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Evaluation of repeatability of baseline lengths in the VLBI network around the Tokyo metropolitan area

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Abstract. Since 1995, VLBI measurements using fixed VLBI stations around the Tokyo metropolitan area have been continually producing data of station positions and baseline lengths. The accuracy of baseline length measurements is evaluated in terms of repeatability, conventionally defined as a standard deviation of those obtained by five continuous sessions. Continuous improvement both in system hardware and in the observation method have resulted in a remarkable improvement in measurement accuracy. Repeatability reaches about a 2-mm level in baseline length in our VLBI network.

Introduction

The determination of the precision of baseline length using very long baseline interferometry (VLBI) has been improving remarkably since the technique came into practical use during the 1970's. Initially precision on an order of several meters intercontinental distance measured [e.g., *Cannon et al.,* 1979], soon it reached a subdecimeter level [e.g., *Herring et al.,* 1981; *Ryan et al.,* 1986]. Since then geodetic precision has continued to be improved by the use of better analysis models [e.g., *Herring et al.,* 1990] as well as better instrumentation and observing strategies [e.g., *Clark et al.,* 1985] and now precision has reached a subcentimeter level.

In Japan, the Communications Research Laboratory (CRL) has led the development of the VLBI system. At first CRL developed the K-3 VLBI system compatible with the Mark-III VLBI system developed by the US group [*Clark et al.,* 1985] and successfully carried out US-Japan VLBI [*Saburi et al.,* 1984]. After that CRL developed the K-4 VLBI system, which facilitated ease in both operation and transportation [*Kondo et al.,* 1992]. Applying these experiences to further system development, CRL has started a new project; the establishment of the sophisticated VLBI system 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 relating to earthquake prevention.

In January, 1995 the KSP started regular observations. Now routine observation results are open to the public through the KSP web homepage (http://ksp.crl.go.jp). As it has entered a stable operation phase recently, we have begun an evaluation of total system performance in terms of measurement precision, because it is important to know the level of accuracy being obtained by the current measurement system for discriminating anomalies in crustal deformation. How accurately can the baseline length among KSP stations that use the current system (here current system means both hardware and analysis software) be measured?

In this paper, we will present the evaluation results of the precision of measured baseline lengths on the KSP VLBI network and discuss the evolution of improvement in the precision.

System and observations

A VLBI system dedicated to precise geodetic measurements around the Tokyo metropolitan area has been developed by CRL, Japan and it is called the KSP VLBI system. Four stations were newly constructed for the KSP. These are at Kashima, Koganei, Miura and Tateyama (Figure 1). The longest distance between any two KSP stations is about 135 km (Kashima-Tateyama). Considering that VLBI has been developed as a tool to measure intercontinental distance, we can say that the KSP network is very compact as a VLBI network.

Each VLBI station is equipped with the same VLBI facilities (i.e., a parabolic antenna with a 11-m diameter mounted on an AZ/EL mounting and a highly automated data acquisition system newly developed for the KSP). Dual S (2 GHz) and X (8 GHz) band signals from quasars are received by the antenna. Received signals are finally converted into 16 video channels available to assign 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 according to the procedure used in the conventional VLBI technique. Hence the total data rate is 64 Mbps and 256 Mbps for 2 MHz and 8 MHz video bandwidths, respectively. A stable hydrogen maser frequency standard is used as a station clock and there is a frequency standard at each station.

Digitized signals are recorded on a magnetic tape in the case of "tape-based" VLBI and are transmitted to a cen-

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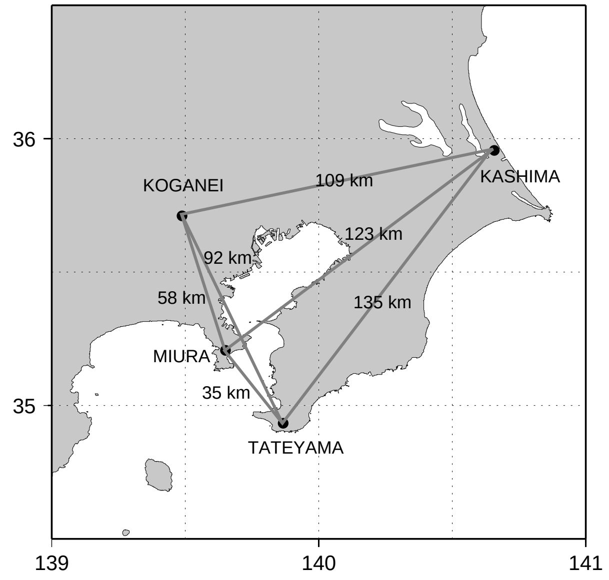

Figure 1. Configuration of the Keystone Project VLBI network.

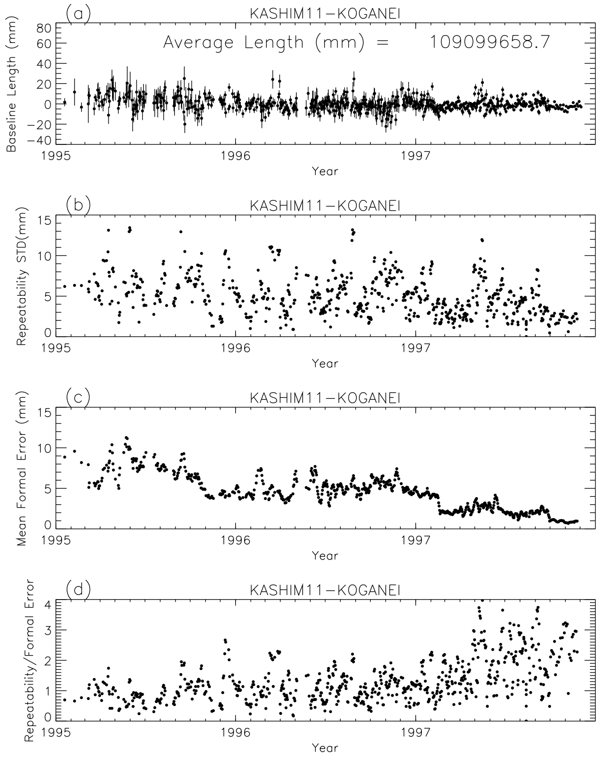

Figure 2. Evolution of baseline length between Kashima and Koganei (a), repeatabilities (b), mean formal errors (c), and ratio of repeatability to mean formal error (e) of five continuous samples of baseline length.

tral processing station through a digital link in the case of "real-time" VLBI. In both cases, correlation processing to determine observables, such as delay time, takes place at the central station, Koganei. The observation system is designed to make unmanned operation possible and 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. In the case of the real-time VLBI, correlation processing for the 6 baselines is carried out simulatneouly by observation using data transmitted from each station through the digital link which connects all stations to the Koganei central station.

In January, 1995 regular observations on the baseline between Kashima and Koganei were begun. In September, 1996 daily observations spanning 5-6 hours using all four stations started. In addition, to present time we have continued to improve instrumentation as well as observing strategies and analysis models. In parallel with the daily observations using a conventional tape recording method, we were establishing, in cooperation with the Nippon Telephone and Telegraph Co., the real-time VLBI which means real time correlation processing using 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 the KSP correlator is located, in real time through the network. 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 restrictions arising from the correlation processing in the case of tape-based VLBI. A continuous 120-hour test session was therefore carried out from July 28 to August 1, 1997 in order to evaluate the improvement in precision by extending the length of the session. This test session was carried out successfully, and 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 an overload on the system, in particular, on the antenna. On September 30, 1997 routine observations under this new strategy began.

Evaluation of precision

In essence, baseline analysis is automatically carried out on a session basis. Our analysis software is based on that developed by the Goddard VLBI group. As our procedure is not so very different from that used in the analysis of ordinary geodetic VLBI, we will not describe it in detail, but 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. However atmospheric gradient estimation is not yet installed in our KSP analysis software. According to *MacMillan* [1995], station position may be affected at the subcentimeter level by atmospheric asymmetry.

We use measured baseline lengths to evaluate the precision of measurements for convenience' sake. In this study, we define repeatability of measurement results as a standard deviation of five continuous samples of baseline lengths. The reason why we choose five continuous samples as a unit is partly because we intended to evaluate the results obtained from a 120-hour test session conducted from July 28 - August 1, 1997 that is divided into five sub-sessions. The other reason is to separate long term fluctuations, such as seasonal variation probably arising from model imperfectness in the baseline analysis from short term ones. L_k and ϵ_k are the kth sample of a measured baseline length and its

Table 1. Average repeatabilities (σL) and average mean formal errors ($\overline{\epsilon}$)

Baseline	June 4 – Sept. 30, 1997		Oct. 2 – Dec. 3, 1997	
	σL (mm)	$\overline{\epsilon}$ (mm)	σL (mm)	$\overline{\epsilon}$ (mm)
KASHIMA–KOGANEI	4.0±1.7	2.1±0.5	2.2±0.6	0.9±0.2
KASHIMA–MIURA	3.7±1.5	2.2±0.5	1.8±1.0	1.0±0.1
KASHIMA–TATEYAMA	5.2±2.7	2.4±0.5	2.4±1.0	1.1±0.1
KOGANEI–MIURA	5.3±2.7	2.5±0.8	1.6±0.8	0.9±0.2
KOGANEI–TATEYAMA	5.8±2.9	2.6±0.8	2.3±1.0	0.9±0.1
MIURA –TATEYAMA	5.1±2.4	2.2±0.6	1.5±0.5	0.8±0.1

formal error of baseline analysis and standard deviation of five continuous samples of the baseline length starting from the kth sample, σL_k, is computed from

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

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 samples is different depending on the session frequency. They span approximately 4 days for the data measured before September 30, 1997, but 9 days for the data measured after that time except for a few occasions when routine observations failed. Using σL_k and $\overline{\epsilon_k}$ we evaluated the precision of the KSP VLBI system.

Results

Figure 2 shows the evolution of measured baseline lengths for the Kashima-Koganei baseline and standard deviations, mean formal errors and their ratio for the five continuous samples of the baseline length data. Kashima-Koganei is the first baseline to go into operation in the KSP, so that the history of system development is fully reflected in this baseline. We therefore omit plots for other baselines to save space. In the meantime, the KSP network is located in a compressional stress field of roughly east-west direction owing to subducting oceanic plates, the Pacific plate and the Philippine sea plate. Shortening seen in the baseline length plot is thought to be consistent with a reflection of this stress field.

Formal error obtained from each baseline analysis almost corresponds to the standard deviation of O-C residuals after parameter fitting in a session. System performance improved drastically at several epochs, resulting in stepwise structures that can be clearly seen in the plot of mean formal errors, in particular at three epochs, which are at the end of October, 1995, at the middle of February, 1997, and at the end of September, 1997. The first two correspond to improvements in system hardware, such as an increase in temperature stability in the receiver room, while the last one corresponds to the extention 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 as clearly seen in the plot.

Figure 3 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 for which we do not plot here) data points tend to concentrate in the lower-left portion of each plot.

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 the effect that differences in video bandwidth may cause. Table 1 summarises averaged repeatabilities and mean formal errors for the period June 4,

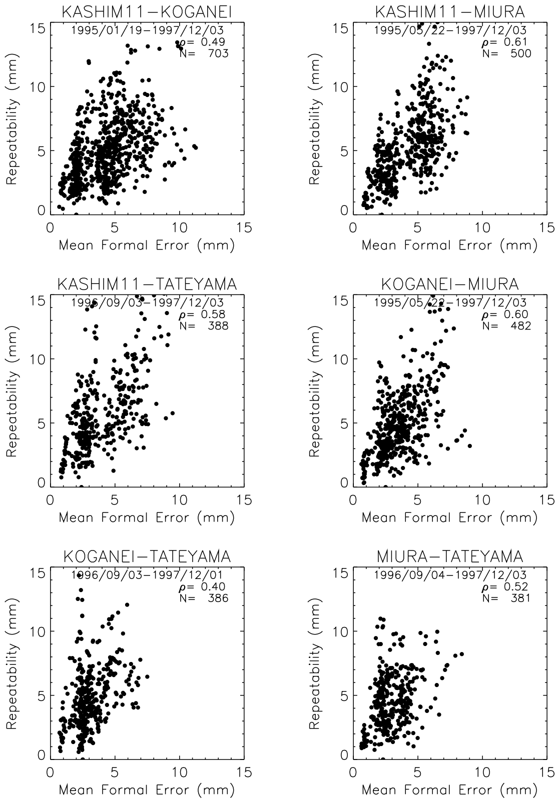

Figure 3. Scatter plots of σL_k (repeatabilties) and $\overline{\epsilon_k}$ (formal errors) for six baseline combinations. ρ is the correlation coefficient between parameters.

1997 - September 30, 1997 (corresponding to a 6-hour span) and October 2, 1997 - December 3, 1997 (24-hour span). It can be clearly seen from the table that 24-hour observation gives better repeatability and formal errors than observation for only 6 hours a day. 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., a four-times longer span session results in a two-times improvement in 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 and formal errors for 24-hour spans are 2.0 mm and 1.0 mm, respectively. These values are concluded to be the precision of the KSP VLBI system at the present time.

Conclusions

We have developed the KSP VLBI system and have been monitoring the crustal deformation around the Tokyo metropolitan area. Moreover, to obtain reliable measurement results, we have 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. If we assume that crustal deformation is very small over several days, it would suggest that the model applied in a session baseline analysis is insufficient for a time scale longer than one day. In the current KSP VLBI baseline analysis software, azimuthal asymmetries in the atmospheric refractive index are unmodeled. This might be the cause of an error source in baseline estimation at the subcentimeter level as pointed out by *MacMillan* [1995] and could account for a larger variation in day to day baseline estimates. 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 unmodelled effect in the baseline analysis. As KSP stations with the exception of Koganei are located close to the ocean (Figure 1), the azimuthal asymmetry in the wet atmospheric component may be large around these stations.

Thus improving physical models, such as azimuthal asymmetry propagation delay models, should be investigated and they should be introduced into the KSP routine analysis software in order to achieve better repeatability over several days of evaluations. Improvements of modeling will stimulate further development of measurement techniques.

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