PULSAR ASTROMETRY +

Joseph H. Taylor, Carl R. Gwinn,
Joel M. Weisberg and Lloyd A. Rawley
Joseph Henry Laboratories and Physics Department
Princeton University
Princeton, N. J. 08544 U.S.A.

High precision measurements of the celestial coordinates of pulsars are desirable for a number of reasons. If carried out at several epochs, the measurements can yield angular proper motions; together with distance estimates based on dispersion measure, the proper motion of a pulsar reveals two of three components of its space velocity, and consequently provides important kinematic information on pulsar ages (see, for example, Manchester, Taylor and Van 1974; Lyne, Anderson and Salter 1982; and references therein). Direct measurements of annual parallaxes are also possible in principle, and are marginally feasible with present techniques for a few of the closest pulsars. Model independent distances obtained from parallax measurements, together with observed pulsar dispersion measures, yield the electron density along the line of sight to the pulsar. Knowledge of the interstellar electron density in the solar neighborhood provides a calibration of the dispersion-based distance scale that is complementary to the calibration derived from neutral hydrogen absorption measurements of more distant pulsars (Weisberg et al. 1980), and permits appropriate statistical analyses to be made of the local space density of pulsars and their birthrate (e.g. Taylor and Manchester 1977). Finally, pulsar astrometry can be expected to yield important information on the relative orientations of fundamental reference frames. In particular, pulse timing observations yield positions in a reference frame based on motions of the planets, while interferometric position measurements are based on an Earth-equatorial system. At present the relative orientation of these two coordinate systems is known to only $\sim 0\rlap{.}''2$ accuracy, though the potential precision of both types of measurements is much higher.

Pulse arrival times can be measured with typical accuracies of $0.1 \lesssim \Delta t \lesssim 1$ ms. Therefore, if a series of timing observations extending over a year or more are available, a pulsar's position can be estimated with an accuracy of approximately $c\ \Delta t/(1\ \mathrm{AU})$, or typically a few tenths of an arc second or better. When data spanning several years are available, proper motions can also be measured in this way (Gullahorn and Rankin 1978a,b; Helfand et al. 1980; Downs and Reichley 1983). Some pulsars have intrinsic timing irregularities which

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accumulate to several milliseconds or more after a few years; these irregularities are unpredictable, and produce systematic errors that limit the astrometric accuracies attainable. In the best cases, however, the pulsar clock remains "perfect" (within measurement errors) even after several years; for these pulsars, position accuracies of < 0".1 and proper motions of a few milli-arc seconds per year are achievable (Downs and Reichley 1983).

Pulsar astrometry by connected-element interferometric techniques has been done most notably by Backer and Sramek (1981, 1982) and by Lyne, Anderson and Salter (1982). Backer and Sramek measured the positions of five pulsars to accuracies of 0".2 (absolute) or 0".03 (relative to nearby comparison sources), and the proper motions of the same pulsars to accuracies of 3 to 40 mas/yr. In addition, they placed an upper limit of 0".004 on the annual parallax of one object, PSR 1929+10. The more extensive project of Lyne et al. used a phase referencing technique, with calibration sources within the same beam area. They measured the proper motions of 26 pulsars, with accuracies of 1 to 20 mas/yr, and the annual parallaxes of nine sources, with uncertainties of 2 to 9 mas. Only one of the parallaxes was significantly nonzero, however; for PSR 1929+10, they obtain a parallax of 0".022 ± 0".008, considerably larger than the upper limit of Backer and Sramek. Thus, the unsatisfactory situation regarding pulsar parallax measurements is summarized in Table 1:

Table 1. Parallax Estimates for PSR 1929+10

Annual Parallax of PSR 1929+10	Reference
0".022 ± 0.008	Lyne et al., 1982
≤ 0.004	Backer and Sramek, 1982
0.011	Expected value, from dispersion measure

It is clear that VLBI techniques should be capable of better results than those already discussed. The greatest practical difficulty in doing pulsar astrometry by VLBI involves the compromise that must be made in choice of observing frequency: the pulsars are relatively weak sources with steep spectra, suggesting a low observing frequency; however, at frequencies below ∿ 1 GHz, ionospheric irregularities pose severe problems. Thus, when we embarked about two years ago on a program designed to measure the parallaxes of several nearby pulsars, we chose to observe at 1.6 GHz and to use the large collecting area of the Arecibo telescope.

The other stations involved are Green Bank and Owens Valley. We use standard Mark II recording techniques, except that pulsar pulse phase information is encoded on the tapes recorded at Arecibo. This information is used to inhibit correlation during the off-pulse periods, thereby increasing the signal-to-noise ratio by the inverse square root of the pulsar duty cycle -- a factor of three to five. Each pulsar is observed alternately with a comparison source, with cycle times of 4-7 minutes, for as long as the sources are in Arecibo's tracking range, or about 90 minutes. As shown in Table 2, we are observing six pulsar-quasar pairs, in addition to three quasar-quasar pairs, for calibration purposes.

Table 2. Source List

Source	Reference Source	Angular Separation (degrees)
PSR 0823+26	0822+272	0.5
PSR 0950+08	0938+119	4.8
PSR 1133+16	1119+184	4.0
PSR 1237+25	1222+217	4.9
PSR 1919+21	1923+210	1.3
PSR 1929+10	1947+079	5.4
1421+122	1427+109	2.1
1548+115	1551+130	1.8
1756+237	1751+288	5.2

After cross-correlating the recorded data, we slow the fringe rates as much as possible by using the best available values of station coordinates, source coordinates, polar motion, and UT1-UTC. We also remove the Arecibo clock drift, calculated from the change in delay on one source observed at the same sidereal time on two consecutive days. Finally, we remove an ionospheric path length, calculated from satellite Faraday rotation data, and a simple troposheric model (Reid 1983).

The Faraday rotation data are obtained from the World Data Center in Boulder, Colorado. Data are available from earth satellite receiving stations in Boulder, Sagamore Hill (Massachusetts), and Ramey (Puerto Rico), presented as hourly values of integrated electron content at the zenith over a geographic point near the receiver (for details see Klobuschar 1975). The Ramey location is very close to Arecibo, so these data were used directly; for Green Bank and Owens Valley we used the Sagamore Hill and Boulder data, respectively, retarded by 1/2 hour to account for the effective longitude differences. We interpolated the hourly measurements, and applied geometric factors appropriate for a spherical ionosphere at a height of 400 km. We believe that this procedure usually gives the ionospheric phase delays to within a few turns in the daytime, and < 1 turn at night. Thus, the differential ionospheric phase delays between members of a source pair, caused by large-scale ionospheric structure, should be known to $\lesssim$ 0.1 turns. None of our observations were taken during times of severe ionospheric disturbance, and on most days we see little evidence of localized, short term ionospheric fluctuations.

After the ionospheric corrections have been applied, the residual fringe rates are typically less than 3 mHz. Fluctuations of the

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residual phase about a straight line vary from 0.1 to 1 turn over 1.5 hours, and are dominated by the behavior of the Rubidium clock at Arecibo and by the unmodeled part of ionospheric activity. We fit the residual fringe rates to a first or second order polynomial. The polynomial is then integrated and used to rotate the phases by the appropriate integral number of turns, for phase connection.

We then fit a simple model to the fringe phases. The model includes the position offset of the source, relative to the calibrator; a polynomial, typically of degree five, which models the Arecibo clock and residual ionosphere; a polynomial of order two or three which absorbs variations due to the Owens Valley ionosphere and calibrator position offsets; and clock offsets for two of the three stations. The position offset is sensitive to the difference of the fringe phases; all other parameters are sensitive to their sum. Thus, the position offset is only weakly covariant with the other parameters, and the details of the rest of the fitted model are largely unimportant. In most of our data, it is easy to detect deliberately (or accidentally) misconnected fringes by inspecting the post-fit residuals.

The short tracking time available at Arecibo limits our u-v plane coverage so much that several positions may have approximately equal values of chi-squared after the fit. Such points are separated by integral numbers of turns of phase on the Arecibo-Green Bank and Arecibo-Owens Valley baselines. Therefore, we have assumed that the pulsars' proper motions are described approximately by the results of Lyne, Anderson, and Salter (1982) and that the quasars move by much less than a fringe between sessions. Using these assumptions, we translate the measured position offsets to the appropriate fringe.

In Fig. 1 we show our results for the quasar pair 1421+122 and 1427+109 on four different dates. A formal solution for the relative proper motion of 1421+122 over this seven month span yields $\mu_\alpha = 3 \pm 5$ mas/yr, $\mu_\delta = -3 \pm 6$ mas/yr. Thus, our results are fully consistent with zero relative motion between the sources, as expected.

For the pulsar-quasar pair PSR 0950+08 and 0938+119, we have obtained usable data on seven dates spanning ten months. By resolving fringe ambiguities so as to be most nearly consistent with the proper motion given by Lyne, Anderson and Salter (1982), and then fitting our data for proper motion and parallax, we obtain the results shown in Figure 2 and in the top line of Table 3. We also tried shifting all of the measured positions by up to 2 fringes in each direction of ambiguity, and found only one other solution even marginally consistent with the Jodrell Bank data and a reasonable value of parallax. This alternative solution is listed below our preferred solution in Table 3, followed by the Jodrell Bank results for proper motion.

The error bars plotted in Figs. 1 and 2 are considerably larger than the formal standard errors from the fits for position offset, and represent our best estimates of the systematic errors in the model

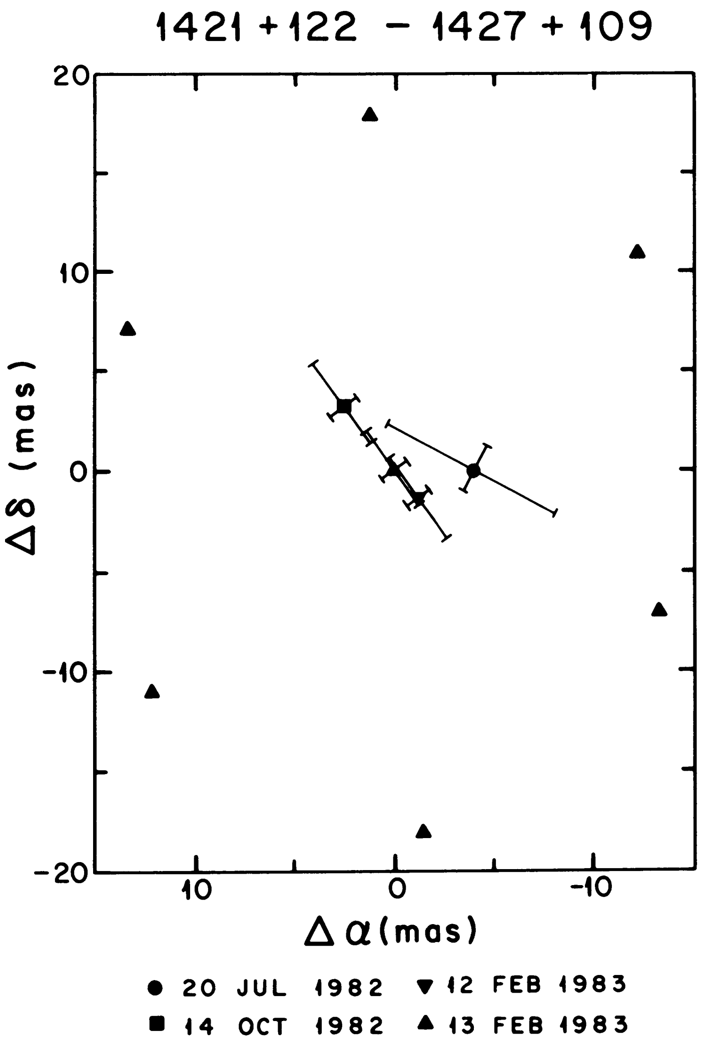

Fig. 1. Measured position of the radio source 1421+122, relative to that of 1427+109, on four different dates. The black triangles show the closest six lobe-shifted positions corresponding to the 13 February point. The much larger error bars for the 20 July measurement are the result of having no ionospheric data from Boulder on that day.

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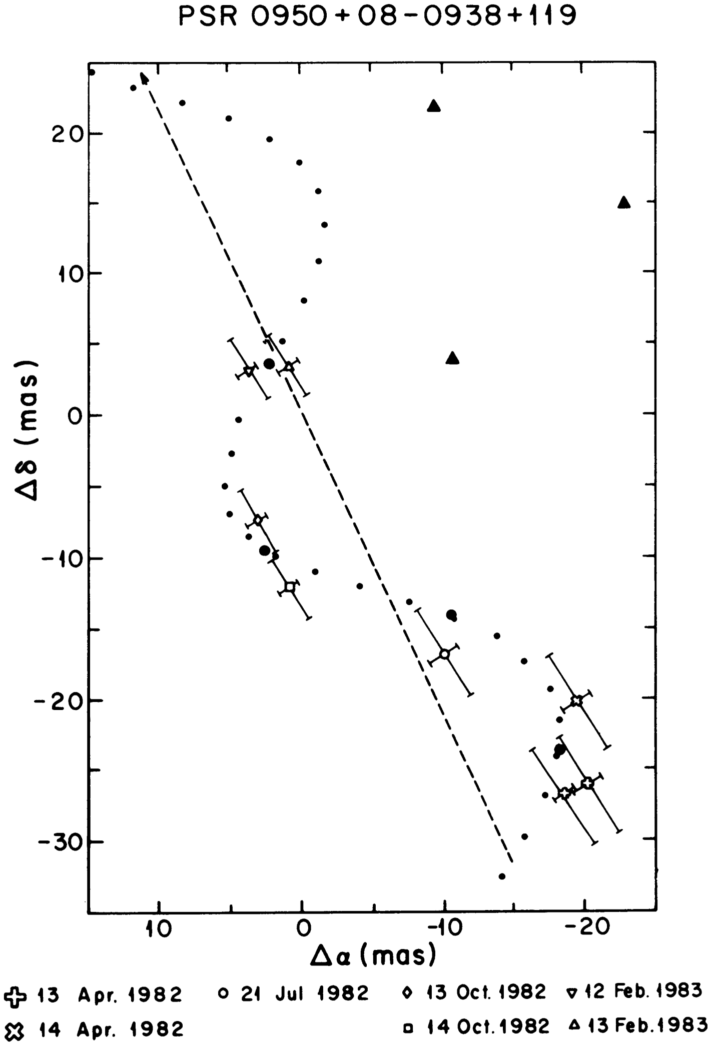

Fig. 2. The positions of PSR 0950+08, relative to 0938+109, on seven dates. Small block dots illustrate the path of the pulsar, according to our best-fitting solution for proper motion and parallax; large black circles give the expected position at the times of our four sessions. The dashed line gives the proper motion alone, and is in good agreement with that measured by Lyne, Anderson, and Salter (1982).

Table 3. Astrometric Data for PSR 0950+08

	$\mu_\alpha \cos\delta$ (0".001/yr)	μ_δ (0".001/yr)	π (0".001)
Preferred solution	17 ± 4	35 ± 5	7.5 ± 0.8
Alternative solution	27 ± 4	26 ± 5	14.6 ± 0.8
Lyne et al. (1982)	15 ± 8	31 ± 5	---

ionosphere, UT1-UTC, and polar motion. Further observations should help to ascertain whether these estimates are always realistic.

We provisionally conclude, at the time of this progress report on an ongoing project, that the distance to PSR 0950+08 is 130 ± 15 pc. Since the dispersion measure is 2.969 cm^{-3} pc, the average density of free electrons along the line of sight must be $\langle n_e \rangle = 0.022 \pm 0.003$. This value is in good agreement with the electron densities determined along the lines of sight to more distant pulsars through HI absorption measurements (Weisberg et al. 1980).

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