

## Development of Real-time Gigabit Geodesy e-VLBI Using the Super-Sinet

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## スーパー SINET を用いた ギガビット・リアルタイム測地 e-VLBI の開発

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## 要 旨

ギガビット・リアルタイム e-VLBI 測地化システムの開発について報告する。国立情報学研の運用する「スーパー SINET」を用いて、国土地理院・つくば 32m 鏡と国立天文台・三鷹、岐阜大学 11m 鏡の間を 2.4 Gbps の光回線で接続し、実験を行った。光回線の双方向伝送を活かし、上りと下りで S/X 帯の 2 Gbps のデータをそれぞれ伝送し、国立天文台および岐阜大学に設置された相関器で分散相関処理を行うことで 4 Gbps という世界最高速度のリアルタイム測地 e-VLBI を実現した。広帯域データによる遅延時間決定について、ガウスフィット法を用いる方法を導入し、高精度の遅延時間決定ができる

ことが明らかになった。また、位相傾斜による遅延時間の決定法についても開発を行い、ガウスフィット法とほぼ同程度の遅延時間決定精度があることがわかった。国土地理院のJADE観測で従来の磁気記録方式(K4, K5)とe-VLBIの同時観測を行い、遅延時間を比較したところ、K4, K5に比べてe-VLBIの遅延時間は1日で数100 ps移動することがわかった。これはホーンの前からP-cal信号を注入してバンド幅合成を行なうK4, K5ではキャンセルされる、観測室と受信機間のケーブル長の温度変動がe-VLBIでは現れたためと考えられる。この変動は基線解析ではクロックの推定で吸収され、K4, K5とe-VLBIの基線長が3 mm以内で一致する測地結果を得ることができた。

#### Abstract

This paper reports the development of a gigabit real-time e-VLBI (Very Long Baseline Interferometry) geodetic system. For an experiment using the Super-Sinet of the National Institute of Informatics, the 32-m telescope at the Geographical Survey Institute in Tsukuba City, the National Astronomical Observatory of Japan in Mitaka City, and the 11-m telescope at Gifu University were connected using a 2.4 Gbps optical line. By two-way transmission through the optical line, S/X band data was transmitted by uplink and downlink at 2 Gbps. Their distributed correlation processing by the correlators at the National Astronomical Observatory of Japan and Gifu University realized the world's fastest real-time geodesy e-VLBI at 4 Gbps. Gaussian fitting was employed for the delay search from broadband data, enabling very accurate searches. A delay search method using phase inclination was also developed and proved to be about as accurate as the Gaussian fitting method. For the Japanese Dynamic Earth (JADE) observation by VLBI at the Geographical Survey Institute, observations by a conventional magnetic recording system (K4/K5) and the e-VLBI system were conducted simultaneously and their delays were compared. Unlike the delay of K4/K5, that of the e-VLBI was found to migrate by several hundred picoseconds a day. This is cancelled by K4/K5, which injects P-cal signals in front of the feed horn for bandwidth synthesis. However, e-VLBI may show the temperature fluctuations along the cable length between the observation room and the receiver. By baseline analysis, we could obtain geodetic results according to which this fluctuation was absorbed by clock estimation and the difference of the baseline length between K4/K5 and e-VLBI less than 3 mm.

## 1. Introduction

VLBI used magnetic tapes to record digitized data. After the observation, the magnetic tapes were transported to the analysis center. The National Institute of Information and Communications Technology (NICT) in Japan developed a correlation processing system capable of transmitting observation data in real time through an ultrahigh-speed optical network. Using this system, the data of four stations could be successfully transmitted at 256 Mbps through a 2.4 Gbps optical line (OC-48) (Kiuchi *et al.*, 1999). Since then, VLBI observation by data transmission using a network has also been developed in Europe, USA, Australia and China, and it is now generally referred to as e-VLBI, including VLBI of data transmission through a network after observation as well as real-time VLBI.

Real-time e-VLBI has the following advantages: 1) Observation status can be checked in real time for quick troubleshooting; 2) Observation results can be obtained immediately for real-time geodetic observation, if forecasted Earth Orientation Parameters are used; and 3) Observation and analysis can be automated for continuous geodetic observation.

These advantages were demonstrated by NICT's Key Stone Project (KSP) observation (Koyama *et al.*, 1999).

In the KSP project, the data transmission speed was 256 Mbps, identical to the speed of the data recorder. NICT developed a VLBI observation system using a 1 Gbps data recorder (Nakajima *et al.*, 2001). The ultra-high-speed sampler (ADS1000) developed there has data output of 2 Gbps (1 Gbps, 2 bits) data output (Koyama *et al.*, 2001). Therefore, the National Astronomical Observatory of Japan, NICT, Institute of Space and Astronautical Science (ISAS), and Nippon Telegraph and Telephone Corp. (NTT) initiated a gigabit-level e-VLBI experiment in the metropolitan area. This experiment, named Galaxy, was a 2 Gbps e-VLBI linking the 64-m telescope in Usuda, the 34-m one in Kashima, and the 11-m one in Koganei (Fujisawa *et al.*, 2001). The purpose was to detect sources of feeble celestial radio sources.

The National Astronomical Observatory of Japan made an application to connect nationwide radio telescopes using the Super-Sinet of the Ministry of Education, Culture, Sports, Science and Technology (MEXT). The Super-Sinet is an ultrahigh-speed optical line network running throughout the Japanese Archipelago. Through the Super-Sinet, the 32-m telescope of the Geographical Survey Institute in Tsukuba City was connected in 2002 and the 11-m telescope of Gifu University in 2004. From the Super-Sinet, two 2.4 Gbps lines were provided for the simultaneous processing of two channels in the S and X bands to enable geodesy. Moreover, by using Super-Sinet, geodesy VLBI does not require bandwidth synthesis (Whitney *et al.*, 1976) and makes a delay free of ambiguity.

Since celestial radio source's detection sensitivity is high for the gigabit e-VLBI, if the integration time is the same, increasing the signal-to-noise ratio (SNR) improves the delay search accuracy. If the SNR is the same, increasing the observation count increases the geodetic accuracy. In addition, increasing the observation count is expected to improve the accuracy of estimating the atmospheric gradient.

Thus, the gigabit e-VLBI system is strongly expected to show the higher performance and better geodetic accuracy and to open the new era of fields of geodesy, earth rotation study and radio astrometry. In particular, e-VLBI is important for astrometry such as VERA project of NAOJ, because VERA antennas are required the accuracy of position to be less than 1 mm for 10-micro arcsecond astrometry with 2000 km baseline length (Jike *et al.*, 2005). In this study, therefore, a real-time gigabit geodesy e-VLBI system was developed and evaluated.

## 2. Observation

In this study, simultaneous observation with K4/K5 was attempted in the Japanese Dynamic Earth (JADE) observation by VLBI experiment by the Geographical Survey Institute. For simultaneous observation in the S and X bands, 24-h observations were repeated 11 times from March 2004 to June 2006. In July and August 2006, two-channel observation of the X band was also conducted. Table 1 shows the observation frequencies.

### 2.1. Observation System

Figure 1 shows the system diagram.

#### (1) Hardware

Table 1 Observation frequencies

Band	Frequency (MHz)	Bandwidth (MHz)
S	2250 - 2400	150
X (low)	7780 - 8200	420
X (high)	8180 - 8600	420

In normal geodesy VLBI, we had used S and X (high) bands. X (low) was used for the system check (Section 3.2.) in this study.

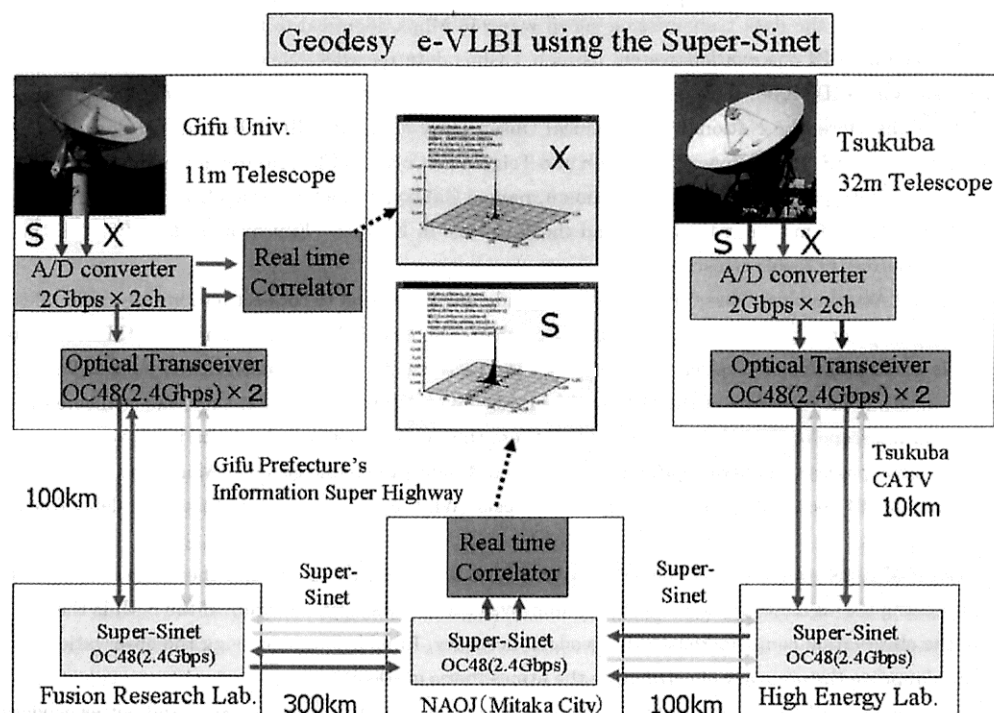


Fig. 1 Configuration for the gigabit geodetic experiment using the Super-Sinet.

#### • Network

The trunk network in this study is the Super-Sinet of the National Institute of Informatics, which connects main universities throughout the country and the national research institutes of MEXT.

The Tsukuba station requested a cable television (CATV) company to lay four optical fibers to connect the High Energy Accelerator Research Organization at a Super-Sinet node about 10 km away.

The Gifu University station connected the National Institute for Fusion Science by borrowing optical fibers from the Gifu Information Super Highway of Gifu Prefecture. The optical fiber extension distance is about 100 km. To compensate for the influences of attenuation and dispersion, one regenerative optical amplifier was installed in the middle. The Gifu University Station secured two lines of OC48 (2.4 Gbps) by wavelength multiplexing of one optical fiber each for transmission and reception.

The sampler is ADS1000, developed by NICT. It obtains data at 2048 Mbps in a frequency band from 512 to 1024 MHz by two-bit sampling in 1024 MHz high-order mode.

The optical transmitter is VOA-100, developed by the National Astronomical Observatory of Japan. It transmits 2048 MHz through an ATM line (2.4 Gbps) of the OC48 standard.

The correlator is VLBI2220 (Kawaguchi, 2008), developed by the National Astronomical Observatory of Japan. It correlates two-bit data at 1024 Mbps in real time with 256 lag. For a priori calculation, the correlator uses software developed by NICT's gigabit correlator. Three baseline VLBI2220 units are installed at Gifu University and the National Astronomical Observatory of Japan in Mitaka City for distributed correlation processing.

#### (2) Software

- Automatic observation software

General-purpose correlator automatic control software available for both geodetic and astronomical purposes was developed. The GUI (Graphical User Interface), continuous scheduling, real-time fringe monitoring, and correlator network control functions are supported for distributed correlation processing.

### 3. Results

#### 3.1. Accurate Delay Search

For an accurate delay search, conventional geodesy VLBI extends the effective band by bandwidth synthesis method that combines phase inclinations using P-cal signals after scattered narrowband recording, because a whole band of observation frequencies cannot be recorded.

Since a whole band of observation frequencies can be used in this study, P-cal signals are fundamentally unnecessary. There are two probable methods of delay search from complex correlation results in an ultra-broadband. One is the peak fitting method that locates the peak position of lag power data. The other is the phase inclination method that calculates the inclination of frequency-phase data. The former is for a coarse search and the latter for a fine search. Then we compared these methods using X-band data.

##### 3.1.1. Peak Fitting Method

For peak fitting, the following two functions were compared: a parabolic function (quadratic function) and a Gaussian function. For the former, we used three data around the peak value. As the latter is a non-linear function, we used Newton's method and applied all data for the least-squares fitting process.

Method 1) Peak fitting of all data by discrete Fourier transform (DFT)

By applying two-dimensional DFT to correlation data obtained each second, the intensity of the correlation between delay and delay change rate was investigated to determine them at the maximum correlation intensity. This corresponds to the conventional coarse search.

Method 2) One-second integral peak fitting plus linear fitting

A peak was obtained from one-second integral correlation data as a delay and all delay data obtained at every second was linearly approximated to calculate the delay in the middle of the observation time and the delay change rate.

As a result of comparing the combinations of the four methods, the delay was found to be 12 ps (rms) and was similar for 1) and 2) when a Gaussian function was used.

Figure 2 illustrates the relationship of SNR with the delay difference between delays by the abovementioned method 1) using a Gaussian function and by the abovementioned method 2) using a Gaussian function. The delay difference is about 10 ps and tends to become small as the SNR becomes large.

Figure 3 illustrates the relationship of SNR with the difference between delays obtained by the abovementioned method 1) using a Gaussian function and by the abovementioned method 2) using a parabolic function. The delay difference is over 50 ps and shows no relationship with the SNR. Therefore, a fine delay search was not possible with a parabolic function. A fringe should become a sync function and its linear approximation should become a parabolic function. However, the fringe showed the phenomenon of asymmetric expansion because the in-band delay characteristics are different for ultra-broadband signals. Since a parabolic function fits at three points near a peak, the delay search accuracy sensitive to the asymmetric expansion of the fringe might have deteriorated.

##### 3.1.2. Phase Gradient Method

The phase inclination method obtains the frequency and phase from one-second integral correlation data by

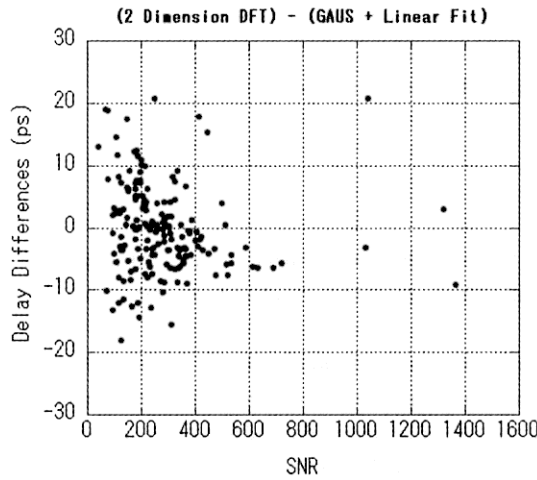


Fig. 2 Comparison of delay between the DFT method and the every-second peak fitting method with a Gaussian function.

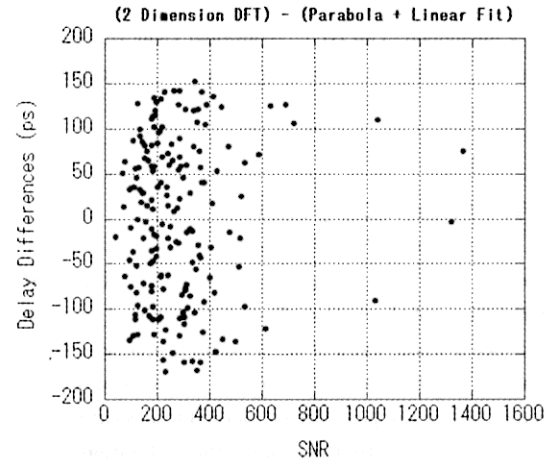


Fig. 3 Comparison of delay between the DFT method and the every-second peak fitting method with the parabolic function.

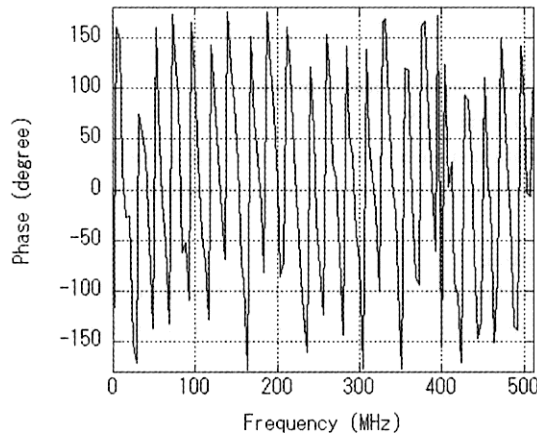


Fig. 4 Original phase-frequency diagram.

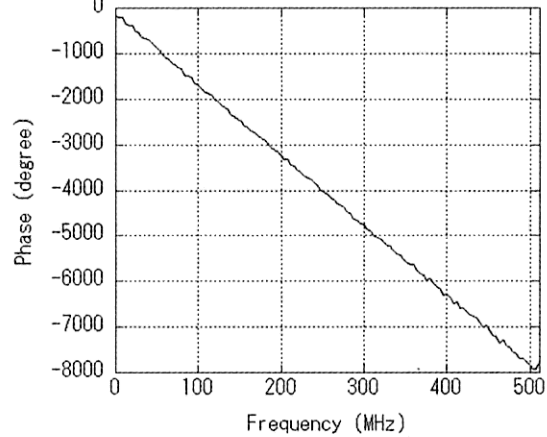


Fig. 5 Shift phases 360 degree when jump exists and connects them.

Fourier transform and calculates the delay from the inclination by the following equation:

$$\tau = \frac{\Delta\phi}{\Delta f} \times \frac{10^9}{360} \quad \begin{array}{l} \phi : \text{Phase (deg.)} \\ f : \text{Frequency (MHz)} \end{array}$$

As in the peak fitting method of 2), all delay data obtained at every second was linearly approximated to calculate the delay in the middle of the observation time and the delay change rate.

The steps for obtaining phase inclination are explained here. Figure 4 shows the original data. The phase is displayed at  $\pm 180$  degrees and varies greatly with the frequency. This data is searched in the frequency direction and processed by the point correction of a jump over 180 degrees (Figure 5). By linear approximation, a delay can be obtained. As the result of a detailed investigation of the phase and frequency, the phase was found curved at both ends of the observation band, as shown in Figure 6. This is due to the phase characteristics of the band-pass filter and other factors. In this study, therefore, the frequency band was limited to 320 MHz from 80

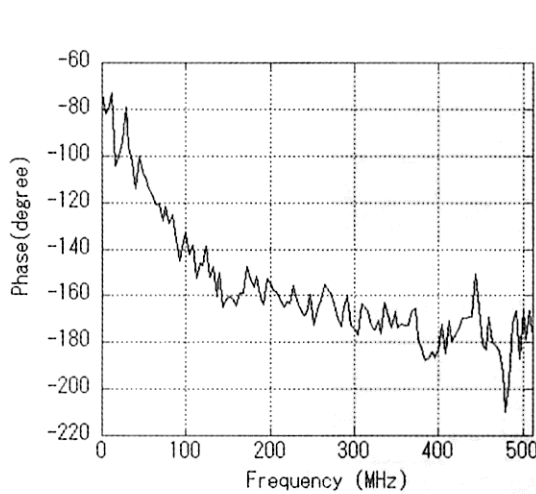


Fig. 6 Phase curve exists at the band edge.

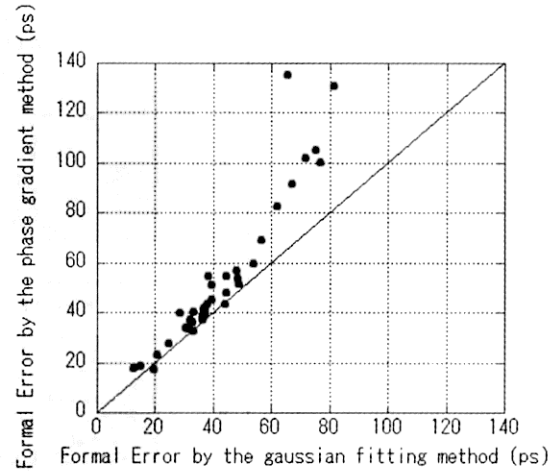


Fig. 7 Formal Error by the Gaussian fitting method vs. phase gradient method.

to 400 MHz and the delay was searched by linear approximation.

Figure 7 shows the results of standard deviation calculations for every second of delay by the two methods of Gaussian function and phase inclination. Both results are almost similar. For a celestial radio source of a great standard deviation (weak correlation intensity), the phase inclination method produces a greater value. This is probably because the phase jump cannot be corrected well and the delay search is not very accurate.

Consequently, it was found that delay search by the phase inclination method is possible for a celestial radio source detected by sufficient SNR, but the peak fitting method using a Gaussian function is currently more effective.

### 3.2. Comparison of Delay between K4/K5 and Gigabit e-VLBI

Regarding the delay in a 24-h observation, conventional K4 and K5 systems and the gigabit e-VLBI system in this study were compared. Consequently, the delays of the K4 and K5 systems were almost similar, but that of the gigabit e-VLBI system showed drift of nearly 1 ns in 24-h. Figure 8 compares the delay in JD0509 between the K5 system and the gigabit e-VLBI. In both the X and S bands, fluctuations are 24-h sine curves. Similar fluctuations were observed in other experiments as well.

We conducted two more experiments and found that the delay did not fluctuate much but was about 15 ps. One was a gigabit e-VLBI experiment of correlation processing with the X band of the Gifu station using two different samplers for the X band of the Tsukuba Station, and the other was in a two-channel simultaneous experiment of X-band high and low channels at the Tsukuba station and Gifu stations.

The large time fluctuation could indicate that a delay fluctuation attributable to the temperature-affected cable length appears in the gigabit e-VLBI system, although it is partly cancelled by bandwidth synthesis because they use same cable for the reference signal transfer for local oscillator and the P-cal processor.

### 3.3. Baseline Analysis

For a baseline analysis, Calc Version 9.12 and Solve Revision 2003.05.16 were used, a Mark III database was created from a gigabit e-VLBI delay database using software developed for NICT's KSP and for geodetic analysis with a gigabit recorder. For the delay and delay change rate, the values obtained by the DFT method with a

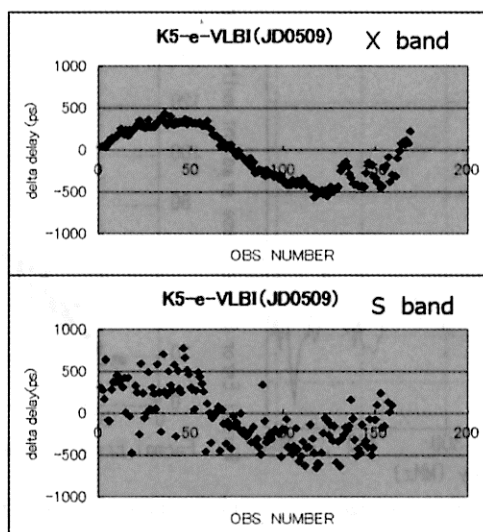


Fig. 8 Comparison of delay in JD0509 between K5 and gigabit e-VLBI (SINET).

Gaussian function were used. This is because artificial interference sometimes produces stronger correlation than a celestial radio source, particularly in the S band, and causes a false delay in every-second peak fitting. Since a peak due to interference migrates greatly with the passage of time, a real peak often appears stronger in the DFT method due to dispersion, and a correct delay can be obtained.

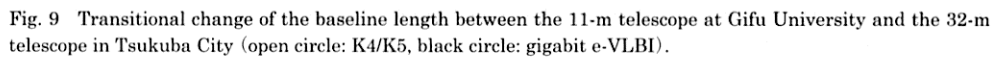
Figure 9 shows the result of a baseline analysis between the 11-m telescope at Gifu University and the 32-m telescope of GSI at Tsukuba City. The baseline length of gigabit e-VLBI and K4/K5 was similar with a difference less than 3 mm and the baseline reduction tendency was also almost similar,  $-10.1$  mm/yr for K4 and K5,  $-8.4$  mm/yr for e-VLBI. The results proved the effectiveness of this system. Regarding the accuracy of the e-VLBI system, the error bar was large in the gigabit e-VLBI experiment until March 2005, because of occasional correlator hang-up and observation loss. The error bars in the K4/K5 analysis are small as a result of analyzing six baselines at four stations using the data of correlation with the 10-m telescopes at Aira and Chichijima Island as well as with the 32-m telescope at Tsukuba. In the analysis of one baseline, both K4/K5 and e-VLBI showed accuracy of about 3 mm. Since the SNR of e-VLBI is about four or five times better, the delay search accuracy and geodetic accuracy are also assumed to be better. In this study, however, the observation count is the same because observations are conducted simultaneously with K4/K5. Therefore, the estimation accuracy for atmospheric effect and clock fluctuation that determines the geodetic accuracy is almost the same.

#### 4. Discussion

As the next-generation geodesy VLBI, Working Group 3 of the International VLBI Service for Geodesy & Astrometry (IVS) is discussing VLBI2010 of a very wide observation frequency band, from 1 to 14 GHz. For geodetic observation in this super broadband, a delay search method by phase inclination will be very important. Therefore, VLBI2010 will use P-cal for an accurate delay search.

In this study, band edges could not be used because of a phase characteristic problem attributable to the band-pass filter and other factors. This problem may be solved by the P-cal signal injection for collection that is adopt-





## 5. Conclusion

In simultaneous observation by gigabit e-VLBI and K4/K5, only the former was found to have a systematic drift of the delay that fluctuates nearly 1 ns in 24-h cycles. This is probably because the thermal fluctuation of the cable length between the observation room and the receiver appears in the gigabit e-VLBI system, although it is eliminated by the bandwidth synthesis method. According to the results of the baseline analysis, the baseline length of the gigabit e-VLBI system and K4/K5 was similar with a difference of less than 3 mm. This indicated no significant problems in the gigabit e-VLBI system.

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