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Short Note

MILLISECOND PULSAR OBSERVATION USING THE KASHIMA 34 M ANTENNA

By
Yuko ABE, Michito IMAE, Hitoshi KIUCHI, and Shin'ichi HAMA

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ABSTRACT

Communication Research Laboratory (CRL) started a new project of establishing a reference clock system through measurements of highly stable pulse timing of millisecond pulsars, such as PSR1937+21. Using the 34 m antenna and primitive observation system in Kashima, a test observation of PSR1937+21 was carried out at 1.5 GHz and the pulses were successfully detected. We are now developing a multichannel observing system in order to improve the accuracy of timing measurements.

1. Introduction

Millisecond pulsar PSR1937+21 discovered in 1982(1) has a quite short pulse period P (about 1.6 msec) and a small period derivative dP/dt (about 10^{-19} s/s)(2) compared with other pulsars. Active studies about such special characteristics are in progress to make its physical properties clear(3)(4), on the other hand, various applications of its marvelous frequency stability are being considered(3)(5)(6). One of them is an application of their pulse timing signals as a new reference of time. According to the timing data of PSR1937+21 taken at the Arecibo Observatory (Puerto Rico) from 1984 to 1987, the long term fractional frequency stability for this period reached up to 10^{-13} (see Fig. 1)(2), which is almost the upper limit as the data acquired by using atomic clocks. The period derivatives of millisecond pulsars are between 10^{-18} s/s and 10^{-20} s/s (Table 1), which are smaller than that of other ordinary pulsars by four or five orders. By comparing the timing signals of these highly stable millisecond pulsars to each other, it will be possible to construct a new clock system whose long term stability is much better than that of current atomic clocks.

CRL has been developing the atomic frequency standards, keeping them, and also carrying out precise time comparison using the space techniques as a national institute of time and frequency standard. The 34 m antenna (built in 1987) at Kashima Space Research Center of CRL has an ability to catch the weak signal from millisecond pulsars. These show that CRL is a special laboratory which can directly compare the pulsar timing with the atomic time by itself.

For investigating the feasibility of this new clock system, we started a new project about precise measurement of pulse timing (shown in Fig. 2) in 1989. We are now developing the basic pulsar observation system. Recently a part of this system has been completed, and test observation of PSR1937+21 was successful. We will report here our current system and demonstrate some preliminary results of our observations. Future plans are also described.

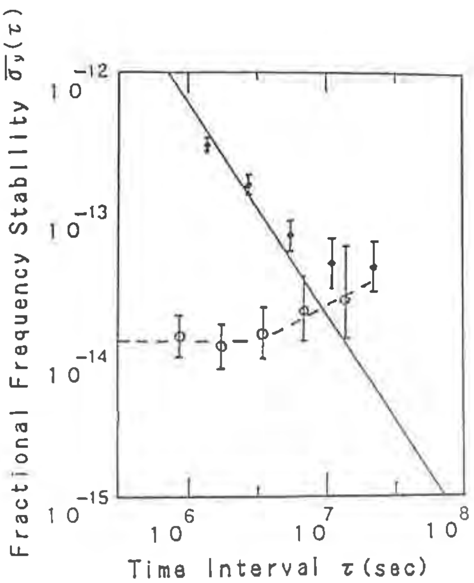

Fig. 1 Fractional frequency stability of 1937+21. The filled circle is of PSR1937+21 relative to UTC (NBS), the open circle is UTC (NBS) relative to other atomic standards, the dashed line is a model of the stability of UTC (NBS), The solid line is the locus of $\sigma_y(\tau)$ values that would be observed for a perfect clock, measured once every 16 days with 300 nsec random measurement errors (white phase noise) (from L.A. Rawlay, *et al.*[(2)]).

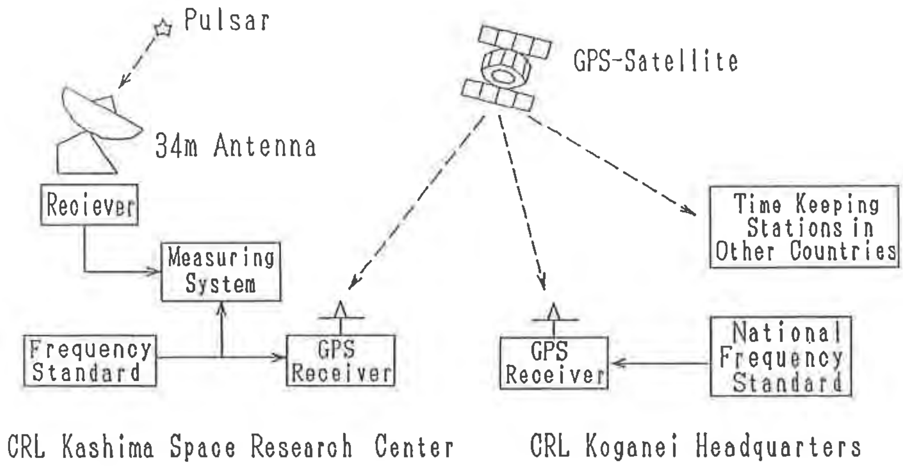

Fig. 2 CRL's plan of pulsar timing application to time scale.

Table 1 Parameters of millisecond pulsars

pulsar	period[1] (ms)	period derivative[2] (10^{-19} s/s)	pulse width[3] (μs)	mean flux density[3] at 1.3GHz(mJy)	dispersion measure[1] ($cm^{-3}pc$)
PSR1620-26	11.076	8.2	~250	~1.6	63
PSR1821-24	3.054	16	~45	~1.1	120
PSR1855+09	5.362	0.2			13
PSR1937+21	1.558	1.1	~25	~8	71
PSR1953+29	6.133	0.3			104
PSR1957+20	1.607	0.2			29

(1) R.S.Foster and D.C.Backer, "Constructing a Pulsar Timing Array," RAL Preprint No.168, 1990
(2) D.C.Backer and S.R.Kulkarni, "A NEW CLASS OF PULSAR," Physics Today, pp 26-35, March, 1990
(3) A.G.Lyne and F.G.Smith, Pulsar Astronomy, pp.244-259, Cambridge University Press, 1990

2. Observation System

2.1 Principle

To apply the observed pulse timing signal to the time standard, several kinds of error should be considered. Many considerable error courses exist such as fluctuation of dispersion error, ephemeris error, clock error, system error and so on[12], however, we discuss only system error dT_{obs} in this paper. dT_{obs} is given by[3][4][7][8]:

$$dT_{obs} = \frac{(dt)^{3/2} \times T_{sys}}{(B \times T \times P)^{1/2} \times \langle S \rangle \times G} \quad \text{(sec)} \qquad (1)$$

where

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

This error is not intrinsic, so the observation system should be designed to make dT_{obs} as small as possible. As long as the same antenna and receiver are used for the observation, G and T_{sys} are of constant value. Then there are two possible ways to improve the observing timing accuracy, i.e.:

(a) Averaging of many pulses (increasing T in Eq. (1)), and
(b) Expanding the bandwidth (increasing B in Eq. (1)).

About method (a), we introduce a general purpose image processor as a box-car integrator which averages numerous data quickly by hardware. Another way is to calculate an average of data by software in off-line, but this method requires much calculation time and memory. Hence, we average data in this processor as many times as possible. When further averaging is necessary, we use the averaging by off-

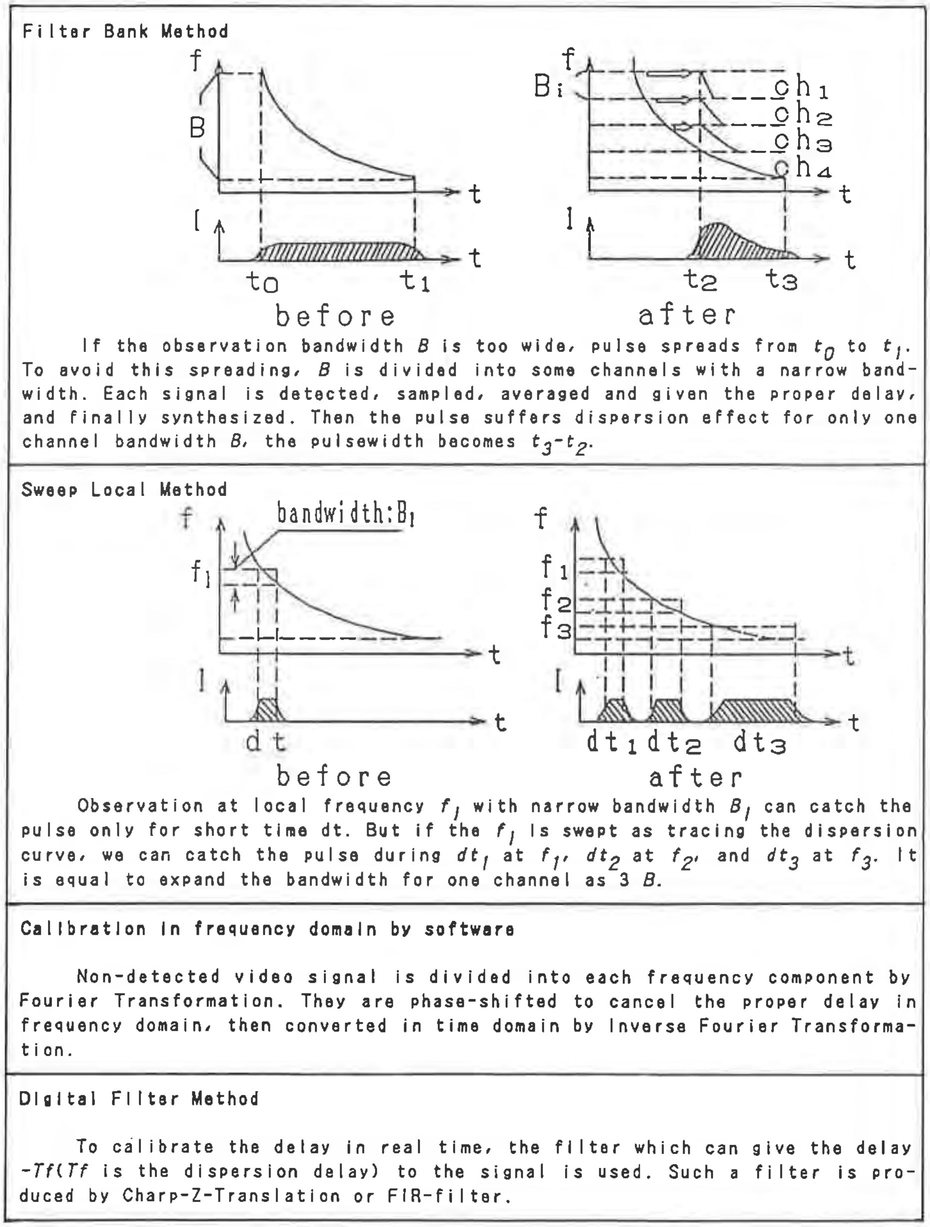

Fig. 3 Various de-dispersion methods in pulsar timing measurement.

line software. The out-line of this processor is described in 2.2.

The method (b) is used popularly in radio astronomical observation to improve a signal to noise ratio. In the case of pulsar timing observation, however, a careful application of expanding the bandwidth must be considered because radio waves propagating through inter stellar plasma suffer dispersion delay depending on its frequency. Therefore too wide a bandwidth at an observation results in broadening of the pulse width. We can estimate this dispersion effect using the following equation(6):

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

where f is the frequency of the wave (GHz), and DM is the dispersion measure which represents the column density of electrons in the path between the pulsar and the Earth (pc/cm^3). In the case of PSR1937+21, DM is 71 (pc/cm^3)(7), so that the maximum difference of estimated pulse arrival time reaches almost one period (1.6 msec) if we take observing bandwidth of 8–9 MHz at 1.5 GHz band. To cancel such dispersion effect and make wide-band observation possible, some methods (shown in Fig. 3) have been devised(10)(11). Among these methods, we are planning to adopt the "Filter-bank-method" and the "Sweep-local- method" simultaneously(13). In current systems, one channel of filter banks has been completed for preliminary observation.

2.2 Observation System

A block diagram of the current observing system is shown in Fig. 4. Radio frequency signals are fed to a 1.5 GHz receiver with a system temperature of about 37 K. Then signals are mixed with the first local signal to convert down into an IF-band (100–500 MHz). The IF-band signals are further frequency converted to video-band (0–16 MHz). To avoid smearing of pulses due to the dispersion effect, bandwidth is limited to 500 kHz in the video-band. The signals are then detected by a crystal detector. The detected signals are passed througsh a band-pass-filter (150–20000 Hz), then A/D converted and fed into the box-car type data processor for averaging.

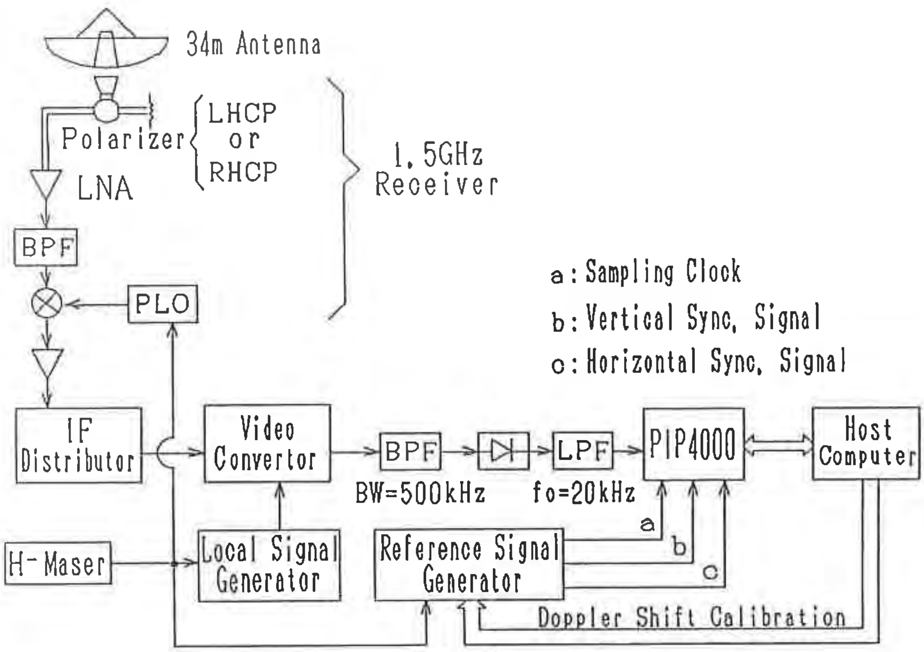

Fig. 4 Block diagram of pulsar observation system at CRL.

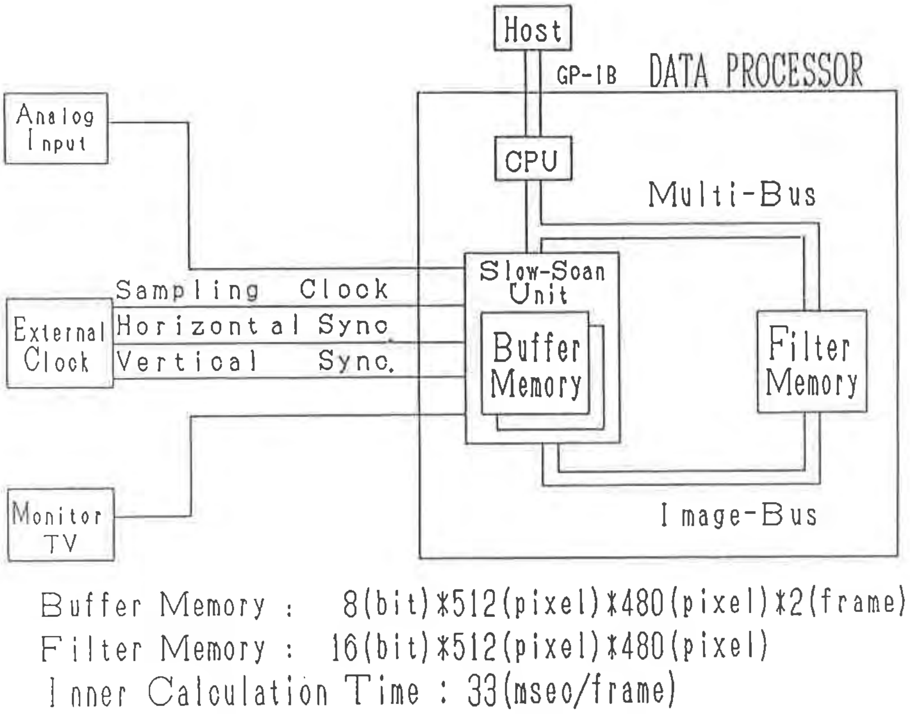

Fig. 5 Schematic block diagram of the box-car type data processor.

A block diagram of this processor is shown in Fig. 5. Analog input signal $A(t)$ is fed to the "Slow-Scan-Unit" (A/D converter), where $A(t)$ is sampled using an external sampling clock (interval T_S) and converted to 8 bit digital signal $D(t)$. T_S is the resolution, and its highest value can be 250 nsec. $D(t)$'s are stored in the "Buffer Memory", which is the frame type memory and can store 512×480 sampling data. Trigger signals are horizontal synchronous signal (interval $T_H = 512\ T_S$) and vertical synchronous signal (interval $T_V = 480\ T_H$). There are two Buffer Memories (called B_1, B_2), which acquire data alternately. As soon as B_1 is filled with data, B_2 starts data acquisition. While B_2 is taking data, all of the data in B_1 are transferred and piled up in the 16 bit frame type "Filter Memory" which has the inner calculation function. Data are summed up in the Filter Memory in the following manner:

$$D_{sum}(t_i) = D(t_i + mT_V) \quad (i = 1, 2, \ldots\ldots, 512 \times 480) \qquad (3)$$

where m is the number of summed Buffer Memory frames. Data exchangins between memories is carried out through "Image Bus" which is independent from "Multi Bus" used for sending commands from CPU. This independency and inner calculation function make speedy data processing possible. Before B_2 becomes ful1, B_1 can return to the empty state. Thus this processor can get data continuously. Data in the Filter Memory are transferred through GP-IB to a host computer for further data processing by software.

External clocks are supplied from a reference signal generator. In order to synchronize the clocks to the pulsar period, horizontal synchronous signal is set to be as $T_H = nP_{obs}$ (n = integer, P_{obs} = observed pulse period). P_{obs} is slightly different from the true pulse period P because of the Doppler shift caused by the

Earth's rotation and revolution. Therefore clocks are controlled by computer so as to cancel out the Doppler shift.

Every oscillator and signal generator is referred to the hydrogen maser (frequency standard) which has a stability of 10^{-14}.

3. Observation

With the system mentioned in the previous section, we tried to observe PSR1937+21 and successfully detected its pulses. Observed pulse shape for two periods is demonstrated in Fig. 6. True pulse period P was calculated by:

$$P = P(1986.0) + T \times dP/dt \qquad (4)$$

where $P(1986.0)$ = ~~1.55780644887275~~ 1.55780645958572 msec(2) which is a period at epoch 1986.0, dP/dt = 1.1 × 10^{-19} s/s(2) and T is a time span from 1986.0 to the observing time. Then resolution T_S is calculated to be about 12 μs from $T_S = T_H/512 = nP_{obs}/512$, where $n = 4$, $P_{obs} = P+$ (Doppler shift at the observation time). In this figure, pulses were averaged for approximately 6 × 10^6 times (corresponds to about 2.6 hours). However, about 2 × 10^5 pulses' averaging is enough to recognize only the pulse shape. A weaker inter pulse can also be seen in this figure.

From this figure, pulse width is about 100 μs, which is wider than the postdetection time constant of low pass filter (50 μs). The pulse width broadening caused by the dispersion delay in 500 kHz bandwidth at 1.5 GHz band is calculated to be about 90 μs from Eq. (2). This is comparable to an observed pulse width. We can hence conclude that the main cause for the pulse width broadening is dispersion effect due to propagating media. Another considerable cause is an insufficient Doppler calibration.

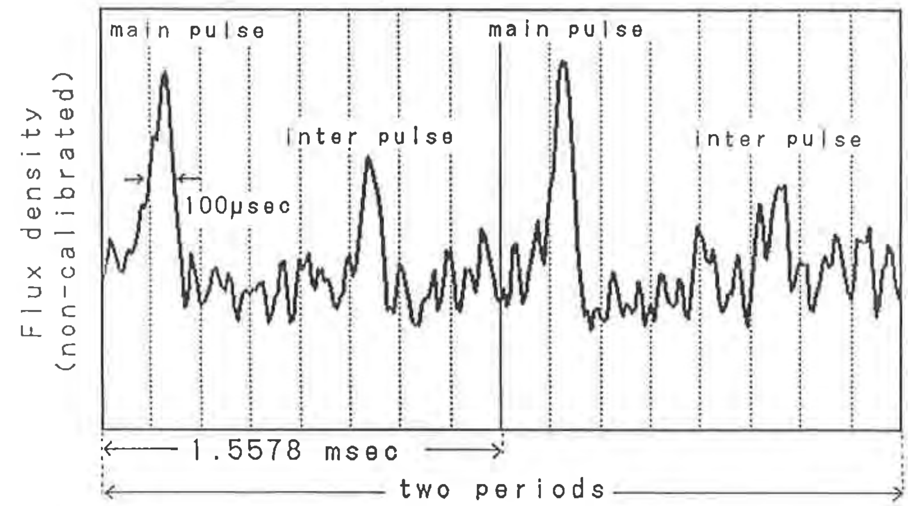

Fig. 6 Pulse figure of PSR1937+21 observed at CRL. The observation was carried out at 1.5 GHz on January 6, 1991. This figure is after averaging 6, 123, 520 pulses.

4. Conclusion

We have detected millisecond pulsar PSR1937+21 by using the 34 m antenna and preliminary receiving system. Arrival time error dT_{obs} in this observation is estimated to be approximately 4 μs by Eq. (1), where T = 9540 s, T_{sys} = 37 K, B = 500 kHz, P = 1.5578 msec[2], ⟨S⟩ = 8 mJy[7], G = 0.42 K/Jy and dt = 100 μs. This is not yet accurate enough to establish the reference time system. In order to improve the timing accuracy, the current system is now expanding to be multi channel. Figure 7 shows the block diagram of the observation system under development consisting of 16 channels of filter bank. The total bandwidth will increase from 500 kHz to about 4 MHz. After completion, we will employ the local sweep method as well. Then total bandwidth will further increase to about 32 MHz, resulting in an improvement of the dT_{obs} If 8 hours integration time is taken using this system, dT_{obs} is to be less than 300 nsec. This is considered to be comparable to the Arecibo's system error dT_{obs}, which is estimated to be about 350 nsec at 1.4 GHz receiver from Eq. (1) using the values of P = 1.5578 msec[2], T_{sys} = 40 K[9], ⟨S⟩ = 8 mJy[7], G = 8 K/Jy[9], B = 16 MHz, T = ~~2~~ 120 sec[2] and dt = 100 μsec.

In addition to this upgrade of the measurement system, an improvement of the 1.5 GHz receiver is also planned. The present system receives either right-handed-circular-polarization wave or left-handed-circular-polarization wave. We are planning to add one more low noise amplifier to the receiver to get both polarization waves simultaneously. This will help us to obtain more information about the pulsar signals such as Stokes parameters.

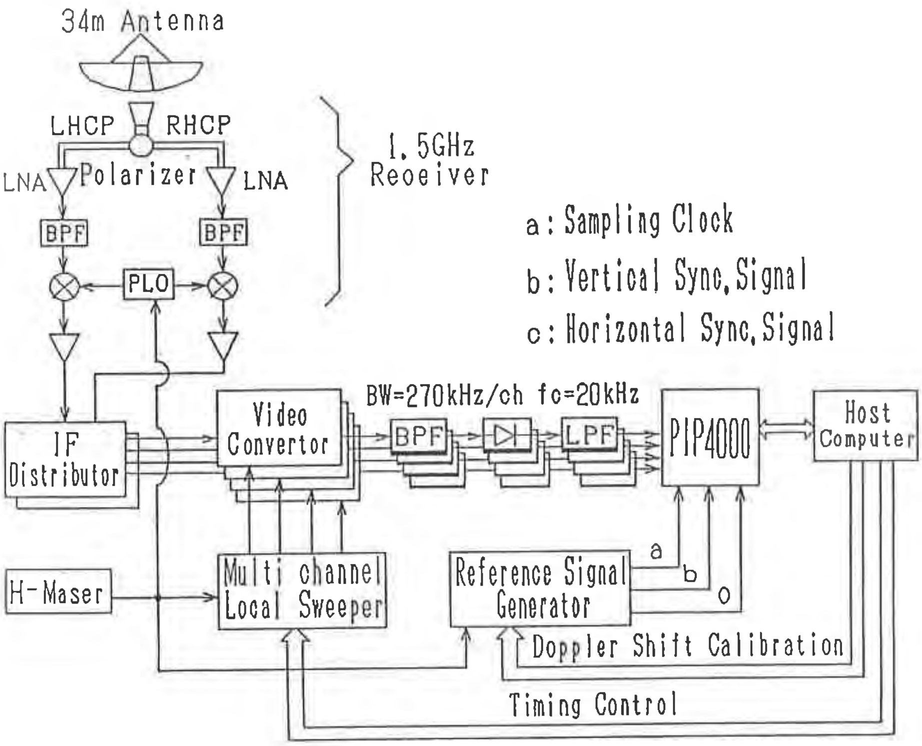

Fig. 7 Observation system of pulsar timing under development.

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