Crustal Deformation Monitoring Using the Real-time VLBI System in the Tokyo Metropolitan Area and its Performance

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Aabstract

The Communications Research Laboratory has been monitoring crustal deformation in the Tokyo metroplitan area using a compact VLBI network consisting of four stations since 1995. In 1997 the so-called "real-time" VLBI technique was installed in this VLBI network. Continuous improvement both in system hardware and in the observation method have resulted in a remarkable improvement in measurement accuracy. The repeatability in our VLBI network currently reaches about a 2-mm level in baseline length.

1. Introduction

The Communications Research Laboratory (CRL) has lead the development of the VLBI system in Japan. CRL developed the K-3 VLBI system which is compatible with the Mark-III VLBI system developed by the US group [*Clark et al.,* 1985] and successfully carried out a US-Japan VLBI [*Saburi et al.,* 1984]. CRL then developed the K-4 VLBI system, which facilitated ease in both operation and transportation [*Kondo et al.,* 1992].

By applying these experiences to further system development, CRL has started a new project; the establishment of the sophisticated VLBI network. This network consists of four stations and it monitors the crustal deformation around the Tokyo metropolitan area in Japan. It utilizes 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 September, 1996 the KSP entered a full operation phase consisting of daily observations spanning 5 to 6 hours using a conventional tape recording method system. Along with these daily observations, we established a real-time VLBI in cooperation with the Nippon Telephone and Telegraph Co. Real-time VLBI means a correlation processing in real time using high-rate transmission links (maximum network speed is 2.4 Gbps) between the four KSP stations. This real-time processing 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-recording-based VLBI.

After a continuous 120-hour test session using the real-time VLBI technique, we extended the length of each session to 24 hours in order to improve the geodetic precision. But the session frequency was reduced to on every other day basis in order to avoid overloading the system, in particular, on the antenna driving system. We began routine observations under this new strategy on September 30, 1997.

Thus we have been making continuous improvement both in system hardware and in the observation method to improve measurement accuracy. Now repeatability reaches about a 2-mm level in baseline length in our VLBI network [*Kondo et al.,*1998].

In this paper, we discuss the evolution of accuracy using the latest results by extending the evaluation period up to the end of September, 1998.

2. VLBI System and observations

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

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, then they are converted into video signals consisting of 16 channels that are 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

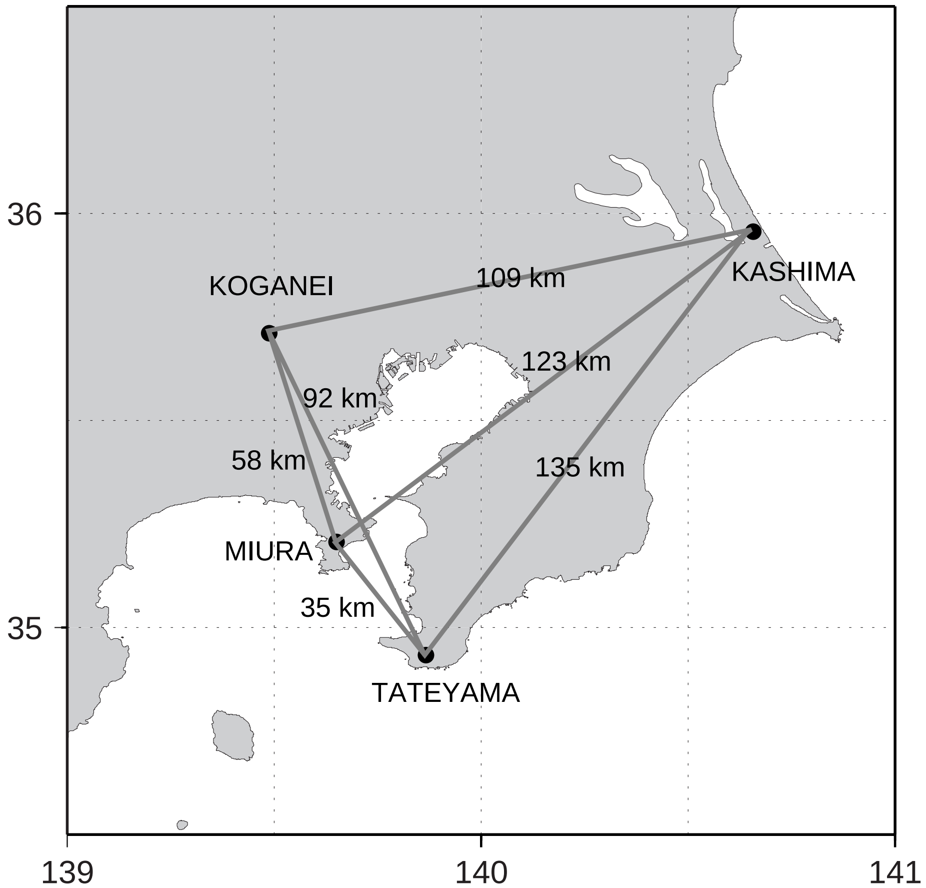

Figure 1. Configuration of the Keystone Project VLBI network.

a Nyquist frequency and then they 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

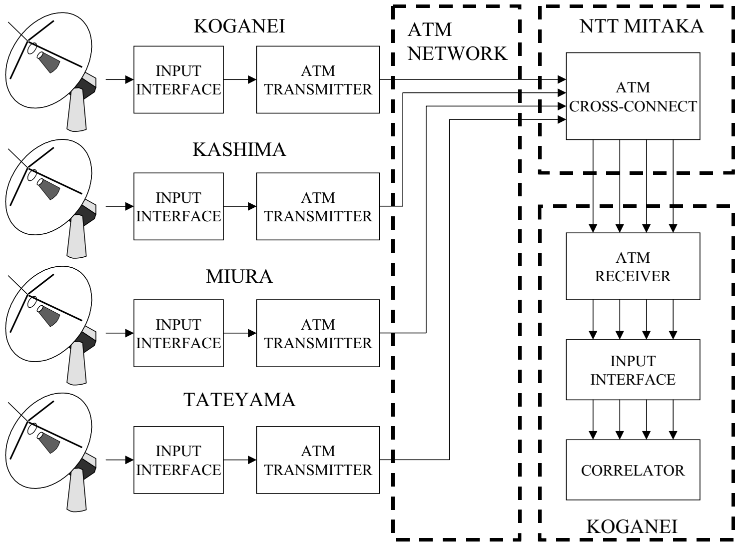

Figure 2. Block diagram of the KSP real-time VLBI system.

on the baseline between Kashima and Koganei. In September, 1996 all four stations started daily observations spanning 5 to 6 hours.

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 (Figure 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 for the real-time VLBI compared with those for the tape-based VLBI. Hence we can increase the number of scans in a unit time to improve accuracy.

From July 28 to August 1, 1997, continuous 120-hour test session was carried out in order to evaluate the improvement in precision by extending the length of the session and increasing the number of scans. Because this test session was successfull, we decided to extend the length of each session to 24 hours in order to improve the geodetic precision, but the session frequency was reduced to on 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 that was developed for the KSP based on that developed by the Goddard VLBI group [*Ma et al.*,1990]. 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, 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 *Kondo et al.* [1998] to evaluate the system precision, that is, we define the repeatability of the measurement results as a standard deviation of five continuous samples of baseline lengths. In order to separate long term fluctuations, such as seasonal variation 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

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

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

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

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

4. Results

Table 1. Averaged repeatabilities (σL) and averaged mean formal errors ($\bar{\epsilon}$)

Baseline	1997/10 – 1998/09		1997/10 – 1998/03		1998/04 – 1998/09	
	σL (mm)	$\bar{\epsilon}$ (mm)	σL (mm)	$\bar{\epsilon}$ (mm)	σL (mm)	$\bar{\epsilon}$ (mm)
KAS –KOG	2.3±1.0	1.1±0.3	1.9±0.8	1.0±0.3	2.8±1.0	1.2±0.2
KAS –MIU	2.4±1.1	1.3±0.3	1.7±0.7	1.0±0.2	3.1±1.0	1.5±0.2
KAS –TAT	2.4±1.0	1.3±0.3	2.0±0.9	1.0±0.2	2.7±1.0	1.5±0.2
KOG–MIU	2.5±1.5	1.2±0.3	1.8±0.9	1.0±0.4	3.2±1.7	1.3±0.2
KOG–TAT	2.5±1.2	1.2±0.3	2.0±0.9	1.0±0.4	2.9±1.3	1.3±0.2
MIU –TAT	2.1±1.0	1.0±0.3	1.6±0.5	0.8±0.1	2.5±1.1	1.2±0.2

KAS:Kashima, KOG:Koganei, MIU:Miura, TAT:Tateyama

We present the results of standard deviations and mean formal errors by representing six baselines for the Kashima-Koganei baseline because it is the first baseline on which routine obseravtions started in the KSP. Figure 3 shows the evolution of measured baseline lengths for the Kashima-Koganei baseline, and the standard deviations and mean formal errors of the five continuous samples of the baseline length data 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 (at the end of October, 1995, at the middle of February, 1997, and at the end of September, 1997). This demonstrates a drastic improvement in system. The first two correspond to improvements in the 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. However, the effect of this cannot be clearly seen in the plot. Since the end of September, 1997 the system's operation method and hardware have not experienced any change. Hence to evaluate the system performance we calculated the average value of repeatabilities and the mean formal errors for the period October, 1997 to September, 1998 (i.e., a full year span). Since a seasonal effect can be seen in Figure 3, we devided 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 made statistical calculations for the two sub-periods. Table 1 summarizes averaged repeatabilities and mean formal errors for these three periods by baseline. In Figure 4 they are plotted for the two sub-periods.

The simple average of all baselines for repeatabilities is 2.4 mm and the simple average of the formal errors is 1.2 mm. These values are the precision of the KSP VLBI system at the present time.

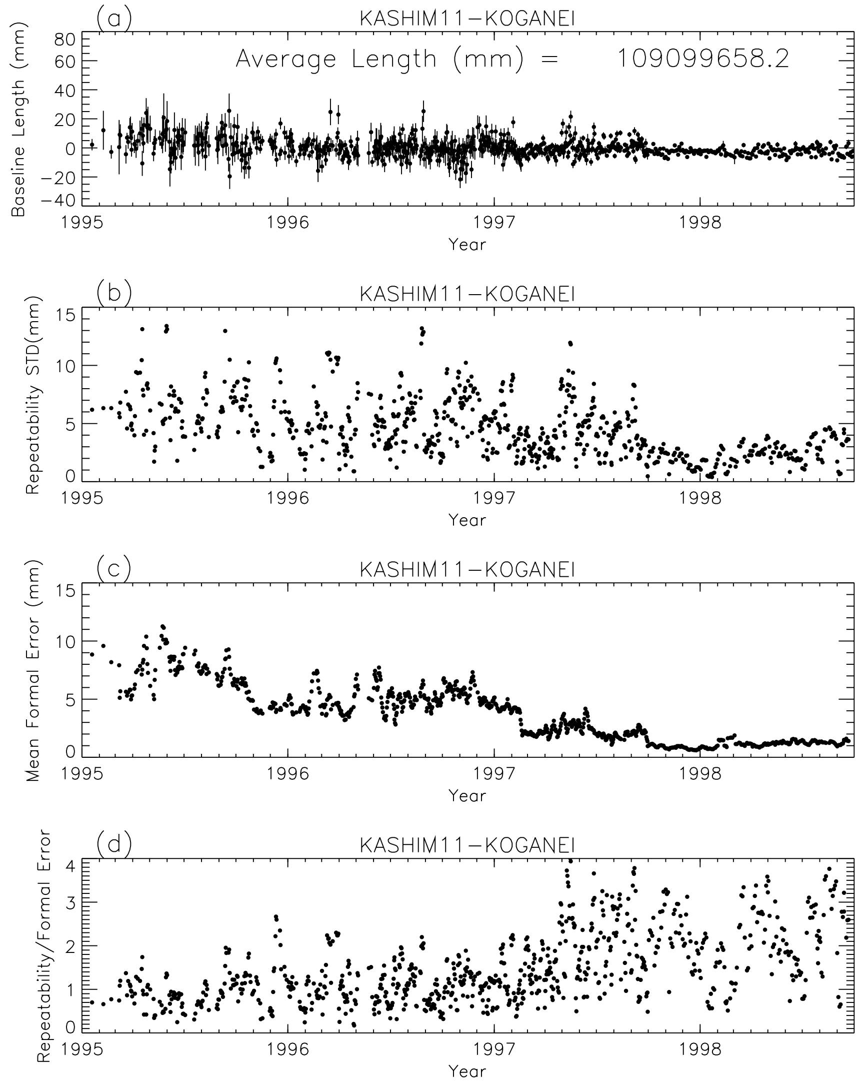

Figure 3. Evolution of baseline length between Kashima and Koganei (a), repeatabilities (b), mean formal errors (c), and ratio of repeatability to mean formal error (d) of five continuous samples of baseline length.

The simple average of all baselines for repeatabilities for the winter season is 1.8 mm and for the summer season is 2.9 mm. The simple avverage for mean formal errors for the winter season is 1.0 mm and for the summer season is 1.4 mm. Both repeatability and mean formal error become worse in the summer season by factors 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

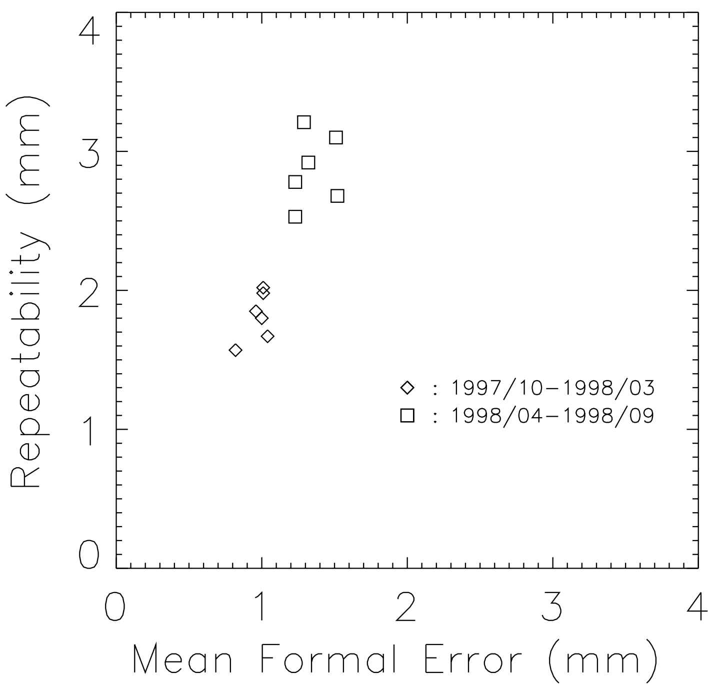

Figure 4. Scatter plots of σL_k (repeatabilties) and $\overline{\epsilon_k}$ (formal errors) for six baseline combinations for the two sub-periods.

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. 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. In the current KSP VLBI baseline analysis, azimuthal asymmetries of this mapping function is unmodeled. This might be cause of an error source in a baseline estimation as pointed out by *MacMillan* [1995] 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 water vapor does not affect VLBI observations so much.

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

Acknowledgments

A real-time VLBI technique for the KSP has been 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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