Pulsar-based Navigation for Deep Space Probes

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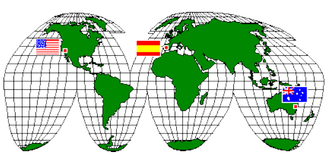
Overview

We are currently working on at least two areas that are relevant to advancing pulsar-based navigation strategies over the next few years. We have developed and are currently commissioning a state of the art, wide bandwidth, precision pulsar timing program for NASA's Deep Space Network. In order to demonstrate the capability of this system, we have begun weekly observations of a subset of millisecond pulsars (MSPs) with timing residuals better than 100 ns. One of the goals of this program is to eventually provide high cadence, precision timing of MSPs, as well as daily timing solutions of the Crab pulsar to NASA's NICER mission for high SNR, robust, cross correlation with NICER pulse profiles obtained in X-ray wavelengths. We are also developing an end-to-end simulation tool that incorporates many observational aspects of pulsar timing, including noise characteristics, detector response function, and geometrical constraints, as well as non-linear signal processing algorithms for enhanced deep-space navigation. The goal of this work is to mitigate the various error sources to dramatically improve the accuracy of pulsar-based navigation for deep space probes.

The Deep Space Network

The Deep Space Network (DSN) is the spacecraft tracking and communication infrastructure for NASA's deep space missions. The facility consists of three sites located in Goldstone in California, Robledo in Spain, and Canberra in Australia. These complexes are approximately equally separated in longitude, with multiple radio telescopes at each sites. At each of these sites is a 70m diameter antenna.

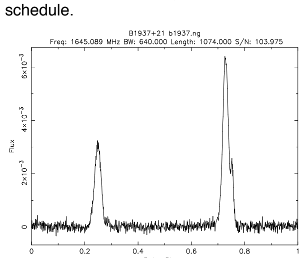


Location of DSN complexes.

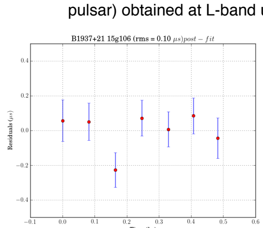
DSN 70m antenna

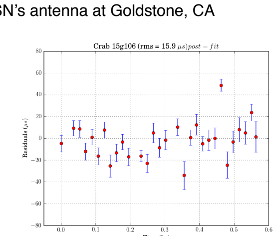
Pulsar Timing at the DSN

The 70m antennas of the DSN are equipped with a narrowband L-band feed. We are currently in the process of widening the available bandwidth to 500 MHz at two of the complexes, with future plans to do the same at the third complex. We are also planning on adding an additional polarization channel at two of the complexes. To match the expected increase in bandwidth, we have developed a dedicated pulsar timing backend capable of producing precision TOAs. The new backend is capable of processing over 500 MHz of bandwidth in real-time, using a farm of GPUs. We are now planning on developing automation techniques that will enable daily monitoring of the Crab pulsars as well as routine monitoring of a subset of MSPs, using short tracking gaps in the DSN schedule.



Pulse profiles and timing residuals for PSR B1937+21 and PSR B0531+21 (Crab pulsar) obtained at L-band using DSN's antenna at Goldstone, CA

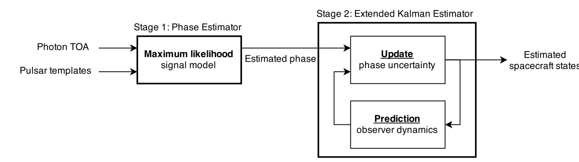




Positioning Estimation Techniques

Basic idea

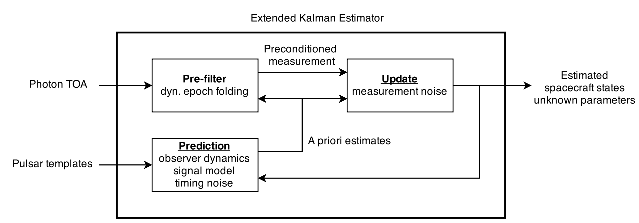
- Determine the spacecraft states (position, velocity) by observing pulsars
  - Track the phase of the pulsar signals relative to a reference frame
  - Estimate spacecraft states from the phase information



Disadvantages

- Two separate estimators usually means some information is lost.
  - Timing noise (Red noise) neglected.
  - Phase estimator is unaware of the motion of the observer.
- Difficult to obtain efficient maximum likelihood estimator for multiple estimates.

New Approach



Advantages

- Simplicity—single estimator
- Photon TOAs are processed in a dynamic manner
- Filtering architecture is flexible
  - Include timing noise, i.e. Brownian motion in phase or frequency
  - Include complex observer dynamics with disturbances
  - Include pulsar dynamical model
  - Estimate unknown parameters, e.g. frequency, background noise, etc.

Assumptions

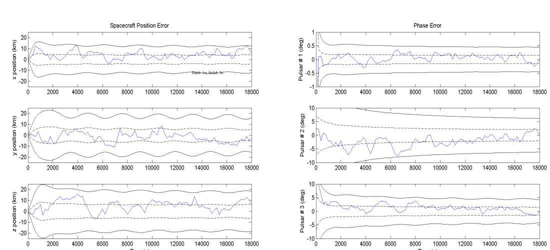
- Earth-centered reference system
- X-ray detector is located on a spacecraft in low Earth orbit (ISS-NICER)
- Observe 6 pulsars simultaneously and continuously (not necessary)
- Poisson detection process with noise
- Brownian motion in phase
- Small initial variance

Table 1: Employed Pulsar Parameters

Label	Pulsar	Freq. (Hz)	Gal. Longitude (°)	Gal. Latitude (°)
1	B0531+21	29.8	184.56	-5.78
2	B1821-24	327.9	7.8	-5.58
3	J0030+0451	205.3	113.14	-57.61
4	J0437-4715	173.6	253.39	-41.96
5	B1937+21	641.0	57.51	-0.29
6	J0218+4232	431.0	139.51	-17.53

Table 2: Employed Pulsar Rates

Label	Pulsar	λ_b (photon/s)	λ_s (photon/s)	SNR	Direction
1	B0531+21	1386	66	1.7320	x
2	B1821-24	0.22	0.029	0.0581	x
3	J0030+0451	0.2	0.193	0.3079	z, y
4	J0437-4715	0.64	0.283	0.2978	z, y
5	B1937+21	0.24	0.029	0.0559	x, y
6	J0218+4232	0.2	0.082	0.1517	x, y, z



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