Rapid Turn Around EOP Measurements by VLBI over the Internet

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Abstract. At present, promptness of the data processing of the international Very Long Baseline Interferometry observations is limited by the time required to ship observation tapes from radio telescope sites to a correlation processing site. It usually takes more than two weeks to transport all the data tapes to the correlation processing site in typical observation sessions for Earth Orientation Parameter measurements. The e-VLBI technique uses high speed communication network to transport observation data electrically and it has a possibility to dramatically improve the promptness of the data processing and hence the accuracy of the near real-time prediction of the Earth Orientation Parameters. To realize the e-VLBI observations by using shared network environment, PC based data acquisition systems and data processing systems have been developed. By using the newly development system, international e-VLBI observations were performed and rapid estimations of the UT1-UTC less than one day after the observations were demonstrated.

Keywords. VLBI, EOP, UT1, e-VLBI

1 Introduction

Currently, minimum delay time to obtain results from global geodetic Very Long Baseline Interferometry (VLBI) observations is about two weeks for typical one day experiments with several observing stations. This delay becomes shorter for so called intensive sessions where only one baseline is used and the duration is only about 1.5 hours, but it is still about one week or more. The purpose of the intensive sessions is to estimate the value of UT1-UTC by geodetic VLBI observations and the sessions are performed four or five times every week by using either KokeePark-Wettzell baseline or Tsukuba-Wettzell baseline. Since only the geodetic VLBI technique can precisely measure UT1-UTC value independently from any other measurement techniques, the results of the intensive sessions are used as essential information to generate predicted values of the UT1-UTC (McCarthy, 1993). Since UT1-UTC randomly varies reflecting the dynamic phenomenon on the surface of the Earth and the interior of the Earth, the accuracy of the predicted UT1-UTC values deteriorates with time. Therefore, it is expected that the accuracy of the predicted UT1-UTC can be improved by shortening the delay time from the observations to the data processing of geodetic VLBI. The report of the IVS Working Group 2 for Product Specification and Observing Program (Schuh, et al., 2002) pointed out it is very important to shorten this processing time delay to improve the accuracy of the Earth Orientation Parameters (EOP) including UT1-UTC. The report also set the goal of the IVS observing program to make the time delay from observing to product less than one day by the year 2005.

To achieve this goal, it is necessary to transfer observation data electrically over the high speed global communication network from the observing sites to the correlator site. This form of VLBI is recently called as e-VLBI to distinguish it from the conventional VLBI which uses magnetic tapes to record observed data. The first operational e-VLBI system was realized in the Key Stone Project of the Communications Research Laboratory (CRL) by using dedicated high speed research networks. In the system, four VLBI observing sites were connected with 2.4 Gbps Asynchronous Transfer Mode (ATM) network lines and the one day geodetic VLBI sessions were performed every two days. Although the baselines were relatively short to estimate EOP values precisely, rapid turn around EOP measurements less than one hour was technically demonstrated with the system (Koyama, et al., 1999).

After the routine observations of the Key Stone Project were terminated in 2001, new system developments were initiated to realize e-VLBI over the shared high speed networks. In this paper, newly developed observation and data analysis systems for e-VLBI will be introduced and the results of test observations by using the systems will be reported.

Fig. 1 A picture of the prototype K5 VLBI system (VSSP).

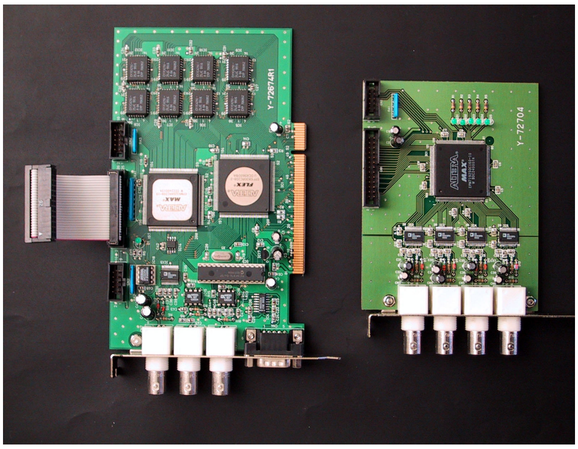

Fig. 2 A picture of the main board (left) and the auxiliary board (right) of the IP-VLBI (VSSP) board. Two boards are connected by the cable attached to the main board in the picture.

2 System Developments

IVS Technology Development Centers including Haystack Observatory and CRL have been concentrating their efforts to realize the e-VLBI in the global geodetic VLBI observations. At CRL, the K5 VLBI system has been developed based on the UNIX PC systems while the Mark-5 VLBI system has been developed at Haystack Observatory (Whitney, 2003). The K5 VLBI system (Fig. 1), or also called as Versatile Scientific Sampling Processor (VSSP), is designed to perform real-time VLBI observations and correlation processing using Internet Protocol over commonly used shared network lines. It is consist of four UNIX PC systems. Each UNIX PC system has one IP-VLBI data sampling board (Fig. 2), or also called as a VSSP board, on its PCI interfacing bus. Table 1 lists the specifications of the board. The board can sample 4 channels of base-band signals at various sampling rates ranging from 40kHz to 16MHz. The timing of the sampling is controlled by the provided 10MHz and 1PPS reference signals so that precise timing information can be reproduced from the sampled data. Quantization bits can be set from 1, 2, 4, and 8. Because the board has these many sampling modes, it has many possibilities to be used not only for VLBI observations but also for various other scientific researches which require precise timing information in the data.

Table 1. Specifications of the IP-VLBI (VSSP) board.

Reference Signals	10MHz (+10dBm) and 1PPS
# of Input Ch.	1 or 4
A/D bits	1, 2, 4, or 8
Sampling Freq.	40kHz, 100kHz, 200kHz, 500kHz, 1MHz, 2MHz, 4MHz, 8MHz, or 16MHz
Bus Interface	PCI
OS	FreeBSD, LINUX, or Windows2000

Device driver software of the board has been developed on LINUX, FreeBSD, and Windows2000 operating systems, and FreeBSD is used in the prototype K5 data acquisition terminals. Two prototype K5 data acquisition systems have been configured. Four PC systems are mounted in the lower part of the 19-inch standard rack. A signal distributor unit for 1-PPS and 10 MHz signals and 16-channel base-band signal variable amplifier unit are mounted in the upper part of the rack. The monitor and the keyboard on the top of the rack are connected to the four PC systems by using a four-way switch. Each PC system is equipped with four removable hard disk drives of the data capacity of 120 GBytes each. The sampled data can be transferred to the network by using TCP/IP protocol or can be recorded to internal hard disks as ordinary data files. The maximum recording speed is currently restricted by the speed of the CPU and the speed of the PCI internal bus. Currently, the total recording speed of 512 Mbps has been achieved. It can be expected to record data up to 1024 Mbps by using faster PCI bus and faster CPU in near future. To process the data sampled with the K5 data acquisition system, software correlation processing program is also under development on FreeBSD PC systems. The correlation processing program receives data from K5 data acquisition systems over the network using TCP/IP protocol and then calculates cross correlation functions in real-time. It can also read data files on internal hard disks. These capabilities allow to transfer observed data in real-time if the connecting network is fast enough, or in near real-time if data buffering is required. Since easily re-writable software programs and general PC systems are used, the processing capacity and the function of the correlator can be easily expanded and upgraded.

3 Network

Fig. 3 and Fig. 4 show the schematic route of the high speed network used in the e-VLBI test experiments. Two VLBI stations, one is 34-m and the other is 11-m, at Kashima and 11-m VLBI station at Koganei are connected to the Galaxy network under the collaboration between CRL and NTT laboratories. The maximum data rate of the Galaxy network is 2.4 Gbps and it supports ATM. At Kashima, an IP interface unit is connected to the ATM switch and it provides IP connection at the maximum data rate of 622 Mbps. The Galaxy network is then connected to the Super-SINET network at National Institute for Informatics at Hitotsubashi. In the United States, the 18-m Westford VLBI station is connected to the Abilene network operated by the Internet2 consortium. The speed of the backbone of the Abilene network is now at 10 Gbps. The Abilene network and the Super-SINET network are connected at New York with a trans-Pacific link. The connection between two networks is currently at 622 Mbps. There is another route which uses GEMnet between Galaxy and Abilene network. There is a plan to upgrade the speed of the GEMnet route to 155 Mbps in near future, but the current speed is limited to 20 Mbps because of a bottleneck between Musashino and the Tokyo access point. During the test session on March 25, the route of Super-SINET was used.

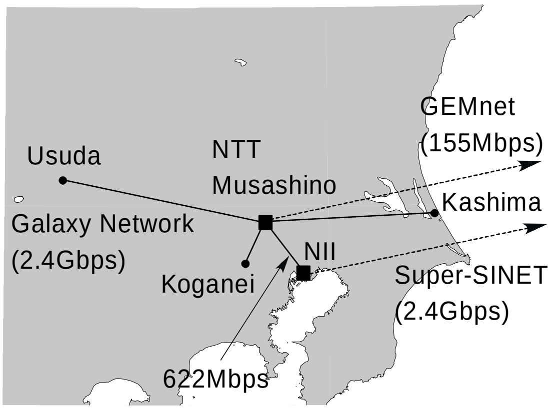

Fig. 3 Configuration of the high speed network in Japan.

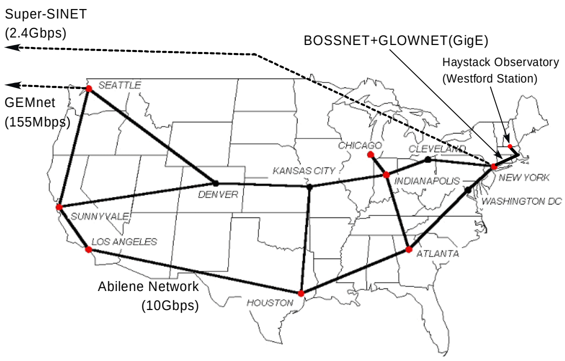

Fig. 4 Configuration of the high speed network in the United States.

4 Experiments

4.1 Kashima-Koganei Experiment

After completing two prototype K5 VLBI data acquisition terminals, 24 hours of geodetic e-VLBI experiment was performed using two 11-m antennas at Kashima and Koganei from January 31 to February 1, 2003. Eight channels were assigned to both X-band and S-band and the total data rate was 64 Mbps. Observed data were stored in the internal hard disks as the data files. The data files were read by the software correlation program and the cross correlation processing was performed after all the observations finished. Then the bandwidth synthesis processing was performed and the obtained data were analyzed by CALC and SOLVE software developed by Goddard Space Flight Center of

National Aeronautics and Space Administration. During the observations, tape-based K4 data acquisition systems were used at both sites in parallel to compare the results. The data obtained with the K4 systems were processed with the K4 correlator at Kashima and analyzed similarly with the data obtained with the K5 systems. The results are compared in Table 2.

Table 2. Comparison of baseline lengths estimated from the data obtained with K4 and K5 systems.

	Baseline Length	RMS Residual	
		Delay	Rate
	(mm)	(psec)	(fsec/sec)
K4	109099657.0 ± 6.7	76	136
K5	109099641.2 ± 3.2	33	92

From the comparison, the estimated baseline lengths are consistent with each other within two time the estimated uncertainties. In addition, the comparison of the RMS residuals of delay and delay rates suggests the performance of the K5 systems is better than the K4 systems. The part of the reason of the improvement can be considered that the phase calculation of the phase calibration signals by the software correlation processing uses precise formula whereas the K4 hardware correlator uses a three level approximation for sine and cosine functions for faster processing and to make the design of the hardware correlator very simple.

4.2 Kashima-Westford Experiments

A test e-VLBI session was performed for two hours from 16:00 UT on March 25, 2003 with the Kashima-Westford baseline. The 34-m antenna VLBI station at Kashima and 18-m antenna station at Westford were used for the observations. This was the fourth test in the series of e-VLBI test observations. During the previous tests, successful detections of the fringes from the e-VLBI observations were demonstrated and the software developments have been continued with the obtained data sets.

At the Kashima station, K5 VLBI system was used to record observed data. At the Westford station, Mark5 VLBI system developed by Haystack Observatory was used to record observed data. The observed data were recorded to internal hard disks at each site and transferred to Kashima and Haystack Observatory after the observations by using FTP. For this purpose, a program was executed to extract the data from the Mark5 and to generate data files. At Haystack Observatory, K5 data files were converted their format and recorded to Mark5 system. After the conversion, both data recorded at Kashima and at Westford were processed for cross correlation processing using the Mark4 correlator at Haystack Observatory. At Kashima, Mark5 data files were converted to K5 file format and then both data recorded at Kashima and at Westford were processed for cross correlation processing by using the software correlator on the K5 VLBI system. After the cross correlation processing, bandwidth synthesis processing was done and two database files (one for X-band and another for S-band) were generated for data analysis. The total data volume was hence 56Mbps. The observations were performed with 14 channels (8 for X-band and 6 for S-band) and 2MHz for each channel. The file size of the Mark5 system was checked from the extracted files from the Mark5 disks. Since there are 16 input channels both in K5 and Mark5 systems, two channels were used as redundant channels.

After the data processing, CALC and SOLVE software were used to perform data analysis. In the estimation process, positions of both Kashima and Westford stations were fixed to the ITRF2000 values and the UT1-UTC was estimated along with the clock offset, clock rate, and the atmospheric zenith delay. The estimated UT1-UTC value is shown in the Table 3 as well as the values published in the Bulletin B of the International Earth Rotation and Reference Systems Service (IERS). As shown in the Table 3, the UT1-UTC was estimated with the uncertainty of 23.9 microseconds, which is comparable to the results from intensive sessions. The comparison of the estimated value with the results reported in IERS Bulletin B suggests there is a discrepancy between them. It is necessary to investigate the cause of the discrepancy. Especially, the consistency of the station coordinates and a priori information used in the data analysis has to be set carefully.

Table 3. Estimated value of UT1-UTC from the Kashima-Westford e-VLBI session and reported values from IERS Bulletin B 183, May 2, 2003.

	Epoch (UT)	UT1-UTC (μsec)
e-VLBI	20:00 on Mar. 25	-338727.0±23.9
IERS	00:00 on Mar. 25	-337951
IERS	00:00 on Mar. 26	-338610

Next e-VLBI session was performed again for two hours from 13:00 UT on June 27, 2003. The observation mode, configuration of the observing systems, and the baseline were identical to the previous e-VLBI session performed in March, 2003. The purpose of the session was to demonstrate how fast the UT1-UTC can be actually estimated from the international e-VLBI session. Therefore, the file transfer servers as well as the network switches were carefully tuned to improve the file transfer speed over the network. Because the transmission delay over the network is quite large, about 200 msec., the default buffer size of the servers had to be increased from 64 kBytes to more than 4 Mbytes. As the results of this tuning, the file transfer speed was improved from about 2.2 Mbps to more than 100 Mbps. Table 4 shows the actual time sequence of the observations, file transfers, and data processing during the e-VLBI session. As shown in the table, the file transfer speed reached to 107 Mbps in the direction from Kashima to Haystack Observatory. The opposite direction was not as fast, but the speed was about 45 Mbps. In total, the UT1-UTC was estimated within 21 hours and 20 minutes after the session finished. Thus the rapid estimation of the EOP less than one day was successfully demonstrated by the international e-VLBI observations and data analysis.

Table 4. Time sequence from the observations to the data analysis. Time is in Japanese Standard Time and start from 22:00 on June 30

Time	Event
22:00	Observations Start
00:00	Observations End
~04:20	File extraction and transmission From Kashima to Westford : 107Mbps (41.54GByte in 51m 35s) From Westford to Kashima : 44.6Mbps (41.54GByte in 2hr 04m 02s)
~08:10	File Conversion (Mark5 to K5)
~20:30	Software Correlation
~21:20	Bandwidth Synthesis Processing, Database Generation, Data Analysis

5 Conclusions and Future Plan

Since file transfer speed became so fast, the longest time is required for data correlation processing. But since it is done by the software correlator, the time can be easily decreased by increasing the number of CPUs to be used to the correlation processing. File conversion is also time consuming processing, but this becomes unnecessary if K5 systems are used at both observing sites or file format between different systems become compatible. The discussions about the standard file format for e-VLBI have just begun, it is expected that the file conversion processing will become unnecessary in the near future. By combining these efforts, it will become feasible to estimate UT1-UTC within a few hours after the observations without major difficulties.

The successes of the series of e-VLBI experiments have many important meanings. Two different recording systems have been developed by two independent teams and these two systems were used but the compatibilities between the two different systems were easily achieved by preparing file conversion software programs. The establishment of the file format standard for e-VLBI will further improve the compatibilities among different systems. It was also demonstrated that the international network connection has been drastically improved recently and the e-VLBI observations with intercontinental baselines are becoming realistic. Finally, the success of the bandwidth synthesis and the data analysis in the from the data obtained with the K5 systems showed the improved performance of the prototype K5 VLBI data acquisition terminal compared with the conventional systems.

In the future, we are planning to continue similar e-VLBI sessions until the e-VLBI observations become reliable and robust. Since the trans-Pacific network has more capacity than we have used, it is expected we can still increase the file transfer speed by investigating the bottleneck of the network route. In parallel, we are planning to develop a CPU array system for distributed correlation processing for fast and effective processing. The real-time data transfer and processing software programs will also be developed to further improve the promptness to obtain results from geodetic VLBI observations. After these system developments, it will become possible to perform routine e-VLBI sessions with international baselines for rapid turn around EOP measurements. To realize e-VLBI observations with isolated radio telescope sites, satellite communications have great possibilities. If the satellite communications are utilized in the real-time

VLBI applications, variable communication delay will become the most different factor. It is highly desired to pursuit the use of satellite communications in the e-VLBI experiments as soon as possible.

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