# Comparison with GPS Time Transfer and VLBI Time Transfer

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*Abstract*: To compare the results with Global Positioning System (GPS) Time Transfer and Very Long Baseline Interferometry (VLBI) Time Transfer, we carried out the geodetic VLBI experiments for four times. The averaged formal error ($1\sigma$) of the clock offsets that were estimated every one hour in the geodetic VLBI analysis procedure (CALC/SOLVE), was 33 picoseconds. Especially, in the case of using K5/VSSP32 system, the averaged formal error was 29 picoseconds. The results of the VLBI time transfer were very consistent with the results of the GPS time transfer. The difference of both results was about $\pm 500$ picoseconds. In term of frequency stability, the Allan deviation showed that VLBI time transfer is more stable than GPS time transfer between 2000 seconds to 60000 seconds (uncertainty of under $3 \times 10^{-14}$).

## 1. Introduction

Universal Time Coordinated (UTC) is computed and maintained by the International Bureau of Weights and Measures (BIPM) using a weighted average from about 250 atomic clocks located in about 50 national laboratories to construct a time scale called International Atomic Time (TAI). National Institute of Information and Communications Technology (NICT) is a one of the laboratory contribute to the UTC maintenance. NICT have 18 sets of cesium atomic clocks and 4 sets of hydrogen-maser clocks, and also generate Japan Standard Time (JST). And also, NICT is research and development of the next-generation frequency standards. One of the products of the primary frequency standard called "NICT-O1" is capable of realizing the definition of the second with an uncertainty of $6\times10^{-15}$. In addition, the atomic fountain frequency standard and optical frequency standard under development aim at an uncertainty of $1\times10^{-15}$. To realise such an uncertainty, it is necessary to compare regularly with these clocks and domestic and foreign research laboratories with precision and accuracy. These comparison are commonly undertaken through time transfer methods using GPS (GPS Time Transfer, Common-View method or Carrier Phase method) or communication satellites (Two-way Satellite Time and Frequency Transfer: TWSTFT), with an inaccuracy of the order of several hundreds picoseconds. In the future, it will be necessary to improve present comparison accuracy of time transfer greatly.

In the usual geodetic VLBI analysis, the clock offsets and their rates of change at all stations except for the reference station are estimated. The averaged formal error ($1\sigma$) is about 20 picoseconds in the International VLBI Service (IVS) general experiments. This accuracy is more accurate than GPS time transfer and TWSTFT. In addition, VLBI community are improving VLBI system and they aim about 4 picoseconds of the formal error with a per-observation (VLBI2010; Niell et al., 2007 [2]).

Because of the current VLBI system need large antenna and frequency standard, VLBI time transfer isn't practical use though the high accuracy. However, it begins to solve the problem by the ongoing research. For example, the development of a compact VLBI system by NICT (Ishii et al., 2007 [1]) and the above mentioned work of VLBI2010. In this study, to confirm the potential of the VLBI time transfer aiming at the practical use of the VLBI time transfer in the future, we compared the results of the VLBI time transfer and the GPS time transfer.

## 2. VLBI Experiments for Time Transfer

The details of performed VLBI observation are listed in Table 1. GPS observation was also carried out at the same time near the VLBI station. Until the k07059 experiment, we used the receiver for time transfer (KOGANEI: Septentrio PolarRX2 TR, KASHIMA: Ashtech Z-XII3T Metronome with a choke ring antenna). But, we replaced them with the geodetic receivers (KOGANEI and KASHIMA: Ashtech Z-XII3 with a choke ring antenna) before the k07166 experiment, and moved KASHIMA GPS station from near the Kashima 11m to near the Kashima 34m. Figure 1 is the map of the KASHIMA station that show the layout of VLBI antennas, GPS antenna and the frequency standard (hydrogen maser). The distance from the Kashima 11m to the frequency standard is about 200 meter.

The VLBI observations were made with standard geodetic observation mode. Then we analyzed that data by CALC/SOLVE software, which is a standard VLBI analysis software developed by NASA/GSFC. The averaged formal errors ($1\sigma$) of

*Table 1. Details of the VLBI observations*

| Code | Term (UT) | Baseline | Mode | Sysetm |
|---|---|---|---|---|
| k07011 | Jan.11 09 - Jan.12 15 | KASHIM11-KOGANEI11 | 4Mbps/ch,1bit,16ch,64bps | K5/VSSP |
| k07022 | Jan.22 10 - Jan.23 16 | KASHIM11-KOGANEI11 | 4Mbps/ch,1bit,16ch,64bps | K5/VSSP |
| k07059 | Feb.28 15 - Mar.03 15 | KASHIM11-KOGANEI11 | 4Mbps/ch,1bit,16ch,64bps | K5/VSSP |
| k07166 | Jun.15 02 - Jun.23 03 | KASHIM34-KOGANEI11 | 16Mbps/ch,1bit,16ch,256Mbps | K5/VSSP32 |


*Figure 1. Layout map of KASHIMA station*

the clock offsets at KOGANEI station referred to KASHIMA station are listed in Table 2. In the k07166 experiment, the data was split into the 3 parts because of the operation mistake. So we analyzed that data individually (k07166A, k07166B and k07166C). The result of the k07011 experiment was not shown after here, because of the enough data was not able to be acquired by the trouble of HDD.

Every after the experiment, we evaluated the schedule and SNR of the obtained data and improved the schedule for the next experiment. In addition, we changed the VLBI system of both of the stations from K5/VSSP to K5/VSSP32 that is more sensitive (about 4 times) and the antenna of KASHIMA station from Kashima 11m to Kashima 34m in the k07166 experiment. The averaged formal errors have decreased by the experiment. Finally, the averaged formal error of all experiment is 33 picoseconds. Especially, in the K5/VSSP32 system case, the averaged formal error was 29 picoseconds.

*Table 2. The averaged formal error (1$\sigma$) of the clock offsets at KOGANEI station referred to KASHIMA station*

| Code | Formal Error [ps] |
|---|---|
| 1) k07022 | 51 |
| 2) k07059 | 36 |
| 3) k07166A | 28 |
| 4) k07166B | 40 |
| 5) k07166C | 23 |
| average all | 33 |
| average K5/VSSP | 39 |
| average K5/VSSP32 | 29 |

## 3. Comparison with VLBI Time Transfer to GPS Time Transfer

### 3.1 Time Series of the Time Transfer

Figure 1 shows the difference time series between GPS and VLBI clock offsets at KOGANEI station

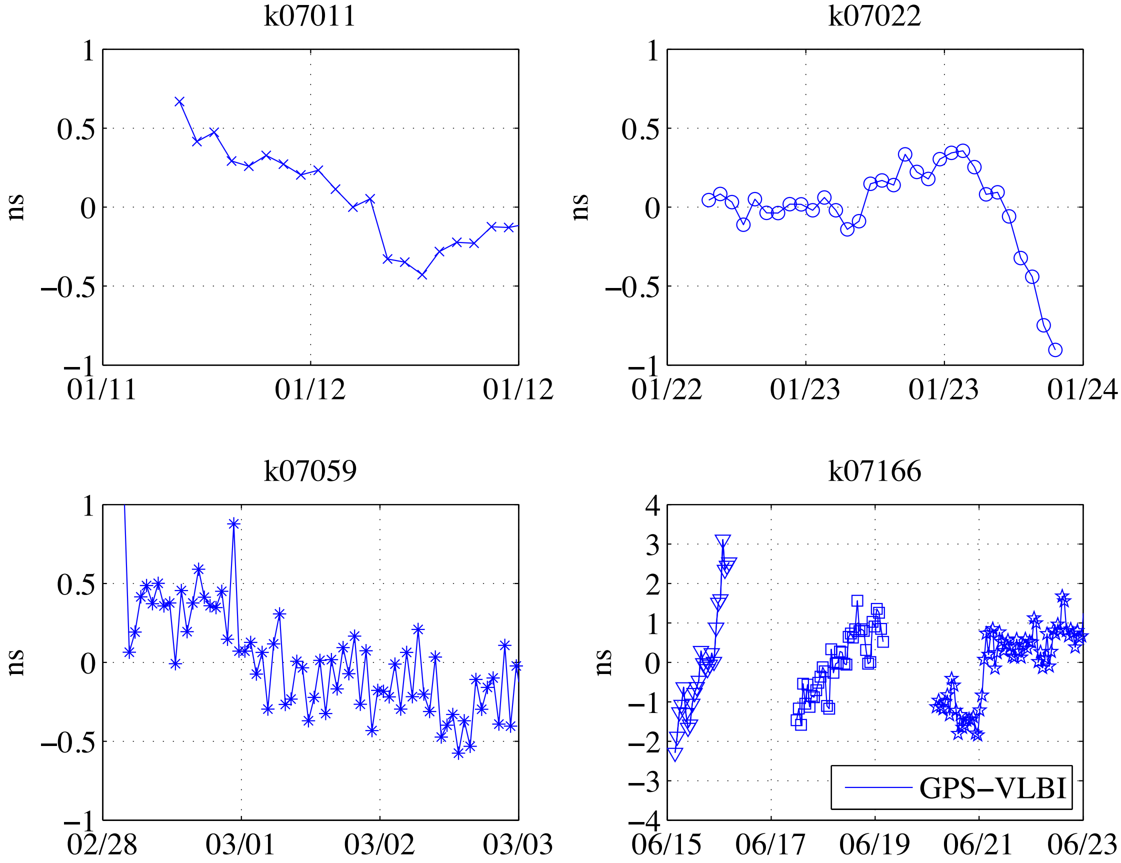


*Figure 2. Time series of the difference between GPS clock offsets and VLBI clock offsets at KOGANEI station referred to KASHIMA station*

referred to KASHIMA station. We extracted the GPS clock offsets every 1 hour to compare with the VLBI clock offsets, even though GPS clock offsets were estimated every 5 minutes (Carrier Phase method).

The results of the VLBI time transfer were very consistent with the results of the GPS time transfer, in the case of using the receiver for time transfer. The difference between both results were about ±500 picoseconds. In the case of using the geodetic receiver (k07166), the difference between GPS and VLBI were over ±1 nanoseconds. We confirmed that the geodetic receiver is unsuitable for high accuracy time transfer.

### 3.2 Stability of VLBI Time Transfer

Figure 3 shows the Allan deviation that were calculated from the clock offsets of VLBI (blue), GPS (red), "GPS-VLBI" (light blue) and frequency standard (green and pink).

#### 3.2.1 Kashima 11m - Koganei 11m Baseline

About the Kashima 11m and Koganei 11m baseline (k07011, k07022 and k07059), the stability of the VLBI time transfer (blue dotted lines) are stable than GPS time transfer (red lines) in the period from 3600 seconds to 10000 seconds. But, after 10000 seconds, both stabilities were tended to be unstable. It seems that that change has peak at 30000 seconds. The results of the GPS minus VLBI (the stability of measurement system that removes common noise) were change along the $1/\sqrt{\tau}$ (frequency noise). It means that that peaks were not caused by noise of the measurement system. The first candidate is the distance from the frequency standard to the antenna at KASHIMA station, if except the noise of the measurement system. The distance from the frequency standard to the Kashima 11m antenna is about 200 meter. We calculated the stability of the frequency standard at the recorder of Kashima 11m antenna using

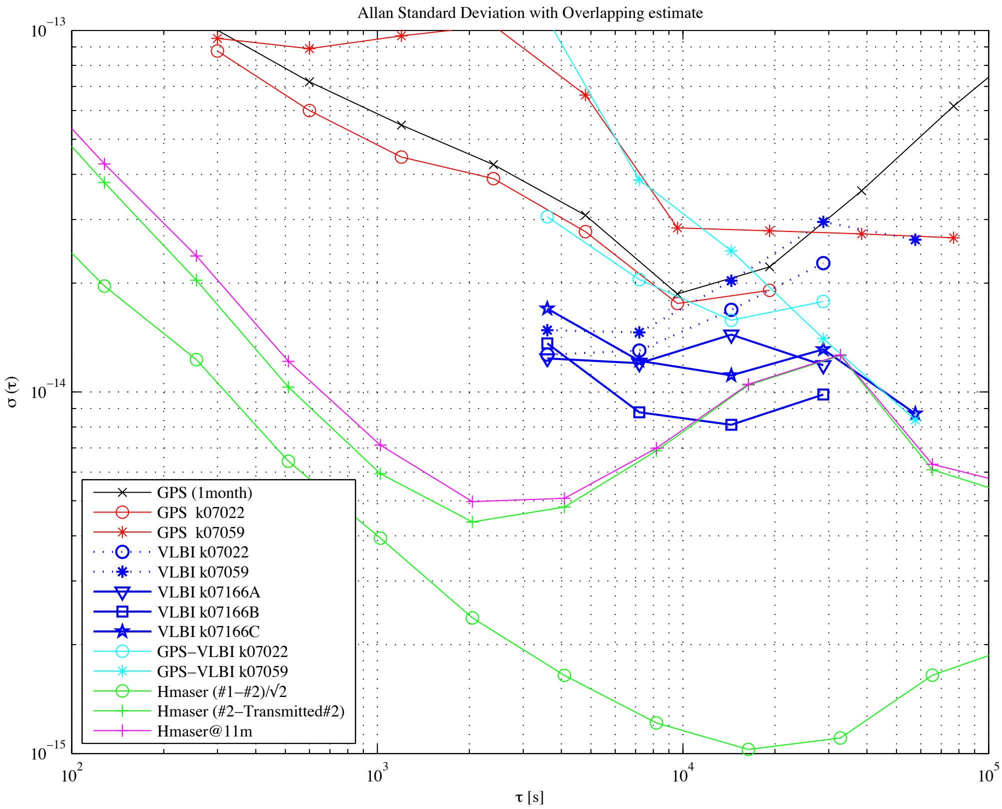


*Figure 3. Frequency stability comparison (in term of Allan deviation) between VLBI solution (blue), GPS solution (red), "GPS-VLBI" solution (light blue) and frequency standard (green and pink)*

two hydrogen masers (pink line and crosses). The green line and circles in Figure 3 are the stability of the frequency standard in the maser room, the green line and crosses are the stability of the signal turned back from Kashima 11m antenna. The frequency standard at the recorder of Kashima 11m antenna has peak at 30000 seconds like the results of VLBI. It means that the baseline with Kashima 11m is unsuitable for time transfer.

#### 3.2.2 Kashima 34m - Koganei 11m Baseline

The blue lines in Figure 3 are the results in the baseline of Kashima 34m and Koganei 11m (k07166). These stabilities are more stable than the baseline of Kashima 11m and Koganei 11m. And it seems that these stabilities have also small peak at 30000 seconds, but it's not clear. The distance of the frequency standard and the recorder for Kashima 34m antenna is about 10 meter. We can't conclude from only these experiments, it might appear the peak at 30000 seconds (periods of about 16 hours), if the recorder is far some distance from the frequency standard. These results shows that the VLBI time transfer is more stable than GPS time transfer, especially between 3600 seconds to 60000 seconds.

#### 3.2.3 Stability Calculated from the Delay Residuals plus Clock Offsets

We evaluated the stability calculated from the data that added the clock offsets to the delay residuals which were obtained from every scan. Because of the data (delay residuals + clock offsets) is not equal interval, we interpolated that to calculate the Allan deviation. To verify the validity of this interpolation, we extracted the equal interval data and calculated the Allan deviation. Figure 4 shows the results of the k07166 experiment (k07166C, blue crosses). The black line that is Allan deviation calculated from clock offsets, traced the average of distribution of Allan deviation calculated from equal interval data. It shows that Allan deviation calculated from interpolated data like clock offsets and "delay residuals + clock offsets" is appropriateness. The Allan deviation calculated from the data interpolated every 60 seconds is shown in Figure 4 (red line) and Figure 5.

The stability of VLBI changed from stable to unstable between 1000 seconds to 2000 seconds in

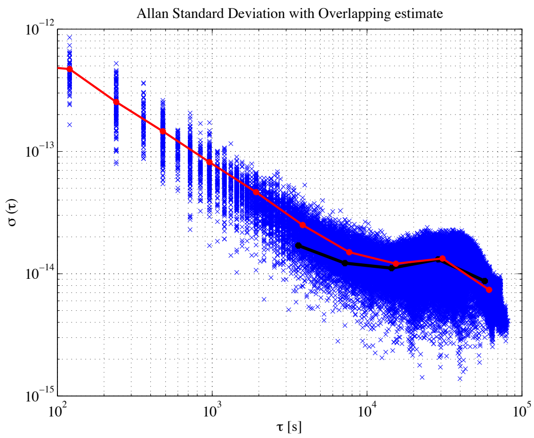


*Figure 4. Allan deviation calculated from equal intervals data (blue crosses) and interpolated data every 60 seconds (red line) of the k07166 experiment (k07166C). The black line is the Allan deviation calculated from the clock offsets estimated by CALC/SOLVE.*

Figure 5. Synthetically, in term of frequency stability, the Allan deviation showed that VLBI time transfer is more stable than GPS time transfer between 2000 seconds to 60000 seconds (uncertainty of under $3 \times 10^{-14}$).

## 4. Conclusions

To compare the results with GPS Time Transfer (Carrier Phase) and VLBI Time Transfer, we carried out the geodetic VLBI experiments for four times. The averaged formal error($1\sigma$) of the clock offsets when estimated every one hour in the geodetic VLBI analysis procedure (CALC/SOLVE), was 33 picoseconds. Especially, in the K5/VSSP32 system case, the averaged formal error was 29 picoseconds. The results of the VLBI time transfer were very consistent with the results of the GPS time transfer. The difference of both results was about ±500 picoseconds. In term of frequency stability, the Allan deviation showed that VLBI time transfer is more stabile than GPS time transfer between 2000 seconds to 60000 seconds (uncertainty of under $3 \times 10^{-14}$). And we confirmed that the "delay residual + clock offsets" estimated from the VLBI analysis software could use for evaluation of frequency stability in term of the Allan deviation. These results are meaningful that we confirmed the stability of the VLBI time transfer in actual exper-

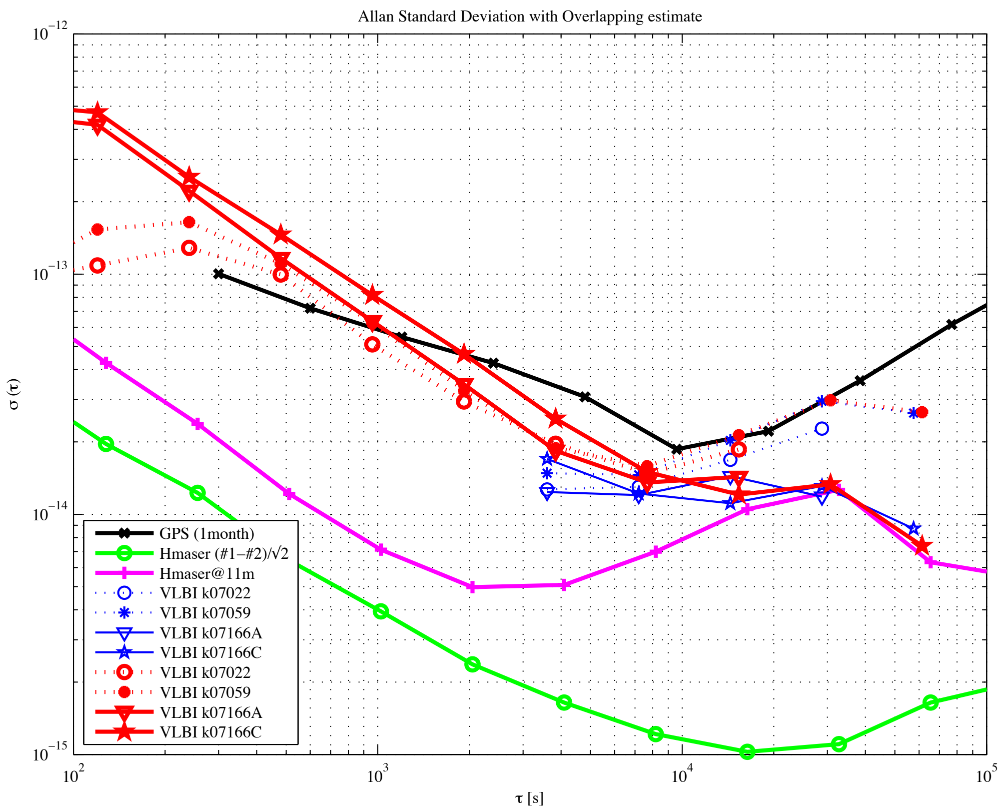


*Figure 5. Allan deviation calculated from data that interpolated "delay residuals + clock offsets" every 60 seconds*

iment though can expect from the potential of the VLBI system. We will improve the VLBI system aiming at practical use in the future.

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