High Speed Data Transmission and Processing Systems for e-VLBI Observations

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Currently, 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. To realize the e-VLBI observations by using shared network environment, PC based data acquisition systems and data processing systems have been developed. In this report, the developments of these systems are introduced and the results of the test observations performed with these new systems are presented.

Introduction

Developments of the Very Long Baseline Interferometry (VLBI) technologies had been practically realized along with the improvements of the data recording technologies using magnetic tapes. In the conventional VLBI observations, radio signals from celestial radio sources are received at two or more radio telescopes and are recorded to magnetic tapes. The tapes are then shipped to a correlation processing site and the data recorded in the tapes are processed to calculate cross correlation functions between the signals received at different radio telescopes. In this observation scheme, the sensitivity and the timeliness to obtain results from observations are limited by the maximum speed of data recording on magnetic tapes and the slow delivery of the tapes from the observing sites to the correlation processing site. To overcome these limitations, many efforts have been made to transfer the VLBI data from observing sites to the correlation site electrically. The observed data are transferred either in real-time if the connecting network is fast enough to transfer the observed data rate, or in near real-time if any kinds of data buffering is required at the observing site. In either case, the technique is called as e-VLBI to distinguish it from the traditional tape-based VLBI.

Many radio telescopes around the glove are regularly participating in the various VLBI observation sessions for research in geodesy, astrometry, and astronomy by using the tape-based systems. If we can connect these observatories with high-speed data link by using satellite communications and the e-VLBI observing systems, it will dramatically improve the timeliness to obtain results from observations. Especially, the value of UT1-UTC can only be determined precisely by geodetic VLBI observations and the routine e-VLBI observation is desired by various research fields which require accurate satellite orbits or rely on accurate terrestrial and celestial reference frames. In addition, if the data transfer rate becomes faster than the maximum recording speed on magnetic tapes, the sensitivity of the VLBI observation will be dramatically enhanced and it will expand the horizon of the radio astronomical observations.

System Developments

As a technology development center of the International VLBI Service for Geodesy and Astrometry (IVS), Communications Research Laboratory has been developing next generation systems for VLBI observations and data processing. K5 VLBI system is being developed to perform real-time VLBI observations and correlation processing using Internet Protocol over commonly used shared network lines. The K5 data acquisition system is consist of four PC systems each equipped with a main board and an auxiliary board of the IP-VLBI board[1]. The board is also called as the Versatile Scientific Sampling Processor (VSSP) Board because it was designed to be used by various scientific data acquisition purposes. The IP-VLBI board can sample base-band signals at various sampling rates selectable from 40 kHz, 100 kHz, 200 kHz, 500 kHz, 1 MHz, 2 MHz, 4 MHz, 8 MHz, and 16 MHz. The sampling level can be selected from 1, 2, 4, or 8-bits. The PC systems run on the LINUX, FreeBSD, and MS-Windows operating systems. Two prototype K5 data acquisition systems have been configured. Fig. 1 shows a picture of the prototype K5 data acquisition system and Fig. 2 shows a picture of the IP-VLBI (VSSP) board. 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 within a year or two years. 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.

Fig. 1. The prototype K5 VLBI data acquisition system.

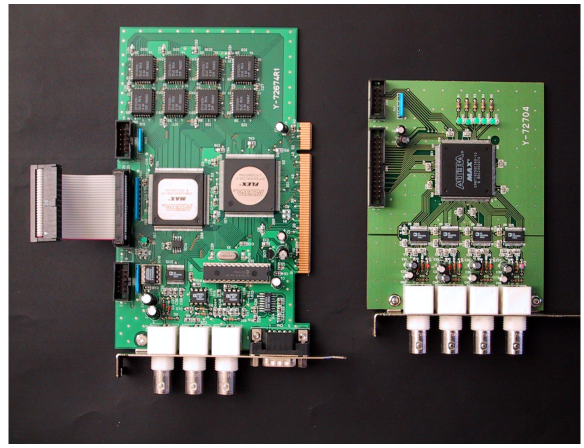

Fig. 2. A picture of the main board (left) and the auxiliary board (right) of the IP-VLBI (VSSP) board. Two boards are connected by the cable attached to the main board in the picture.

Fig. 3 shows a picture of the PC-VSI system and the ADS1000 A/D sampler unit[2]. The PC-VSI system can record data stream through a VSI-H data input connector at the data rate of 1024Mbps. VSI is the acronym of the VLBI Standard Interface and VSI-H corresponds to VSI Hardware specifications which were discussed by representatives from broad community of VLBI research and developments to standardize physical and electrical properties of the VLBI data stream[3]. The term VSI is also used as an acronym of Versatile Scientific Interface because it can be used in variety of scientific research fields which require precise timing information for the data acquisition. The first official version of the VSI-H specifications was agreed and published in August 2000 and was accepted as the standard to be followed by IVS. The recorded data are stored in a RAID disk array mounted on the LINUX operating system. ADS1000 is a sampler unit which can sample single wide-band signal from 0 Hz to 512 MHz at the sampling rate of 1024 MHz. The sampling level can be selected from 1 bit or 2 bits and thus the highest data rate is 2048 Mbps. Under the VSI-H concept, slower sampling rate observations can be done by omitting a part of the sampled data stream periodically. For example, the sampling rate can be decreased by a factor of two by skipping one sampling data alternatively. By using this mechanism, ADS1000 sampler unit can be used for different sampling speeds. The ADS1000 sampler unit has been developed for astronomical VLBI observations which require high sensitivity with wide frequency bandwidth.

Fig. 3. PC-VSI system (left) and ADS1000 A/D sampler unit (right). The board in front of the PC-VSI system is the PC-VSI2000-DIM board.

Experiments

By using the new VLBI observations and data processing systems described in the previous section, a series of test experiments have been carried out. Three baselines were selected for these test experiments. The first baseline was the Kashima-Metsähovi baseline. The 34-m antenna at Kashima and 14-m antenna at Metsähovi, Finland were used for the experiments. The second baseline was the Kashima-Westford baseline. The 34-m antenna at Kashima and the 18-m antenna at Westford, Massachusetts, USA were used. The third baseline was the Kashima-Koganei baseline. The 11-m antennas at Kashima and at Koganei, Tokyo were used.

Kashima-Metsähovi Experiments

A series of test e-VLBI experiments were performed with Kashima-Metsähovi baseline from the end of September 2002. The 34m antenna at Kashima and 14m antenna at Metsähovi Radio Observatory in Finland were used for these experiments. The RF frequency from 21.98GHz to 22.48GHz were received by both antennas and converted to the base-band signals. The base-band signals were then sampled with ADS1000 sampler units. In the test e-VLBI experiments, 1-bit sampling mode of the sampler unit was used. At Kashima, the PC-VSI disk based recorder system equipped with PC-VSI2000-DIM board was used to record the data. At Metsähovi, two Linux PC systems each equipped with VSIB VSI-H PCI data acquisition boards were used to record the data. Both systems are capable of recording digital data through VSI-H interface connectors.

The data recorded at Metsähovi were transferred to Kashima by using FTP protocol after observations and processed for correlation processing on a Linux PC system using software correlator programs. The first successful fringe was detected from the observation towards the W3OH maser source made on October 16, 2002. Fig. 4 shows the cross power spectrum after 15 seconds of integration time.

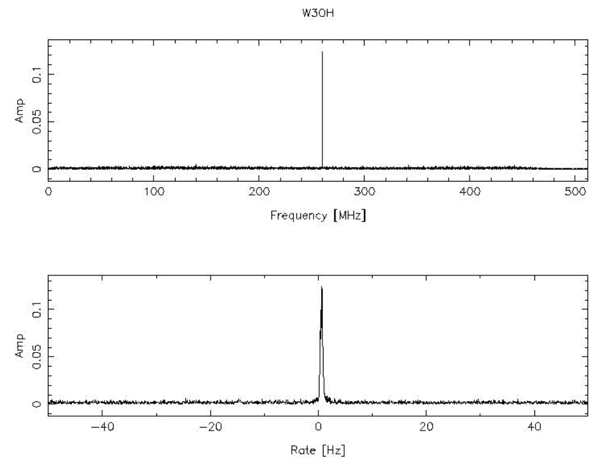

Fig. 4. The cross power spectrum of the W3OH observation with the Kashima-Metsähovi baseline.

Kashima-Westford Experiments

Three sessions were scheduled with the Kashima-Westford baseline. The dates and time of these sessions are shown in Table 1. In evlbi1 and evlbi3 sessions, K5 VLBI data acquisition system was used at Kashima and Mark-5 VLBI data recording system[4] was used at Westford. Eight frequency channels were assigned to X-band and six frequency channels were assigned to S-band. Sampling rate of each channel was 4MHz and the total data rate was 56Mbps. Frequency assignment was same with the conventional geodetic VLBI experiments. In the evlbi2 session, K5 VLBI data acquisition system was used at Kashima and the 4 channels configuration of the K5 VLBI data acquisition system was used at Westford. The latter system is consist of a PC system running on the FreeBSD operating system and an IP-VLBI board. Only the X-band signals were recorded with the system both at Kashima and at Westford.

Table 1. Three e-VLBI sessions performed with the Kashima-Westford baseline.

Exp.Code	Date	Time
evlbi1	October 8, 2002	17:30UT-19:30UT
evlbi2	October 9, 2002	12:00UT-15:00UT
evlbi3	October 15, 2002	17:30UT-18:40UT

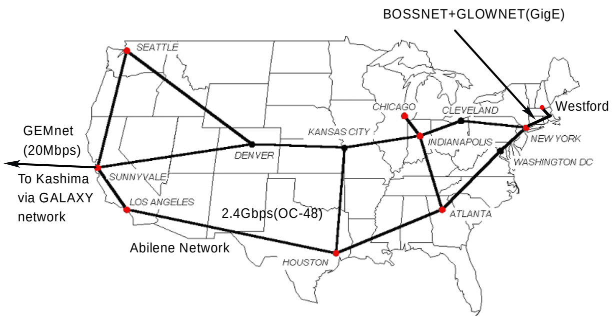

Fig. 5. The high speed network route used in the Kashima-Westford e-VLBI experiments.

Fig. 5 illustrates the high speed network route used in the test e-VLBI experiments. To prepare the international e-VLBI experiments, the GALAXY network was connected to the GEMnet network which is the high speed research network of the NTT Laboratories. The GEMnet has an international link between Japan and the USA at the data rate of 30Mbps. 20Mbps of the bandwidth is assigned to the connection to the Abilene network which are used by universities and institutions along the USA. Haystack Observatory has been connected to the Abilene network by using BOSSnet and GLOWnet. At the time of the e-VLBI experiments, the BOSSnet was not available, and the alternative route was used. The backbone of the Abilene network has a capacity of 2.4Gbps (OC-48). In total, the expected limit of the data rate was 20Mbps which was restricted at the transpacific connection provided by GEMnet.

After evlbi1 and evlbi3 sessions, the data recorded by the Mark-5 system at Westford were converted to transferable files and transferred to Kashima by using the high speed network and FTP protocol. The data files were then converted to K5 compatible format and processed with the data recorded with the K5 system at Kashima for correlation processing. Software correlator programs of the K5 system were used for the correlation processing. On the other hand, the data recorded with the K5 system at Kashima were transferred to Haystack Observatory by using the high speed network. The data files were then converted to Mark-5 disk system and processed with the data recorded with the Mark-5 system at Westford. The Mark-4 hardware correlator system was used for the correlation processing. Although evlbi1 session was not successful, fringes were successfully found from the evlbi3 session by both of the correlators. Fig. 6 shows the detected fringes at X-band and S-band for the radio source 4C39.25.

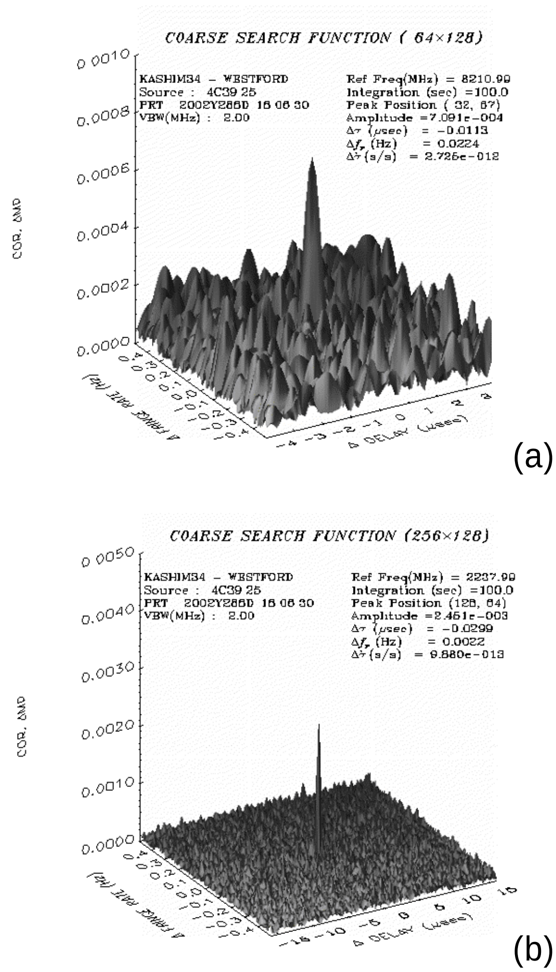

Fig. 6. Detected fringes at X-band (a) and S-band (b) observations towards 4C39.25. The software correlation program was used for correlation processing.

The evlbi2 session was performed to evaluate the current performance of the real-time data transmission between K5 VLBI data acquisition systems over the intercontinental distances. The K5 system is capable of transmitting observed data in real-time to the network by using IP protocol. The real-time transmission was tried and succeeded at various data rate from 40 kbps to 1 Mbps. The transmission speed of 1 Mbps was almost the theoretical limit by the TCP/IP protocol with the large transmission delay from Westford to Kashima. The maximum speed is expected to be increased by using UDP/IP protocol up to the capacity of the network which was 20 Mbps in the case of Kashima-Westford e-VLBI experiments and the data transmission program is under further developments to incorporate the capability to use UDP/IP protocol along with the TCP/IP protocol.

Kashima-Koganei Experiments

After completing two prototype K5 data acquisition systems, 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[6]. During the observations, K4 data acquisition systems[7] were used at both sites in parallel to compare the results. The data obtained with the K4 data acquisition systems were processed with the K4 correlator at Kashima and analyzed similarly with the K5 data. The results are compared in Table 2.

Table 2. Comparison of baseline lengths estimated from K5 and K4 observations.

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

The comparison suggests the performance of the K5 systems is better than the K4 systems. The part of the reason of the improvement is considered that the phase calculation of 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.

Conclusions

The successes of the series of test experiments have many important meanings. The 1024Mbps Kashima-Metsähovi experiment demonstrated high sensitivity VLBI observations. In addition, two different VSI recording systems have been developed by two independent teams and these two systems were used with the same sampler unit interfaced with the VSI-H specifications. The successes to exchange data recorded by different recording systems demonstrated the intended results of the standardization of the interface by VSI-H. The success of the Kashima-Westford experiments demonstrated that the PC disk based recording systems are flexible enough and it is possible to achieve compatibility between one system and the other by software programs. It 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 Kashima-Koganei experiments showed the improved performance of the K5 VLBI data acquisition system compared with the conventional systems. In the future, we are planning to continue similar test experiments until the e-VLBI observations become reliable and robust. 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 pursue the use of satellite communications in the e-VLBI experiments as soon as possible.

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