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Astrometric VLBI Observation of PSR 0329+54

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Abstract

We conducted VLBI experiments on the pulsar PSR 0329+54 with the Kashima (Japan)–Kalyazin (Russia) baseline in 1995 March and 1996 May. An absolute astrometric measurement was applied by using the analysis software SOLVE and CALC, which were developed by NASA/GSFC for geodesy and astrometry. Our measurement results are consistent with the former results of a VLBI observation by Bartel et al. (1985, AAA 39.041.005) and a VLA observation by Fomalont et al. (1984, AAA 38.041.014) when proper motion (Harrison et al. 1993, AAA 57.126.049) is taken into account. By using our data set and Bartel et al.'s data, the most precise proper motion and pulsar position in ICRF were obtained. The proper motion as μ_α : 17.3 ± 0.8 mas yr^{-1}, μ_δ : -11.5 ± 0.6 mas yr^{-1} and the coordinates at the epoch of 1995.0 are $\alpha : 03^{\mathrm{h}}32^{\mathrm{m}}59\overset{\mathrm{s}}{.}376 \pm 0.001$, and $\delta : 54°34'43\overset{''}{.}504 \pm 0.007$.

Key words: astrometry — pulsars: individual (PSR 0329+54) — proper motion — techniques: interferometric — VLBI

1. Introduction

VLBI is the most precise method for measuring radio-source astrometric parameters. VLBI observations of pulsars determine precise coordinates of pulsars in ICRF (International Celestial Reference Frame), which is defined by VLBI observations of extragalactic objects (Ma et al. 1998). On the other hand, a pulsar timing observation determines a pulsar's coordinates in a dynamical reference frame, which is based on the planetary orbit and is used in ephemeris (e.g., DE200, and DE403). Especially for millisecond pulsars, their timing position accuracy has been 30–50 μas. (e.g., Cognard et al. 1995). Thus, a pulsar is a very important object for a frame tie between the quasar reference frame and a dynamical reference frame (e.g., Dewey et al. 1996; Bartel et al. 1996).

Except for the frame tie, astrometric parameters are also important for investigating pulsars. Proper-motion measurements of pulsars will help us to understand the association between pulsars and their progenitors—Super Nova Remnants. Nice and Taylor (1995) have reported that an error on the proper motion affects the derived value of the intrinsic pulsar spin-down rate $\dot{P}_{\mathrm{int}}$, and that it might cause an incorrect estimation of the characteristic age of a pulsar. Thus, a pulsar timing observation requires independent measurements of the astrometric parameters.

The Communications Research Laboratory (CRL) in Japan and the Lebedev Physical Institute (LPI) in Russia started joint VLBI observations of pulsars since 1995. Our purposes are two-fold. One is to obtain astrometric parameters of pulsars by using the interferometric method. The other is to contribute to the frame tie between the extragalactic reference frame measured in VLBI and the dynamical reference frame of ephemeris, which is used in pulsar timing analysis. For the first target of our experiment, the brightest northern radio pulsar PSR 0329+54 was observed with VLBI and the absolute astrometric technique.

2. Observation

We used the Kalyazin 64-m diameter radio telescope (TNA-1500 of the Special Research Bureau of Moscow Power Engineering Institute in Russia) and the Kashima 34-m radio telescope (CRL). The baseline length is about

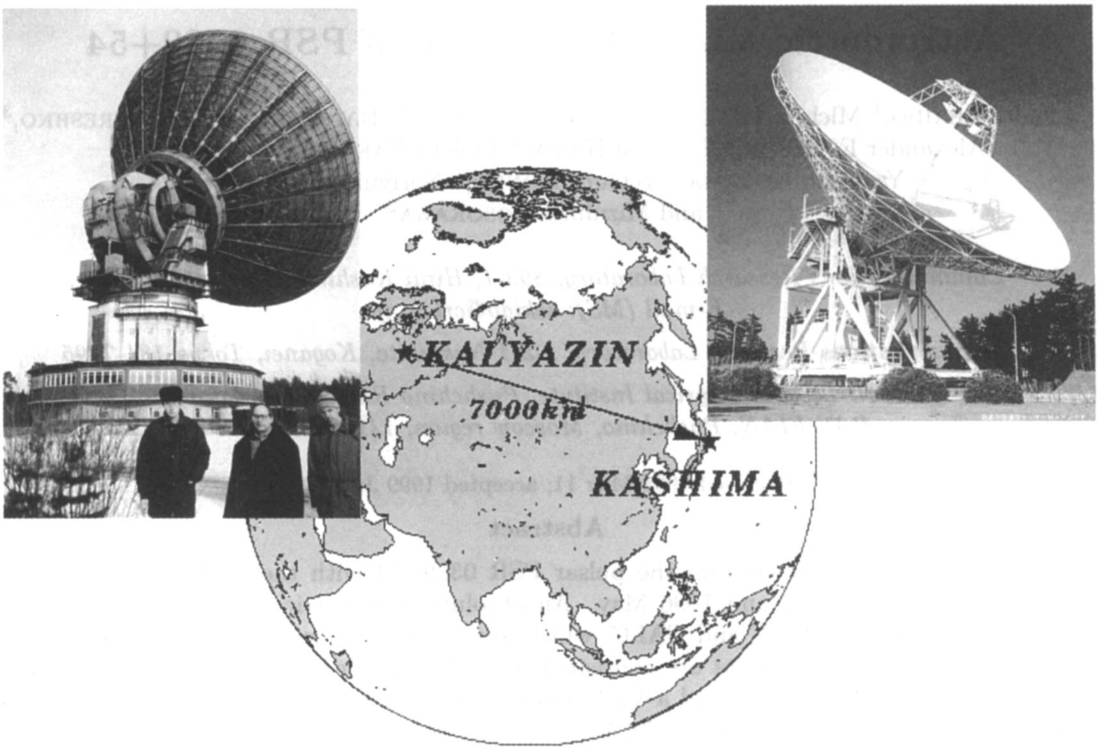

Fig. 1. Baseline of the Japan–Russia pulsar VLBI experiment. The Kashima 34-m diameter antenna of the CRL (upper right) and the Kalyazin 64-m diameter antenna of Moscow Power Engineering Institute (upper left) were used.

7000 km (see figure 1). The first VLBI experiment took place on 1995 March 14 and the second on 1996 May 12. Generally, because pulsars have a large negative spectral index (typically −2 to −3) their flux density decreases rapidly as the frequency increases. A lower frequency observation is good at a higher signal-to-noise ratio, but variation in the radio-wave propagation delay due to the ionosphere is more severe at lower frequency. Because the magnitude of the variations is inversely proportional to the square of the radio frequency, a higher frequency observation is superior from the viewpoints of smaller ionospheric disturbances and higher angular resolution. The frequency band of 1.4 GHz (*L*-band) was used as the observation frequency to compromise between these two restrictions. PSR 0329+54 was chosen as the first target of our pulsar astrometry project, since it is the brightest radio pulsar in the northern hemisphere and its high declination is good for wide UV coverage with our East–West long baseline.

2.1. *The 1995 March Experiment*

The first VLBI experiment was carried out on 1995 March 14. The observation frequency range was 1395–1425 MHz. Seven channels of 2 MHz bandwidth Upper Side Band (USB) signal with a 5 MHz frequency interval and the same number of Lower Side Band (LSB) signals were sampled in one-bit quantisation and recorded with the K4 VLBI system (Kiuchi et al. 1997). However, only the upper sideband was correlated due to correlator trouble. Extragalactic radio sources 0300+470, 0316+413 (3C 84), and 0355+508 (NRAO 150), which were chosen from the IERS catalogue (ICRF92), were used as reference sources. Also they are alternatively observed with pulsar. Since the coordinates of sources in the IERS catalogue are well determined by intercontinental geodetic and astrometric VLBI observations, they are suitable for the calibrating atmospheric and clock parameters in VLBI data analysis. Additionally, we expected that an ionospheric delay calibration will be made with these sources, which is discussed in more detail in section 3. The angular distances from the pulsar were $8^\circ\!.6$, $13^\circ\!.2$, and $5^\circ\!.4$ for 0300+470, 3C 84, and NRAO 150, respectively. Two observation sessions were carried out, one between 4:40–8:40 and the other between 11:45–14:13 on 74 doy (day of year) in UT, and the total observation time was 6.5 hours. The observation cycle was 15 min for the pulsar, 2 min for antenna slewing, and 5 min for

Table 1. Reference sources of PSR 0329+54 in 1995 March and 1996 May experiments.

Source name	1995 March	1996 May	Angular distance (deg.)	ICRF remarks*
0133+476	···	○	19.2	D
0212+735	···	○	20.7	O
0300+470	○	○	8.6	O
3C 84	○	○	13.2	O
NRAO 140	···	○	22.3	O
NRAO 150	○	···	5.4	O
3C 119	···	○	16.3	—
3C 138	···	○	43.3	D

*Character indicating category of extragalactic source in ICRF catalogue. D indicates it is a defining source of the ICRF, O indicate that they failed to clear some criteria as a defining source, but they are still useful for frame tie or for the other astrometric purposes (Ma et al. 1998).

the reference sources.

2.2. *The 1996 May Experiment*

The experiment took place on 1996 May 12. The observation frequency range was 1392–1436 MHz, except for the 1418–1421 MHz range, since there was strong interference from commercial communication signals in this range. Fourteen channels of 2 MHz bandwidth USB signal with 3 MHz frequency interval were sampled and recorded with the K4 VLBI system.

The observation sessions were between 18–22 o'clock on 133 doy, 23 on 133 doy to 04 on 134 doy, and 05–11 on 134 doy in UT. The total observation time was about 15 hours. The reference sources were also primarily chosen from the IERS catalogue for the same reason as described in subsection 2.1. All reference sources are listed table 1. The pulsar and a few reference sources are observed alternatively, and the duration of the observation time was 5 min for PSR 0329+54 and 4 min for the reference sources.

3. Data Processing and Analysis

3.1. *Absolute Astrometry Analysis*

Correlation processing was performed by using the K3 correlator at the Kashima Space Research Center of CRL. Although the correlator has a gating function, it was not used for two reasons. One is that PSR 0329+54 is one of the most brightest pulsars in radio frequency and did not require the pulsar gating to achieve a good signal-to-noise ratio (SNR). The other is that the pulsar gating may introduce random pseudo-group delay noise in the bandwidth synthesis procedure (Sekido et al. 1998). The group delay and the phase delay rate were derived by using the bandwidth synthesis software "KOMB" (Takahashi et al. 1991), and the data were stored in the Mark-III database for astrometric analysis. The analysis was carried out with the software CALC (v. 8)/SOLVE (v. 5.25), which were developed by NASA/GSFC for geodetic and astrometric analysis. An absolute source-position estimation using the group delay and phase delay rate was employed in the analysis in the same way as in the geodetic VLBI measurement. The Earth orientation parameters were taken from the IERS bulletin B (Feissel et al. 1996), which has an accuracy of 0.3 mas.

Since the reference source's positions used in both experiments were determined very accurately (the accuracy was no more than 1 mas), they were useful for calibrating the interferometer parameters, such as the clock parameters and atmospheric parameters. In the VLBI data analysis, the clock offset and rate must be calibrated with reference sources because of incomplete time-synchronization information of the atomic clocks at both stations. The accuracy of the time differences of UTC and the local atomic clock measured by GPS at each station are typically within sub-micro seconds, where the delay measurement accuracy in VLBI is within a nanosecond or less. The clock offset, clock rate, and atmospheric delay were estimated in the analysis.

3.2. *Error Analysis and Results*

The station position of the Kashima 34-m antenna was measured very accurately in the International Terres-

Table 2. Coordinates of PSR 0329+54 from our experiments*

Epoch (year)	Right Ascension	Declination
1995.20	$03^{h}32^{m}59^{s}.3759 \pm 0.0022$	$54°34'43''.516 \pm 0.027$
1996.36	$59^{s}.3793 \pm 0.0025$	$43''.487 \pm 0.012$

*These are the weighted mean of solutions of different analysis conditions.

trial Reference Frame (ITRF) by intercontinental geodetic VLBI experiments. However, the position of the Kalyazin 64-m antenna was just measured with GPS for these experiments. The accuracy of the Kalyazin station position measured by GPS was a few cm in the WGS-84 coordinate system. This accuracy was sufficient for correlation processing, though it will potentially introduce errors in the pulsar coordinates measurements. To evaluate the influence of the baseline uncertainty in the analysis, we performed two cases of estimations, where the Kalyazin station coordinates were estimated in the analysis in one case and the coordinates were fixed in the other.

The ionospheric delay uncertainty is the most significant error source of this measurement. The magnitude of the ionospheric delay is inversely proportional to the square of the observation frequency. Therefore, the turbulence of the ionospheric delay in the 1.4 GHz band is larger than the usual 2/8 GHz geodetic VLBI observation. Additionally, an ionospheric delay measurement obtained by a dual-frequency observation, as in geodetic VLBI, could not be used in our single-band observation. To solve this problem, we used reference sources nearby the pulsar. The observed delays for the reference sources contain all of the radio propagation time differences between the two stations, such as the atmospheric delay and ionospheric delay. The geometrical delays for reference sources can be very accurately calculated if their coordinates are well known. The dry component of the atmospheric delay has also been well estimated with atmospheric pressure data at both observation stations. Other delay components and clock parameters were estimated by using the observed group delays for the reference sources. Those delay parameters of the propagation medium are expected to be almost the same for the pulsar and reference sources if the angular distances between them are small. To take advantage of this strategy, we chose reference sources from ICRF92 which are as close to the pulsar as possible. Consequently, it can be expected that atmospheric delay parameters will absorb a significant part of the ionospheric delay in the procedure of a least squares (LSQ) analysis with reference sources.

To evaluate the effect of the ionospheric correction error still remaining in our analysis, we at first used a radio-signal propagation characteristic in a plasma: that a plasma affects in the opposite sense for the group delay and the phase delay. Since the ionospheric propagation delay affects in an additive sense for the group delay, but in a subtractive sense for the phase delay rate, the effect can be seen by changing the analysis condition as follows. In one case, both the group delays and the phase delay rates are used as observable; in the other case, only group delays are used. Therefore, two cases for a station coordinate treatment and two cases for an observable gave totally 4 kinds of solutions of pulsar coordinates. Then, the pulsar coordinates were determined as a weighted mean of those four solutions for each epoch.

For a further conservative evaluation of the error in the pulsar position, we tested the accuracy of our analysis by estimating the coordinates of 0300+470 (hereafter "analysis test"). Because this source's position is determined within an error of 0.5 mas in the ICRF catalogue, the deviation of the solution from the catalogue coordinates should represent the magnitude of the error in our analysis. "Analysis tests" were performed in the four cases of analysis conditions as mentioned above. Finally, the one-sigma error of the pulsar coordinate was evaluated by the following formula: $\sigma = \sqrt{\sigma_{\rm formal}^2 + \sigma_{0300+470}^2}$, where $\sigma_{\rm formal}$ is the mean formal error of the pulsar coordinate from SOLVE, and $\sigma_{0300+470}$ is the weighted root-mean square of the deviations of 0300+470's coordinates from the those in the ICRF catalogue. The inverse of the formal error was used as a weight in the calculation. The determined pulsar coordinates at two epochs are given in table 2, and are plotted with 4 solutions under different analysis conditions in figure 2. The points marked with ○ and △ are the mean of solutions in 1995 March and 1996 May, respectively. In each epoch four solutions at the each two epochs obtained under different analysis conditions are indicated by × along with dashed error bars. The pulsar coordinates solutions are distributed a little wider than the formal error of each solution around the mean solution. The rather large error in the declination of the mean solution in the 1995 March experiment is due to a larger deviation of 0300+470 in the "analysis test". It is also because the observation time of the 1995 March experiment was shorter than that of the 1996 May experiment.

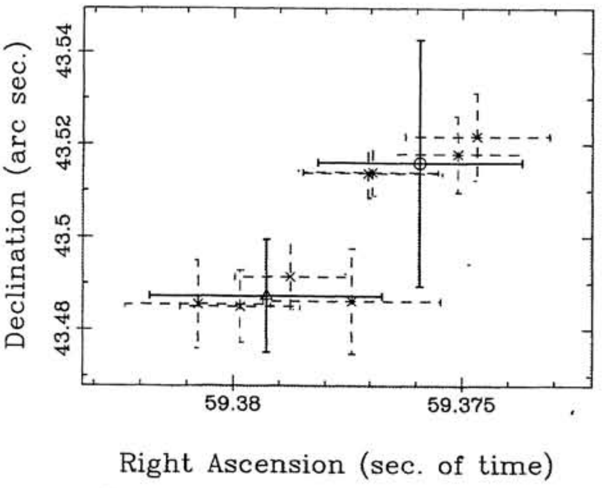

Fig. 2. Pulsar coordinates obtained by our experiments. Points marked with × at the upper right indicate solutions from the 1995 March experiment and those at the lower left are solutions from the 1996 May experiment. The error bar (dashed line) is the formal error from each solution. The open circle indicates the weighted mean of the solution in 1995 March and the open triangle is that in 1996 May. The solid error bar was calculated while taking into account the formal error and deviation solution in the "analysis test" (see text).

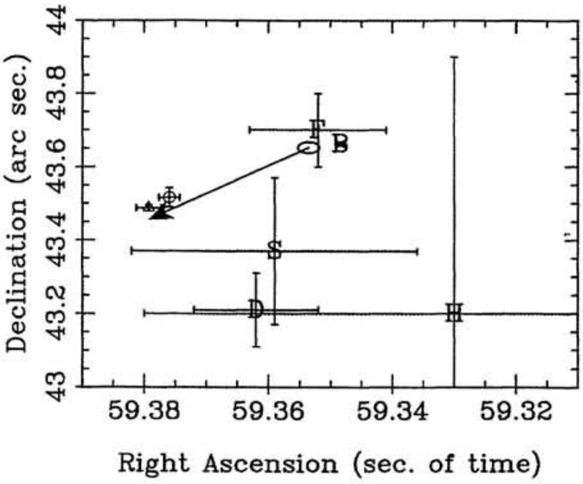

Fig. 3. Coordinates of PSR 0329+54 in J2000 system obtained by our measurements and by others. The open circle and the triangle are our measurement coordinates at 1995.20 and 1996.36, respectively. Other measurement points cited from a paper by Bartel et al. (1985) are marked by the character.'B': Bartel et al. (1985, VLBI), 'F': Fomalont et al. (1984, VLA), 'S': Backer and Sramek (1981, NRAO 35 km interferometer), 'D': Downs and Reichley (1983, timing), and 'H': Helfand et al. (1980, timing). These cited coordinates are at the epoch of 1981.21. The arrow and a ellipsoid at its origin indicate the proper motion and its one-sigma error during 15 years extrapolated from the value obtained by Harrison et al. (1993).

4. Discussion

4.1. Comparison with Other Measurement Results

Due to the advantage of the larger flux density of PSR 0329+54, timing observations for the pulsar have a long history; also coordinates measurements using the interferometric method have been performed several times. The pulsar coordinates of our results and other measurements are plotted in figure 3. All of the data, except for ours, are cited from a paper by Bartel et al. (1985); their epoch is 1981.21. All of the coordinates are expressed in the J2000 system. The arrow and the ellipsoid at its origin indicate the proper motion during 15 years and its one-sigma error measured by Harrison et al. (1993). The position of the arrow is shifted to avoid over-drawing. When the proper motion is taken into account, our measurement points are consistent with the VLBI measurement result obtained by Bartel et al. (1985) and a VLA measurement obtained by Fomalont et al. (1984). Other measurement results are despersed, but agree within their larger error bar.

4.2. Proper Motion Estimation

As for the absolute coordinate of PSR 0329+54, the measurement by Bartel et al. (1985) was the most accurate one by using the interferometric method; that by Fomalont et al. (1984) was the second most accurate. We derived the proper motion of the pulsar using our data and the result by Bartel et al. (1985) or that of Fomalont et al. (1984). Bartel et al. had measured pulsar coordinates with differential VLBI by using both the group delays and the phase delay rates as observable. The pulsar coordinates were determined with respect to the coordinates of NRAO 150. The coordinates of NRAO 150 which Bartel et al. had used differ from that of the ICRF by 0.14 ms of time in right ascension and minus 0.5 mas for declination. We corrected Bartel et al.'s pulsar coordinates by using these amounts to derive the proper motion. The coordinate difference between the ICRF and VLA which Fomalont et al. used is not so accurately known, and it may not affect to the derived proper motion because of the larger error level in his results. Therefore, a coordinated correction was not performed for Fomalont et al.'s pulsar coordinates.

A LSQ analysis was performed separately for right ascension and declination. In figure 4, the positions by Bartel et al. (1985), Fomalont et al. (1984), the 1995

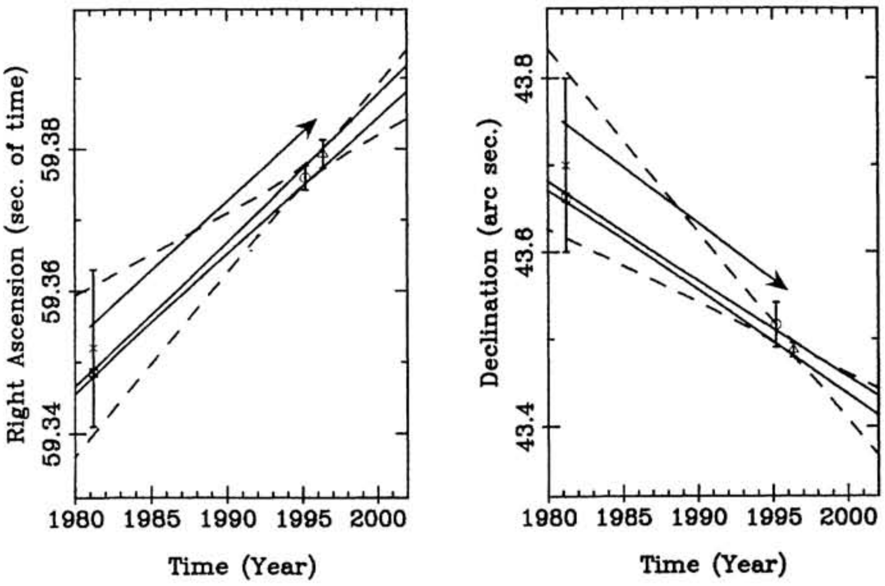

Fig. 4. Proper motion and pulsar coordinates. The combined analysis solutions by using 'Fomalont + ours' (dashed line) and 'Bartel + Ours' (solid line) are indicated, respectively. The area closed by two dashed lines indicate where the pulsar will exist with 68% (one sigma) probability estimated from 'Fomalont + Ours', and the area closed by the solid line is that from 'Bartel + Ours'. The open triangle and the open circle are our measurement positions and the × and the open box are that of Fomalont et al. (1984) and Bartel et al. (1985), respectively. The arrow indicates the proper motion for 15 years by using the data of Harrison et al. (1993).

Table 3. Derived pulsar coordinates and proper motion (epoch: 1995.0).

Data set	Right Ascension	Declination
'Fomalont + Ours'..................................	$03^h32^m59^s.376\pm 0.001$	$54°34'43''.51\pm 0.01$
'Bartel + Ours'....................................	$59^s.376\pm 0.001$	$43''.504\pm 0.007$
'Fomalont + Ours'..................................	16 ± 6 (mas yr^{-1})	-14 ± 6 (mas yr^{-1})
'Bartel + Ours'....................................	17.3 ± 0.8 (mas yr^{-1})	-11.4 ± 0.6 (mas yr^{-1})

March experiment, and the 1996 May experiment are plotted. Two pairs of hyperbolic lines indicate a 68% (one sigma) probability border line computed from a correlation matrix of the LSQ estimation. The dashed and solid lines correspond to the data set of 'Fomalont + Ours' and 'Bartel + Ours', respectively. It clearly shows that the two data sets are consistent and 'Bartel + Ours' is more accurate. The arrow in the figure indicates the proper motion obtained by Harrison et al. ($17 \pm 1, -13 \pm 1$ mas yr^{-1}) corresponding to 15 years. The derived proper motion and pulsar coordinates at the epoch of 1995.0 are summarised in table 3. The proper-motion parameters derived from the data set 'Bartel + Ours' are the most accurate ever achieved and are consistent with that of Harrison et al. within his two-sigmas error level. There seems to be a slight difference in the proper motion in declination. One of possible reasons is a difference in the reference frame that may still remain between ours and Bartel et al.'s.

5. Summary

The coordinates of PSR 0329+54 on ICRF were measured at two epochs by the Japan–Russia VLBI. Absolute astrometry was applied using the SOLVE/CALC geodetic and astrometric analysis software. The derived pulsar coordinates were consistent with the other results obtained by interferometric method and pulsar timing within their one-sigma error level. By using the 'Bartel+Ours' data set, the proper motion of

PSR 0329+54 was derived with the highest precision for this pulsar, and possible pulsar coordinates in ICRF are sketched in figure 4 with one-sigma probability lines by assuming a Gaussian probability distribution. The derived proper motion agrees with the result obtained by Harrison et al. within their two-sigmas level. One of the possible reasons for the slight difference in the proper motion in declination is a difference of the reference frame between ours and Bartel et al.'s.

Finally, the authors wish to emphasise the importance of an absolute astrometric observation in the same reference frame. Part of our achievement is due to the accurate absolute position measurement by Bartel et al. 15 years ago. An absolute coordinates measurement on a basic reference frame is not only useful for a frame tie, but also gives a chance to produce even more improved measurements of astrometric parameters by similar absolute astrometry with a large time interval.

Note added in proof (1999 August 27)

On the slight difference in the proper motion in declination (section 4), we could add another possible reason that is unevaluated small biased error of ionospheric delay. It will become clear by a further time series of atomospheric VLBI observations for this pulsar

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