VLBI Measurements for Time and Frequency Transfer

H. Takiguchi[1] (htaki@nict.go.jp), Y. Koyama[1] (koyama@nict.go.jp), R. Ichikawa[1] (richi@nict.go.jp), T. Gotoh[2] (tara@nict.go.jp), A. Ishii[1] (ishii@nict.go.jp), T. Hobiger[1] (hobiger@nict.go.jp), M. Hosokawa[2] (hosokawa@nict.go.jp)

[1] *Space-Time Standards Group, Kashima Space Research Center, National Institute of Information and Communications Technology, 831-1 Hirai, Kashima, Ibarak, 314-8501, Japan*

[2] *Space-Time Standards Group, National Institute of Information and Communications Technology, 4-2-1 Nukui-Kitamachi, Koganei, Tokyo 184-8795, Japan*

BIOGRAPHY

We compare the frequency transfer precision between VLBI and GPS carrier phase using IVS and IGS observation data in order to confirm the potential of VLBI time and frequency transfer. The results show that VLBI time transfer is more stable than GPS time transfer on the same baseline and same period. Moreover, we have started the development of a compact and transportable VLBI system for time transfer of the Kashima-Koganei baseline and have carried out a test experiment.

INTRODUCTION

Modern cold-atom-based frequency standards have already archived the uncertainty of 10^{-15} at a few days. Moreover cold-atom-based optical clocks have the potential to realize the uncertainty of from 10^{-16} to 10^{-17} level after a few hours [1]. On the other hand, time transfer precision of two-way satellite time and frequency transfer and GPS carrier phase experiments have reached the 10^{-10}@1sec (10^{-15}@1day) level [2] etc. In order to compare such modern standards by these time transfer techniques, it is necessary to average over long periods. Since these techniques are not sufficient to compare next standards improvements of high precision time transfer techniques are strongly desired.

Space geodetic techniques like Very Long Baseline Interferometry (VLBI), Satellite Laser Ranging (SLR) and Global Positioning System (GPS) are based on precise time measurement using very stable reference signals. VLBI measures the arrival time delays between multiple stations utilizing radio signals from distant celestial radio sources like quasars and pulsars. By using VLBI, it is possible to measure subtle variation of rotation and Earth orientation parameters (EOP). 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 (1 sigma) of the clock offsets is typically about 20 picoseconds when analyzing geodetic VLBI experiments which 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 two-way satellite time transfer. It is feasible to use geodetic VLBI for comparison of primary frequency standards when radio telescopes are deployed at time and frequency laboratories. For this purpose, we have started to develop a compact and transportable VLBI system [3].

The first part of this paper introduces the VLBI system and observing technique. The second part describes the comparison experiments between VLBI and GPS carrier phase using data from the IVS and the International GNSS Service (IGS). The third part describes the comparison experiments on the Kashima-Koganei baseline which is planned to be carried out after the compact VLBI system has been completed. Finally, we discuss our results.

VLBI SYSTEM AND TECHNIQUES

VLBI is a technique that measures the arrival time delays between multiple stations utilizing radio signals from distant celestial radio sources like quasars and pulsars, as mentioned above. The principles of VLBI are as follows and shown in Figure 1. Each VLBI station is equipped with an antenna, a highly stable local oscillator (Hydrogen maser), and a recording system (K5 or Mark5 system etc.). In general, VLBI observations are carried out on S- and X-band frequencies for geodesy, astrometry and time comparison. The received signals in radio-frequency are down-converted to video-band signals. These signals are then digitized and recorded onto HDD at high recording speed. Then the data is cross-correlated with each other and the bandwidth synthesis gives the final observables, which are written into a Mark3 data base. Beside the observational data, weather information, theoretical delay and delay rate, and their partial derivatives are stored in the database. The time difference (clock offset) between the atomic clocks at the two stations can also be restored within VLBI analysis, where the observed delay is split into geometrical delay, the instrumental delay difference, the atmospheric delay difference and the clock difference [4]. In the usual geodetic VLBI analysis, positions, velocities and atmospheric delay at each station are estimated together with clock offsets and their rates of change with respect to a selected reference station.

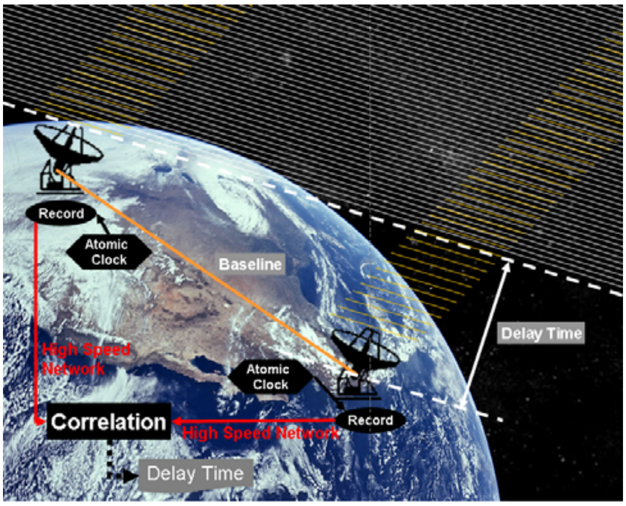

Figure 1. VLBI principle.

THE COMPARISON EXPERIMENTS BETWEEN VLBI AND GPS CARRIER PHASE USING IVS AND IGS DATA

First, we checked the ability of time transfer of VLBI and GPS carrier phase using IVS and IGS data.
We selected the two stations (Onsala, Wettzell) which belong to IVS and IGS network. These two stations have in common that at each site VLBI and GPS are sharing the hydrogen maser (Figure 2). Table 1 shows a list of the data used for this study.

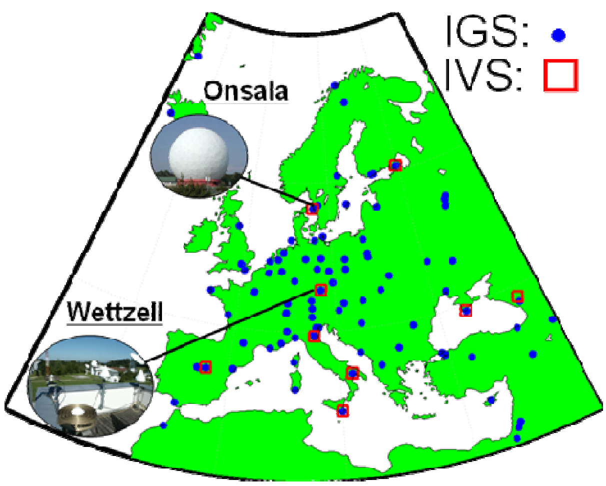

Figure 2. Map of IVS and IGS stations in Europe.

Table 1. Data lists.

DOY (2007)	IVS Session	IVS Station	IGS Station
092	R1270	ONSALA60, WETTZELL	onsa, wtzr
100	R1271		
113	R1273		
122	R1274		

The details of the analysis of VLBI and GPS are listed as follows:

VLBI

- Software : CALC/SOLVE
- Strategy
  - multi baseline
  - S/X ionosphere-free linear combination
  - reference station: Wettzell
- estimate
  - station coordinates
  - atmospheric delay / 1h
  - clock offset / 1h

GPS

- Software : GIPSY-OASIS II
- Strategy : Precise Point Positioning (PPP) [5]
- estimate
  - station coordinates
  - atmospheric delay / 5min
  - clock offset / 5min
- Time Difference
  - clock offset A – clock offset B

Due to the code noise, the clock offsets of the GPS solutions show discontinuities at the day boundaries. The averaged day boundary discontinuity was 94ps. Figure 3 shows one of the VLBI results of clock offsets. The averaged formal errors (1 sigma) of the estimated clock offsets at Onsala station referred to Wettzell station was 16.1ps.

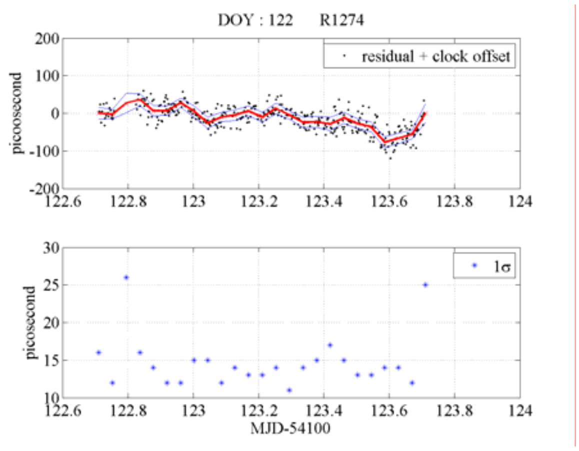

Figure 3. Time series of the clock offsets (upper) and the formal error (lower) at Onsala station referred to Wettzell station.

Figure 4 shows that the time series of the clock difference between Onsala and Wettzell (session R1274) calculated from GPS (black) and VLBI (blue) respectively. The lower part of Figure 4 is the difference between GPS and VLBI clock offsets showing a good agreement within +/-200ps.

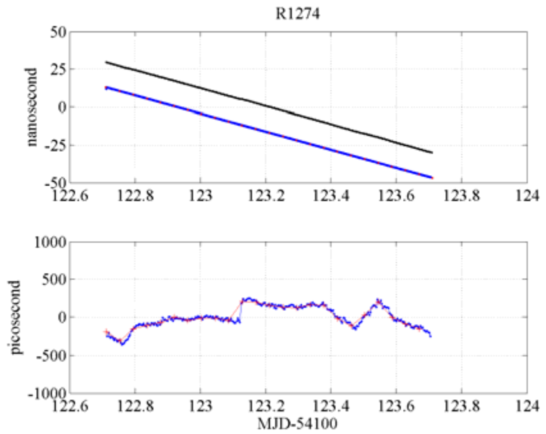

Figure 4. Time series of the clock difference (upper plot) calculated from GPS (black) and VLBI (blue) respectively. The lower plot is the difference between GPS and VLBI clock offsets.

Figure 5 and 6 illustrates the frequency stability of clock difference as obtained from VLBI (red) and GPS (blue). The short term stability of by GPS carrier phase seems to be slightly better than those from VLBI for averaging periods up to 10^3s. However, VLBI is more stable at averaging periods longer than 10^3s in any sessions.

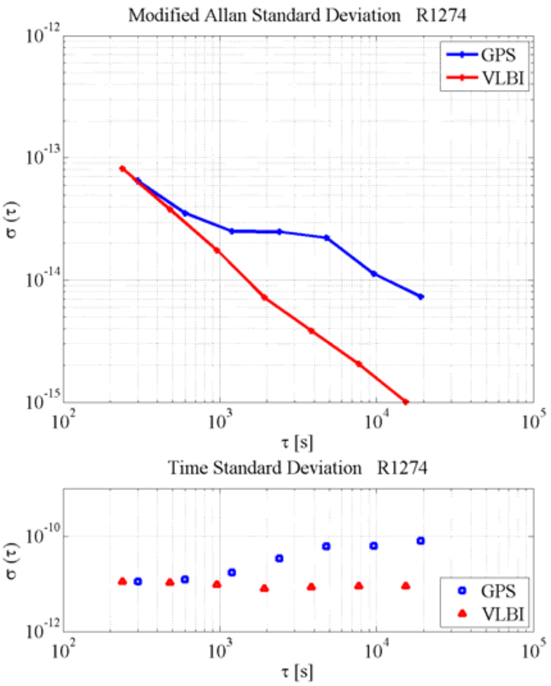

Figure 5. Modified Allan deviation (top) and Time Standard Deviation (bottom) of VLBI and GPS carrier phase results from R1274 session.

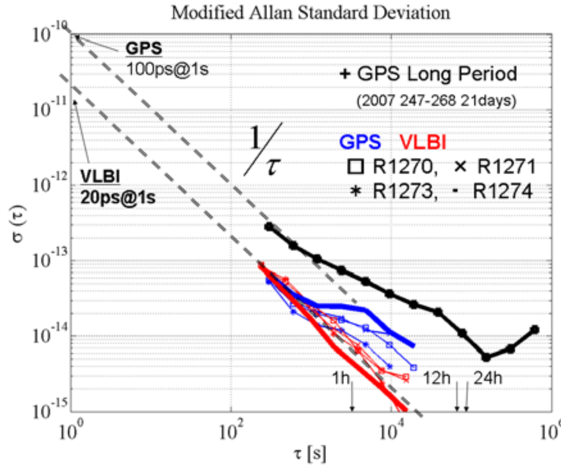

Figure 6. Modified Allan deviation of VLBI and GPS carrier phase results from all sessions.

In general, the VLBI frequency transfer stability follows a 1/tau law very close when averaging up to 10^4s. And that shows the stability have reached about 2×10^{-11} (20ps) at 1 sec.

THE COMPARISON EXPERIMENTS BETWEEN VLBI AND GPS CARRIER PHASE USING KASHIMA-KOGANEI BASELINE

We also carried out geodetic VLBI experiments using Kashima-Koganei baseline in order to compare the results with GPS time transfer (carrier phase). We will also use this baseline for test observations of our compact VLBI system which is currently under development. The Kashima station has 34-m and 11-m radio telescope, it's located about 100 km East of Tokyo Japan. The Koganei station has 11-m radio telescope, and is located in the western part of Tokyo. The baseline length is 109 km (Figure 7).

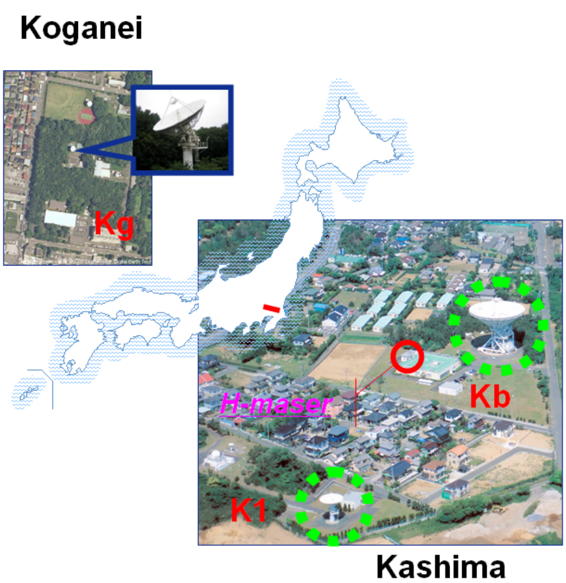

Figure 7. Layout map of KASHIMA and KOGANEI station.

Both stations have a permanent GPS receiver (ksmv, kgni and ks34) which are sharing the H-maser with VLBI since last spring. It was necessary to adopt some parts of these VLBI and GPS equipment for the needs of the time and frequency transfer purpose because these systems are usually set-up for geodetic purposes.

At first, we carried out a test experiment with the following in the unchanged systems. The details and data quality of performed VLBI and GPS observations are listed in Table 2. The quality of the GPS observations was not good (except for the K08049 experiment) due to troubles with the GPS receivers. In the K08049 experiment we used a new GPS receiver (Trimble NetRS). In this paper, we discuss only k07166 and k08049 experiments.

Table 2. Details of VLBI and GPS observations, which were dedicted to time- and frequency-transfer.

Ssion	Baseline	Duration	Data Quality	
			VLBI	GPS
k07022	K1-Kg	24 hours	errors	errors
k07059	K1-Kg	3 days	errors	errors
k07166	Kb-Kg	1 week	OK	Failed
k08049	Kb-Kg	3 days	OK	OK

* K1: KASHIM11, Kg : KOGANEI, Kb : KASHIM34

The analysis setup is almost the same as the one described in the previous section. The averaged formal errors (1 sigma) of the estimated clock offsets at Koganei station referred to Kashima station were 23ps (k07166) and 18ps (k08049) in VLBI results.

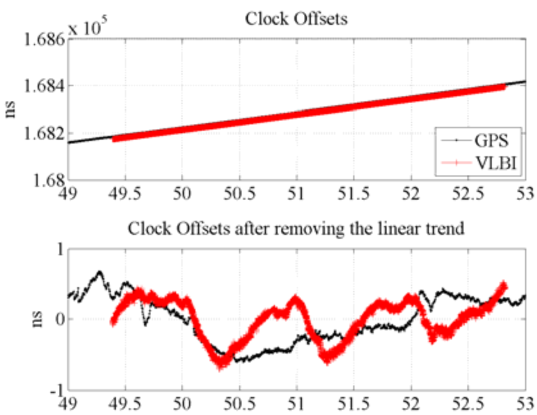

Figure 8. Comparison between VLBI and GPS results (upper plot: clock offsets, lower plot: clock offsets after removing a linear trend).

Figure 8 presents the comparison between VLBI and GPS. After removing a linear trend (lower plot), the clock offsets of VLBI reveal a diurnal variation which can not be seen in the GPS results. The cable length between the point where the reference signal from the H-maser is injected and the observing system itself is different for VLBI and GPS as shown in Figure 9. Additionally, the cable of the VLBI system inside the antenna is not temperature controlled. Figure 10 shows the time series of the clock offset of VLBI and the outside temperature. It reveals that the clock offsets of VLBI are strongly affected by the outside temperature (correlation coefficient : -0.72, lag : 2hours). Thus, for current experiments, we have decided to monitor variations of the reference signal through the transmission cable of the VLBI system by the Dual Mixer Time Difference (DMTD) method [6].

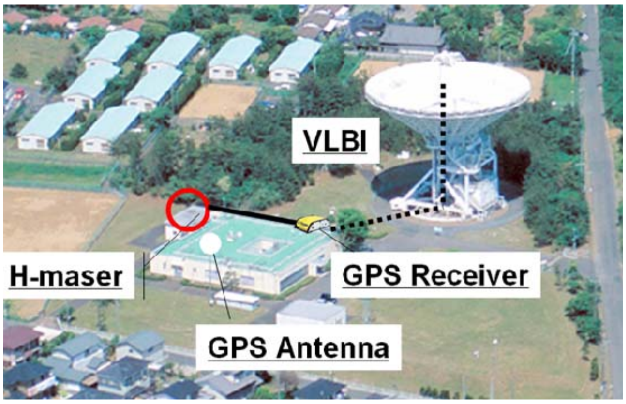

Figure 9. Layout of the H-maser, GPS receiver and VLBI antenna.

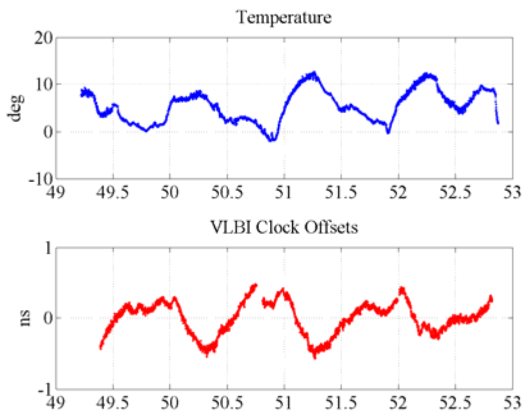

Figure 10. Time series of the outside temperature and clock offsets of VLBI.

These results suggest that it is necessary to calibrate the instrumental delay of the VLBI system. In the next step, we are planning to measure the instrumental delay of the VLBI system by the zero baseline interferometry (ZBI) method [7], [8], and we also want to replace the transmission cable by optical fibers.

SUMMARY

To compare the results of VLBI and GPS (carrier phase) frequency transfer, we have analyzed IVS and IGS data. The results of the VLBI frequency transfer show that the stability follows a 1/tau law very close (phase noise dominant). And that shows the stability have reached about 2×10^{-11} (20ps) at 1 sec. In this study, the results show that VLBI frequency transfer is more stable than GPS on the same baseline and same period.

And also, we started the instrumental setting that used Kashima-Koganei baseline by time and frequency transfer for test observations of our compact VLBI system which is currently under development.
Figure 11 shows the future image of the time transfer by the compact VLBI system and high speed networks.

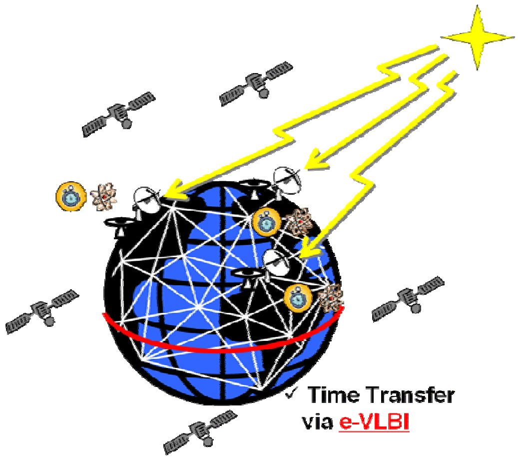

Figure 11. Future image of the time transfer by the compact VLBI system and high speed networks.

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