7.1 Accuracy Improvement in KSP VLBI System

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Abstract

The Communications Research Laboratory has developed a compact VLBI network consisting of four stations. This VLBI network is dedicated to monitoring the crustal deformation around the Tokyo metropolitan area in Japan, and it began daily observations spanning five to six hours in 1995. Since then continuous improvements in both system hardware and in the observation method have been made to increase system reliability and the accuracy of measurements. In 1997 the so-called "real-time" VLBI technique was newly installed in this VLBI network. By introducing the real-time VLBI the length of a session was extended to 24 hours. Consequently, the measurement accuracy was significantly improved. The repeatability in the KSP VLBI network has reached about a 2-mm level in baseline length.

Keywords : real-time VLBI, repeatability, accuracy

1. Introduction

The Communications Research Laboratory (CRL) has lead the development of the VLBI system in Japan. CRL first developed the K-3 VLBI system compatible with the Mark-III VLBI system developed by the US group(1) and successfully carried out US-Japan VLBI(2).. After that CRL developed the K-4 VLBI system, which facilitated ease in both operation and transportation(3). By applying these experiences to further system development, CRL has started a new project: the establishment of a sophisticated VLBI network consisting of four stations which monitors the crustal deformation around the Tokyo metropolitan area in Japan in order to utilize the data for the study of earthquake prediction. We named the project Keystone Project (KSP) after the Japanese traditional saying that relates to earthquake prevention.

In January, 1995 the KSP started regular observations using two VLBI stations. The construction of the fourth VLBI station was completed in September, 1996. KSP has entered a full operation phase consisting of daily observations spanning 5 to 6 hours using a conventional tape recording method system. In parallel with these daily observations, we established a real-time VLBI in cooperation with the Nippon Telephone and Telegraph Co. This real-time VLBI has been used in routine operations since June 4, 1997. On September 30, 1997, we began 24-hour observations every other day.

Thus we have been making continuous improvements in both system hardware and in the observation method to improve measurement accuracy. Currently, repeatability has reached about a 2-mm level in baseline length in our VLBI network. Evaluation of the measured baseline length's accuracy on the KSP VLBI network was made in our previous paper(4). In this paper, we discuss the evolution of accuracy using the latest results. We not only follow the method applied in the previous paper to evaluate the accuracy but we extend the evaluation period up to the end of September, 1998.

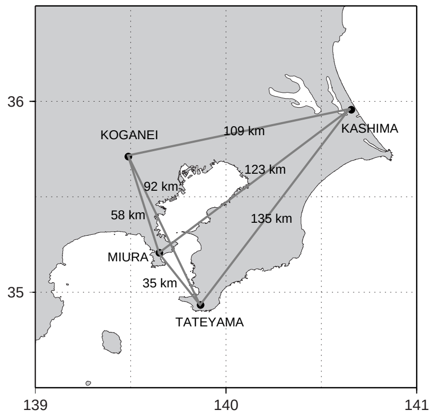

Figure 1. *Configuration of the Keystone Project VLBI network.*

2. VLBI System and observations

The KSP VLBI system consists of four stations (Kashima, Koganei, Miura, and Tateyama) that were newly constructed around the Tokyo metropolitan area (Fig. 1). The longest distance between any two KSP stations is about 135 km (Kashima-Tateyama). Therefore the KSP network is a compact VLBI network, because VLBI has been developed as a tool to measure very long distances such as intercontinental distances.

Each VLBI station is equipped with the same VLBI facilities and is dedicated to a geodetic measurement. Dual S (2 GHz) and X (8 GHz) band signals from quasars are received by an antenna with an 11-m diameter. They are then converted into video signals consisting of 16 channels that can be assigned to either an S or X band. Either a 2-MHz or 8-MHz bandwidth can be selected as a video bandwidth. Video signals are sampled at a Nyquist frequency and are converted into one-bit digital signals. Hence the total data rate is 64 Mbps for a 2-MHz video bandwidth and 256 Mbps for an 8-MHz video bandwidth. A stable Hydrogen maser frequency standard is employed as a station clock and frequency standard.

Digitized signals are recorded on a magnetic tape in the conventional VLBI system ("tape-based" VLBI). After a series of observations, magnetic tapes are sent to the central station where the correlation processing takes place. Therefore after observations are finished, it takes several days to obtain results. Moreover the number of observations is limited not only by the number of tapes but also by the capacity of correlation processing.

The observation system is designed to make an unmanned operation possible and its observation status is always automatically monitored at both Koganei and Kashima stations. Observation schedules are delivered in advance to each station from the Koganei station through the Internet.

The KSP started as a tape-based VLBI. In January, 1995, regular observations began on the baseline between Kashima and Koganei. In September, 1996, all four stations started daily observations spanning 5 to 6 hours.

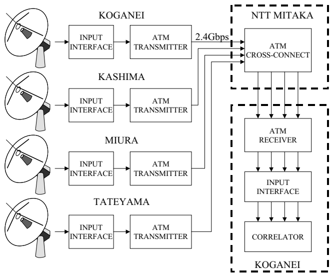

Figure 2. *Block diagram of the KSP real-time VLBI system.*

During the daily tape-based observations, we were also establishing a "real-time" VLBI in cooperation with the Nippon Telephone and Telegraph Co. "Real-time" VLBI means a correlation processing in real time using data transmitted through an ATM (Asynchronous Transfer Mode) network of high-rate transmission links (maximum speed is 2.4 Gbps) between the four KSP stations. Digitized signals observed at each station are transmitted to Koganei, where a KSP correlator is located, in real time through the ATM network (Fig. 2). In the case of the real-time VLBI, correlation processing for the 6 baselines is carried out simultaneously by observation using data transmitted from each station.

This real-time process has been used in routine operations since June 4, 1997. Since then the length of a session, which is a series of scans of quasars, has become free from a restriction arising from the correlation processing in the case of a tape-based VLBI. Moreover the time necessary for the synchronization of the two data streams is negligible in the real-time VLBI compared with that for the tape-based VLBI. Hence we can increase the number of scans in a unit time to improve the accuracy.

From July 28 to August 1, 1997, a continuous 120-hour test session was conducted in order to evaluate the improvement in precision by both extending the length of the session and increasing the number of scans. Since this test session was carried out successfully, we extended the length of each session to 24 hours and increased the number of scans from 140 to 600 in order to improve the geodetic precision. However, the session frequency was reduced from on everyday basis to on an every-other-day basis in order to avoid overloading the system, in particular, on the antenna. We began routine observations under this new strategy on September 30, 1997.

Baseline analysis is automatically carried out on a session basis using analysis software developed for the KSP based on that developed by the Goddard VLBI group. The latest version of the geophysical and astronomical model calculation program (CALC8.1) developed by the Goddard VLBI group is used for calculating the *a priori* value.

3. System evaluation

VLBI measurements can give a three-dimensional station position. However, in this study, the measured baseline lengths are used to evaluate the precision of measurements, because the estimation of the baseline length is more reliable than that of the station position against model uncertainties, such as earth rotation parameters. We adopt the same method described in our previous paper(4) to evaluate the system precision; that is, we define repeatability of measurement results as a standard deviation of five continuous samples of baseline lengths. In order to separate long-term fluctuations (such as seasonal variations probably arising from model imperfectness in the baseline analysis) from short-term ones we chose five continuous samples as a unit. L_k and ϵ_k are the kth sample of a measured baseline length and its formal error of a baseline analysis. A standard deviation of five continuous samples of the baseline length starting from the kth sample, σL_k, is computed from

$$\sigma L_k = \sqrt{\frac{\sum_{i=0}^{4}\left(L_{n+i} - \frac{\sum_{i=0}^{4} L_{n+i}}{5}\right)^2}{4}}. \tag{1}$$

As for formal error representing the five samples, we take a simple mean of five continuous samples of formal errors, i.e.,

$$\overline{\epsilon_k} = \frac{\sum_{i=0}^{4} \epsilon_k}{5}. \tag{2}$$

We only take five continuous samples in the time series of data for statistical study. Thus the time span for the five continuous samples is different depending on the session frequency. The samples span for approximately 5 days for the data measured before September 30, 1997, and for 9 days for the data measured after that time except for a few occasions when routine observations accidentally failed. Using σL_k and $\overline{\epsilon_k}$ we evaluated the precision of the KSP VLBI system.

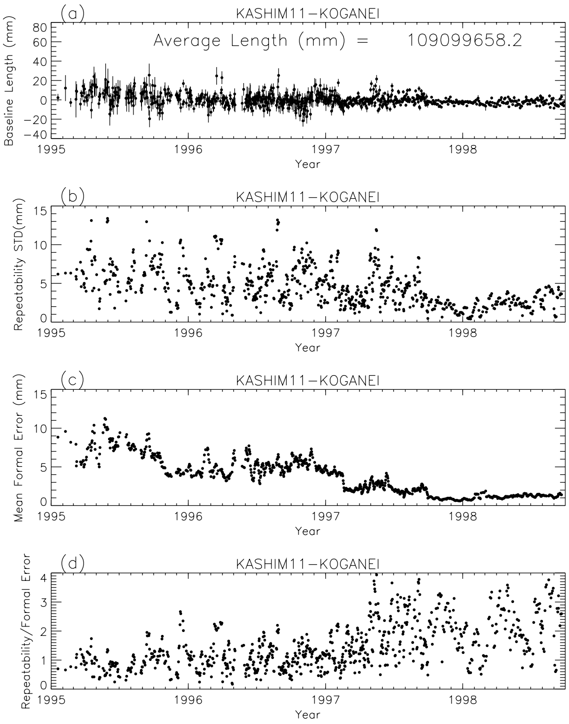

Figure 3. *Evolution of (a) baseline length between Kashima and Koganei (b) repeatabilities (c) mean formal errors and (d) ratio of repeatability to mean formal error of five continuous samples of baseline length.*

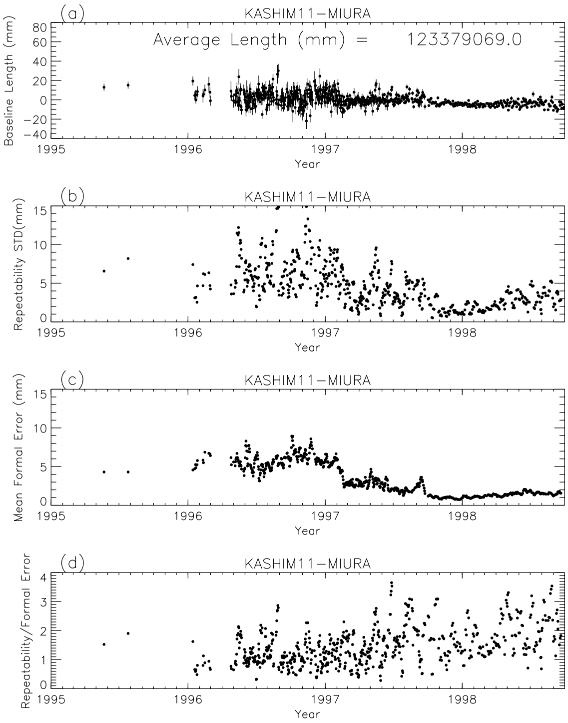

Figure 4. *Same as Fig. 3 for Kashima-Miura baseline.*

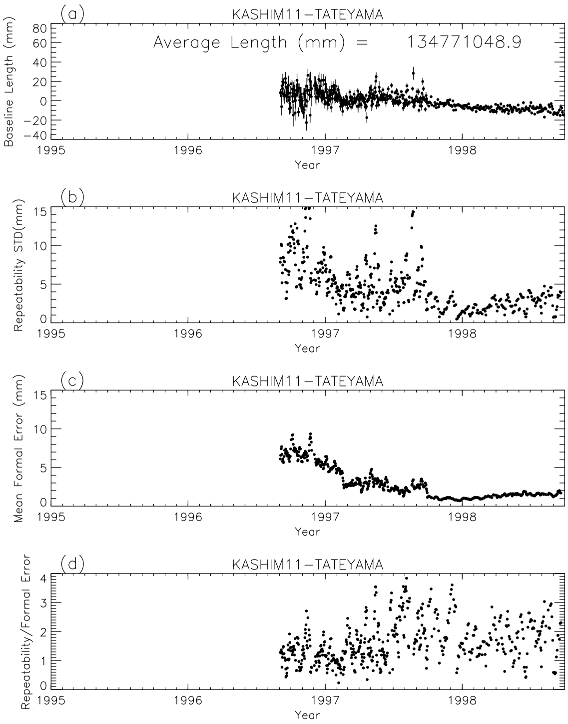

Figure 5. *Same as Fig. 3 for Kashima-Tateyama baseline.*

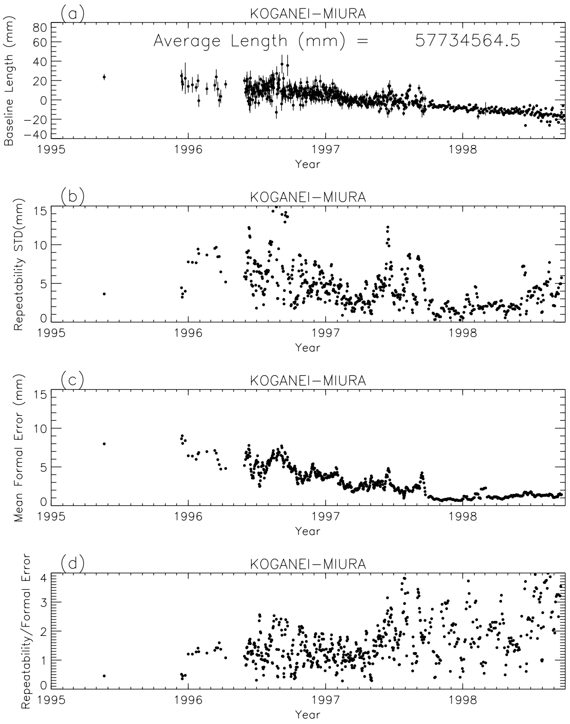

Figure 6. *Same as Fig. 3 for Koganei-Miura baseline.*

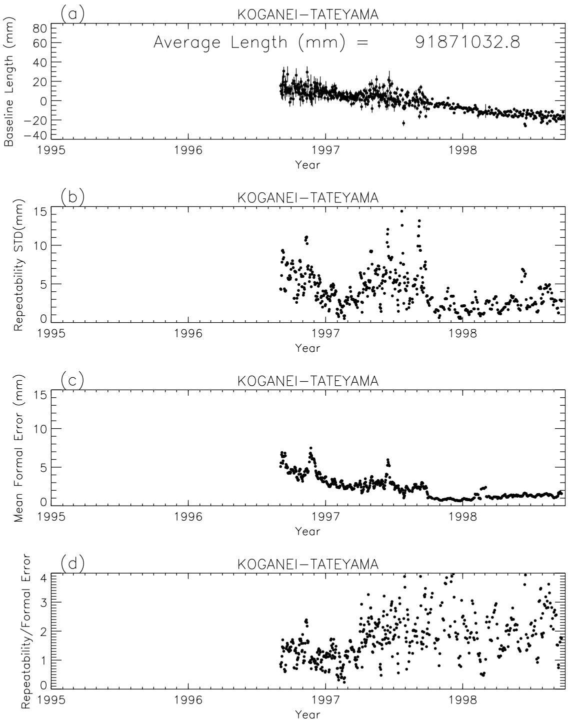

Figure 7. *Same as Fig. 3 for Koganei-Tateyama baseline.*

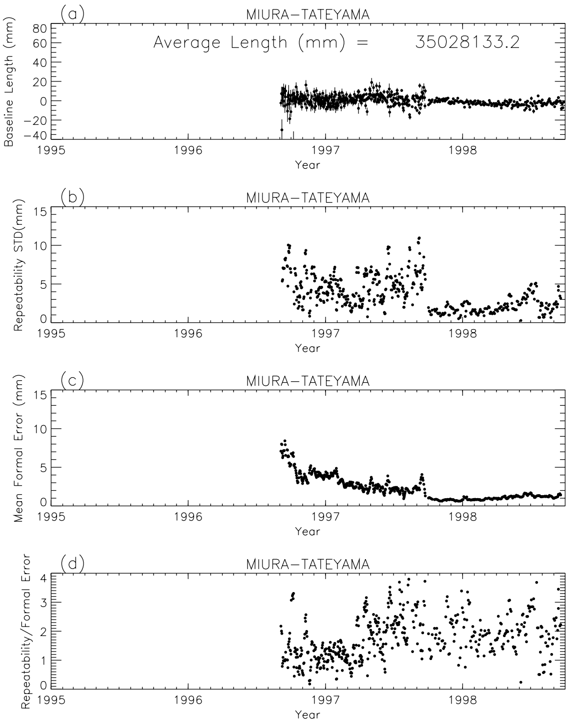

Figure 8. *Same as Fig. 3 for Miura-Tateyama baseline.*

4. Results

Figures 3–8 show the evolution of measured baseline lengths, standard deviations, mean formal errors and their ratio for the five continuous samples of the baseline length data for the six baselines for the period from January, 1995 to September, 1998. The formal error obtained from each baseline analysis almost corresponds to the standard deviation of O-C residuals after parameter-fitting in a session. We can see stepwise structures in the plot of mean formal errors, in particular at three epochs in the Kashima-Koganei baseline (at the end of October, 1995, in the middle of February, 1997, and at the end of September, 1997). This demonstrates a drastic improvement in the system. The first two correspond to improvements in system hardware (such as an increase in temperature stability in a receiver room), while the last one corresponds to the extension of the session time. On June 4, 1997 we changed the video bandwidth from 2 MHz to 8 MHz.

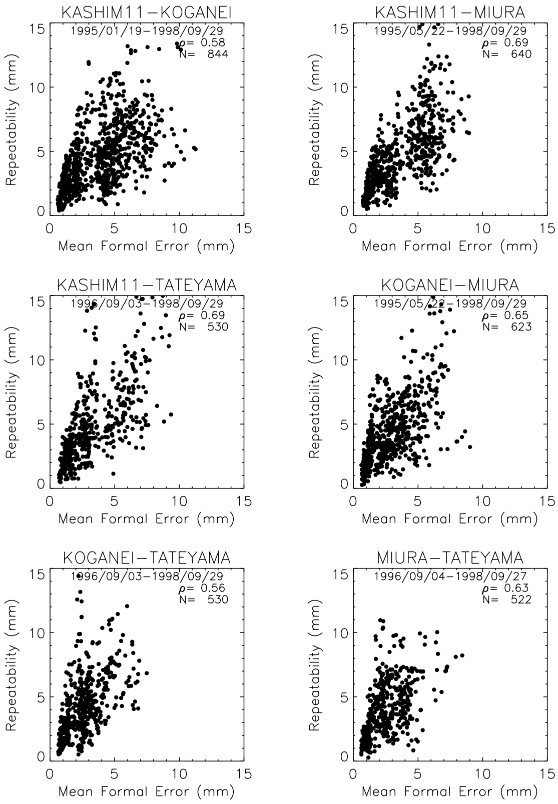

Figure 9. *Scatter plots of σL_k (repeatabilities) and $\overline{\epsilon_k}$ (formal errors) for six baseline combinations for the period from the start of routine observation to September, 1998. ρ is the correlation coefficient between parameters.*

Fig. 9 represents scatter plots of σL_k and $\overline{\epsilon_k}$ for all baseline combinations of the KSP network. In each panel ρ is the correlation coefficient and N is the number of samples plotted in the figure. Note that we can see a weak correlation between σL_k and $\overline{\epsilon_k}$, but repeatabilities are more scattered than the mean formal errors. When we limit the data period to after October, 1997, (i.e., selecting only 24-hour sessions) data points tend to concentrate in the lower-left portion of each plot (Fig. 10).

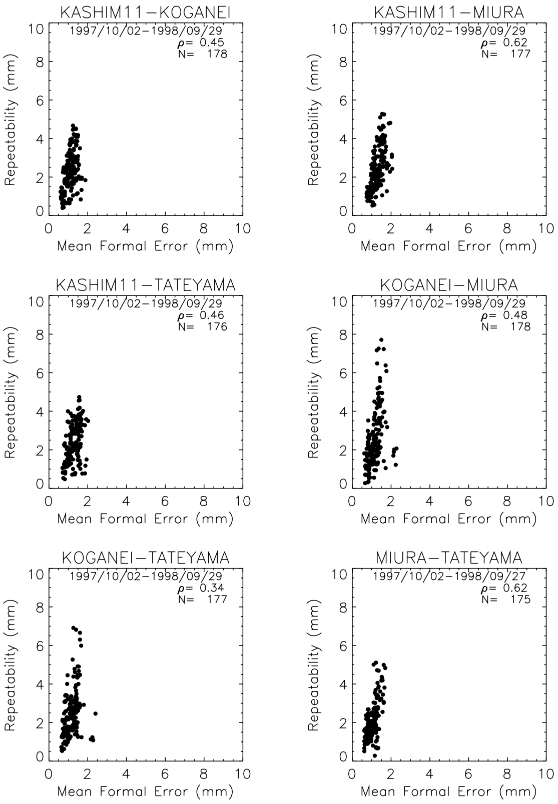

Figure 10. *Same as Fig. 9 but for the period after October, 1997. Axis scales are different here.*

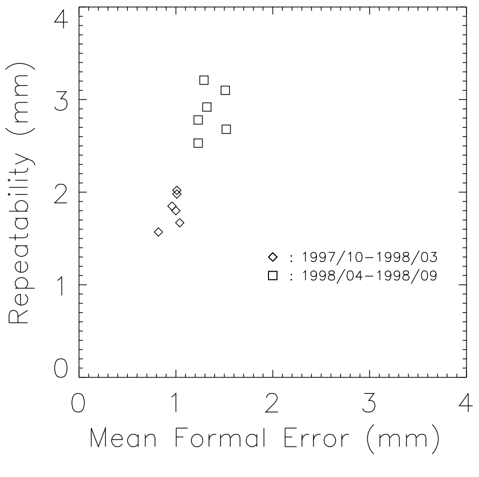

Figure 11. *Scatter plots of σL_k (repeatabilities) and $\overline{\epsilon_k}$ (formal errors) for six baseline combinations for the two sub-periods.*

To evaluate the differences that arose because sessions had different time spans, we calculated the average value of repeatabilities and mean formal errors for different time spans. The data are limited to those obtained after June 4, 1997 in order to exclude

Table 1. *Comparison of average repeatabilities (σL) and average mean formal errors ($\overline{\epsilon}$) in the period June - September, 1997 (corresponding to a 6-hour span session) and in the period October, 1997 - September, 1998 (24-hour span session)*

	June – Sept., 1997		Oct., 1997 – Sept., 1998	
Baseline	σL (mm)	$\overline{\epsilon}$ (mm)	σL (mm)	$\overline{\epsilon}$ (mm)
KASHIMA–KOGANEI	4.0±1.7	2.1±0.5	2.3±1.0	1.1±0.3
KASHIMA–MIURA	3.7±1.5	2.2±0.5	2.4±1.1	1.3±0.3
KASHIMA–TATEYAMA	5.2±2.7	2.4±0.5	2.4±1.0	1.3±0.3
KOGANEI–MIURA	5.3±2.7	2.5±0.8	2.5±1.5	1.2±0.3
KOGANEI–TATEYAMA	5.8±2.9	2.6±0.8	2.5±1.2	1.2±0.3
MIURA –TATEYAMA	5.1±2.4	2.2±0.6	2.1±1.0	1.0±0.3

the effects that differences in video bandwidth may cause. Table 1 summarizes averaged repeatabilities and mean formal errors for the period June 4, 1997 to September 30, 1997 (corresponding to a 6-hour session) and October 2, 1997 to September 29, 1998 (a 24-hour session). It can be clearly seen from the table that a 24-hour session gives better repeatability and formal errors than a 6-hour session. By comparing the two periods it is concluded that both repeatabilities and mean formal errors are improved by about a factor of two, which is consistent with our expectations (i.e., making the session four-times longer doubles the precision). However, the repeatability is worse than the formal error for all baselines by about a factor of two. The simple average of all baselines for repeatabilities for 24-hour spans is 2.4 mm and the simple average of formal errors for 24-hour spans is 1.2 mm. These values are the precision of the KSP VLBI system at present.

Since the end of September, 1997, we have not changed the system's operation method or hardware. However, we can see a seasonal effect in Figs. 3–8. In order to investigate this effect in detail we divided a year into two sub-periods representing winter and summer seasons (i.e, October, 1997 to March, 1998 and April, 1998 to September, 1998) and we made statistical calculations for the two sub-periods. Table 2 summarizes averaged repeatabilities and mean formal errors for these three periods by baseline. In Fig. 11 they are plotted for the two sub-periods.

The simple average of all baselines for repeatabilities for the winter season is 1.8 mm and for the summer season it is 2.9 mm. The simple average of all baselines for mean formal errors for the winter season is 1.0 mm and for the summer season it is 1.4 mm. Both repeatability and mean formal error become worse in the summer season by factors of about 1.6 and 1.4 compared with those in the winter season. Moreover the repeatability is worse than the mean formal error by about a factor of two.

5. Conclusions

We have developed the KSP VLBI system and have been monitoring the crustal deformation around the Tokyo metropolitan area. We have also continued to improve instrumentation as well as observing strategies and analysis models. The current precision in terms of repeatability defined as a standard deviation of five continuous samples of a measured baseline length is about 2 mm. However, this is about two times larger than that of the formal error of session analysis. This suggests that the model applied in a 24-hour session baseline analysis is insufficient for a time scale longer than one day. Correlation coefficients between σL and $\overline{\epsilon}$ are about 0.5 and they are a bit lower than the statistical expectation in the case of five degrees of freedom (about 0.8 for a Gaussian distribution). This also suggests the existence of an unmodeled effect in the baseline analysis.

Moreover the precision tends to become worse in the summer season by a factor of about 1.5 compared with the winter season. Generally speaking, the summer in Japan is very humid. In the VLBI observation, the propagation delay caused by the water vapor is the most unknown error source at present. It is estimated in the baseline analysis using a proper mapping function that models excess delay with a function of elevation angle. As KSP stations with the exception of Koganei are located close to the ocean (Fig. 1), the azimuthal asymmetry in the wet atmospheric component may be large around these stations. In the current KSP VLBI baseline analysis, azimuthal asymmetries of this mapping function are unmodeled. This might be the cause of an error source in a baseline estimation(5) and it could account for a larger variation in day-to-day baseline estimation in the summer season, since the winter season is very dry and the wa-

Table 2. *Averaged repeatabilities (σL) and averaged mean formal errors ($\bar{\epsilon}$) for winter and summer seasons*

Baseline	Oct.,1997 – Mar.,1998		Apr.,1998 – Sept.,1998	
	σL (mm)	$\bar{\epsilon}$ (mm)	σL (mm)	$\bar{\epsilon}$ (mm)
KASHIMA–KOGANEI	1.9±0.8	1.0±0.3	2.8±1.0	1.2±0.2
KASHIMA–MIURA	1.7±0.7	1.0±0.2	3.1±1.0	1.5±0.2
KASHIMA–TATEYAMA	2.0±0.9	1.0±0.2	2.7±1.0	1.5±0.2
KOGANEI–MIURA	1.8±0.9	1.0±0.4	3.2±1.7	1.3±0.2
KOGANEI–TATEYAMA	2.0±0.9	1.0±0.4	2.9±1.3	1.3±0.2
MIURA –TATEYAMA	1.6±0.5	0.8±0.1	2.5±1.1	1.2±0.2

ter vapor does not affect VLBI observations so much.

Thus improving physical models, such as the azimuthal asymmetry propagation delay models, should be investigated in order to achieve better repeatability over several days. The baseline length is very short; technical difficulties therefore remain in introducing these asymmetry models. We have started to investigate the relation between the fluctuation of baseline length and local weather conditions to overcome this difficulty.

Acknowledgments.

The real-time VLBI technique for the KSP was developed in cooperation with the Telecommunication Network Laboratory Group of Nippon Telegraph and Telephone Corporation (NTT). We thank all staff members of NTT involved in the real-time VLBI Project for their efforts to maintain the high-speed network of the KSP.

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