Space Navigation with Optical Pulsars

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Admission to third year - 06/09/2022

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:

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

- the number of space missions will very likely increase in the next years, requiring larger telescope networks and human intervention.

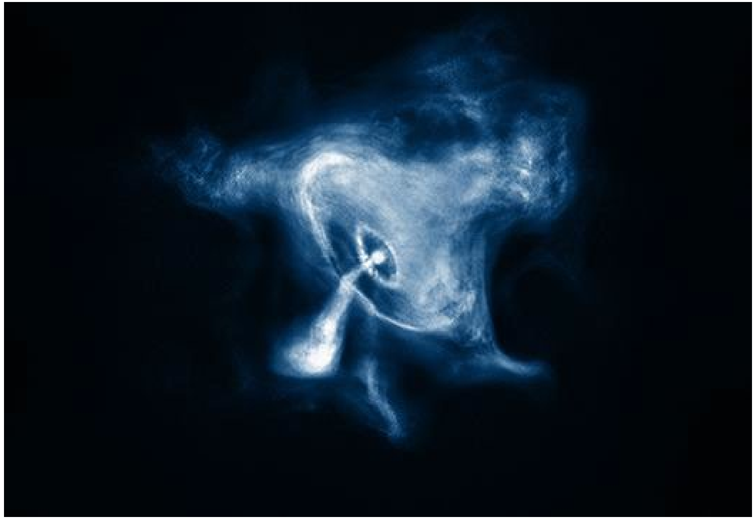
A solution to these issues could be found in pulsar stars.

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

Pulsars

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.

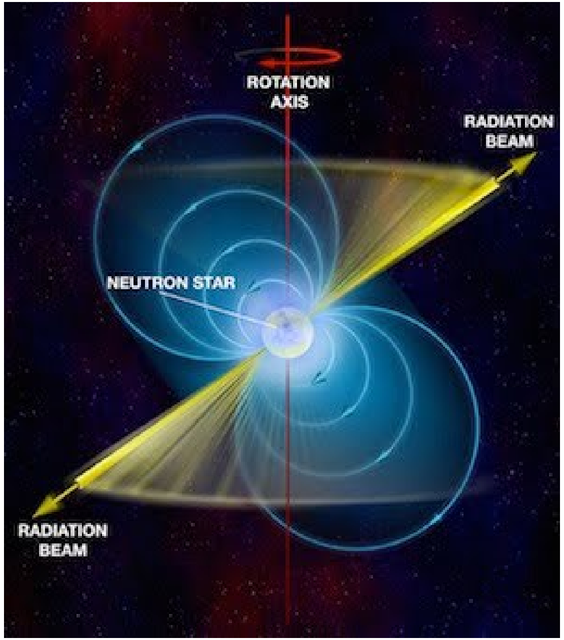
Nevertheless, some timing irregularities have been found:

1. timing noise;
2. glitches.

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

Crab pulsar period: 0.03374455 ± 1.7e-12 s

(19th January 2018)



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

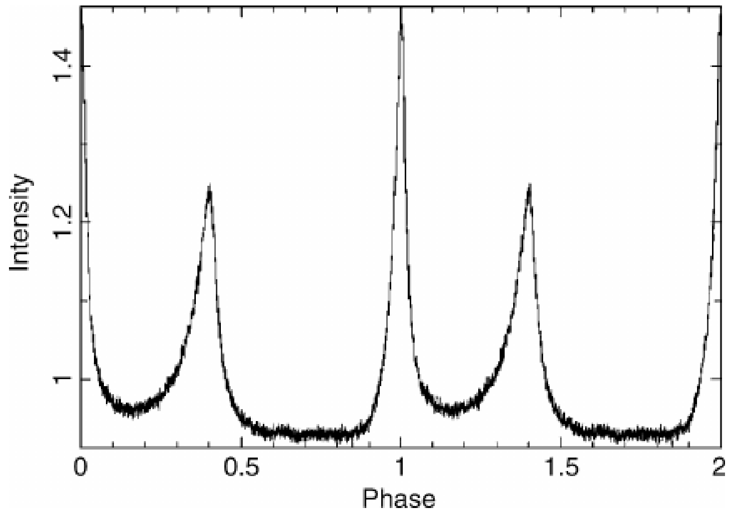
Pulsar Navigation

Firstly proposed by Downs in 1974.

- radio bands: too large antennas on the satellite;

- X-rays: most of researches and in-orbit demonstrations have been carried out with X-ray pulsars. However, quite low photon fluxes (the larger, the better);

- 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)

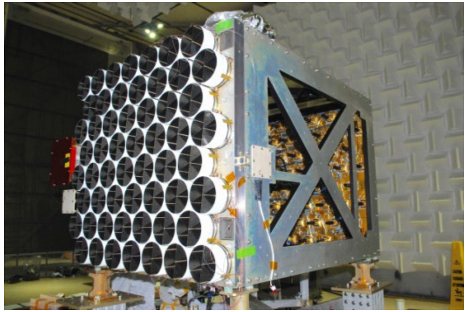
Navigation with Optical Pulsars

Optical pulsars show higher statistics with respect to X-ray pulsars, leading to:

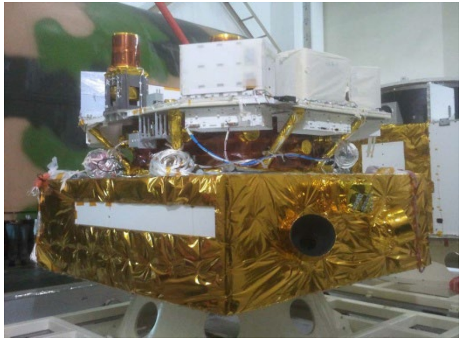
- Shorter observation times;
- Smaller telescopes;
- Much more tried and tested technologies.

> For these reasons, **a higher positioning accuracy is expected**.

> Such accuracies are theoretically **independent of the distance from the Earth**!



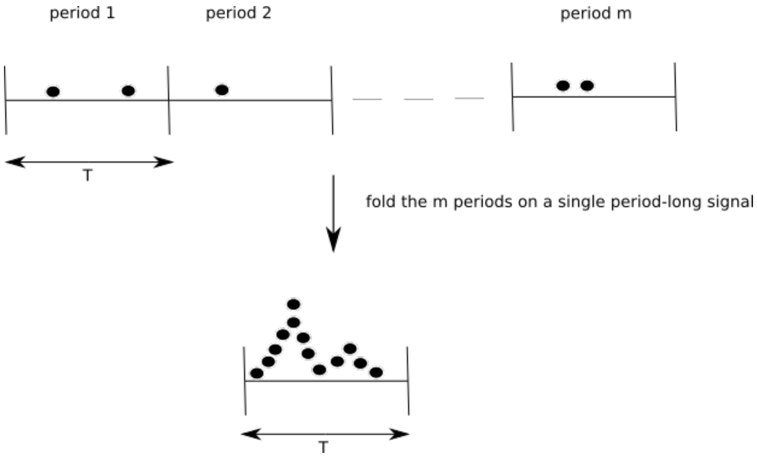
> NICER (CREDIT: nasa.gov): XNAV in-orbit demonstration.

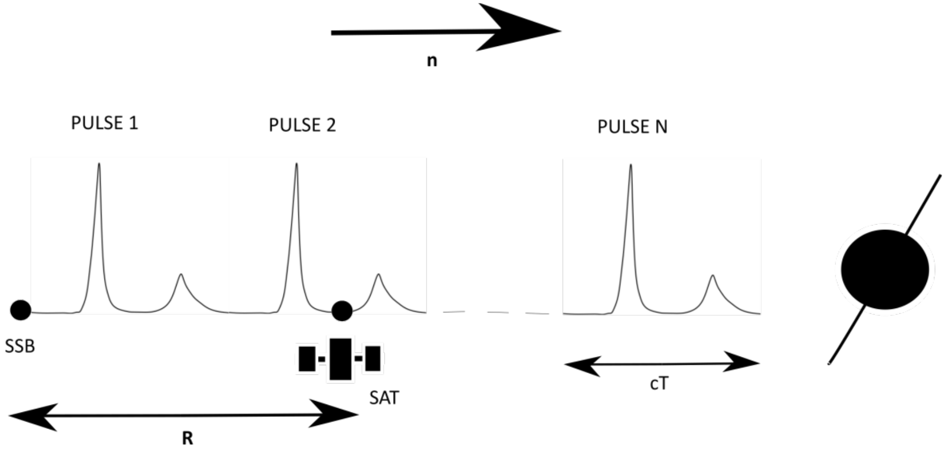


> Insight- HXMT (CREDIT: spaceflight101.com): XNAV in-orbit demonstration.

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*.

Main outcomes

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.

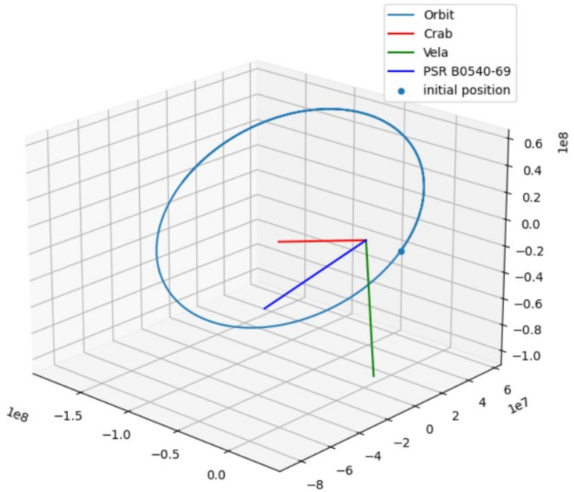
Second year results:

- 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.

Orekit: Orbit Extrapolation Kit

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

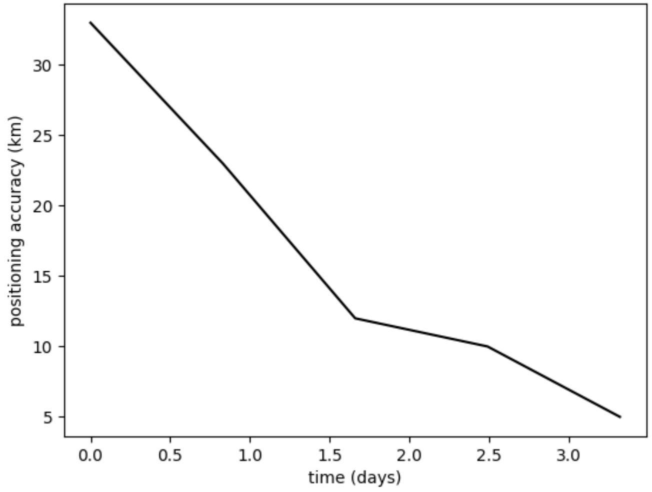
Orekit provides basic elements (orbits, dates, attitude, frames, ...) and various algorithms to handle them (conversions, propagations, pointing, ...).



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

Results: Highly Elliptical Orbit around the Earth

→ an initial positioning error of 33 km has been provided to the satellite;
→ a single observation lasted 4000 s;
→ only Crab pulsar measurements have been exploited;
→ telescope diameter: 0.3 m, field-of-view diameter: 1 arcsec.



Future objectives

- simulate a Near Rectilinear Halo Orbit to test the performance of the system (Lunar Gateway);
- repeat the analysis for a simulated hyperbolic trajectory;
- estimate the position of the Copernicus telescope in Asiago with real pulsar data.

Publications

1. P. Zoccarato, S. Larese, G. Naletto, L. Zampieri and F. Brotto, Deep Space Navigation by Optical Pulsars (ready for submission).

2. S. Larese, G. Naletto, P. Zoccarato and L. Zampieri, Parametric Design of a Photon Counter Photometer for Space Navigation by Optical Pulsar (ready for submission).

3. S. Larese, P. Zoccarato and G. Naletto, PODS: a Pulsar-based Orbit Determination Software (ready for submission).

Thanks for the attention

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