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Pulsar VLBI Observations

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Abstract. Pulsar VLBI coordinates when combining with the timing coordinates based on the analysis of time of arrivals of pulsar pulses allows to link quasar and related with the planetary ephemeris dynamical reference frames. Pulsar parallaxes give distances to pulsars directly. Pulsar proper motions along with pulsar ages helps to determine the birth places of pulsars.

The main limiting factors for obtaining maximal accuracy of pulsar positions are 1) low signal to noise ratio (SNR) caused by pulsar weakness and short integration time, 2) fluctuations of electron density in the Earth ionosphere which affects propagation time of pulsar signal. It is possible to increase SNR extending the coherence time to a few hours using the phase-reference technique which excludes the bulk of the phase variations due to clock and atmosphere instabilities (Lestrade 1993). Another way to increase SNR in pulsar VLBI is to use pulsating property of pulsar signal (Sekido 1994). It is possible to correlate only when pulse is "on". This approach increases SNR $\propto \sqrt{P/w}$, where P - pulsar period, w - pulse width and requires prediction of pulsar phase and period (Rodin 1997).

This paper presents the results of processing Japan – Russia pulsar VLBI observations.

1. Observations

Russia - Japan observations have been commenced in March 1995. The main purpose is to determine pulsar coordinates in the International Celestial Reference Frame (ICRF). The 64 m radio telescope (RT-64) near Kalyazin (Russia) and 34 m radio telescope at Kashima (Japan) were used for the observations. Baseline length is about 7000 km. Japanese K4 data acquisition system from Communications Research Laboratory (CRL) was used on both stations.

All pulsar VLBI observations were processed with K4 correlator of CRL. This correlator has possibility to process pulsar data using gating function which improves signal to noise ratio by a few times thus more weak pulsars become detectable.

Absolute group delay method was used to measure pulsar coordinates. In this method integration time is limited by atomic clock stability so one can use relatively long integration time. This method allows to use well known standard software CALC-SOLVE developed at Goddard Space Flight Center (GSFC) NASA. Absolute pulsar positions are useful for link of celestial reference frames and identification of pulsars with objects at other wavelengths.

A total of 26 pulsars were observed in period 1995-1998 at 1.4 GHz (L-band) and 2.3 GHz (S-band). Fringes of 8 pulsars (B0329+54, B0355+54, B0809+74, B0950+08, B1929+10, B1933+16, B2020+28, B2021+51) were detected and positions of 5 pulsars were measured.

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2. Data processing

One of the limiting factors to achieve maximum possible positional accuracy is low signal to noise ratio. In the case of pulsars it is possible to increase SNR by correlating only part of the pulsar period when pulse is "on". To apply gate-function it is necessary to predict precisely apparent pulsar period and phase. For this purpose special software[1] have been developed.

Figure 2 shows improvement of correlation amplitude and SNR for pulsars PSR B0329+54 (upper) and PSR B1933+16 (lower)2001.

Another factor which makes worse measurement accuracy is fluctuations of the electron density in the Earth ionosphere. It was the main reason why S-band were used for pulsar VLBI. Since pulsars have steep spectra this way is convenient only for the most strong pulsars. Another method to take into account ionosphere influence have been applied (Sekido 2001). Total electron content (TEC) data based on the two frequency GPS signal measurements have been used for construction of Global Ionospheric Map (GIM) (Schaer 1998). GIM data were sufficient to remove $\sim 90\%$ of ionosphere contribution to group delay.

As a part of phase differential method which is under construction a differential group delay method were applied to pulsar VLBI experiments. Figure 3 displays differential delay "pulsar minus quasar" with fitted sine curves (upper panel) and post-fit residuals (lower panel). Fitted parameters were difference between pulsar and quasars coordinates and clock rate.

[1] ftp://alpha.prao.psn.ru/users/rodin/soft/calp.tar.Z

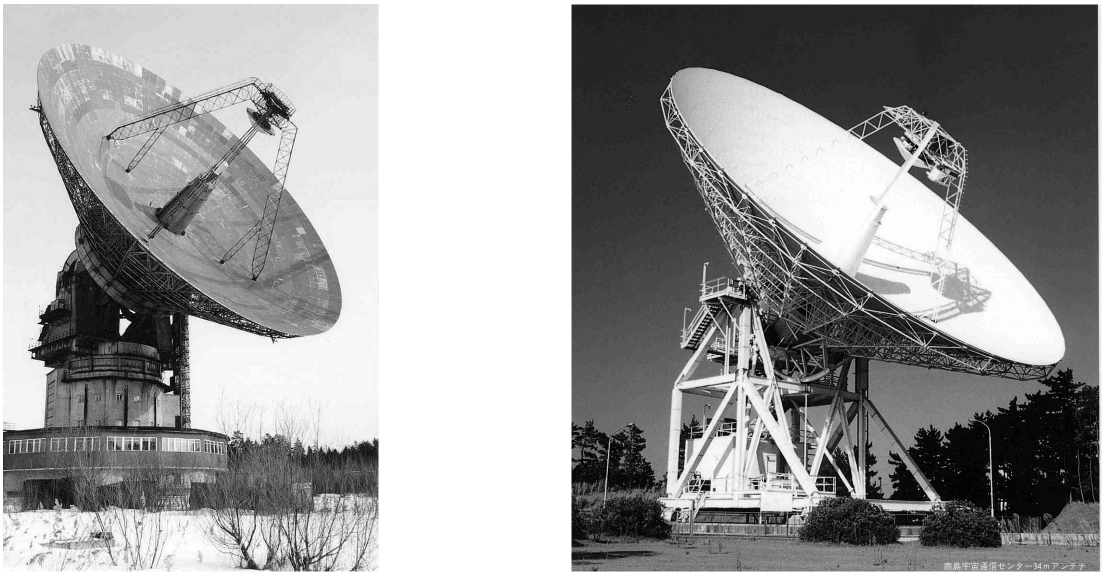

Fig. 1. Radio telescopes at Kalyazin, Russia (left) and Kashima, Japan (right) participating in pulsar VLBI observations.

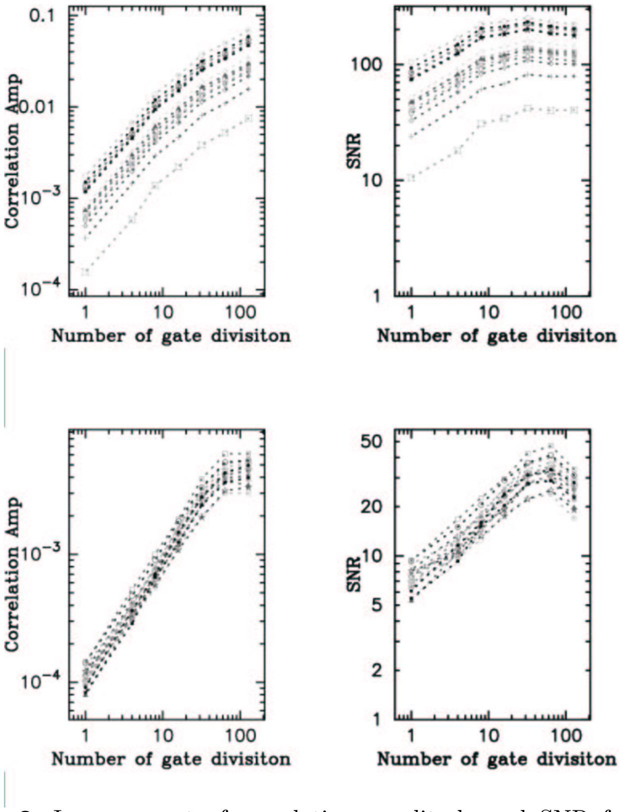

Fig. 2. Improvement of correlation amplitude and SNR for pulsars PSR B0329+54 (upper) and PSR B1933+16 (lower). Correlation amplitude is growing $\propto N$, SNR is growing $\propto \sqrt{N}$, where N is number of gate division.

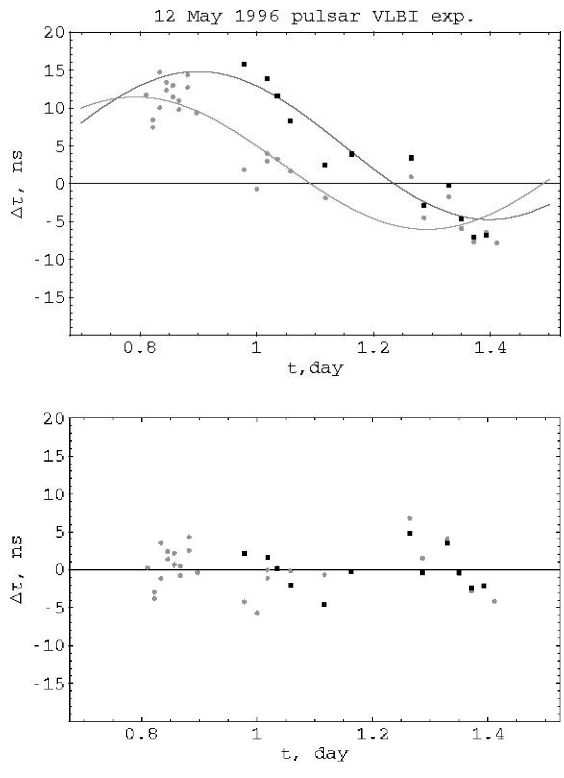

Fig. 3. Differential group delay "pulsar minus quasar" (upper) and post-fit residuals (lower)(Rodin 2001). Pulsar: PSR B0329+43, quasars: 0300+470 (black squares) and 3C84 (gray circles). Fitted parameters were clock rate and pulsar coordinates. The ionosphere differential delay contributes less than 10% of total diff. delay and is within 1σ error.

3. Results

ICRF positions of pulsars B0329+54, B0355+54, B0950+08, B1933+16 and 2021+51 are presented in Table 1. The rest three pulsars B0809+74, B1929+10, B2020+16 were detected but their positions were not measured due to insufficient data.

Table 1. Pulsar coordinates.

Pulsar PSR B	Right ascension & declination (J2000)	Epoch
$0329+54$	$03^h32^m59^s.3758 \pm 0.0004$	1995.0
	$54°34'\,43''.518 \pm 0.003$	
$0355+54$	$03^h58^m53^s.713 \pm 0.003$	1995.20
	$54°13'\,13''.75 \pm 0.1$	
$0950+08$	$09^h53^m09^s.30 \pm 0.01$	1996.36
	$07°55'\,35''.8 \pm 0.8$	
$0950+08$	$09^h53^m09^s.309 \pm 0.001$	1998.40
	$07°55'\,36''.15 \pm 0.07$	
$1933+16$	$19^h35^m47^s.824 \pm 0.006$	1995.20
	$16°16'\,40''.07 \pm 0.27$	
$2021+51$	$20^h22^m49^s.866 \pm 0.005$	1995.20
	$51°54'\,50''.30 \pm 0.01$	

PSR B0329+54 as the most strong pulsar observed has as accurate coordinates as a few milliarcsecond. Other pulsars are not so strong and their coordinates are measured not so accurately. For low declination pulsars (B0950+08, B1933+16) there is problem of short mutual visibility time for the east-west baseline and strong correlation between right ascension and declination. This problem can be solved using additional north-south baselines.

Pulsar B0329+54 when combined with data by Bartel at al. (1985) has well measured proper motion: $\mu_\alpha = 17.3 \pm 0.3$ mas/yr, $\mu_\delta = -10.6 \pm 0.4$ mas/yr.

Pulsar VLBI coordinates which relate with the rotating Earth (e.g. ICRF) when combined with pulsar timing coordinates related with the Earth orbit (e.g. DE200) allow to link different celestial reference systems. For the most of pulsars their timing and VLBI coordinates differs due not only to different orientation of the systems but also due to timing noise which affects pulsar timing position (Rodin 2000). Rotation angles from DE200 to ICRF reference system at epoch 1993.0 based on the comparison VLBI and improved timing pulsar coordinates is written as following

$$\begin{aligned} A_X &= \ \ -4 \pm 2 \ \text{ mas} \\ A_Y &= -13 \pm 3 \ \text{ mas} \\ A_Z &= -17 \pm 5 \ \text{ mas.} \end{aligned} \tag{1}$$

This angles are in satisfactory accordance with the angles by Folkner et al. (1994):

$$\begin{aligned} A_X &= \ \ -2 \pm 2 \ \text{ mas} \\ A_Y &= -12 \pm 3 \ \text{ mas} \\ A_Z &= \ \ -6 \pm 3 \ \text{ mas.} \end{aligned} \tag{2}$$

Use of more accurate pulsar coordinates allows to improve link accuracy. Currently the main uncertainty arises from errors of the timing coordinates. A few millisecond pulsars measured by differential phase method and which have good timing coordinates give possibility to link celestial frames with accuracy much better than 1 mas.

4. Conclusion and future plans

This paper presents joint Russia-Japan pulsar VLBI observations carried out in 1995- 1998. Absolute method based on the group delay and delay rates have been used to derive pulsar positions in ICRF. Eight pulsars with flux density $\geq 20 \div 25$ mJy were detected . Five pulsar have positions measured with accuracy $0.003 \div 0.8$ arcseconds.

Phase differential method are planned to be used for increasing accuracy of the pulsar observations. This method requires as precise a priori model of delay and delay rate as possible. For this purpose CALC software have been modified and ported from HP-UX to Linux OS[2].

For more effective use of the gate function it is planning during the day of VLBI experiment to make quasi-simultaneous timing observation of the same pulsars. Currently pulsar fringes are detected visually in single 2 MHz channel. Quasi-simultaneous timing will give possibility to know pulse time of arrival precisely and detect fringes from more weak pulsars in all bandwidth automatically.

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[2] ftp://alpha.prao.psn.ru/users/rodin/soft/clc.tar.gz