A VLA Survey for Pulsar Astrometry with the VLBA

We propose VLA observations that will enable a multi-epoch VLBA project that aims to measure the parallaxes and proper motions of a large sample of pulsars. Currently, parallax measurments exist for 17 pulsars, as summarized in Table 1. We propose to double this sample with a large VLBA campaign. VLA observations are required to determine sub-arcsecond pulsar positions and to search for in-beam calibrators.

1. Justification

There is a rich science case for determining the distances and proper motions of a large sample of pulsars. Listed below are some of the highlights: a more complete science case is in the accompanying VLBA proposal.

Galactic n_e: Most pulsar distances are estimated from their readily measured dispersion measures and a model of the Galactic electron distribution, such as by Taylor & Cordes (1993). Accurately measured distances, coupled with pulsar dispersion measures, help determine the Galactic electron density distribution. Additionally, in combination with interstellar scattering data, pulsar parallaxes can constrain the distribution of scattering material along the lines of sight (e.g. Chatterjee et al. 2001).

Pulsar velocities: Parallaxes and proper motions combine to provide the transverse velocity of pulsars, and address the velocity distribution of the population. Pulsars, being fast-moving supernova products, can be used to constrain models of supernova core collapse. Astrometry can be used to strengthen or refute supernova remnant associations. An established association provides accurate ages for both objects as well as confirming pulsar spin-down models (as was challenged by Gaensler & Frail, 2000).

Reference frame ties: Astrometry of millisecond pulsars (MSPs) allows the verification of solar system–extragalactic reference frame ties and the accuracy of timing parallaxes. These measurements also constrain the model fitting of orbital and relativistic parameters for MSPs in binary systems.

Several tested observational techniques will be used for high-precision astrometry with the VLBA. All are variants on phase-referencing. These include:

In-beam calibration: In order to minimize the distorting effects of Earth's atmosphere and ionosphere it is essential to use a phase calibrator that is very near the target pulsar. A calibrator less than $25'$ from the pulsar can be observed simultaneously with the pulsar. This offers concurrent phase calibration over a very short angular separation. Since the mean distance from any point on the sky to its nearest VLBI calibrator is about $2.5°$, a dedicated search must be done to find in-beam sources around individual pulsars. This technique was used successfully on PSR B0919+06 (Chatterjee et al. 2001) and is being used on several other pulsars.

GPS-based ionosphere calibration: GPS data can be used to construct global models of the ionosphere. These can be used to partially correct the visibility phases, thus improving the accuracy of the astrometry. This technique can be used in combination with the other techniques (Walker & Chatterjee 1999).

Modified self-calibration: VLBI data that spans a large fractional bandwidth ($> 20\%$) can be used to separate the effect of the ionosphere from the visibility phases without use of external calibration information. The method, based on self-calibration, can only be used on sufficiently bright pulsars (> 10 mJy). This technique was demonstrated on PSR B0950+08 (Brisken et al. 2000), and was later used to determine the parallaxes of eight other pulsars.

As a preliminary investigation, a two-phase VLA survey is required in order to determine sub-arcsecond pulsar positions and identify in-beam reference source candidates. This information will be used to refine the list of target pulsars from 62 to about 30, by retaining the sources with the best prospects of a successful parallax measurement. Of the 62 targets, 44 are too weak for modified self-cal, and will require in-beam calibrators that are to be identified with this VLA survey. Based on past experience with in-beam calibrator searches, it is expected that about 1/3 of these pulsars will have a sufficiently bright (> 10 mJy) compact (< 10 mas) source within $25'$.

The accompanying large VLBA proposal contains a detailed scientific justification. That proposal requests 500 hours of observing time on the VLBA; here, we propose a preliminary survey that will enable a large fraction of the VLBA observations. More information about this project, including figures and tables, can be found online, at: `http://www.astro.cornell.edu/~shami/psrvlb`

2. In-Beam Search Experience with PSR B0656+14

PSR B0656+14 is a young, nearby pulsar, detected at radio, optical, UV, and X-ray wavelengths. In an ongoing project (BB136), we are attempting to measure its distance via parallax and separate the blackbody component from the pulsar spectrum. A measurement of the neutron star radius should be possible (to about 10%), which will place strict limits on the neutron star equation of state. This pulsar is rather weak (about 3 mJy at 1.4 GHz), ruling out 5 GHz observations and the use of modified self-calibration. Using VLA data at 1.4 GHz, 4 candidate sources were identified within $25'$ of the pulsar. 8.4, 15, and 22 GHz follow-up observations revealed that one of the four sources was probably compact, and a VLBA observation confirmed the suitability of this source as an in-beam calibrator. The first two VLBA observations of this pulsar suggest that the position can be measured to about 0.2 mas. A preliminary parallax will be determined using a third VLBA epoch, observed recently.

3. Source Selection

The target pulsars were chosen from a sample with declinations north of $-20°$, dispersion derived distances less than 5 kpc, and flux densities $\gtrsim$ 2 mJy at 1.4 GHz. These criteria were relaxed slightly for pulsars with particular scientific interest, such as MSPs or suspected associations with supernova remnants. All but three sources have known VLBA phase calibrator sources within $3°$. A complete list of target pulsars is provided in the VLBA proposal.

4. Observations

This pulsar field survey has two parts. 1.4 GHz observations are requested very early in the A-array period. Each pulsar will be observed for $\sim$ 15 minutes using 25 MHz bandwidth, 15 channel mode. Pulsar positions better than 0.5 arcseconds will be obtained from these observations. Bright sources ($>$ 10 mJy) within the primary beam will be inspected for compactness. Twelve of the 62 target pulsars have archival observations that will be sufficient. The FIRST survey only covers about 10 of the fields and does not detect the pulsars to the needed precision. The observing time required for the fifty remaining pulsars at 1.4 GHz is thus about 17 hours.

Plausible in-beam calibrators will then be re-observed at 8 GHz (continuum). We expect two to three in-beam candidates per pulsar. Since the targets for 8 GHz observations depend on the results of the 1.4 GHz observations, these follow-ups need to be scheduled $\sim$ 1 month later. Snapshot observations (5 min) will be used to place stricter limits on the compactness of the in-beam candidates, as well as determining their spectral indices, another clue in predicting the compactness of the sources. The amount of time needed for these observations at 8 GHz is about 15 hours. Weak ($<$ 5 mJy) pulsars with no in-beam candidates will be dropped from the experiment at this point. A maximum of 30 sources will be retained for VLBA observations.

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Table 1. Most recent parallaxes and distances for 18 pulsars

Pulsar	Parallax (mas)	Distance (kpc)	Velocity† (km s^{-1})	Reference
B0329+54	0.94 ± 0.11	$1.03^{+0.13}_{-0.12}$	95^{+12}_{-11}	1
J0437−4715	7.19 ± 0.14	$0.139^{+0.003}_{-0.003}$	$92.8^{+2.0}_{-2.0}$	2
B0809+74	2.31 ± 0.04	$0.433^{+0.008}_{-0.008}$	102^{+2}_{-2}	1
B0823+26	2.8 ± 0.6	$0.36^{+0.10}_{-0.06}$	194^{+55}_{-34}	3
B0919+06	0.83 ± 0.13	$1.21^{+0.19}_{-0.19}$	505^{+80}_{-80}	4
B0950+08	3.82 ± 0.07	$0.262^{+0.005}_{-0.005}$	$36.6^{+0.7}_{-0.7}$	5
B1133+16	2.80 ± 0.16	$0.35^{+0.02}_{-0.02}$	631^{+38}_{-35}	1
B1237+25	1.16 ± 0.08	$0.85^{+0.06}_{-0.06}$	475^{+34}_{-30}	1
B1451−68	2.2 ± 0.3	$0.46^{+0.07}_{-0.06}$	90^{+13}_{-13}	6
B1534+12	0.93 ± 0.13	$1.08^{+0.16}_{-0.14}$	131^{+20}_{-17}	7
J1713+0747	0.9 ± 0.3	$1.1^{+0.5}_{-0.3}$	30^{+20}_{-10}	8
J1744−1134	2.8 ± 0.3	$0.36^{+0.04}_{-0.03}$	36^{+4}_{-4}	9
B1855+09	1.1 ± 0.3	$0.9^{+0.4}_{-0.2}$	26^{+12}_{-6}	10
B1929+10	3.02 ± 0.09	$0.33^{+0.01}_{-0.01}$	163^{+4}_{-5}	1
B1937+21	< 0.28	> 3.5	> 8.0	10
B2016+28	1.03 ± 0.10	$0.97^{+0.10}_{-0.08}$	$30.9^{+4.4}_{-4.0}$	‡
B2020+28	0.37 ± 0.12	$2.3^{+1.0}_{-0.6}$	256^{+114}_{-61}	1
B2021+51	0.50 ± 0.07	$1.9^{+0.3}_{-0.2}$	115^{+18}_{-15}	1

References. — (1) Brisken (2001); (2) van Straten et al. (2001); (3) Gwinn et al. (1986); (4) Chatterjee et al. (2001); (5) Brisken et al. (2000); (6) Bailes et al. (1990); (7) Stairs et al. (1998, and later work); (8) Camilo, Foster & Wolszczan (1994); (9) Toscano et al. (1999); (10) Kaspi, Taylor, and Ryba (1994); (‡) Brisken (in preparation). Earlier results on B0950+08 (Gwinn et al. 1986), B1929+10 (Salter, Lyne & Anderson 1979; Backer and Sramek 1982) and B2021+51 (Campbell et al. 1996) have been replaced by recent results.

† Velocities are uncorrected for differential Galactic rotation.