# A VLBI Distance and Transverse Velocity for PSR B1913+16

A. T. Deller\(^1\)\, J. M. Weisberg\(^2\)\, D. J. Nice\(^3\), and S. Chatterjee\(^4\)

\(^1\)Centre for Astrophysics and Supercomputing, Swinburne University of Technology, Mail Number H11, P.O. Box 218, Hawthorn, VIC 3122 Australia
\(^2\)Department of Physics and Astronomy, Carleton College, Northfield, MN 55057, USA
\(^3\)Department of Physics, Lafayette College, Easton, PA 18042, USA
\(^4\)Cornell Center for Astrophysics and Planetary Science, Cornell University, Ithaca, NY 14853, USA

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## Abstract

Using the Very Long Baseline Array, we have made astrometric observations of the binary pulsar B1913+16 spanning an 18-month period in 2014–2015. From these observations we make the first determination of the annual geometric parallax of B1913+16, measuring \(\pi = 0.24^{+0.06}_{-0.08}\) mas (68% confidence interval). The inferred parallax probability distribution differs significantly from a Gaussian. Using our parallax measurement and prior information on the spatial and luminosity distributions of the millisecond pulsar population, we infer a distance of \(d = 4.1^{+2.2}_{-0.8}\) kpc, which is significantly closer than the 9.8 \pm 3.1 kpc suggested by the pulsar’s dispersion measure (DM) and analyses of the ionized interstellar medium. While the relatively low significance of the parallax detection (\(\sim 3\sigma\)) currently precludes an improved test of general relativity using the orbital decay of PSR B1913+16, ongoing observations with improved control of systematic astrometric errors could reach the 10% distance uncertainty required for this goal. The proper motion measured by our Very Long Baseline Interferometry astrometry differs substantially from that obtained by pulsar timing, a discrepancy that has also been found between the proper motion measurements made by interferometers and pulsar timing for some other pulsars, which we speculate is the result of timing noise or DM variations in the timing data set. Our parallax and proper motion measurements yield a transverse velocity of \(15.3^{+8.0}_{-4.4}\) km s\(^{-1}\) in the solar reference frame. Analysis incorporating galactic rotation and solar motion finds that the space velocity of the pulsar relative to its standard of rest has a component \(22.1^{+3.9}_{-1.7}\) km s\(^{-1}\) perpendicular to the galactic plane and components on the order of 100 km s\(^{-1}\) parallel to the galactic plane.

**Key words:** astrometry – gravitation – pulsars: individual (PSR B1913+16) – stars: neutron – techniques: high angular resolution

## 1. Introduction

The double neutron star system containing PSR B1913+16 was the first binary pulsar system discovered (Hulse \& Taylor 1975), and has proved to be an outstanding laboratory for the study of relativistic gravitation owing to its extreme physical conditions. The observation of orbital decay at the rate expected from general relativity (GR) provided the first evidence for gravitational radiation emission (Taylor \& Weisberg 1982), and improved observational data has led to ever-tighter constraints on the agreement with GR predictions (Weisberg \& Huang 2016).

As the measurement precision has improved, it has become important to account for non-GR contributions to the observed orbital period derivative \(\dot{P}_b\). Damour \& Taylor (1991) pointed out, for example, that \(\dot{P}_b\) is affected not only by gravitational radiation emission but also by acceleration in the galactic gravitational potential and by the apparent acceleration imposed by the pulsar’s transverse motion (Shklovskii 1970). Until now, our knowledge of these contributions, and hence the accuracy of the \(\dot{P}_b\) test of gravitational radiation and GR, has been limited primarily by the uncertainty in the pulsar distance and, to a lesser degree, by the proper motion uncertainty. The pulsar distance has previously been best constrained by careful modeling of the galactic electron density along the line of sight toward it, and then determining a distance based on the pulsar’s dispersion measure (DM; Weisberg et al. 2008). The timing signature of annual parallax is too small to be measured with the currently available precision, while the timing signature of proper motion may be distorted by any unmodeled influences on measured pulse arrival times, such as rotation irregularities (“timing noise”) or variations in interstellar dispersion not accounted for in the timing analysis. Accordingly, these quantities must be obtained using another procedure. Therefore, in an effort to improve the \(\dot{P}_b\) test, we have embarked on a Very Long Baseline Interferometry (VLBI) astrometric program to measure the parallax and proper motion of this pulsar.

Differential VLBI astrometry (measuring the position of a target source relative to the reference position of a nearby calibrator) has been employed to measure the proper motion and parallax of dozens of radio pulsars (e.g., Chatterjee et al. 2009; Deller et al. 2009). When the calibrator–target angular separation is small (\(<1°\)), the calibrator and target source can be observed simultaneously in a single pointing at the low frequencies where pulsars are brightest, in which case this differential offset can typically be measured with submilliarc-second precision. By observing a number of times over a period of 1–2 years, effects such as proper motion and annual geometric parallax that change this offset can be measured to very high accuracy.

In this paper, we describe our VLBI measurements (Section 2) of PSR B1913+16 and use them to obtain independent measurements of the pulsar’s distance and transverse velocity (Section 3). In Section 4, we compare these results to other constraints on these parameters, and obtain a best estimate for the kinematic contributions to \(\dot{P}_b\), which we use to revise the gravitational radiation test with PSR B1913+16. Our conclusions are set forth in Section 5.
2. VLBI Observations and Data Processing

2.1. Observations

All observations of PSR B1913+16 were performed with the Very Long Baseline Array (VLBA). Before commencing astrometry, we first sought a suitable “in-beam” calibrator source by making snapshot VLBA images of all sources brighter than 3 mJy within 30' of PSR B1913+16, so as to identify sources that were sufficiently bright and compact on VLBI scales. This observation took place in May of 2011 as a part of the PSR$\pi$ campaign (Deller et al. 2011a, 2016) and identified the 6 mJy source J191621.8+161853, which is separated by 18' from PSR B1913+16, to be sufficiently compact.

Between 2014 May and 2015 November, eight astrometric observations were made with the VLBA (project code BD178). Two observations were made every six months, close to the parallax extrema in April and October. Each observation was 4 hr in duration, during which time phase referencing was performed between the target (a pointing center midway between PSR B1913+16 and J191621.8+161853) and a primary phase calibrator at an angular separation of 1°.1 (J1911+1611). The phase reference cycle time was 4 minutes, with 3 minutes spent on the target and 1 minute on the phase reference source. To calibrate the instrumental bandpass, we observed the bright “fringe finder” source J1925+2106 once per observation. The maximum recording rate of 2 Gbps was used, sampling a total bandwidth of 256 MHz in two circular polarizations. Eight 32 MHz sub-bands distributed between 1392 and 1744 MHz were used, avoiding regions of the radio spectrum most contaminated by radio frequency interference. Correlation was performed using the DiFX correlator in Socorro (Deller et al. 2011b), with two correlation passes used to provide separate data sets centered on J191621.8+161853 and PSR B1913+16. On-pulse gaging was used to improve sensitivity on PSR B1913+16, with the pulsar duty cycle of 12% leading to a factor of $1/\sqrt{0.12} \approx 3$ improvement in signal-to-noise ratio.

2.2. Data Reduction

We used the same astrometric data-reduction pipeline described in Deller et al. (2013) and refined in Deller et al. (2016). Briefly, this ParsecTongue (Kettenis et al. 2006) script applies a priori and user-supplied flags, applies a priori amplitude calibration, corrects for ionospheric propagation delays, and then derives and applies successive calibration corrections using the “fringe finder” source (time-independent delay and bandpass), primary phase reference source (time-dependent delay, amplitude, and phase), and the nearer in-beam calibrator (phase only). For the ionospheric correction, the global model (grid resolution 2°5 in latitude, 5° in longitude, and 2 hr in time) produced by the International GNSS Service$^5$ was used. The phase solutions on the in-beam calibrator were derived with a solution interval of 2.2 minutes, short enough to allow two solutions per scan on the target but long enough to minimize the number of failed solutions. After all calibration was applied, the target data were split and exported for imaging in difmap (Shepherd 1997).

The imaging and position extraction was identical to that performed in Deller et al. (2016), fitting a single point source model to the visibility data and making a single Stokes $I$ image per epoch. An astrometric position and uncertainty was obtained from each resultant image by using the task JMFIT in AIPS (Greisen 2003) to fit an elliptical Gaussian to the source. With a typical synthesized beam size of 5 x 10 mas at position angle $\sim$0° and a typical detection significance of $\sim$40$\sigma$, the formal fit uncertainties at each epoch were $\sigma R.A./f \sim 0.05$ and $\sigma decl./f \sim 0.11$ mas in R.A. and decl., respectively. We also split each observation into 30 minute chunks and extracted position fits for each chunk separately so as to assist with the estimation of systematic position shifts due to the ionosphere as described subsequently.

3. Astrometric Results

The uncertainties on the fitted positions $\sigma R.A./f$, $\sigma decl./f$ that we obtain are purely determined by the interferometer resolution and signal-to-noise ratio of the image, and do not account for potential systematic offsets introduced by the differential ionosphere between the in-beam calibrator and target pulsar, or by structure evolution in the calibrator source. Such systematic errors $\sigma R.A./sys$, $\sigma decl./sys$ are expected to be

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$^5$ Available from http://cddis.gsfc.nasa.gov/gps/products/ionex/.
comparable to or greater than \( \sigma_{\text{R.A.}} \) and \( \sigma_{\text{decl.}} \) based on the nominal accuracy of the global ionospheric models used, and on the previous experience of pulsar astrometry at these frequencies (e.g., Chatterjee et al. 2009). This is confirmed by making a simple least-squares fit of reference position, proper motion, and parallax to our measured positions using only the formal position fit uncertainties \( \sigma_{\text{R.A.}} \), \( \sigma_{\text{decl.}} \). The rms of the residual position offsets is 0.11 mas in R.A. and 0.17 mas in decl., leading to a \( \chi^2 \) of 51 for 11 degrees of freedom. This fit is shown in Figure 1.

If this simple fit were taken at face value, we would obtain a parallax for B1913+16 of 0.22 \( \pm \) 0.02 mas, where the uncertainty is obviously underestimated. In order to obtain realistic uncertainties on the astrometric parameters, we need to account for the systematic error contributions \( \sigma_{\text{R.A.-sys}} \) and \( \sigma_{\text{decl.-sys}} \) to the position uncertainty at each epoch. In the past, two main approaches have been employed (e.g., Chatterjee et al. 2009; Deller et al. 2012, 2013):

1. Assume that \( \sigma_{\text{R.A.-sys}} \) and \( \sigma_{\text{decl.-sys}} \) are independent Gaussian-distributed variables, and estimate their variance by choosing values that give a reduced \( \chi^2 \) of 1.0 for the astrometric fit.

2. Perform a bootstrap fit (e.g., Efron & Tibshirani 1991) to obtain realistic estimates for the uncertainties on the fitted parameters despite the fact that the uncertainties of the input positions are underestimated. We conducted 100,000 trials, where each trial was conducted by sampling with replacement from the eight position measurements (where each measurement consists of a R.A. and decl. pair).

In addition to applying these approaches, we used a third technique for estimating \( \sigma_{\text{R.A.-sys}} \) and \( \sigma_{\text{decl.-sys}} \) which makes use of the apparent positional wander within a single observation. In this procedure, for each epoch, the variance in the R.A. and decl. positions was calculated from the subdivided, 30 minute time resolution data sets and used to set \( \sigma_{\text{R.A.-sys}} \) and \( \sigma_{\text{decl.-sys}} \) respectively for that epoch. Accordingly, the estimated systematic error contribution varied from epoch to epoch. If the apparent shifts on short timescales are a good proxy for the mean residual offset over a 4 hr period, then this approach would provide a more accurate estimation of the systematic errors than assuming them to have a Gaussian distribution with a fixed variance (the first approach described).

We compared the results of all three approaches and found that the fitted astrometric values (reference position, proper motion, and parallax) all agreed to \( \leq 0.5 \sigma \), while the estimated uncertainty values varied by up to \( \sim 30\% \). We report the results of the bootstrap fit, which gave the most conservative error bars for the fitted parameters of the three approaches. The results are reported in Table 1 and plotted in Figure 2. Absolute positions are provided in the International Celestial Reference Frame and are determined using the out-of-beam phase reference source 1911+1611, whose position was taken as 19h11m58.257403+16d11.468.86517.

### 3.1. Estimating the Distance to PSR B1913+16 from the VLBI Parallax

In order to improve the PSR B1913+16 test of relativistic gravitation, the most important quantity we wish to extract is the distance to the pulsar. We compared the results of all three approaches and found that the fitted astrometric values (reference position, proper motion, and parallax) all agreed to \( \leq 0.5 \sigma \), while the estimated uncertainty values varied by up to \( \sim 30\% \). We report the results of the bootstrap fit, which gave the most conservative error bars for the fitted parameters of the three approaches. The results are reported in Table 1 and plotted in Figure 2. Absolute positions are provided in the International Celestial Reference Frame and are determined using the out-of-beam phase reference source 1911+1611, whose position was taken as 19h11m58.257403+16d11.468.86517.

| Table 1 | Fitted Astrometric Parameters and 68% Confidence Intervals for PSR B1913+16 |
|---------|--------------------------------------------------------------------------------|
| R.A. (J2000)\(^b\) | 19:15:27.9986 \(\pm 0.0001\) |
| Decl. (J2000)\(^b\) | 16:06:27.381 \(\pm 0.002\) |
| R.A. offset (mas)\(^f\) | \(-775182.05 \pm 0.04\) |
| Decl. offset (mas)\(^f\) | \(-746525.86 \pm 0.06\) |
| Position epoch (MJD) | 57050 |
| R.A. proper motion \(\mu_x\) (mas yr\(^{-1}\)) \(^c\) | \(-0.77 \pm 0.06\) |
| Decl. proper motion \(\mu_y\) (mas yr\(^{-1}\)) \(^c\) | \(0.01 \pm 0.17\) |
| Parallax \(\pi\) (mas) \(^c\) | \(0.24 \pm 0.08\) |

Notes.

\(^a\) Quoted uncertainties include systematic error estimates, and are derived from a bootstrap fit (see text).

\(^b\) Uncertainty in absolute position is dominated by the absolute position uncertainty for the in-beam calibrator.

\(^c\) The relative offset between PSR B1913+16 and the in-beam calibrator reference position (which is much more precise than the absolute position).

![Figure 2](image_url)
from our astrometric fit is the pulsar distance, which is constrained by the parallax. A simple inversion of the measured parallax and its upper and lower limits gives a nominal 68% distance confidence interval of $d = 4.2^{+2.0}_{-0.9}$ kpc. However, this result needs to be interpreted with caution for two reasons:

1. The distribution of parallax values obtained from the bootstrap fit is somewhat non-Gaussian, as can be seen in Figure 3.
2. The significance of the parallax measurement is relatively low ($\sim 3\sigma$), meaning that biases can substantially affect the distance inferred from the measured parallax (e.g., Verbiest et al. 2010, 2012; Igoshev et al. 2016).

The accuracy of a distance (and distance error) inferred from a single low-significance parallax is strongly influenced by the choice of priors used (e.g., Bailer-Jones 2015). For radio pulsar parallaxes, the most important priors are the galactic pulsar population distribution and the radio pulsar luminosity function, both of which are relatively poorly constrained. The resultant distance, therefore, is strongly influenced by the assumed (yet poorly known) pulsar population characteristics. Somewhat fortunately, the two priors act in opposite directions: more pulsars are expected along the line of sight to PSR B1913+16 at $d > 4.2$ kpc than at $d < 4.2$ kpc, but a $\sim 0.45$ mJy radio pulsar such as PSR B1913+16 is more likely to be located at $d < 4.2$ kpc than at $d > 4.2$ kpc. (See Figure 4.)

For the purpose of exploring the impact on tests of GR, we derive the pulsar distance from the VLBI parallax, corrected for the Lutz–Kelker bias (Verbiest et al. 2010, 2012; as modified by Igoshev et al. 2016), using our own parallax distribution function (Figure 3) and the same galactic pulsar population distribution and radio pulsar luminosity function used by Verbiest et al. (2010, 2012). This procedure modestly shifts our

$$d = 4.1^{+2.0}_{-1.2}$$

Figure 3. Histogram of parallax values resulting from the bootstrap fit (black solid line). The best-fit parallax value is indicated with a vertical dashed line, and the 68% confidence interval is indicated with vertical dashed–dotted lines. The distribution is not well approximated as a Gaussian, exhibiting a secondary peak; the spiky structure in the distribution is an unavoidable result of bootstrap fitting with a small number of input samples possessing non-Gaussian errors. The light gray line shows the Gaussian probability confidence interval resulting from a least-squares fit to the astrometric positions, after including an estimate for $\sigma_{\text{R.A.}}$ and $\sigma_{\text{Decl.}}$, that results in a reduced $\chi^2$ of 1.0; if this method were used, the parallax uncertainty would likely be underestimated.

Figure 4. Probability distribution of the pulsar distance (black solid line), which is the product of the parallax probability distribution obtained from our bootstrap fit (red dashed line), the volumetric term (yellow dotted line), and the luminosity term (blue dashed–dotted line) as given by Verbiest et al. (2010, 2012) and Igoshev et al. (2016). For display purposes, all probability distributions are shown normalized to a peak relative probability of 1.0. The most probable distance is shown by a vertical black dashed line, and the 68% confidence interval for distance is shown by vertical black dashed–dotted lines. A smoothing kernel of width 0.3 kpc was applied to the parallax probability distribution to mitigate the large fluctuations on short distance scales that result from the small sample size available for the bootstrap.

4. Discussion

4.1. Non-GR Contributions to $P_b$

Damour & Taylor (1991) derived the “galactic” correction caused by kinematic effects, $P_b^{\text{gal}}$, to the observed orbital period derivative, $P_b^{\text{obs}}$, which is required in order to determine the intrinsic orbital period derivative at the pulsar system’s barycenter, $P_b^{\text{int}}$:

$$P_b^{\text{int}} = P_b^{\text{obs}} - P_b^{\text{gal}},$$

where

$$P_b^{\text{gal}} = (P_b/c)[\vec{n}_p \cdot (\vec{a}_p - \vec{a}_\odot) + \mu^2 d],$$

(Nice & Taylor 1995). Here, $\vec{n}_p \cdot \vec{a}_\odot$ is the unit vector pointing from the solar system to the pulsar, $\vec{a}_p$ and $\vec{a}_\odot$ are the centripetal acceleration of the pulsar and solar system barycenters in the galactic potential, and $\mu$ and $d$ are the pulsar’s proper motion and distance. For PSR B1913+16, with galactic latitude $b = 2^\circ 1$, it is sufficient to consider only the galactic planar components of $\vec{n}_p$. Consequently,

$$P_b^{\text{gal}} = \frac{P_b}{c} \times \left\{ -\frac{\Theta_0^2}{R_0} \left[ \cos l + \left( \frac{\Theta_{ps}}{\Theta_0} \right)^2 \right] \right\} \left[ \frac{(d/R_0) - \cos l}{1 - 2(d/R_0) \cos l + (d/R_0)^2} \right]$$

$$+ \frac{P_b}{c} \mu^2 d$$

(3)
Table 2
Comparison of PSR B1913+16 VLBI Astrometry to Previous Results

| Parameter | VLBI This work | Weisberg & Huang (2016) | Yao et al. (2017) |
|-----------|---------------|-------------------------|------------------|
| Fitted Parameters |
| $\mu_0$ (mas yr$^{-1}$) | $-0.77^{+0.16}_{-0.06}$ | $-1.23 \pm 0.04$ | |
| $\mu_0$ (mas yr$^{-1}$) | $0.01^{+0.10}_{-0.08}$ | $-0.83 \pm 0.04$ | |
| $\pi$ (mas) | $0.24^{+0.08}_{-0.08}$ | ... | |
| Derived Parameters |
| $d$ (kpc) | $4.1^{+2.0}_{-0.7}$ | $9.8 \pm 3.1^a$ | $5.25^b$ |
| $v_T$ (km s$^{-1}$) | $15^{+4}_{-4}$ | $69^{+2.4}_{-2.5}$ | |

Notes:

$^a$ Analysis from Weisberg et al. (2008).

$^b$ The relative distance uncertainty is 0.9 (95% C.I.).

(Damour & Taylor 1991), where $\Theta_0$ is the (circular) velocity of the local standard of rest and $\Theta_{sys}$ is the equivalent quantity at the pulsar, $R_0$ is the galactocentric radius of the solar system, $l$ is the pulsar’s galactic longitude, and $\mu$ is its proper motion. (Note that the magnitude of the galactocentric centripetal acceleration at any point is given by $a = \Theta^2 / R$, where $\Theta$ and $R$ are the systemic galactocentric circular speed and radius at that point.)

4.2. Using the VLBI Measurements and Galactic Parameters to Evaluate $P_b^{\text{intr}}$

In order to evaluate Equation (3) so as to subtract off the influence of the “galactic” term from $P_b^{\text{obs}}$, one needs to know the values of the pulsar’s distance and proper motion, and of various galactic constants. Our pulsar VLBI measurements detailed in Sections 3 and 3.1 supply the former quantities, while a number of other experiments have determined the latter parameters, particularly $R_0$ and $\Theta_0$, via a variety of techniques. A concerted VLBI parallax campaign targeting galactic star-forming regions (Reid et al. 2014) considerably improved the precision of the galactic quantities: $\Theta_0 = 240 \pm 8$ km s$^{-1}$, $R_0 = 8.34 \pm 0.16$ kpc, and $d\Theta/dR = -0.2 \pm 0.4$ km s$^{-1}$ kpc$^{-1}$. Two more recent works have critically and comprehensively reviewed the galactic parameter determinations. Bland-Hawthorn & Gerhard (2016) concluded that $R_0 = 8.2 \pm 0.1$ kpc and $\Theta_0 = 238 \pm 15$ km s$^{-1}$; while de Grijs & Bono (2016), focusing principally on $R_0$, found its value to be $8.3 \pm 0.2$ [statistical] $\pm 0.4$ [systematic] kpc, with an implied $\Theta_0$ from recent measurements of $270 \pm 14$ km s$^{-1}$. Newer “visual” binary measurements of S star orbits at the galactic center by Boehle et al. (2016) suggested a significantly lower value of $R_0$, but when these measurements were incorporated into similar ones by Gillessen et al. (2017), the discrepancy disappeared.

We calculated the value of $P_b^{\text{gal}}$ based upon each of the preceding works, with an assumption of a flat rotation curve in each case except that of Reid et al. (2014), whose rotation curve slope was explicitly given (and still consistent with zero to within its errors as listed). Most of them yield a similar value of $P_b^{\text{gal}}$, so our choice of a single best rotation curve is somewhat arbitrary. Nevertheless, these galactic parameters are covariant. Therefore, we adopted the galactic parameters of Reid et al. (2014) due to their explicit simultaneous evaluation of all three relevant parameters $R_0$, $\Theta_0$, and $d\Theta/dR$, the latter of which affects the value of $(\Theta_{PSR}/\Theta_0)$ in Equation (3).

These quantities, along with our newly determined pulsar distance and proper motion (summarized in Table 2) and its known galactic longitude $l = 50^\circ$, yield $P_b^{\text{gal}} = -(0.008 \pm 0.003) \times 10^{-12}$ s$^{-1}$. Inserting this value and $P_b^{\text{obs}} = -(2.423 \pm 0.001) \times 10^{-12}$ from Weisberg & Huang (2016) into Equation (1), we find that $P_b^{\text{intr}} = -(2.415 \pm 0.003) \times 10^{-12}$. If we normalize this corrected “intrinsic” quantity by the expected GR-calculated value of $P_b^{\text{GR}} = -(2.40263 \pm 0.00005) \times 10^{-12}$ (Weisberg & Huang 2016), we find

$$\frac{P_b^{\text{intr}}}{P_b^{\text{GR}}} = 1.005^{+0.001}_{-0.001}.$$ 

In contrast, Weisberg & Huang (2016) determined a value of 0.9983 $\pm 0.0016$. They calculated the galactic correction of Equation (1) using a pulsar distance estimate from Weisberg et al. (2008), as described in the next section.

4.3. Comparison of PSR B1913+16 Distance Estimates

At the time of the Weisberg & Huang (2016) $P_b^{\text{gal}}$ analysis, the best estimate of the pulsar distance was given by Weisberg et al. (2008). In the absence of a direct distance measurement, these authors used measurements of the distance and mean electron density toward pulsars whose lines of sight were near to PSR B1913+16’s so as to determine the distance based on its DM. This procedure is akin to that undertaken with global galactic electron density models (e.g., Cordes & Lazio 2002, which predicts a distance of 5.9 kpc), except that it used newer data and was performed over a more limited region. Weisberg et al. (2008) found $d = 10.0 \pm 3.2$ (8.5 kpc) kpc. Taking $R_0 = 8.34 \pm 0.16$ kpc (Reid et al. 2014) gives $d = 9.8 \pm 3.1$ kpc, which was the estimate used for the galactic correction $P_b^{\text{gal}}$ in Weisberg & Huang (2016). Meanwhile, the newer “YMW16” galactic electron density model (Yao et al. 2017) yields a DM distance of $d_{\text{YMW}} = 5.25$ kpc and estimates that the predicted distance $d_{\text{YMW}}$ will fall in the range $0.55 < d_{\text{YMW}} < 1.45$ kpc in 68% of cases.

While more precise than the Weisberg et al. (2008) and Weisberg & Huang (2016) distance estimates, the VLBI distance presented here is in mild tension with the value of $d = 7.2$ kpc that is obtained by imposing the constraint $P_b^{\text{obs}} = P_b^{\text{gal}} + P_b^{\text{GR}}$ and solving for $d$. The most probable VLBI distance differs from this value of 7.2 kpc by 1.6$\sigma$. However, as shown in Figure 4, the distance probability distribution is quite asymmetric, with the VLBI distance more likely to be underestimated than overestimated.

An improvement to the tests of GR with PSR B1913+16 would require improving our astrometric accuracy by a factor of 3, reducing the parallax uncertainty to $<$20 $\mu$as. Simulations suggest that if our systematic error budget remained unchanged, then a further 15–20 astrometric epochs would be required to approach this level of parallax. However, new techniques such as the use of multiple primary calibrators (“MultiView;” Rioja et al. 2017) offer the potential to better model and remove the ionospheric contamination, reducing these systematics. Moreover, the bulk of our observations took place close to solar maximum, when ionospheric activity (the
Recently, Deller et al. (2016) showed that the uncertainties of proper motion estimates derived by timing for a number of millisecond pulsars were substantially underestimated. The pulsars with the largest errors in timing proper motion were preferentially located at low ecliptic latitudes, where timing observations have reduced sensitivity to position changes in ecliptic latitude, and furthermore the effect of the solar wind on DM variations is greatest. PSR B1913+16, however, is located at an ecliptic latitude of 38°, where these effects should be small or negligible.

Using a longer timing data set, Arzoumanian et al. (2018) found good agreement between VLBI and timing proper motions for two millisecond pulsars, including one of the discrepant cases identified by Deller et al. (2016). They suggest that the previous disagreement was due to underestimation of the effect of bias due to timing noise in those data. Here we explore the possibility of noise bias in the timing proper motion of PSR B1913+16.

The B1913+16 timing observations of Weisberg & Huang (2016) consist of two types of observing sets: (1) many short-term campaigns in which all pulsar orbital phases were observed over a short period of time, typically separated by one or more years, and (2) two campaigns of observations spread over a year or more, one in 1985–1988 and one in 2004. In these latter two campaigns, removal of the annual variation of time-of-flight delays across the Earth’s orbit depends very sensitively on the position of the pulsar; in effect, then, they yield pulsar position measurements in 1985–1988 and again in 2004; the combination of these two sets of position measurements yields the proper motion. (In practice, the timing proper motion was actually measured while simultaneous fitting for many other pulsar timing parameters; nevertheless, this division of the data set into campaigns is a useful paradigm for analyzing the proper motion measurement.)

A plausible explanation for the discrepancy between the VLBI and timing proper motion is that the timing in these around-the-year observations was influenced by noise in the observational time series on the ~1 year timescale needed to make timing position measurements. We compared the original Weisberg & Huang (2016) timing solution with a timing solution in which the proper motion is fixed at the VLBI value, and we found differences in timing residuals with approximately annual time delays, whose amplitude was ~15 μs over the course of these campaigns. The resulting fit was marginally worse, with a reduced χ^2 = 1.11 for 9227 degrees of freedom, versus reduced χ^2 = 1.00 for 9225 degrees of freedom, and most fitted parameters shifted by (1–2)σ between the two fits. Next, we explore two possible sources that could introduce noise into the timing data at this level.

One possible source of such noise is pulsar rotation irregularities (commonly called “timing noise”). In fact, Weisberg & Huang (2016) observed significant timing noise in PSR B1913+16, which they modeled as 10 higher-order spin frequency derivatives. Their data set was approximately 32 years long, so this effectively smoothed the data on timescales of roughly 32/10 = 3.2 years and longer. However, timing noise on a ~1 year timescale, if present, would have remained in the data. Thus, this cannot be ruled out as a source of noise in the B1913+16 data set and the biased proper motion measurement.

A second possible source of such noise is variations in the DM of the pulsar due to the motion of the Earth–pulsar line of
sight through the interstellar medium. DM variations are a common feature of high-precision pulsar data sets. Mimicking the \( \sim 15 \mu \text{s} \) timing residual at a typical observing frequency of 1400 MHz would require DM variations of \( \Delta \text{DM} = 0.007 \text{ pc cm}^{-3} \) on a timescale of 1 year. Prior to 2003, the timing of B1913+16 was done at a single observing frequency, so timing variations due to DM variations cannot be distinguished from timing noise intrinsic to the pulsar rotation. After 2003, observations were made over a range of radio frequencies from 1170 to 1570 MHz, potentially allowing epoch-by-epoch measurement of DM. We searched for DM variations in the 2004 data, but the results were inconclusive at the level of interest, largely because the measurement uncertainty at any given epoch was around 0.003 \( \text{pc cm}^{-3} \), not much smaller than the DM variations needed to bias the observed proper motion.

To further consider the plausibility of DM variations of the order 0.007 \( \text{pc cm}^{-3} \), we sought out pulsar data sets for pulsars with DM similar to PSR B1913+16. A relatively close match is PSR J1747−4036; it has a DM of 152.96 \( \text{pc cm}^{-3} \), comparable to the DM of 168.35 \( \text{pc cm}^{-3} \) for PSR B1913+16, and a proper motion of \( \sim 2 \text{ mas yr}^{-1} \), only about twice that of PSR B1913+16. A measured DM time series for PSR J1747−4036 is given in Figure 28 of Arzoumanian et al. (2018); it shows variations of around 0.006 \( \text{pc cm}^{-3} \) on timescales of several years. This is only moderately smaller than that needed to explain the PSR B1913+16 proper motion bias, and it adds credibility to the thesis that DM variations may play at least a partial role in explaining the PSR B1913+16 proper motion timing bias.

However, the VLBI proper motion is also subject to potential systematic influences that could lead to an underestimated error. The chief concern is evolution in the structure of the calibrator source J191621.8+161853. Radio active galactic nuclei (AGNs) can possess jets that evolve on the timescales of years, leading to a shift in the source centroid position. Since we by necessity use a static model for the calibrator source structure, any changes will manifest as a shift in the relative position of our target, PSR B1913+16. However, very few radio AGNs exhibit apparent centroid motion at a level greater than our proper motion uncertainty. Moór et al. (2011) studied a sample of objects comparable to our calibrator source and found that 80\% exhibit apparent motion of less than 20 \( \mu \text{as yr}^{-1} \). Just 1 source out of 61 had an apparent motion \( >0.1 \text{ mas yr}^{-1} \), the level necessary to match or exceed our nominal VLBI proper motion uncertainty.

A continued VLBI campaign over several years would reduce the VLBI proper motion uncertainty to below that of the timing value, which would aid in pinpointing the cause of the discrepancy.

4.5. Space Velocity of PSR B1913+16

The total proper motion of the pulsar, \( \mu = 0.77 \text{ mas yr}^{-1} \), combined with its distance of \( d = 4.1^{+0.0}_{-0.7} \text{ kpc} \), implies a transverse speed of \( v = 15^{+2}_{-3} \text{ km s}^{-1} \) in the solar system barycentric (SSB) frame. This is a remarkably low speed. Because PSR B1913+16 is several kiloparsecs from the Sun, the motion of the standard of rest at the pulsar’s position in the galaxy differs significantly from that of the local standard of rest. This difference alone could result in apparent transverse motion. Accounting for both this difference (using the galactic structure model of Reid et al. 2014) and for the solar motion relative to the Sun’s local standard of rest (Schönrich et al. 2010), a star at rest relative to the standard of rest at the position of the pulsar would have an observed SSB transverse speed \( v = 110^{+30}_{-39} \text{ km s}^{-1} \). The observed transverse speed of the pulsar is much smaller than this, which can only be explained by fortuitous cancellation of the motion of its standard of rest relative to the SSB and the motion of the pulsar relative to its own standard of rest. Thus, the motion of the pulsar relative to its standard of rest is likely on the order of 100 \( \text{km s}^{-1} \). The exact direction depends on its unknown line-of-sight velocity, but is likely dominated by motion radially away from the galactic center. Weisberg et al. (2010) reached a similar conclusion; they used different proper motion and distance estimates, but also found the observed pulsar velocity from galactic rotation to be smaller than expected.

Because the pulsar is very close to the galactic plane (galactic latitude \( b = 2^{+1}_{-2} \)), it is possible to robustly measure its velocity perpendicular to the galactic disk, as it is nearly independent of the line-of-sight velocity and is not biased by galactic rotation. After accounting for solar motion, we find the pulsar velocity perpendicular to the galactic plane to be \( v_{z} = 22^{+3}_{-3} \text{ km s}^{-1} \). Because the pulsar was discovered in a survey at low galactic latitudes (Hulse & Taylor 1975), this low value of \( v_{z} \) may be an observational selection effect.

The formation and evolution of double neutron star (DNS) binaries is of interest for interpreting Laser Interferometer Gravitational-Wave Observatory (LIGO) sources such as GW170817 (Abbott et al. 2017). Tauris et al. (2017) undertook a comprehensive Monte Carlo analysis of this subject based on all available observational data on (DNS) binaries (pre-GW170817). They found that most DNSs received small birth kicks, but a small number of systems, including PSR B1913+16, must have received larger kicks (see also, e.g., Wong et al. 2010; Beniamini & Piran 2016). For B1913+16, they found that the supernova explosion forming the second neutron star in the system must have been accompanied by a particularly large kick. They calculated that the kick velocity was in the range \( 185-465 \text{ km s}^{-1} \) if the system was at a distance of \( 9.8 \text{ kpc} \) (Weisberg et al. 2010), or some \( 50-100 \text{ km s}^{-1} \) smaller if \( d = 5.25 \text{ kpc} \) (Yao et al. 2017). Our own distance measurement is consistent with Yao et al. (2017) and thus favors the latter, still large, kick-velocity estimate. A fuller analysis of the three-dimensional motion of PSR B1913+16 is beyond the scope of the present paper.

5. Conclusions

We have conducted the first astrometric measurements of PSR B1913+16 using VLBI, with the intention of measuring its parallax and proper motion. Our principal motivations were to make robust determinations of these quantities and to improve the precision of the orbital acceleration contribution to the observed orbital decay of binary pulsar B1913+16. When estimating the pulsar distance, we have extended the approach taken in previous works to incorporate not only prior information on the millisecond pulsar spatial and luminosity distributions, but also the asymmetric parallax probability distribution obtained from our VLBI astrometric fit.

Our measured distance differs from the best-fit DM-derived value (Weisberg et al. 2008) by \( \sim 3 \sigma \), while our measured proper motion differs from the previous best timing-derived value (Weisberg & Huang 2016) by \( >4 \sigma \). These new measurements provide a galactic acceleration-induced correction to the measured
orbital decay, leading to a test of general relativistic gravitational radiation damping that is of similar precision and lower accuracy than previous results, with a formal discrepancy from GR of 1.6σ.

Our measured distance and proper motion confirm earlier suggestions that the second neutron star formed in this binary system suffered an unusually large birth kick.

We plan to conduct additional timing and interferometric measurements. In this fashion, we will improve our experimental precision and further quantify both our random and systematic errors, a process that should resolve the somewhat discrepant results of the two techniques and probably the implied discrepancy with GR. We note that most other binary pulsar orbital decay measurements are consistent with GR (Weisberg & Huang 2016).

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**ORCID iDs**

A. T. Deller @ https://orcid.org/0000-0001-9434-3837

J. M. Weisberg @ https://orcid.org/0000-0001-9096-6543

S. Chatterjee @ https://orcid.org/0000-0002-2878-1502

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