FREQUENCY STANDARDS AND INSTRUMENTAL DELAY CALIBRATION SYSTEM

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Abstract

This reference signal distribution system provides highly stable reference signals (1 PPS, 5 MHz, and 10 MHz) and the UTC time code for the VLBI data acquisition system. The reference signals are generated from the hydrogen maser atomic frequency standard which has a frequency stability of about 2 ～ 3 x $10^{-13} / \tau$, and the time code is obtained from the GPS station clock. The reference signal distribution system is built to be highly reliable and stable. Instrument status and monitored data are reported to the Central KSP control station located at the Koganei head quarters of Communications Research Laboratory (CRL) by the automatic monitoring system. The delay calibration system is necessary for the systematic delay canceling for the VLBI observations. This system is newly designed for KSP system.

1. Introduction

In this paper, we introduce a reference signal distribution system and a delay calibration system for the VLBI observation systems of the Key Stone Project (KSP). Both systems are not concerned with data acquisition directly, but play an important role maintaining highly accurate observations.

The reference signal distribution system supplies the reference frequency signals to the observation instruments, and keeps and monitors the time for the data acquisition systems. The VLBI technique developed with improvements in the atomic frequency standard, the stability of which has a direct effect on the precision of the delay when making VLBI observation.

The delay calibration system adds information about the systematic delay and the phase difference among multi-channels to the observation signals. This information is necessary for calibrating systematic error when analyzing data.

We introduce the reference signal distribution system in the section 2 of this paper, delay calibration system in section 3.

2. Reference signal distribution system

2.1 Its role in VLBI observations

In a VLBI observation, weak radio signals from quasars are integrated for the time necessary to improve the signal to noise ratio. If the signal's phase fluctuates during integration, the data quality worsens. In data acquisition systems, frequency conversion and sampling processes may affect signal quality. In order to prevent this, each instrument's oscillator must be synchronized to the same high stable standard frequency signal. The hydrogen maser type frequency standard is one of the most suitable for the VLBI system, because VLBI integration time is about several hundreds second and a hydrogen maser is the most stable of all atomic clocks in this time range. The reference signal distribution system has a hydrogen maser at each observation station. Their signals are distributed to the observation instruments as frequency reference signals for phase synchronization. The internal clock rate of these instruments depends on these reference signals.

It is important to know the time difference of two stations clocks because simultaneous data obtained at different stations is necessary for a VLBI observation. In order to compare the time of each station, we use UTC time code supplied from a GPS station clock as the reference time. We measure the time difference between each station's clock and UTC , and this data is used for data processing.

2.2 Construction

The instruments for the reference signal distribution system are classified into three groups according to their functions. Those in the first group generates the reference signals, those in the second distribute the signals, and in the last monitor the signals.

Fig. 1 shows the appearance of the system, and Fig. 2 shows a block diagram. The instruments for generating the reference signals are the hydrogen maser and the GPS station clock. The hydrogen maser generates 5 MHz and 10 MHz reference frequency signals that are used for phase synchronization in the observation systems. The GPS station clock generates the Inter-Range Instrumentation Group (IRIG) - B time code signal from UTC time that is obtained from GPS satellites. This then becomes the reference time signal for the observation systems. The GPS station clock also generates a 1 pulse per second (1 PPS) signal that is synchronized to UTC within an accuracy of 100 ns and it is used to synchronize time of all the instruments. For example, the hydrogen maser also generates a 1 PPS signal from its own 5 MHz signal which must be synchronized to the 1 PPS signal of the GPS station clock before being used as the reference time signal.

The instruments for distribution are the reference signal distribution amplifier and the pulse distribution amplifier. They distribute the hydrogen maser's 5 MHz and 10 MHz signals, the 1 PPS signals from both of the hydrogen maser and the GPS station clock, and the IRIG-B time code from the GPS station clock to the observation instruments. The time code reader is included in this group and it converts the IRIG-B time code to a parallel output signal which it supplies to the workstation.

The instruments for monitoring the signal are the time interval counter and the hydrogen maser's monitoring system. The GPS station clock is also included in this

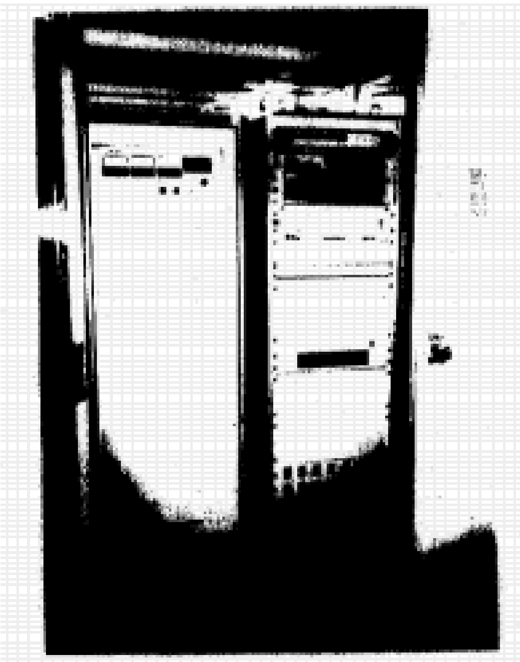

Fig .1 Appearance of the reference signal distribution system.

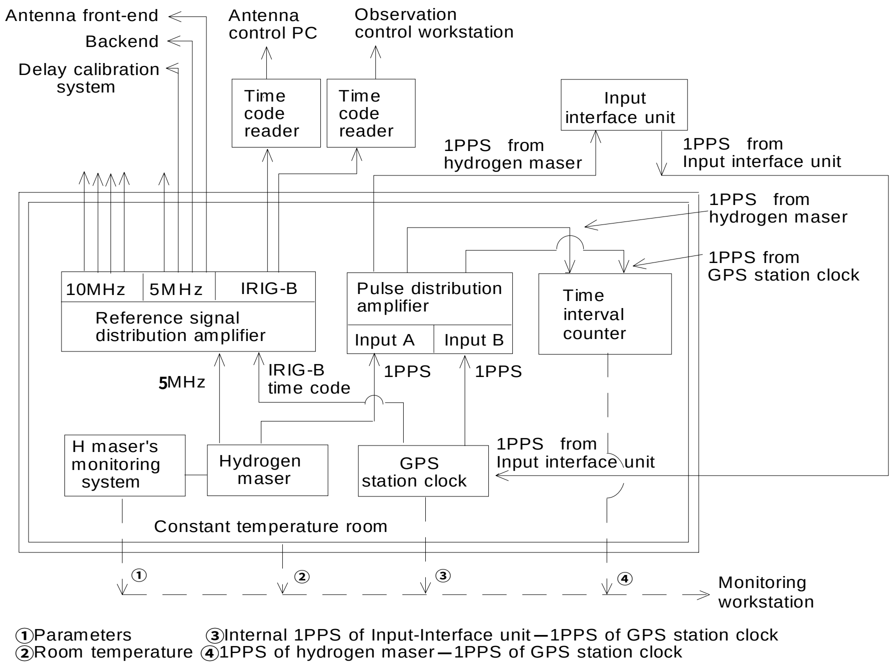

Fig. 2 Block diagram of the reference signal distribution system.

group because of its monitoring function. It measures the time difference between UTC and the 1 PPS signal of the input interface unit in the data acquisition system. The clock of the input interface unit is quite important because its time is stamped on the data and used for the data acquisition time during data processing. If this time is not correct, it becomes difficult to search a fringe in the correlation procedure. Of course, it must be synchronized to UTC within several microseconds at all stations, however, strictly speaking, its time begins to shift from UTC after synchronization because its internal clock follows the rate of the hydrogen maser's 5 MHz signal at each station. The time difference between the input interface unit and monitored UTC at the GPS station clock is recorded by the monitoring workstation every minute and is referred to during data processing. The time interval counter measures the time difference of the hydrogen maser's 1 PPS signal and the GPS station clock's 1 PPS signal in order to establish the frequency drift of the hydrogen maser from UTC over the long term. We can also confirm the hydrogen maser's performance from this data which is recorded every minute at the monitoring workstation.

2.3 The instruments

2.3.1 Hydrogen maser (RH401A Anritsu Corp.)

A hydrogen maser is an atomic frequency standard which uses the transition frequency between the energy levels in the hyperfine structure of a hydrogen atom's ground state.[(1)] Compared to other atomic clocks, a hydrogen maser has superior frequency stability in the short term.

Table 1 shows the specifications of the maser in this study, and Fig. 3 shows its structure. The H_2 molecules supplied from a gas cylinder are dissociated into atoms at the dissociater, and only those atoms in a suitable state for maser oscillation are selected by 6-pole magnets and fed to the storage bulb. Here H-atoms are

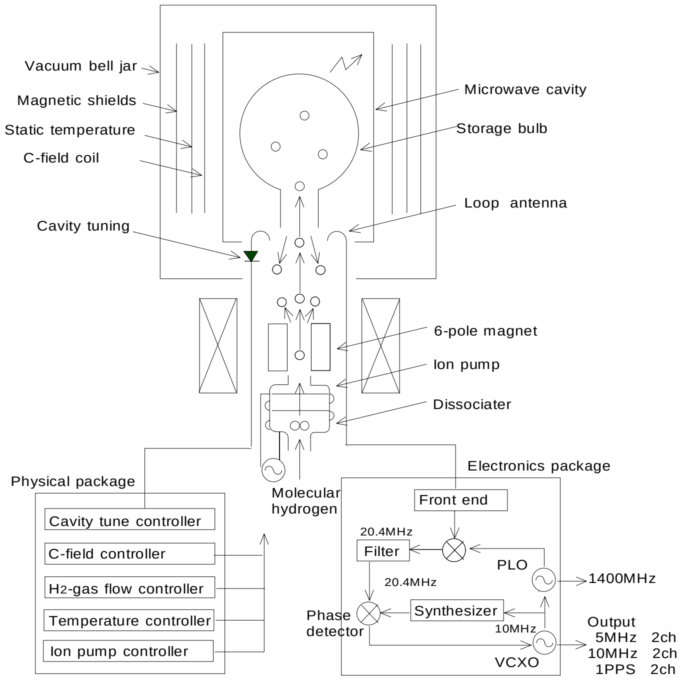

Fig. 3 Structure of a hydrogen maser.

resonant with the electromagnetic field inside the microwave cavity and where they decay to a lower energy level, at which point the maser oscillation has occurred. This oscillation frequency (1.42 GHz) is fed to the electronic receiver, and a phase locked VCXO generates the 5 MHz and 10 MHz carrier signals and the 1 PPS signal. The output frequency can be adjusted to a 7 x 10^{-16} resolution, and it is set to trace the UTC rate. Because the output frequency is sensitive to temperature, the hydrogen maser is placed in a room with a constant temperature. In order to find any trouble as early as possible, 30 parameters at various points are always monitored by the hydrogen maser's monitoring system. The most important three parameters are sent to the monitoring workstation by GPIB every minute where alarms are installed. The system has a battery with enough power for 24 hours of normal operation in case of an AC power emergency.

2.3.2 GPS station clock

The GPS station clock automatically receives signals from a maximum of 6 satellites. It supplies the IRIG-B time code of UTC and the 1 PPS signal synchronized to UTC within an accuracy of 100 ns. Table 2 shows its specifications. It has a highly stable crystal oscillator inside and can maintain stability of 5 x 10^{-12} even if it failed to receive signals from the GPS satellites. It measures the time difference between the external input 1 PPS signal and the internal 1 PPS signal synchronized to UTC. The results are available for reading by GPIB. It also retains the internal operation parameters when its power is turned off.

Features of the GPS station clock's 1 PPS signal include phase hopping (about 100 ns), which occurs when switching between receiving satellites, and fluctuation due to the selective availability of the satellites themselves. So we use the hydrogen maser's 1 PPS signal synchronized to UTC for the input interface unit's time synchronization which requires a continuous 1 PPS signal. The GPS station clock's 1 PPS signal is not suitable for measuring short term stability, but it is useful for monitoring the time drift from UTC over the long term.

Table 1. Specifications of hydrogen maser （RH401A： Anritsu Corp.）

Frequency stability		$\sigma_y = 4 \times 10^{-13}$ (τ =1s)
		$\sigma_y = 3 \times 10^{-15}$ (τ =1h)
Output signal	10MHz	+13dBm±2dB/50Ω 2ch
	5MHz	+13dBm±2dB/50Ω 2ch
	Harmonic signals	< -30dBc
	Isolation between ports	> 120dB
		>80dB(only for the ch2 of 5MHz)
1PPS output	TTL levels	2ch
Clock synchronization	Time reference	rising edge
	Resolution	0.1μs
Environment	Setting temperature	20℃±5℃
	Change of temperature	set value±0.5℃
	Relative humidity	30～90%
	External magnetic field	geomagnetic field(<0.7Gauss）
	Change of magnetic field	< 5mGauss
	Power	60VA

Table 2 Specifications of some instruments

Pulse distribution amplifier		
Inputs	number	2
	Level	< 5VDC
	Sensitivity	> 15mV RMS
	pulse width	25nsec ～ 100μs
Output	number	8ch (4 per module）
	level	5Vpeak into 50Ω
	rise time	< 4ns
	differential delay	< 1ns (between two outputs)
		20ns (between input and output)
temperature stability		< 20ps/℃（20～30℃）
		< 100ps/℃（0～20℃,30～50℃）
GPS station clock		
Receiver description		L1 C/A code pseudo-ranging
Channels		6 independent, continuous tracking channels
Outputs	1 PPS	accurate to within 100 ns of GPS/UTC time
Time code	IRIG B	
Time comparison		The time interval between the external 1PPS signal and UTC reference is measured with 20 ns resolution.
Internal oscillator		high performance crystal oscillator
Reference signal distribution amplifier		
Carrier inputs		5MHz, 10MHz
	Level	< 20V
Carrier outputs	delay	30ns (between input and output)
	Isolation	60dB（between input and output）
		50dB（between two outputs）
	phase noise	(5MHz outputs) -145dBc/Hz (1～10kHz)
		(10MHz outputs) -140dBc/Hz (1～10kHz)

2.3.3 Time code reader

Time code reader converts the IRIG-B time code from the GPS station clock to the parallel time code. Each station has two time code readers; one is for the antenna control PC and another is for the observation control workstation.

2.3.4 Reference signal distribution amplifier

The reference signal distribution amplifier distributes the input 5 MHz carrier signal from the hydrogen maser to 8 channels of 5 MHz and 4 channels of 10 MHz carrier signals. We used an instrument with quite low phase noise to maintain the quality of the input signal. The input level is 3 dBm at 50Ω and output level is 13 dBm at 50Ω. The IRIG-B time code from the GPS standard clock is distributed to four channels, two of which are transmitted to the time code readers. This amplifier is constructed in modular form, and each module can be easily replaced, if there are hardware trouble.

2.3.5 Pulse distribution amplifier

Pulse distribution amplifier has two independent modules. One module distributes the hydrogen maser's 1 PPS signal, that is used for synchronizing the time of the input interface unit and the start signal of time interval counter. Another module distributes the GPS station clock's 1 PPS signal that is used for the stop signal of time interval counter. These modules are also easily changed in the case of hardware troubles.

2.3.6 Time interval counter

Time interval counter measures the time difference between the 1 PPS signals of the hydrogen maser and the GPS station clock. The external reference is the hydrogen maser's 10 MHz signal and the time resolution is 4 ps. The measured data is sent to the monitoring workstation by GPIB every minute. The counter also retains the internal operation parameters when its power is turned off.

2.3.7 Constant temperature room

This room keeps the room temperature at a set level (usually 23 degree) ± 0.3 degree. The hydrogen maser, the GPS station clock, the reference signal distribution amplifier, the pulse distribution amplifier, the time interval counter, and the ground unit of the delay calibration system are equipped inside this room. A hydrogen gas alarm is equipped for the hydrogen maser. The room temperature and humidity data are sent to the monitoring workstation by GPIB every minute.

2.4 Stability measurement of the hydrogen maser

We tested the hydrogen maser in order to confirm its frequency stability. We used the heterodyne measurements of frequency(2) to compare the beat frequency of the 100 MHz signal generated by the 5 MHz signal of RH401A hydrogen maser at Koganei station with the 100 MHz + 1 Hz signal of a Russian CH1-75 hydrogen maser. Fig. 4 shows the result of the short term stability measurement. The horizontal axis is the averaging time τ *(s)* and the vertical axis is the root of the Allan variance σ_y^2, which indicates the characteristics of frequency stability. The frequency stability almost follows the $1/\tau$ slope in $\tau < 100$(s) and the stability at $\tau = 1$ is about 3×10^{-13}. Both of the CH1-75 and the RH401A have a stability of 3×10^{-13} at $\tau = 1$ in their specifications, so we confirmed the performance of the RH401A.

We also checked the long term stability of the data acquisition system's reference time. Fig. 5 shows the result of a time comparison between the 1 PPS signal of the input interface unit and UTC measured by the GPS station clock over about 150 days. The horizontal axis is the observation date and vertical axis is the measured time difference. A small trend due to the hydrogen maser's aging is shown, but it does not affect the accuracy of VLBI data. There is no phase hopping, so we can confirm that the hydrogen maser and the other instruments have been supplying a stable reference time signal.

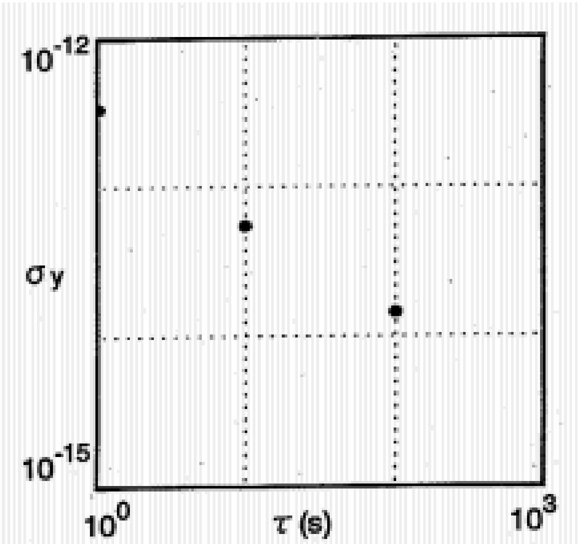

Fig. 4 Short term stability of the RH401A hydrogen maser.

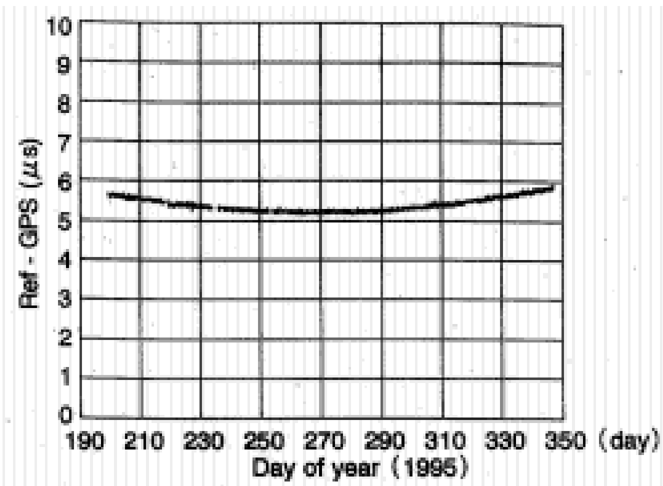

Fig. 5 Long term stability of the 1 PPS signal of the input interface unit.

3. VLBI delay calibration system

3.1 Function of the system

In a VLBI observation, the accuracy of an observation improves as the receiving bandwidth widens. It is difficult, however, to expand the total receiving bandwidth because this requires a recording rate that is too high for the recorder. The bandwidth synthesis method was developed to solve this problem.[(3)] By synthesizing some suitable narrow band channels picked up from a wide band signal, we can obtain the same precision as we could by taking the whole bandwidth. This method improves the accuracy of the measured delay when the recording rate is limited. We use this method in the KSP VLBI system which has a maximum recording rate of 256 Mbps.

When using the bandwidth synthesis method, a reference signal is necessary for phase calibration between the channels. The IF signal obtained from the antenna system is divided and sent to a 16 channel video converter in the data acquisition system, where they are independently converted into video signals. In this process, the 16 conversions may cause different phase shifts and phase fluctuations. To calibrate the phase differences, a marker signal must be added to the observation signal before dividing them into 16 channels.

This marker or calibration signal can be used as the reference signal for instrument delay calibration. If a marker signal is injected from the RF signal at the antenna system, it shows changes in the delay of the signal transmission cable. Systematic error due to the transmission cables can be removed by using this data.

The purposes of the delay calibration system are summarized as following;

(1) to supply the phase reference signal to each video channel for use in band synthesizing, and
(2) to measure the reference signal's phase shift due to the change in the length of transmission cable that is used between the signal injection point and the data acquisition system in the observation room.

The equipment used for the former purpose is called a phase calibrator and that used

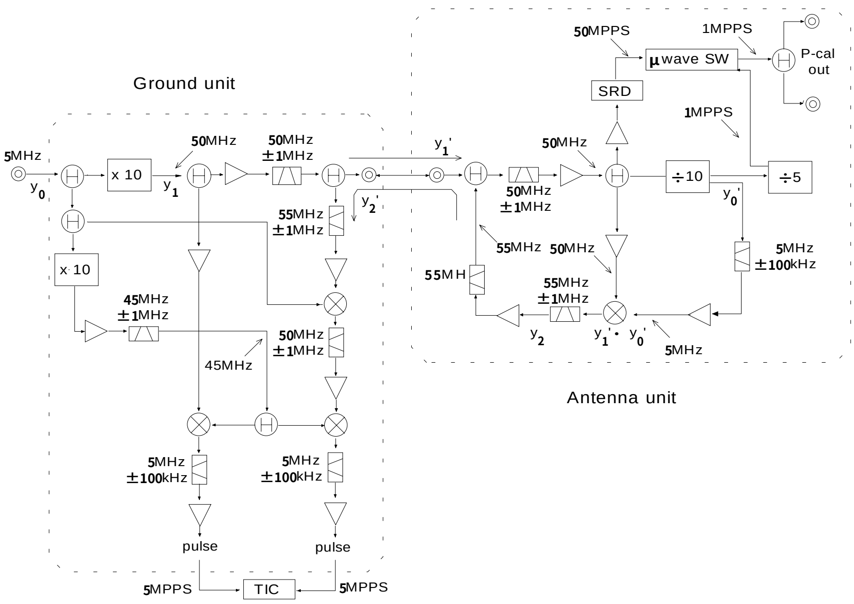

Fig. 6 KSP delay calibration system

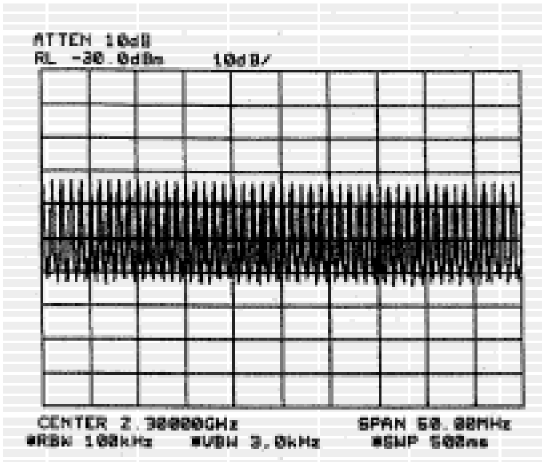

Fig. 7 Output comb pulse of the delay calibration system in the S-band.

for the later purpose is called a cable delay calibrator.

There are two main requirements for a delay calibration system;

(1) to generate comb signal with a 1 MHz interval for convenience when selecting the receiving frequency, and

(2) to have a short term accuracy under 5 ps (～100 sec) and a long term accuracy of 10 ps for measuring the cable length.

3.2 Delay calibration system for the KSP VLBI system

Communications Research Laboratory (CRL) has developed the delay calibration system for K3 VLBI system,(4) but it has some problems. The most significant are phase fluctuation in the calibration signal and fluctuation in the measured length of the transmission cable, which are both due to temperature changes near the delay calibration system. In order to reduce this effect, the KSP

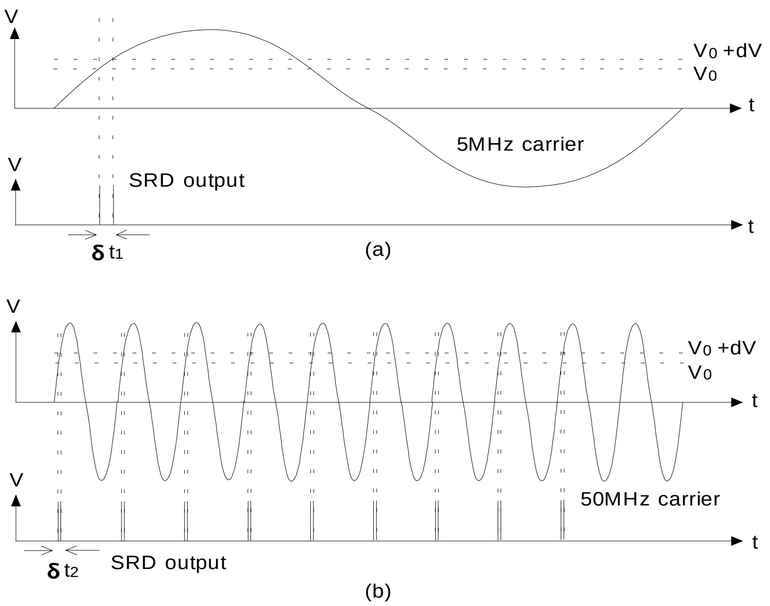

Fig. 8 Phase fluctuation of the comb pulses at the delay calibration system.
(a) Case of using the 5 MHz carrier signal.
(b) Case of using the 50 MHz carrier signal.

system has been modified by;

(1) using a high frequency carrier signal (50 MHz) for making the calibration pulses instead of a 5 MHz carrier signal, and
(2) changing the method for measuring cable length.

Fig. 6 shows the complete KSP delay calibration system. It consists of the ground unit in the observation room and the antenna unit in the antenna receiving room. The ground unit generates the 50 MHz carrier signal from the hydrogen maser's 5 MHz signal and sends it to the antenna unit. Using this 50 MHz carrier signal, the SRD in the antenna unit generates narrow pulses with a 20 ns time interval. From these pulses, 1 MPPS pulse is created by picking up one pulse per 50 pulses. This 1 MPPS pulse consists of comb signals with a 1 MHz interval in the frequency region. These comb signals are added to the observation RF signals as the phase reference signal. Fig. 7 shows the output comb pulses of the antenna unit in the S-band. The level of the peaks are -62～ -63 dBm per pulse and are flat over the 50 MHz bandwidth.

The merit of using a 50 MHz carrier signal is explained in Fig. 8. The SRD generates the pulse at the moment when the input carrier signal is over the trigger level V_0. If V_0 fluctuates due to temperature changes, the output pulse phases also fluctuates in δt_1 (Fig. 8(a)). This phase fluctuation can be reduced to δt_2 by using a 50 MHz carrier signal instead of a 5 MHz carrier signal because the rising time at the trigger level is reduced (Fig. 8(b)). The fluctuation should be 1/10th of that of the K3 system. Of course the temperature of the multiplier which generates the 50 MHz signal must be stable and so the ground unit is placed in the constant temperature room.

Cable length measurement is very different from the method used in the K3 system. The phase synchronization method with phase shifter used in the K3 system has been abandoned, because it is sensitive to temperature changes. The cable delay measurement in the new systems explained below. The 5 MHz reference signal (y_0) and its multiple 50 MHz signal (y_1) are expressed as follows;

$$y_0 = \cos \omega_0 t \qquad (1)$$

$$y_1 = \cos 10\omega_0 t \qquad (2)$$

This 50 MHz signal is transmitted to the antenna unit with delay dt_1 and becomes y_1'.

$$y_1' = \cos 10\omega_0 (t - dt_1) = \cos (10\omega_0 t - \phi_1) \qquad (3)$$

$$\phi_1 = 10\omega_0 dt_1 \qquad (4)$$

In the antenna unit, this 50 MHz signal (y_1') and the 5 MHz signal (y_0') made from 50 MHz are mixed, then a 55 MHz signal (y_2) is generated.

$$\begin{aligned} y_1' \quad y_0' &= \cos (10\omega_0 t - \phi_1) \quad \cos (\omega_0 t - \phi_1/10) \\ &= 1/2 \quad \{ \cos (11\omega_0 t - \phi_1 - \phi_1/10) + \cos (9\omega_0 t - \phi_1 + \phi_1/10) \qquad (5) \end{aligned}$$

$$y_2 = \cos (11\omega_0 t - \phi_1 - \phi_1/10) \qquad (6)$$

This 55 MHz signal is sent back to the ground unit with a delay of dt_2 and becomes y_2'.

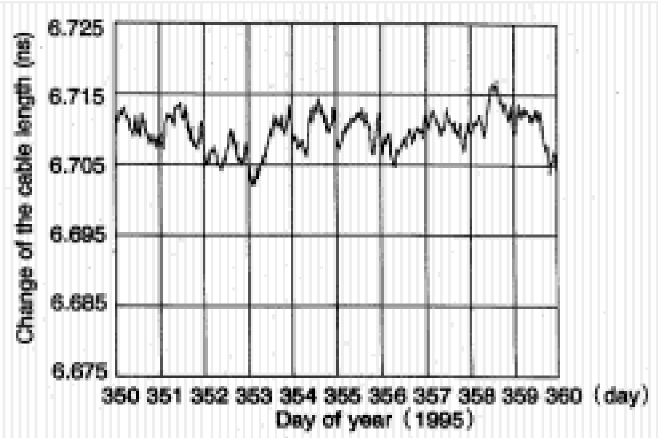

Fig. 9 Change of the transmission cable length.

$$y_2' = \cos\{11\omega_0(t - dt_2) - \phi_1 - \phi_1/10\} = \cos(11\omega_0 \quad t - \phi_2) \qquad (7)$$

$$\phi_2 = 11\omega_0 \quad dt_2 + \phi_1 + \phi_1/10 = 11\omega_0(dt_2 + dt_1) \qquad (8)$$

The cable delay dt_1+dt_2 emerges in the phase of the returned 55 MHz signal, and we can measure it using the time interval counter. We used a counter with a high time resolution in order to limit the phase expansion factor to 10, and succeeded in obtaining a time resolution of 0.5 ps for a one shot measurement. If the phase expanding factor becomes large, the effect of the local signal's fluctuation becomes large. We also used the counter's averaging function in order to improve the time resolution even more.

We tested the performance of the cable length measuring device over 10 days. The ground unit and the antenna unit were set in the constant temperature room. As shown in Fig. 9 , the fluctuation due to the system itself is within 10 ps, which means that the system can measure the change of cable length with an accuracy of 10 ps.

4. Conclusion

We have developed a reference signal distribution system and a delay calibration system which influence the accuracy of VLBI observations. The systems must be stable and work continuously, because KSP VLBI observations are basically carried out everyday without an operator. We selected the instruments according to their reliability as much as their performance. We equipped the Koganei and Kashima stations in 1993, the Miura stations in 1994, and the Tateyama station in 1995 with the reference signal distribution systems. There were some hardware troubles at first but the system almost satisfies our expectations. With the delay calibration system, we have not obtained the expected precision over the whole system because some devices have trouble with temperature variations, and we are making effort to rectify this.

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