

Using Pulsars For Clock Steering and Time Transfer

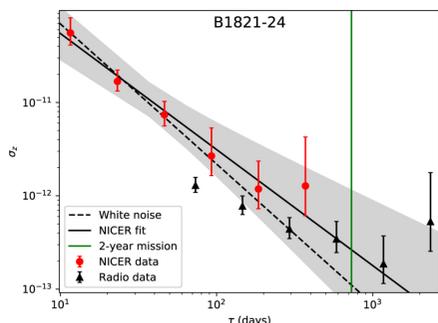
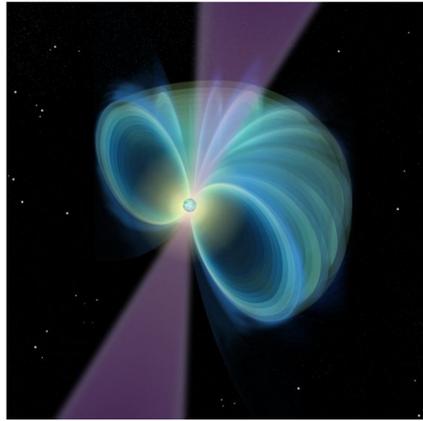
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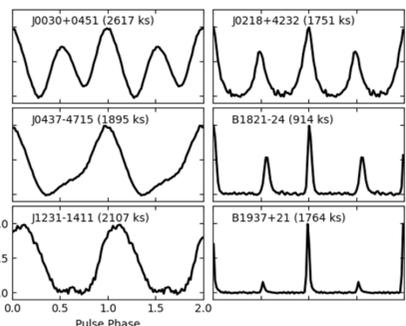
As we prepare for extended missions on the Moon and in cislunar space, precise time synchronization between lunar and terrestrial clocks becomes increasingly critical for navigation, communication, and science measurements. One promising technique is the use of millisecond pulsars, which are highly magnetized, rapidly rotating neutron stars emitting beams of electromagnetic radiation. These celestial clocks offer extraordinary stability and precision, with rotational periods ranging from about 1 to 10 milliseconds and timing stability comparable to laboratory atomic clocks on Earth. Pulsars can provide a common time reference for clock comparisons, allowing time transfer independent of a communications link.

Properties of Pulsars

- Rotating neutron stars, formed in supernova explosions of massive stars
- Emit lighthouse-like beams of radio, X-ray and gamma-ray radiation
- Millisecond pulsars (MSPs) are spun up to periods of 1–10 ms by accretion of matter from a binary companion
- Spin periods are exceptionally stable, changing by $\sim 1 \mu\text{s}$ every million years
- Several hundred MSPs can be observed with large radio telescopes
- About 10 MSPs have bright enough X-ray pulsations to be observed with modest size X-ray telescope from a satellite



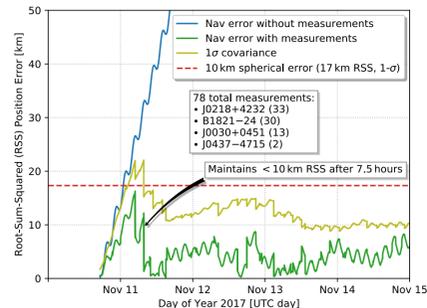
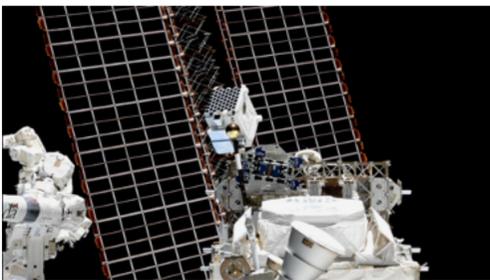
Above: Timing stability (σ_z , a statistic similar to the Allan deviation; see Matsakis et al. 1997) vs. integration time for the MSP B1821–24.



Above: Pulse profiles of 6 X-ray millisecond pulsars, observed with NICER

Pulsar Navigation Demo with NICER/SEXTANT

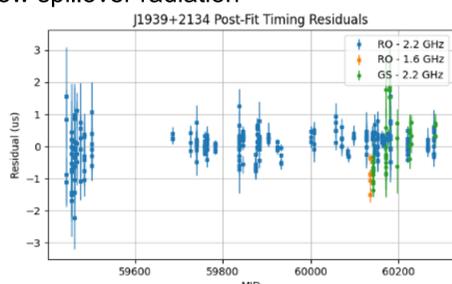
- NICER is an X-ray instrument mounted on the International Space Station, that observes pulsars in the 0.2-12 keV band.
- The Station Explorer for X-ray Timing and Navigation Technology (SEXTANT) demonstrated a GPS-like absolute position determination capability by observing millisecond pulsars, thus enabling autonomous navigation throughout the Solar System and beyond (Mitchell et al. 2018).



Left: The NICER instrument mounted on ISS. Right: Navigation error vs time for the SEXTANT demonstration of pulsar-based navigation. Blue is the error without measurements and green is the error with pulsar measurement input to the Kalman filter, showing few km accuracy over several days with no GPS inputs.

Maintaining Pulsar Ephemerides Using DSN

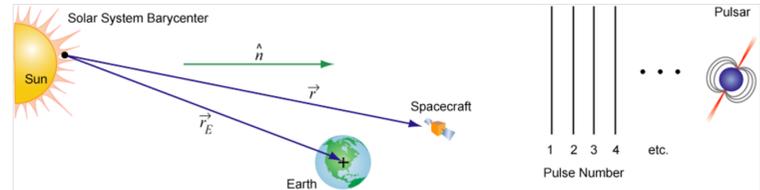
- Pulsar timing models must be maintained using radio observations, preferably with assets under US control
- DSN has 3 major tracking sites around the globe with 16+ large antennas, providing continuous communication & navigation support for deep space missions
- Each site hosts a 70-m dish + several 34-m dishes: Multiple receive capabilities: 1.4, 2.2/8.4, 8.4/32, 21, and 45 GHz, allowing frequency flexibility
- Over the past decade we have installed dedicated common platform instrumentation at each of the DSN complexes to enable precision pulsar timing measurements
- We are carrying out a pilot monitoring program (on a non-interference basis) to demonstrate the long-term stability of DSN-based TOA measurements
- On the moon:** Taking advantage of long dwell times possible at the lunar surface, we have proposed the use of a choke ring horn antenna to provide high gain at 1–2 GHz, large field of view, and low spillover radiation



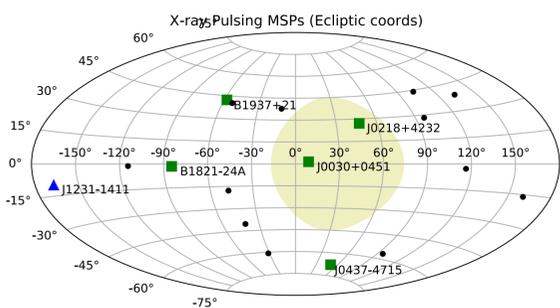
Left: DSN antennas at Goldstone, CA; Right: Timing residuals over > 2 years, yielding post-fit residuals at the 250 ns level. RO (Robledo, Spain), GS (Goldstone, CA)

Pulsars as Sources of Timing/Navigation

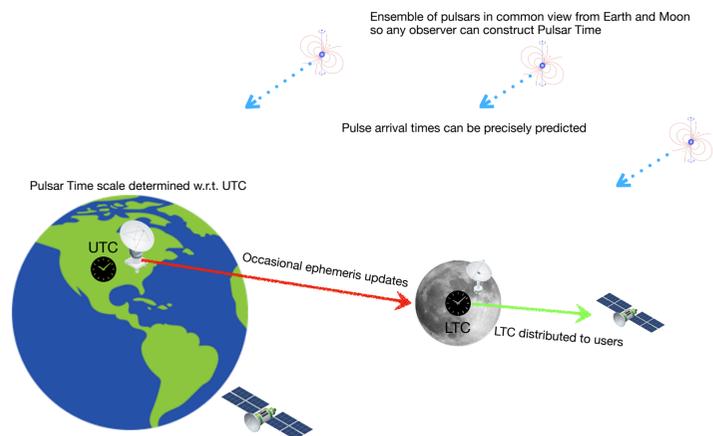
- Physical models fit to long-term timing data provide an ephemeris that accurately predicts pulse times of arrival at the Solar System Barycenter for months to years into the future
- If you know your location, this can be used to steer a clock, or you can solve for position and time with observations of multiple pulsars



Above: Geometry of a pulsar timing/navigation measurement. A model describes the arrival time of each pulse at the Solar System Barycenter (SSB), so a measurement at a spacecraft provides its position along the direction towards the pulsar.



Above: Sky map of the best X-ray MSPs for navigation and timing applications (Ray et al. 2017). Green are best, blue is next tier, black are too faint.



Above: Overview of an architecture for pulsar time reference for LTC/UTC

Pulsars As Lunar Time References

- White House OSTP Memo of April 2024 states that a lunar time standard should have:
 - Traceability** to Coordinated Universal Time (UTC);
 - Accuracy** sufficient to support precision navigation and science;
 - Resilience** to loss of contact with Earth; and
 - Scalability** to space environments beyond the Earth-Moon system
- Pulsars can help address these requirements by providing a common timescale for traceability that is independent of contact with Earth, and usable throughout the Solar System and beyond.
- An ensemble **pulsar time scale** can be defined through observations of multiple pulsars from Earth and LEO satellites, and tied to UTC. This has been realized both as a paper timescale (Hobbs et al. 2020) and as a real-time product (Piriz et al. 2019).
- Observations from stations on the Moon or in cislunar orbit can then track the tie between LTC (lunar time) and UTC
- If the link to the Earth is lost, pulsar time can maintain the knowledge of the tie to UTC for a long time (months to years, depending on accuracy required)

References

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