Precision Pulsar Timing in X-rays: Application to Spacecraft Navigation

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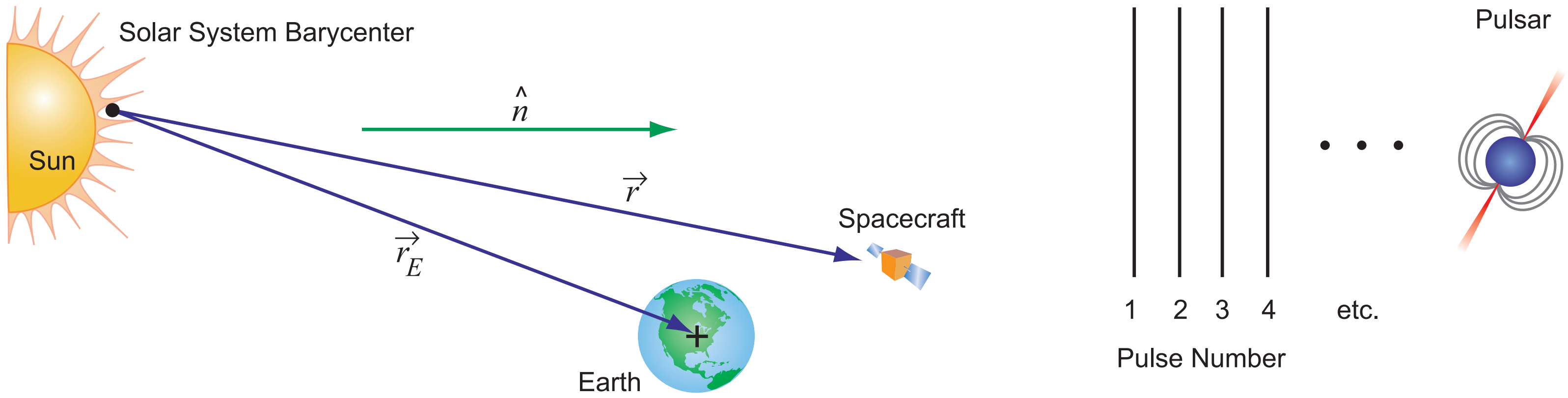
Introduction to X-ray Navigation



Pulsating X-ray sources, predominately rotation-powered pulsars, can be used as navigation beacons to provide position and time information for a spacecraft. This is the inverse problem to TEMPO and is a kind of natural analog to the Global Positioning System (GPS).

- ⇒ TEMPO: Given observatory position and clock corrections; use measured TOAs to fit parameters of timing model.
- ⇒ X-ray Navigation: Given pulsar timing models; use measured TOAs to fit for satellite position and clock corrections.

Requires an array of pulsars with excellent timing models that predict well into the future.

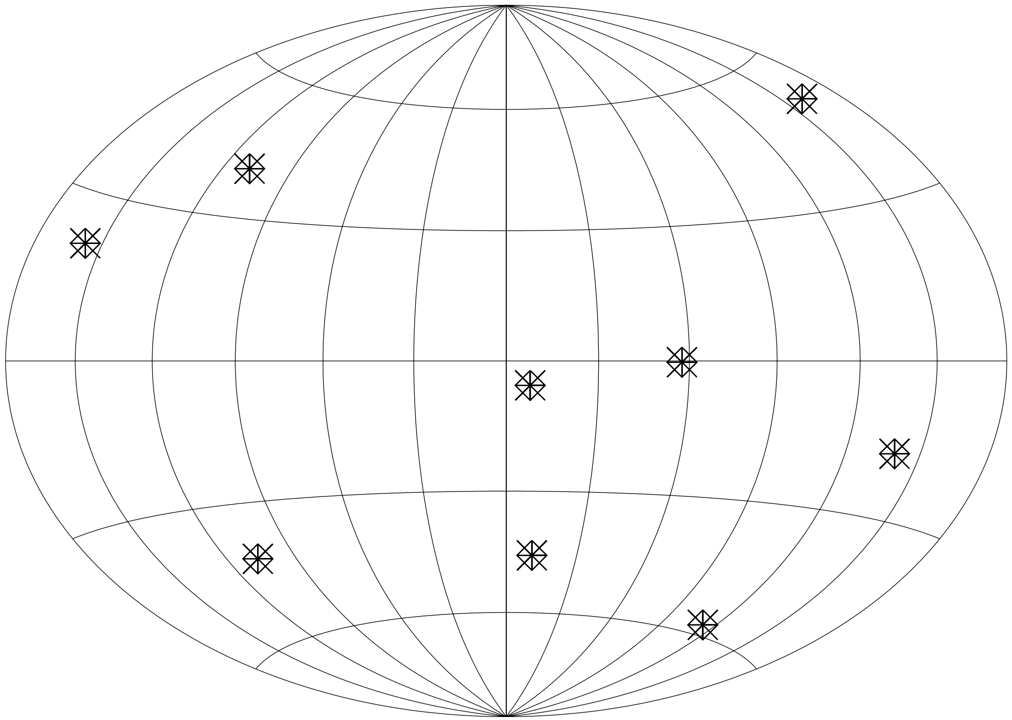
X-ray Millisecond Pulsars

There are currently 9 known rotation-powered millisecond pulsars that have detected X-ray pulsations. These could form the basis of a navigation system.

Name	P (ms)	Flux 2-10 keV ph/cm^2/s	Pulsed Fraction	Duty Cycle
B1937+21	1.55	0.0000507	0.9	0.06
B1821-24	3.05	0.0000468	0.9	0.026
J0218+4232	2.32	0.0000383	0.69	0.11
J1012+5307	5.26	0.0000092	0.77	0.09
J0437-4715	5.75	0.0000079	0.4	0.35
J2124-3358	4.93	0.0000046	0.56	0.40
J0030+0451	4.86	0.0000038	0.69	0.15
J0751+1807	3.48	0.0000038	0.52	0.31
J1024-0719	5.16	0.0000004	0.52	0.40

X-ray MSP Sky Distribution

In solving for the satellite position, the Geometric Dilution of Precision (GDOP) is determined by the sky distribution of sources and the TOA accuracy attained from each source. The sky distribution, in Galactic coordinates, is shown below.



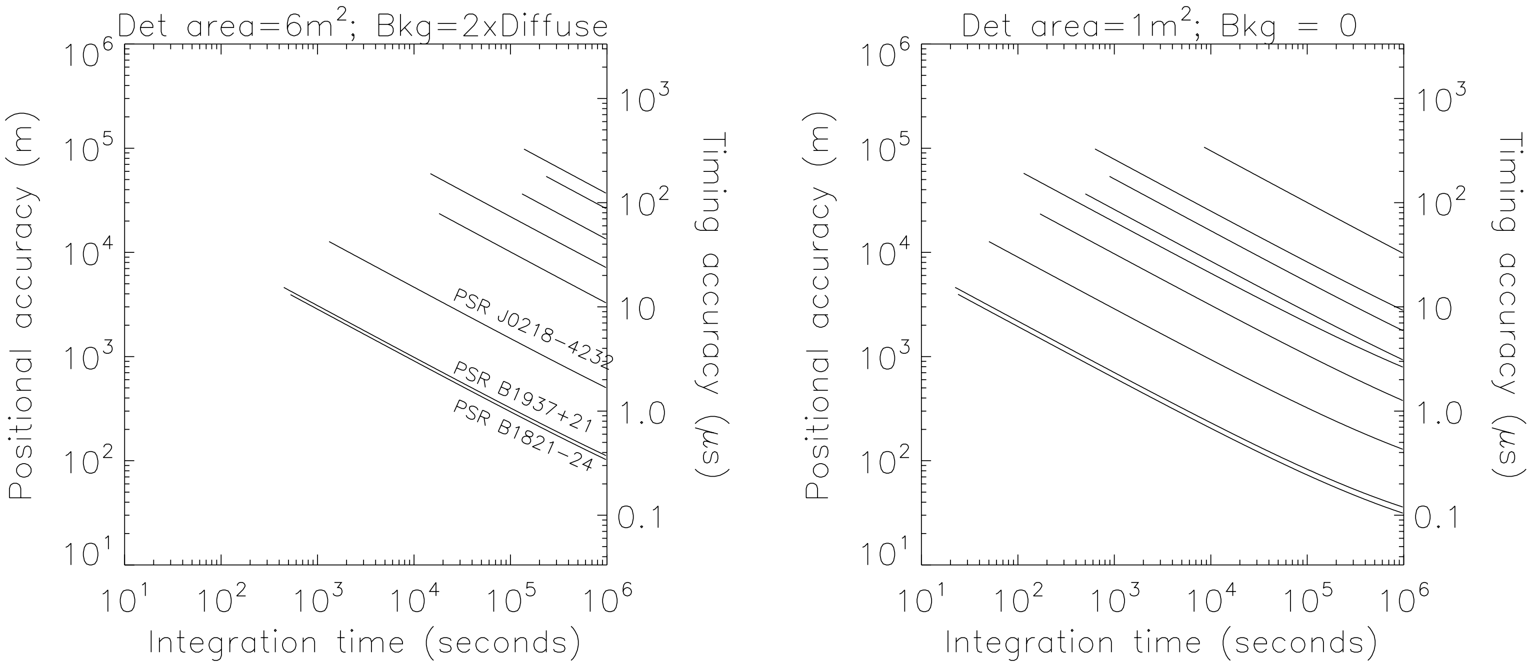
Prospects For More X-ray MSPs

The number of known millisecond pulsars has greatly increased recently (to ~ 130), thanks to the Parkes multi-beam survey and targeted searches with the GBT. The top few sorted by $\dot{E}/D^2$ are listed here, with known X-ray pulsars indicated with $\star$. This provides a good starting point for observations to look for pulsed X-ray emission.

Name	P (s)	DM (pc cm^{-3})	W50 (ms)	$\dot{E}/D^2$
$\star$ J0437-4715	0.005757	2.65	0.969	6.13e+35
$\star$ J2124-3358	0.004931	4.62	0.510	1.08e+35
$\star$ B1821-24	0.003054	119.86	0.150	9.34e+34
$\star$ B1937+21	0.001558	71.04	0.100	8.47e+34
B1957+20	0.001607	29.12	0.035	6.84e+34
$\star$ J0030+0451	0.004865	4.33	–	6.48e+34
$\star$ J1024-0719	0.005162	6.49	1.200	4.34e+34
J1744-1134	0.004075	3.14	–	4.09e+34
J1909-3744	0.002947	10.39	–	3.22e+34
B1257+12	0.006219	10.19	0.580	3.17e+34

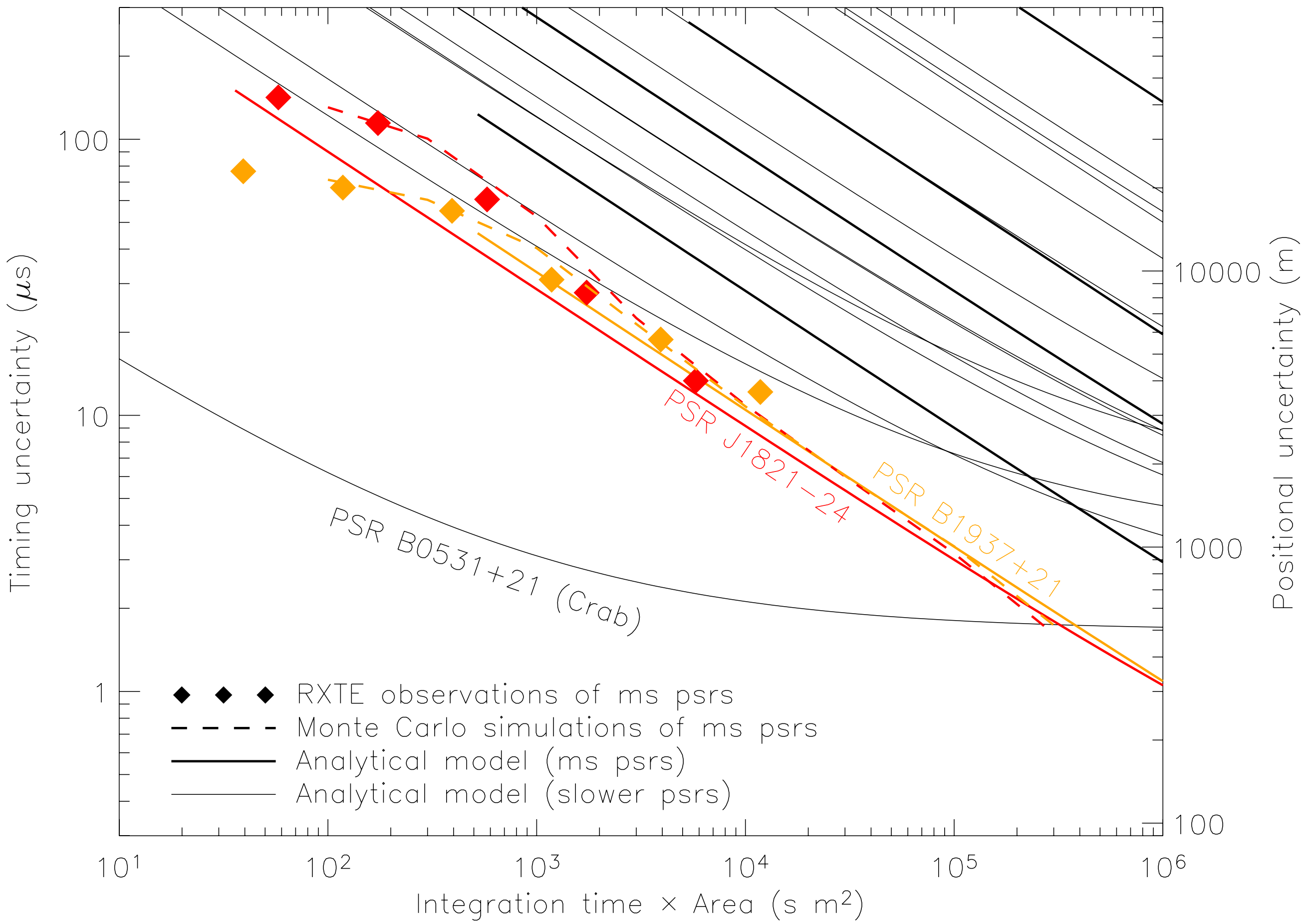
Achievable TOA Accuracy

Plot of the TOA accuracy expected for the known X-ray MSPs, and the Crab pulsar for comparison. The TOA error is estimated as the HWHM of the pulse divided by the detection signal to noise ratio. The left panel is for a collimated detector ∼10x RXTE while the right panel is for a large focusing instrument.



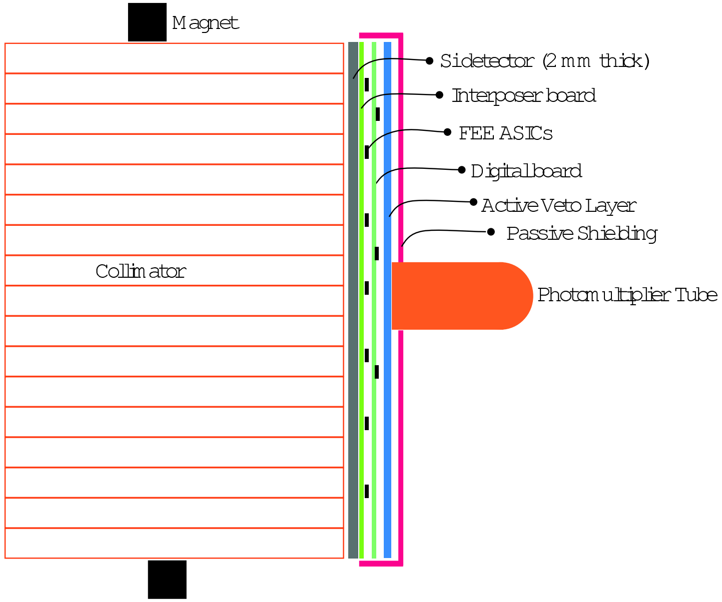
Comparison with RXTE Data

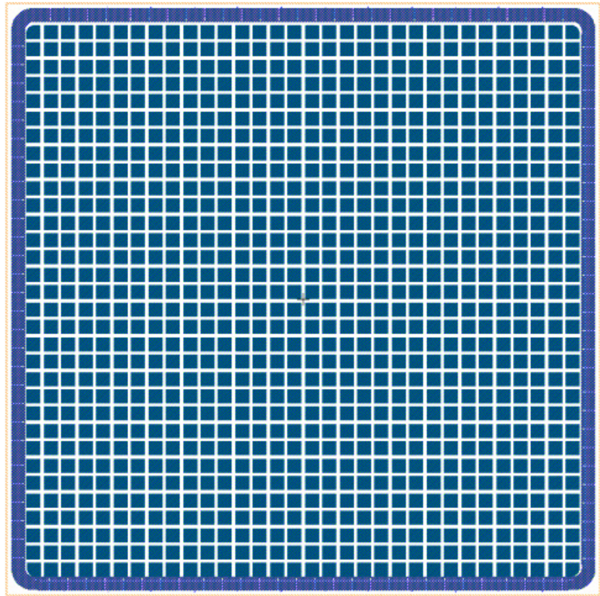
Plot of the measured TOA accuracy obtained with RXTE for PSR J1821-24 and PSR B1937+21 compared with our analytical model.



X-ray Detector Development

X-ray detector concept currently being developed to the laboratory prototype level.





- Detector element is 10 cm $\times$ 10 cm silicon that is 2 mm thick which is pixelated into 2.5 mm $\times$ 2.5 mm pixels.
- Target energy range is 2–30 keV; Time resolution goal is ~ 300 ns.
- Low-noise low-power front-end ASIC being developed by Brookhaven National Laboratory
- Each module operates on 1 W and has 81 cm^2 effective area.

Why Not Use Radio?

- Very large antennas required for precise timing of MSPs
- May require low-temperature electronics for receiver, which are impractical for space use.
- DM changes can not be predicted and dual-frequency measurements are required.
- Scintillation can cause large flux variations from day to day

Timing Model Accuracy Limitations

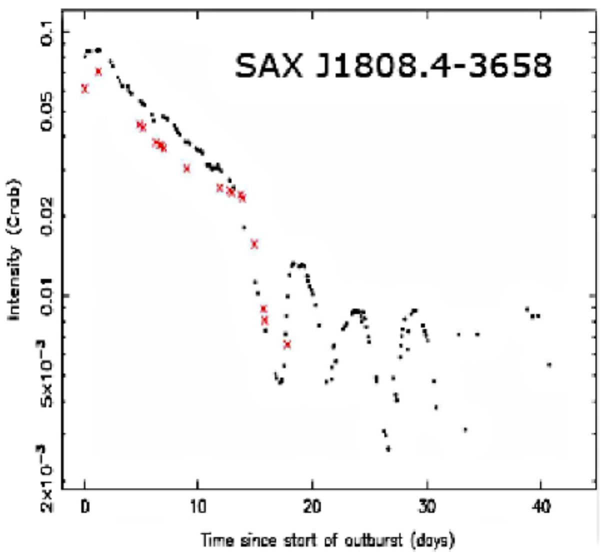
- Timing noise
- Transfer of timing model from radio to X-ray
  - Radio/X-ray phase alignment
  - Dispersion measure knowledge
- Pulse to pulse jitter.
- Accuracy of model parameters plus unmodeled residuals combine to limit the length of time into the future a model can usefully be extrapolated.

Accretion-Powered Millisecond Pulsars

Seven accretion-powered millisecond pulsars are also potentially useful for navigation, but have several drawbacks:

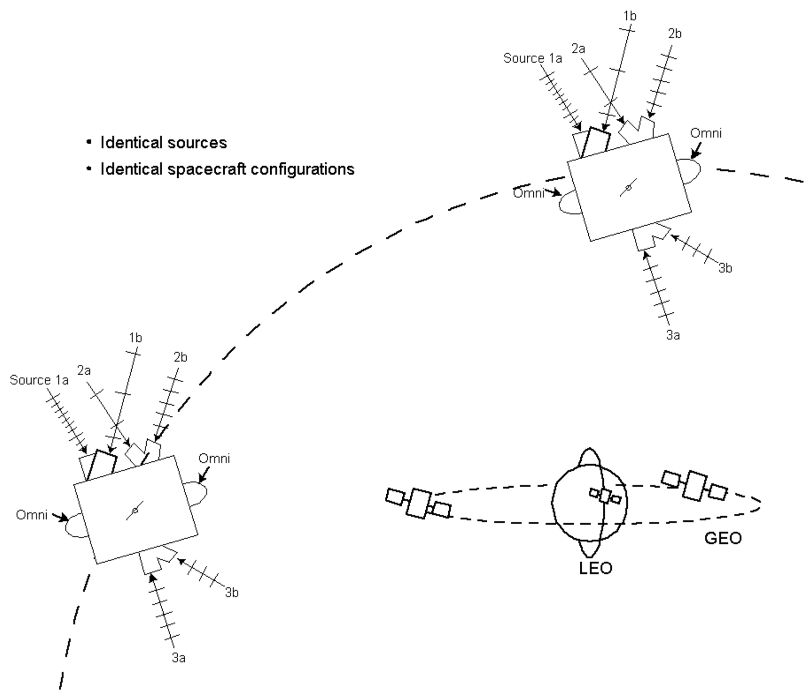
- Transient, only on for a month or so every couple of years.
- Nearly sinusoidal profiles $\Rightarrow$ poor TOA accuracy.
- Accretion torques cause additional timing noise.
- None have very good timing solutions so far because of small number of observations.
- Not radio pulsars, so they can't be timed from the ground.

But, when they are on, they are bright and have pulse fractions of $\sim 5\%$, so they are worth further study.



Potential Operations Concepts

- A supplement to Deep Space Network (DSN) tracking for interplanetary or interstellar missions
- A backup to GPS for critical satellites in the event of an interruption of GPS services.
- A time synchronization tool independent of GPS.



Future Work

- Study detector performance and evaluate various detector type to optimize signal-to-noise ratio for known MSPs.
- Validate model for TOA accuracy
- Work on techniques to reduce detector backgrounds.
- Search for pulsed X-rays from newly-discovered MSPs.
- Collect timing models for each MSP and evaluate model ability to extrapolate TOA predictions into the future.
- Evaluate various operations concepts and match with known sources and detector concepts.