4-7 VLBI and GPS Carrier Phase Time and Frequency Transfer

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As one of the new frequency transfer technique to compare the next highly stable frequency standards, we proposed the geodetic VLBI technique. We evaluated the ability of VLBI frequency transfer by comparison with GPS carrier phase frequency transfer. These comparisons showed that geodetic VLBI technique has the potential for precise frequency transfer. In this paper, we describe the previous comparison with VLBI and GPS carrier phase.

Keywords
Very Long Baseline Interferometry, Global Positioning System, Time and frequency transfer

1 Introduction

The atomic fountain primary frequency standards (NICT-CsF1) developed by National Institute of Information and Communications Technology (NICT) have already achieved uncertainty at the level of 1.9×10^{-15}[1]. Moreover, optical frequency standards currently under development are expected to achieve uncertainty level of 10^{-16} to 10^{-17}[2]. In order to contribute the uncertainty of these primary frequency standards to the International Atomic Time (TAI), it is necessary to precisely determine the difference of frequency between the primary frequency standards and TAI. However, because the precision of two-way satellite time and frequency transfer (TWSTFT) and GPS carrier phase time transfer techniques, the current methods for comparing the time difference between the primary frequency standards and atomic clocks, are at the 10^{-15} level[3], it is necessary to average over several days in order to evaluate the uncertainty of these primary frequency standards. In addition, it would be necessary to carry out continuous operation from several dozen days to several months in order to evaluate the next generation frequency standards. However, that evaluation is impossible in reality. Therefore, a high precision time transfer technique which can evaluate the uncertainty at less averaging time is highly desired.

Very Long Baseline Interferometry (VLBI) is one of the space geodetic techniques which precisely measures the arrival time delays between multiple stations utilizing radio signals from distant celestial radio sources. Generally, the S band (2GHz) and X band (8GHz) are used in the geodetic VLBI experiment. In the usual geodetic VLBI analysis, clock offsets and their rates of change at each station are estimated with respect to a selected reference station. The averaged formal error (1σ) of the clock offsets is typically about 20ps when analyzing the geodetic VLBI experiments that are regularly conducted by the International VLBI Service for Geodesy and Astrometry (IVS). This precision is nearly one order better than other techniques like GPS or TWSTFT.

For this reason, we propose the geodetic

VLBI technique as one of the new time and frequency transfer technique for comparison of highly precise primary frequency standards such as atomic fountain frequency standards and optical frequency standards[4][5]. At the same time, to confirm the potential of the current VLBI time and frequency transfer technique we are comparing the results of the VLBI and other techniques[6]-[9]. Research and development on the application of geodetic VLBI technique to time and frequency transfer has been ongoing since the time of the Radio Research Laboratories, the predecessor of NICT[10][11], and international experiments have been carried out for many years. At this time, we are simultaneously developing the compact VLBI system (MARBLE : Multiple Antenna Radio-interferometer for Baseline Length Evaluation)[12] which is aimed at practical application in the future. Usually the diameter of VLBI antenna which is used for geodetic experiment is over 10m. The diameter of antenna which is developed at this compact VLBI system is 1.6m. In this compact VLBI system, we are considering the strategy based on 3 baselines which consist of 2 developing small antennas and 1 existing large antenna. See[13] for the current status of the development of this compact VLBI system. In this paper, we describe the comparison of the time and frequency transfer results between VLBI and GPS to confirm the potential of the current VLBI time and frequency transfer.

2 Intercomparison between VLBI and GPS carrier phase method

In order to verify the time and frequency transfer capability of the current VLBI system, we carried out geodetic VLBI experiments and GPS carrier phase time and frequency transfer in parallel on the same baseline, and compared the results. First we show the comparison of the reanalyzed results of data from regular observations carried out at IVS and IGS (International GNSS Service). Then we will explain the experiment using NICT's antenna on the Kashima–Koganei baseline.

2.1 Comparison using IVS and IGS data

We selected the Onsala station (Sweden) and Wettzell station (Germany) both on the IVS and IGS networks (Fig. 1). The VLBI antennas for both stations are of 20m diameter and for GPS onsa and wtzr of the IGS ID were used. Both stations shared a hydrogen maser for both VLBI and GPS as the reference signal. Data used for VLBI was taken from R1 sessions (R1 session is implemented every 2 weeks aimed at determining earth orientation parameters (EOP)) and for GPS because R1 session is a 24-hour observation over the course of a day, a 2 day RINEX file was edited into a single file for use. A list of the data used is shown in Table 1. Since 2008, the Wettzell station GPS receiver was changed, the stability also changed, and it is therefore not used in the comparisons thereafter. The details of the analysis of both VLBI and GPS are shown in Table 2. We employed the calc/solve baseline analysis software which was developed by GSFC (Goddard Space Flight Center) for VLBI analysis. For GPS, we analyzed GPS data by GIPSY-OASIS Ⅱ ver. 5.0 which was developed by

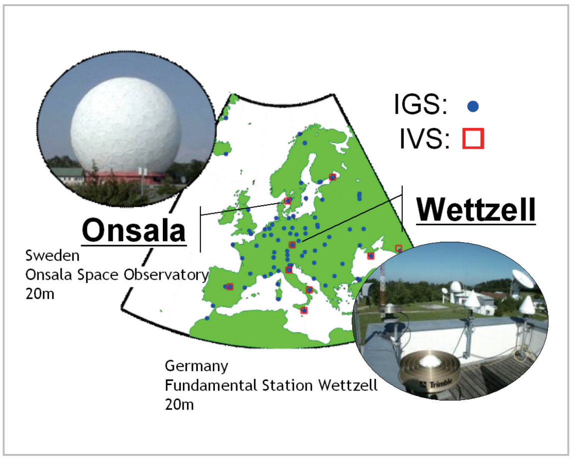

Fig.1 *Distribution of both IVS and IGS stations in Europe*

In verification, we selected two stations (Onsala and Wettzell) which belong to both IVS and IGS network. These two stations share the hydrogen maser at each site VLBI and GPS. The VLBI antennas for both stations are a 20m diameter, and for GPS onsa and wtzr of IGS ID were used.

Table 1 *List of data used*

VLBI			On: Onsala, Wz: Wettzell			GPS				
Session	Date	DOY	Time	Duration	Stations	Date	DOY	Time	Duration	Stations
R1258	07JAN09	9	17:00	24	HhKkNyOnTsWfWz	07JAN09	9	—	—	—
R1260	07JAN22	22	17:00	24	KkNyOnTcTsWfWzZc	07JAN22	22	0:00	48	onsa, wtzr
R1262	07FEB05	36	17:00	24	HhKkNyOnShTsWfWz	07FEB05	36	0:00	48	onsa, wtzr
R1263	07FEB12	43	17:00	24	HhKkNyOnShTcWfWz	07FEB12	43	0:00	48	onsa, wtzr
R1265	07FEB26	57	17:00	24	KkMcNyOnTcWfWzZc	07FEB26	57	0:00	48	onsa, wtzr
R1270	07APR02	92	17:00	24	HhKkNyOnShTsWfWz	07APR02	92	0:00	48	onsa, wtzr
R1271	07APR10	100	17:00	24	KkNyOnTcTsWfWzZc	07APR10	100	0:00	48	onsa, wtzr
R1273	07APR23	113	17:00	24	KkMcNyOnTcTsWfWz	07APR23	113	0:00	48	onsa, wtzr
R1274	07MAY02	122	17:00	24	FtHhNyOnTcWzZc	07MAY02	122	0:00	48	onsa, wtzr
R1285	07JUL16	197	17:00	24	HhKkOnWfWz	07JUL16	197	0:00	48	onsa, wtzr
R1291	07AUG27	239	17:00	24	KkNyOnTcTsWfWz-Zc	07AUG27	239	0:00	48	onsa, wtzr
R1292	07SEP04	247	17:00	24	HoKkNyOnTcTsWfWz	07SEP04	247	0:00	48	onsa, wtzr
R1293	07SEP10	253	17:00	24	KkNyOnTcTsWfWz	07SEP10	253	0:00	48	onsa, wtzr
R1294	07SEP17	260	17:00	24	HhKkNyOnWfWz	07SEP17	260	0:00	48	onsa, wtzr
R1295	07SEP24	267	17:00	24	HhKkNyOnTcWfWz-Ho	07SEP24	267	0:00	48	onsa, wtzr
R1311	08JAN14	14	17:00	24	BdFtHhNyOnTcWfWz	08JAN14	14	—	—	—
R1312	08JAN22	22	17:00	24	FtHhNyOnTcWfWz	08JAN22	22	—	—	—
R1315	08FEB11	42	17:00	24	FtHhOnTcWfWz-Ny	08FEB11	42	—	—	—
R1316	08FEB19	50	17:00	24	FtHhNyOnTcWfWz	08FEB19	50	—	—	—
R1325	08APR22	113	17:00	24	BdFtHhOnTcWz-NyWf	08APR22	113	—	—	—
R1327	08MAY05	126	17:00	24	BdFtHhNyOnTcWfWz	08MAY05	126	—	—	—
R1334	08JUN23	175	17:00	24	FtHhMaNyOnTcWfWz	08JUN23	175	—	—	—
R1336	08JUL07	189	17:00	24	FtHhNyOnTcWfWz-Bd	08JUL07	189	—	—	—

Table 2 *Analysis strategies for VLBI and GPS*

Experiment	Category	VLBI	GPS
IVS vs. IGS Kashima–Koganei baseline	Software	Calc/Solve	GIPSY-OASIS Ⅱ
	Strategy	multi baseline S/X ionosphere-free linear combination reference station: Wettzell / Kashima34m	Precise Point Positioning (PPP) After each station analysis, subtract each estimated clock offset values.
	Estimate Parameter	station coordinates atmospheric delay /1h clock offset /1h	station coordinates atmospheric delay /5min clock offset /5min

JPL (Jet Propulsion Laboratory) along with JPL's satellite ephemerides and satellite/station clocks.

We compared the variation of the time differences estimated from VLBI and GPS at Wettzell and Onsala station. In VLBI analysis, we estimated the clock offsets hourly from the delays of each scan. At this time the estimated error in all sessions was 15ps. Due to the code noise, the clock offsets of the GPS results show discontinuities at the day-boundary. The averaged the day-boundary discontinuity was 94ps. Despite the day-boundary discontinuity found with GPS, the overall variation trends of VLBI and GPS were fairly well matched (±200ps).

Figure 2 shows the frequency stability of clock offsets which were obtained from VLBI and GPS (VLBI: circular+solid line, GPS: triangular+solid line). Further, VLBI results

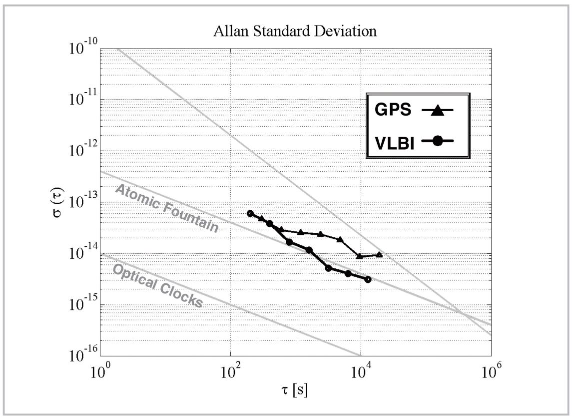

Fig.2 *Frequency stability calculated from VLBI and GPS results*

There was no difference between VLBI and GPS in short-term stability, however at an averaging time of 10^3s or more VLBI results were more stable. In addition, at an averaging time of 10^3s VLBI results reached the stability of atomic fountain frequency standards. Overall, VLBI stability maintained a variation of around 1/τ at an averaging time of up to 10^3s.

were plotted an averaged data at every 100 seconds, because VLBI data cannot be obtained at an averaging time of 1 second. There was no difference between VLBI and GPS in short-term stability, however at an averaging time of 10^3s or more VLBI results were more stable. In addition, at an averaging time of 10^3s or more VLBI results reached the stability of atomic fountain frequency standards. Overall, VLBI stability maintained a variation of around $1/\tau$ as far as an averaging time of 10^4s. These results show that the geodetic VLBI technique has the potential for precise frequency transfer as expected.

2.2 Comparison on the Kashima–Koganei baseline

The results obtained from the intercomparison between VLBI and GPS using IVS and IGS data showed that the geodetic VLBI technique has the potential for the precise time and frequency transfer as expected. However, we couldn't obtain the results of long-term stability about VLBI, because the IVS observations are usually only 24-hour. Therefore, we carried out long term parallel experiments using the NICT's own VLBI stations (Kashima 34m, Kashima 11m, Koganei 11m) and GPS stations (ks34, ksmv, kgni: Trimble NetRS), and compared the results. The positions of the Kashima station and Koganei station antennas are shown in Fig. 3. The Kashima 34m and Kashima 11m antennas share the same hydrogen maser, and the reference signal is sent to the both antennas by the coaxial cables. The distance from hydrogen maser to Kashima 11m antenna is approximately 300m. For GPS, we installed the GPS antenna near the VLBI antennas, and connected the same reference signal which is used in VLBI to GPS receiver.

Fig.3 *Layout of Kashima station and Koganei station*

We carried out the Kashima–Koganei baseline experiment repeatedly since 2007. Especially, we show the results of the Kashima 34m–Koganei 11m baseline experiment which was carried out in August 2008. In this experiment, we carried out the observation for more than one week consecutively. In addition to VLBI and GPS, we also carried out frequency transfer by the Dual Mixer Time Difference (DMTD)[14] on the Kashima 34m–Kashima 11m baseline. The strategy of the analysis was same as the strategy which I described above (Table 2). The time difference results obtained from the 3 methods, VLBI, GPS and DMTD, are shown in Fig. 4. As for the results of VLBI, the variation of the around several days agree with the results of DMTD well. However, it doesn't agree with DMTD, when the variation is beyond 500ps in several hours. Contrastively, as for the results of GPS, the variation of several hours agrees with the results of DMTD well. However, due to the code noise, the clock offsets of the GPS show discontinuities at the day-boundaries. It seems that the reason why the result of VLBI doesn't agree with DMTD when the variation of DMTD is beyond 500ps at the short period is analysis strategy and schedule of scan time. The cause of time difference variations of 500ps for several hours was temperature changes caused by the air conditioning in the back-end room of the Kashima 11m antenna. In addition, the diurnal variations were found with all 3 results. It suggests that these diurnal variations were caused from the transmission system of the reference signal which is shared in all 3 methods, because these variations were found in all 3 results. To reduce the influence of temperature change, we installed a precise temperature control room at the Kashima 11m building, and set the transmission system of the reference signal into this room. The temperature inside this room is stable to within ±0.1°C. Figure 5 shows the results of the August 2010 Kashima–Koganei experiments which were carried out after these corrective measures. The common trends of these results were already removed up to 2nd-order. Though this experiment was carried out in mid-summer, there were nearly no diurnal variations. Placing the reference signal transmission system in the precise temperature control room was effective. However, we didn't perform the measures to reduce temperature influence for the coaxial cable between the Kashima 11m building and the maser room. Therefore, it can be assumed that some minor influence of cable contraction due to temperature variations still remained in these results.

The frequency stability calculated from the VLBI results is shown in Fig. 6. In the results of the Kashima 34m–Koganei 11m baseline which used the same reference signal, the same stability as atomic fountain frequency standards was achieved at an averaging time of 10^5s or more.

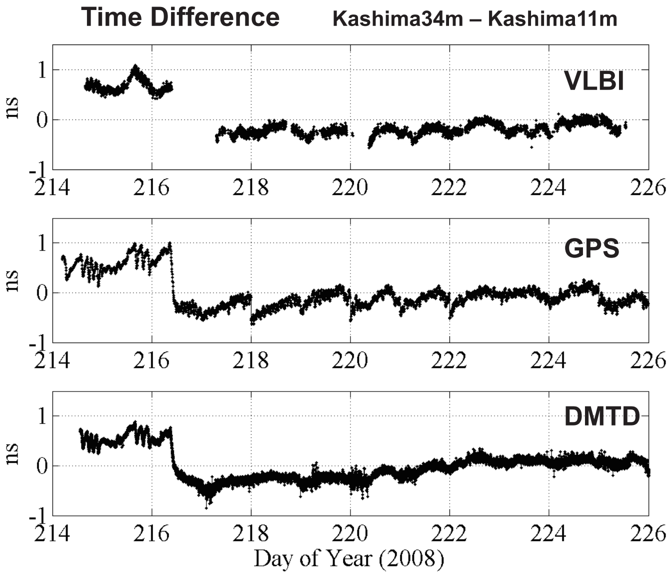

Fig.4 *The time difference results of the 3 techniques: VLBI, GPS and DMTD*

Kashima 34m–Kashima 11m baseline

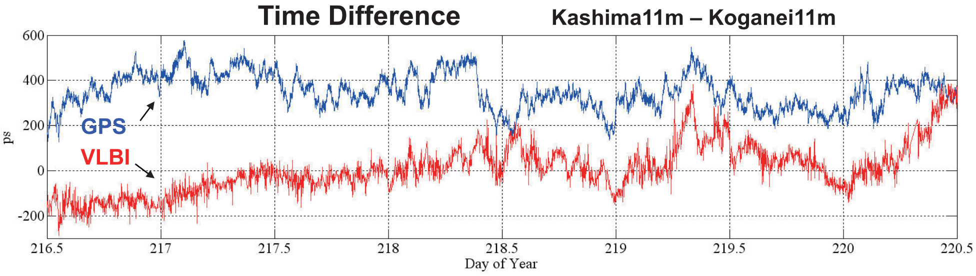

Fig.5 *Time difference in August 2010 experiments*

Kashima 11m–Koganei 11m baseline

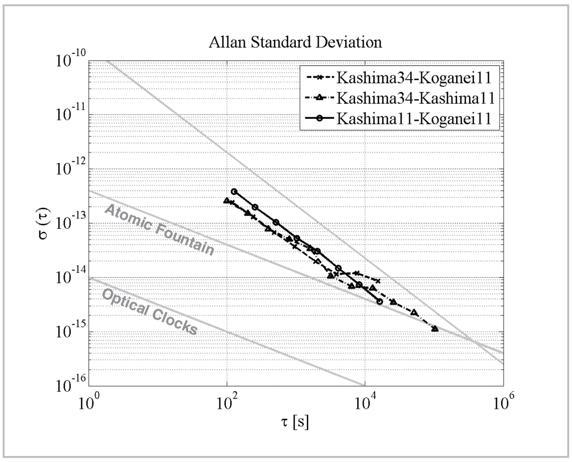

Fig.6 *Frequency stability of VLBI on the Kashima–Koganei baseline*

Kashima 34m–Koganei 11m and Kashima 34m–Kashima 11m were the August 2008 experiments. Kashima 11m–Koganei 11m was the August 2010 results.

Fig.7 *The coaxial phase shifter*

It was made by Nihon Koshuha Co., Ltd. The maximum time change is 333.7ps. An internal U-shaped circuit can be expanded and contracted by turning the dial.

2.3 Comparison using a coaxial phase shifter

Furthermore, in order to verify whether VLBI and GPS were correctly measuring time difference, we compared the precision of the both techniques by expanding or contracting a coaxial phase shifter (Fig. 7). We used the coaxial phase shifter which was made by Nihon Koshuha Co., Ltd. The variable stroke of this coaxial phase shifter is 100mm (air line), therefore it can change the delay up to 333.7ps. We then compared to what degree this maximum delay change amount of 333.7ps was being correctly measured using VLBI and GPS.

For VLBI the Kashima 34m and Kashima 11m antennas were used, and GPS observation was carried out in the 34m building maser room sharing 1 antenna with 2 receivers with different external input reference signal routes. The Kashima station maser (No. 1) was used as the reference signal for both VLBI and GPS. The reference signal was transmitted by optical fiber and coaxial cable. The coaxial phase shifter was inserted in the path of the reference signal from hydrogen maser to Kashima 11m antenna. Details are shown in Fig. 8.

Usually, geodetic VLBI observes multiple sources that uniformly cover the sky. And usually clock, atmosphere and station coordinates are estimated with in the analysis. However, during this experiment, in order to obtain a time difference every 10 seconds, observation was carried out tracking only 1 source (3C84), and only clock offset was estimated during analysis. The differences with normal VLBI experiments are shown in Table 3. We employed calc/solve in the VLBI analysis. In the GPS analysis, we employed NRC's (Natural Resources Canada) PPP software and used the IGS's satellite ephemerides and satellite/station clocks data. Artificial changes were carried out by hand every several minutes by expanding or contracting the coaxial phase shifter.

Figure 9 shows the time differences calculated from both VLBI and GPS (excluding the offset for each). The large changes like step (1 to 7) indicate the artificial delay change produced by the coaxial phase shifter. There are no large difference between VLBI, GPS and DMTD. Table 4 summarizes the difference between the delay change (nominal value) of the coaxial phase shifter estimated from the manufacturer provided maximum delay change of 333.7ps and the delay change nominal values calculated from VLBI and GPS results. Results of VLBI were slightly closer to the nominal values compared to GPS. The average difference between VLBI and the nominal value was 10ps or less. Anyway, the result of our experiment clearly shows that the geodetic VLBI technique can measure the correct time difference.

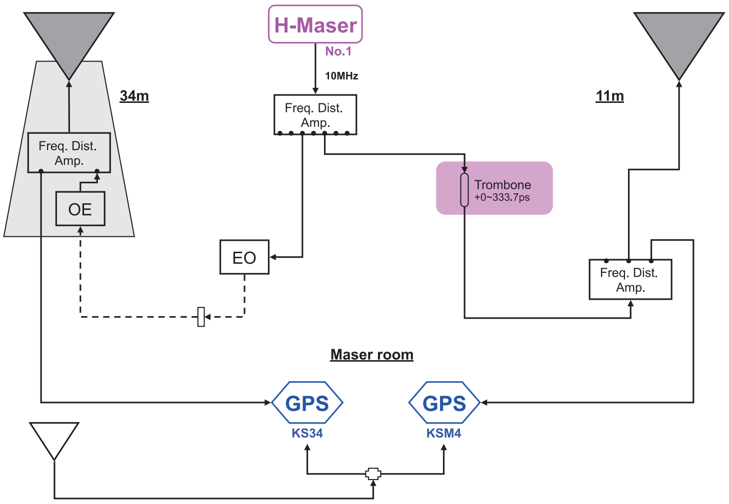

Fig.8 Route map of the reference signal (10MHz)

Solid lines indicate coaxial cable, dashed lines indicate optical fiber.

Table 3 Differences between this experiment and normal geodetic VLBI experiments

	Normal Geodetic VLBI	This study
Observation	multiple sources antenna slew time different scan time 24 hours	one source: 3C84 no antenna slew time same scan time a few hours
Data Analysisn	estimate clock parameter, atmospheric delay, and station coordinates	estimate only clock parameter station coordinates: fixed to a-priori coordinates

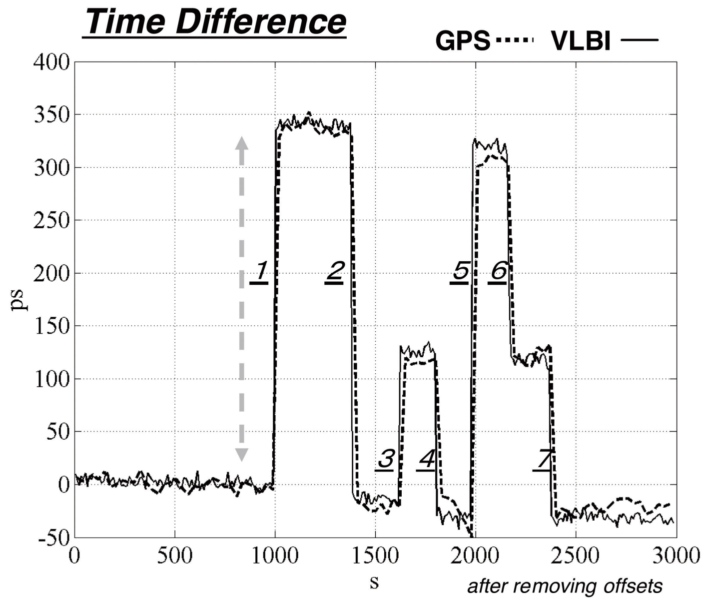

Fig.9 Time difference variation calculated from VLBI and GPS

Large step-shaped variations indicate artificial time change using by the coaxial phase shifter.

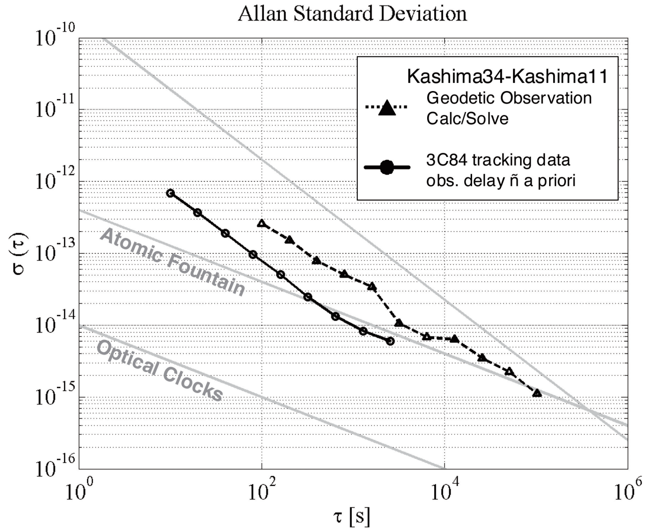

Fig.10 *Frequency stability calculated from VLBI 10 second integral, 10 second interval data*

At an averaging time of 500s, results reached the stability of atomic fountain frequency standards.

Table 4 *Differences between nominal values and results of VLBI and GPS*

	Nominal Value	Difference from the nominal value GPS	VLBI	
1	333.7	3.6	2.8	
2	333.7	16.5	15.2	
3	147.2	12.8	0.0	
4	147.2	17.0	4.6	
5	333.7	11.6	19.5	
6	186.7	0.6	9.8	
7	147.0	9.2	7.3	
	average	**10.2**	**8.5**	ps

Figure 10 shows the frequency stability calculated from the VLBI data of period which do not include artificial time changes. This was calculated from the delay residual excluding a priori values from the observed delay obtained by integrating consecutive tracking records of the single source (3C84) for 10 second every 10 second. The frequency stability has 1/τ trend up to an averaging time of 500 seconds as in our past research. As noted earlier, this differs from normal geodetic VLBI, however by adjusting the schedule and using a high speed sampler such as the currently in development ADS3000+, it is possible to obtain the same 1 second integral data as with GPS.

3 Conclusion

We carried out the intercomparison experiments between VLBI and GPS in order to show the capability of VLBI frequency transfer by using current VLBI system and to propose the geodetic VLBI technique as one of a new frequency transfer technique. In verification using IVS and IGS data, at an averaging time of 10^3s or more VLBI results reached the stability of atomic fountain frequency standards. These results show that geodetic VLBI technique has the potential for precise frequency transfer as expected.

In addition, we carried out an intercomparison experiment which introduced artificial delay changes by expanding or contracting a coaxial phase shifter in order to show that VLBI can measure the correct time difference. At the artificial changes, VLBI and nominal value show good agreement, less than 10ps. Consequently, the geodetic VLBI technique can measure the correct time difference.

Currently, we are evaluating the VLBI time and frequency transfer technique using the compact VLBI system (MARBLE) and the high-speed sampler (ADS3000+).

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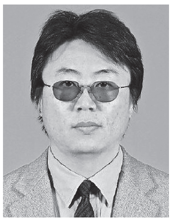

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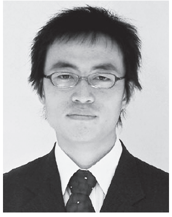

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