Mission concept for demonstrating small-spacecraft true anomaly estimation using Millisecond X-Ray Pulsars

SSC21-VI-08

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Outline

- A Brief Introduction to XNAV
    - About X-ray Pulsars
    - Why use X-ray Pulsar Navigation?
- Navigation using X-ray Pulsars
- Pulsar Source Selection Study
- Constraining Detector Specifications
- Instrument Design
- Mission Concept and True Anomaly Estimation
- Satellite Systems Design

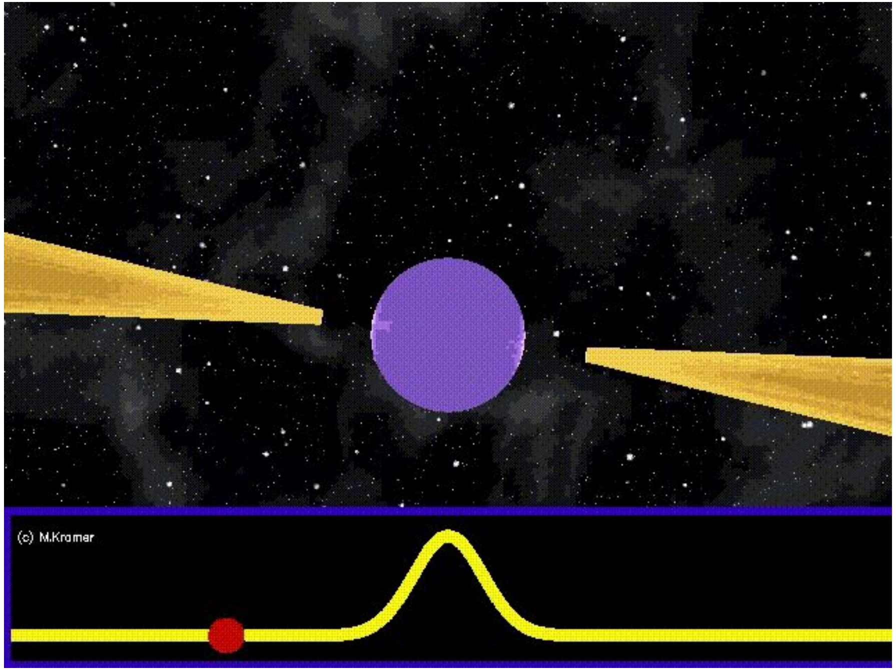


Fig: Animation of observed Pulsar Radiation [1]

Brief Introduction to XNAV

- X-ray Millisecond Pulsars
  - Fast spinning Neutron Star with strong magnetic fields
  - Period ~ 10s of ms
  - Stable period – rival atomic clocks
  - Unique pulse profile
- Emit over the entire EM spectrum, but most energy in the X-ray regime
- Detector sizes in X-ray smaller compared to Radio

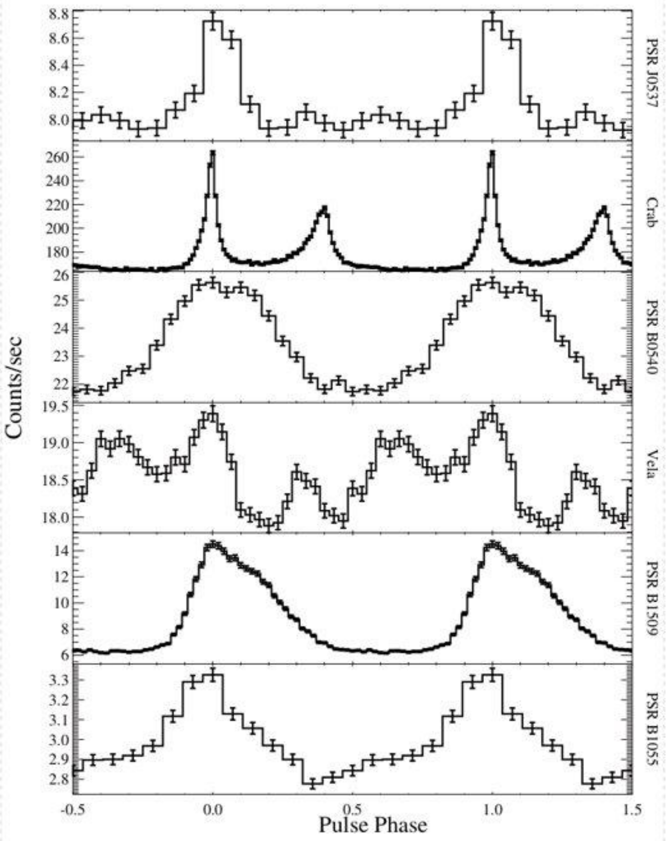
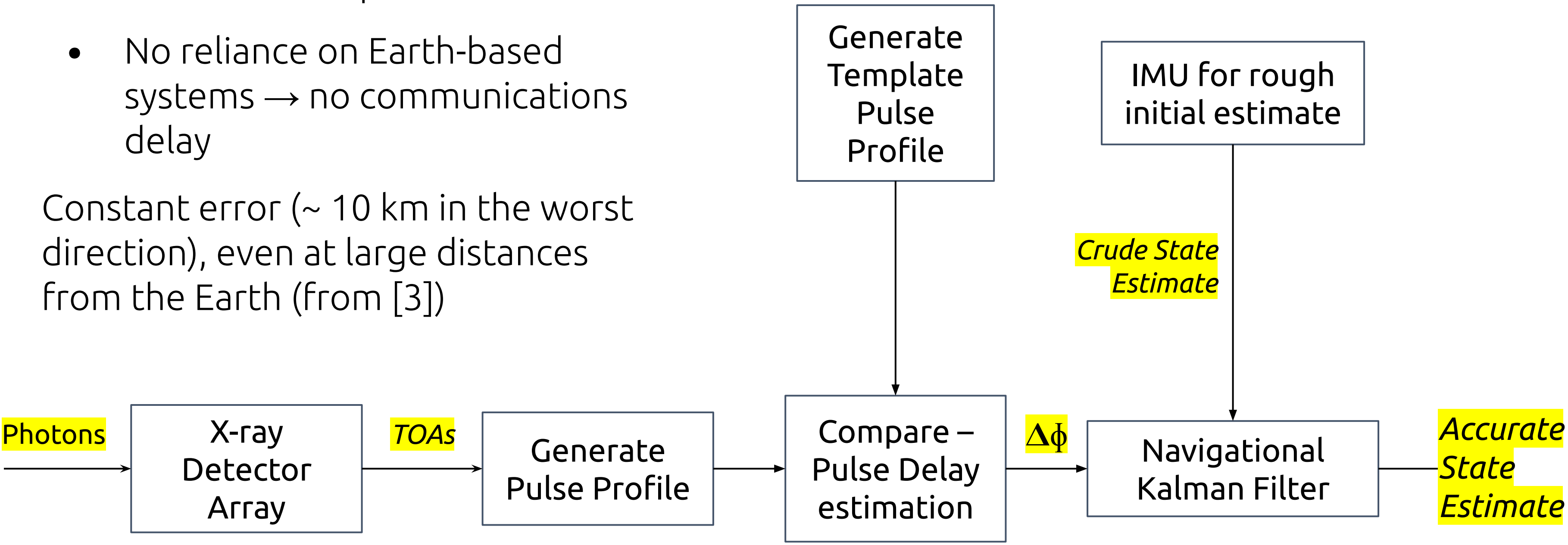


Fig: Various Pulsar Pulse Profiles [2]

Methodology and Advantages of XNAV

- Autonomous Navigation Solution
  - On-board computations
  - No reliance on Earth-based systems → no communications delay
- Constant error (~ 10 km in the worst direction), even at large distances from the Earth (from [3])



Pulsar Source Selection

- List of known millisecond Pulsars compiled from literature
- Rank pulsars based on :
  - Visibility from orbit
  - Duration of time with Sun Angle > 30°
  - SNR – f(t, A_{eff}) → helps constrain detector area
- Measure # of bright/faint sources near a source:
  - Rough measure of local background X-ray noise
  - Helps constrain Pointing System accuracy

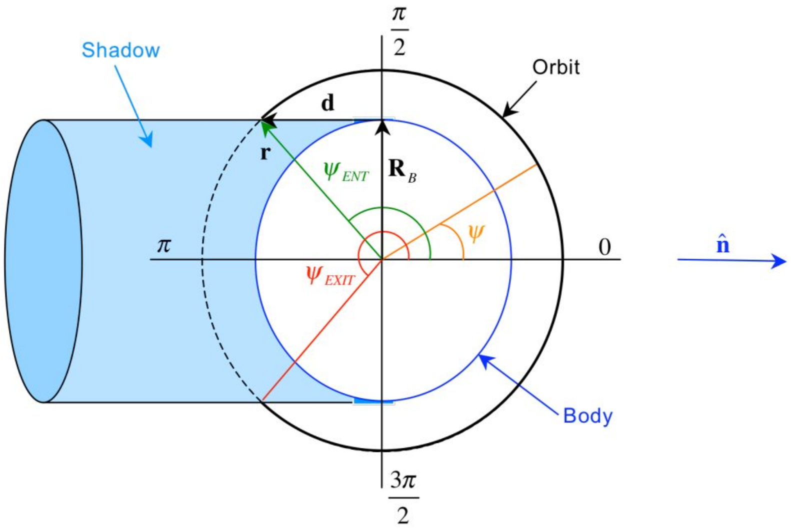


Fig: Geometry used to calculate Source Visibility in a particular orbit [4]

Pulsar Source Selection 2

- Rank the pulsars according to their "Score", where:

$$\text{Score} = 50(\mathcal{F}_{\text{vis}} + \mathcal{F}_{\text{Sun-source}}) - 20 \cdot \mathcal{N}_{>10} - \frac{\mathcal{N}_{>0.01}}{50}$$

- For the Crab pulsar (B0531+21) [5]:
  - 2–10 keV flux of 1.54 photons cm^2 s^{-1}
  - 7.74 x 10^{-6} photons are detected in 1 μsec (for a combined active area of ~5 cm^2)

Pulsar Name	Score
J1846-02	99.86
B0531+21	*99.78*
J1811-19	99.62
J0631+10	99.12
B1821-24	98.58
B0656+14	79.22

Table: Top 6 Pulsars from the Source List, ranked according to their score

Constraining Detector Specs. Using SNR

$$S = \frac{F_X A p_f t_{\mathrm{obs}}}{\sqrt{[B_X + F_X(1-p_f)](A t_{\mathrm{obs}} d) + F_X A p_f t_{\mathrm{obs}}}}$$

- Use a configuration with A_g=5 cm^2, and t_{int} = 100 s
- This gives an average SNR $\gtrsim$ 10
- Full Monte-Carlo simulations being carried out for validation

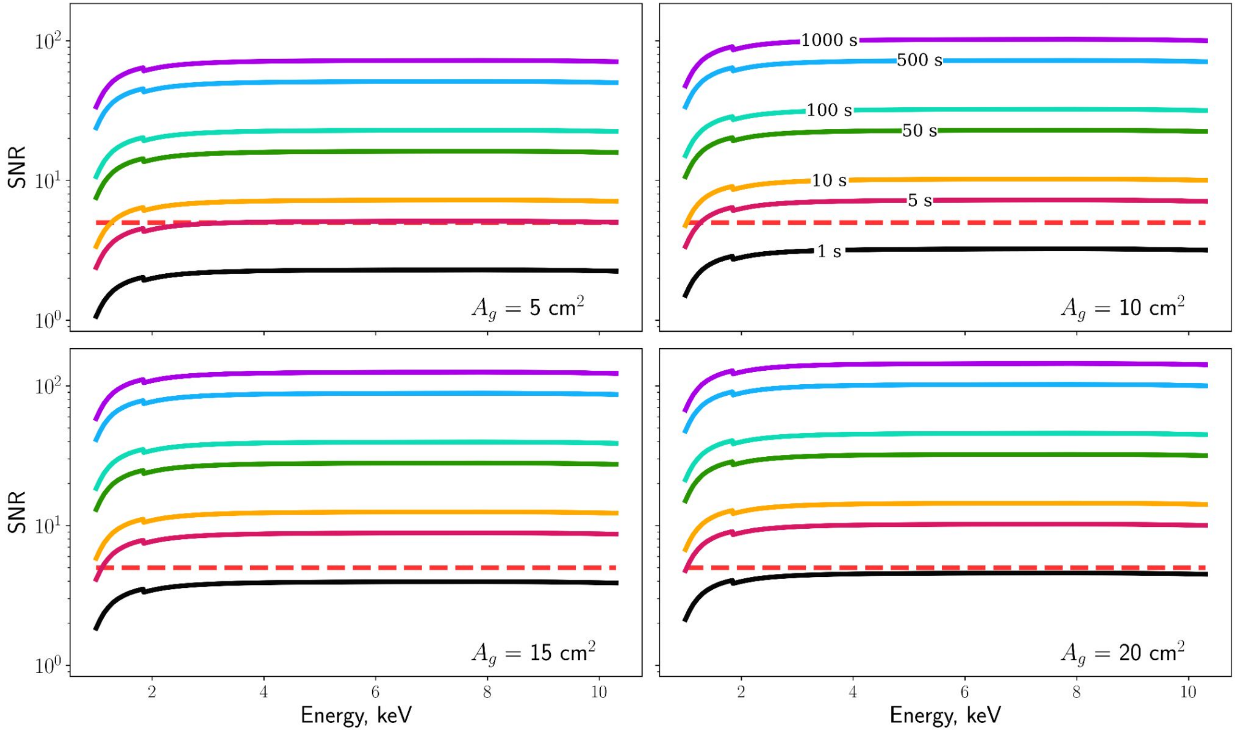


Fig: Variation of SNR with Energy (E) and Integration Time (t), for various geometric area

Instrument Design

- **Design Requirement:**

  Extract timing information from detected photons of the pulsar source and use it to generate the required pulse profile.

- Instrument Consists of:

  a. 10 SDDs (COTS, Amptek)

  b. 10 Hollow Tube Collimaters

  c. Custom Designed Processing PCBs.

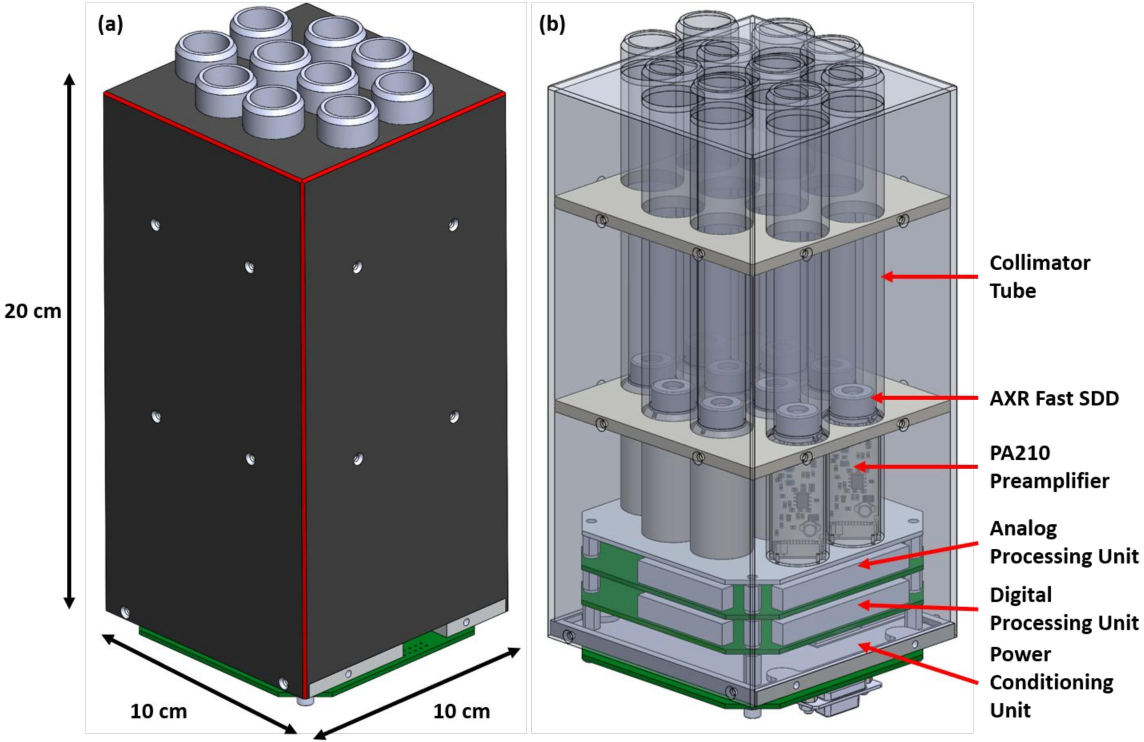


Figure: Instrument CAD Model

Instrument Design Contd.

1. Amptek FAST SDD and Preamplifier:
    - TO-8 Package with CMOS Preamp, Be Window, Multilayer Collimator and Thermoelectric Cooler
    - Total Area: 70 mm^2 , Active Area: 50 mm^2
2. Analog Processing Unit (APU)
    - Fast Timing amplifier
    - Constant Fraction Discriminator, Comparator
3. Power Conditioning Unit (PCU)
    - DC-DC regulators
4. Digital Processing Unit (DPU)
    - SoC FPGA, Non-Volatile Memory

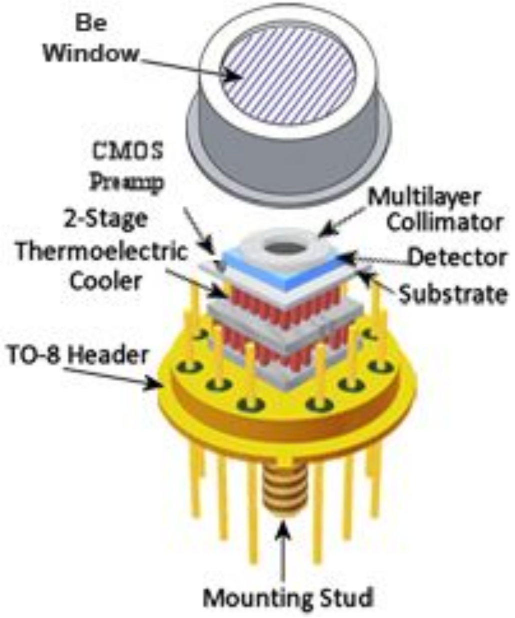
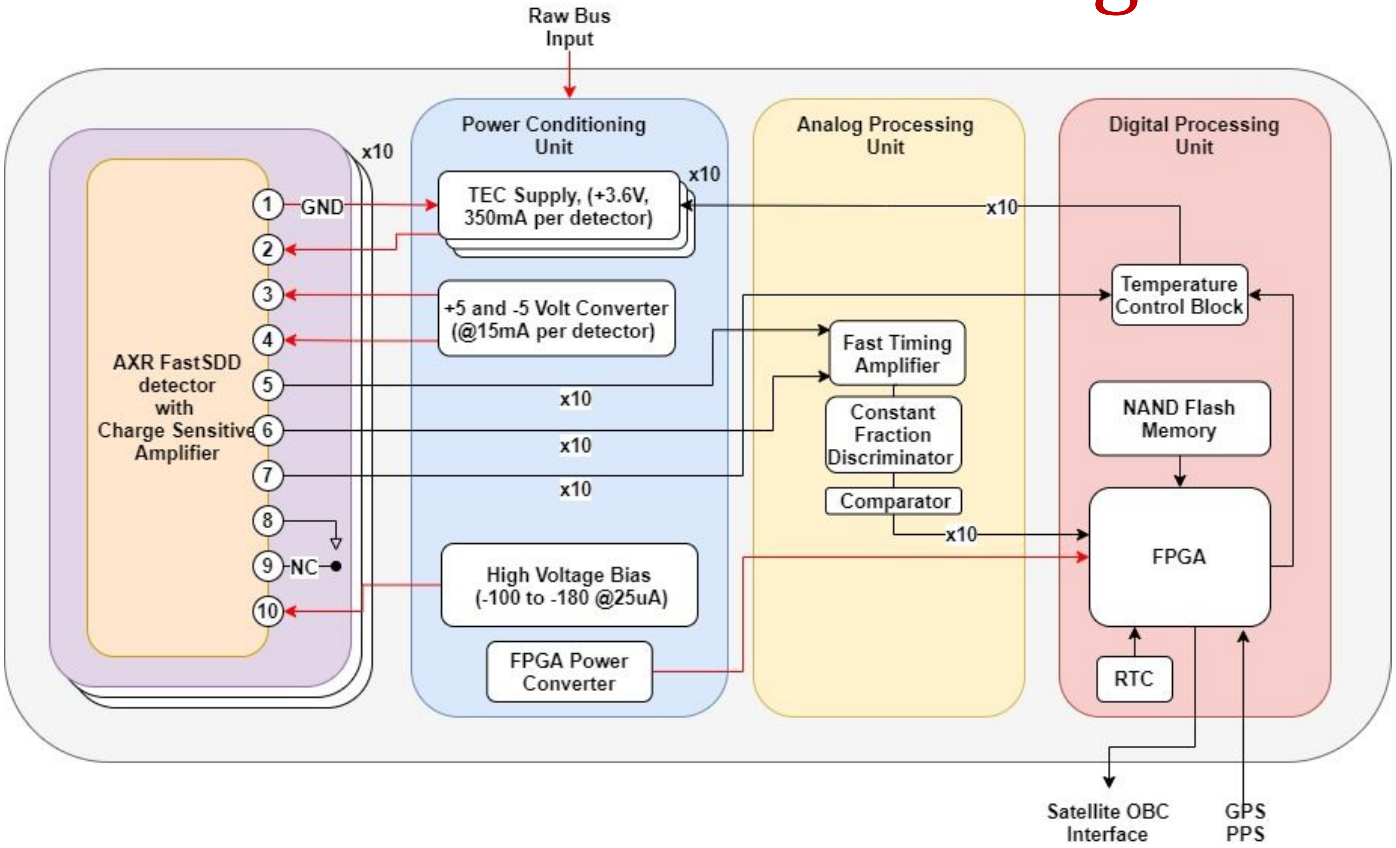


Figure: Amptek FastSDD [6]

Instrument Functional Block Diagram



Mission Concept

- **Mission objective:** Validate the functionality of the XNAV instrument, by estimating true anomaly of a small satellite in the Low Earth Orbit (LEO)

- **Chosen Orbit:** Circular, Sun-synchronous orbit at 500 km, i = 97.8°
  - Compute only true anomaly
  - Single pulsar sufficient for single parameter estimation
  - Target : position error ~30 km, worst direction

- **Key Technologies To Be Demonstrated:**
  - High timing resolution (~100 ns) for the detector system
  - Small form factor (→ no large X-ray focusing systems)

Satellite True Anomaly Estimation

- $$\vec{r}_{\text{sat,ICRF}} \cdot \vec{n}_{\text{pulsar,ICRF}} = c \cdot t_d$$

- The procedure of calculating the true anomaly, consist of two steps:
  - **Step-1:** Generating the time delay (t_d) using the X-ray photon count measurements
  - **Step-2:** Using the time delay (t_d) value to estimate true anomaly of the satellite.

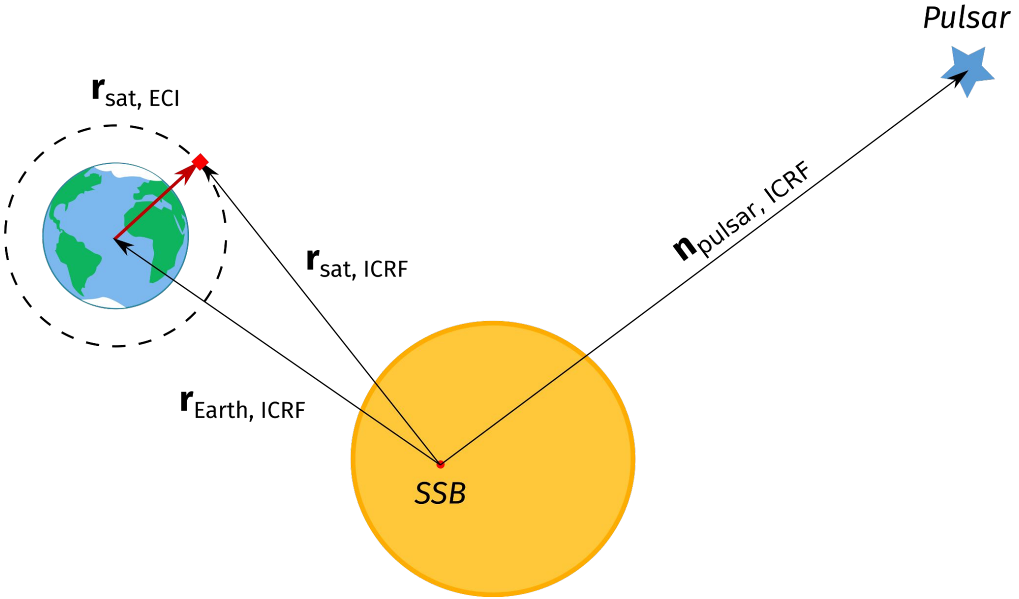


Figure: Navigation Problem Geometry

Step 1: Time Delay Estimation

- Time Stamping X-Ray Photons
- Arrival Times compensation for doppler shift
- Epoch folding
- Comparison with reference pulse profile

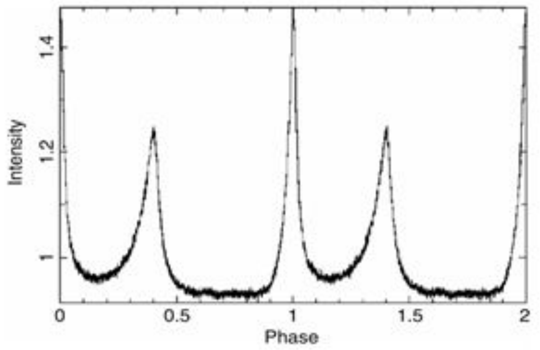


Fig : Pulse Profile of Crab Pulsar [3]

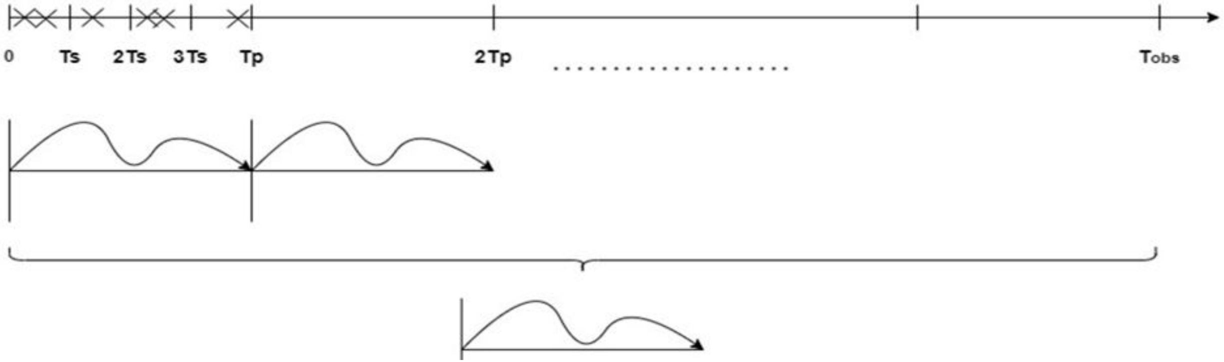


Figure : Epoch Folding

Step 2: True Anomaly Estimation

Formula derived for calculating true anomaly of the satellite using t_d measurements.

$$\vec{r}_{\text{sat,icrf}} \cdot \vec{n}_{\text{pulsar,icrf}} = c \cdot t_d$$

ICRF frame to Orbit Frame transformation:

$$\vec{r}_{\text{sat,icrf}} = \vec{r}_{\text{sat,eci}} - \vec{r}_{\text{SSB, eci}}$$

$$\vec{r}_{\text{sat,eci}} = Q \cdot \frac{a \cdot (1 - e^2)}{1 + e \cdot \cos\theta} \cdot \begin{pmatrix} \cos\theta \\ \sin\theta \\ 0 \end{pmatrix}$$

$$(Q \cdot \frac{a \cdot (1 - e^2)}{1 + e \cdot \cos\theta} \cdot \begin{pmatrix} \cos\theta \\ \sin\theta \\ 0 \end{pmatrix} - \vec{r}_{\text{SSB,eci}}) \cdot \vec{n} = c \cdot t_d$$

$$\theta = \begin{cases} \sin^{-1} \frac{f(t)}{\sqrt{k_1^2 + k_2^2}} - K_2 & \text{if } \vec{v_e} \cdot \vec{n} > 0 \\ \pi - \sin^{-1} \frac{f(t)}{\sqrt{k_1^2 + k_2^2}} - K_2 & \text{if } \vec{v_e} \cdot \vec{n} < 0 \end{cases}$$

Where,

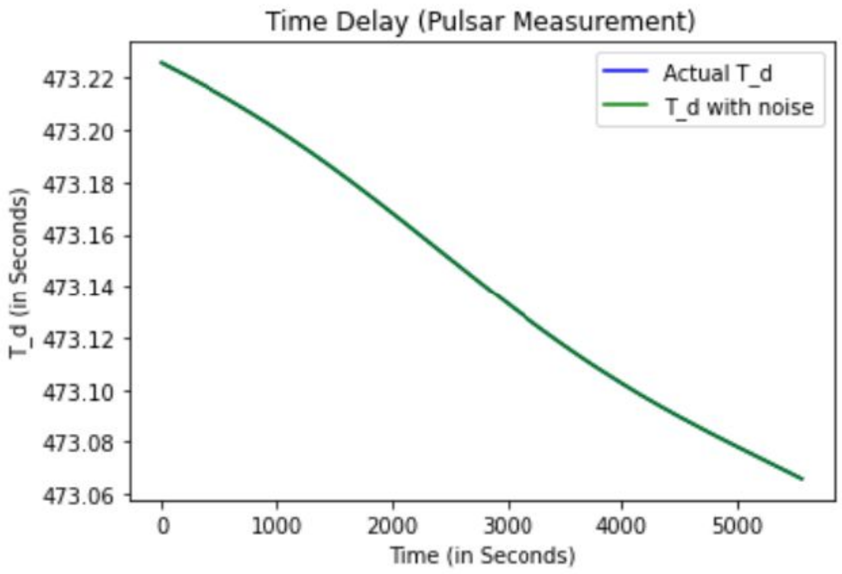
$$f(t) = \frac{ct_d - \vec{n} \cdot \vec{r}_{\text{SSB,eci}}}{a \cdot (1 - e^2)}$$

$$K_2 = \sin^{-1} \left(\frac{k_1}{\sqrt{k_1^2 + k_2^2}} \right)$$

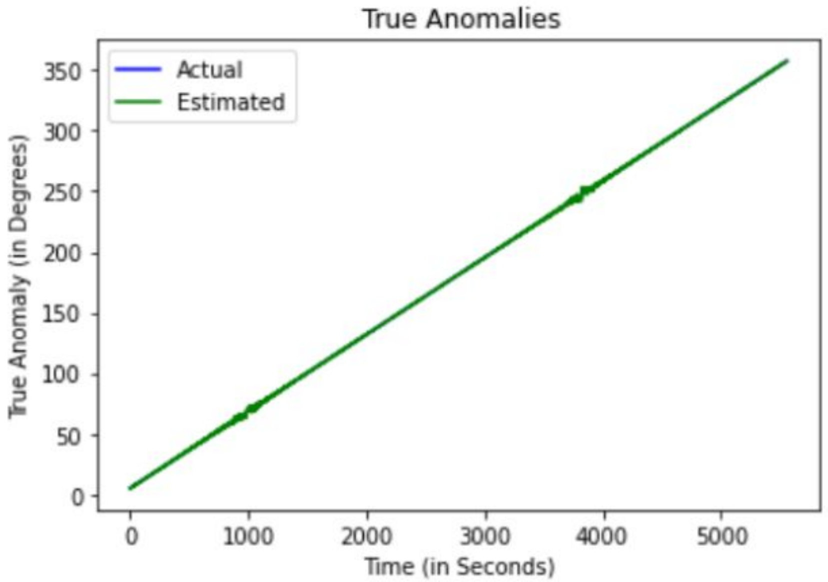
Algorithm Simulation

- Simulation performed to verify algorithm and estimate errors.

Simulated Pulsar Measurements



Estimated True Anomaly



Satellite Overview

6U Configuration

In-house developed subsystems:

1. OBC
2. EPS
3. Structures

COTS subsystems:

1. ADCS
2. Comm. UHF
3. Comm. SBand
4. GPS Receiver

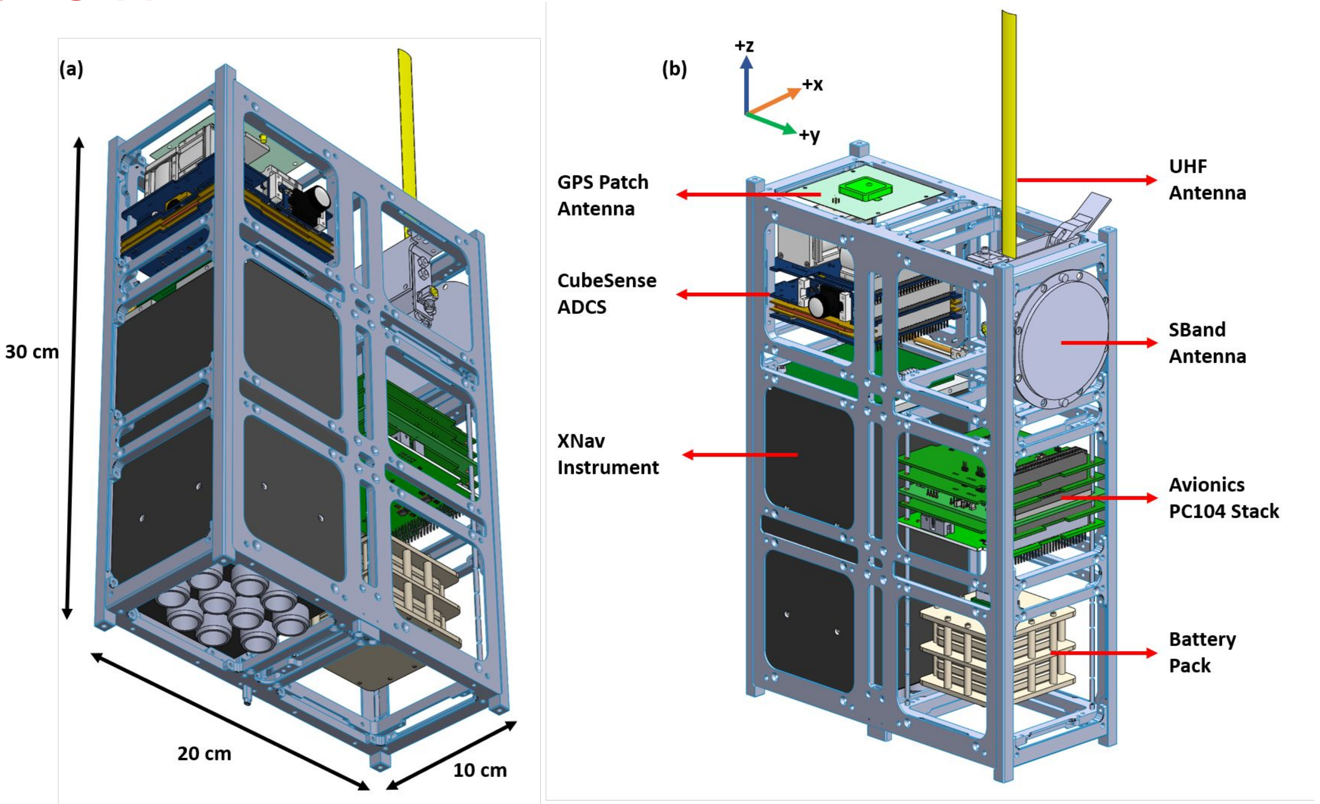
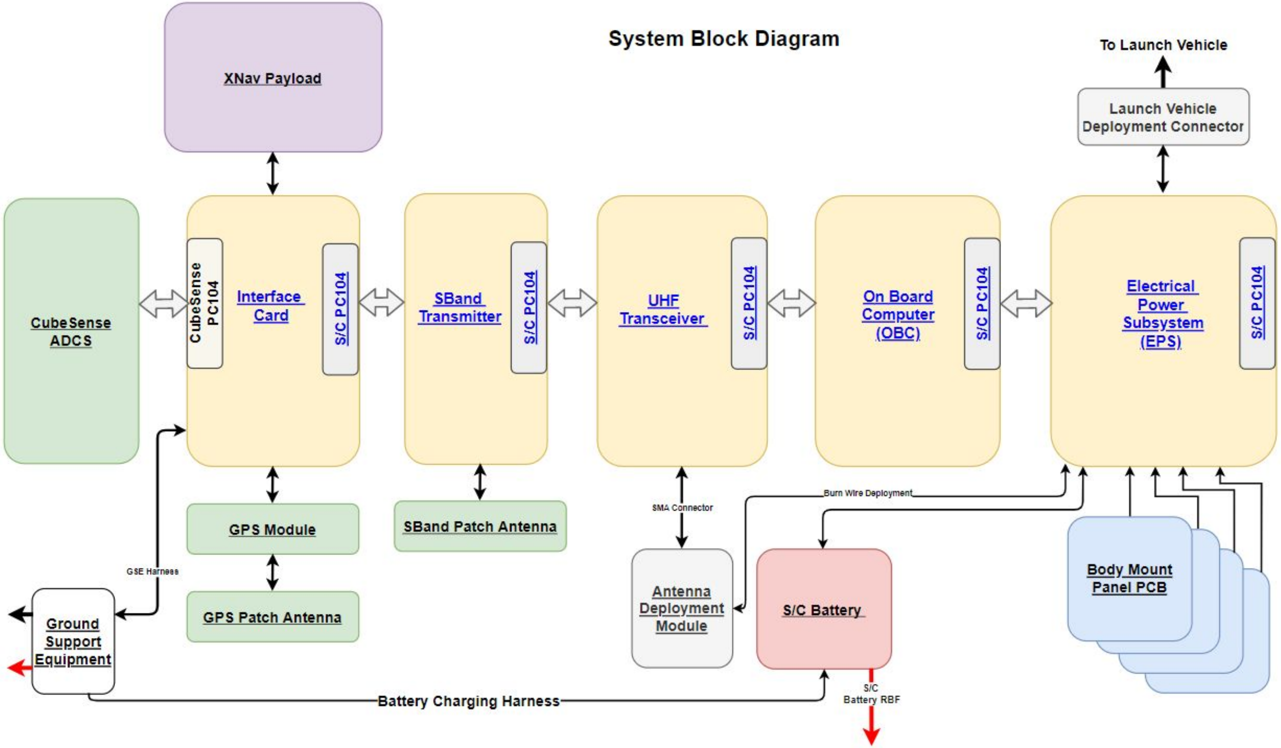


Figure: Satellite CAD Model

Satellite System Block Diagram

- On Board Computer:
  - Microsemi SF2 SoC FPGA
- Electrical Power System:
  - ~ 14 W Power generation
  - 5000 mAh Battery
- Communication System:
  - 9600 bps UHF
  - 2 Mbps S-Band
- ADCS:
  - 3 axis stabilized
  - 0.2 deg. pointing accuracy



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Thank You!