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Evaluation of a Laser-pumped Cs Gas-cell Frequency Standard on Geodetic VLBI

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レーザ励起 Cs ガスセル型原子発振器の測地 VLBI における性能評価

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要　旨

近年開発されたレーザ励起 Cs ガスセル型原子発振器（以下 Cs ガスセル発振器）は，従来から VLBI の周波数標準として利用されている水素メーザ原子発振器（以下 水素メーザ発振器）に近い周波数安定度を有する発振器である．その周波数安定度はアラン標準偏差で平均化時間 10 秒において 2×10^{-13}，平均化時間 1000 秒では 2.5×10^{-14} まで達する．これは S 帯，X 帯の周波数で VLBI 観測を行う際の干渉性を保つのに十分な周波数安定度である．この Cs ガスセル発振器は，デスクトップ PC 一台ほどの形状・重量で水素メーザと比較すると取扱いも容易である．この Cs ガスセル発振器が VLBI の周波数標準として利用可能であれば，VLBI 観測局に必要とされるスペースは劇的に小さくなり，移動型の VLBI 観測局への利用が期待できる．そこで，一方の観測局の周波数標準を Cs ガスセル発振器とし，もう一方の観測局の周波数標準を水素メーザ発振器として 110 km の基線（茨城県鹿嶋市と東京都小金井市）で測地 VLBI 実験を実施した．この測地 VLBI 実験で推定された基線長は，両方の観測局とも周波数標準として水素メーザ発振器を用いた測地 VLBI 実験の結果と 1 mm 以内で一致した．この結果より，Cs ガスセル発振器は測地 VLBI の周波数標準として十分な安定度を持っていると結論づけた．

Abstract

The laser-pumped Cs gas-cell type atomic frequency standard (hereafter, we called the “Cs gas-cell oscillator") , this was developed in recent years, has a stability between a hydrogen maser oscillator and a Cs beam-type frequency standard. The square root of Allan variance for this atomic frequency standard is 2×10^{-13} at 10 sec and reaches 2.5×10^{-14} at about 1000 sec. This stability is good enough to maintain coherence for VLBI observations at the frequencies of 2 and 8 GHz. It is very small and easy to operate compared with the hydrogen maser oscillator. The size and weight of this oscillator is roughly equal to a desktop PC. If we can use this Cs gas-cell oscillator as a frequency standard for VLBI, the space required for a VLBI station will be dramatically reduced. Hence, this oscillator is suitable for a transportable VLBI station. A geodetic VLBI experiment with a 110 km baseline was conducted, where the Cs gas-cell oscillator was used at one station, and a hydrogen maser oscillator was used at the other station. The length of the baseline vector estimated by this experiment was coincident within 1 mm compared with the result of an experiment using only conventional hydrogen maser oscillators. The results of these experiments indicated that the Cs gas-cell oscillator is sufficiently stable to use as a frequency standard for geodetic VLBI observations.

1. Introduction

Very Long Baseline Interferometry (VLBI) is one of the most precise measurement techniques for geodesy, Earth rotation, astronomy, and international time comparison. Usually a high stability frequency standard is necessary for VLBI experiments in order to maintain the coherence during the integration period. In standard VLBI experiments for geodetic purposes, each antenna receives signals from a radio source for a hundred seconds or more in one observation. This observation is then repeated, changing between multiple radio sources during a nominal 24-hour session. The frequency standard for VLBI must be stable over a long time range (around 24 h), as well as over a short time range (around 100 s). Short time range stability is essential for maintaining coherence and long time range stability is necessary for regulating the times of the observations. Only the hydrogen maser oscillator satisfies these requirements.

However, a hydrogen maser oscillator is large in size, difficult to operate, and expensive compared to other types of atomic frequency standards. The hydrogen maser oscillator of the Anritsu Co. (RH401A) is 600 mm in width, 1610 mm in height, and 675 mm in depth, with a weight of 450 kg. A Cs beam-type atomic frequency standard with a magnetic state selector has a high stability over a long time range, but it lacks stability over a short time range. For instance, the square root of Allan variance for the Cs beam-type frequency standard made by the Symmetricom Corp. (5071A Option 001) is 3.5×10^{-12} at 10 s and 8.5×10^{-14} at 10000 s. A Rb gas-cell type atomic clock is small and inexpensive, but its stability is no better than that of a high-performance Cs beam-type atomic clock. For instance, the square root of Allan variance of the Rb gas-cell oscillator made by Stanford Research Systems, Inc. (PRS10) is 4×10^{-12} at 10 s and 3×10^{-13} at 10000 s. A frequency standard that combines a crystal oscillator and a Cs beam-type oscillator has previously been developed (Kiuchi *et al.*, 1989). This frequency standard uses a crystal oscillator for the short time range, and the phase synchronizes with the Cs beam-type oscillator over the long time range (over 100 s). Its square root of Allan variance is 3×10^{-13} at 10 s and 5×10^{-14} at 10000 s. Although this frequency standard can be applied to geodetic VLBI, the measurement error (1 sigma) of the baseline length becomes at least three times greater than that obtained when geodetic VLBI employing hydrogen masers is used. The Cs gas-cell oscillator was developed in recent years, has the stability between a hydrogen maser oscillator and a Cs beam-type frequency standard (Ohuchi *et al.*, 2000). The basic mechanism of the Cs gas-cell oscillator is the same as the Rb gas-cell type atomic oscillator. However, a conventional discharge lamp is not used as the pumping source for the oscillator, which uses a laser

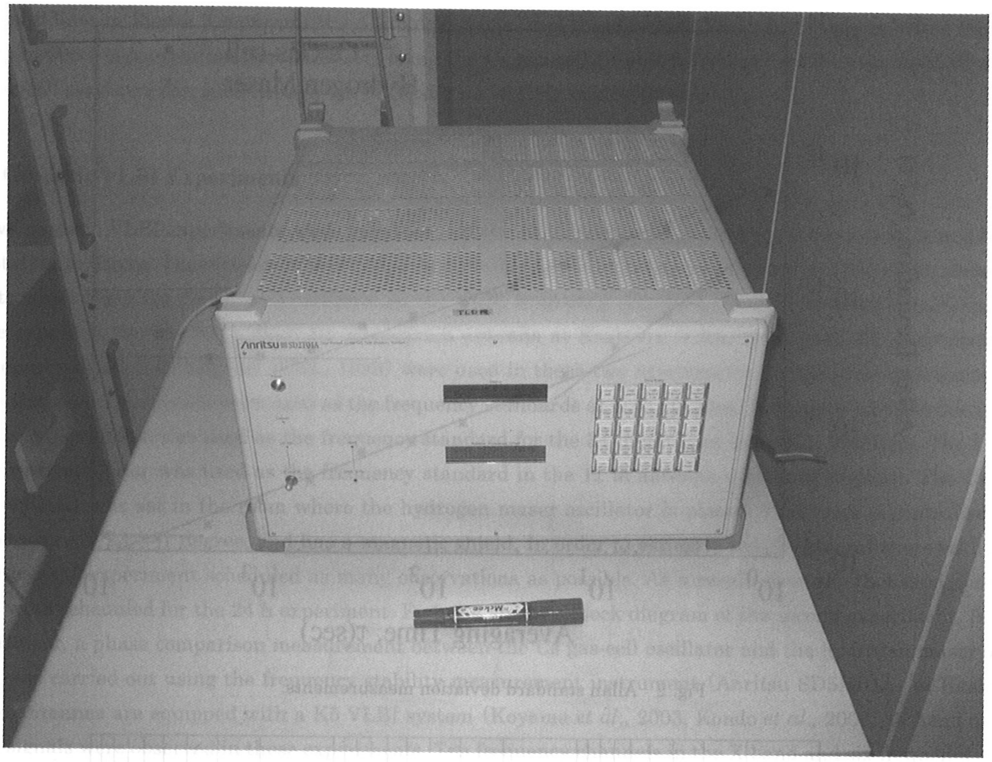

Fig. 1 The Cs gas-cell oscillator (Anritsu SD2TD01A). It is 426 mm in width, 222 mm in height and 451 mm in depth. Its weight is 25 kg.

diode to improve the signal-to-noise ratio (SNR) of the resonance signal. A high SNR makes the oscillator stabile. The size and weight of this oscillator are roughly equal to those of a desk-top PC (Figure 1). Furthermore, this Cs gas-cell oscillator is easier to operate than the hydrogen maser oscillator.

If this oscillator can be used for geodetic VLBI, the required space for a VLBI station can be dramatically reduced, and it will be applicable to a transportable VLBI station.

2. Coherence Check for Cs Gas-cell Oscillator

The stability of the Cs gas-cell oscillator (Anritsu SD2TD01A) was obtained by measuring the time difference compared to a hydrogen maser oscillator. The measurement of the time difference was performed by a frequency-stability measurement system (Anritsu SD5M01A). This measurement system consists of a pair of high-speed analog-to-digital converters (ADCs) and a digital-signal-processing (DSP) circuit on a field programmable gate array. This system has sufficient stability to evaluate a hydrogen maser oscillator (Mochizuki *et al.*, 2007). The stability of the hydrogen maser oscillator usually used for VLBI at Kashima station was also measured for comparison. This measurement was performed by comparing two hydrogen maser oscillators. Figure 2 shows the results of the measurements. These results showed that the Cs gas-cell oscillator had the expected stability. From the measured Allan deviation, the coherence was calculated for the measurements frequencies of 2 GHz and 8 GHz. The coherence function $C(T)$ is given by:

$$C(T) = 1 - \omega_0^2(\alpha_p/6 + \alpha_f T/12 + \alpha_y^2 T^2/57)$$

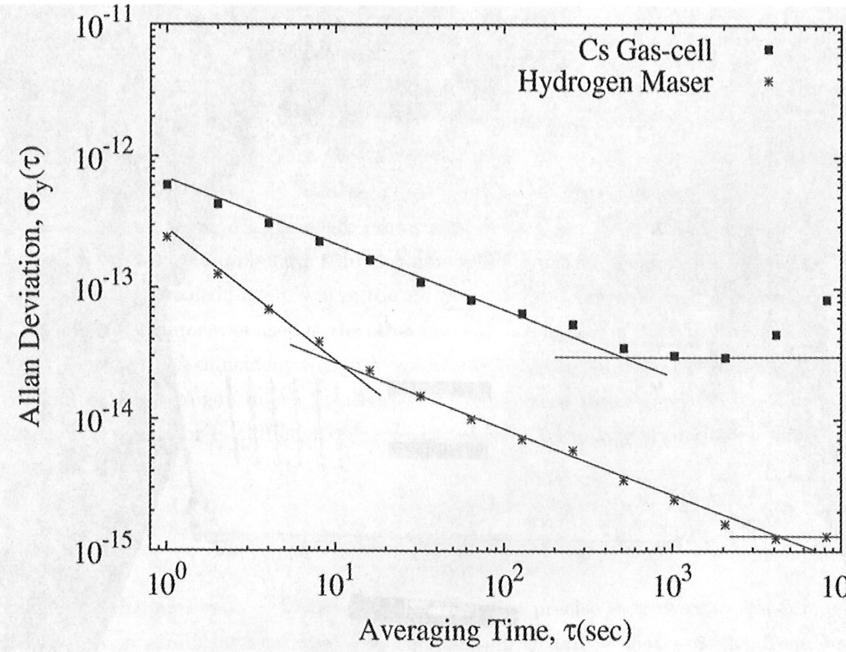

Fig. 2 Allan standard deviation measurements.

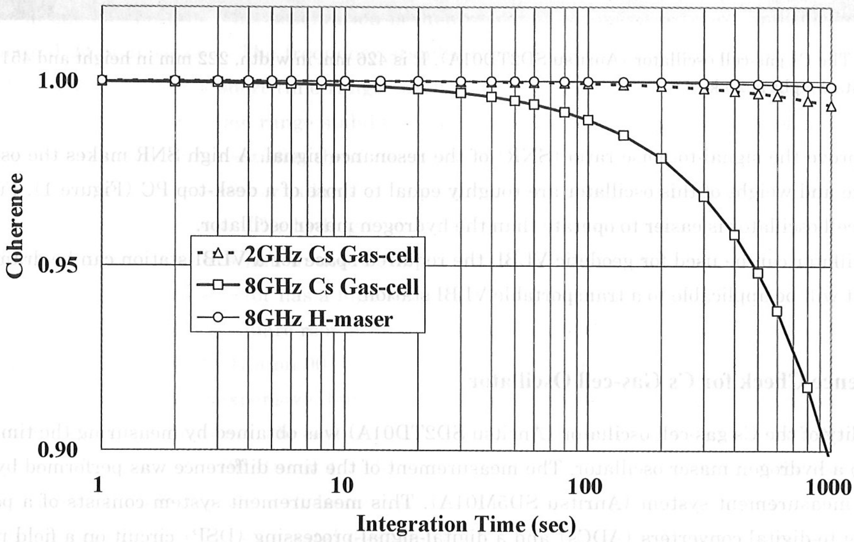

Fig. 3 Coherence calculated from measured stability.

where T is the integration time; ω_0 is the angular frequency of a local oscillator; α_p is the Allan variance of white phase noise at 1 s; α_f is the Allan variance of white frequency noise at 1 s; α_y is the constant Allan variance of Flicker frequency noise (Kawaguchi, 1983). Figure 3 shows the calculated coherence. In this calculation, the square roots of α_p, α_f, and α_y − 6.8×10^{-13}, 6.8×10^{-13}, and 3.0×10^{-13}, respectively, for the Cs gas-cell oscillator and 2.8×10^{-13}, 8.5×10^{-14}, and 1.3×10^{-15}, respectively, for the hydrogen maser oscillator — were used.

The solid lines in Figure 2 represent the Allan deviations from these values. The coherence was better than 0.9 for up to 900 s of integration time at 8 GHz using the Cs gas-cell oscillator. This shows that the stability of the Cs gas-cell oscillator was good enough for VLBI at 2 and 8 GHz measurements.

3. Geodetic VLBI Experiments

Two geodetic VLBI experiments were performed on the 110 km baseline between Kashima station and Koganei station in Japan. The purpose of these experiments was to evaluate the accuracy of baseline vector measurements when using the Cs gas-cell oscillator as the VLBI frequency standard. Table 1 shows the conditions for these experiments. The 34 m diameter Cassegrain antenna at Kashima (CRL, 1995) and the 11 m diameter Cassegrain antenna at Koganei (CRL, 1999) were used in these two experiments. In the first experiment, the hydrogen maser oscillators were used as the frequency standards at both stations. In the second experiment, the Cs gas-cell oscillator was used as the frequency standard for the 34 m antenna system at Kashima. The hydrogen maser oscillator was used as the frequency standard in the 11 m antenna system at Koganei. The Cs gas-cell oscillator was set in the room where the hydrogen maser oscillator is placed. This room is controlled to a temperature of 23 ± 1 degree, and has a magnetic shield. In order to estimate the clock parameters with high accuracy, the experiment scheduled as many observations as possible. As a result, over one thousand observations were scheduled for the 24 h experiment. Figure 4 shows a block diagram of the second experiment. In this experiment, a phase comparison measurement between the Cs gas-cell oscillator and the hydrogen maser oscillator was carried out using the frequency stability measurement instrument (Anritsu SD5M01A) at Kashima. These antennas are equipped with a K5 VLBI system (Koyama *et al.*, 2003; Kondo *et al.*, 2008). X-band and S-band signals were observed in these experiments. Ten frequency channels in the X-band and six frequency channels in the S-band were used. The frequency bandwidth was 8 MHz per channels. The signal of each channel was converted into 1-bit digital signals at a sampling frequency of 16 MHz and recorded by the K5 VLBI system. Hence, the total recorded data rate was 256 Mbps.

A cross correlation was performed by the K5 software correlator (Kondo *et al.*, 2008). After the correlation processing, a baseline analysis was made for each VLBI experiment using the obtained delay. In this baseline analysis, several parameters were estimated using the least square method. The baseline analysis was performed by using the geodetic VLBI analysis software packages CALC/SOLVE, developed at NASA's Goddard Space Flight Center. The estimated parameters were the position of Kashima station (X, Y, Z), the clock parameters of Kashima station, and zenith atmospheric delays. The clock function was modeled as a sum of two functions. One of these functions was a quadratic function for the gross clock behavior, and the other was a piecewise linear continuous clock parameters. The position of the Koganei station was fixed using the ITRF2000

Table 1. VLBI experiment conditions

	Experiment Name	
	K07172	Cs7200
Date	6/21/2007	7/19/2007
Using station	Kashima 34 m / Koganei 11 m	Kashima 34 m / Koganei 11 m
Freq. standard	Hydrogen maser oscillator (Both stations)	Cs gas-cell oscillator (Kashima) Hydrogen maser oscillator (Koganei)
Number of radio sources	70	70
Number of observations	1030	1049
Actual duration	23.9 h	24.0 h

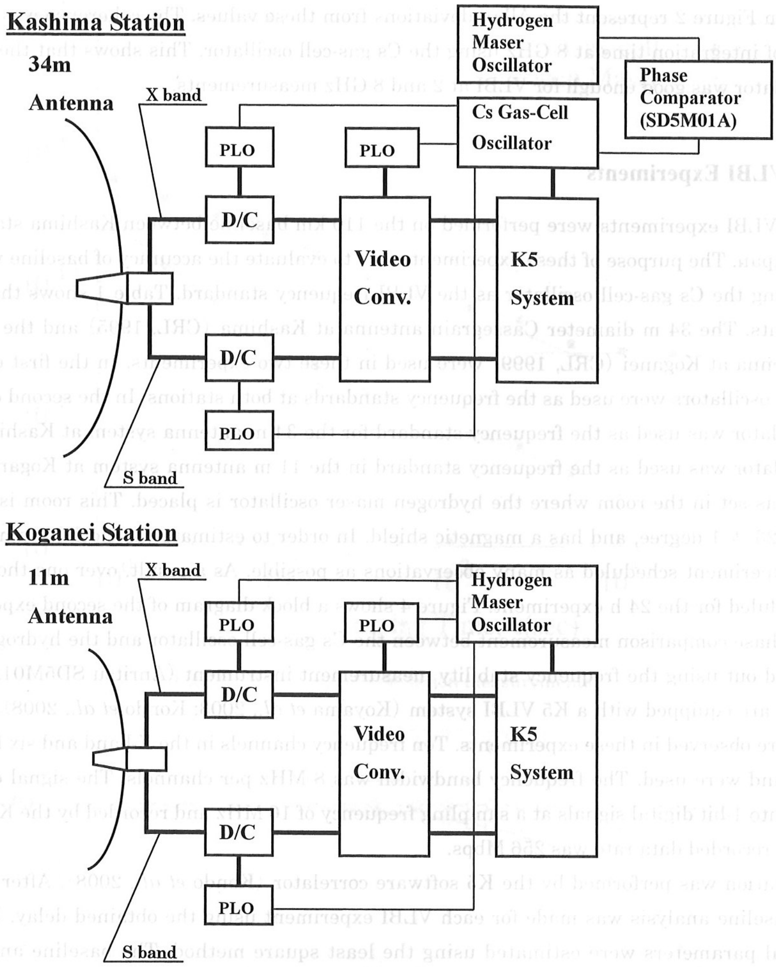

Fig. 4 Block diagram of the second VLBI experiment (Cs7200).

Table 2. The results of the baseline analysis

Experiment Name	Residual Delay (ps)	Baseline Length (mm)	Position of Kashima Station		
			X (mm)	Y (mm)	Z (mm)
K07172	36	109337421.5 ± 1.3	− 3997649243.5 ± 3.5	3276690826.5 ± 2.8	3724278730.5 ± 3.2
Cs7200	39	109337422.4 ± 1.5	− 3997649243.9 ± 3.6	3276690825.3 ± 2.9	3724278728.0 ± 3.4

coordinates and the earth orientation parameters were obtained from the IERS bulletin B. The source positions were also fixed using the positions that had been determined by astrometric global solution 2005f_astro (Petrov, 2006). Astrometric global solution 2005f_astro was supplied by NASA's Goddard Space Flight Center.

4. Results

In the first experiment, the SNRs of the correlation amplitude were over 20 for 95% of the over one thousand observations on the observation schedule. The ratio in the second experiment was 96%. The radio sources used in those experiments and, the integration time for each radio source were the same in both experiments. The integration time for an observation in these experiments ranged from 30 s to 86 s. This result indicates that coherence loss was not a problem in the second experiment, as expected in Section 2.

Table 2 shows the results of the baseline analysis. The lengths of the baseline vector estimated by the first experiment (K07172) and second experiment (Cs7200) were coincident within 1 mm. The estimated position of Kashima station (X, Y, Z) in the second experiment agreed with the result of the first experiment within 3 mm. Figures 5 and 6 show the distribution of the residual delays after the parameter fitting for the first and second experiments, respectively. The root mean squares (RMS) values for the residual delay were 36 ps and 39 ps respectively. In Figures 5 and 6, the data points not used for the baseline analyses because of large residual delays and low SNRs were not plotted. The ratios of the data not used for the analyses were 6.0% and 3.4% for the first and second experiments, respectively. Figure 7 shows the clock parameters estimated from the VLBI experi-

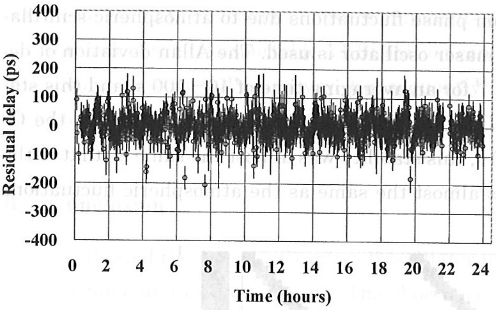

Fig. 5 Residual delays after the parameter fitting of the first VLBI experiment (K07172).

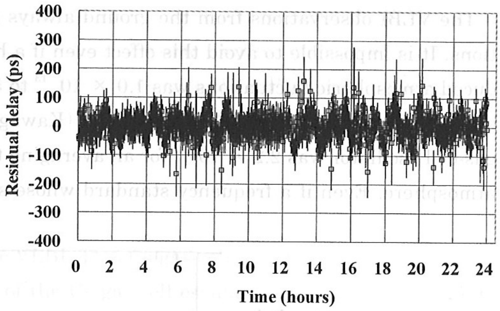

Fig. 6 Residual delays after the parameter fitting of the second VLBI experiment (Cs7200).

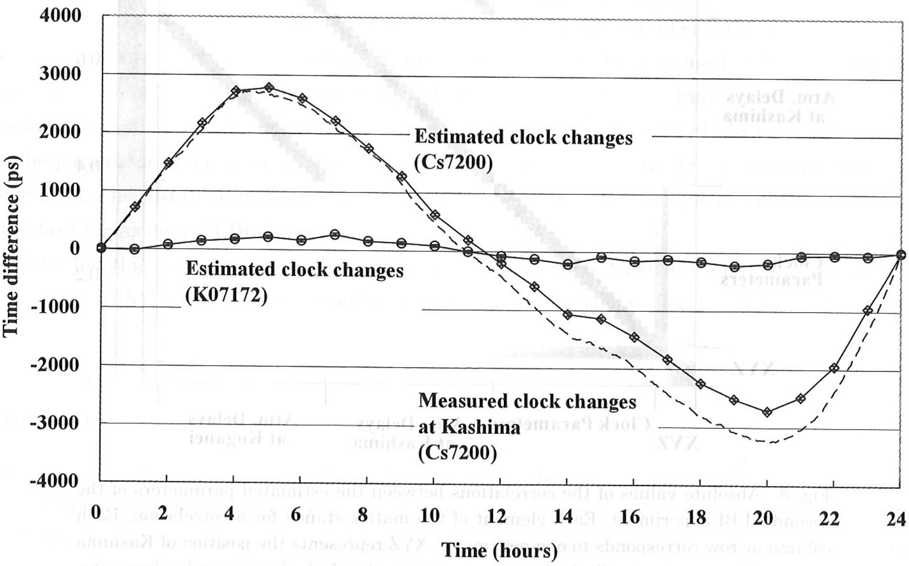

Fig. 7 Estimated clock changes in the first VLBI experiment (solid line, circle, and error bar), estimated clock changes in the second VLBI experiment (solid line, diamond, and error bar), and clock changes measured by phase comparator at Kashima station (dashed line). Error bar stand for 1 sigma.

ments and the clock changes by the phase comparator. These clock parameters show only a part of a linear spline. The measured clock change in this figure indicated that the clock rate and the frequency rate were absorbed in clock changes in the estimation procedure. The clock parameters in the second experiment changed widely compared with the first experiment. The changes reached 5000 ps or more for the peak-to-peak value. However, the estimation error for those parameters was small and the behavior of the changes was corresponded to the measured clock changes. Figure 8 shows the correlation coefficients between the estimated parameters. It can be seen that the position of Kashima station (X, Y, Z) was not correlated from the clock parameters and atmospheric delays. The clock parameters were also not correlated from the atmospheric delays and the XYZ coordinates. These results indicate that there was no problem with estimating the clock changes and the position even though the clock changed for 5000 picoseconds or more.

5. Discussion

The VLBI observations from the ground always suffer from phase fluctuations due to atmospheric scintillations. It is impossible to avoid this effect even if a hydrogen maser oscillator is used. The Allan deviation of deduced atmospheric fluctuations was 1.0×10^{-13} to 5.0×10^{-13} for an averaging time of 10 − 100 s, and this stability depended on the weather conditions (Kawaguchi *et al.* 2000). The Allan deviation measured for the Cs gas-cell oscillator was 2.2×10^{-13} for an averaging time of 10 s, this stability was almost the same as that of the atmosphere. Even if a frequency standard whose stability is almost the same as the atmospheric fluctuations

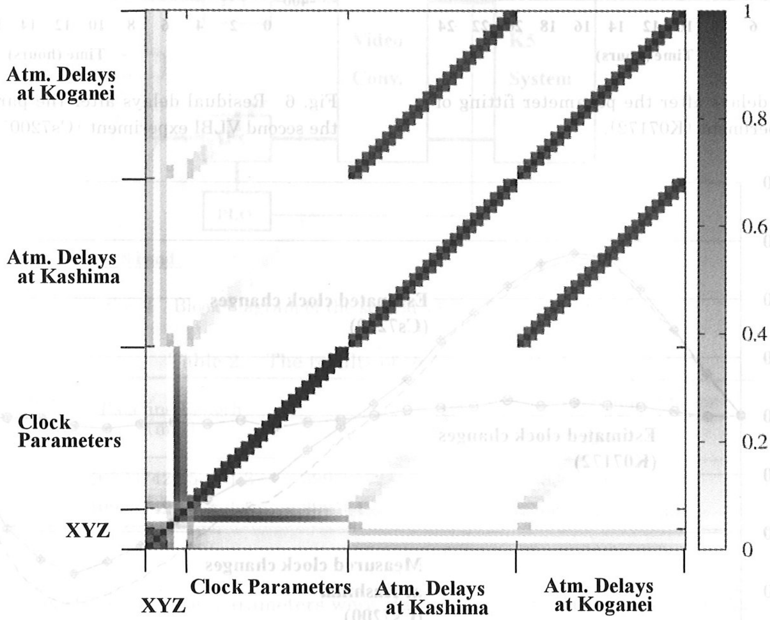

Fig. 8 Absolute values of the correlations between the estimated parameters of the second VLBI experiment. Each element of the matrix stands for a correlation. Each column or row corresponds to one parameter. XYZ represents the position of Kashima station (3 parameters). Clock parameters refer to the clock changes at Kashima station. These are the parameters of the quadratic function (three parameters) and clock offsets for every hour (24 parameters). Atm. delays include 25 parameters for the zenith atmospheric delay for every hour for each station.

(Cs gas-cell oscillator) is used instead of a frequency standard whose stability is greater than the atmospheric fluctuations (hydrogen maser oscillator), it is expected that the fringe amplitude will be almost the same. This hypothesis was confirmed from the results of our VLBI experiments. In addition, the measurement accuracy for the baseline vector with the Cs gas-cell oscillator was almost the same as the case using the hydrogen maser oscillator.

The Cs gas-cell oscillator is suitable for a transportable VLBI station because of its small size and handling ease. The volume of the Cs gas-cell oscillator is about 1/8 that of the hydrogen maser oscillator (Anritsu RH401A), based on the sizes given in Figure 1 and Section 1. On the other hand, the volume of the backend for a geodetic VLBI station (VLBI sampler, recorder, baseband converter, etc.) is roughly the same as the two 19-inch racks that are 1.5 m tall. The Cs gas-cell oscillator and the backend can be stored in a general purpose van. This means the form used for VLBI observations can become freer than before. For instance, the Cs gas-cell oscillator could be used for two or more transportable VLBI stations, while the hydrogen maser oscillator is used for a large-fixed VLBI station. Highly accurate observations become possible in various places by performing observations using the baselines between numerous transportable VLBI stations and a large-fixed VLBI station. If the antenna of the transportable VLBI station can be made small, it will become easy to compare with a Global Positioning System (GPS) survey. Consequently, it will be possible to calibrate the GPS survey by using the VLBI technique.

6. Conclusion

We evaluated the use of a Cs gas-cell oscillator for geodetic VLBI. This Cs gas-cell has the advantage of being transportable and easy to operate. The short-term stability of the Cs gas-cell oscillator was measured, and its coherence when this was applied to VLBI was estimated. As a consequence, it was shown that the coherence was better than 0.9 for up to 900 s of integration time with a measurement frequency of 8 GHz.

Two geodetic VLBI experiments using Kashima station and Koganei station were conducted. In the first experiment, hydrogen maser oscillators were used at both stations. In the second experiment, the Cs gas-cell oscillator was used at the Kashima station and the hydrogen maser oscillator was used at Koganei station. In both experiments, more than 95% of the scans had an SNR greater than 20. Each component of the estimated position of Kashima station in the two experiments was coincident within 3 mm. The RMS values of the residual delays after the parameter fitting were at the same level. The estimation errors for the baseline length were also at the same level. The results of this study indicate that the Cs gas-cell oscillator is sufficiently stable as a frequency standard for geodetic VLBI observations.

We conclude that this oscillator is suitable for use in a transportable VLBI station. If the transportable VLBI station is realized with a small antenna, it will be easy to compare with a Global Positioning System (GPS) survey.

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