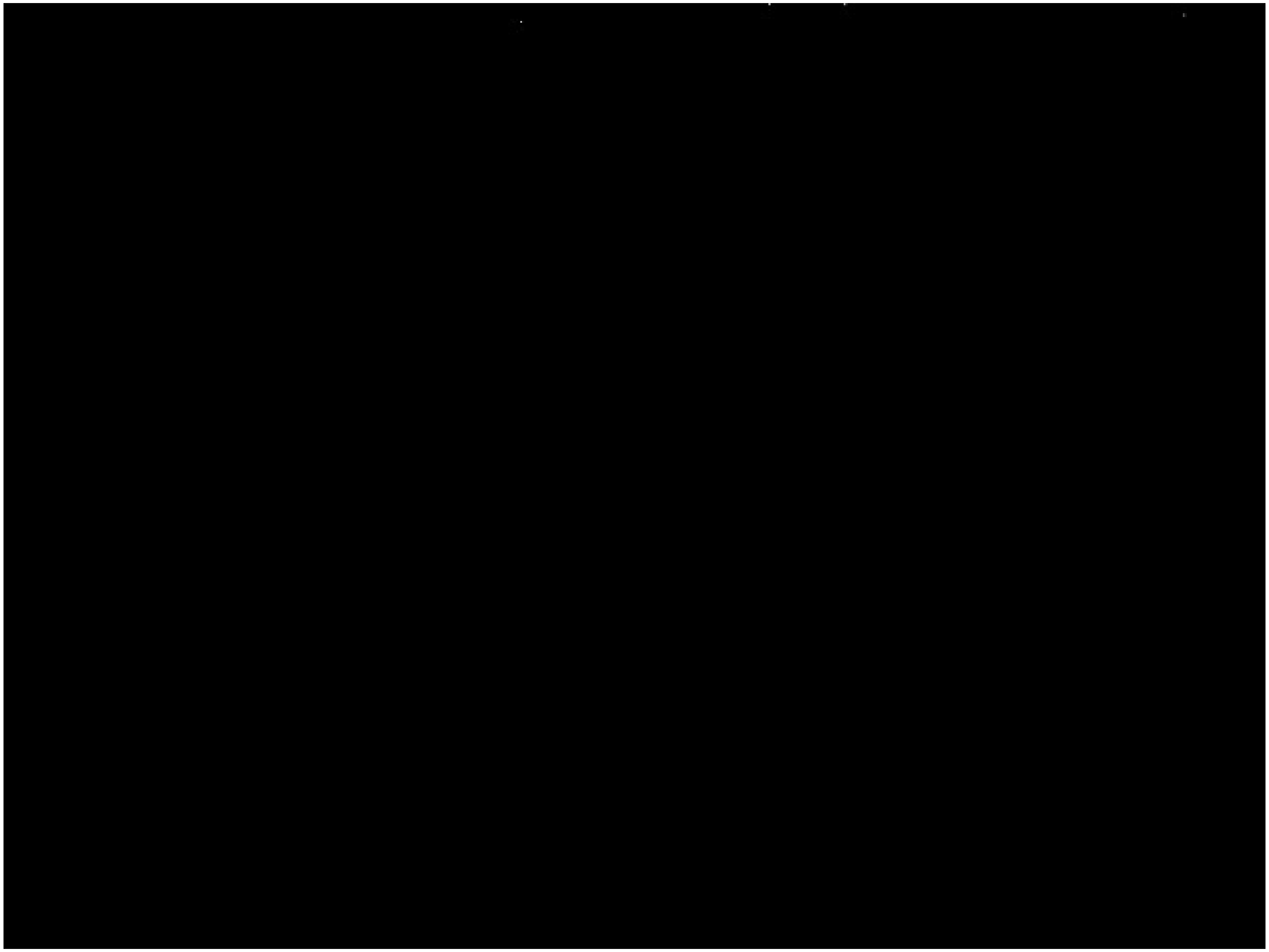
PULSAR SOURCES

- Pulsars can be viewed in optical, radio, infrared, X-ray, and gamma-ray wavelengths
- X-ray pulsars are bright in the X-ray band
- X-ray pulsars can only be viewed outside the earth’s atmosphere

Notional XNAV CONOPS



XNAV Animation



XNAV Performers/Gov. Teams at a Glance

XNAV Phase 1 performer teams:

- **Team 1: Naval Research Lab (prime)**
  Subcontractors:
  - **Brookhaven National Lab**
  - **MIT/LL**
  - **MIT**

- **Team 2: Ball Aerospace (prime)**
  Associate contractors:
  - **National Institute of Standards and Technology**
  - **Los Alamos National Lab**
  - **Johns Hopkins University Applied Physics Lab**
  - **UCBerkeley, Univ. of Leicester via subcontract to LANL**

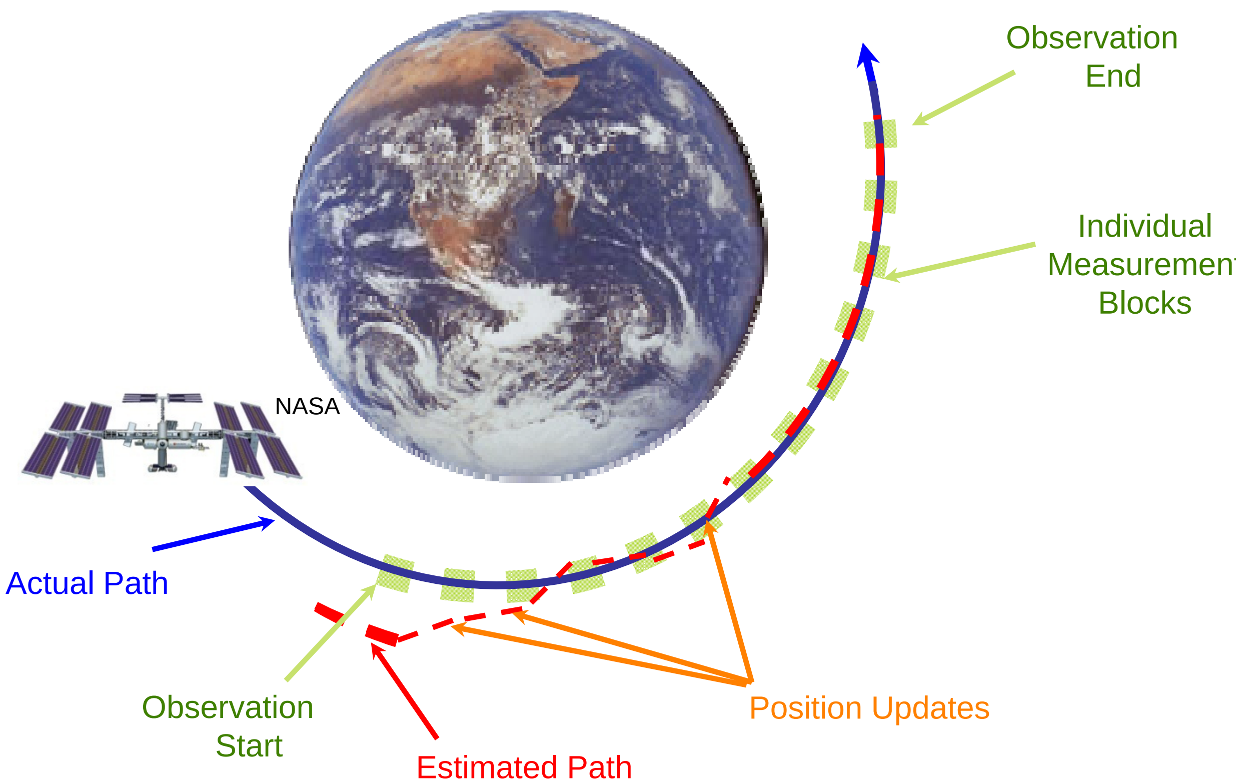
- **NASA Goddard Space Flight Center (GSFC) X-ray Test Facility**

Position Updates From Delta-Range

– Accumulate photons over <u>short</u> time blocks
– Compute phase and delta-phase over time
– Continually correct position estimate
– Correct only along line of sight to pulsar


NASA

Blend dynamics and measurements in Kalman Filter




NASA/CXC/ASU/J.Hester et al.

NKF Performance Summary

Orbit	Case	Measurement Type	Minimum SEP (m)		
			After 1000 s	After One Orbit	After One Day (86400 s)
ISS	3 Pulsars	Absolute Range	336	157	171
	Crab-Only	Absolute Range	1083	154	161
	Crab-Only, Low Q & I.C.	Absolute Range	1083	164	72
	Crab-Only	Relative Range	340	89	65
	Crab-Only, Low Q & I.C.	Relative Range	187	64	24
GPS	3 Pulsars	Absolute Range	251	238	249
	Crab-Only	Absolute Range	251	410	334
	Crab-Only, Low Q & I.C.	Absolute Range	137	187	113
	Crab-Only	Relative Range	128	145	75
	Crab-Only, Low Q & I.C.	Relative Range	60	35	26
GEO (DirecTV 2)	3 Pulsars	Absolute Range	249	770	445
	Crab-Only, Low Q & I.C.	Absolute Range	136	319	140
	Crab-Only, Low Q & I.C.	Relative Range	40	79	36

I.C. =
Initial Condition Error

XNAV Phase I Feasibility Demonstrated

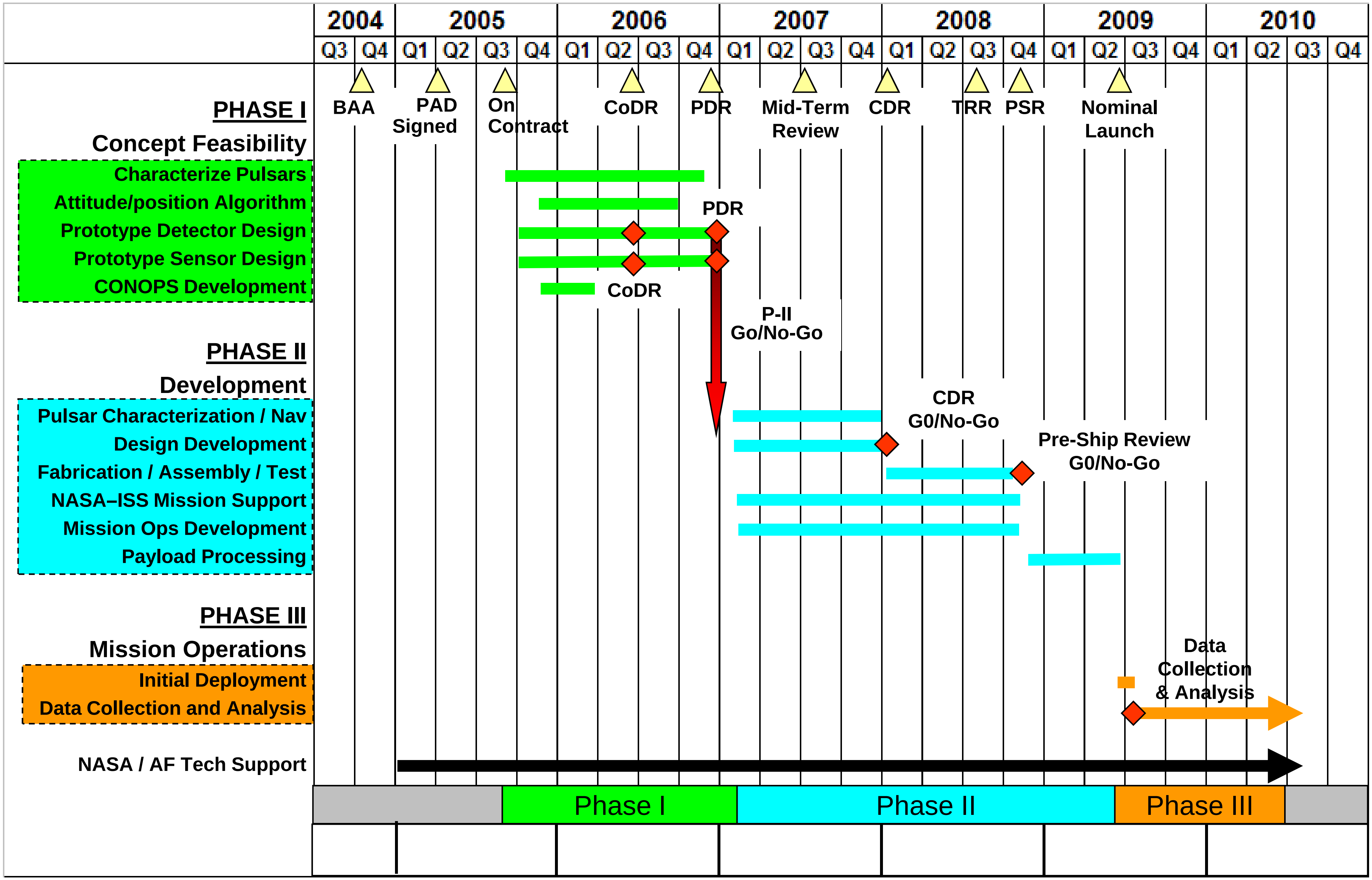
GPS-free, spacecraft autonomous navigation capability, anywhere in the solar system, with a position accuracy < 30 m SEP

At the end of XNAV Phase I (September 2006), DARPA:

- Identified more than 10 candidate pulsars with navigation-grade characteristics
- Completed X-ray sensor trade studies and down-selected to an optics/detector concept which meets XNAV timing and sensitivity requirements
- Completed fabrication of a timing sensor element consisting of the selected X-ray optics, ultra-fast detectors, and readout electronics
- Performed characterization and performance testing of the X-ray timing sensor element at GSFC X-ray test facility to verify the approach meets XNAV requirements
- Demonstrated prototype navigation algorithms for pulsar “clock recovery” and spacecraft position/velocity determination
- Completed a Preliminary Design of an XNAV demonstration payload appropriate for transport aboard the Shuttle and hosting on one of the International Space Station’s (ISS) Express Logistics Carrier (ELC) platforms
- Negotiated an MOA with HQ NASA for integration and transport aboard STS-128 (ISS flight ULF3), hosting aboard the ISS, and XNAV payload data dissemination

XNAV Program Schedule

For Official Use Only



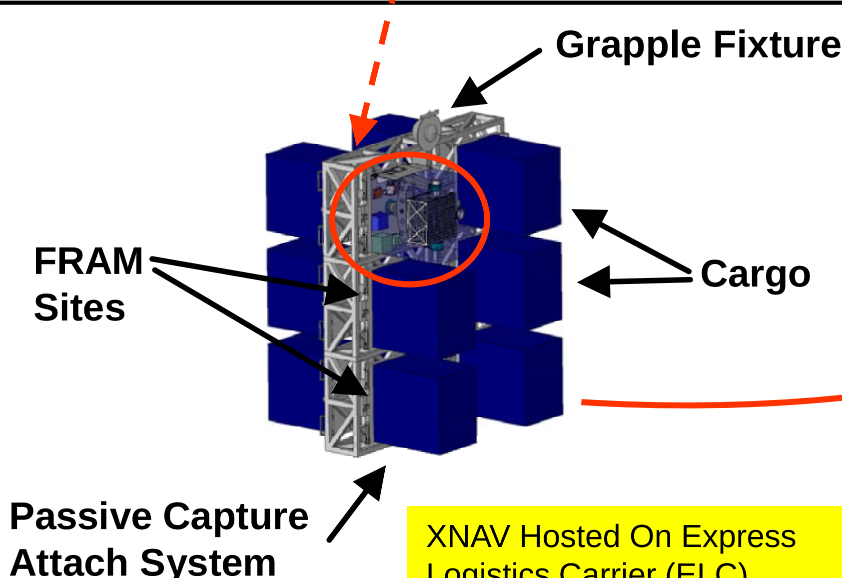
XNAV Phases II and III Development and Demonstration Program

XNAV Payload

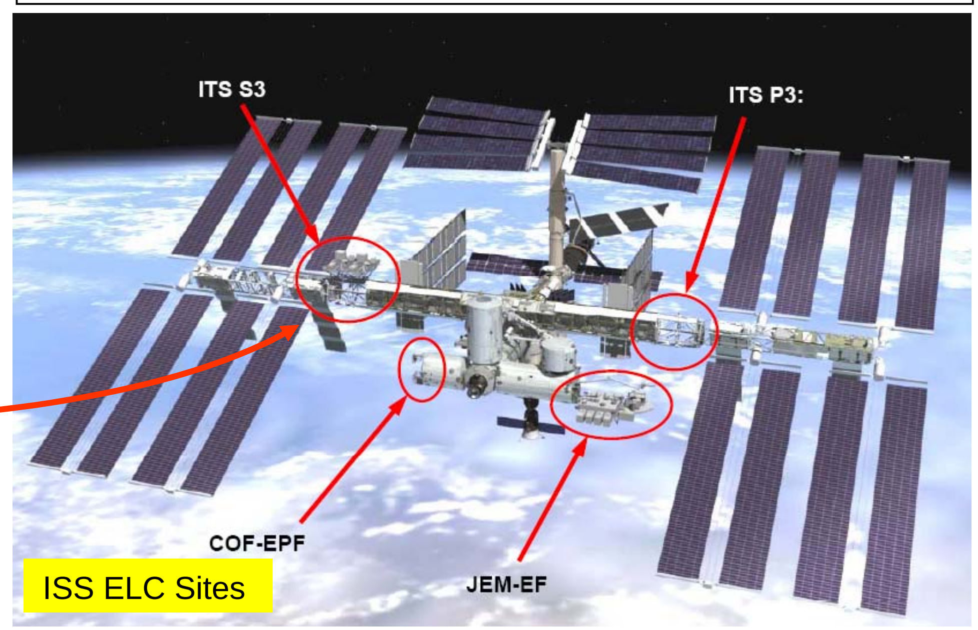
- **NFOV and WFOV Sensors / Electronics**
- **Validation Subsystem**
  - **GPS**
  - **IMU**
  - **Star Trackers (2)**
- **Gimbal Assembly**
- **Payload Processing and Interfaces**
- **RbAtomic Clock**
- **Thermal Control System**
- **ExPA Adapter Plate on FRAM**

XNAV Program Milestones

- Phase II
  - Purchase long leads parts
  - Develop detailed XNAV payload design
  - Critical Design Review (Go/No-go decision #1)
  - Fabricate, integrate, and test XNAV payload
  - Pre-ship Review (Go/No-go decision #2)
  - Shipment and integration on ISS ELC
- Phase III
  - Launch, transport to ISS, and integration onto ISS
  - Begin XNAV demo – data collection and analysis



XNAV Hosted On Express Logistics Carrier (ELC)



ISS ELC Sites

Spacecraft Position Determination

Reference: Space Mission Analysis and Design, Ed. Larson and Wertz, 1992.

Method	Advantages	Disadvantages	Operating Range	Accuracy (3σ)
Ground-based Tracking Systems	- Traditional approach -- Methods and tools well established	- Accuracy depends on station coverage -- Not autonomous/operation intensive	LEO only	5 - 100 km
Landmark/Ground Object Tracking	- Can use data from observing payload	- Landmark id may be difficult -- May have geometry singularities	Principally LEO	Several km
Stellar Refraction (Horizon Crossings)	- Could be autonomous for pos & att - Uses attitude-sensing hardware	- Fairly new concepts (not mature?)	Principally LEO	150 m - 1 km
TDRS Tracking System	- NASA spacecraft - High accuracy - Same hardware for tracking & data	- Not autonomous - Mostly NASA missions	LEO	???
Satellite Crosslinks	- Can use satellite crosslink hardware	- Unique to each constellation - Only relative position (no absolute) -- Potential problems with system deployment and S/C failures	LEO	<10m (in theory)
Star/Moon Sextant	- Could be autonomous for pos & att	- Fairly new concepts (not mature?) - Heavy and high power	LEO to GEO	250 m
Sun, Earth & Moon Observer	- Could be autonomous for pos & att - Uses attitude-sensing hardware	- Flight tested -- Initialization and convergence depend on geometry	LEO to Interplanetary	100 m-400 m (in LEO)
Global Positioning System	- High accuracy - Full nav solution: pos, att, and time	-- Only semi-autonomous (GPS system maintenance)	LEO (< GPS)	15 m-100m (in LEO)
X-ray Pulsar System	- High accuracy - Full nav solution: pos, att, and time	- New concept - Depends on non-controlled transmitters	LEO to Interplanetary	30 m (or better?)

Spacecraft Attitude Determination

Reference: Space Mission Analysis and Design, Ed. Larson and Wertz, 1992.

Method	Advantages	Disadvantages	Operating Range	Performance
Inertial Measurement Unit (gyros and accels)	- Angular rate data and acceleration	- Require external aide	LEO to Interplanetary	Gyro drift rate: 0.003°/hr to 1°/hr Accel linearity: 1 to 5 *10-6 g/g^2
Sun Sensors	- Can use data from observing payload	- Require unobstructed view of sun	LEO to Interplanetary	0.005° to 3°
Star Sensor - Cameras - Trackers/Mappers	- High accuracy	- Expensive	LEO to Interplanetary	0.0003° to 0.01°
Horizon Sensor - Scanner/Pipper - Fixed Head (Static)	- Infrared sensing of earth limb	- Low operating range	LEO	0.1° to 0.25°
Magnetometer	- Simple, reliable, lightweight	- Uses earth magnetic field - - May require separation from payload	LEO	0.5° to 3°
Global Positioning System	- High accuracy - Full nav solution: pos, att, and time	- - Only semi-autonomous (GPS system maintenance)	LEO (< GPS)	0.005° to 3° (antenna sep.)
X-ray Pulsar System	- High accuracy - Full nav solution: pos, att, and time	- New concept - - Depends on non-controlled transmitters	LEO to interplanetary	0.0003° to 0.01° ????

Publications/Patents

Journal Papers

•Sheikh SI, Pines DJ, Ray PS, et al. Spacecraft Navigation Using X-ray Pulsars Journal of Guidance, Control and Dynamics 29 (1): 49-63 JAN-FEB 2006

•S.I. Sheikh, D.J. Pines, "Recursive Estimation of Spacecraft Position Using X-ray Pulsars*", Vol. 53, Journal of the Institute of Navigation*.

Conference Papers

The Use Of X-Ray Pulsars For Spacecraft Navigation
Sheikh, Suneel I; Pines, Darryll J; Ray, Paul S; Wood, Kent S; Lovellette, Michael N; Wolff, Michael T
Advances in the Astronautical Sciences. Vol. 119, Part I: Spaceflight Mechanics 2004, pp. 105-119. 2005

FLIGHT EXPERIMENT: NAVIGATION STUDIES UTILIZING THE NRL-801 EXPERIMENT AND THE ARGOS SATELLITE

K.S. Wood (E.O. Hulburt Center for Space Research, Code 7621, Naval Research Laboratory, Washington DC 20375)

Published in *Small Satellite Technology and Applications III*, ed. B. J. Horais, SPIE Proceedings vol. 1940, pp. 105-116 (1993).

PhD Dissertation

Principles of **X-ray Navigation**. John Eric Hanson. Stanford Linear Accelerator Center. Stanford University. Stanford, CA 94309. SLAC-Report-809 **...**

PATENT:

Navigational system and method utilizing sources of pulsed celestial radiation

Document Type and Number:

United States Patent 20050192719 Kind Code: A1

http://www.freepatentsonline.com/20050192719.html

Abstract:

A system and method for navigation utilizing sources of pulsed celestial radiation are provided. A spacecraft, satellite, or other vehicle (12) has a pulse sensor (22) mounted thereto for detecting signal pulses (14) generated by a plurality of pulsars or other celestial objects (16). The detected signal pulses (14) are synchronously averaged at the known period of the pulsar or other celestial object (16) with respect to a timer (24). Timer (24) measures the pulse time of arrival at the pulse sensor (22) by comparing the pulse signal (14) with a pulse shape template (52), and a processing means (30) calculates the offset time between the measured pulse time of arrival at sensor (22) with a calculated pulse time of arrival at the solar system barycenter (SSBC). The positions and pulse profile characteristics of the pulsars (16) are stored in a digital memory (34) and combining the calculated time offset with the known positions of pulsars (16), the navigational position, velocity, attitude and time of spacecraft (12) with respect to the SSBC can be calculated.

Summary

- XNAV provides a autonomous navigation capability for DoD missions:
  - Not instantaneous like GPS. Requires long term observations (100s to 1000s seconds)
- Superior alternative to optical star cameras
  - Higher accuracy due to extremely short wavelengths (sub-arcseconds)
  - Inherently radiation hardened due to their relatively large feature sizes, making them useful in high radiation environments.
  - Cannot be blinded by laser/Sun/Moon/Earth crossings, eliminating need for keep out zones.
  - Low risk of damage by contaminants (X-rays get through)
- Time accuracy better or equivalent to cesium atomic clocks
- Supports future growth in non-LEO DoD assets
- Has lead to a revolution in spacecraft position, attitude and time determination (Europe, Russia, and China).

Potential Benefits

New navigation system

Single system could provide full navigation solution

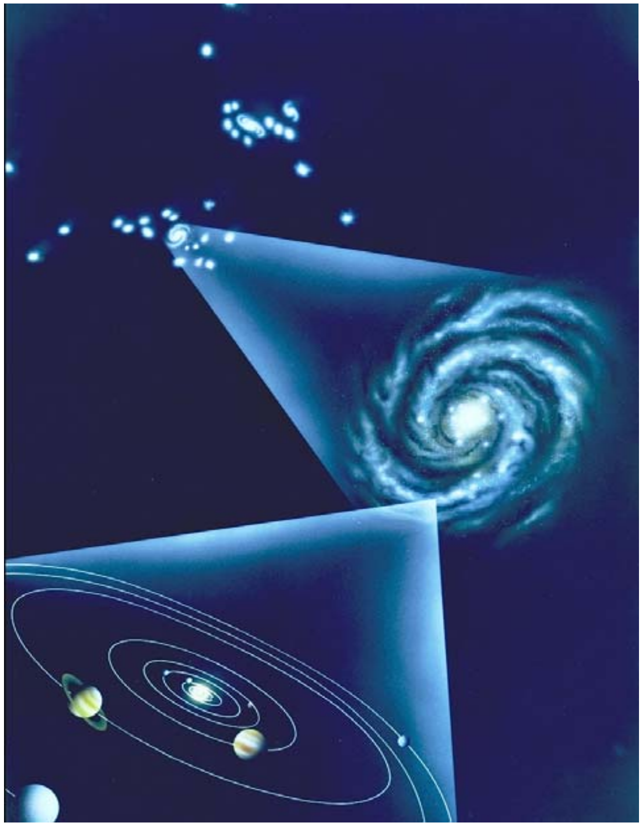
- Position, velocity, attitude, and time!

Could allow for autonomous vehicle operation

Backup for existing systems

Wide operating range

- LEO and GEO
- Highly elliptical orbits
- Lunar Orbits
- Interplanetary orbits
- Someday … interstellar orbits



XTIM

X-ray Timing System

Derek Trouneaur

- Goals: create a universal timescale, Pulsar Time.
- Benefits:
  - Stability: Slave an atomic clock to an ensemble of pulsars over long observation times (weeks to months)
  - Autonomy: independent precise measurement of time. No regular communication with other assets.
  - Universality: Celestial sources making them available to any user. Could be used to correlate events measured between two s/c.