PSRπ: A large VLBA pulsar astrometry program

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Abstract

Obtaining pulsar parallaxes via relative astrometry (also known as differential astrometry) yields distances and transverse velocities that can be used to probe properties of the pulsar population and the interstellar medium. Large programs are essential to obtain the sample sizes necessary for these population studies, but they must be efficiently conducted to avoid requiring an infeasible amount of observing time. This paper describes the PSRπ astrometric program, including the use of new features in the DiFX software correlator to efficiently locate calibrator sources, selection and observing strategies for a sample of 60 pulsars, initial results, and likely science outcomes. Potential applications of high-precision relative astrometry to measure source structure evolution in defining sources of the International Celestial Referent Frame are also discussed.

Keywords pulsars, techniques: interferometric

1 Introduction

Due to their unique combination of high density, high magnetic field and high angular momentum, pulsars provide a rich laboratory for investigating phenomena in the fields of nuclear physics, particle physics, gravitational physics and many others (see e.g., Lorimer, 2008, and references therein). However, studies of pulsars are hampered by the uncertainty in distance–dependent quantities introduced by the reliance on dispersion measure (DM) distance estimates. Due to the highly non–uniform distribution of ionized material in the ISM on sub-kpc scales, the correspondence between a pulsar’s DM and its distance often remains uncertain, despite the development of detailed models of the ionized interstellar medium (e.g., the TC93 model; Taylor & Cordes 1993, and the NE2001 model; Cordes & Lazio 2002). Although distances estimated from the TC93 and NE2001 models are generally assumed to be accurate to within 20%, previous astrometric pulsar observations have shown that much greater errors are sometimes possible for individual objects (e.g., a factor of 4.5 error in the distance for PSR J0630–2834; Deller et al., 2009), and systematic biases are likely (Lorimer et al., 2006).

Thus, independent distance measures to pulsars are vital, both to enable the confident estimation of distance–dependent parameters for individual pulsars and to refine DM–based distance models for the remainder of the pulsar population. Whilst distance estimates can also be provided from associations with other astrophysical objects (e.g. Camilo et al., 2006)
2 In–beam calibrator search observations

The steep spectrum exhibited by most pulsars dictates that a large astrometric survey using current VLBI facilities must observe at relatively low frequency (~1.6 GHz) where enough pulsars are sufficiently bright. At these frequencies, the predominant source of systematic contribution to astrometric error is the differential ionosphere between the calibrator and target sources, and so minimising the calibrator–target angular separation is the most important consideration for obtaining accurate astrometry (e.g., Chatterjee et al., 2004). An “in–beam” calibrator, which can be observed contemporaneously with the pulsar target, is always preferred. However, on average the distance to a known VLBI calibrator source is ~2°, much greater than the primary beam width of a 25m antenna (such as is used in the VLBA). Thus, suitable bright and nearby compact calibrators must be identified prior to the astrometric program. The 1σ sensitivity of a single VLBA baseline at 1.6 GHz is 1.7 mJy in 5 minutes at the current maximum bandwidth of 128 MHz; this will improve to 0.8 mJy at the 512 MHz bandwidth to become available in 2011. Thus, if a S/N ratio of 10 is required at each of the VLBA’s 10 stations, calibrators of peak flux density ≥6 mJy can be used currently, while those ≥3 mJy will become available with future higher bandwidths.

In the past, this “in–beam search” operation was time–consuming, due to the need to identify sources likely to be compact before snapshot VLBI observations were used to determine their true flux one at a time. However, a new “multifield” mode of the DiFX software correlator (Deller et al., 2011) enables all known sources within the telescope primary beam to be inspected at VLBI resolution simultaneously, meaning only a single snapshot observation is required, regardless of the number of candidates. The VLBA can reach a 1σ sensitivity of 300 μJy in less than 4 minutes on–source, and so phase–referenced VLBI observations can quickly and reliably detect all VLBA in–beam calibrators that will be useful at current or future data rates.

The first phase of the PSR π project is a search for in–beam calibrators around potential astrometric targets. Figure 1 shows an example of the pointing layout used, with known background sources identified by circles. In each case, the observations were referenced to the nearest known suitable VLBA calibrator (defined here as R) using the following scan sequence:

R-P1-P2-R-P3-P4-R-P1-P2-R-P3-P4-R

Two minute scans on each target pointing were used, for a total on–source time of four minutes per pointing. Generally, five target pulsars with relatively small angular separations were grouped and observed sequentially in a single observation to minimise calibration overhead. Correlation was performed using the DiFX software correlator (Deller et al., 2011) with one phase centre placed on each known source. Sources

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1 The VLBA is operated by the National Radio Astronomy Observatory as a facility of the National Science Foundation, operated under cooperative agreement by Associated Universities, Inc.

2 The VLBA sensitivity upgrade program is described at http://www.vlba.nrao.edu/memos/sensi/
were extracted from the FIRST survey (Becker et al., 1995) where available, and the NVSS survey (Condon et al., 1998) in areas not covered by FIRST. Correlation was performed with a spectral resolution of 4 kHz to avoid bandwidth smearing, but the output visibilities were averaged in time to 4 second resolution and in frequency to 1 MHz resolution.

Currently, the in–beam search observations for PSR$\pi$ are nearly complete, with 77 hours of observing time expended searching around 200 pulsars. Over 7000 potential calibrators have been imaged, with 530 detected in our VLBI maps at $>9\sigma$. One or more satisfactory in–beam calibrators were found for 97% of sources, with the remainder largely being lost due to scattering in the Galactic plane. The detection rate was comparable for FIRST and NVSS sources; although the FIRST catalog is more compact on average, it also contains objects fainter than our VLBI detection threshold, so this is not surprising. These observations were optimized to locate sufficiently bright in–beam calibrators, and so the raw results in terms of VLBI detection fractions should be interpreted with caution.

### 3 Astrometric scheduling

Of the sources with one or more sufficiently bright in–beam calibrator candidates, 110 were selected for exploratory astrometric observations. The exploratory phase is used to confirm the suitability of both the pulsar and the in–beam calibrators, since the pulsar flux density is often uncertain and the snapshot observations provide limited constraints on source morphology. From these observations, 60 sources will be selected for full astrometric observations encompassing 8 epochs over 1.5 years.

For both exploratory and final astrometric observations, pulsars are grouped in pairs to minimise calibration overhead and improve $uv$ coverage. Each pulsar is observed in two groups of phase referenced scans, with 30 minutes of on–source time per group. The remainder of the time was spent slewing or on external calibrator sources. Matched filtering (Deller et al., 2007) is applied when correlating pulsar data, using pulsar ephemerides obtained from pulsar timing. Figure 2 shows the pointing setup and the VLBI detections of the source PSR J0323+3944 and its two in–beam calibrators.

Several possibilities exist for taking advantage of the fortunate case of multiple in–beam calibrator sources. The simplest is to re–reduce the datasets using each calibrator independently (Chatterjee et al., 2009). This provides robustness against calibrator variability, but cannot easily take advantage of the partially independent results. A more sophisticated approach is to appropriately weight the calibrator visibilities and coherently sum them. This averages over the partially independent atmospheric errors, and also reduces the random component of the solution error because of the improved S/N. Sources too faint to provide solutions in isolation can then be used in the sum, but each source must be accurately modeled in order to be added coherently. Furthermore, if any of the included sources varies in position then the sum and the astrometric results may be adversely affected.

A third, and ideal, possibility is that three or more calibrators would be used to solve for a calibration plane, rather than point, above each antenna at regular intervals in the observation. Whilst it is presently challenging to obtain sufficiently high signal to noise observations on three or more calibrators, it may be possible for a small number of PSR$\pi$ targets, and future high–sensitivity, wide–field instruments such as the Square...
Kilometre Array (SKA) should use this approach routinely. Further opportunities offered by multi-source astrometric datasets are discussed in Section 5 below.

4 PSRπ outcomes

The completion of the first phase of PSRπ will bring about a six-fold increase in the number of pulsars with a parallax measured to an accuracy of 50µas or better. Combined with the small number of existing accurate pulsar distance measures, this will give a moderately sized (≈70 objects) pool of pulsars with reliable distance measurements which can be used for unbiased investigations of the pulsar luminosity and velocity functions. The significant increase in the number of accurate distance measures will also be used as part of the next major upgrade to the Galactic electron density distribution model, following NE2001 (Cordes & Lazio, 2002). The addition of a large number of new sightlines with accurate electron column density measurements will enable a significant improvement to the model, both in terms of removing systematic biases in the large
scale structure, and including many refinements in the form of small scale under- and over-densities within several kpc of the solar system.

Finally, in a sample of 60 pulsars, it is expected that a significant number of unexpected and interesting results will be uncovered based on individual pulsars. These could take the form of high velocity pulsars (e.g., Chatterjee et al., 2005), associations with supernova remnants (e.g., Thorsett et al., 2002), revision to measurements of high-energy emission (e.g., Deller et al., 2009), or breaking degeneracies in pulsar timing models (e.g., Deller et al., 2008).

5 Novel applications of multi-source astrometric datasets

Studying the structural evolution of calibrator sources at the $\mu$as level is challenging using absolute astrometry (Titov et al., 2011), and is practically impossible for faint sources. However, source structure evolution is likely to become the limiting factor for extremely precise astrometry using future instruments such as the SKA, and so understanding its characteristics is a topic of considerable importance. Relative astrometry offers the precision necessary to probe this regime, but the use of a single calibrator-target pair leaves an ambiguity as to the source of any variability. Multiple-source datasets, however, offer an opportunity to break this degeneracy.

Overcoming the usual limitations of sensitivity and the ionosphere is difficult; discerning evolution at the level of 10 $\mu$as or below would limit the angular separation to a maximum of 5’ (which dictates the use of sub-mJy targets) and require a S/N ratio of several hundred (meaning an image rms of $\sim$10 $\mu$Jy must be obtained). Although challenging, such observations are possible today using the European VLBI Network or the High Sensitivity Array.

Such an observing program could be used to monitor the source structure stability of a small sample of ICRF sources, allowing better estimation of the level at which source structure evolution contaminates the ICRF (by using the ICRF source as a calibrator and investigating the correlated motion of the other in-beam sources). This could be undertaken commensally with other astrometric projects using these calibrators. However, it would be necessary to obtain a deep image of the field around the source with a lower resolution instrument to first identify the potential VLBI sources.

6 Conclusions

The PSR$\pi$ program, which will measure 60 pulsar parallaxes to an accuracy of better than 50 $\mu$as, is underway with the VLBA. A new capability of the DiFX software correlator has been used to greatly speed up the identification of the in-beam calibrators necessary to reach this level of accuracy, with over 7,000 potential targets imaged using less than 80 hours of observing time. Once completed, the PSR$\pi$ program will provide the necessary information for a substantial improvement in the Galactic electron density distribution model, and the improved distance information for the pulsar population (both directly for some pulsars and through the model refinement for the remainder) will be used to update models of the pulsar velocity and luminosity distributions. Finally, the PSR$\pi$ dataset will provide opportunities to explore calibration techniques relevant to future interferometers such as the SKA.

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