

# High Sensitivity VLBI: Neutron Star Astrometry with Arecibo

Shami Chatterjee

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**Summary:** High-precision astrometry with Very Long Baseline Interferometry has a wide range of scientific applications. Here we focus on the astrometry of neutron stars, and argue that high sensitivity VLBI, anchored by Arecibo acting in concert with other large telescopes and the Very Long Baseline Array, provides us with unique scientific capabilities. Leveraging existing resources and ongoing technology development, such as ALFA, large-bandwidth receivers, multi-pixel VLBI recording capabilities, and focal plane feed arrays, makes high sensitivity VLBI with Arecibo a scientifically compelling proposition.

**Scientific Goals:** When a neutron star is visible at radio wavelengths, high-precision VLBI over multiple epochs can provide us with its basic astrometric parameters: position, proper motion, and in some cases, an annual trigonometric parallax.

**Position:** When a radio pulsar is a stable rotator, as is typical for the recycled (or millisecond) pulsars, its radio pulses can be timed over years to provide the same astrometric parameters as above. However, pulse timing measures these parameters in the Solar system reference frame, while VLBI measurements are tied to the distant quasars. Thus, simply measuring precise positions for recycled pulsars, many of which were discovered at Arecibo in the first place, enables fundamental reference frame ties between the Solar system and extragalactic reference frame (the ICRF<sup>12</sup>).

**Proper Motion:** The proper motion of neutron stars allows them to be traced back to their birth sites in massive stellar clusters<sup>9,18</sup>. For very young objects, associations with their progenitor supernova remnants can be verified or refuted, leading to independent age estimates for both the neutron star and the supernova remnant itself<sup>13,7</sup>. The rotation of such young pulsars is typically not stable enough for astrometry via pulse timing, and interferometry is thus required.

Combined with estimates for their distances, the proper motions of neutron stars lead to velocity estimates. The high velocity tail of the distribution implies that large kicks are imparted to proto-neutron stars during core collapse<sup>3,4</sup>, imposing a stringent constraint on the ongoing hydrodynamic simulations of supernovae. The comparison of velocities estimated for radio pulsars and magnetars (as first done for the radio-emitting magnetar XTE J1810–197<sup>8</sup>) uniquely tests the role of intense magnetic fields versus hydrodynamic asymmetries in mediating natal kicks.

**Parallax:** When a parallax measurement is possible, it provides a *model independent* estimate for the distance and velocity of the neutron star. First, each such measurement calibrates global models of the Galactic electron density<sup>16,5</sup>, thus improving distance estimates from pulse dispersion measure for the rest of the radio pulsar population.

Next, for individual objects, each velocity measurement potentially constrains supernova core collapse<sup>4</sup>, as outlined above. It also permits accurate determinations of birth sites and associations with supernova remnants, stellar clusters, and runaway stars<sup>9,18</sup>. Finally, for young, hot neutron stars, observed thermal radiation from the neutron star surface can be used in combination with a precise distance to constrain the ‘size’ of the

neutron star photosphere, and thus the Equation of State of matter at extreme pressures and densities.

The timing of binary pulsars is of particular relevance<sup>10</sup> to Arecibo, and it leads to fundamental tests of theories of gravitation<sup>17,11</sup>. The measurement of each post-Keplerian parameter for a double neutron star system further constrains permissible theories, and General Relativity has successfully met each challenge so far. However, the measurement of the rate of orbital period decay  $\dot{P}_b$  is contaminated by the distance-dependent Shklovskii effect (the changing Doppler effect due to the changing line of sight). For PSR B1534+12, for example<sup>14</sup>, an interferometric parallax and proper motion would improve the constraints on General Relativity.

**Why Arecibo and the HSA are Essential:** Astrometry at Arecibo has a long history, since the earliest pulsar parallaxes utilized baselines to Arecibo. Currently, the Very Long Baseline Array offers full-time, dedicated VLBI capability, allowing a good mix of baseline lengths and well-controlled systematic effects, but falling very far short of Arecibo in sensitivity. With a gain of 10 K/Jy, Arecibo can provide baselines to the VLBA telescopes (gain  $\sim 0.1$  K/Jy) which are a factor  $\sim \sqrt{10/0.1} = 10$  more sensitive than the VLBA-only baselines.

Not only are most pulsars faint, but the most interesting categories, namely the youngest pulsars and the recycled ones, appear to be disproportionately faint. Adding Arecibo to the VLBA allows observation targets that are simply not accessible to astrometry with the VLBA alone. With the discovery of radio pulses from two magnetars (XTE J1810–197<sup>2</sup> and 1E 1547.0–5408<sup>1</sup>) and a VLBA proper motion<sup>8</sup> for one of them, as well as the VLA measurement of the expansion of the radio afterglow of the giant flare from SGR 1806–20<sup>15</sup>, it appears that radio astrometry can be brought to bear on other classes of neutron stars besides standard radio pulsars. To exploit such serendipitous occurrences, flexible arrays with high sensitivity are essential, and within its sky coverage, Arecibo is without peer in this regard.

**Required Technique Development:** The primary caveat to the preceding discussion is the difficulty of calibration. Systematic errors contributed by the ionosphere and the troposphere are the primary impediments to sub-milliarcsecond astrometry. Progress has been made, for example, with GPS-based ionospheric calibration schemes. In-beam calibration<sup>6</sup>, using a faint source in the same primary beam as the target source, has proved to be effective, but Arecibo’s added sensitivity does not compensate for the reduced number of sources expected by chance in its much narrower primary beam.

The available ALFA multibeam system offers a route around this problem at 1.4 GHz, if different beams can be assigned to track the target and the in-beam source. The hardware is already in place; such a project “merely” requires the appropriate control software and a multiplexed (or dual-pixel) VLBI recording system.

Further in the future, focal plane feed arrays have been identified as a key technology for instruments now on the drawing board, including the Square Kilometer Array. By effectively offering much larger fields of view, a focal plane array would allow Arecibo to view as many faint reference sources as the much smaller telescopes of the VLBA, and thus open up a large fraction of the pulsar population to high-precision astrometry. Arecibo should consider exploiting the synergy with SKA-related technology development to test and deploy such a focal plane feed array.

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