Millisecond Pulsar Observation System at CRL

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Abstract

Millisecond pulsars attract attentions as a future reference clock in place of present atomic clocks, by reason of their highly stable pulse timing. CRL (Communications Research Laboratory) has been developing an observation system to measure the pulse timing of millisecond pulsar precisely, and recently has completed its basic part. By using it, we observed PSR1937+21 at 1.5GHz band and got a pulse timing with a precision of $16\mu sec/\tau$ by 5 days observation.

Introduction

CRL has a responsibility for keeping and supplying the time and frequency standard of Japan, and has been developing atomic clocks such as hydrogen maser and cesium clocks. We search for new methods to get more stable reference time scale, and started a project for establishing a reference clock system using the pulse timing of millisecond pulsars, such as PSR1937+21.

A pulsar is an object which radiates quite periodic pulse signal, which is considered a rotating neutron star. Generally this pulse arrival timing is stable, and especially so called millisecond pulsar has highly stable pulse timing in long term. According to the timing data of millisecond pulsar PSR1937+21 observed at Arecibo Observatory [1], shown in Fig.1, the long term fractional frequency stability reaches up to 10^{-13} ($\tau = 10^7 sec$). This is comparable to the stability of the most stable atomic clock, and it shows the possibility of a new clock using millisecond pulsars.

In the 21st PTTI meeting, we introduced our observation plan of millisecond pulsars [2]. Since then, we have been developing the observation system of millisecond pulsars using the 34m antenna at Kashima Space Research Center, and recently completed its basic part. In this paper, the feature of our system and the results of the observation for PSR1937+21 will be described.

Observation system

An observed pulse arrival time includes the error dt_{obs} , which depends on parameters of an antenna and an observation system. An observation system must be designed to make this error as small as possible. dt_{obs} is given by [3], [4];

$$dt_{obs} = \frac{(dt)^{3/2} \cdot T_{sys}}{\sqrt{B \cdot T \cdot P} \cdot \langle S \rangle \cdot G} \qquad (sec) \tag{1}$$

where

dt	:	half width of the observed pulse (sec),
P	:	pulse period (sec),
T_{sys}	:	system noise temperature (K),
$\langle S \rangle$	:	mean flux density of pulse (Jy),
G	:	antenna gain (K/Jy),
B	:	observed bandwidth (Hz),
T	:	integration time (sec).

To decrease dt_{obs} under the given antenna parameters such as T_{sys} and G, we must take the wide observing bandwidth B and long integration time T. Our data acquisition system was designed to meet these requirements.

Fig.2 shows the block diagram of our system. It has 16 channels in order to expand the observation bandwidth reducing the dispersion effect. A signal suffers dispersion delay according to its frequency from inter stellar plasma, which is expressed as follows [5];

$$dt_{DM}(f) = 0.00415 \times f^{-2} \times DM \qquad (sec) \tag{2}$$

where f is the frequency of the radio signal (GHz), and DM is the dispersion measure (pc/cm^3). If one channel's bandwidth becomes wide, the difference of $dT_{DM}(f)$ becomes large and the observed pulse width becomes broad. So we at first receive a pulse signal in narrow band (270kHz for each channel) to get a sharp pulse. Then to get a signal with wide bandwidth, each channel's signal are all added in off-line after canceling of each dispersion delay. Final data corresponds to the data observed by about 4MHz bandwidth.

To average many pulses quickly, we have introduced a data processor which works as both an A/D converter and a box-car averager. It averages pulses of each channel by hardware, which saves calculation time and memory for data storage.

Sampling clocks for A/D conversion and trigger clock for averaging are obtained from a signal generator. It gives an *a priori* frequency corresponding to the pulsar period received at the observation station [6],[7]. The reference signal of this signal generator is the hydrogen maser.

Observation of PSR1937+21

By using above system, the observation of PSR1937+21 was carried out at 1.5GHz band from Oct. 31 to Nov. 4, 1991. Fig.3 shows the detected pulse figure in one period, which is after averaging of about 1.5 million pulses (corresponds to about 40 minutes). The second peak is an interpulse. Observed pulse width is about 70 μsec , which is reasonable value compared with the estimated pulse width 60 μsec . This value is the maximum difference of dispersion delays for 270kHz bandwidth at 1383.67MHz (the lowest frequency band in this observation), and is calculated by Eq.2 where $DM =$ 71 (pc/cm^3).

We got such averaged pulses every 1 hour, and defined their peak points. If the calculated pulsar period was equal to the observed pulsar period, these peaks were to appear at the same point in any interval. At first, however, the peak points seemed to drift as time went, as if they were dominated by some systematic effect. We considered this was an apparent change caused by incomplete compensation of Doppler effect, and removed this drift by the least square method. Fig. 4 shows the residual of each data from the least square fitting line. The error bar represents a typical dt_{obs} 6.4 μsec calculated by Eq.1, where $dt = 70$ μsec , $P = 1.557806$ $msec$ (epoch = 2445303.2940 Julian ephemeris date) [7], $T_{sys} = 37$ K, $B = 270$kHz, $< S > = 8$mJy, $G = 0.42$ K/Jy, and $T = 2400$ sec are assumed. The standard deviation calculated from these data is 9.7 μsec .

From the residual shown in Fig.4, we calculated the Allan variance by;

$$\sigma_y^2(\tau) = \frac{1}{2}\left\langle \left[\frac{R(t+\tau) - R(t)}{\tau} - \frac{R(t) - R(t-\tau)}{\tau}\right]^2 \right\rangle \tag{3}$$

where $R(t)$ is a residual at time t, and the angled bracket is an average taken over all available triplets. The $\log \sigma_y(\tau)$ is plotted in Fig.5. Each data is corresponds to $\tau = 1, 2, 3, 4, 5, 24$, and 48 hours. The value at $\tau = 48$ hours has a large error bar, because the number of samples was very few. Except this one, data seems to be on a straight line with the precision of 16 μsec $/\tau$.

Conclusion

We developed an observation system for millisecond pulsars, and observed the pulse timing of PSR1937+21 with the precision of about 16μsec $/\tau$. Our main purpose is to use the pulsar timing as a most stable clock, so our measurement precision should be better than present value by at least one order. For this improvement, we plan to expand the observation bandwidth B further to decrease dt_{obs} , and investigate some methods. The local sweep method is one of them. By using it, one channel can track one pulse in some frequency band by sweeping a local frequency and shifting its observable frequency band along with the dispersion curve. It is equal to expanding the bandwidth of one channel.

Besides the use as a clock, various applications of a millisecond pulsar's pulse timing are considered. Its high stability is expected to be a good probe of detecting the dispersion fluctuation, gravitational wave and so on. We will study these subjects when we can take timing data with enough precision.

References

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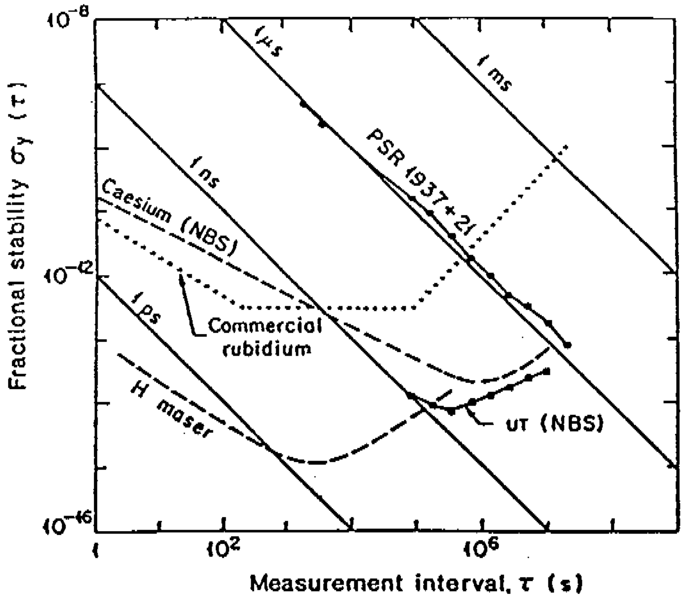

Figure 1 Fractional frequency stability for PSR1937+21 at Arecibo observatory [1]

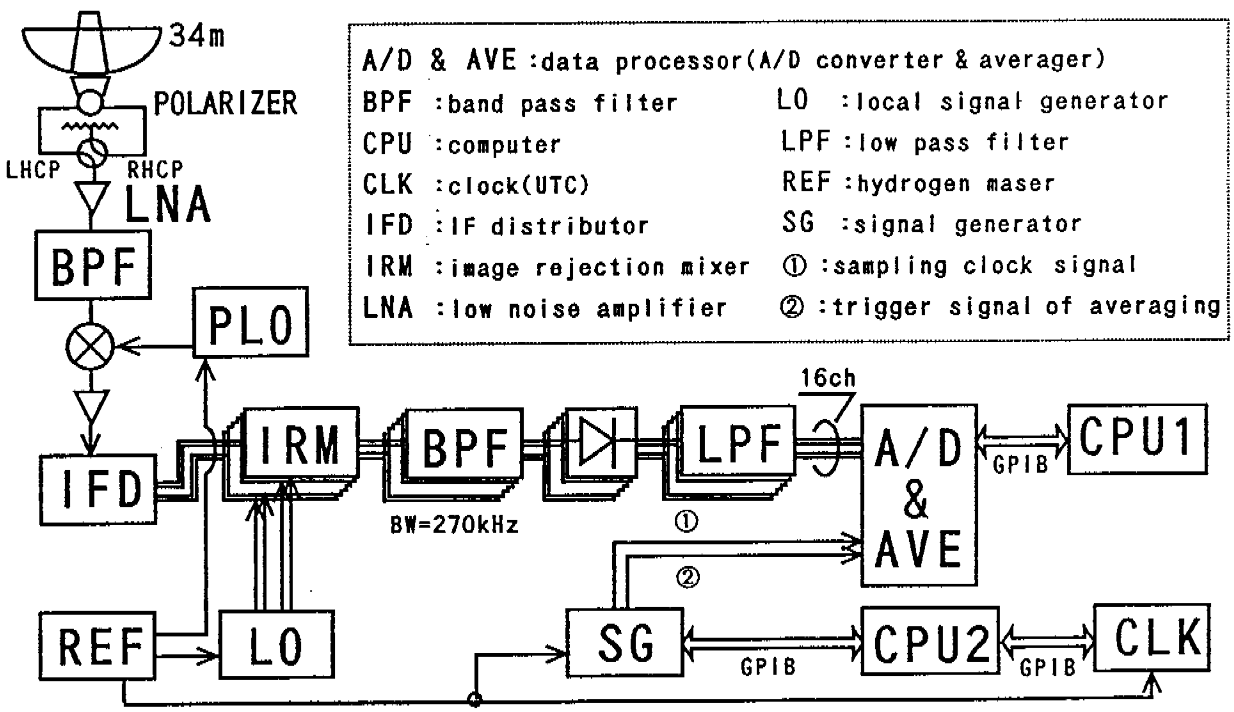

Figure 2. Block diagram of pulsar observation system at CRL.

Pulsar signal from 1.5GHz receiver is down converted at the first mixer to IF-band(100-500MHz). Divided IF signal from IFD is converted to video band at IRM, restricted in 270 kHz bandwidth, then detected. Detected signal is restricted from 150 Hz to 20 kHz at LPF, A/D converted and averaged in data processor, then saved in the host computer(CPU1). Another computer (CPU2) controls clock signals for the data processor . It reads time from CLK and calculates the pulse period received at the observation station in real time, then sends the period to the signal generator.

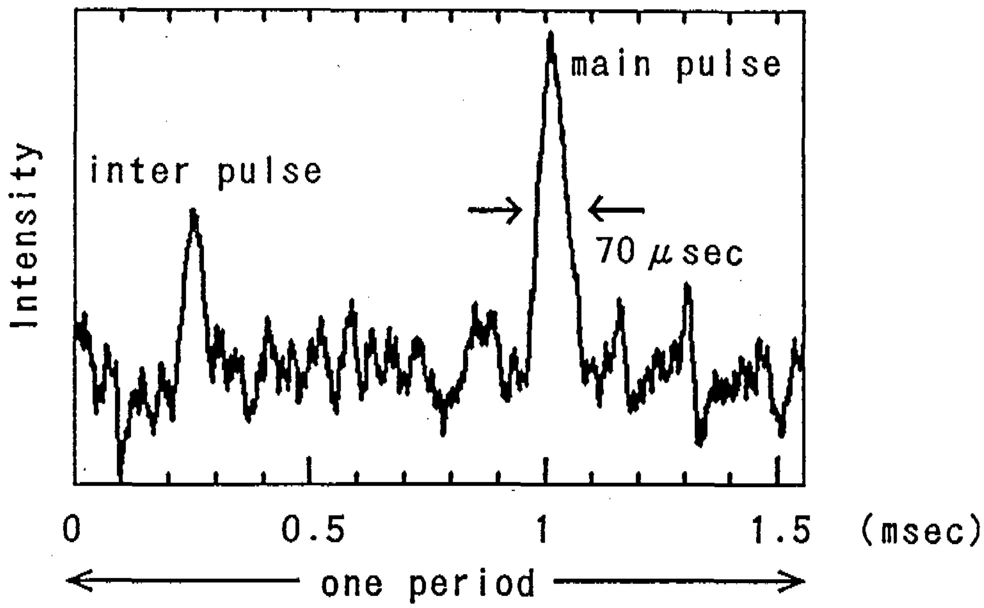

Figure 3. Pulse figure of PSR1937+21 observed at 1.5GHz.

It is acquired after averaging of 1.5 million pulses.

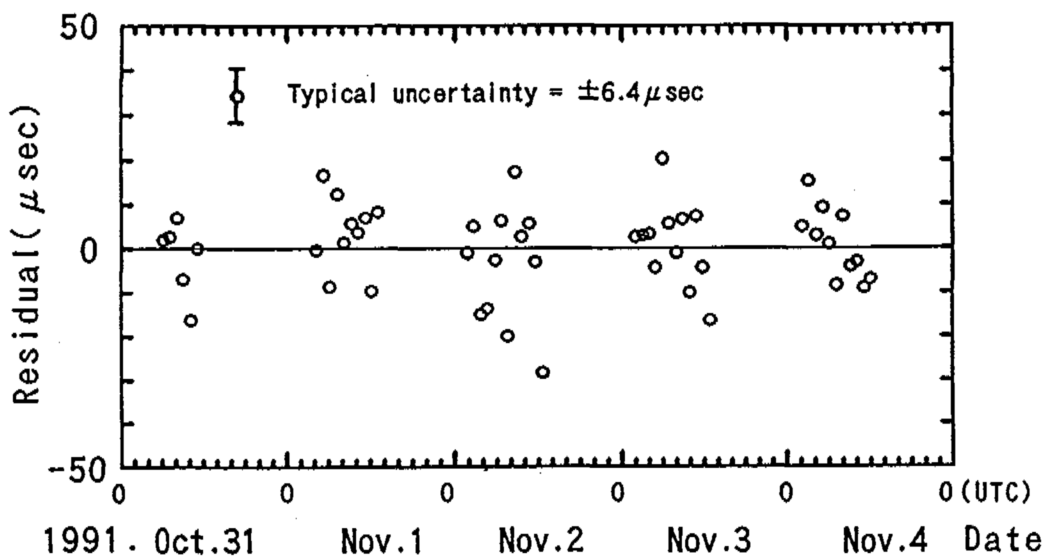

Figure 4. Post-fit arrival time residuals for PSR1937+21.

Arrival times are acquired from the peak points of averaged pulses taken over one hour. The least square fitting is carried out as canceling the drift of data. The residuals are derived from the fitting line.

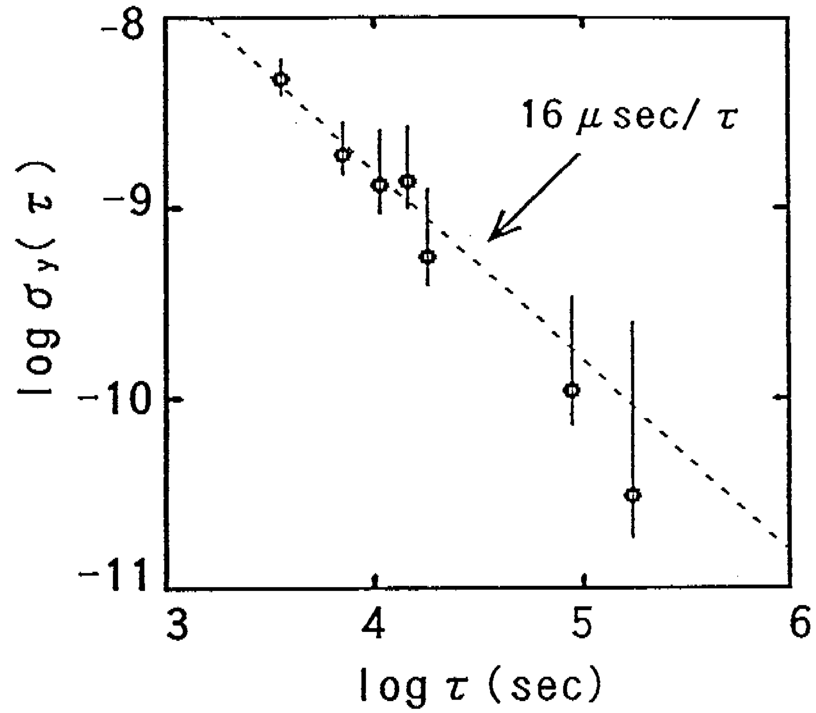

Figure 5. Fractional frequency stability for PSR1937+21 at CRL.

Each circle is calculated from the data of 5 days observation. The broken line corresponds to the precision of our system, 16 μsec/τ.