SUB-MILLIARCSECOND PRECISION OF PULSAR MOTIONS: USING IN-BEAM CALIBRATORS WITH THE VLBA

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ABSTRACT

We present Very Long Baseline Array (VLBA) phase-referenced measurements of the parallax and proper motion of two pulsars, B0919+06 and B1857−26. Sub-milliarcsecond positional accuracy was obtained by simultaneously observing a weak calibrator source within the 40′ field of view of the VLBA at 1.5 GHz. We discuss the merits of using weak close calibrator sources for Very Long Baseline Interferometry (VLBI) observations at low frequencies, and we outline a method of observation and data reduction for these type of measurements. For the pulsar B0919+06 we measure a parallax of 0.31 ± 0.14 mas. The accuracy of the proper motions is ≈0.5 mas yr⁻¹, an order of magnitude improvement over most previous determinations.

Key words: astrometry — pulsars: general

1. INTRODUCTION

The determination of pulsar proper motions and parallaxes using position measurements at the sub-milliarcsecond level over many years is relevant for a number of astrophysical questions, including: (1) The proper motion may indicate the birth area of the pulsar and its ejection velocity (see, e.g., Kaspi, V. M. 1996). (2) The unambiguous distance determined from the parallax can determine the intrinsic properties of the pulsar and calibrate dispersion-based distance measurements (see, e.g., Taylor, Manchester, & Lyne 1993). (3) Comparing pulsar positions derived from Very Long Baseline Interferometry (VLBI) with positions determined from pulsar timing analysis can be used to compare the quasar reference and planetary ephemerides (Fomalont et al. 1984).

Since the opening of the Very Long Baseline Array (VLBA) in 1994, we have conducted an experimental program to investigate methods for obtaining high-precision pulsar motions and parallaxes. With the use of VLBI techniques, radio images are routinely made with a resolution of a few milliarcseconds. If the object being imaged is relatively bright and small in angular extent, positional accuracies of about 1% of the resolution are possible. However, because pulsars are generally much stronger at lower frequencies, most observations are made below 3 GHz, where ionospheric refraction is large and variable, leading to position errors and image distortion. The primary goal of our program was to characterize these ionospheric errors and minimize their effect with appropriate observational and reduction techniques.

Most previous VLBI astrometric observations of pulsars used the measured group delay and delay rates to derive accurate positions (Gwinn et al. 1986). This technique does not use the interferometer phase information directly, but rather the rate of change of phase with frequency (group delay) and time (delay rate). Although the technique does not require long-term phase stability, the accuracy is proportional to the spanned bandwidth divided by the observing frequency, generally less than 20% compared with using the interferometer phase directly.

In order to obtain sub-milliarcsecond positional accuracy for pulsars, especially the weaker pulsars, phase-connection (also known as phase-referencing) techniques must be used. With these techniques the position of a pulsar is measured with respect to an adjacent celestial source (calibrator) by alternating observations every few minutes between the pulsar and calibrator (which we will call the noding calibrator). Interpolation of the phase corrections derived for the calibrator source to the target source removes first-order effects of instrumental and electronic delays, and unknown atmospheric, ionospheric, and geometric errors (Beasley & Conway 1995). As long as the calibrator source is stationary and unchanging, it provides a firm fiducial point over time for measuring the relative position of the pulsar.

However, the temporal and spatial properties of this phase connection process—source/calibrator angular separation, temporal switching cycle, frequency coverage, multicalibration sources—may limit the positional sensitivity of the technique, rather than that imposed by the noise limits of the observations. Since most previous work has focused on observations at frequencies higher than 3 GHz (e.g., Beasley & Conway 1995), where tropospheric effects dominate, additional tests were needed to examine the temporal and spatial properties of ionospheric refraction. Below a frequency of about 2 GHz, differential ionospheric delays between the calibrator and target sources may be large even for very fast switching times and small separations.

This paper discusses one particular solution to this problem—the calibration of a pulsar position using a faint radio source which is within the primary beam of the VLBA antenna—with recommendations on procedures to obtain high-precision positional accuracy. The advantages of using
in-beam calibrators are twofold: (1) no repointing of the antenna is required (only recorrelation at the calibrator position); and (2) the angular separation of the target and calibrator (e.g., $<25'$) minimizes the errors due to spatial variations in ionospheric delay. This technique is not limited to pulsars, of course, but is only applicable at relatively low frequencies where there is a reasonable chance of finding a suitable in-beam calibrator.

2. SELECTION OF PULSARS AND RADIO OBSERVATIONS

We selected four pulsars which had been previously observed with a VLA pulsar astrometry program between 1984 and 1993 (Fomalont et al. 1992; Fomalont et al. 1996). These pulsars were generally strong enough to be detected with the VLBA without pulsar gating and all had at least one nearby background source within the 25 m antenna primary beam region ($<25'$) from the pulsar. Subsequent VLA observations at a higher frequency identified those background sources with a flat radio spectrum and angular sizes less than $2'$. Information on these four pulsars, their nodding calibrator, and the possible in-beam calibrator, is given in Table 1.

VLBA observations were made on 1994 November 9, 1995 September 23, and 1996 April 1, each day for 16 hours. These dates were chosen to maximize the parallax offset in right ascension for the sources. In order to obtain relatively long periods of phase connection data on each pulsar, we observed each pulsar and its nodding calibrator for one contiguous hour, alternating hourly among the four pulsar fields. All observation cycles were five minutes on pulsar and two minutes on calibrator, with about 30 seconds lost in slewing between two observations. This cycle time was considered to be short enough to allow interpolation of atmospheric and ionospheric phase changes between calibrator observations most of the time.

The eight independent-frequency channels were tuned to 1410, 1418, 1442, 1586, 1583, 1642, 1678, and 1694 MHz, each with 8 MHz bandwidth, in order to span a large frequency range. It is possible to remove ionospheric refraction effects by comparing the images obtained at different frequencies, although this calibration was not needed with the in-beam calibration approach we discuss in this paper. The pulsar data were correlated twice, at the pulsar position and at the position of the in-beam calibrator. The data were sampled every 2 seconds, and 32 frequency channels were provided for each of the 8 observing frequencies.

Two additional observations of B0919 +06 were made on 1998 March 26 and March 30 as part of a larger project not originally intended for use with this in-beam project. The B0919 +06 data were re-correlated at the in-beam calibrator position (J0923 +068). This additional fourth and fifth epoch (only four days apart) of this pulsar can be used to determine possible systematic error, which cannot be obtained with only three epochs. The nodding calibrator used for these observations was not 0906 +015, but J0914 +0245 (Beasley 1998); however, the nodding calibrator is used only to determine the gross calibration of the observations and not for phase connection.

3. DATA REDUCTION

The first part of the calibration of these data is identical to that used for typical nodding calibration as practiced at the VLBA. These procedures are summarized below. The second part, using the weak in-beam calibration to improve further the phase calibration, is described in more detail. While this calibration method has been used and discussed previously (e.g.,Marcaide & Guirado 1994; Bradshaw, Fomalont, & Geldzahler 1999), we are attempting to push this reduction method to faint levels and this requires somewhat different considerations in this part of the phase calibrations.

3.1. Phase Connection to Nodding Calibrator

The data reduction steps used for phase connection between a nodding calibrator and a target source have been described by Beasley & Conway 1995. The separation of these calibrators from the pulsar fields were in the range 4°–11° and are now considered to be too separated for good phase connection at 1.4 GHz; but this was not known at the beginning of the project. In addition, we hoped to rely on the next stage—in-beam calibration—for more accurate imaging.

Images for the four pulsars and their in-beam calibrators were made after phase connection to their nodding calibrator. As summarized in Table 1, we did detect B0919 +06 and B1857 –26 and their in-beam calibrator, but failed to detect the B1822 –09 pulsar or its in-beam calibrator. The pulsar B0950 +08 was easily detected, but its in-beam calibrator was not. The images of the detected pulsars and in-beam calibrators were significantly distorted because of the large angular distance between the nodding calibrator and the pulsar field. We estimate that the position accuracy was no better than about 10 mas and most images showed several secondary peaks.

For further analysis of the strong pulsar B0950 +08, where there is no in-beam calibrator available for further phase calibrations, other methods are being investigated to determine and remove the residual ionospheric phase

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1 See http://magnolia.vlba.nrao.edu/vlba_calib/index.html.

| PULSAR       | NODDING   | SEPARATION (deg) | IN-BEAM   | SEPARATION (minutes) | PEAK FLUX DENSITY (mJy) |
|--------------|-----------|------------------|-----------|----------------------|-------------------------|
| B0919 +06…  | 0906 +015 | 6                | J0923 +063 | 12                   | 11.0 ± 0.5              |
| B0919 +06…  | J0914 +0245 | 4                | J0923 +063 | 12                   | Used for last two epochs|
| B0950 +08…  | 1004 +141 | 7                | J0948 +0800 | 14                   | In-beam not detected    |
| B1822 –09…  | 1741 –038 | 11               | J1825 –0944 | 13                   | Neither detected        |
| B1857 –26…  | 1921 –293 | 6                | J1900 –2602 | 7                    | 6.4 ± 0.4               |
errors, and these methods will be reported on elsewhere (Brisken et al. 1999). More specifically, the dependence of pulsar position (or visibility phase) on frequency can be used to determine the amount of ionospheric refraction (the cause of the image distortions), which can then be removed to produce an improved image.

3.2. Using the In-Beam Calibrator

For the pulsars B0919+06 and B1857–26, for which both the pulsars and in-beam calibrators were detected, we proceeded with the next stage of phase connection between the in-beam calibrator and the pulsar (or vice versa). Since the in-beam calibrator and/or pulsar are likely to be relatively weak, special considerations are needed, especially in regard to increasing coherence time in order to determine the phase calibration with small errors. For this reason the following section will go into some detail concerning with the AIPS reduction package generally used for VLBA calibrations.

Choose the stronger of the in-beam calibrator or the pulsar [which may be gated for the purpose of increasing the signal-to-noise ratio (S/N)] as the primary phase reference. If the correlation position of this source is not within about 50 mas of the true source position, shift the phase center of the data appropriately. Otherwise, phase drifts resulting from this large position error will decrease the effective coherence time of the data and produce phases differences between the individual frequency channels. Since we are dealing with weak sources, a more accurate phase solution can be accomplished with longer integration times or with combined frequency channels.

The AIPS calibration program, CALIB, determines the calibration phase \( \phi \) as a function of time \( t \), frequency \( v \), and telescope \( i \), \( \phi(t, v, i) \), for the in-beam calibrator. This program essentially determines the calibration phase needed to produce a point source from the existing data. Since the data have already been calibrated with respect to the nodding calibrator (and an image, even if distorted, already made), the additional phase calibrations should not be very variable in time, permitting the averaging of the data for many minutes. For this reason the initial use of the nodding calibration is important to increase the coherence time of the data associated with the in-beam calibrator in order to use weaker sources.

Before running CALIB, some consideration should be given to the expected S/N of the solutions. For VLBA observations the nominal rms noise associated with a phase calibration solution, using one minute of integration with an 8 MHz bandwidth, is 20 mJy.\(^2\) For example, if the correlated flux density of the source is greater than 50 mJy, then the phase solution for each frequency channel of 8 MHz bandwidth (of which there are eight) with 1 minute integration will have S/N of about 2.5 to 1, which produces an rms phase error of about 20°. Since this phase error is nearly stochastic, the averaging of eight frequency channels over long periods will average out these fluctuations.

For relatively weak in-beam calibrators, solution times of many minutes and averaging of the frequency channels are required to obtain valid solutions. As another example, a source with 5 mJy correlated flux density will require sufficient averaging to obtain a less than 2.5 mJy noise level for each phase integration. This would require a integration time of 8 minutes and averaging of all 8 frequency channels, each of 8 MHz, assuming the use of the VLBA. While much longer integration times and frequency averaging may increase the S/N of the solutions, coherence may be lost.

An illustration of the phase determination from a weak source is shown in Table 2. We have used the in-beam calibrator J1900–2602 for the pulsar B1857–27 for the 1996 data. For a range of parameters, we have taken the phase calibration determined from J1900 and applied it to B1857–26, which was then imaged. Because this calibration method determines the phases that make J1900 a point source, the image quality obtained for J1900 is no longer relevant. If the phase calibration is sound, then the image of B1857 should display a reasonable point source.

The averaging time for the solutions ranged from 1 to 20 minutes, with a solution made for each frequency channel or for all frequency channels combined for better sensitivity. In all cases the resulting in-beam source looked pointlike, and its peak flux density was at least equal to the expected solution noise per averaging time. In other words the phase determination algorithm does produce a point source even with noise data. However, when this phase calibration is transferred to the pulsar and images are

\[ \text{TABLE 2} \]

| SOLUTION INTERVAL (minutes) | FREQUENCY USED | SOLUTION NOISE | IN-BEAM PEAK FLUX | Peak Flux | Quality |
|-----------------------------|----------------|----------------|--------------------|-----------|---------|
| 1                           | Each           | 20.0           | 17.9               | 1.2       | Noise   |
| 3                           | Each           | 11.6           | 11.7               | 2.5       | Noise   |
| 3                           | All            | 4.1            | 6.1                | 4.9       | Poor    |
| 5                           | Each           | 8.9            | 10.1               | 3.0       | Poor    |
| 5                           | All            | 3.2            | 5.7                | 6.1       | Good    |
| 10                          | Each           | 6.3            | 8.0                | 3.7       | Fair    |
| 10                          | All            | 2.2            | 4.8                | 5.6       | Good    |
| 20                          | Each           | 4.5            | 6.0                | 3.6       | Fair    |
| 20                          | All            | 1.6            | 3.9                | 5.0       | Good    |

\(^2\) See VLBA sensitivities on NRAO web site (http://www.nrao.edu/vlba/obstatus/obssum.vlba/obssum.vlba.html). For all subsequent calculations we will assume that the observations used the entire VLBA at 1.5 GHz, with a system temperature of 40K and 8 recorded frequencies each with a bandwidth of 8 MHz. This sensitivity should be scaled by the relative sensitivity of the array, the number of telescopes used for the self-calibration solution, the integration time, and the total bandwidth used in the solution.
made, the peak flux density and the quality of the pulsar images indicate the accuracy of the phase calibration. Solutions with at least five minutes solution time, with all frequencies added together, produced good pulsar images. The slight decrease in pulsar peak flux from 5 minute integration to 20 minute integration may be caused by a loss of coherence over this relatively long period of time. The images in which all frequencies have been averaged with a solution interval of 5, 10, or 20 minutes are acceptable and do not differ in the location of the peak (see Table 2).

4. RADIO IMAGES AND ASTROMETRIC RESULTS

The procedure outlined above was used, with a calibration solution interval of 5 minutes and with all eight frequencies averaged together. The peak flux density (and its spread over the three observations) of the in-beam calibrator for B0919 +06 and for B1857 −26 are given in Table 1. Both were substantially unresolved. A typical calibrated phase solution is shown in Figure 1 for the 1996 observations of J1900 −2602, the in-beam calibrator for B1857 −26.

After these in-beam calibration phases were applied to the pulsar data, images were made for each of the three epochs. They all showed essentially a point source. The images were then CLEANed with tight boxes. This process increases the positional accuracy somewhat by removing the distortions associated with the point-spread function and permitting a better check on the quality of the image. The position of the pulsar was determined from a Gaussian fit to the image. The position error is proportional to the distortion divided by the S/N of the peak of the pulsar.

Since the pulsar observations are tied to the same calibrator in all three observations, they are on the same position grid, and the results from the three images can be directly compared to show the motion of the pulsar. Figure 2 shows the composite image for B0919 +06, where we have simply summed the three epoch images. This increases the noise background by a factor 1.7, but is illustrative of the general results.

Figure 3 shows the similar results for B1857 −26. Since the pulsar was relatively weak during the 1994 observation (upper component) and the location of the 1995 and 1996 positions were relatively close, we did not use a simple sum of the three epochs to obtain this image. This figure is composed of the representative parts of the images from the three epochs of B1857 −26, with no overlapping. Both figures are illustrative, with the proper motion and parallax fits made on the positions derived from each observations.

The results for all five epochs for B0919 +06 are listed in Table 3. With the additional two observations in 1998, a better analysis of the accuracy of this experiment can be ascertained. For simplicity we have listed the relative position of B0919 +06 for the five observations; these relative positions are with respect to a nominal position of B0919 +06. All positions have been tied to the in-beam calibrator J0923 +0638 with the assumed position given in the table.

For B0919 +06 the fit to the five epochs gives \( \mu_x = 17.7 \pm 0.3 \text{ mas yr}^{-1}, \mu_y = 79.2 \pm 0.5 \text{ mas yr}^{-1}, \pi = 0.31 \pm 0.14 \text{ mas} \). In Figure 4, the position of the pulsar for the five epochs, after removal of the best-fit proper motion and position, is compared with the parallax of 0.31 mas yr\(^{-1}\), shown by the sinusoid. The error bars are those expected from the image noise, with the error equal to the image

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**Fig. 1.**—Self-calibrator phases for in-beam calibrator J1900 −2602. Each plotted point shows the residual phase determined every five minutes averaging all eight frequency channels. Antenna 5 at Los Alamos was the reference antenna. The scatter becomes somewhat larger for MK and SC, which are the longer baselines. The continuity of the phases with time is far from random for this 7 mJy source.

**Fig. 2.**—Motion of pulsar B0919 +06, as sum of the three images made for the pulsar B0919 +06 following calibration with J0923 +0638, a 12 mJy in-beam calibrator. The lowest contour level is 1.5 mJy, with increasing steps of a factor 1.4. The resolution is 15 × 10 mas in position angle 0. The peak flux densities at each epoch are: 1994, 4.7 mJy (bottom); 1995, 10.0 mJy (middle); 1996, 0.2 mJy (top).
resolution divided by the S/N at the peak of the pulsar. Since three parameters have been determined (pulsar position, proper motion, and parallax) using four well-separated epochs, there is only one degree of freedom, making the fit look better than it really is. The agreement of the two 1998 observations, which were separated by four days, is also better than expected. The north/south motion of the pulsar is much less sensitive to the parallax, because the observations were preferentially scheduled at maximum east-west parallax signal. The north-south scatter from the best position and proper motion are considerably larger than they are for the east-west direction.

TABLE 3
PROPER MOTION FOR B0919+06

| Observation Date | East – West (arcsec) | North – South (arcsec) |
|------------------|----------------------|------------------------|
| 1994.85          | -0.0453 ± 0.0002     | -0.2640 ± 0.0004       |
| 1995.77          | -0.0289 ± 0.0001     | -0.1892 ± 0.0002       |
| 1996.25          | -0.0209 ± 0.0001     | -0.1437 ± 0.0002       |
| 1998.23          | +0.0142 ± 0.0001     | +0.0076 ± 0.0002       |
| 1998.24          | +0.0144 ± 0.0001     | +0.0087 ± 0.0002       |

* With respect to 09:22:14.000, +06:38:22.70. Assumed position of J0923+0638: 09:23:03.989, +06:38:58.98 (J2000.0).

Our measured distance of B0919+06 is 3.2 (+2.6, -1.0) kpc and is consistent with the limit of greater than 3 kpc determined by Taylor et al. 1993. The previous estimate of this pulsar’s proper motion was $\mu_x = 13 \pm 29$ mas yr$^{-1}$, $\mu_y = 64 \pm 37$ mas yr$^{-1}$, consistent with, but an order of magnitude less accurate than, the present VLBA results (Harrison, Lyne, & Anderson 1993).

The best-fit proper motion and parallax for B1857–26, using just three epochs, is $\mu_x = -19.9 \pm 0.3$ mas yr$^{-1}$, $\mu_y = -47.3 \pm 0.9$ mas yr$^{-1}$, $\pi = 0.5 \pm 0.6$ mas. The VLA results (Fomalont et al. 1996) give $\mu_x = -26 \pm 5$ mas yr$^{-1}$, $\mu_y = -47 \pm 6$ mas yr$^{-1}$, in excellent agreement with the VLBA results. The distance limit derived with these observations of greater than 0.9 kpc is consistent with that of 1.7 kpc derived by (Taylor et al. 1993).

5. DISCUSSION

The parallax and proper motion obtained for B0919+06 and B1857–26 are among the most accurate yet obtained for pulsars or other galactic objects (see, e.g., Bradshaw et al. 1999). The precision limits are consistent with the S/N of the observations. The additional epochs for B0919+06 clearly improve the precision and decouple the proper-motion and parallax solutions, and we suggest that a minimum of five well-separated epochs should be considered for obtaining accurate parallaxes. The consistency of the data with the fit for B0919+06 suggests that systematic errors at the level of 0.1 or 0.2 mas are not significant when using in-beam calibrators within about 10° from the target source.

From analysis now underway on determining and removing the ionspheric effects associated with B0950+08 (Brisken et al. 1999), we estimate that the ionspheric refraction can lead to systematic error of about 5 mas for a source-calibrator separation of about 7°. Assuming that this systematic error is caused by the differential ionspheric refraction between the calibrator and source, it should
decrease linearly with the source-calibrator separation, because the residual phase is a coherent difference rather than a stochastic difference. For a 12′ separation we would expect such errors to be about 0.15 mas in size. This value is about the rms level of accuracy of the present experiment. With the additional epochs and the use of pulsar gating, systematic errors (probably caused by differential ionospheric refraction) may start to dominate the errors. However, removal of the ionospheric content by using the image changes over the frequency range 1.4 to 1.7 GHz may reduce this error.

When attempting to reach the 0.1 mas astrometric precision, the variability in structure of the calibrator source can introduce uncertainties at this level. Many bright sources are 10 mas in size, with variable core flux densities and moving components. The cores often shift with frequency because of optical depth effects. Reaching astrometric limits that are only 1% of the angular size of the source can be difficult. Weaker calibrator sources, at the 10 mJy level, also tend to be smaller in angular size since their stronger counterparts, because of the $10^{12}$ K Compton-limit for extragalactic radio sources.

A general rule is that the closer the phase calibrator is to the target source, the higher quality the images made with phase referencing. The strength of the calibrator is secondary as long as it can be detected. In other words, a source that is just barely detected (say, 3 $\sigma$ for a solution) will produce a phase error of about 10 degrees, which will be stochastic because it is determined from random noise processes. In contrast, the use of a very strong calibrator farther away from the target to obtain phase solutions will have virtually no phase error component caused by noise, but systematic phase errors of tens of degrees may persist over many solution intervals, limiting the dynamic range of the resulting images of the target source. Thus the use of weak in-beam calibrators generally provides better astrometric accuracy and image fidelity. These in-beam calibrators also provide simultaneous calibration of the target source, whereas nodding calibrator phases must be interpolated and then interpolated to apply to the target source.

The problem with routinely using in-beam calibrators is that the field of view for which two sources can be simultaneously observed is limited. For the VLBA at 1.5 GHz, with a maximum separation between the target and calibrator of 25′ (both positioned somewhat within the half-power circle of the primary beam), the NVSS Catalog (Condon et al. 1998) contains an average of 20 sources above 2.5 mJy in such an area and about eight sources above 5.0 mJy. At these flux density levels, however, many sources may not have sufficient correlated flux density to be detectable at 5000 km baselines. With the present sensitivity limits of the VLBA, a source should have about 5 mJy correlated flux density to be detectable with a 64 MHz bandwidth. Weaker sources can be detected using the phased VLA with the VLBA with a 128 MHz bandwidth. If the pulsar is detectable, then an in-beam calibrator is useful as the reference even with a correlated flux density of 1 mJy. Observations are now underway to search several pulsar fields for possible in-beam calibrators and to determine the proportion of faint mJy sources that are detectable with VLBI resolution at 1.5 GHz.

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