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FIRST INTERNATIONAL TIME AND FREQUENCY COMPARISON EXPERIMENT BY USING VERY LONG BASELINE INTERFEROMETRY

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ABSTRACT

This paper discusses the precision of time comparison using VLBI (Very Long Baseline Interferometer) and describes its result by comparison with other method. RRL (Radio Research Laboratory, Japan) and USNO (US Naval Observatory) have conducted the time comparison experiments by using VLBI between Kashima station of RRL and Richmond (Fl. USA) station of USNO in order to attain the precision higher than 1.0 ns. Time comparison with such a high precision is the first attempt in the world.

A test experiment was conducted in October 1984, and regular experiments have been conducted almost every month since April 1985. We also used GPS (Global Positioning System) as a complementary method to compare time at these stations.

In each experiment, 0.2 ns as one sigma of residual O-C for clock offset and 0.02 ps/s for clock rate (corresponding to 2.0×10^{-14} for frequency) were achieved with a few hour experiment. The VLBI results agreed with those of the complementary method within the error for clock offset.

VLBI provides a precision which is a hundred times as high as that for T/F (Time and Frequency) as compared with the conventional method like PC (Portable Clock) and Loran-C. Therefore, these conventional systems can be calibrated by using VLBI.

1. Introduction

RRL developed a VLBI system called K-3 at Kashima Space Research Center(1)(2) and successfully started the Japan-US joint experiment in July 1984 for measuring plate motions with a precision which is higher than 3 cm (0.1 ns)(3). On the other hand, USNO also has a VLBI system at Richmond called Mark-III developed by NASA. K-3 system is compatible with Mark-III.

VLBI provides an extremely high precision not only for geodesy but also for T/F comparison. Though VLBI requires large-scale equipment and complicated processing, it has much higher precision and accuracy than other methods as shown in Table 1.

RRL is in charge of the generation and dissemination of the standard time and frequency in Japan. The data are sent to BIH (Bureau International de l'Heure, France) to contribute to the determination of the international coordinated universal time (UTC).

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Table 1. Features of various time comparison methods

Method	Precision	Accuracy	Coverage	Features
VLBI	0.1 ns	$<$10 ns	global	expensive and complicated
GPS	20 ns	$<$100 ns	global	simple but army system
Loran-C	100 ns	1000 ns	global	simple, chains disconnected
PC	$<$100 ns	$<$100 ns	global	without extra equipment
GMS	20 ns	$<$100 ns	limited	fairly simple
CS-2	2 ns	10 ns	limited	two-way method
TV	10 ns	100 ns	near only	simple

The international time comparison has been made by Loran-C and PC (Portable Clock) regularly. However, VLBI will replace the conventional systems from now on together with the new space technologies such as GPS, GMS (Geostationary Meteorological Satellite), CS (Communication Satellite) and BS (Broadcasting Satellite)(4)(5).

2. Estimation of the Precision

The clock offset τ_c is expressed as follows(6):

$$\tau_c = \tau - \tau_g - \tau_i - \tau_p \quad \ldots\ldots\ldots\ldots \quad (1)$$

where τ_c : clock offset
τ : total delay (VLBI observable)
τ_g : geometrical delay
τ_i : instrumental delay
τ_p : propagation delay

Here we estimate the error budget of clock offset τ_c derived from the VLBI experiment. We must distinguish the variable components from the bias components.

(a) τ

The error of τ is expressed as follows(6):

$$\Delta\tau = (\mathrm{SNR} \cdot \omega_{\mathrm{rms}})^{-1} \quad \ldots\ldots\ldots\ldots \quad (2)$$

where ω_{rms} is the root mean square of the RF angular frequency. $(\omega_{\mathrm{rms}})^{-1}$ is 1.14×10^{-9} and SNR is greater than 10 in these experiments. Therefore, this error is under 0.1 ns.

(b) τ_g

Though the position offsets of radio sources and stations cause an offset to τ_g, the formal error does not increase. But the EOP (Earth Orientation Parameters), which is necessary for the analysis, scatters in every experiment. EOP consists of the wobbling (polar motion which is shown in Fig. 1) and UT1-UTC (irregularity of earth rotation). They cause an increase in the formal error. The delay errors $\Delta\tau$ due to the a priori error of the wobbling

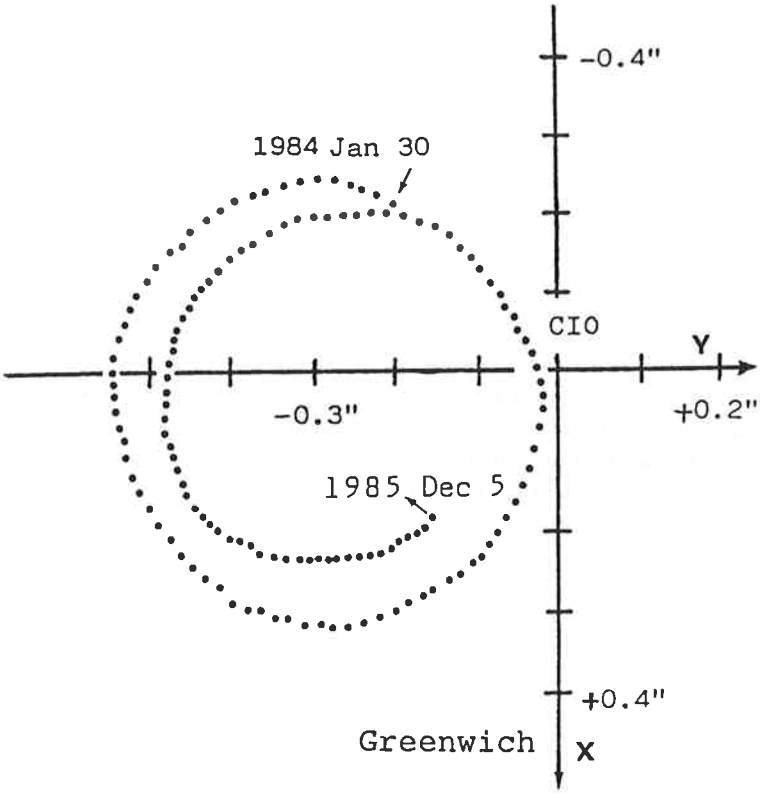

Fig. 1 Wobbling (Polar Motion) from 1984 to 1985.

(ΔX and ΔY) are expressed as follows:

$$\Delta\tau = (-B_Z \cos\delta \cdot \cos HA - B_Y \sin\delta)\, \Delta X/c \quad \text{.......................} \quad (3)$$

$$\Delta\tau = (B_Z \cos\delta \cdot \sin HA + B_X \sin\delta)\, \Delta Y/c \quad \text{...........................} \quad (4)$$

Similarly, the delay error due to the a priori error of UT1-UTC (denoted as ΔU) is expressed as follows:

$$\Delta\tau = (-B_Y \cos\delta \cdot \sin HA + B_X \cos\delta \cdot \cos HA)\, 2\pi \cdot \Delta U/(86400 \cdot c) \quad \text{........} \quad (5)$$

where B_X, B_Y, B_Z : components of the baseline vector
δ, HA : declination and hour angle of the radio source
c : speed of light
86400 : number of seconds included in a day

The most reliable EOP data are supplied from IRIS (International Radio Interferometric

Serveying) network, which conducts VLBI experiments over 24 hours every 5 days. Its precision is about 1-2mas (milli arc second) for wobbling and about 0.1 ms for UT1. From Equations (3), (4), (5) and precisions of IRIS data, the error contribution of ΔX and ΔY to τ_g is dominant for the high declination sources; about 0.2 ns, and that of ΔU is dominant for low declination sources; about 0.2–0.3 ns.

(c) τ_i

The variable component of the instrumental delay τ_i is compensated by using the delay calibrator. τ_i is discussed in detail by Kiuchi et. al.(7). The precision of τ_i calibration is about 0.2 ns.

(d) τ_p

The excess path delay of the radio wave is caused by the ionosphere and the atmosphere (dry and wet components). Ionospheric delay is compensated by dual frequency method (S and X band) and dry component of the atmosphere is easily estimated from the atmospheric pressure at the ground surface. The wet component causes the error for τ_i most dominantly. Because it is well known that even if one set of TPH (Temperature, Pressure, Humidity) at the ground surface is given, a profile of the atmosphere cannot be decided uniquely. We used the following model(8) presented by Marini to calculate the excess path EP caused by the atmosphere:

$$EP = \frac{1}{g} \cdot \frac{A+B}{\sin(El) + \frac{B/(A+B)}{\sin(El) + 0.015}} \quad \cdots\cdots (6)$$

$$A = 0.002277\,[P_s + (1255/T_s + 0.05)\,e_s]$$

$$B = 2.644\times10^{-3} \exp(-0.14372\times10^{-3} H)$$

where			
	g	: gravitational acceleration	[m/s^2]
	El	: elevation	
	P_s	: atmospheric pressure at the ground surface	[mb]
	T_s	: temperature at the ground surface	[K]
	e_s	: water vapor pressure at the ground surface	[mb]
	H	: height	[m]

The difference between the real excess path and the excess path calculated from model is not measured precisely now. This difference seems to be within 0.1 ns at zenith except summer. Kashima and Richmond are going to utilize WVR (Water Vapor Radiometer) to calibrate the effect of the wet component for the compensation.

Thus we get the error budget 0.4–0.5 ns as the RSS (Root Sum Square) of the factors from (a) to (d).

Actually, we got 0.2 ns from the analysis of the experiment as mentioned in Section 5.

3. "Complementary Link"

We used GPS as a complementary method to confirm the result of VLBI. RRL headquarters (Tokyo) and USNO headquarters (Washington D.C.) observe the same GPS satellites every day to get the time difference. As shown in Fig. 2, however, the VLBI route between

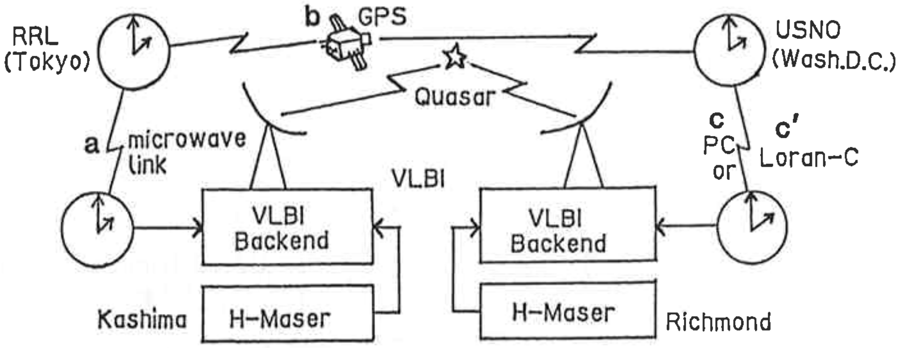

Fig. 2 System of the T/F Comparison Experiments.

Kashima and Richmond is not directly connected with the GPS route; between RRL Tokyo and USNO Wash. D.C. Therefore, we also used the microwave link, and PC or Loran-C to connect these stations at the time of these experiments. Time difference between Kashima and RRL Tokyo is measured with a microwave link of 7 GHz every 4 hours automatically. Time difference between USNO and Richmond had been measured by PC till April 1985, and by Loran-C since June 1985. Let this method (route a+b+c or a+b+c$'$) be designated as "Complementary link" in this paper. GPS has the highest precision over intercontinental baselines except VLBI. The error budget of Complementary link between Kashima and Richmond is as follows:

a. Kashima	–RRL Tokyo	(microwave link)	20 ns
b. RRL Tokyo	–USNO Wash. D.C.	(GPS)	50 ns
c. USNO Wash. D.C.	–Richmond	(PC)	80 ns
c$'$. USNO Wash. D.C.	–Richmond	(Loran-C)	100 ns

The RSS of a+b+c (or a+b+c$'$) comes up to 100–120 ns. In the future, Kashima and Richmond will possess GPS receivers. Then we will be able to confirm the time difference between Kashima and Richmond within 20 ns.

4. Experiment

Fig. 3 shows the geometry of the stations in the time comparison experiments. The condition of these experiments is summarized in Table 2. Dual frequency is necessary for compensation of the delay caused by the ionosphere. Large antennas are needed to get fringes for weak radio sources. The mutual visibility of the radio sources limits what, when, and how we observe on such a long baseline as 10,000 km.

The one sigma of about 0.1 ns is available by 24-hour VLBI experiment. But we have chosen an easier and shorter way for the regular experiment; 8 observations in 2 hours net, which is enough to attain a precision higher than 1.0 ns.

Table 3 is a summary of the experiments.

The first test observation was made in October 1984 between Kashima station of RRL and Richmond station of USNO. The experiment to confirm the estimated baseline vectors among Kashima and Richmond stations and Maryland Point station was conducted in

Fig. 3 Stations Joining the T/F Comparison Experiments.

Table 2. Condition of the time comparison Experiments by VLBI

Radio sources	OJ287, 4C39.25, 3C273B, OQ208 (RHCP)
Frequencies	X-band 8180–8600 MHz, S-band 2200–2320 MHz
Sample rate	4 Mb/s x 14 ch. (8 for X-band, 6 for S-band)
Observation time	400 sec. 2 for each source
Antennas	26 m parabolic antenna at Kashima, RRL 18 m parabolic antenna at Richmond, USNO

Table 3. T/F comparison experiments by VLBI conducted

Date	Stations			Number of obs.	Remarks
	Kashima	Richmond	Maryland Pt.		
Oct. 2 1984	joined	joined	–	8	Fringe test
Dec. 6 1984	joined	joined	joined	85	24 hours
Apr. 5 1985 | *	joined	joined	–	8	Regularly 2 hours (every 1–2 months)

* Regular experiment has been conducted since this date.

December 1984. But the X band data of Maryland Point was not good to make a "closure test"(6). Since April 1985, Kashima and Richmond have made regular experiments for T/F comparison almost every month.

5. Results

Fig. 4 shows the formal error (i.e. precision) of residual clock offset and clock rate between Kashima and Richmond obtained by a series of VLBI experiments. The mean formal error of the clock offset is about 0.2 ns and that of rate is about 0.02 ps/s. This value 0.2 ns is less than the error budget estimated in Section 2. Though the error caused by the atmosphere is expected to be large in summer as mentioned in Section 2 (b), the measured formal errors from June to August 1985 are not so remarkable. Since the number of observations in one experiment is not enough, we are not able to estimate the effect of atmosphere.

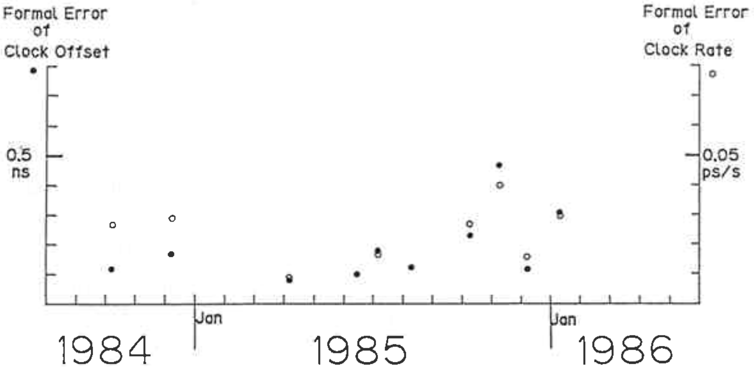

Fig. 4 Formal Error of Clock Offset and Rate in Each Experiment.

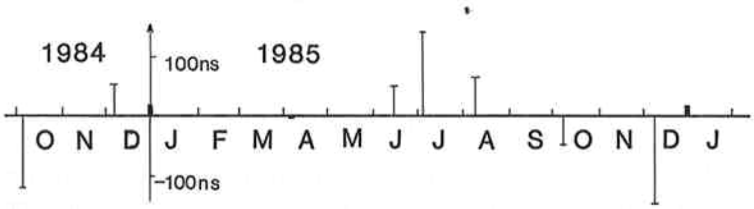

Fig. 5 Difference between the Clock Offset Obtained by VLBI and that by Complementary Link.

Fig. 5 shows the difference between the clock offset obtained by VLBI and that obtained by Complementary link from October 1984 to December 1985. Fig. 6 indicates the behaviors of clock rate derived by VLBI. Ordinate means UTC (Kashima) minus UTC

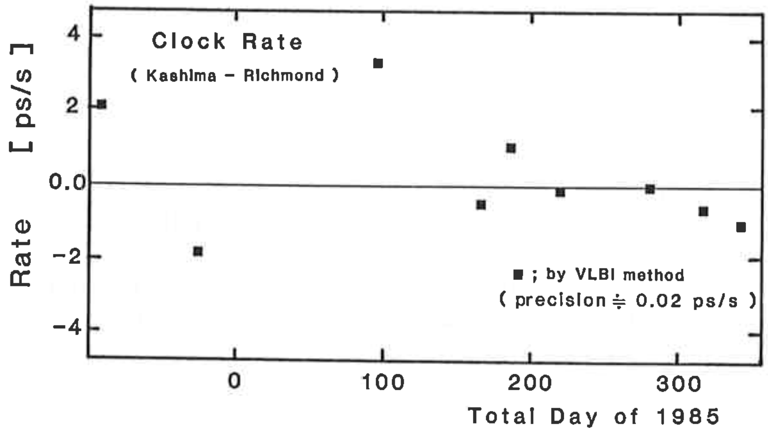

Fig. 6 Clock Rate of UTC (Kashima) – UTC (Richmond).

(Richmond). Most values seem to be within the precision of Complementary link whose error budget is about 100–120 ns as mentioned in Section 3.

We compared the clock rate derived from VLBI method with that from Complementary link for the data obtained in October and December 1984. These two coincided with each other with an error of 0.1 ps/s as shown in Table 4. For other experiments, we could not obtain an adequate set of comparison data from which clock rate is reliably determined.

Table 4. Clock Rate: VLBI method – Complementary link

Methods	'84, 10/2	'84, 12/6
VLBI	–1.19 ps/s	1.36 ps/s
GPS	–1.31 ps/s	1.30 ps/s

6. Conclusion

RRL and USNO have conducted the VLBI time comparison regular experiments almost every month since April 1985. We have attained the precision of 0.2 ns (one sigma) for clock offset and 0.02 ps/s for clock rate.

In order to achieve an accuracy higher than 1.0 ns, we must calibrate the instrumental delay around the antenna and front end which cannot be corrected by the delay calibrator. We are conducting ZBI (Zero Baseline Interferometry) experiments in 1986-87 in order to determine the differential instrumental delay between two stations. The reference receiver developed by RRL is used as a medium in ZBI.

The conventional time comparison methods can be calibrated by using VLBI.

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