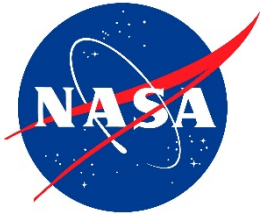
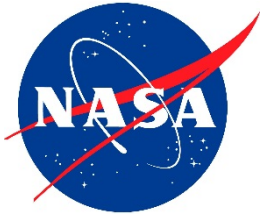


Application of X-Ray Pulsar Navigation: A Characterization of the Earth Orbit Trade Space

WAYNE YU



Agenda

- Introduction
- Background
- Problem Statement
- Simulation Overview
- Results and Analysis
- Conclusions

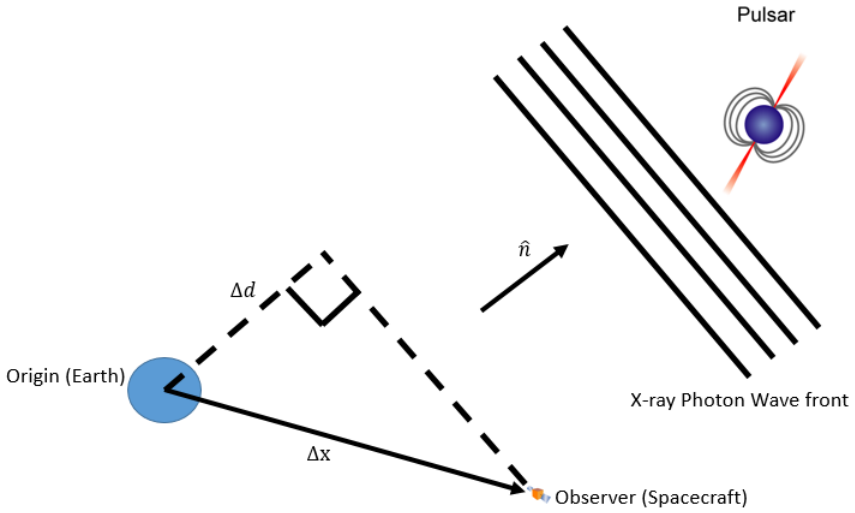
X-ray Pulsar Navigation (XNAV)

A Celestial Navigation System

- A GPS-like system
- Multiple pulsars can provide a state measurement in 3-D

Applicable from Earth to Interstellar Trajectories

- Provides both position and timing information
- Onboard navigation
- Relative formation flying missions
- Interplanetary missions
- Planetary missions beyond Saturn

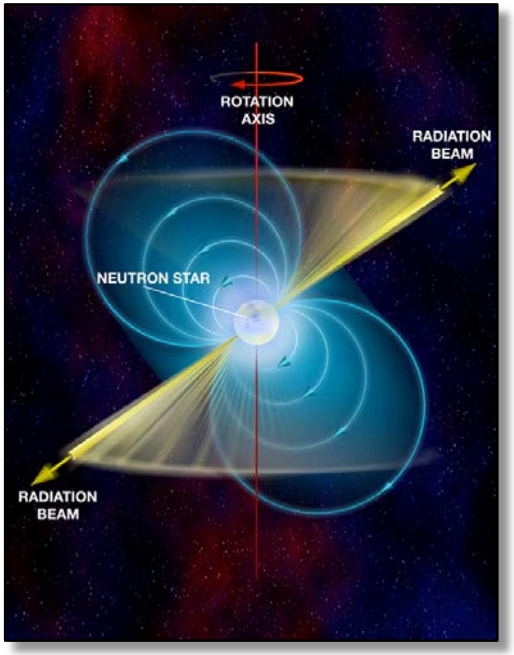


Pulsars (1/2)

A magnetized, rotating neutron star that rotates while emitting a beam of radiation

A subset of pulsars called millisecond pulsar (MSP) rotate with a period between 1.5-16 ms in the X-ray spectrum

- Their emissions are commonly supported by a loss of rotational energy
- MSPs can maintain a stable frequency comparable with atomic clocks



Ref. [4]

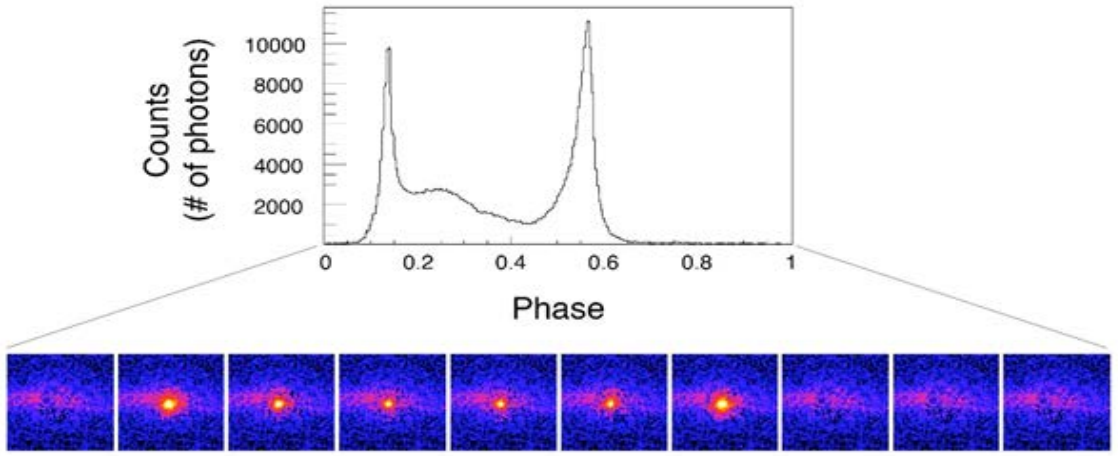
Pulsars (2/2)

Pulsar emissions are measured and presented in the phase/frequency domain

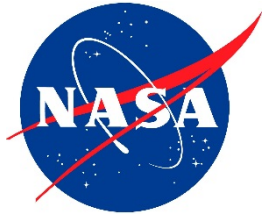
The total photon count rate is characterized by

1. Phase (ϕ)
2. The mean flux (α) from the pulsar source
3. The total background flux (β)
4. Light Curve (h(ϕ))

A pulsar light curve is normalized so the curve integrates to 1 over a single phase



Ref. [3]



XNAV Development History

XNAV has a significant research history beginning with discovery of the first radio pulsar in 1967

- Dr. Sheikh from the University of Maryland, College Park proposed using X-ray pulsar emissions for state estimation with an extended Kalman filter in his dissertation (2005)

Past and Current XNAV Related Projects

- Naval Research Laboratory (NRL) USA experiment (1993-2000)
- DARPA XNAV and XTIM Project, between Ball Aerospace, Microcosm Inc., Lockheed, and NRL (2005-2006)
- NASA NICER / SEXTANT Mission (2013 – Present)

NASA NICER Mission

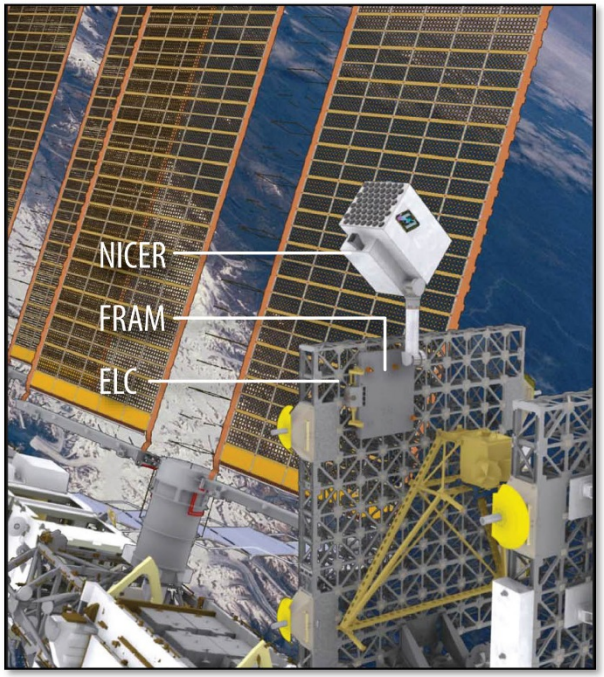
Neutron Star Interior Composition Explorer (NICER)

Science X-ray observatory to explore the structure, dynamics, and energetics of neutron stars

Consists of 56 co-aligned X-ray concentrator optics using silicon drift detectors

Mounted on the International Space Station's Express Logistics Carrier (ELC) with the Flight Releasable Attachment Mechanism (FRAM)

18 month mission duration

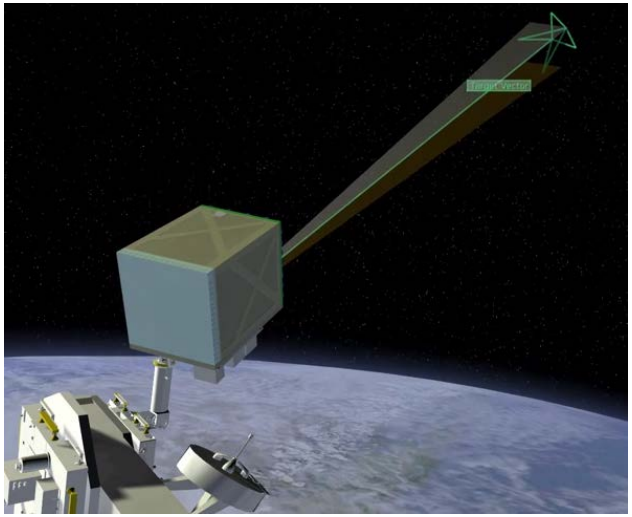


Ref. [4]

NASA SEXTANT Mission

Station Explorer for X-Ray Timing and Navigation Technology (SEXTANT)

- First time technology demonstration of real time onboard XNAV only orbit determination
- A software supplement to the NICER instrument
- Two week primary experiment
- Primary experiment goal of on board position knowledge ≤10 km worst direction
- Expected Launch in late 2016 on the SpaceX-12



Ref. [4]

XNAV Features

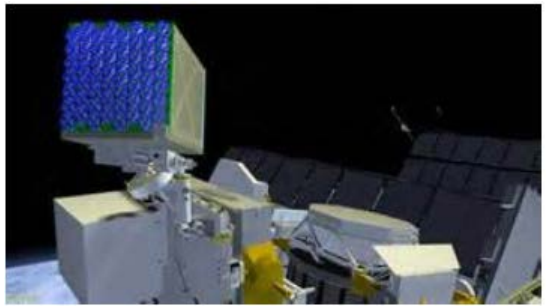
Useful XNAV pulsars are faint targets to a relatively noisy background environment

Celestial object observations are subject to occultations

- Pulsar x-ray detectors must overcome this signal to noise ratio within a reasonable cost/schedule

Observation time drives measurement accuracy

- Optimistic ~1000 second total observation time per measurement
- XNAV generates measurements within ~3-10 km position accuracy



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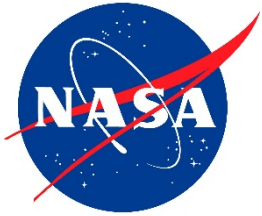
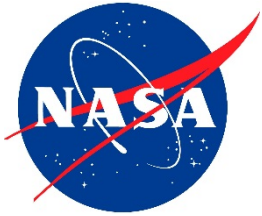


Problem Statement

This thesis is a study of XNAV performance for a wide trade space of bounded Earth orbits with simulated X-ray detector space hardware.

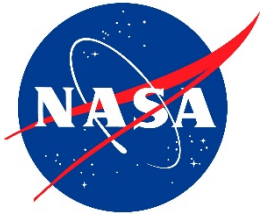


Simulation Overview

The tracking performance of XNAV measurements are compared versus a given initial orbital state that is naturally propagated

The thesis uses these assumptions:

1. Based on the NICER instrument
2. The instrument collects photons from only one target at a given epoch
3. The instrument slews with no hardware restrictions
4. The entire pulsar observation schedule is produced before running the filter state estimate
5. A set amount of observation time is required for each pulsar, for each XNAV measurement
6. The spacecraft hardware can perform within the orbit trade space

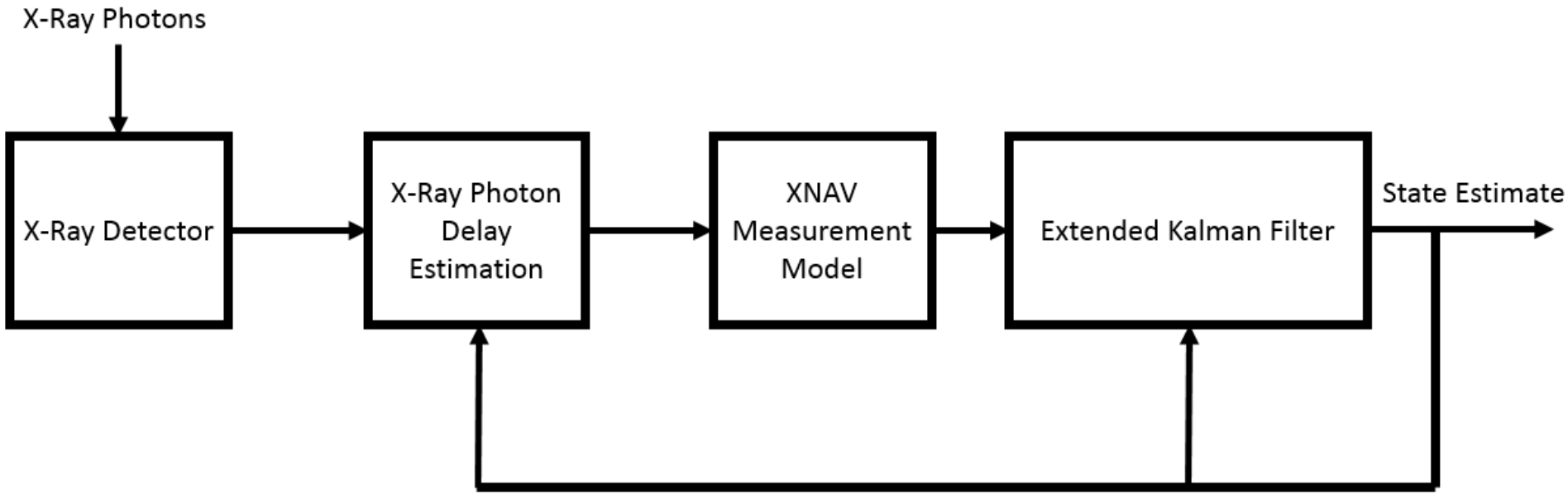


Simulation Trade Space

Spacecraft and Force Model	Value
Geopotential Model	30x30
Third Body Perturbations	None
Atmospheric Drag	None
Solar Radiation Pressure	None

Initial Orbit Parameters	Value
UTC Start Epoch	02/25/2017 00:00:00.000
Experiment Period	3 days
Semi-Major Axis (SMA)	6678 - 42158 km (LEO to Geosynchronous)
Eccentricity (ECC)	0 - 0.8
Inclination (INC)	0 - 180 degrees
Argument of Periapsis (AOP)	0 - 360 degrees
Right Ascension of the Ascending Node (RAAN)	0 - 360 degrees
True Anomaly (TA)	0 degrees

XNAV Flow Diagram



Pulsar Photon Count Rate Model

XNAV pulsars produce different profiles of detected X-ray photons as they arrive

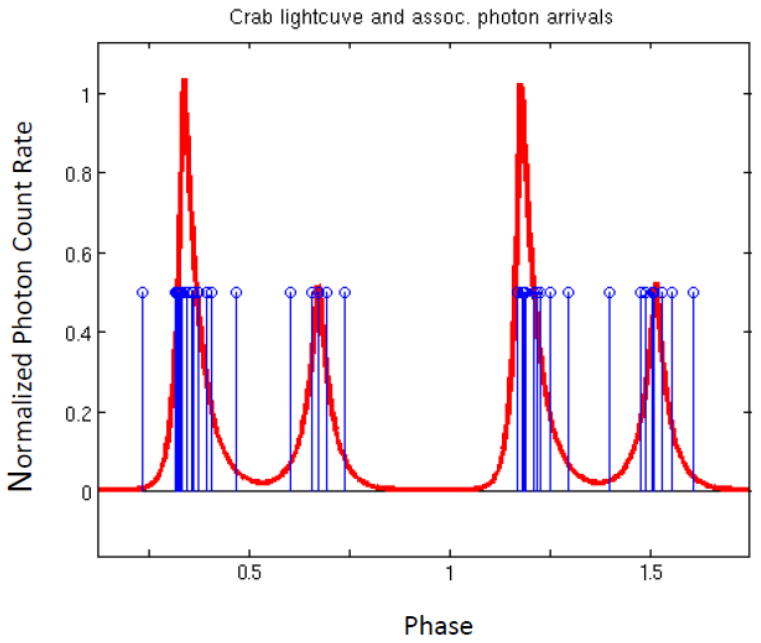
- Each photon's time of arrival is calculated
- Timing accuracy of XNAV is inversely proportional to observation time on the pulsar

Total photon count rate uniquely characterizes each pulsar as part of the Poisson process:

$$\bar{\lambda}(t) = \lambda\big(\phi(t)\big) = \beta + \alpha h(\phi(t))$$

- α = mean pulsed flux from pulsar
- β = total background rate
- h(ϕ) = pulsar light curve function

A nonzero β will bias the associated photon arrivals



$\beta = 0$

Ref. [5]

From Photon Timing to a XNAV measurement

The purpose of processing photon arrival times is to help estimate a phase/frequency difference between the Earth and the detector

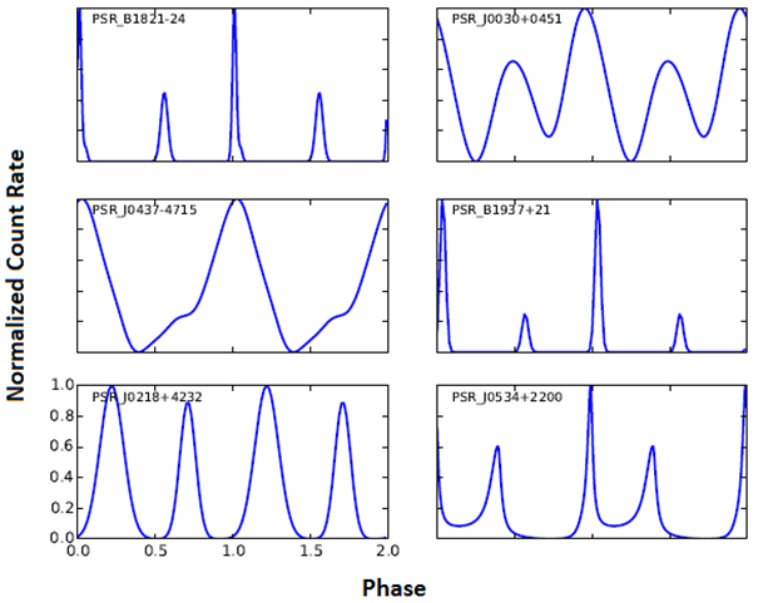
A useful pulsar for XNAV demonstrates light curve behavior for this purpose

- Bright, hard, and narrow peaks
- Predictable dynamics of the pulsar source
- Minimal timing noise / single event offsets

Various operational issues hinder the search for the phase/frequency

- Background Radiation
- Visibility Blockage

Pulsar Light Curve for Various Pulsars Over 2 Phases



Ref. [2]

Background Radiation Model Formulation

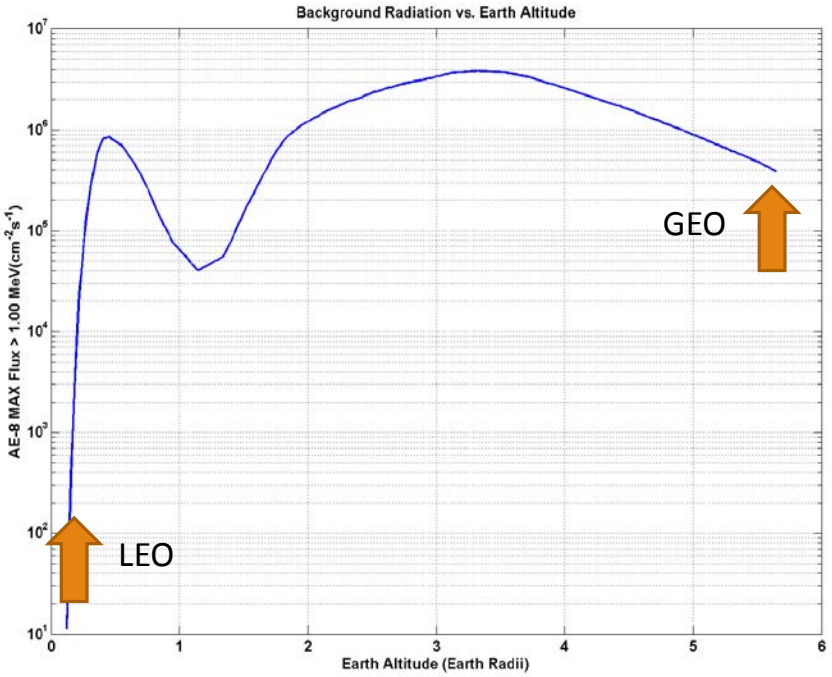
The background environment is scaled in this thesis

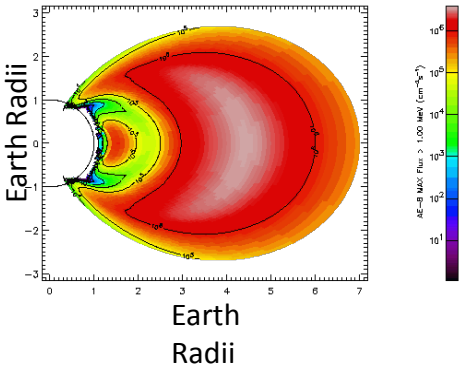
- Based on a nominal value at 0.1 Earth Radii

Scaling maximizes the background flux within the photon processing software limits

Increased background radiation can cause a measurement to be invalid

If the peak phase/frequency estimate is too noisy due to background radiation, it is not used for state estimation





Ref. [1]

Visibility Model Formulation

Periodic blockage of pulsars limit pulsar availability for XNAV measurements

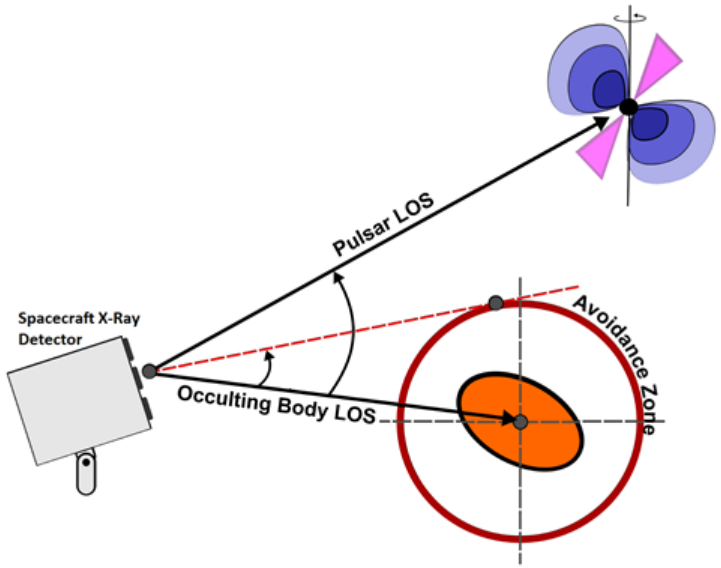
An increase in occultations causes breakup in photon timing data, hindering phase/frequency estimation

Occultation: Sun, Earth, Moon

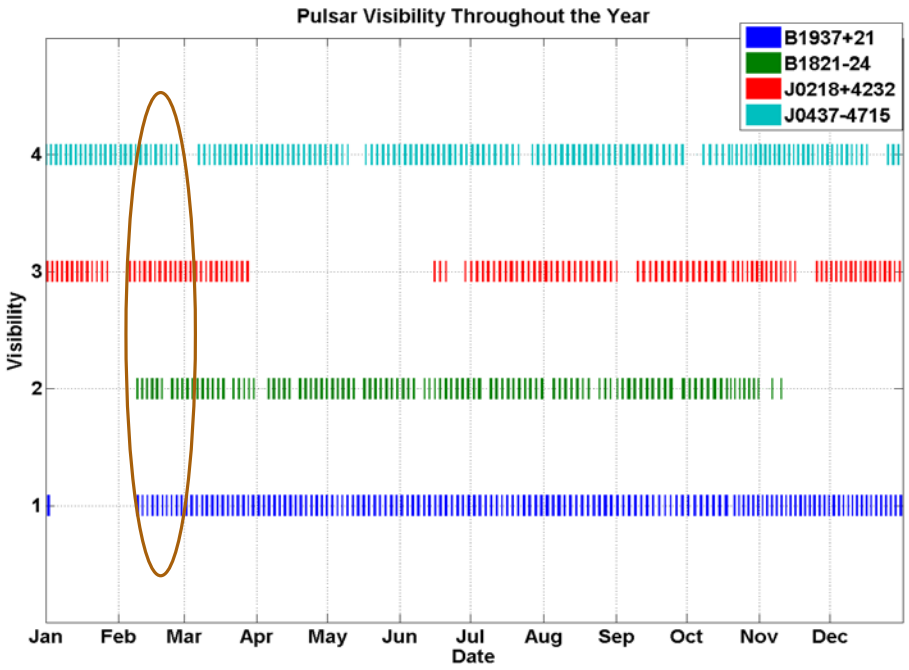
- An avoidance zone from the line of sight (LOS) was enforced

Occultation: Highly variable background radiation areas

- A longitude / latitude area over a range of Earth altitudes was enforced



Annual Pulsar Visibility



Semi-major Axis (SMA): 6678 km

Circular Equatorial Orbit

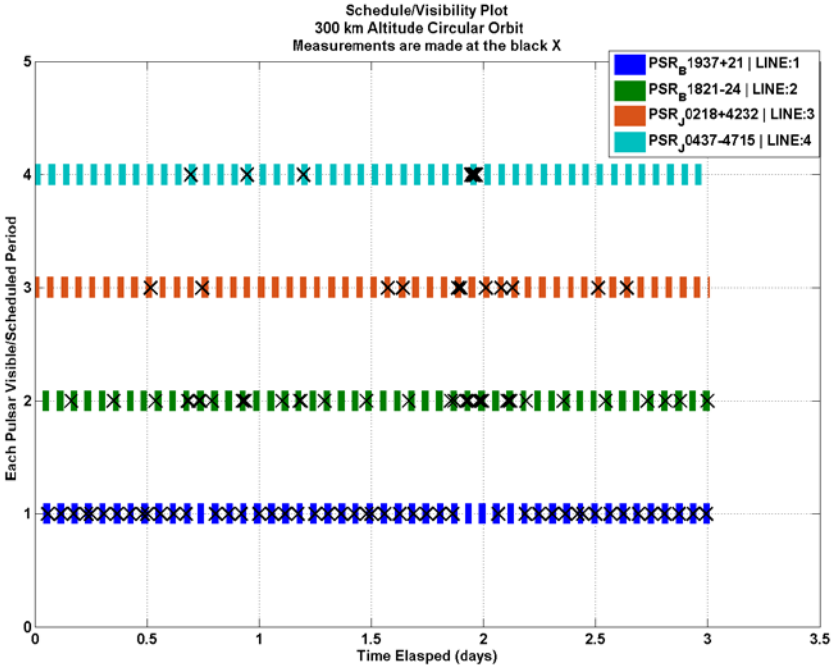
Chosen Start Epoch: 02/25/2017 00:00:00.000

Pulsar Scheduling Model

Each local XNAV measurement is chosen based on a local greedy search heuristic of navigation performance.

Steps to choosing the next XNAV measurement

1. A covariance is propagated directly to each measurement time
2. Potential measurements update the covariance without any photon phase/frequency estimation at their measurement times
3. The measurement that minimizes the resultant semi-major axis variance is chosen



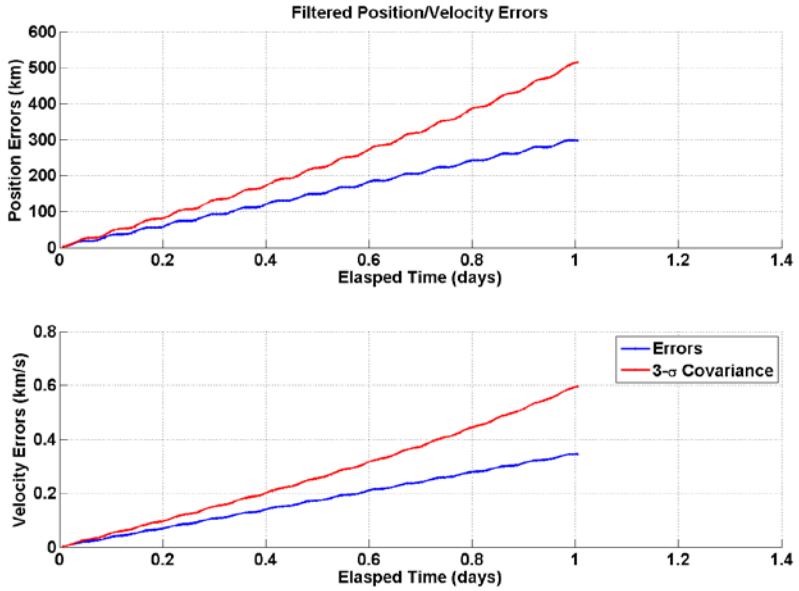
Extended Kalman Filter (EKF) Settings

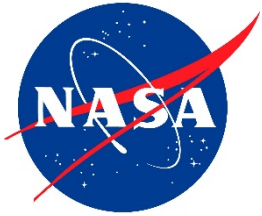
XNAV measurements are the only cause of state estimation convergence.

Modifications made to the filter

1. Process noise matrix is zeroed out
2. The truth / estimator propagation force models are an exact match
3. Initial state error is applied
4. The initial covariance is set so it bounds the actual error

6678 km Semi-Major Axis (SMA) Circular Orbit: Control Scenario with No Measurements





Results

The navigation performance overall was studied by quantifying the following:

1. Measurement Quality (% of measurements rejected and total number of measurements made)
2. Definitive State Error (Difference between the truth and estimate state)

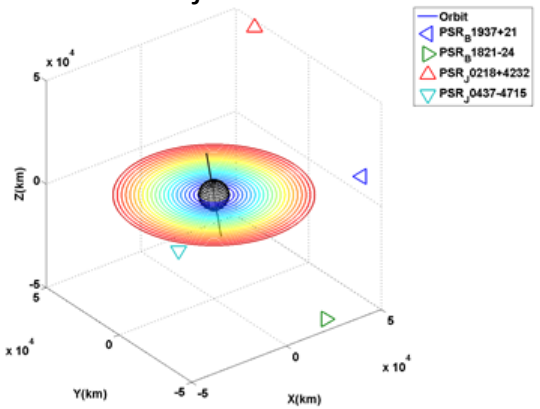
To ensure convergence, the broader metrics for state accuracy are collected over the last day of state propagation

The trade space provides a variety of orbit designs, so the following was studied:

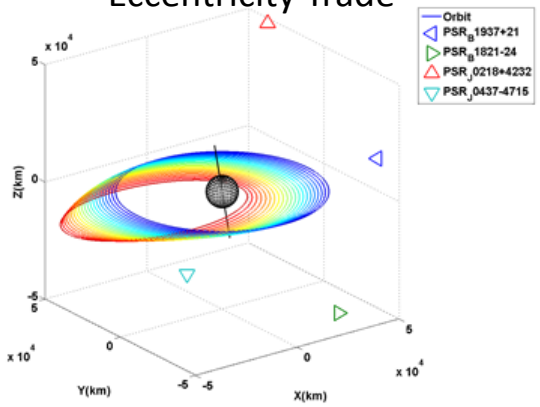
- Sensitivity of changing one orbital element
- Sensitivity of fixing one orbital element and changing the rest

Five orbital elements were studied
Only the study of semi-major axis is presented today

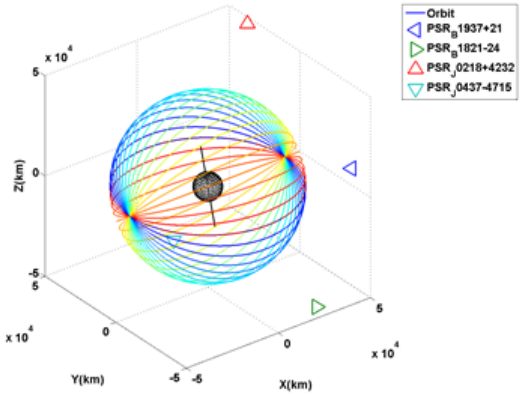
Semi-Major Axis Trade



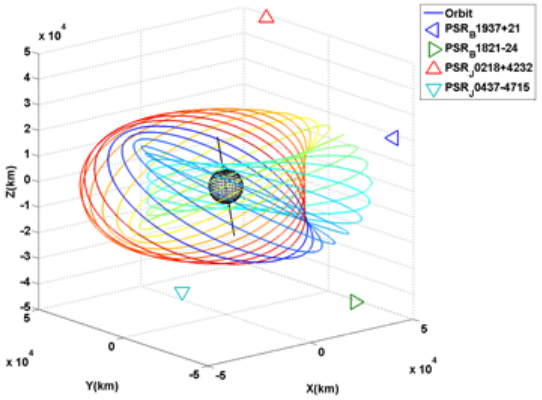
Eccentricity Trade



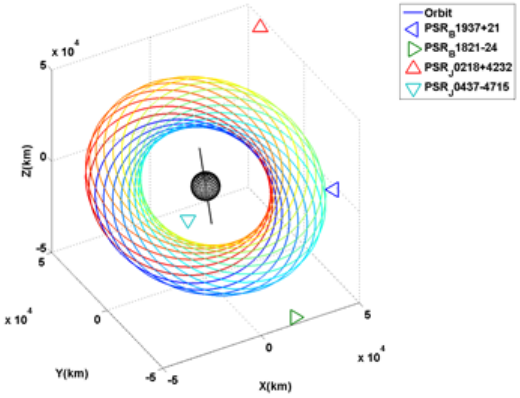
Inclination Trade



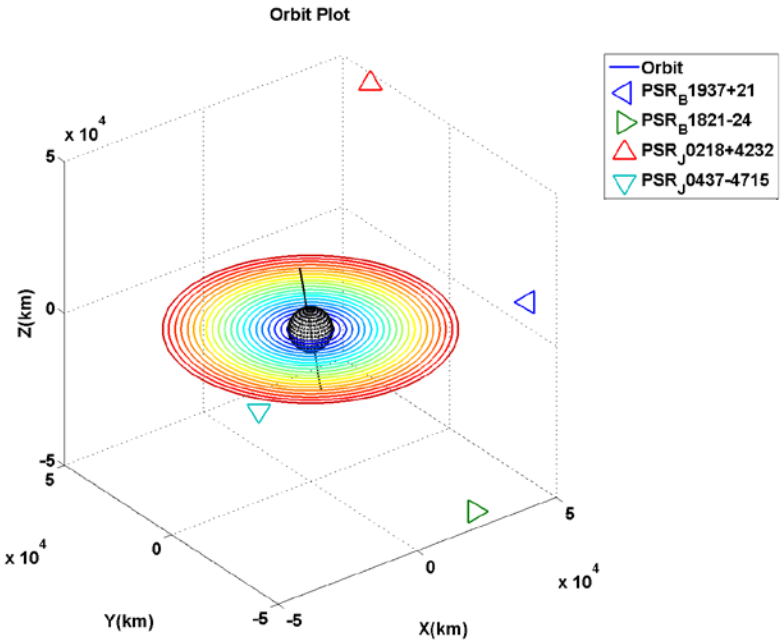
Right Ascension of the Ascending Node



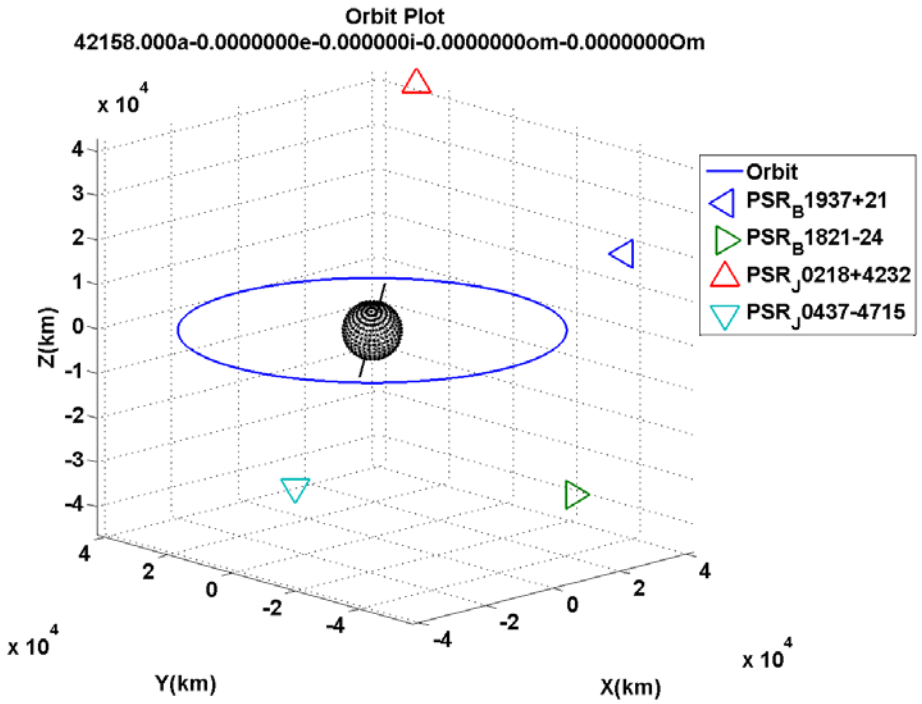
Argument of Perigee Trade

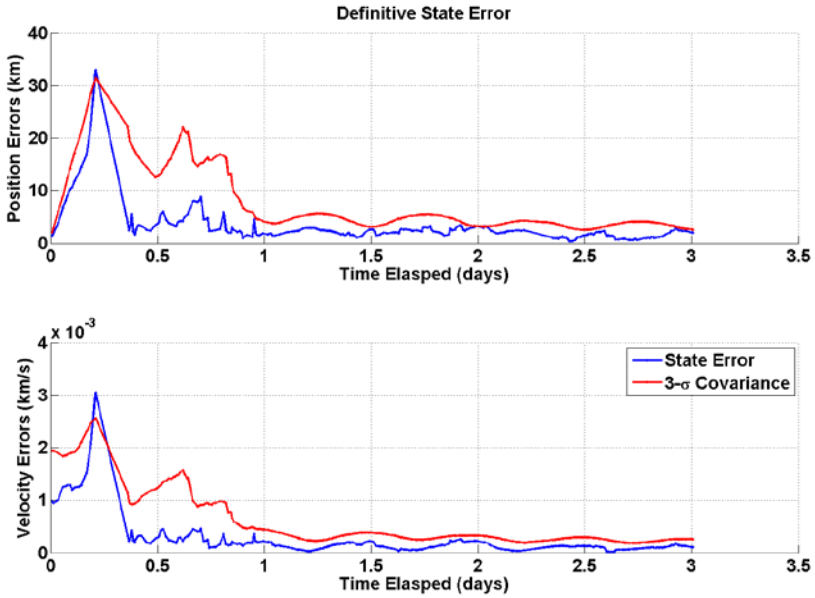


Orbits used for Studying Initial Semi-Major Axis (SMA)

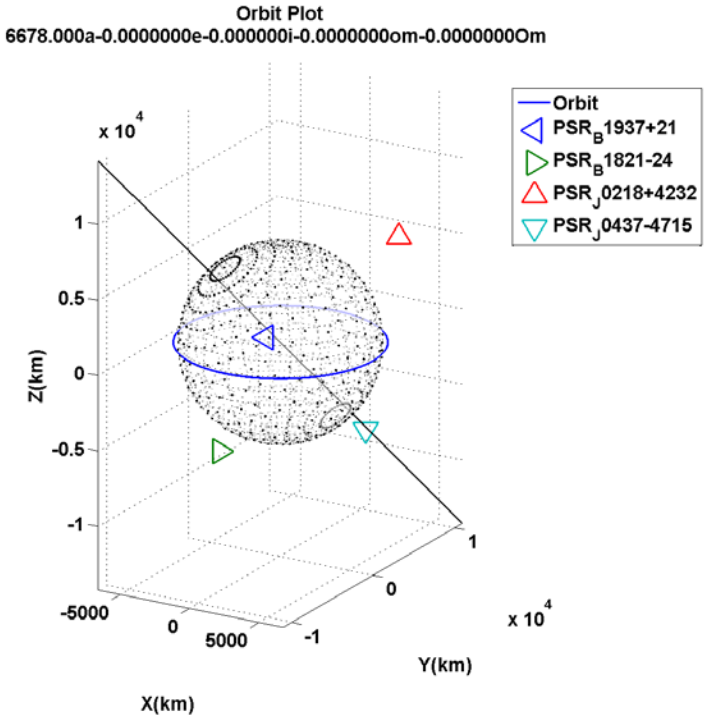


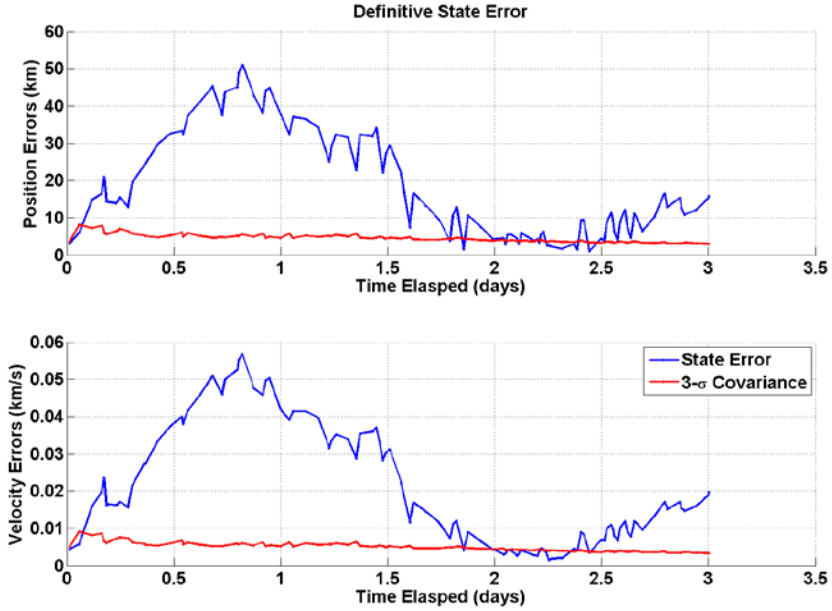
Geosynchronous Orbit



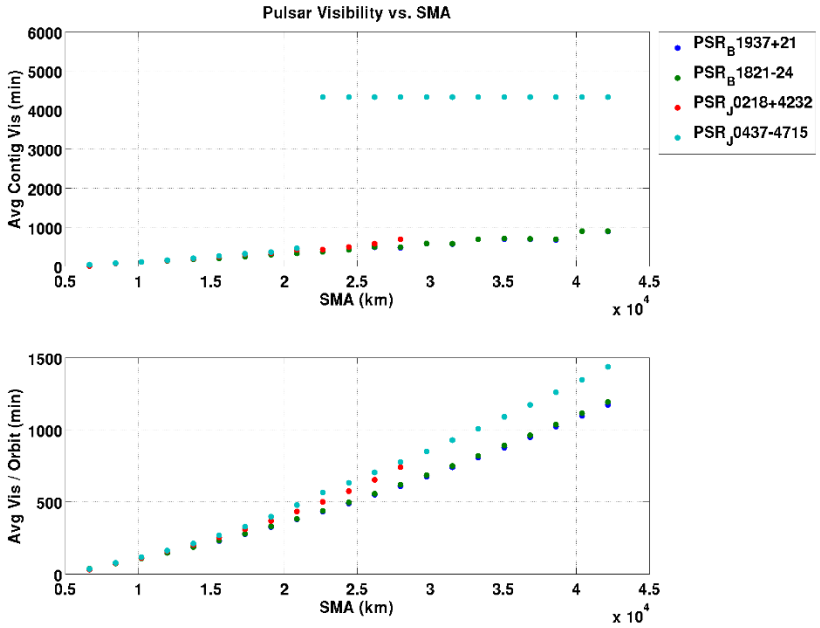


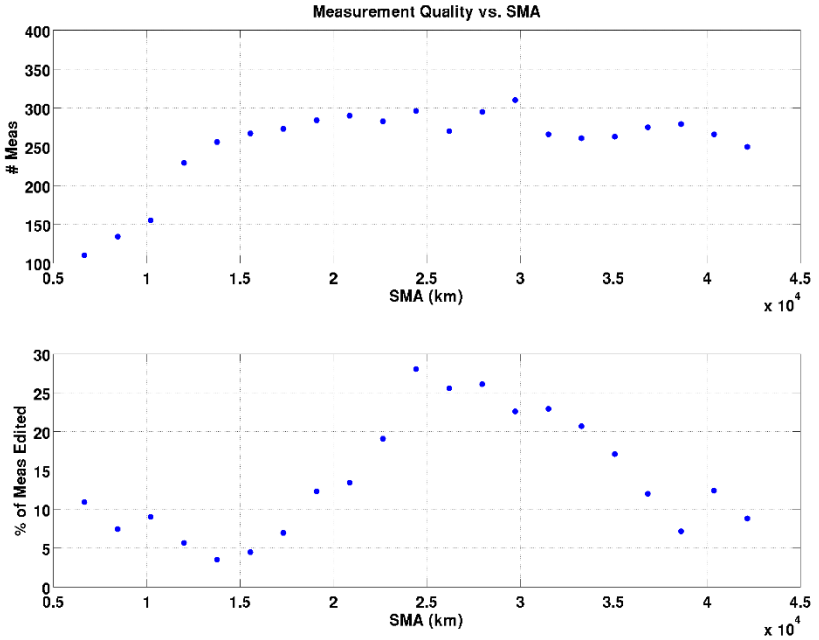
Low Earth Orbit





Varying Only Initial SMA
Circular and Equatorial Orbit (2/2)





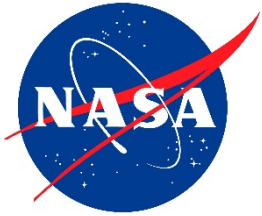
Conclusions

This was a first cut characterization of XNAV performance for tracking closed Earth orbits.
The results are coupled and are sensitive to initial XNAV measurements.
XNAV only tracking can converge to ≤ 10 km position error in 3 days.

Orbit Parameter	Influences	Ideal Orbit Range for XNAV Tracking
Semi-Major Axis	+ Drives pulsar visibility and average orbit speed – Can place orbit in area of high background radiation	Maximum Value in Trade Space
Eccentricity	+ Increase of visibility at apogee – Decreases photon timing information around perigee	0.0-0.2 (Dependent on Semi Major Axis)
Inclination Increases	– Occultation due to magnetic poles causes visibility breakup	Away from 90 degrees
Argument of Perigee	• Rotates periods of pulsar visibility	Use value to define initial XNAV measurements Unnecessary if Eccentricity is 0
Right Ascension of the Ascending Node	• Rotates periods of pulsar visibility	Use value to define initial XNAV measurements Unnecessary if Inclination is 0 degrees

Thank you

NASA Goddard Spaceflight Center Navigation/Mission Design Branch
Dr. Carl Adams / Dr. Russell Carpenter
NASA SEXTANT Team
Dr. Jason Mitchell / Dr. Luke Winternitz
Naval Research Laboratory
Dr. Paul Ray / Dr. Kent Wood



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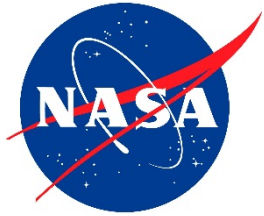
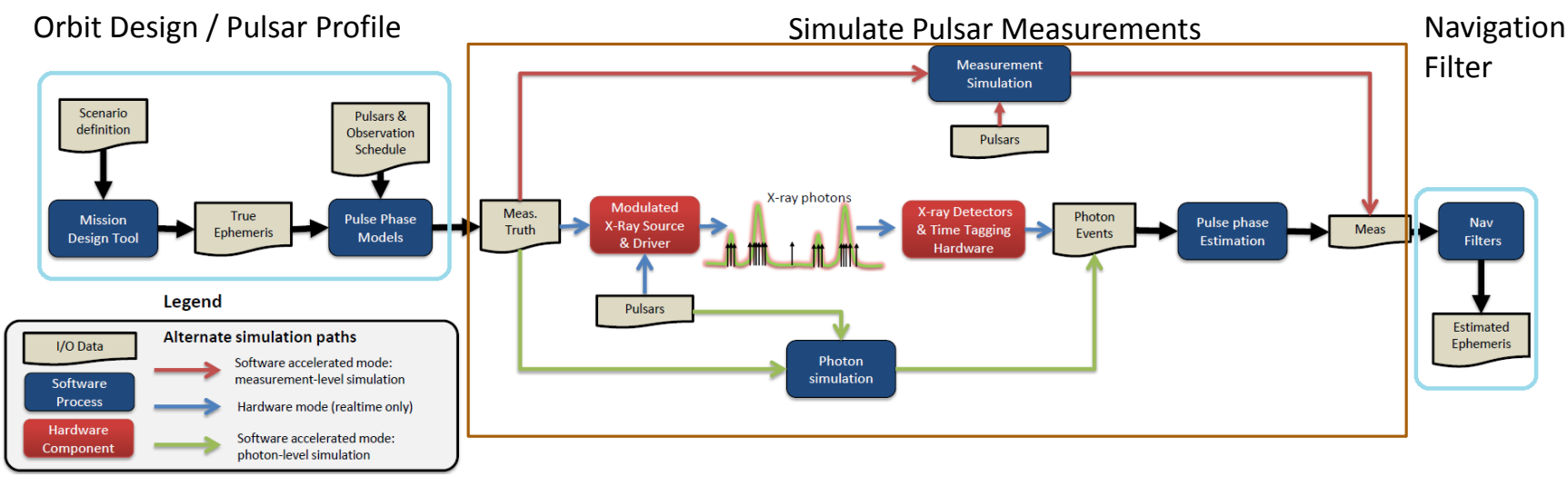
NICER • SEXTANT
MIT • MOOG • DTU
NASA • GSFC • ISS
EX PULSU ASTRIS SCIENTIA ET VIA


NASA

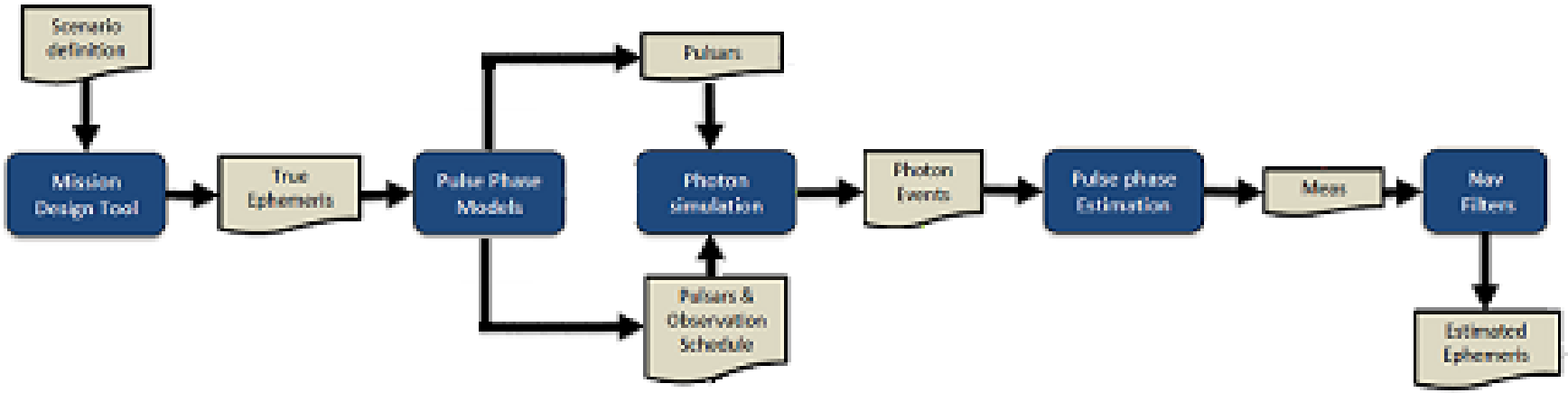
Modified SEXTANT Simulation

This thesis **modifies** the **orbit design**, the **pulsar information** and the **navigation filter** (Cyan Boxes).
It **does not modify** the simulation of pulsar **measurement model** (Orange Box).
It uses the green arrowed path to simulate pulsar measurements.

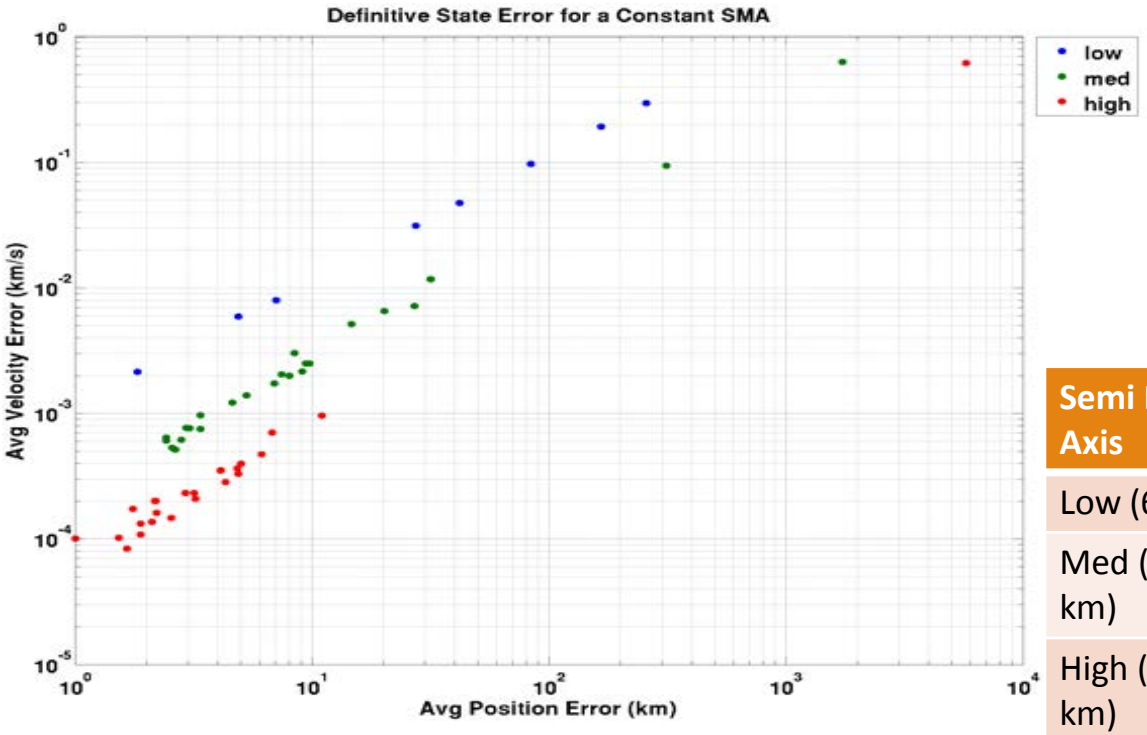


Ref. [2]

XNAV Flow Diagram

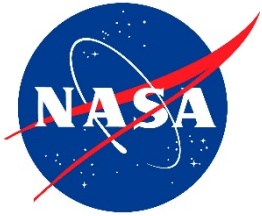


Constant SMA
Variation of the other Orbital Parameters



The increase in SMA decreases the lower bound of velocity state errors.

Semi Major Axis	Velocity Error Lower Bound	Circular Orbit Speed
Low (6678 km)	2.0e-3 km/s	7.2 km/s
Med (18505 km)	5.0e-4 km/s	4.6 km/s
High (42158 km)	8.0e-5 km/s	3.1 km/s



Future Work

1. Running a Monte Carlo to produce performance statistics that randomizes initial state error
2. Focusing the trade space to further decouple orbit parameter relationships
3. Addition of further pulsars / variation of observation times per pulsar
4. Addition of force models to truth/estimate models
5. Filter tuning performance