Università degli Studi di Padova

Space Navigation with Optical Pulsars

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Admission to the thesis evaluation procedure - 14/12/2023

A contract between ESA and CISAS

This PhD research project has been selected by the European Space Agency in the context of the **Open Space Innovation Platform** (OSIP).

→ Direct interaction with ESA experts

→ Use of ESA laboratories

→ ESA is co-funding the 50% of the PhD

A celestial-based navigation system

Satellite navigation strongly depends on ground-based telescope networks. However:

- their positioning accuracy decreases with the distance from the Earth;

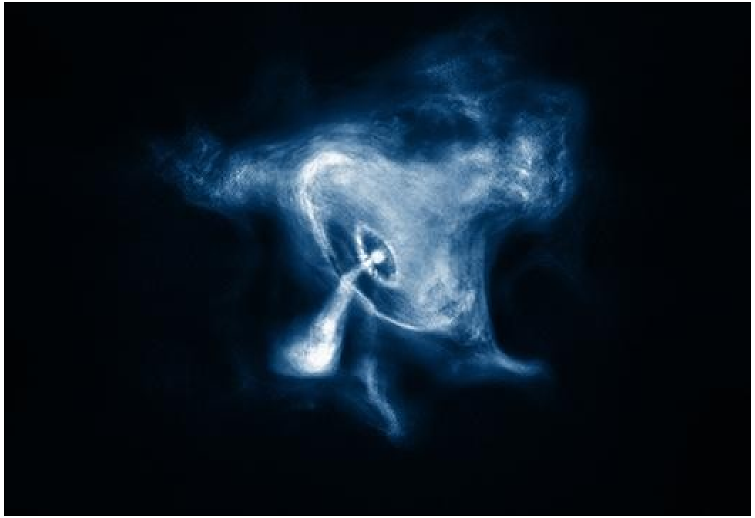
- their limited bandwidth could lead to a point of full utilization in the future.

A solution to these issues could be found in pulsar stars.

> NASA's Deep Space Network, Goldstone Complex (https://www.nasa.gov/directorates/heo/scan/services/networks/dsn/)

High magnetized fast rotating neutron stars, emitting beams of broadband electromagnetic radiation.

A pulsar star is born after the collapse of the nucleus of a massive star (about 8-30 solar masses). Radiation can be observed when a beam of emission is pointing toward our line of sight.



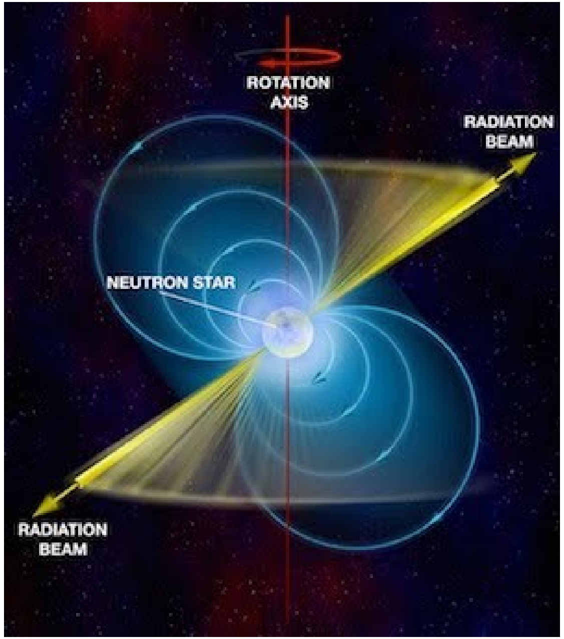
> CRAB PULSAR WITH ITS NEBULA, X-RAY OBSERVATION WITH CHANDRA (https://chandra.harvard.edu/photo/2018/crab/)

The timing model of a pulsar

Pulsar signals have timing stabilities comparable to those of atomic clocks.

Nevertheless, some timing irregularities have been found:

1. timing noise;
2. glitches.



> GRAPHICAL REPRESENTATION OF A PULSAR. CREDIT: B. Saxton, NRAO/AUI/NSF.

Crab pulsar period variation: 3.6×10^{-8} s/day

(19th January 2018)

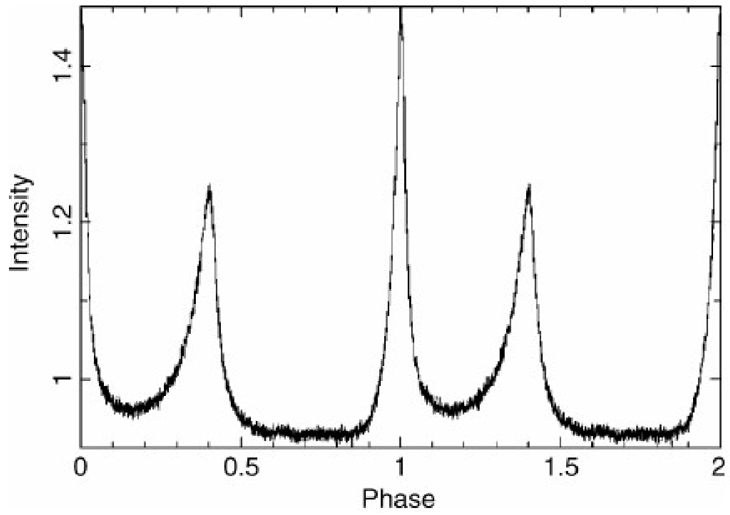
Crab pulsar period: 0.03374455 ± 1.7e-12 s

Firstly proposed by Downs in 1974.

- radio bands: too large antennas on the satellite;

- X-rays: most of research and in-orbit demonstrations have been carried out with X-ray pulsars. However, still quite low signal-to-noise ratio;

- cause of their low number, **optical pulsars have not been considered yet**.



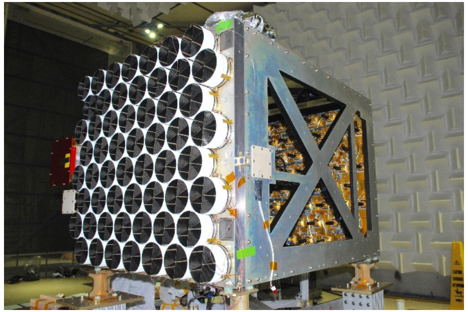
> PULSE PROFILE OF THE CRAB PULSAR (1-15 KeV) OBSERVED BY ARGOS (Emadzadeh and Speyer, 2015)

Navigation with Optical Pulsars

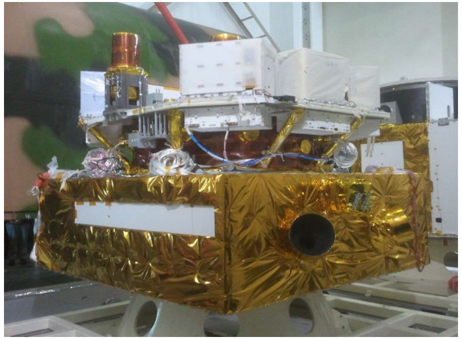
Our aim is to reduce:

- the observation times (several hours in X-ray);
- the positioning error (about 5 km after 10 days in X-ray)
- the payload size ("washing machine"-size in X-ray).

How? Filtering the nebular photons.

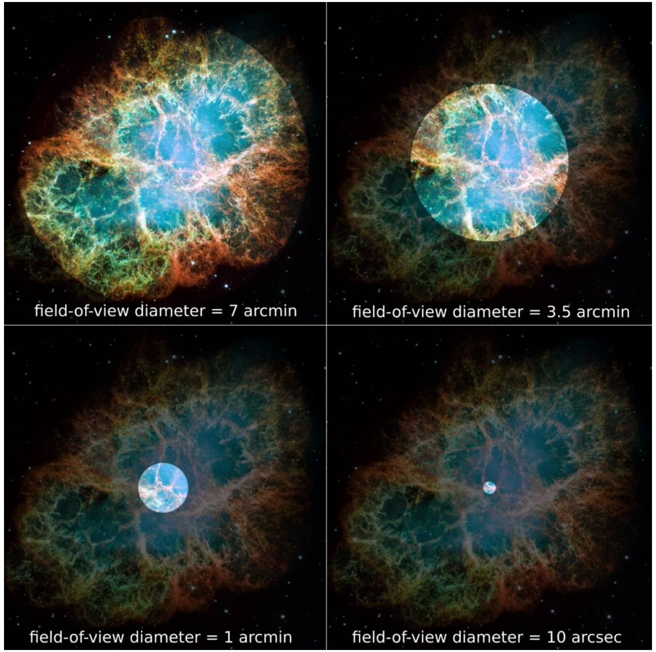


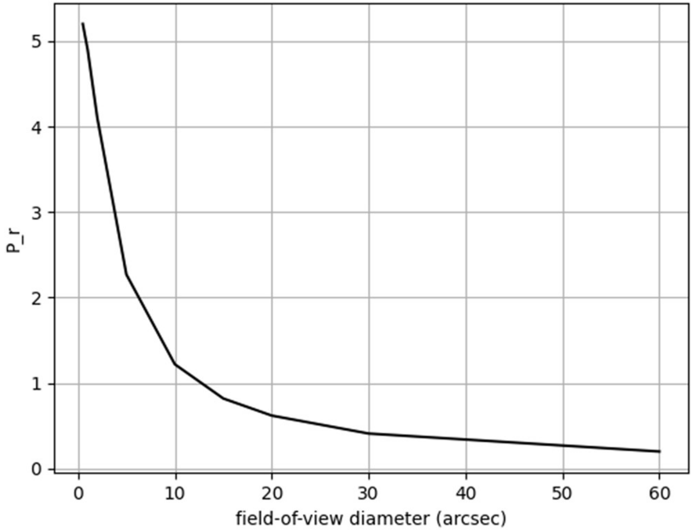
> NICER (CREDIT: nasa.gov): XNAV in-orbit demonstration.



> Insight- HXMT (CREDIT: spaceflight101.com): XNAV in-orbit demonstration.

Filtering the Nebular Photons



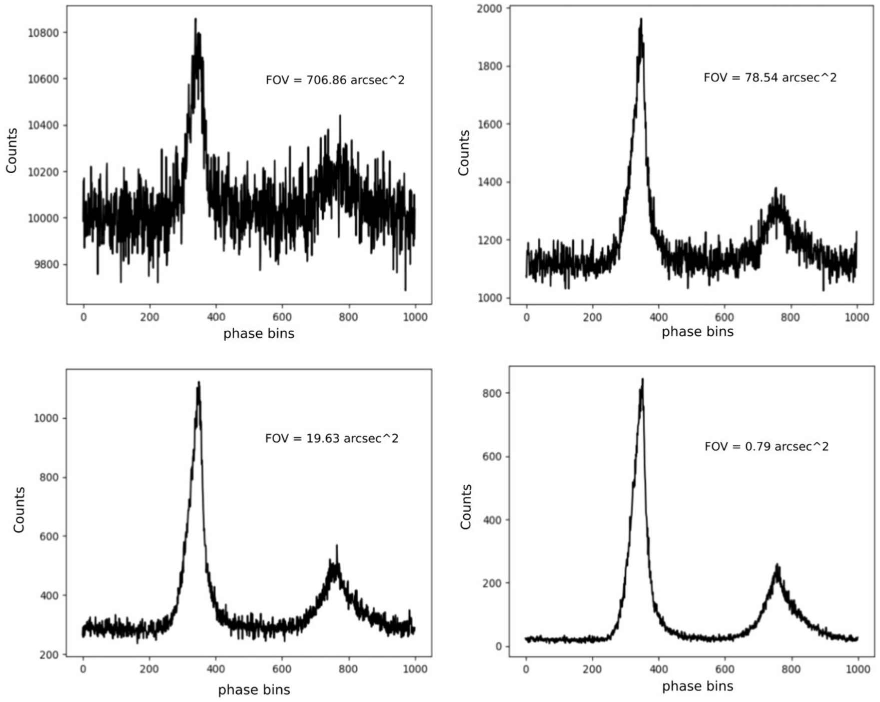


P_r = pulsar-over-nebula ratio

= 0.22 for the Crab pulsar in the X-ray band!

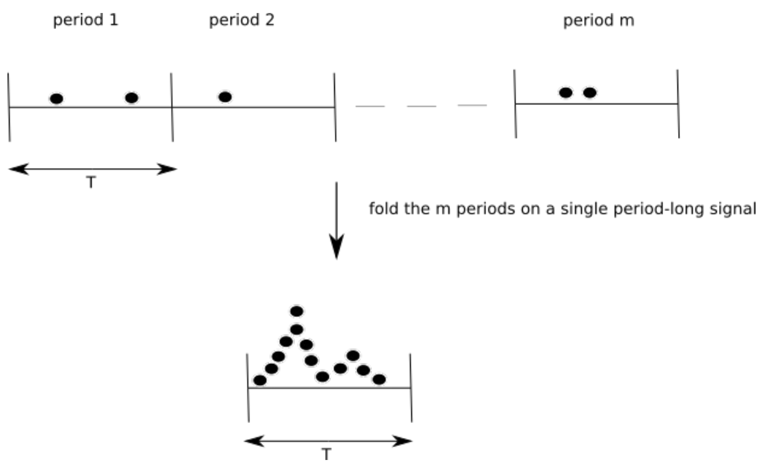
Filtering the Nebular Photons

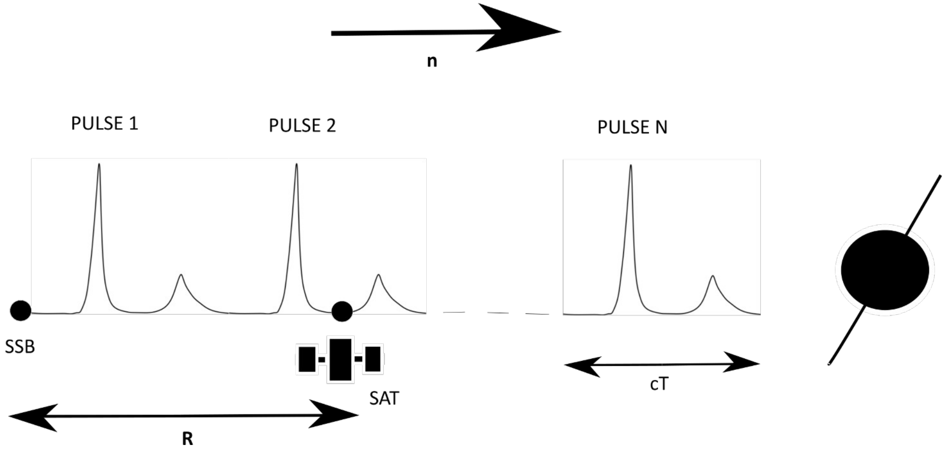
1800 s-long Crab pulsar observation with a 30 cm diameter telescope with different fields-of-view.



Pulsar Navigation Concept

- *First step*: reconstruct the signal starting from the photons ToAs (epoch folding);
- *Second step*: estimate the phase of the reconstructed signal (e.g. via cross-correlation);
- *Third step*: define (and build) the navigation measurement.





Measurement construction

Observed measurement:

$$O_n = c(\phi^s(t) - \phi^{SSB}(t) + i(t) \times n_b) \times dt$$

Computed measurement:

$$C_n = \mathbf{u_k}^T [x_s(t), y_s(t), z_s(t)] + c dt_r(t) + c\Delta R(x_s(t), y_s(t), z_s(t))$$

$$J = \sum_{j=1}^{l} (O_j - C_j)^2$$

→ *Sequential Batch Least Squares Filter*

Goal: find the orbital parameters minimizing *J*.

First year results:

- simulate the photons Time of Arrivals (ToAs) received on-board the satellite in a given orbit;
- estimate the on-board clock error exploiting pulsar stabilities;
- estimate the needed observation time as a function of the SNR, telescope area and field-of-view.

Second year results:

- define the navigation technique to be exploited on-board the satellite;
- improve the simulator with Orekit's force models, integrators and propagators;
- get the first estimation of the achievable positioning accuracy of the system.

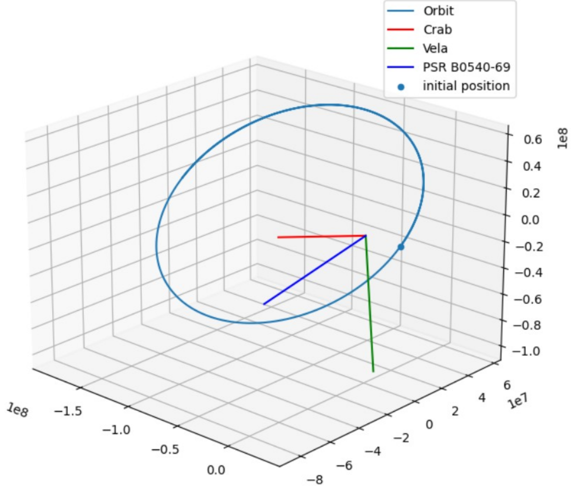
Third year results:

- choose the orbit for the simulations and build it with Orekit;
- definition of the time synchronization technique;
- develop the software for the “multi”-pulsar scenario.

Orekit: Orbit Extrapolation Kit

***Orekit** is an open-source low-level space dynamics library written in Java.*

Orekit provides basic elements (orbits, dates, attitude, frames, ...) and various algorithms to handle them (conversions, propagations, pointing, ...).

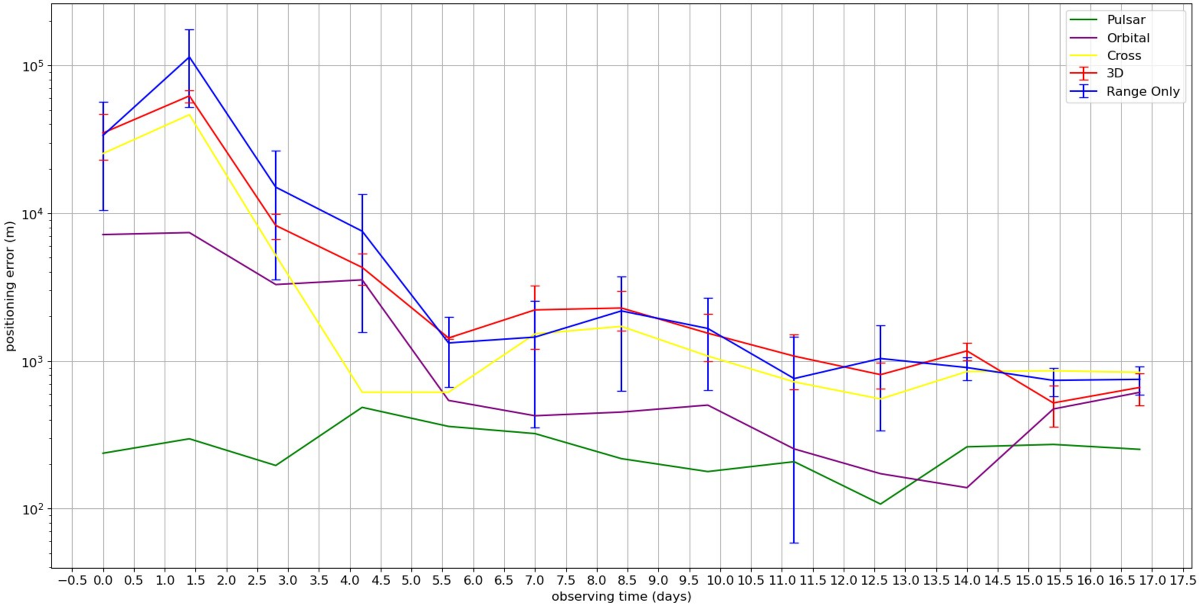


My contributions led to the development of the **Orekit Python Wrapper 11.1.2**.

Lunar Gateway: a cislunar Near Rectilinear Halo Orbit (1)

Telescope diameter: 30 cm
DFoV = 1 arcsec

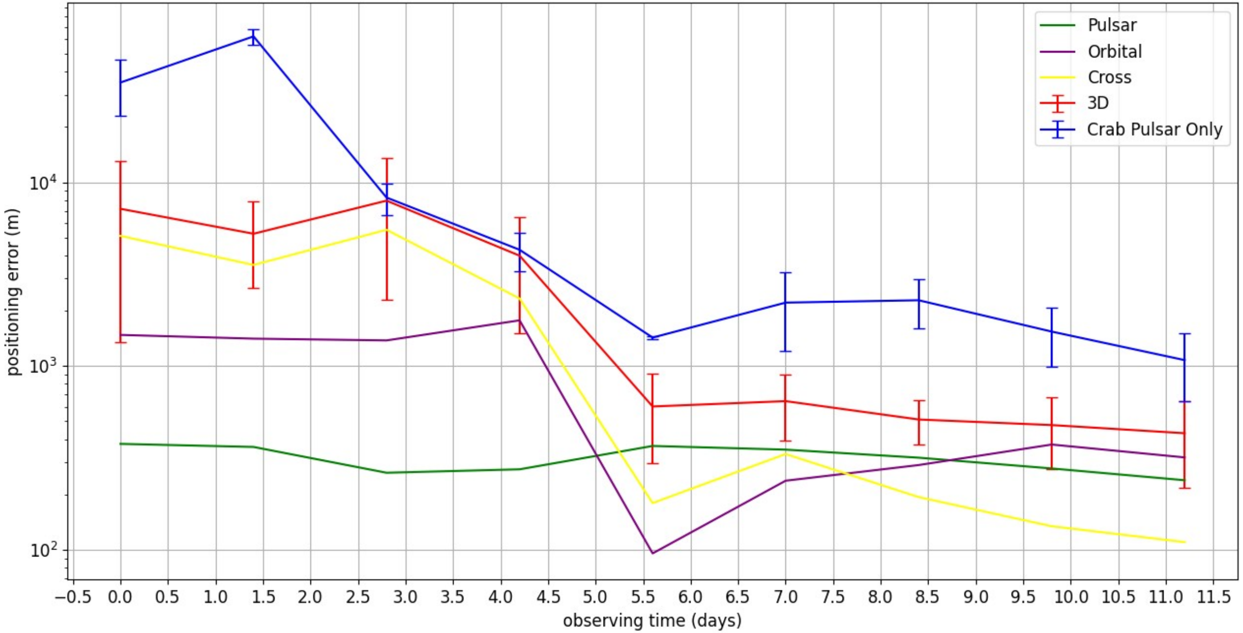
Single pulsar case: Crab



Lunar Gateway: a cislunar Near Rectilinear Halo Orbit (2)

Telescope diameters: 30 cm
DFoVs = 1 arcsec

Multi-pulsar case: Crab, Vela, B0540-69



Publications

1. P. Zoccarato, S. Larese, G. Naletto, L. Zampieri and F. Brotto, Deep Space Navigation by Optical Pulsars, Journal of Guidance, Control and Dynamics, Vol. 46, No. 8, August 2023.

2. S. Larese, G. Naletto, P. Zoccarato, G. Zeni and L. Zampieri, Performance Analysis of an Optical Pulsar-based Navigation System (submitted for publication).

3. S. Larese, P. Zoccarato and G. Naletto, Optical Pulsar-based Orbit Determination and Time Synchronization for Spacecraft in Cislunar Near Rectilinear Halo Orbit (ready for submission).

Thanks for the attention

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