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Recent Activities in CRL

MILLISECOND PULSAR OBSERVATION AT CRL

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ABSTRACT

Millisecond pulsars are attracting attention as future reference clocks, because of their highly stable pulse timings. Communications Research Laboratory (CRL) has started a project which applies the pulse signals from millisecond pulsars to the time and frequency standard, and has developed a basic observation system. By using this system, we carried out an observation of PSR1937+21, and obtained an observed frequency stability of about $1.0 \times 10^{-5}/\tau$. In order to improve the performance, the current observation system is being developed further.

1. Introduction

1.1 Features of millisecond pulsars

Pulsars are objects which radiate periodic pulse signals, and are considered to be rotating neutron stars.

A neutron star is believed to be formed when a massive stars' collapse is accompanied by a burst of supernova. They are extremely dense because of their strong gravitational forces, and rotate every few seconds. As they rotate they radiate electromagnetic beams from their magnetic poles, which can be observed just like a light-house. This is the pulsar model which is generally accepted at present (Figure 1).

As pulsars loose their energy by radiation, their rotation speed slows down. Generally pulsars which have short periods are young and have large period derivative. However an exceptional pulsar was discovered. PSR1937+21 the first "millisecond pulsar" (which has millisecond pulse rate) was discovered in 1982, and its period derivative was reported to be less than those of ordinary pulsars (which have periods between 1/4 and 2 seconds) by the order of 4 or 5. Other millisecond pulsars which have been discovered so far also have small period derivatives (Table 1). From these results, millisecond pulsars are now considered to be in a special category and to have a mechanism which maintains more stable conditions than those found in ordinary pulsars(1).

1.2 Millisecond pulsars as standard clocks

The stable pulse periods of millisecond pulsars are attractive for not only theoretical consideration but also for various other applications. One of them is to use the pulse timings as a standard clock.

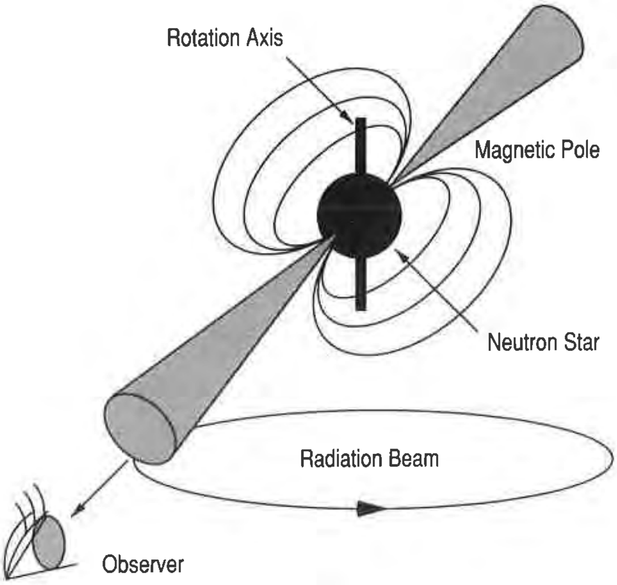

Fig. 1 Pulsar model.

Table 1 Parameters of some millisecond pulsars⁽¹⁾.

Pulsar	Period	Period Derivative
	P (msec)	dP/dt (sec/sec)
PSR1620–26	11.076	7.9×10^{-19}
PSR1821–24	3.054	1.6×10^{-18}
PSR1855+09	5.362	1.6×10^{-20}
PSR1937+21	1.558	1.0×10^{-19}
PSR1953+29	6.133	3.2×10^{-20}
PSR1957+20	1.607	—

Figure 2 shows the fractional frequency stability of millisecond pulsar PSR1937+21 compared with some atomic clocks⁽²⁾ (PSR1937+21's timing data was observed by the 305m antenna at Arecibo (Puerto Rico)). Its long-term stability is known to be 10^{-13} at $\tau = 10^7$sec, which is comparable to that of the cesium clocks. Over longer time periods, the PSR1937+21's stability will possibly exceed that of the cesium clocks.

This data shows the potential of millisecond pulsars to be used as clocks. By combining cesium clocks with millisecond pulsars, we can improve the long-term stability of the current atomic time scale. It will also be possible to construct a pulsar clock system by comparing several high-stable millisecond pulsars with each other⁽³⁾⁽⁴⁾.

In order to investigate such possibilities, several observatories around the world carry out the observation of millisecond pulsars' pulse rates. As for PSR1937+21, the 305m antenna at the Arecibo

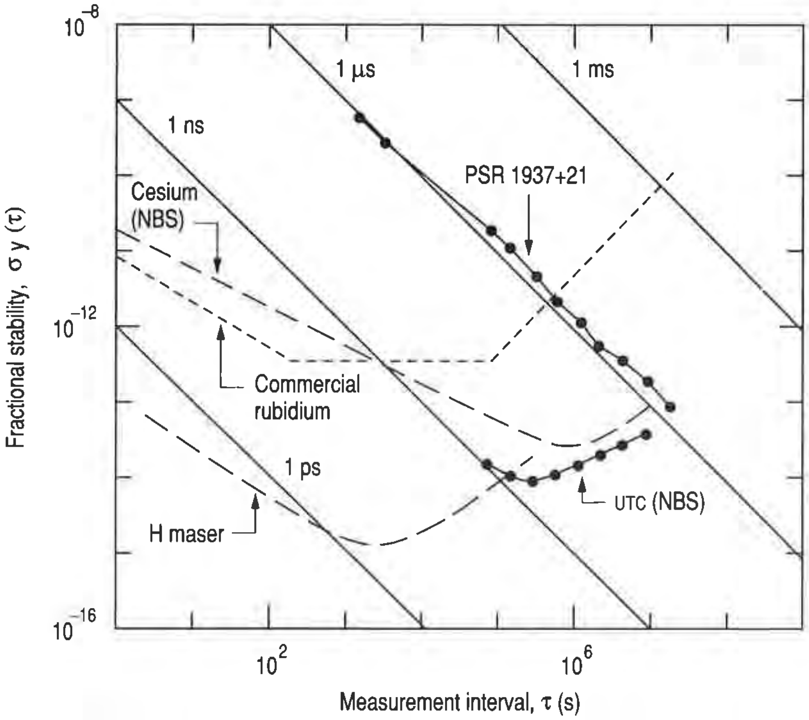

Fig. 2 Fractional frequency stability for PSR1937+21 obtained by Arecibo observatory(2).

Observatory has recorded the most precise data. According to their paper in 1987, an observation precision of 300nsec was reported(5).

1.3 Millisecond pulsar observation project at CRL

In 1989 CRL (the national institute for maintaining the time and frequency standard in Japan) started a project to see if the pulse timing of millisecond pulsars could be applied to standard clocks. Figure 3 shows the concept of this project using our 34m antenna at Kashima Space Research Center (KSRC). The timing data of millisecond pulsars observed by the 34m antenna is checked against the pulses of the atomic clock at KSRC, then linked to the UTC (CRL) and others via the GPS satellites in order to improve the atomic time scale. This project requires the use of various facilities such as equipment for radio astronomical observations, for precise time comparison and atomic clocks. All of them are located in CRL, which makes it an ideal choice for this type of research.

2. Millisecond pulsar observation at CRL

2.1 System design for millisecond pulsars

As the first step in the millisecond pulsar observation project, we began to develop an

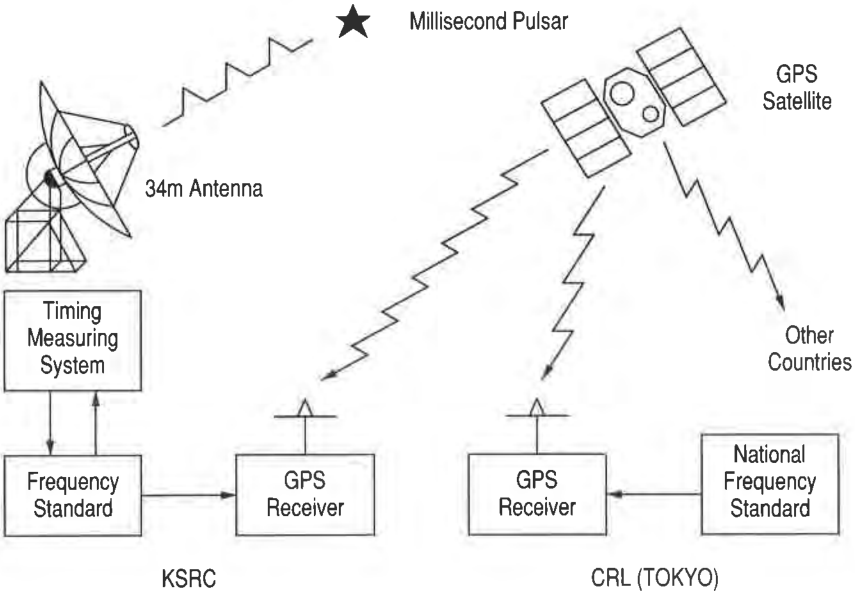

Fig. 3 The application plan of millisecond pulsar at CRL.

observation system.

Our purpose is to measure the arrival pulse timing of millisecond pulsars as precisely as possible. It is difficult, however, because millisecond pulsars' signals are quite weak. Also our 34m antenna is rather small for millisecond pulsar observations, so we must improve the reception sensitivity with signal processing by various methods, such as (A): increasing the integration time, and (B): expanding the detecting bandwidth.

Method (A) is realized by averaging many synchronized pulses. In order to achieve this we have introduced a data processor which can rapidly average many pulses.

Method (B) is popular way to improve the reception sensitivity in radio astronomy, but consideration is necessary for pulsar observation because of the dispersion effect. A signal from a pulsar suffers a dispersion delay dependent on its frequency through the interstellar plasma. When using a wide detection bandwidth, pulses with various timing are received together, and the observed pulse width is broad (Figure 4(a)). We adopted a filter bank method as a conventional way to avoid such a problem. Using this method, the detecting bandwidth is divided into narrow channels and all signals are overlapped after compensating for each delay. This allows us to obtain sharp and strong pulses when using a wide bandwidth (Figure 4(b)).

The basic observation system using the techniques mentioned is outlined in the following section 2.2.

2.2 Observation system at CRL

Figure 5 shows the block diagram of our basic observation system, it is an orthodox system which therefore ensures that we obtain the required data.

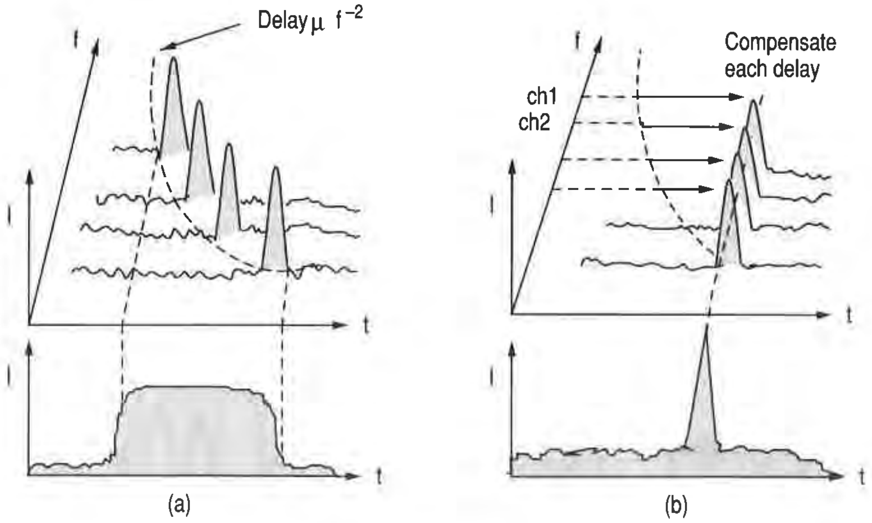

Fig. 4 (a) Pulse broadening by dispersion effect for wide band observation: (b) De-dispersion by filter bank method.

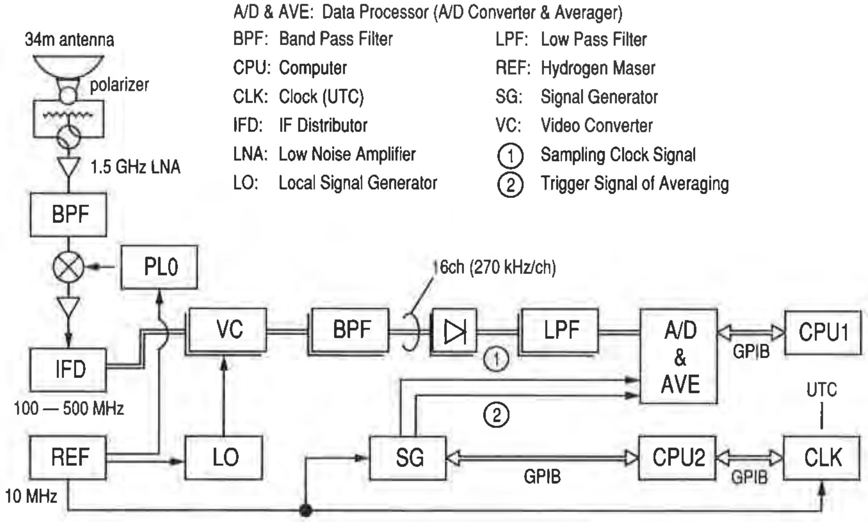

Fig. 5 Block diagram of pulsar observation system at CRL.

It has a bank of 16 narrow channels (270kHz bandwidth) which operate on the 4MHz bandwidth. The detected analog signal of each channel is separately converted to digital one and averaged by the data processor, then transmitted to the host computer. There the averaged data of 16 channels is overlapped after compensation for the dispersion delays.

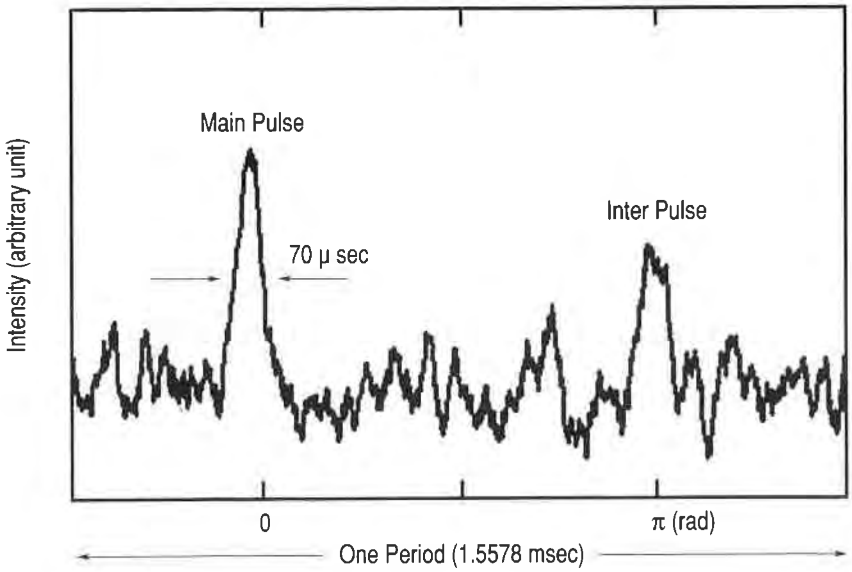

Fig. 6 Averaged pulse profile for PSR1937+21 at 1.5GHz.

The clock signals for the data processor are supplied by a signal generator whose phase is locked to a hydrogen maser. The trigger clock for averaging should be synchronized to the pulse period, but the observed period changes constantly because of the Earth's motion and other factors. To remove these apparent changes, another computer calculates the estimated pulse period (using a program developed by U.C. Berkeley) and controls the signal generator in real time.

The reference time at KSRC is synchronized with UTC(CRL) via the GPS satellite.

2.3 Observation of PSR1937+21 at CRL

By using the system described in section 2.2, we carried out test observations of PSR1937+21 (the most intense millisecond pulsar) on the 1.5GHz band (1350–1750MHz) over a period of 5 days.

Figure 6 shows the pulse profile obtained after averaging about 1.5 million pulses which corresponds to about 40 minutes. The second peak is an interpulse which may reveal a counter beam.

We acquired such averaged profiles every hour, and checked their main pulses' peak phases. Figure 7 shows the residuals of these peak phases. The amount of this scattering indicates the fluctuation of arrival pulse timing. The standard deviation calculated from all data is 13.6μsec. The third day's data looks a little worse than the other day's, and may have been due to the weather and external interference signals.

From these residuals, we calculated the fractional frequency stability using the Allan variance (Figure 8). The results from all the data (black circles) produced a constant gradient of $1.8 \times 10^{-5}/\tau$, but by removing the third day's data, the results (white circles) improved and produced a constant gradient of $1.0 \times 10^{-5}/\tau$. The fractional frequency stability improves in proportion to $1/\tau$, which means that only the white phase noise of the system appears in this region using our system.

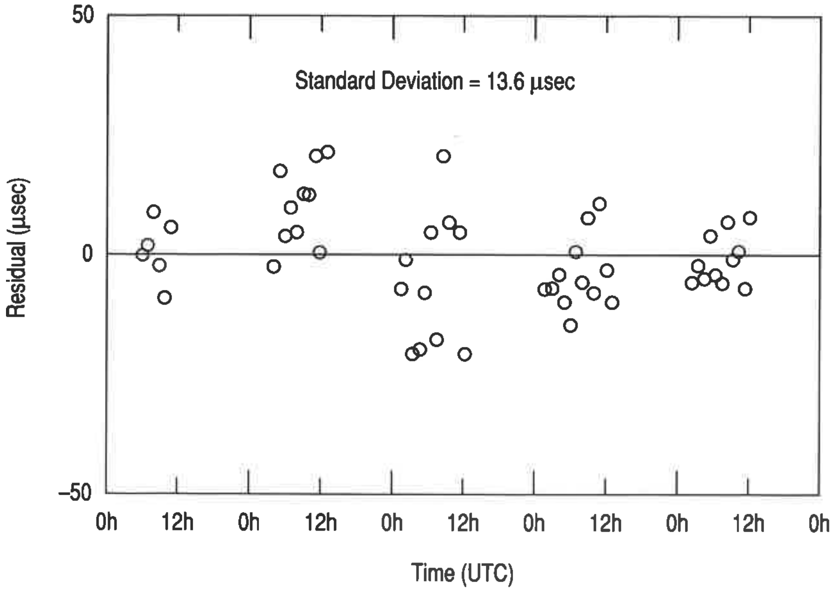

Fig. 7 Timing residuals for PSR1937+21.

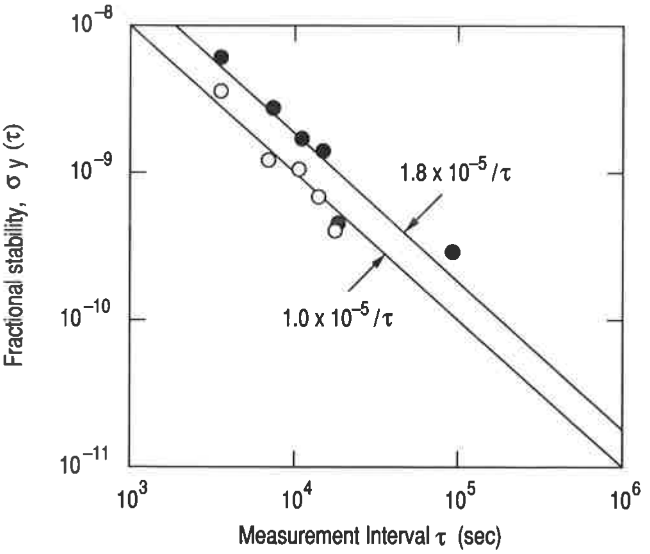

Fig. 8 Fractional frequency stability for PSR1937+21 at CRL.

We only had limited data in this observation, therefore the effects of poor data were significant. In order to improve the reliability, we must take continuous data over a long period. We will also need to improve the system to reduce the system noise.

3. Summary and future plan

CRL has started a project of millisecond pulsar observation for application to time and frequency standard. We developed a basic observation system using the 34m antenna at KSRC, and observed the pulse timing of PSR1937+21. The frequency stability calculated from this data, however, showed the precision was mainly limited by the system noise. Therefore, our next objective is to decrease the system noise. We have started to develop a new system with a wider bandwidth, and are aiming at a system stability of better than $1.0 \times 10^{-6}/\tau$.

We also attempted in VLBI experiments of millisecond pulsar to get an information about pulsar motion, which is necessary in order to achieve highly precise timing measurements. The preliminary experiment using Kashima's 34m antenna and Usuda's 64m antenna was successful(6), and we are now preparing a correlation system for millisecond pulsars.

Besides its use as a clock, various applications of a millisecond pulsar's pulse timing are considered. Its high stability is considered to be a good probe for detecting dispersion fluctuation, the dynamics of the solar system and the gravitational wave(3). We wish to study these subjects further when we can record timing data more precisely.

We greatly appreciate for the help of Dr. D.C. Backer at U.C. Berkeley who permitted us to use the calculation program, and for giving us useful suggestions.

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