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First Pulsar VLBI Experiment in Japan between Kashima and Usuda

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Abstract

We carried out very long-baseline interferometry (VLBI) experiments on the pulsar PSR 0329+54 in August and November of 1992 by using the Kashima 26 m and the Usuda 64 m antennas. A fringe of a pulsar was detected for the first time in Japan by using newly developed correlation software and the K3 VLBI correlator, which were developed by the Communications Research Laboratory (CRL). To check the gating ability of the correlator, the correlation amplitude was measured for various gating times, from which we derived the gating time that produces the highest signal-to-noise ratio.

Key words: Instrumentation: interferometers — Pulsars: individual (PSR 0329+54)

1. Introduction

Many radio observatories are interested in precisely measuring pulsar timing, which is considered to be more stable than any frequency standards on the earth (Allan et al. 1989, for instance). The pulsar's position and proper motion are important parameters for estimating the timing. There are two major methods for determining these parameters: VLBI (e.g., Backer et al. 1985; Bartel et al. 1990; Petit et al. 1990) and a parameter estimation from timing data. Both require a large antenna and a low observation frequency because the intensity of pulsar emission is so small, particularly at higher frequency (the typical spectral index is −1 to −2). The problems with each method are as follows:

—Regarding VLBI, "gating" must be used to filter out data that does not pertain to the pulse, itself. There are two gating methods, with hardware and with software.

—Regarding timing, precise and stable data over a long period and good parameter-estimation software are required.

2. Correlation Amplitude of Pulsar VLBI

2.1. *Ordinary VLBI*

The conditions required for detecting a fringe by using pulsar VLBI are discussed here. In Japan, since the Nobeyama 45 m antenna is dedicated to frequencies higher than 10 GHz, the Usuda 64 m and the Kashima 34 m antennas are considered to be the best pair of antennas for pulsar VLBI. However, because the Kashima 34 m system experienced operational problems from 1992 August to 1993 June, we used the Kashima 26 m antenna for the following estimation.

Table 1 shows the parameters of the observation system in this experiment. The lowest common frequency available for these antennas is 2260–2300 MHz. Suffixes "k" and "u" indicate Kashima and Usuda, respectively. The correlated amplitude (ρ) and the signal-to-noise ratio (S/N) are estimated as

$$\rho = \frac{\pi D_{\rm k} D_{\rm u} s}{8k} \cdot \sqrt{\frac{\eta_{\rm k}\eta_{\rm u}}{T_{\rm k}T_{\rm u}}} \times 10^{-26} \tag{1}$$

and

$$S/N = \rho \cdot \sqrt{2BW \cdot Tint}, \tag{2}$$

where D is the antenna diameter (m), η the antenna efficiency, T the system temperature (K), s the flux density of the star over $Tint$ (Jy), k the Boltzmann constant (J/K), BW the bandwidth (Hz), and $Tint$ the integration time (s).

We selected a strong pulsar, PSR 0329+54, that has a sufficiently long period for gating operation of the K3 correlator (discussed in the next section). When the average flux density over the period is unknown, we must use the peak flux density and the profile instead. However,

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Table 1. Parameters of the pulsar VLBI experiment.

Baseline	Kashima – Usuda (208 km)
Observed Star	PSR 0329+54
Frequency	2299.99 MHz
Bandwidth	2 MHz
Polarization	RHCP
Kashima system	D=26 m, η=0.5, T=100 K
Usuda system	D=64 m, η=0.75, T= 40 K
Correlation	K3 Correlator at Kashima

D : antenna diameter
η : antenna efficiency
T : system temperature

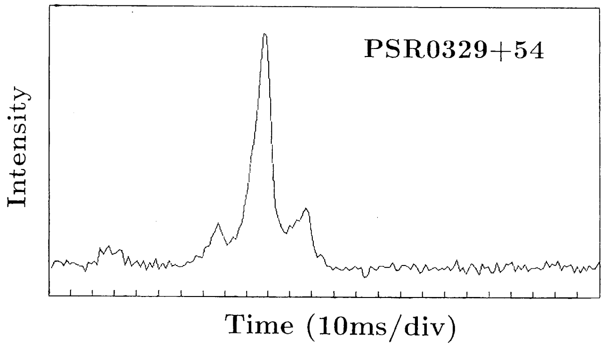

Fig. 1. Profile of PSR 0329+54, period = 0.7145 s, observed on 1990 May 3, with the Kashima 34 m antenna. Intensity is given in arbitrary unit.

in most cases, the data is insufficient to obtain these two parameters. One reason is that they fluctuate with both time and frequency. In the case of PSR 0329+54, we can use the actually observed profile, as shown in figure 1. Downs and Reichley (1983) observed its peak amplitude at 2388 MHz to be 2.6 Jy. We thus assume an average flux density of 0.035 Jy for the entire period (or 2.5 Jy concentrated in 10 ms). Using the parameters shown in table 1,

$$\rho = 1.60 \times 10^{-4} \tag{3}$$

and

$$S/N = 4.5 \qquad (\text{for } Tint = 200 \text{ s}) \tag{4}$$

are obtained.

Detecting a fringe with an integration time of 100 to 200 s and a bandwidth of 2 MHz (common for ordinary VLBI) is difficult because an S/N of, at least, 7 is empirically necessary to detect a fringe in VLBI. Typically, 500 s is the $Tint$ threshold for detecting a fringe of pulsar PSR 0329+54.

2.2. VLBI with Gating Operation

For improved efficiency, it is useful to gate out data which do not contain a pulse, and to integrate only the pulse itself. Since it is generally hard to know the a priori position of a pulse within the period, the gating positions are set in n different ways using n correlation units.

Although gating by software is also possible, and has been used successfully by Petit et al. (1990), software gating takes so much time. We therefore used the hardware gating function of the K-3 correlator.

Using gating to divide the period by n increases the average correlated amplitude n times and improves the S/N by $\sqrt{n}$ times because $Tint$ effectively becomes $1/\sqrt{n}$ (see Sekido et al. 1993). When n = 8 and the antenna pair is the Kashima 26 m and the Usuda 64 m instruments, detecting the fringe is possible as follows:

$$\rho = 1.28 \times 10^{-3} \tag{5}$$

and

$$S/N = 12.8 \qquad (\text{for } Tint = 200 \text{ s}) \tag{6}$$

While an n-times longer observation would also increase S/N by $\sqrt{n}$ times, gating has the following advantages:

1. fewer restrictions on the antenna machine time and slewing;
2. insensitive to any long-term instability in the frequency standard; and
3. less tape consumption and fewer restrictions on the tape length.

3. CRL's Correlation Processing System

We now review the correlation processing system of the CRL. We have developed new software for processing pulsar data based on NKROSS, which is used for ordinary VLBI correlations. NKROSS is written in HP Basic and runs on a host HP 330 computer equipped with a 68020 CPU. The HP 330 gives a priori parameters to the correlator, and the correlation data are acquired by the host computer through GPIB in every PP (parameter period, during which the parameters from the host do not change; usually one to four seconds). The K3 correlation processor gates only once per PP. The ideal PP should be exactly the same as the pulse period. However, since the PP is quantized by 5 ms increments and since a short PP is not possible for the correlation system, we set the PP to one second for convenience. This is rather longer than the period of the pulsar selected. The timing of the gate opening and closing can be set incrementally with one-bit (250 ns) units by the HP 330.

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1994PASJ...46..511H

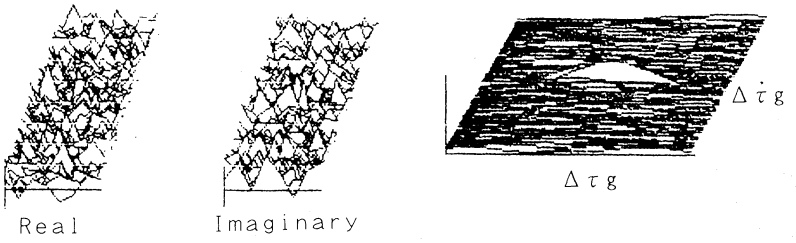

Fig. 2. Correlation of PSR 0329+54 without gating. The amplitude was 3.46×10^{-4} at 2.3 GHz, a bandwidth of 2 MHz and an integration time of 480 s.

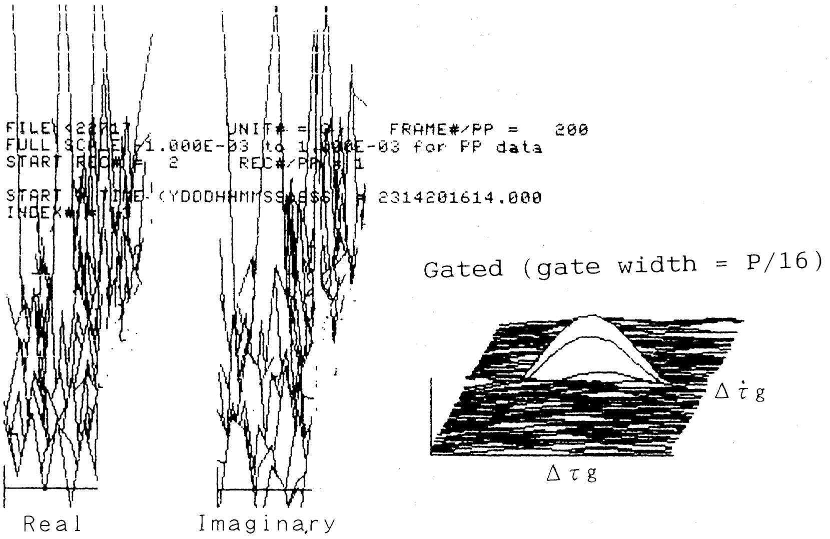

Fig. 3. Correlation of PSR 0329+54 with a gate width of $P/16$, an amplitude of 4.44×10^{-3} at 2.3 GHz, a bandwidth of 2 MHz, an integration time of 490 s.

Dispersion is always a problem in pulsar observation. The pulse shape smears to stretch out to Δt (see Lyne et al. 1990):

$$\Delta t = 8.3 \cdot DM \cdot RF^{-3} \cdot BW \times 10^{-3} \text{ (s)}, \tag{7}$$

where DM is the dispersion measure (pc cm^{-3}), RF the observing frequency (MHz), and BW the bandwidth (Hz). In this experiment, since $DM = 27$ (pc cm^{-3}), $RF = 2300$ (MHz), and $BW = 2 \times 10^6$ (Hz),

$$\Delta t = 36.8 \ (\mu\text{s}) \tag{8}$$

was obtained. This smearing is far smaller than the assumed pulse duration of 10 ms.

4. Experiment

4.1. *Observation*

The results of the November experiment (parameters in table 1) are considered here. We observed a strong pulsar, PSR 0329+54, whose period of $P = 0.7145$ s is sufficiently long for the K3 correlation system. A strong radio source 3C 84 was used for an initial clock search. The period (P) was divided by n at the correlation so that each gating time would be $1/n$ of the pulse period.

4.2. *Results*

Figure 2 shows the results when the data was processed without a gating. Figure 3 shows the results of data processed with a gating time of $P/16$ ($n = 16$) over the same integration time. It shows the fringe more clearly than in figure 2 because the S/N was improved by $\sqrt{16}$ times.

Table 2 shows the correlation amplitudes for both gated-to-$P/16$ and non-gated cases for various integration times. Since there is only one gating in a PP (= 1 s in this case), even if there are two pulses in a PP, the average efficiency of the integration time is $P/1$. Gating therefore improved the amplitude by a factor of $16 \cdot P$ (= 11.4).

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1994PASJ...46..511H

Table 2. Correlation amplitude of PSR 0329+54 with integration time changed at 2.3 GHz, bandwidth = 2 MHz, gating time = period/16

Gated	Non-gated	Integration time (s)
4.44E-3	0.35E-3	490
4.77E-3	0.39E-3	250
4.47E-3	0.46E-3	125

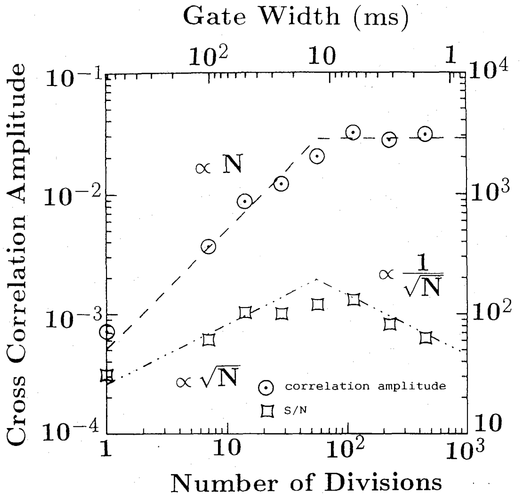

Fig. 4. Correlation amplitude and S/N of PSR 0329+54 with a varying gate width at 2.3 GHz, a bandwidth of 2 MHz, and an integration time of 500 s. S/N saturates around where the gate width equals the pulse width.

5. Discussion

We confirmed how the amplitude increases with an increase in n (the number by which the period is divided), as illustrated in figure 4. The amplitude increases almost directly in proportion to n and saturates when the gate time is around 10 ms, which is nearly the same as the pulse width of PSR 0329+54 in the 2 GHz band. S/N, which was calculated from equation (2), increases in proportion to $\sqrt{n}$ when the gate width is longer than the pulse width and decreases to $1/\sqrt{n}$ when the gate width is shorter.

These increasing and decreasing S/N lines cross at the gate width (around 13 ms) at which the amplitude begins to saturate. This coincidence shows that our experiment is reasonable and that this gate width is the effective pulse width observed by our system.

Work in the 1600–1720 MHz band is currently possible with the Usuda 64 m antenna; since the Kashima 34 m antenna supports a wider 1.5 GHz band, 1350–1750 MHz, researchers have a wider common bandwidth. We can thus carry out effective bandwidth syntheses. Because the difference in the ionospheric delay between the two stations is large at lower frequencies, a dual-frequency experiment is preferable if the baseline is not as short as the Kashima-Usuda baseline (208 km).

We are developing a new VLBI correlator (see Hama et al. 1993) having a pulsar gate which can be opened and closed any number of times during a single PP. Using such a correlator will allow us to process millisecond pulsars (Sekido et al. 1993).

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