Proper Motion Measurements with the VLA: I. Wide-field Imaging and Pulse Gating Techniques

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\textbf{ABSTRACT}

The pulsar velocity distribution provides information about the binary history of pulsar progenitors as well as asymmetries of the supernova events in which pulsars are born. Studies of local pulsars present a biased view of this distribution, since they preferentially select low velocity pulsars that have remained near their birthplaces in the Galactic plane. Using the VLA, we have studied the proper motions of a large sample of distant pulsars. These pulsars are generally faint, and the expected proper motions are small. In this paper, we describe the data analysis techniques that we have developed to allow precise astrometric measurements of faint sources with the VLA. These techniques include “gating” the VLA correlator to increase the signal-to-noise ratio of the pulsar by gathering data only during the pulse. Wide-field imaging techniques, including multiband imaging to account for bandwidth smearing, were used to allow identification of multiple in-beam background sources for astrometric calibration. We present the analysis of three pulsars, and demonstrate that astrometric accuracy of about ten milliarcseconds can be obtained for individual sources with our technique, allowing measurement of proper motions with errors of only a few milliarcseconds per year over our seven year baseline.

\textit{Subject headings: astrometry — pulsars: general — techniques: interferometric}

1. \textbf{Introduction}

Interferometric proper motions have always been hindered by the low flux densities of many pulsars. This restriction results in a bias in which only the closest pulsars are observed. Although

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these pulsars move quickly on angular scales, their absolute motion must be small for them to still be near the plane of the Galaxy. The fastest pulsars, however, have traveled the greatest distances and may be more than a kpc above the Galactic plane. Previous interferometric proper motion projects have been unable to include these distant pulsars due to their low flux densities. The study by Fomalont et al., begun in 1984, was limited to pulsars with $S > 2$ mJy so that an adequate signal to noise could be achieved (Fomalont et al. 1992). Few faint pulsars have proper motion measurements as a result of these selection effects.

This study of proper motions of distant, high $z$ pulsars using the Very Large Array (VLA) of the National Radio Astronomy Observatory\(^6\) began in 1992. We have chosen a group of 28 pulsars, 15 of which have $|z| > 400$ pc, $d \leq 4000$ pc, and $|b| < 30^\circ$. This selection criteria minimizes the uncertainty in the determination of the proper motion in the $z$ direction which enables the study of proper motions of pulsars relative to the Galactic plane. Upon completion, this project will double the number of proper motions measured for distant, high $z$ pulsars. The flux density restriction is overcome by gating the VLA. In order to have the pulsar in the same field as stationary sources, we must create wide-field images with position accuracies of a few mas. This requirement forces us to account for small effects such as annual aberration and Lorentz contraction over the fields.

This paper focuses on the method of data reduction and error analysis used to calculate the proper motions. Three pulsars (B0919+06, B1237+25 and B1937–26) are used as “case studies” demonstrating the accuracy of the method over a range of declinations and flux densities. Proper motions for all 28 pulsars will be presented by Brisken et al. in Paper II.

2. Data and Observational Techniques

Five epochs of data centered on 1992.96, 1994.23, 1995.52, 1998.32 and 1999.47 have been gathered at the VLA, amounting to more than 120 hours of observations. Every pulsar has been observed twice; 25 pulsars have three or more epochs of data.

2.1. Observational Setup

Observations were made in the A array at the VLA with the correlator in the 2 AD mode. A maximum baseline of 36 km provides the highest possible resolution (1.1\(^\prime\)). With this resolution, large sources are resolved out leaving mostly distant, extra-galactic sources in the images. These sources should be stationary over time and are used as reference sources against which to measure the motion of the pulsar.

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The data were gathered at 20 cm (1452.4 MHz) as a compromise between the reduction in pulsar flux density at higher frequencies and decreased resolution at lower frequencies. A 25 MHz bandwidth was divided into fifteen channels ($\Delta \nu = 1.56$ MHz) to provide the large usable field of view ($\approx 36'$) necessary for wide-field imaging (see section 2.2). Observations were made in two circular polarizations to provide the gating capability for pulsars without losing the ability to image weak continuum sources (see section 2.4). Thirteen channels were used to produce final images (see section 3).

Each pulsar was typically observed four times for 15 minutes during an observing run. Each segment was bracketed by five minutes of observation of a bright nearby VLA calibrator that was subsequently used for phase calibration and secondary amplitude calibration.

2.2. Delay Beam & Bandwidth Smearing

The size of the primary beam of the VLA is given by $\theta_p \approx \lambda/d$ where $d = 25$ m is the diameter of the dish. Thus $\theta_p \approx 30'$ at 20 cm defines the field of view contained inside the first null of the primary beam. In practice, observations are made over a band of non-zero width ($\Delta \nu \neq 0$). The range of frequencies in the band results in bandwidth smearing in which sources far from field center are smeared in the radial direction.

Bandwidth smearing is characterized by the delay beam, which is defined as $\theta_d = 2c/\Delta \nu D$ where $D$ is the maximum baseline (36 km for the A array). To maximize the usable field of view, observations are set up so that $\theta_d \approx \theta_p$. Since a single continuum channel ($\Delta \nu = 25$ MHz) has a usable field of view of $\sim 2'$, observations must be made in the spectral line mode with narrow channels. By dividing the band into fifteen channels ($\Delta \nu = 1.56$ MHz) a usable field of view of $\sim 36'$ is attained. Bandwidth smearing is only an important effect for sources more than $\sim 18'$ from field center. The added uncertainty in position of reference sources more than 20' from field center is taken into account in the proper motion fitting program (see section 6)

2.3. Gating

The VLA correlator was gated using the Princeton Mark III Pulsar Timing Machine (Stinebring et al. 1992). This computer allows real-time adjustment of the pulsar gate enabling the correlator to record data only when the pulsar is “on.” All the data during the off-pulse are discarded and only on-pulse portions are retained.

Gating can increase the signal-to-noise ratio (SNR) of a pulsar by up to a factor of five. The gate is matched to the duty cycle of the pulsar to maximize the improvement in the SNR. This improvement is approximately proportional to the inverse square-root of the duty cycle. Because the VLA has only a single gating circuit for all channels, the width of the gate must account for
dispersion smearing across the full 25 MHz bandwidth and typically ranges between 5 and 15% of the period for pulsars in this study. For B0919+06, gating increased the flux density from 6 to 120 mJy while the noise went from 0.1 to 1.5 mJy. B1237+25 showed an increase in flux density of 5 to 55 mJy and an increase in noise of 0.2 to 0.7 mJy. Finally, the flux density of B1937–26 increased from 1 to 15 mJy while the noise increased from 0.2 to 0.6 mJy when the VLA correlator was gated. Therefore, gating increased the SNR of B0919+06 by a factor of ~1.3 while B1235+25 and B1937–26 both showed an increase in SNR of a factor of ~4. In general, gating is not applied to pulsars that are brighter than typical reference sources (~ 10 mJy). However, technique testing (such as LL, RR alignment) was done using gated, bright pulsars while hardware availability prevented gating on some weak pulsars.

For our observations, the VLA is gated in the right circular polarization (RR) in order to increase the SNR of the pulsar. The left circular polarization (LL) is not gated, to permit optimal detection of reference sources in the field. Since the position of the pulsar is compared to those of the reference sources, positions in the right and left polarizations must agree to a few mas. Positions of strong pulsars and reference sources show a typical agreement between polarizations of 3 to 5 mas.

3. Calibration

The processing of the data begins with the removal of discrepant data points using the procedure TVFLG in AIPS (Astronomical Image Processing System). During the first observation of a pulsar, the first 3 to 5 minutes are typically used to determine the optimum position of the gate. Since the ungated data have significantly lower SNR than the gated data, they must be removed from the data set.

Calibrators for each pulsar are positioned at the phase center and are unaffected by bandwidth smearing. Therefore, basic calibrations are done in the continuum data set, which is a sum of the inner 75% of the observing band, and the resulting tables are copied to the spectral line data. 3C286 (J1331+305), 3C48 (J0137+331) and 3C147 (J0542+498) were used as the flux density and bandpass calibrators for the observations. Channels on the edge of the band pass filter are degraded by a roll-off in the band which results in reduced sensitivity in these channels. The first and last channels were removed from the data leaving thirteen channels to be used for final images. Calibration and editing information was applied when splitting the uv data into separate data sets for each pulsar.

For the clean algorithm to converge properly, the brightness and structure of all sources must remain constant, in both time and frequency, over the entire integration. The regular amplitude calibration and removal of data taken without the gate ensure that the time constancy is achieved, and the bandpass calibration flattens the spectrum. Although pulsars have considerably steeper spectra than do most of the reference sources and calibrators, their mean flux density changes by
less than 5% over our band and produces no noticeable cleaning artifacts. Scintillation in frequency and time violate the source constancy that is assumed in the clean algorithm, resulting in cleaning artifacts and an increase in the background noise. Since the noise near each source is used to determine the uncertainty of its position fit, this source of uncertainty is automatically included in the analysis.

3.1. UVFIX

Before imaging, UVFIX is run on the single source data sets. This AIPS program recovers the correct $u$, $v$, and $w$ coordinates of a source that are only approximated by the VLA correlator. The omission of these terms results in a movement in the tangential direction of up to 60 mas for a source 10$'$ from the field center (Fomalont et al. 1992). UVFIX also corrects for Lorentz contraction of the field due to the motion of the Earth along the line of sight. The magnitude of this effect depends on the time of year in which the observations were made and can result in a maximum radial movement of 60 mas for a source 10$'$ from field center (Fomalont et al. 1992).

L. Kogan at NRAO-Socorro revised UVFIX to account for these two effects by recalculating the correct $u$, $v$, and $w$ coordinates as well as moving to a stationary frame relative to the Sun. The results of the updated UVFIX program were tested by comparing reference source position agreement between epochs before and after UVFIX was run. As seen in Figure 1, UVFIX removed the rotation in the field near B0919+06 improving reference source alignment by a factor of three. This new version of UVFIX was incorporated into AIPS in early 1998.

4. Imaging Techniques

Images are made using the Clark “clean” algorithm in AIPS. A pixel size of 0.15$''$ provides more than 5 pixels/beam. Clean boxes are placed around regions containing sources to ensure that sidelobes are removed from these areas. Separate clean boxes are used for the pulsar and each reference source. A robust weighting of zero, which indicates a compromise between natural and uniform weighting, is used for all imaging.

4.1. Wide-field Imaging

A wide-field image (60$'\times60'$) is made in the LL polarization with ungated data for the detection of reference source candidates. Positions of bright sources are recorded and new images are made with separate fields for each source. Ideally, only point sources are retained as reference sources. In cases where there are only a few point sources we choose slightly extended sources as additional reference sources. The larger error in the position estimates of these extended sources results in
additional uncertainty in the final proper motion. All sources, including extended and weak sources are included in the imaging process to remove sidelobes from other fields. Due to the wide field used to image the reference sources and the non-coplanarity of the VLA, the $uv$ coverage at different points within the field of view can differ by an appreciable amount (Perley 1999). To account for this, the pulsar and all reference sources are imaged using $uv$ values appropriate for their part of the sky.

Multiple reference sources have been found for all 28 pulsars. There are typically about eight good reference sources for each pulsar. The quality of each reference source is determined by measuring its proper motion relative to the other reference sources. Extended reference sources are generally not used and point-like reference sources with large motions are also omitted. Sources used as reference sources for the final proper motion calculations have their proper motions listed in Table 1. For the three pulsars considered in this paper, the maximum distance of any detected source from field center is 27.6′. However, no source further than 22.3′ was used for the proper motion calculations.

4.2. Self-calibration

If there is enough flux density in compact sources inside the inner third of the primary beam then self-calibration can improve the signal-to-noise ratio of the detections. In self-calibration, one assumes that the image is degraded by antenna based gain and phase errors which vary in time and prevent perfect calibration. By re-calibrating the data using an initial set of images as a model, corrections to these phase and amplitude errors can be calculated as a function of time.

An accurate model of the flux density distribution across the field is necessary for self-calibration to be successful. Self-calibration is performed in the left hand polarization since the left hand data typically contain more flux density than the gated right hand polarization. In addition, pulsar scintillation is much more prominent in the gated polarization and could introduce additional amplitude errors in the calibration. Solutions from the left hand data are applied to both polarizations. Self-calibration can result in a shift in the field of as much as 20 mas when the initial model is not complete. Since the pulsar and reference sources are equally affected by this shift, the proper motion calculations are not compromised. Self calibration and imaging loops were iterated between 2 and 4 times. Solution intervals of between two and five minutes were used.

5. Position Determination

Positions of the pulsar and reference sources are found from final images using the AIPS task JMFIT. This task fits a gaussian profile to a point source with a width based on the size of the synthesized beam. For extended sources, the program solves for the width of the source as well.
JMFIT also reports an uncertainty in the position estimate. Since this uncertainty directly affects our confidence in the proper motions, tests were run on the output of JMFIT to ensure that it gives a reasonable error estimate. A continuum point source in 41 line-free channels of an HI image of NGC4688 was used for this test. These data were chosen because a bright point source and a large number of channels were available. Using identical parameters, JMFIT was run on each channel individually and the position and error output were recorded. The uncertainties reported by JMFIT agreed with the standard deviation of the 41 positions reported for the point source.

6. Proper Motions

The pulsar positions and proper motions are determined through a global least squares fit. Positions of reference sources and shifts in the coordinate system between epochs are also fit. The beam shape is used with the uncertainty reported by JMFIT to produce a correctly oriented elliptical gaussian uncertainty. An additional uncertainty of $F \cdot R \cdot \Delta \nu / \nu$ is added in quadrature in the radial direction to account for bandwidth smearing where $R$ is the source’s distance from the phase center, $\Delta \nu / \nu$ is the single channel fractional bandwidth, which in our case is close to 0.001, and $F$ is an empirically determined constant. By measuring the scatter in position measurements of point-like reference sources far from the field center in the same way that JMFIT was tested, we have determined that $F = 0.08$ for our data.

A small systematic coordinate offset remains for each epoch, even after UVFIX is applied. This effect ($\leq 30$ mas for a source 10\arcmin from field center) is approximately half as large as the correction made by UVFIX and cannot be adequately modeled by a simple rotation and dilation. Although the source of this offset is not fully understood, it is effectively removed by fitting for a six parameter general linear transformation, $\vec{X}' = A \vec{X} + \vec{B}$, between the coordinate systems of each epoch and the first epoch. $A$ is a two by two matrix whose elements typically deviate from the identity matrix by a few times $10^{-5}$ and $\vec{B}$ is a coordinate frame shift between the two epochs. The amount of correction can be characterized by a dimensionless number equal to the RMS value of the matrix elements. If we define $N_{\text{epochs}}$ as the number of epochs in which the pulsar was observed and $\delta A_{ij} = A_{ij} - \delta_{ij}$, where $\delta_{ij}$ is the identity matrix, then

$$\text{RMS} = \sqrt{\frac{1}{4 \times (N_{\text{epochs}} - 1)} \sum_{e=2}^{N_{\text{epochs}}} (\delta A_{c;11}^2 + \delta A_{c;12}^2 + \delta A_{c;21}^2 + \delta A_{c;22}^2)} . \quad (1)$$

The RMS correction for 28 pulsars is plotted against source declination in Figure 2. Since most of the observations were made near transit the elevation is approximately $90 - |\text{dec} - \text{lat}|$, where $\text{lat}$ is the latitude of the VLA, about $+34^\circ$. The required correction seems to follow the secant of the elevation suggesting that the atmosphere may cause this effect.

A Monte-Carlo bootstrap method was used to better determine the final error ellipses. In this
test, data are randomly resubstituted and the solution is fit thousands of times. The solutions for $\mu_\alpha$ and $\mu_\delta$ are plotted in a scatter plot. The uncertainties are estimated from the width of the distribution with an orientation based on the shape of the distribution in right ascension and declination. The uncertainties obtained in this manner agree well with the least squares errors. For a complete description of this method, see *Numerical Recipes in C* (Press et al. 1992).

7. Case Studies

B0919+06, B1237+25 and B1937–26 demonstrate the proper motion calculation as well as the accuracy of the error analysis. B0919+06 and B1237+25 were chosen because they both have previously published proper motions and can be used to test our results against those obtained from other methods. B0919+06 is especially interesting because it has a VLBA determination of the proper motion accurate to $< 1$ mas yr$^{-1}$ (Chatterjee et al. in preparation). B1937–26 is included because it is a weak pulsar ($\sim 1$ mJy) and is also located at a low declination. At $-26^\circ$, the synthesized beam of the VLA is $2.5''$ in declination compared to only $1.1''$ in right ascension. This elongated beam makes accurate measurement of $\mu_\delta$ difficult. In addition, calibrations for low elevation sources depend strongly on pointing direction. Depending on the distance from pulsar to phase calibrator, this can make self-calibration difficult. The calculated proper motions for all three pulsars can be seen in Table 2.

7.1. B0919+06

B0919+06 provides the most stringent test of the accuracy of our method. We initially compared our measurement of the proper motion ($\mu_\alpha = 18.8 \pm 0.9$ mas yr$^{-1}$, $\mu_\delta = 86.4 \pm 0.7$ mas yr$^{-1}$) to that published by Fomalont et al. (1999) ($\mu_\alpha = 17.7 \pm 0.3$ mas yr$^{-1}$, $\mu_\delta = 79.2 \pm 0.5$ mas yr$^{-1}$). There was an obvious disagreement between the two results, especially in $\mu_\delta$. A recent analysis of more extensive VLBA data (Fomalont et al. data plus additional VLBA observations from October, 1998) by Chatterjee, Fomalont et al. (in preparation) has led to a revision of the initial VLBA result. The revised VLBA values are: $\mu_\alpha = 18.4 \pm 0.2$ mas yr$^{-1}$, $\mu_\delta = 86.7 \pm 0.3$ mas yr$^{-1}$ with a parallax of $\pi = 1.15 \pm 0.25$ mas (Chatterjee et al. in preparation). We agree with this result to less than 1$\sigma$ in $\mu_\alpha$ and $\mu_\delta$. It is important to note that the errors from our new technique are comparable to those of the updated VLBA observations. The new measurement also agrees to within 1$\sigma$ of the proper motion measurement by Harrison, Lyne & Anderson (1993) of $\mu_\alpha = 13 \pm 29$ mas yr$^{-1}$, $\mu_\delta = 64 \pm 37$ mas yr$^{-1}$. Figure 3a shows the new proper motion measurement along with the Chatterjee et al. (in preparation) and Harrison, Lyne & Anderson (1993) results.
7.2. B1237+25

The proper motion measured for B1237+25 ($\mu_\alpha = -104.5 \pm 1.1$ mas yr$^{-1}$, $\mu_\delta = 49.4 \pm 1.4$ mas yr$^{-1}$) also agrees with both previous measurements (see Figure 3b). Our measurement deviates by $<1\sigma$ from the Fomalont et al. (1992) result of $\mu_\alpha = -113 \pm 13$ mas yr$^{-1}$, $\mu_\delta = 43 \pm 14$ mas yr$^{-1}$. It also agrees reasonably well with the Lyne, Anderson & Salter (1982) measurement of $\mu_\alpha = -106 \pm 4$ mas yr$^{-1}$, $\mu_\delta = 42 \pm 3$ mas yr$^{-1}$.

7.3. B1937–26

A proper motion of $\mu_\alpha = 12.1 \pm 2.4$ mas yr$^{-1}$, $\mu_\delta = -9.9 \pm 3.8$ mas yr$^{-1}$ was measured for B1937–26 (see Figure 3c). Due to the low flux density of this pulsar (~1 mJy), B1937–26 has no previous measurement of its proper motion. Despite the elongated beam at low declination, the value for $\mu_\delta$ has a small error. The motion of the pulsar is significant when compared to the small motion of its reference sources (see Table 1).

Without gating, we would not be able to determine the proper motion of this pulsar to such high accuracy. The proper motion of B1937-26 was recalculated using only the ungated, LL polarization for the positions of the pulsar and the reference sources. The resulting proper motion was $\mu_\alpha = 20 \pm 8$ mas yr$^{-1}$, $\mu_\delta = -15 \pm 15$ mas yr$^{-1}$. The increase in error due to the low signal to noise of the pulsar makes the measurement much less significant than the gated case.

The successful proper motion measurements for these three pulsars show the accuracy of this technique. B1937-26 is also limited by low flux density. A precise proper motion measurement would have been impossible without gating. These results confirm our ability to produce proper motions of weak pulsars that are accurate to less than five mas yr$^{-1}$.

8. Conclusion

We have developed a new technique to calculate proper motions of weak pulsars at the VLA. By gating the VLA in one polarization, distant, high $z$ pulsars with flux densities as low as ~1 mJy can be detected with a high signal-to-noise ratio. Previous work by Lyne, Anderson & Salter (1982) and Harrison, Lyne & Anderson (1993) also utilized the advantages of in-beam reference sources and gating. These observations were limited by a small number of baselines (one baseline in Lyne, Anderson & Salter (1982) and two baselines in Harrison, Lyne & Anderson (1993)) and the positions determined using fringe rate mapping rather than imaging could not correct for extended structure in reference sources. In addition, their data was degraded by the ionosphere which is worse at 408 MHz than in our observations at 1452.4 MHz. The 351 baselines and larger total collecting area of the VLA enable detection of much weaker sources and improved imaging. The addition of wide field imaging and a detailed understanding of systematic effects at the VLA also
makes this technique more useful. Wide-field imaging enables sources located up to $\sim 20'$ from the field center to be used as reference sources. By imaging the reference sources, we can exclude sources which show extended structure. These sources are very important in the calculation of plate solutions as well as the pulsars’ motions. Proper motions of the pulsars are fit simultaneously to all reference sources in the field.

Both B0919+06 and B1237+25 agree well with previously published proper motions confirming the accuracy of this technique. The measurement of the proper motion of B1937–26 shows the real success of the method. Ungated, this pulsar has a flux density of only $\sim 1$ mJy at 20 cm. This weak flux density excluded it from all previous proper motion projects. By gating the VLA, proper motions of faint pulsars can now be obtained with accuracies of a few mas yr$^{-1}$ in less than ten years. These accuracies are comparable to those obtained with VLBA observations. Although the larger synthesized beam of the VLA reduces positional accuracies, the VLA has the advantage of more straightforward data reduction and more thoroughly understood systematic effects. The presence of reference sources in the field of view of the VLA images also makes this a favorable technique since VLBA observations generally require out-of-beam reference sources. Therefore, proper motions of faint pulsars can now be obtained at the VLA in just a few years. Proper motions for all 28 pulsars in this study will be reported in Paper II by Brisken et al.

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Fig. 1.— Corrections to reference source positions as a result of the application of UVFIX. Pulsar B0919+06 is denoted by a star while crosses represent the location of reference sources before the application of UVFIX. Ellipses represent the $1\sigma$ error in the final position of the reference sources after UVFIX has been applied. The correction vectors have been increased in amplitude by a factor of 5000. The effects of annual aberration are seen in the counter-clockwise directions of the corrections about the field center.

Fig. 2.— The RMS correction required to align images from different epochs is marked by crosses. Since most of the observations were made near transit the elevation is approximately $90 - |\text{dec} - \text{lat}|$, where $\text{lat}$ is the latitude of the VLA, about $+34^\circ$. Note that the amount of correction is approximately proportional to the secant of the elevation (shown as the dashed line). This implies that the cause of the image misalignment is probably the atmosphere. The RMS plotted here is the fractional distortion defined in Section 6.

Fig. 3.— Proper motions for B0919+06, B1237+25 and B1937–26 are shown as vectors from the origin with the $1\sigma$ result denoted by ellipses. For B0919+06, the Chatterjee et al. (in preparation) result is denoted by a cross and the Harrison, Lyne & Anderson (1993) result is labeled by a star. Note that the Chatterjee et al. error ellipse is smaller than the size of the cross. For B1237+25, the Fomalont et al. (1992) result is denoted by a cross while the Lyne, Anderson & Salter (1982) result is denoted by a star. In all three plots, the result presented in this paper has no symbol at the center of the ellipse.
Table 1. Reference Sources for Proper Motions

| Pulsar       | S (mJy) | α2000       | δ2000       | Δα (arcsec) | Δδ (arcsec) | μα (mas yr⁻¹) | μδ (mas yr⁻¹) |
|--------------|---------|-------------|-------------|-------------|-------------|---------------|---------------|
| B0919+06     | 23.0 ± 0.1 | 09²23'03.90 ± .01 | 06°38'58.6 ± .1 | 743         | 37          | 1 ± 4         | 1 ± 1         |
|              | 3.0 ± 0.5  | 09²22'42.36 ± .01 | 06°48'40.3 ± .1 | 421         | 618         |               |               |
|              | 4.7 ± 0.1  | 09²22'40.34 ± .01 | 06°44'06.5 ± .1 | 392         | 345         | −5 ± 3        | 0 ± 3         |
|              | 2.6 ± 0.1  | 09²22'12.08 ± .01 | 06°46'19.9 ± .1 | −28         | 478         | 0 ± 6         | 2 ± 7         |
|              | 8.9 ± 0.1  | 09²21'59.12 ± .01 | 06°42'20.5 ± .1 | −221        | 239         | 4 ± 2         | −1 ± 2        |
|              | 7.9 ± 0.1  | 09²21'26.95 ± .01 | 06°42'34.0 ± .1 | −701        | 252         | −1 ± 4        | 2 ± 2         |
|              | 10.6 ± 0.1 | 09²21'19.36 ± .01 | 06°40'42.3 ± .1 | −814        | 140         | 2 ± 4         | −3 ± 2        |
|              | 6.5 ± 0.1  | 09²21'16.97 ± .01 | 06°35'44.6 ± .1 | −850        | −157        | −12 ± 5       | 0 ± 2         |
|              | 10.0 ± 0.1 | 09²22'23.19 ± .01 | 06°27'30.1 ± .1 | 137         | −652        | 1 ± 2         | 2 ± 4         |
|              | 4.8 ± 0.1  | 09²22'38.63 ± .01 | 06°30'53.1 ± .1 | 367         | −449        | −3 ± 4        | −1 ± 4        |
|              | 1.7 ± 0.2  | 09²21'01.42 ± .01 | 06°36'23.9 ± .1 | −1081       | −118        |               |               |
|              | 3.0 ± 0.2  | 09²21'52.62 ± .01 | 06°15'17.3 ± .1 | −319        | −1385       |               |               |
|              | 3.1 ± 0.2  | 09²22'57.06 ± .01 | 06°25'46.1 ± .1 | 642         | −756        | −5 ± 7        | −4 ± 8        |
|              | 2.2 ± 0.2  | 09²23'24.3 ± .01  | 06°26'16.0 ± .1 | 1330        | −726        |               |               |
|              | 9.2 ± 0.1  | 09²23'49.86 ± .01 | 06°37'58.6 ± .1 | 1339        | −23         | 2 ± 7         | −2 ± 2        |
|              | 1.0 ± 0.2  | 09²23'30.18 ± .01 | 06°50'24.2 ± .1 | 881         | 721         |               |               |
|              | 2.2 ± 0.2  | 09²23'28.34 ± .01 | 06°58'55.1 ± .1 | 1107        | 1233        |               |               |
|              | 2.6 ± 0.2  | 09²22'29.14 ± .01 | 06°54'51.6 ± .1 | 12          | 990         |               |               |
|              |          |             |             |             |             |               |               |
| B1237+25     | 8.7 ± 0.1  | 12²40'31.71 ± .01 | 24°58'19.2 ± .1 | 698         | 270         | 1 ± 5         | −2 ± 3        |
|              | 26.4 ± 0.2 | 12²41'16.50 ± .01 | 25°01'09.4 ± .1 | 1305        | 440         |               |               |
|              | 9.0 ± 0.1  | 12²40'09.24 ± .01 | 25°06'22.1 ± .1 | 391         | 753         | 1 ± 3         | 4 ± 6         |
|              | 1.6 ± 0.1  | 12²40'43.06 ± .01 | 25°11'19.0 ± .1 | 850         | 1049        |               |               |
|              | 7.5 ± 0.1  | 12²38'57.75 ± .01 | 24°53'54.9 ± .1 | −581        | 5           | 1 ± 5         | −5 ± 2        |
|              | 8.2 ± 0.1  | 12²38'30.04 ± .01 | 24°50'32.1 ± .1 | −958        | −197        | −2 ± 7        | −5 ± 2        |
|              | 0.7 ± 0.1  | 12²39'07.26 ± .01 | 24°51'05.2 ± .1 | −451        | −164        |               |               |
|              | 11.5 ± 0.1 | 12²39'39.64 ± .01 | 24°48'10.1 ± .1 | −11         | −340        | −1 ± 1        | 2 ± 3         |
|              | 2.6 ± 0.1  | 12²40'58.92 ± .01 | 24°49'27.8 ± .1 | 1069        | −262        | 3 ± 10        | 6 ± 6         |
|              | 3.0 ± 0.1  | 12²38'57.47 ± .01 | 24°45'27.9 ± .1 | −585        | −502        | −3 ± 6        | −9 ± 5        |
|              | 1.8 ± 0.1  | 12²39'47.36 ± .01 | 24°42'38.8 ± .1 | 95          | −671        | 5 ± 5         | 9 ± 8         |
|              | 2.0 ± 0.1  | 12²40'20.14 ± .01 | 24°50'37.9 ± .1 | 677         | −192        | −4 ± 7        | 6 ± 6         |
|              |          |             |             |             |             |               |               |
| B1937−26     | 43.0 ± 0.1 | 19²41'23.61 ± .01 | −26°01'15.6 ± .1 | 313         | 50          | 0 ± 4         | 2 ± 3         |
|              | 4.4 ± 0.1  | 19²40'48.26 ± .01 | −25°58'20.9 ± .1 | −164        | 225         | −3 ± 4        | 6 ± 6         |
|              | 2.6 ± 0.1  | 19²40'27.74 ± .01 | −25°59'28.2 ± .1 | −441        | 157         | 7 ± 6         | −2 ± 9        |
|              | 3.7 ± 0.1  | 19²39'59.37 ± .01 | −25°59'12.4 ± .1 | −826        | 173         | −3 ± 9        | −6 ± 8        |
|              | 3.2 ± 0.1  | 19²41'27.42 ± .01 | −26°08'05.4 ± .1 | 364         | −359        | −3 ± 6        | −4 ± 10       |
Table 1—Continued

| Pulsar | S (mJy) | $\alpha_{2000}$ | $\delta_{2000}$ | $\Delta\alpha$ | $\Delta\delta$ | $\mu_\alpha$ | $\mu_\delta$ |
|--------|---------|-----------------|-----------------|----------------|----------------|--------------|--------------|
|        |         |                 |                 | arcsec         | arcsec         | mas yr$^{-1}$| mas yr$^{-1}$|
| 4.7 ± 0.1 | 19$^h$42$^m$04$^s$.81 ± .01 | -25$^o$55$'$.06$''$.9 ± .1 | 869 | 419 | 4 ± 9 | -4 ± 8 |
| 2.6 ± 0.1 | 19$^h$42$^m$02$^s$.76 ± .01 | -25$^o$56$'$.16$''$.9 ± .1 | 841 | 349 | 56 |
| 1.2 ± 0.1 | 19$^h$40$^m$08$^s$.65 ± .01 | -26$^o$01$'$.08$''$.0 ± .1 | -698 | -179 | -1365 |
| 18.0 ± 0.1 | 19$^h$40$^m$47$^s$.06 ± .01 | -26$^o$24$'$.50$''$.9 ± .1 | -179 | 934 | -748 |
| 2.7 ± 0.1 | 19$^h$42$^m$09$^s$.80 ± .01 | -26$^o$14$'$.34$''$.2 ± .1 | 934 | 757 | -217 |
| 0.1 ± 0.1 | 19$^h$41$^m$43$^s$.25 ± .1 | -26$^o$05$'$.43$''$.1 ± .1 | 546 | 165 | 6 ± 8 |
| 1.8 ± 0.1 | 19$^h$41$^m$40$^s$.93 ± .01 | -26$^o$04$'$.51$''$.1 ± .1 | 546 | 165 | 6 ± 8 |
| 1.3 ± 0.1 | 19$^h$41$^m$03$^s$.46 ± .01 | -25$^o$48$'$.33$''$.6 ± .1 | 41 | 812 |

Note. — Sources without proper motions were not used in the determination of pulsar proper motions.

Table 2. Proper Motions

| PSR     | S (mJy) | Gated S (mJy) | Epochs | Num. of Ref. | $\mu_\alpha$ (mas yr$^{-1}$) | $\mu_\delta$ (mas yr$^{-1}$) | Cov($\mu_\alpha$, $\mu_\delta$) |
|---------|---------|---------------|--------|--------------|-----------------------------|-----------------------------|-------------------------------|
| B0919+06 | 5.7 ± 0.1 | 120.8 ± 1.5   | 95, 98, 99$^\dagger$, 99 | 11 | 18.8 ± 0.9 | 86.4 ± 0.7 | 0.0 |
| B1237+25 | 4.6 ± 0.2 | 55.0 ± 0.7    | 92, 95, 98, 99$^\dagger$ | 9 | -104.5 ± 1.1 | 49.4 ± 1.4 | 0.1 |
| B1937−26 | 1.0 ± 0.2 | 14.8 ± 0.6    | 94$^\dagger$, 98$^\dagger$, 99$^\dagger$ | 7 | 12.1 ± 2.4 | -9.9 ± 3.8 | 0.1 |

$^\dagger$Indicates that the observation was gated
B0919+06

+ Chatterjee & Cordes, 1999
× Harrison, Lyne & Anderson, 1993
B1237+25

+ Fomalont et al, 1992
* Lyne, Anderson & Salter, 1982

\[ \mu_\delta \text{ (mas/yr)} \]

\[ \mu_\alpha \text{ (mas/yr)} \]

Circle represents uncertainty.
