Pulsar Astrometry by Using VLBI (PSR0329 between Kashima 26mφ & Usuda 64mφ)

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Abstract

Communications Research Laboratory (CRL), carried out a VLBI (Very Long Baseline Interferometer) experiment of the pulsar 0329+54 on November in 1992 between Kashima 26mφ and Usuda 64mφ. We got a correlation for it by using K-3 VLBI correlator, which was developed by CRL. Though we observed a slow pulsar this time, we are going to make millisecond pulsar experiments by making good use of this result and by using K-4 correlator which is under developing in CRL. Its result will give us precise positions and proper motions of pulsars which are useful for obtaining precise pulsar timing.

Introduction

Many radio observatories are interested in measurement of precise pulsar timing. Its position and the proper motion are important parameters to estimate the pulsar timing. There are two major methods to get them --- deriving from the timing data itself, and VLBI. The problems of each method are as follows:

timing: precise and stable data over a long range is necessary
a good software for parameter estimation is necessary

VLBI: two large antennas are necessary
"gating" is necessary to throw away the data which doesn't contain the pulse itself

Pulsar VLBI was conducted several times so far. For example,
by VLA [(1)] --- short baselines
by VLBI [(2)] --- making use of gating function of Mk-IIIa correlator
by VLBI [(3)] --- gating by software
The pulsar gating function of K-3 correlator was used this time.

Correlation Amplitude of Pulsar VLBI

The condition required for pulsar VLBI is discussed here. In Japan, as Nobeyama 45mφ antenna is dedicated for frequency over 10GHz, Usuda 64mφ and Kashima 34mφ are taken as the best couple of antenna. In practice Kashima 34mφ has been in trouble since this August. Kashima 26mφ antenna, therefore, is selected for this estimation. Let them have suffix "u" and "k". Then estimated correlated amplitude ρ is;

$$\rho = \frac{\pi D_k D_u S}{8k} \cdot \sqrt{\frac{\eta_k \eta_u}{T_k T_u}} \times 10^{-26} \qquad (1)$$

where D; antenna diameter [m]

η; antenna efficiency
T; system temperature [K]
s; flux density of the star [Jy]
k; Boltzmann constant [J/K]

Generally speaking data of pulsar strength and profile is not so sufficient. One of the reason is they are not stable over time and frequency. So, this is just a rough estimation. In the case of PSR0329, Downs et.al.[4] gives its peak amplitude in 2388MHz as 2.6Jy and Lyne et.al.[5] gives its profile as shown in Fig.1. Then we can adopt an average strength 0.5Jy over 50ms. By using the following parameters ;

D_k=26[m], D_u=64[m], η_k=0.5, η_u=0.7, T_k=100[K], T_u=30[K], k=1.38E-23

$$\rho = 1.79\times10^{-4} \quad (2)$$

is obtained. This is not easy to detect for 100~200 second integration time which is popular for geodetic VLBI.

So it is useful to gate out the data which doesn't contain pulse and to integrate only the pulse as shown in Fig.2. As it is generally hard to know the a priori position of the pulse in the period, the gating positions are set n different ways using n correlation units. Gating by software is also possible and is tried successfully by Petit et.al.[3]

How gating improves correlated amplitude and S/N ? Let's think about the case shown in Fig.2 where noise has average amplitude 1 and a rectangle pulse signal has amplitude A and duration 1/n of the pulse period.
In a normal correlation processing, S (signal) is A/n and N (noise) is 1, which makes S/N = A/n
In the case of gating the pulse, the integration time is 1/n which makes the average amplitude of the noise $\sqrt{n}$. As S is A, S/N becomes A/$\sqrt{n}$. Thus S/N is improved $\sqrt{n}$ times. In case n=8 and the antenna pair is the Kashima 26mø and the Usuda 64mø, the detection of the fringe is possible as follows;

$$\rho = 1.43\times10^{-3} \quad (3)$$

It is true that n times long observation also improves its S/N $\sqrt{n}$ times, but gating has the following merits;
1. Restrictions of the antenna machine time and slewing are less
2. Not sensitive to the long-term instability of the frequency standard
3. Tape consumption and restrictions of the tape length are less
4. Good for faint pulsars because the correlated amplitude itself is large

Correlation Processing System of CRL and its problems

The correlation processing system of CRL is shown in Fig.3. Both K-3 and K-4 tape are possible to be processed. The software NKROSS was modified for pulsar processing. It is written with HP Basic and run on a personal computer HP330 (the CPU is 68020). A priori parameter is given from the HP330 to the correlator and the correlation data is acquired by the host through GPIB every PP (parameter period; usually one through four seconds). The gating function of the K-3 correlation processor is only once per PP. So we selected PSR0329+54 which has long period as 714.5ms and is strong enough to get the fringe. The ideal PP should be the same as the pulse period. But, as PP is quantized by 5ms we set PP 1 second which is close to the pulse period. The timing of opening and closing of the gate can be set in the unit of bit (250ns) by the host.

The dispersion is always problem for pulsar observation. The pulse period is stretched out to Δt as[5]:

Δt = 8.3E3*DM*RF^{-3}*BW [sec] (4)

where, DM: Dispersion Measure [pc/cm^3]

RF: Observing Frequency [MHz]

BW: Bandwidth [MHz]

In this experiment PSR0329 gives

DM=27[pc/cm^3], RF=2300[MHz], BW=2[MHz] then,

$\Delta t = 36.8 \mu s$ (5)

is obtained. This value is far smaller than 50ms which is estimated as the pulse duration in the last section. Moreover, when the bandwidth ranges over 100MHz for bandwidth synthesis, Δt is only 1.97ms which is still smaller than the 50ms. Of course this should be compensated in the case of bandwidth synthesis.

A small problem appeared in the actual processing. Fringe rotation (=RF*$d\tau$, $d\tau$ is delay rate) was very small because the baseline is short (200km), frequency is low (2.3GHz), the right ascension is high. Our K-3 correlator makes use of 3 level-quantized sinusoidal function (as Fig.4) to compensate fringe rotation. On the other hand the data to be integrated within a PP is small because of gating. Some PP's, therefore, have most data on the correlation-restricted area. It means that such PP is given heavy weighting even if its quality is bad. This is notable in the case of short period pulsars.

The Result of the Experiment

The parameters of the experiments are shown in Table 1. Strong radio source 3C84 is used for an initial clock search. The period P=714.5ms is divided by n so that each gating time is 1/n of the pulse period.

Fig.5 shows the result when the data is processed in normal geodetic mode. Fig.6 is processed with the gating of P/16 over the same integration time. Fig.6 has a clearer fringe than Fig.5 because the S/N is improved as mentioned before. Sometimes PP with a large correlation amplitude is seen in Fig.6. The reason is probably that mentioned in the last section.

Table 2 shows the correlation amplitude for both gated to period/16 and non-gated when the parameter is integration time. As there is only one gating (P/16 in this case) in a PP (= 1sec this time), the efficiency of the integration time is P/1. Gating, therefore, improved the amplitude by the factor 16*P/1(=11.4).
In Table 3 the amplitude is compared between pulse area and non-pulse area.
In Table 4 the parameter is n; the number the period is divided with. The integration time is 480sec. The amplitude increases almost in proportion to n.

Pulsar VLBI for Millisecond Pulsars

We plan to make VLBI experiment also for millisecond pulsar. In the case of 1937+21, let's confirm if we get its fringe by using Eq.1. Kashima 34mϕ is taken this time instead of the 26mϕ antenna. As shown in Table 5, average intensity[6] is so small that normal correlation gives the fringe which is under the limit of the detection. But after the gating of P/16(=97us), fringe can be detected. The dispersion of 1937+21, whose DM is 71[pc/cm^3], becomes;

Δt = 43.7ns for RF=1.5GHz, BW=250kHz
Δt = 349.2ns for RF=1.5GHz, BW=2MHz
Δt = 96.9ns for RF=2.2GHz, BW=2MHz

In the case of 1.5GHz, wide bandwidth as 2MHz makes wave wider than P/16. So wider gating and narrower bandwidth should be selected for lower frequency.

References

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(2) Bartel, Cappallo, Whitney, Chandler, Ratner, Shapiro, Tang, "Frame Tie *via* Millisecond Pulsar VLBI", Workshop on Impact of Pulsar Timing & Cosmology, 1990

(3) Petit, Fayard, Lestrade, "A Method to enhance the cross correlation of millisecond-pulsar VLBI data: observations of PSR1937+214", 1990 *A & A*.**231**

(4) Downs, Reichley, "JPL Pulsar Timing Observations II", 1983 *Ap.J.Suppl*.**53**

(5) Lyne, Graham-smith, "Pulsar astronomy" p157 Cambridge U. Press 1990

(6) Foster, Fairhead, Backer, "A Spectral Study of Four Millisecond Pulsars", *Ap.J.* **378**, 1991

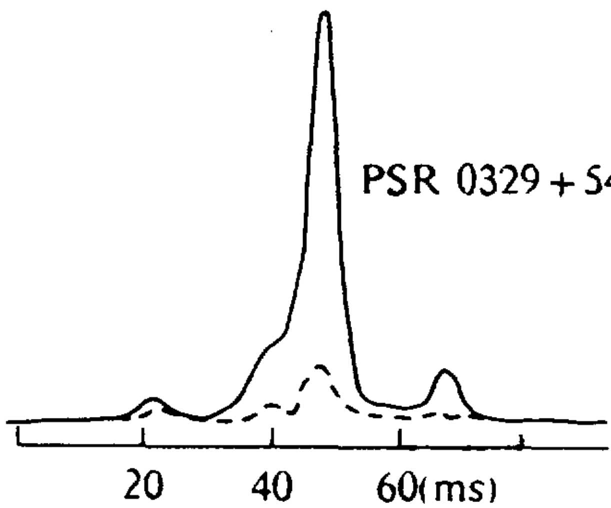
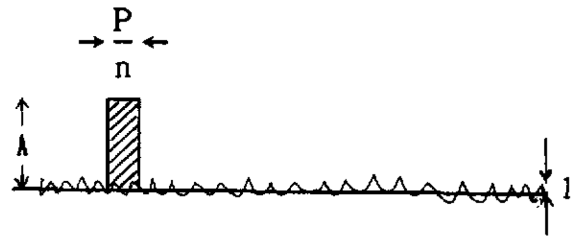


Fig.1 Profile of PSR0329+54



P : period of the pulse

Normal	S=A/n	N=1	S/N=A/n
Gated	S=A	N=$\sqrt{n}$	S/N=A/$\sqrt{n}$

Fig.2 Gating for Pulsar

Correlation & Integration only within the shadowed area

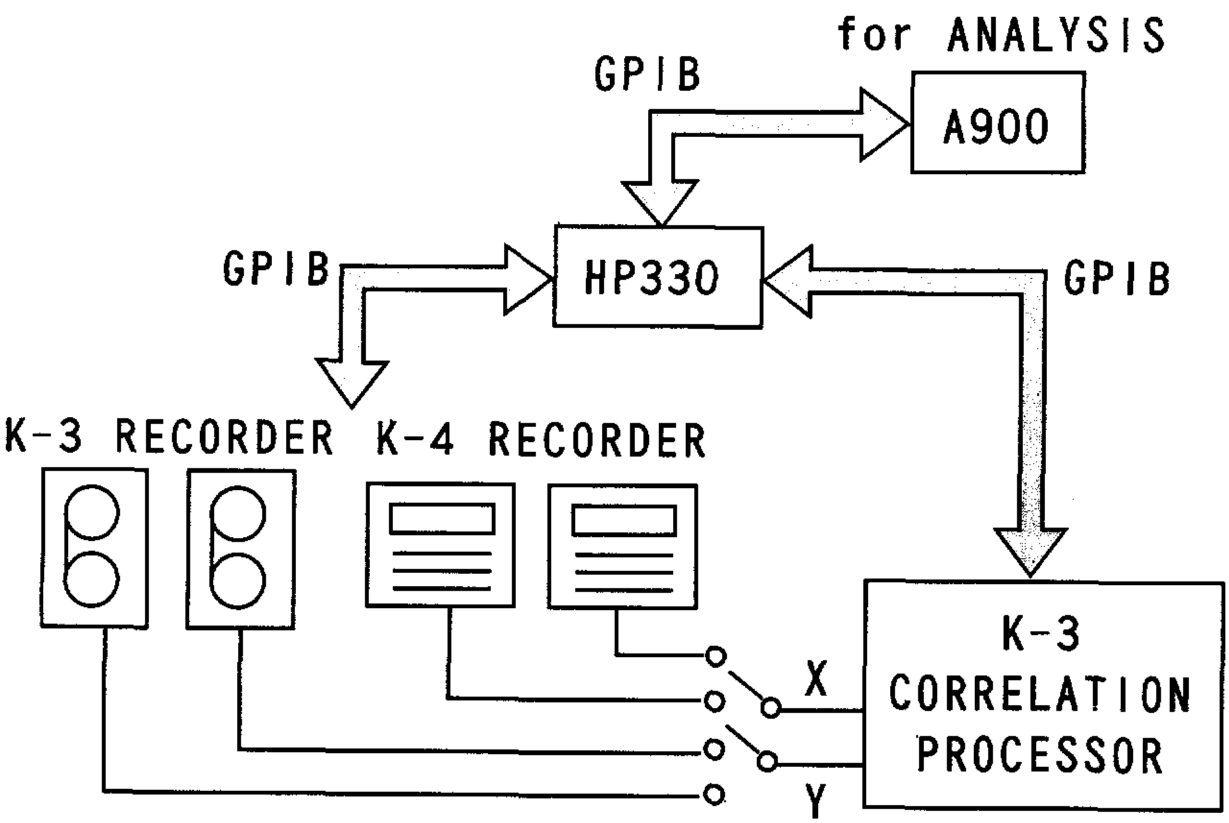


Fig.3 Correlation Processing System of CRL

Table 1 Parameter of the pulsar VLBI experiment

Baseline	Kashima26mø-Usuda64mø
Observed Star	PSR0329+54, 3C84
Frequency	2222.99MHz
Bandwidth	2MHz
Polarization	RHCP
Correlation	K-3 correlator at Kashima

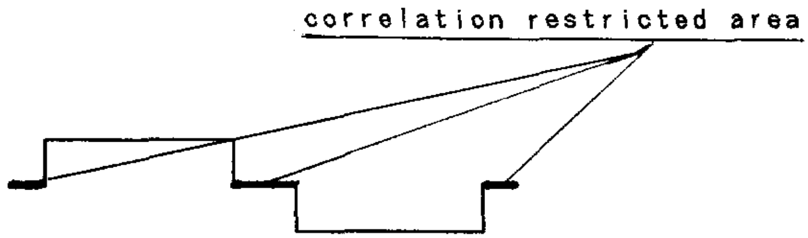


Fig.4

3-level sin function for compemsation of fringe rotation

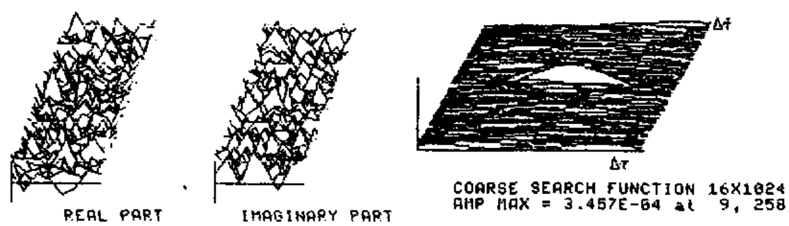


Fig.5 Normal correlation of PSR0329
(at 2.3GHz, BW=2MHz, Integration=480sec)

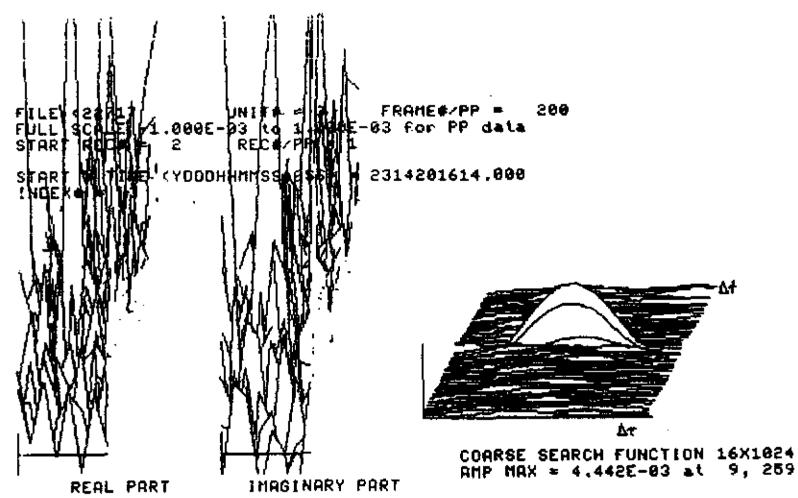


Fig.6 Gated correlation of PSR0329
(at 2.3GHz, BW=2MHz, Integration=480sec)

Table 2 Correlation Amplitude
(Gate time = period/16)

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

Table 3 Correlation Amplitude
(Integration time = 250sec)

1.04E-3	(area A)
4.77E-3	(area B)
1.22E-3	(area C)

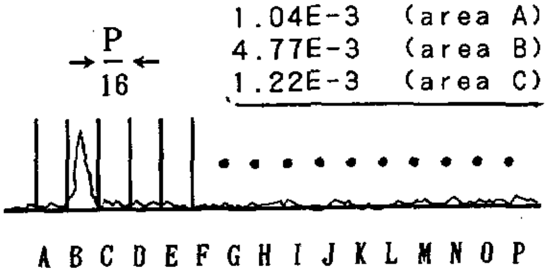


Table 4 Correlation Amplitude
(Integration time = 480sec)

0.35E-3	without gating
0.93E-3	(n=4)
2.01E-3	(n=8)
4.44E-3	(n=16)

Table 5 Correlation Amp. of millisecond pulsar 1937+21
(assumed gating covers 3/4 of the total flux)

	Average Intensity	Without gating	Gated (n=8)	Gated (n=16)
1.5GHz	9mJy	9.5E-5	5.7E-4	1.1E-3
2.2GHz	3.3mJy	2.9E-5	1.8E-4	3.5E-4

(gating time is period/n)

Dispersion
Δt = 43.7ns for RF=1.5GHz, BW=250kHz
Δt = 349.2ns for RF=1.5GHz, BW=2MHz
Δt = 96.9ns for RF=2.2GHz, BW=2MHz

QUESTIONS AND ANSWERS

D. Allan, Allan Time: Do you have any stability measurements against any reference clocks? eg: *The arrival time stability against a reference clock.*

S. Hama, CRL: Now we use a reference clock; a cesium. The Cesium is compared to UTC Japan by using GPS.

D. Allan: Do you have some results?

S. Hama: For timing measurement, I do not have the figure, but we are conducting timing measurement experiment. We have some results, so I can show you later.

D. Allan: Thank you.