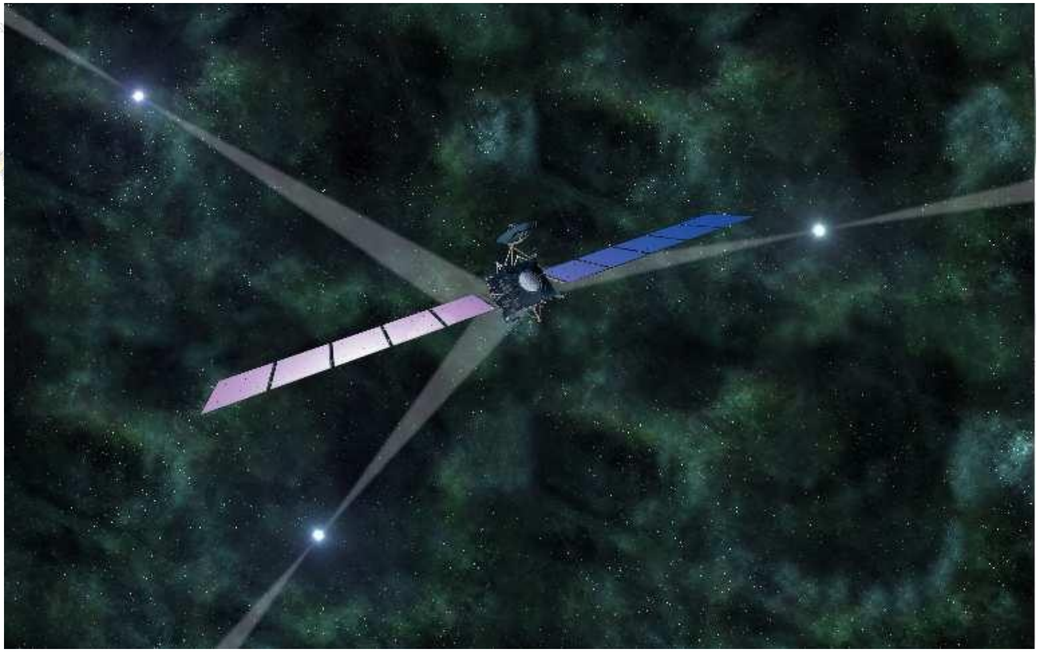
Pulsar-based Navigation



Directly based on (1) Becker, W., Bernhardt, M. G., & Jessner, A. (2013). Autonomous Spacecraft Navigation With Pulsars. arXiv preprint arXiv:1305.4842, and (2) Buist et al., "Overview of Pulsar Navigation: Past, Present and Future Trends" NAVIGATION: Journal of The Institute of Navigation Vol. 58, No. 2, Summer 2011

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https://scholar.google.es/citations?user=Tm-DcsMAAAAJ&hl=en

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Summary

- An external reference system suitable for deep space navigation can be defined by fast spinning and strongly magnetized neutron stars, called pulsating stars (*pulsars*).
- Their beamed periodic signals have timing stabilities comparable to atomic clocks and provide characteristic temporal signatures that can be used as natural navigation beacons, quite similar to the use of GPS satellites for navigation on Earth.
- By comparing pulse arrival times measured on-board a spacecraft with predicted pulse arrivals at a reference location, the spacecraft position can be determined autonomously and with high accuracy everywhere in the solar system and beyond.
- The unique properties of pulsars make clear already today that such a navigation system will have its application in future astronautics.

Space-time Earth location with pulsars for anyone... (1 of 3)

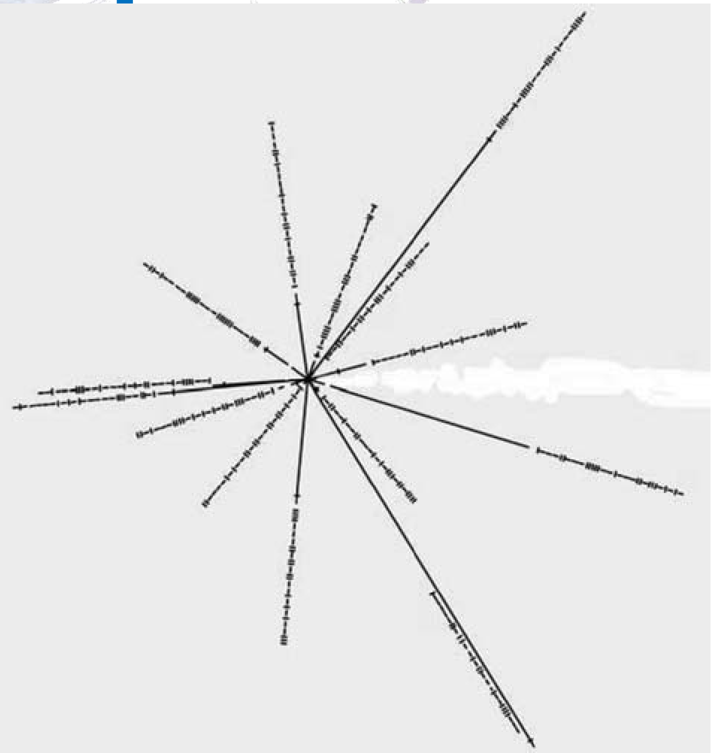

Fig. 1–The pulsar map, engraved in the plaques launched with Pioneer 10, 11 and Voyager 1 and 2 .The line representing the relative distance of the Sun to the center of the galaxy is not shown (from Buist et al. 2011).

- Pulsar discovery on 1968.
- On 1972 NASA installed a plaque on their Pioneer 10 and 11 spacecraft showing the location of the Sun with respect to the center of the galaxy using the direction of 14 known pulsars, along with their pulse periods.
- The lengths of the lines in the figure show the relative Sun-Earth distances.

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Space-time Earth location with pulsars for anyone (2 of 3)

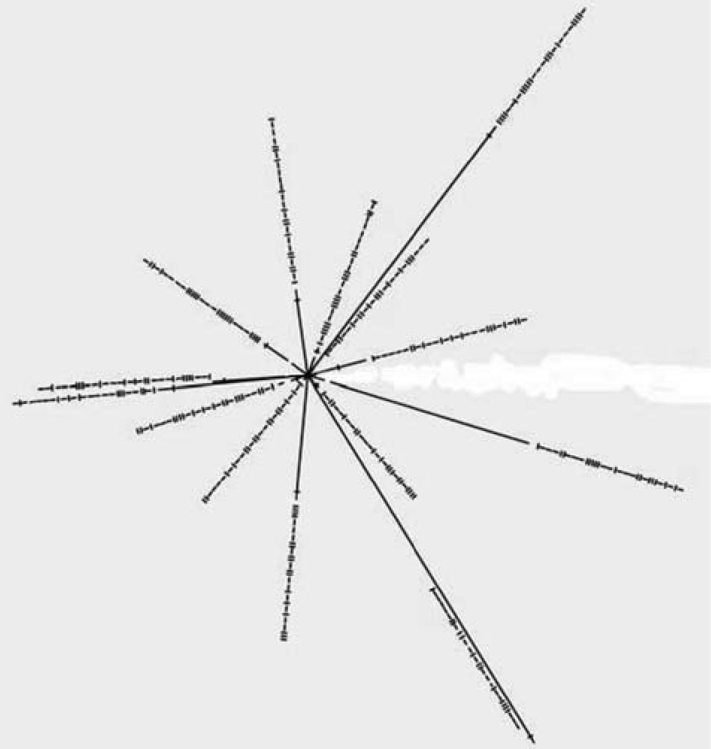

Fig. 1–The pulsar map, engraved in the plaques launched with Pioneer 10, 11 and Voyager 1 and 2 .The line representing the relative distance of the Sun to the center of the galaxy is not shown (from Buist et al. 2011).

- The pulse periods are indicated by long binary numbers corresponding to the pulsars.
- Since these periods change over the time, not only the location of the Sun but also the epoch of launch of the probe can be calculated.
- In this way another civilization would be able to find the location of Earth.

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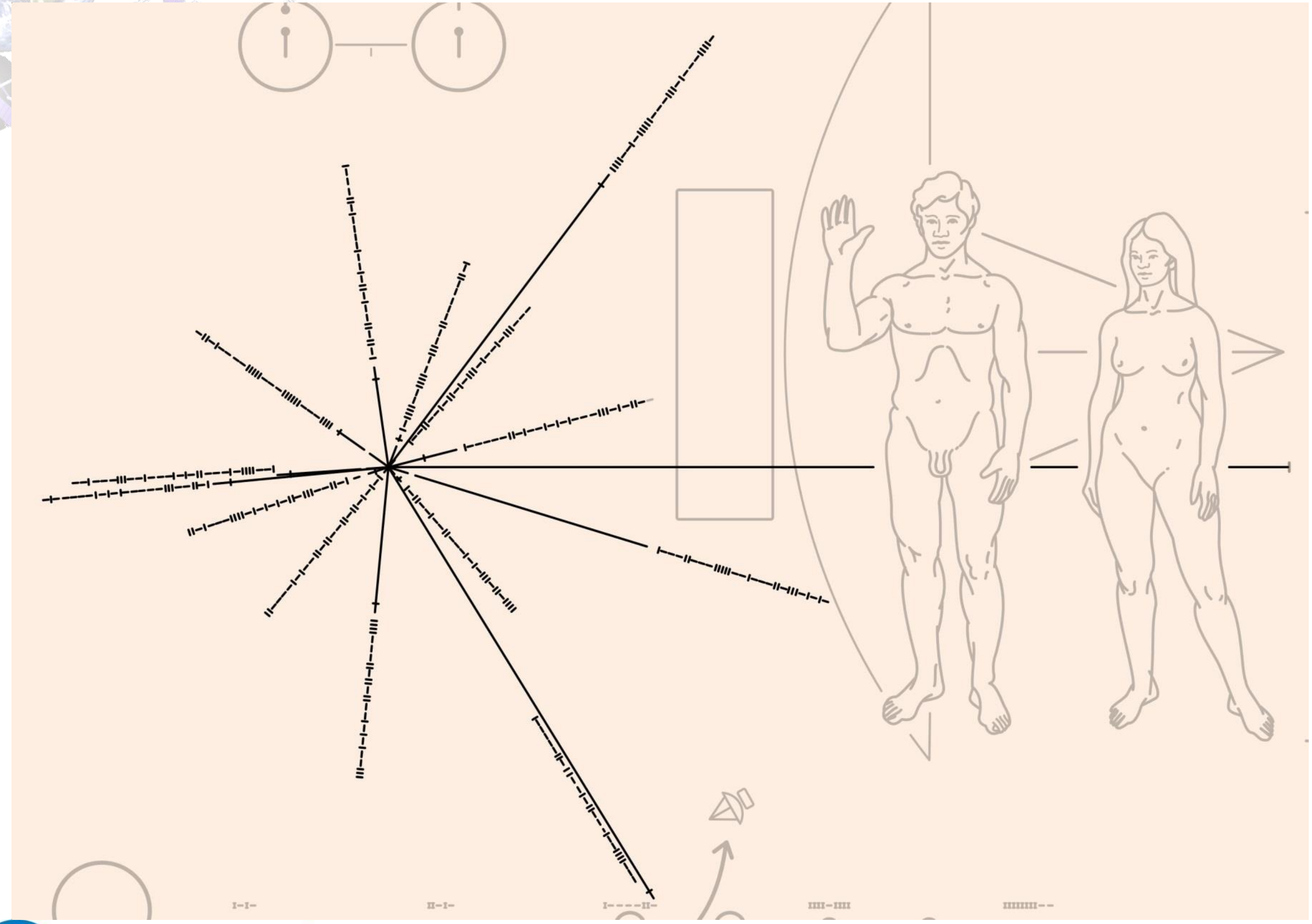
Space-time Earth location with pulsars for anyone (3 of 3)

- Pulsars, unlike man-made navigation satellites, are immune to solar flares or hostile attempts at disabling them and due to their broad- band nature, jamming their signals is rather difficult.
- These aspects, combined with the fact that there are already over 1800 known pulsars in the celestial sphere, gives them a very firm base for governmental and civilian use, as well as military applications not only for space.

Details of the Pioneer Plaques



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Interplanetary navigation today (1 of 3)

- Today, the standard method of navigation for interplanetary spacecraft is a combined use of radio data, obtained by tracking stations on Earth, and optical data from an on-board camera during encounters with solar system bodies.
- Radio measurements taken by ground stations provide very accurate information on the distance and the radial velocity of the spacecraft with typical random errors of about 1 m and 0.1 mm/s.

Interplanetary navigation today (2 of 3)

- The components of position and velocity perpendicular to the Earth-spacecraft line, however, are subject to much larger errors due to the limited angular resolution of the radio antennas.
- Interferometric methods can improve the angular resolution to about 25 nrad, corresponding to an uncertainty in the spacecraft position of about 4 km per astronomical unit (AU) of distance between Earth and spacecraft: ±200 km at the orbit of Pluto and ±500 km at the distance of Voyager 1.

Interplanetary navigation today (3 of 3)

- Nevertheless, this technique has been used successfully to send space probes to all planets in the solar system and to study asteroids and comets at close range.
- However, it might be necessary for future missions to overcome the disadvantages of this method, namely the dependency on ground-based control and maintenance, the increasing position and velocity uncertainty with increasing distance from Earth as well as the large propagation delay and weakening of the signals at large distances.

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Possible spatial autonomous navigation systems (1 of 6)

- It is therefore desirable to automate the procedures of orbit determination and orbit control in order to support autonomous space missions.
- In principle, the orbit of a spacecraft can be determined by measuring angles between solar system bodies and astronomical objects; e.g., the angles between the Sun and two distant stars and a third angle between the Sun and a planet.
- However, because of the limited angular resolution of on-board star trackers and sun sensors, this method yields spacecraft positions with uncertainties that accumulate up to >~10^3 km

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Possible spatial autonomous navigation systems (2 of 6)

- Alternatively, the navigation fix can be established by observing multiple solar system bodies: It is possible to triangulate the spacecraft position from images of asteroids taken against a background field of distant stars.
- This method was realized and flight-tested on NASA's Deep-Space-1 mission (Oct. 1998 – Dec. 2001): The Autonomous Optical Navigation (AutoNav) system on-board provided the spacecraft orbit with 1s errors of ±250 km and ±0.2 m/s.
- The resulting errors were nevertheless relatively large compared to ground-based navigation

Possible spatial autonomous navigation systems (3 of 6)

- The Unconventional Stellar Aspect experiment (proposed in the 1980s by NRL, USA) was launched in 1999 on the Advanced Research and Global Observation Satellite (ARGOS).
- This experiment demonstrated a method of position determination based on stellar occultation by the Earth's limb as measured in X-rays. This technique, though, is limited to satellites in low Earth orbit.

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Possible spatial autonomous navigation systems (4 of 6)

- An alternative and very appealing approach to autonomous spacecraft navigation is based on pulsar timing (the idea goes back to the 1970s).
- By comparing pulse arrival times at the spacecraft with those at a reference location: spacecraft position errors on ~1500 km after 24 hours of signal integration (technology limitations and a set of only 27 radio pulsars were available).
- A possible improvement in precision by a factor of 10 was estimated if better (high-gain) radio antennas were available for the observations.

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Possible spatial autonomous navigation systems (5 of 6)

- In the 1980's this idea was adapted to the use of X-ray pulsars (~12 were known at the time), instead of radio pulsars.
- It was estimated that 24 hours of data collection from a small on-board X-ray detector with 0.1 m2 collecting area would yield a three-dimensional position accurate to about 150 km.
- The analysis, was not based on simulations or actual pulsar data; neither did it take into account the technological requirements or weight and power constraints for such a navigation system.

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Possible spatial autonomous navigation systems (6 of 6)

- However, pulsar astronomy has improved considerably over the last 30 years since these early proposals.
- Meanwhile, pulsars have been detected across the electromagnetic spectrum and their emission properties have been studied in great detail
- Along with the recent advances in detector and telescope technology this motivates a general reconsidera- tion of the feasibility and performance of pulsar-based navigation systems.

Physical origin of pulsars (1 of 10)

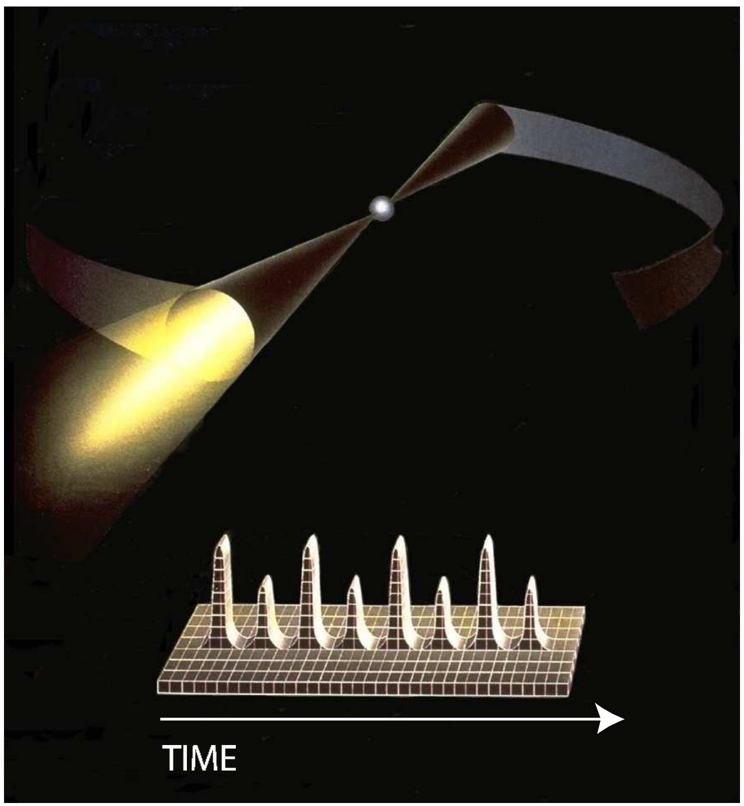
- Stars are stable as long as the outward-directed thermal pressure, caused by nuclear fusion in their central region, and the inward-directed gravitational pressure are in equilibrium.
- The outcome of stellar evolution, though, depends solely on the mass of the progenitor star. A star like our sun develops into a white dwarf. Stars above ≈ 8 $M_\odot$ undergo a gravitational collapse once their nuclear fuel is depleted.
- Very massive stars (>~30 $M_\odot$) end up as black holes and stars in the intermediate mass range of about 8 to 30 $M_\odot$ form neutron stars.

Physical origin of pulsars (2 of 10)

- It is assumed that a neutron star is the result of a supernova explosion, during which the bulk of its progenitor star is expelled into the interstellar medium.
- The remaining stellar core collapses under its own weight to become a very compact object, primarily composed of neutrons – a neutron star. With a mass of typically 1.4 $M_{\odot}$, compressed into a sphere of only 10 km in radius, they are quasi gigantic atomic nuclei in the universe.
- Because of their unique properties they are studied intensively since their discovery in 1967.

Physical origin of pulsars (3 of 10)

- Fast spinning and strongly magnetized neutron: If this radiation cone crosses the observer's line of sight a pulse of intensity is recorded in the observing device (*pulsar*).



Artist's impression of a rotation-powered pulsar. The neutron star appears as a pulsating source of radiation if the rotating emission beam crosses the observer's line of sight. Averaging these periodic pulses of intensity over many rotation cycles results in a stable pulse profile. Because of the timing stability of most pulsars, the arrival time of pulses can be predicted with very high precision, which is an essential requirement for a navigation system based on pulsar observations (from Becker et al. 2013).

Physical origin of pulsars (4 of 10)

There are three different classes of pulsars, according to the electromagnetic energy source, but only one class is suitable for spacecraft navigation:

- **Accretion-powered pulsars:** are close binary systems in which a neutron star is accreting matter from a companion star, thereby gaining energy and angular momentum (CONS: unsteady and non-coherent timing behaviour)
- **Magnetars:** Isolated neutron stars with exceptionally high magnetic dipole fields (CONS: X-ray burst activity, long-term timing behavior is virtually unknown).
- **Rotation-powered pulsars:** radiate broad- band electromagnetic radiation (from radio to optical, X- and gamma-rays) at the expense of their rotational energy, i.e., the pulsar spins down as rotational energy is radiated away by its co rotating magnetic field (e.g. Crab pulsar).

Physical origin of pulsars (5 of 10)

There are two types of rotation-powered pulsars:

(1) Field pulsars, which have periods between tens of milliseconds to several seconds and constitute more than 90% of the total pulsar population.

(2) About 10% of the known pulsars are so-called millisecond pulsars, which are defined to have periods below 20 milliseconds. They are much older than normal pulsars, posses weaker magnetic fields and, therefore, relatively low spin-down rates. Accordingly, they exhibit very high timing stabilities, which are comparable to atomic clocks.

Physical origin of pulsars (6 of 10)

- It is assumed that millisecond pulsars are born as normal pulsars in a close binary system, but their rotation accelerates as they pass through a phase of accretion in which mass and angular momentum are transferred from the evolving companion star to the pulsar.
- However, the fact that millisecond pulsars are often found in binary systems does not affect their suitability for spacecraft navigation as the binary motion can easily be accounted for in pulsar timing.

Physical origin of pulsars (7 of 10)

- Some rotation-powered pulsars have shown glitches in their spin-down behavior, i.e., abrupt increases of rotation frequency, often followed by an exponential relaxation toward the pre-glitch frequency.
- This is often observed in young pulsars but very rarely in old and millisecond pulsars.
- Nevertheless, the glitch behavior of pulsars should be taken into account by a pulsar-based navigation system.

Physical origin of pulsars (8 of 10)

- Today, more than 2200 rotation-powered pulsars are known. More than 150 have been detected in the X-ray band and approximately 1/3 of them are millisecond pulsars.
- Their ephemerides (RA, DEC, *P*, *dP/dt*, binary orbit parameters, pulse arrival time and absolute pulse phase for a given epoch, pulsar proper motion etc.) are known with very high accuracy.

Physical origin of pulsars (9 of 10)

- Indeed, pulsar timing has reached the 10^{-15} fractional level, comparable with the accuracy of atomic clocks.
- This is an essential requirement for using these celestial objects as navigation beacons, as it enables one to predict the pulse arrival time of a pulsar for any location in the solar system and be-yond.

Physical origin of pulsars (10 of 10)

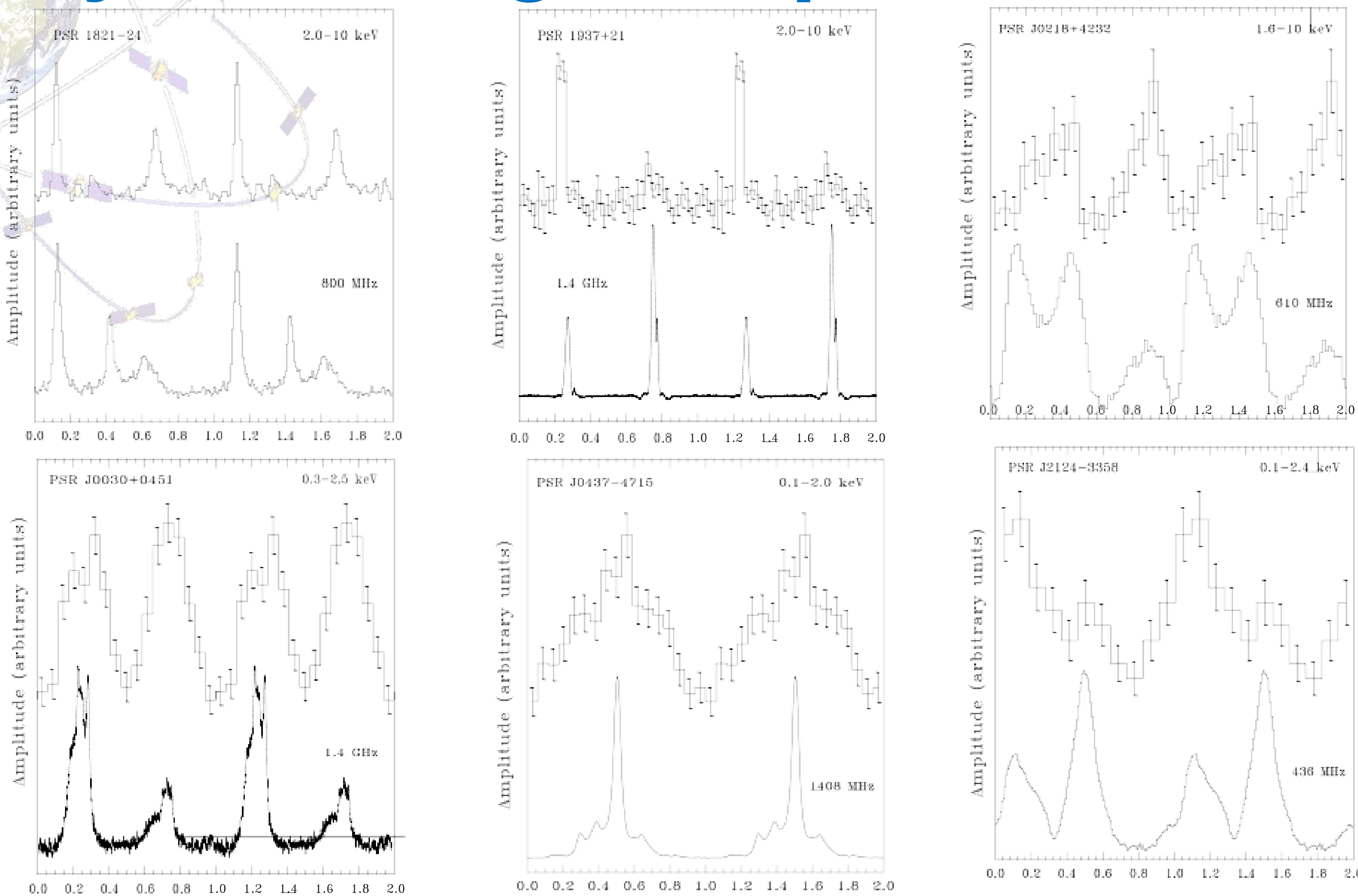


Figure 3: X-ray and radio pulse profiles (amplitude vs. pulse phase) for the six brightest millisecond pulsars. Two full pulse cycles are shown for clarity (from Becker et al. 2013).

Principles of pulsar navigation (1 of 5)

The concept of using pulsars as navigational aids is based on measurements of pulse arrival times and comparison with predicted arrival times at a given epoch and reference location.

Principles of pulsar navigation (2 of 5)

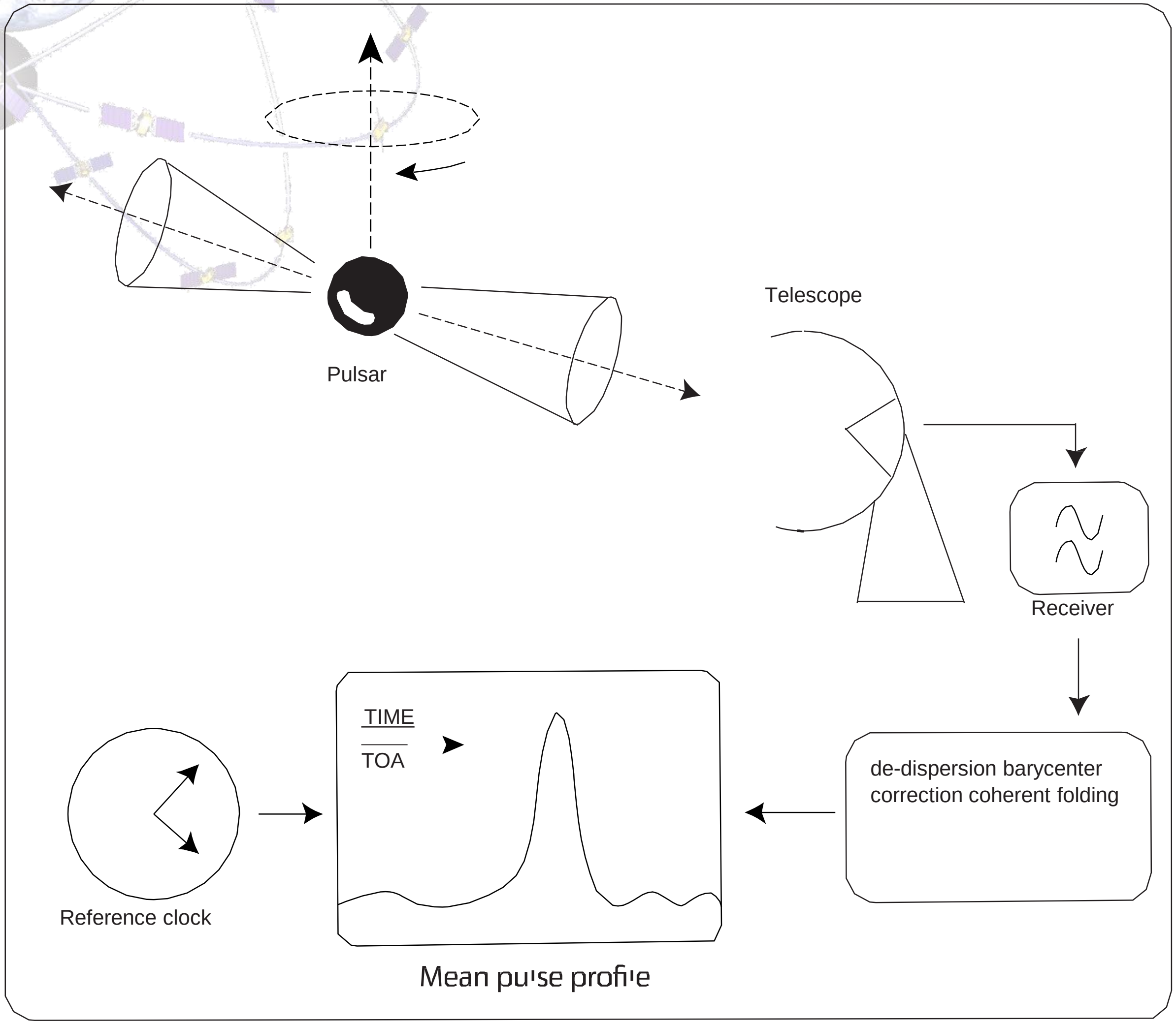


Figure 4: Typical pulsar detection chain. The pulsar beams sweep across the radio antenna. Radio signals are recorded and analyzed in order to produce a mean pulse profile. The data processing comprises a removal of dispersion effects caused by the interstellar medium (“de-dispersion”), correction for the position and proper motion of the observatory (“barycenter correction”) and coherent folding of many pulses. The time of arrival (TOA) of the pulse peak is measured against a reference clock (from Becker et al. 2013).

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Principles of pulsar navigation (3 of 5)

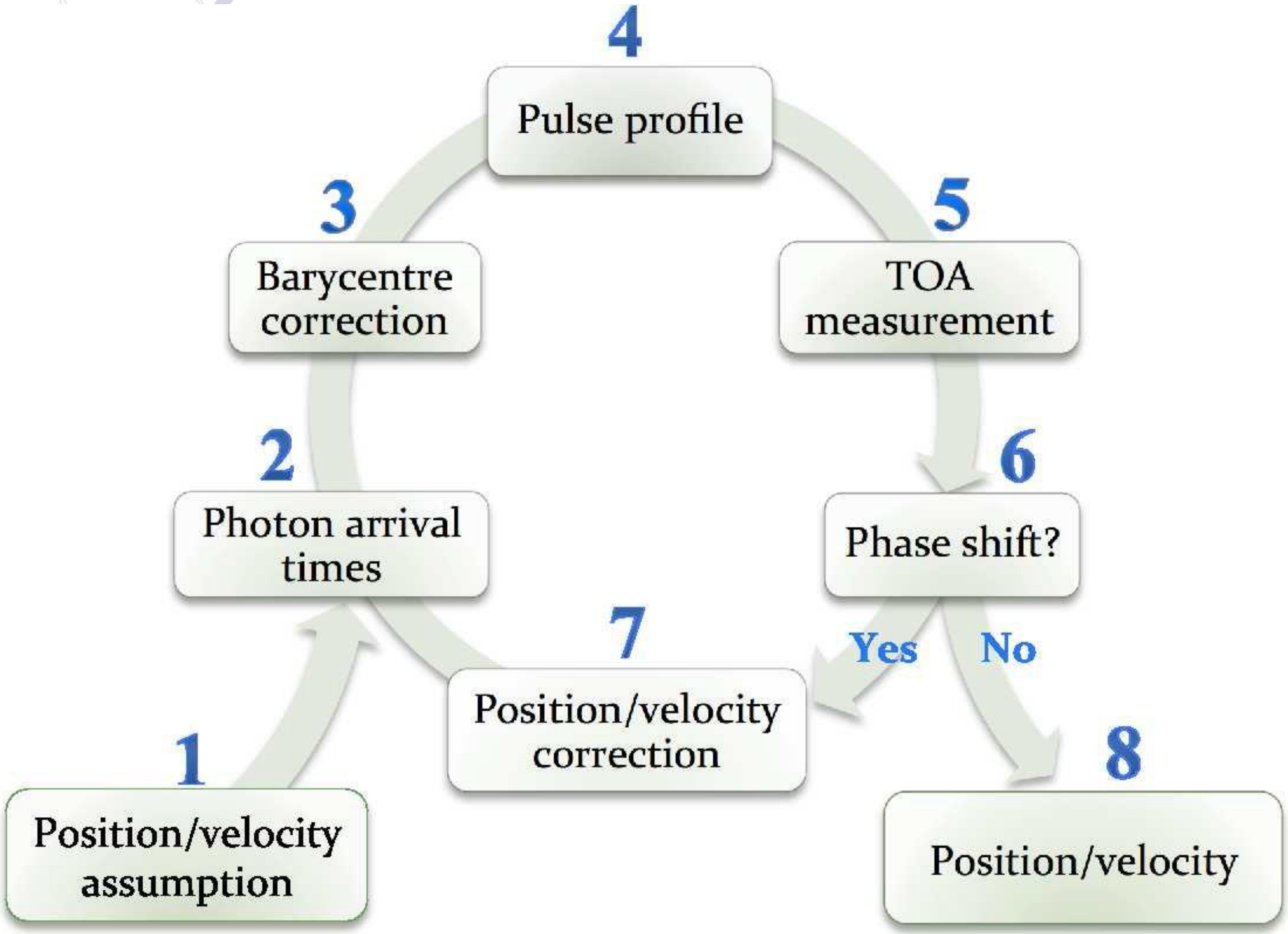

Figure 5: Iterative determination of position and velocity by a pulsar-based navigation system (from Becker et al. 2013).

Principles of pulsar navigation (4 of 5)

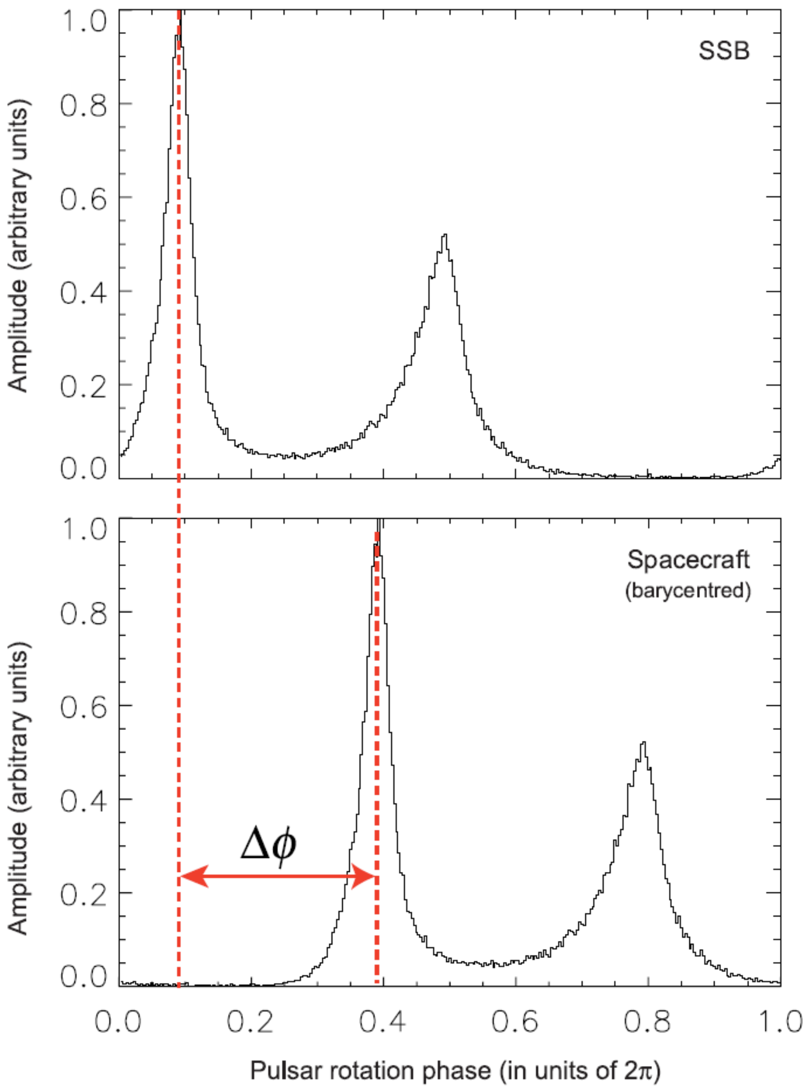

Figure 6: Measuring the phase difference between the expected and measured pulse peak at an inertial reference location; e.g., the solar system barycenter (SSB). The top profile shows the main pulse peak location as expected at the SSB. The bottom profile is the one which has been measured at the spacecraft and transformed to the SSB by assuming the spacecraft position and velocity during the observation. If the position and velocity assumption was wrong, a phase shift is observed (from Becker et al. 2013).

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Principles of pulsar navigation (5 of 5)

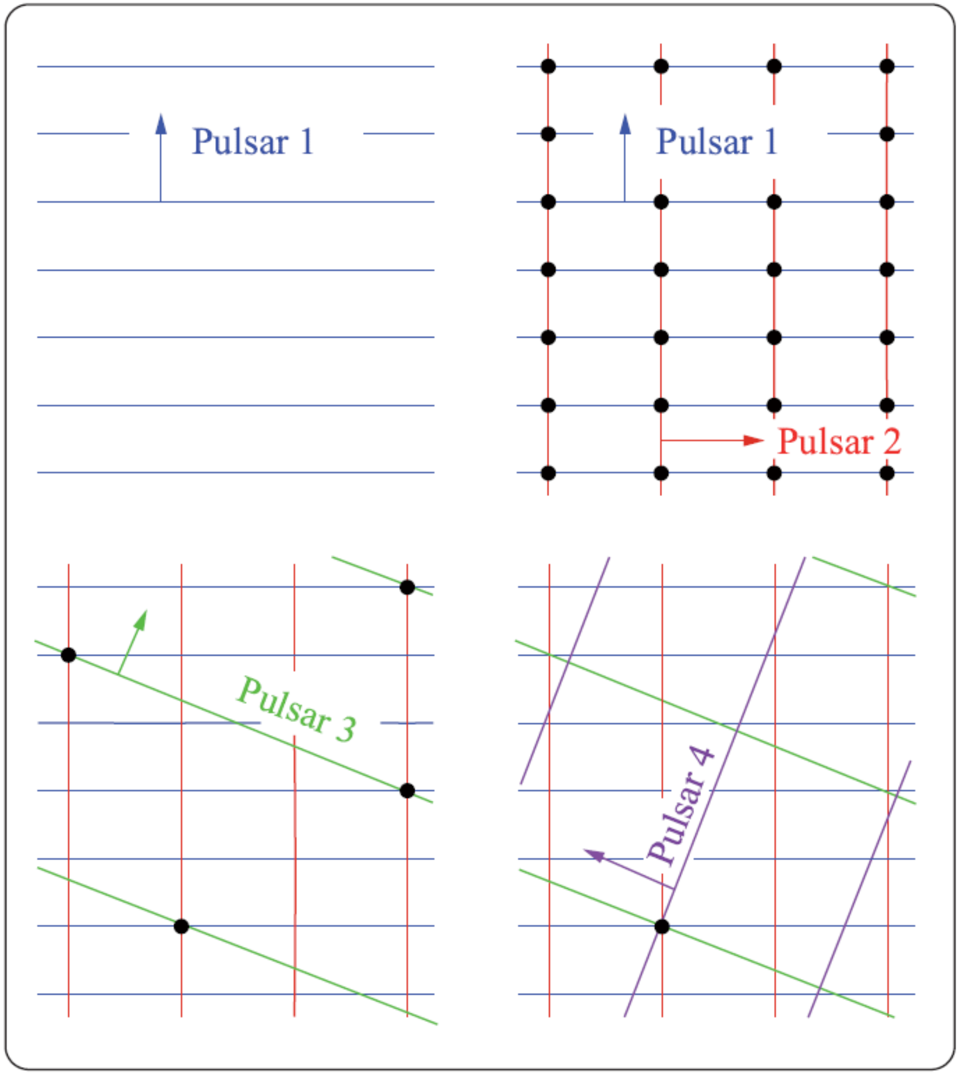

Figure 7: Solving the ambiguity problem by observing four pulsars (drawn in two dimensions). The arrows point along the pulsar's lines-of-sight. Straight lines represent planes of constant pulse phase; black dots in- dicate intersections of planes (from Becker et al. 2013).

Expected error of pulsar navigation

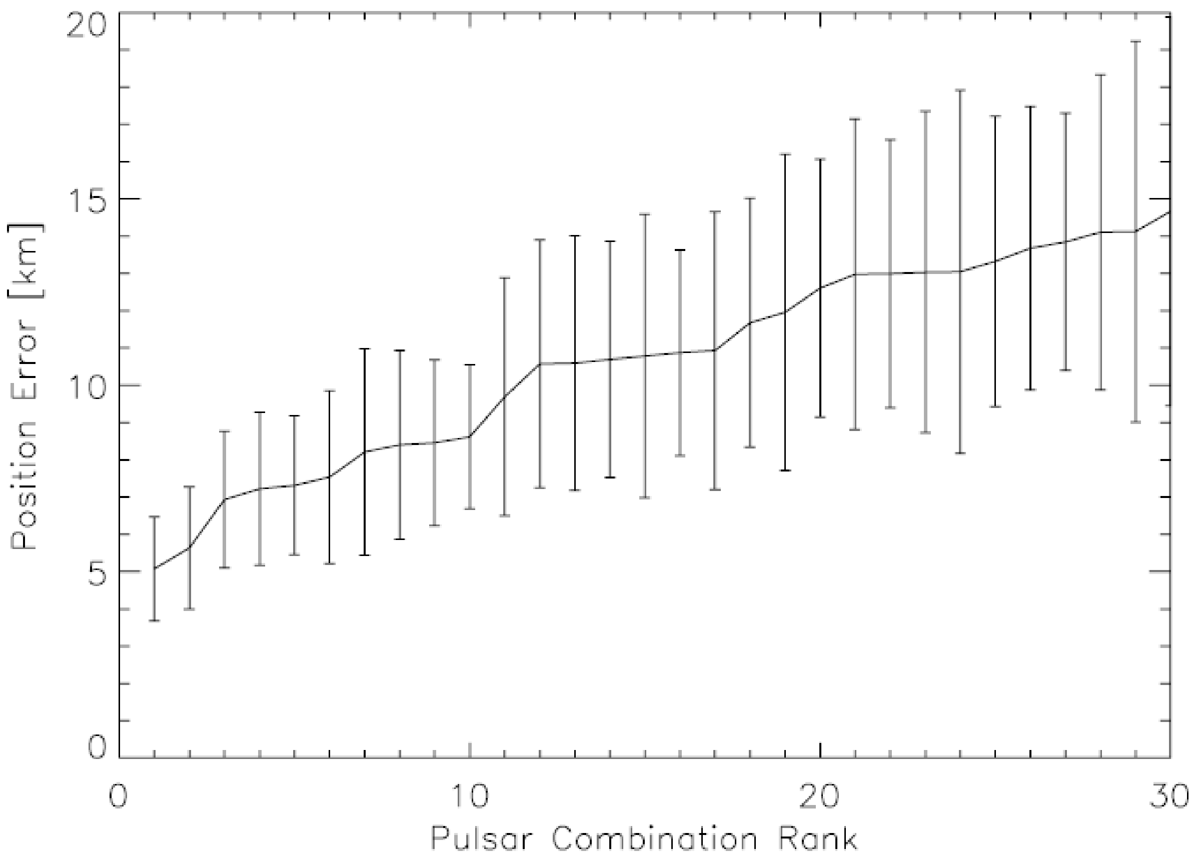

Figure 8: Spacecraft position error as a function of possible pulsar 3-combinations. The diagram shows the mean position errors and standard deviations for the best 30 combinations, going down to 5 km.

From Bernhardt et al. (2010).

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Next future?

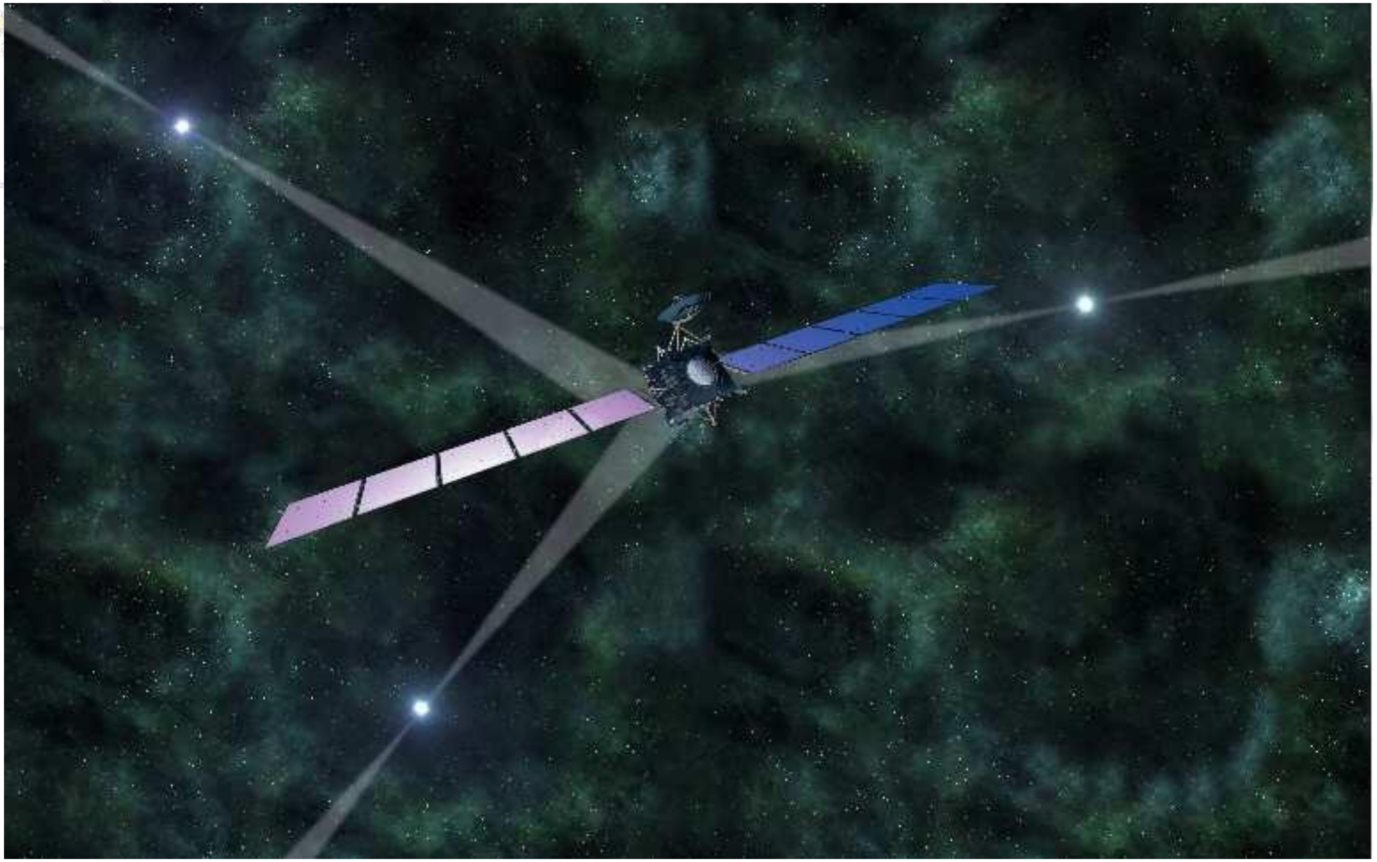

Figure 12: Artist's impression of Rosetta, if it navigated in deep space using pulsar signals. The characteristic time signatures of pulsars are used as natural navigation beacons to determine the position and velocity of the spacecraft (from Becker et al. 2013).

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THANK YOU!

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