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Internet VLBI System Based on the PC-VSSP (IP-VLBI) Board

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Abstract. A new real-time VLBI system using Internet protocol (IP) technology has been developed to reduce network-cost and to expand connection sites of VLBI network. We call this system "IP-VLBI" or "Internet VLBI". We are developing the system consisting of a personal computer (PC)-based sampler equipped with a PCI-bus Versatile Scientific Sampling Processor (VSSP) board and FreeBSD (and/or Linux) software to carry out real-time data transmission, reception and correlation. The IP-VLBI system developed at CRL is dedicated to taking over current geodetic VLBI system. A geodetic VLBI system usually receives 14 to 16 frequency channels at S and X bands. A VSSP board on a PC can sample 4 channel data, hence 4 PCs can cover the current geodetic VLBI system. Each PC (4-channel) data are transmitted to a PC for correlation processing independently through the Internet. Thus by only establishing the system for a PC sampler, we can easily expand it to the multi-PC sampler system, i.e., geodetic VLBI system. In parallel with the development of the real-time system, we are also developing a quasi-real time (QRT) VLBI system. In the QRT system data are stored in a hard disk at first, then transmitted to a correlation site with a possible transmission speed of network. Of course off-line operation is also possible. In this case, data are transmitted after observations are made using an FTP or equivalent file transmission protocol.

1. Introduction

Communications Research Laboratory has been developing the new real-time VLBI system adopting the Internet protocol (IP) technology to real-time data transmission from observation sites to correlation processing site. In conventional VLBI observations, signals from a radio star received at two or more antennas are recorded on magnetic tapes, then the tapes are shipped to a processing center, and correlation processing is carried out there. In the Key Stone Project (KSP), which is dedicated to monitoring crustal deformation around the Tokyo metropolitan area, a real-time VLBI system for routine use was developed for the first time in the world (Koyama et al. 1998; Kiuchi et al. 2000). Radio signals are converted into 16 base band signals (BBS) with an 8 MHz bandwidth each in the KSP VLBI sytem. One BBS channel is converted to 1

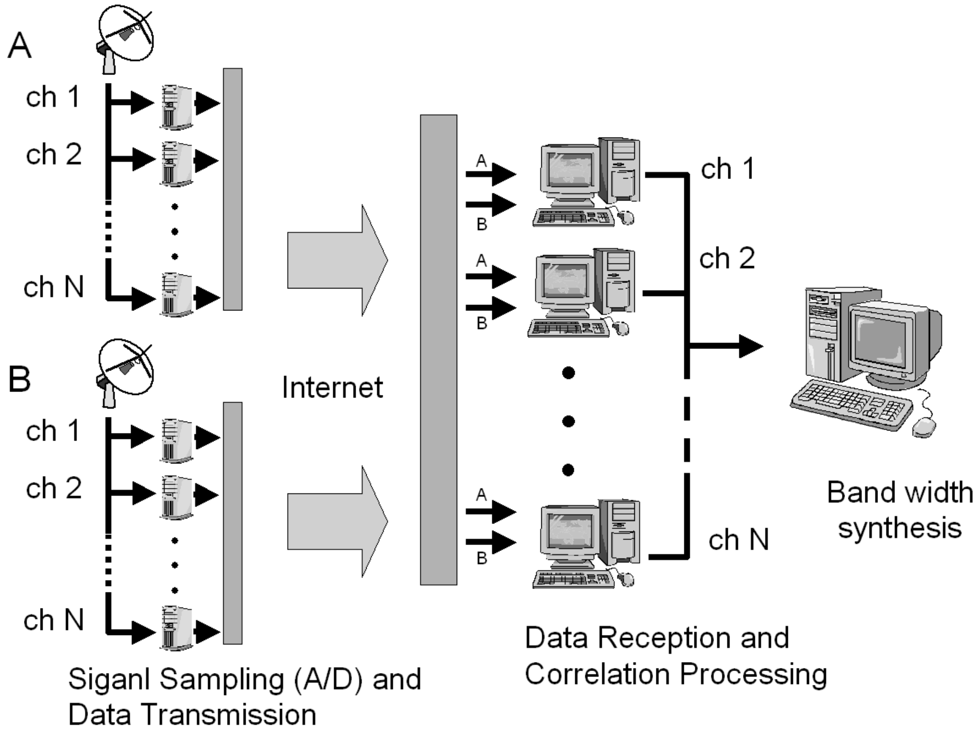

Figure 1. A schematic block diagram of IP-VLBI system. Each BBS is sampled and converted to digital signals by using a PCI-bus Versatile Scientific Sampling Processor (VSSP) board developed for the IP-VLBI system. Sampled signals are stored on hard disk drives (HDD) and/or transmitted to a remote PC where software correlation processing is carried out. Correlated data are further processed to get multi-band group delay etc.

bit digital signals with a sampling frequency of 16 MHz, so that total data rate is 256 Mbps for 16 BBS channels. Digital signals are transmitted to a correlation center in real time through the high-speed (2.4 Gbps) Asynchronous Transfer Mode (ATM) network instead of recording them on a magnetic tape. At the correlation center a dedicated correlator connected to the ATM network processes the data in real-time. We call this real-time VLBI system "ATM-VLBI" or "VLBI over ATM".

However, network-cost is still expensive and connection sites are still limited, so that the ATM-VLBI is not yet well-generalized even though it was established in 1988. Hence, it has been aimed to develop new real-time VLBI system using IP technology that has already spread widely, to reduce network-cost and to expand connection sites of network. We call this real-time system "IP-VLBI" or "VLBI over IP".

Two kinds of system are considered as an IP-VLBI system. One is the substitution of protocol from ATM to IP. In this system, serial high-speed data stream is directly sent by using IP instead of ATM (ATM may be used at the

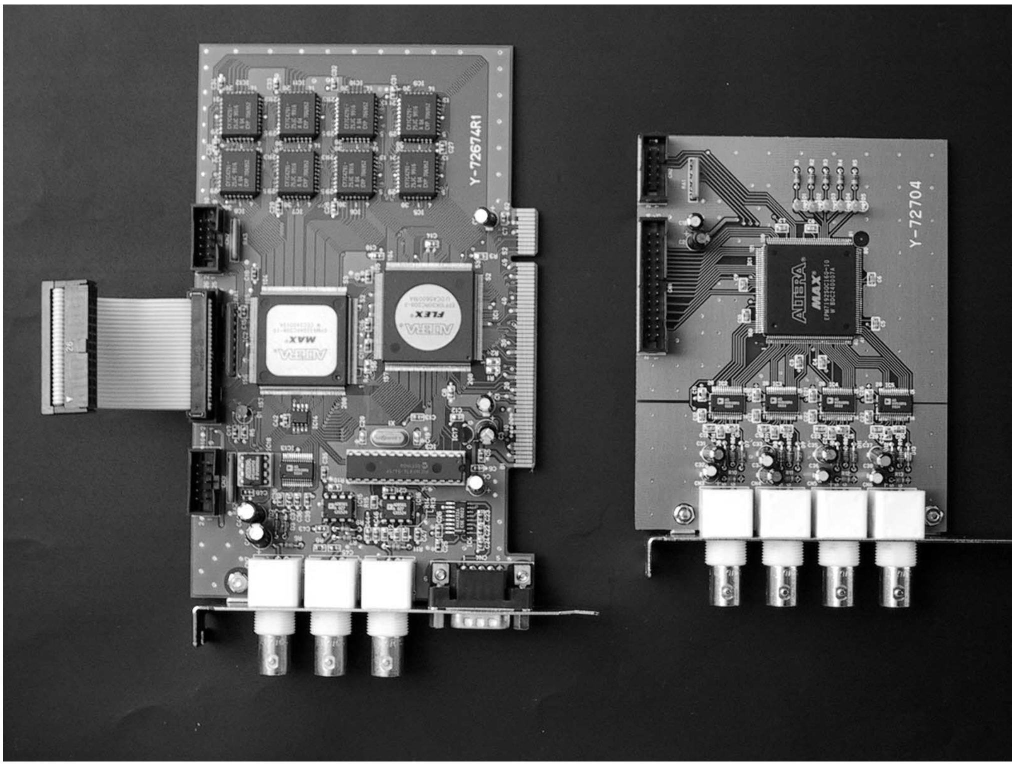

Figure 2. A PCI-bus Versatile Scientific Sampling Processor (VSSP) board developed for the IP-VLBI system (left) and an auxiliary board for 4ch BBS inputs (right).

networking physical layer, but we do not care about that). We refer to the system as "High-speed IP-VLBI". Although the data are consisted from several numbers of BBS channel data, no channel-distinction is made in the transmission process. The Nippon Telegraph and Telephone Corporation collaborating with the CRL have developed this system, and succeeded in preliminary experiment carried out on January 17, 2002 on Kashima-Usuda baseline (Iwamura et al. 2002).

The other one is on the basis of BBS channel data processing. A geodetic VLBI system usually receives 14 to 16 BBS channels at S and X bands. Each channel data are transmitted independently by using the IP. We refer to this system as "Multi-channel IP-VLBI". Advantage of the system is easiness to develop the system because if we establish the system for one BBS channel, we can easily expand it to multi-channel system. A requirement for one channel system to take over the current geodetic VLBI system is not so hard. It is sufficient to transfer one channel data with a speed of 16 Mbps, and it is not so difficult requirement even for a low-cost PC. Only the network speed limits the total number of channels and sampling frequency. On the way to realize full real-time operation, we have been developed offline operation and quasi real-time operation system. In this paper, we use the term "IP-VLBI" only for representing the multi-channel IP-VLBI system.

Table 1. Specifications of a VSSP board.

Reference signals	10MHz +10dBm, 1PPS
Number of input channels	max 4 ch
A/D resolutions	1, 2, 4, 8 bits
Sampling frequencies	40kHz, 100kHz, 200kHz, 1MHz, 2MHz, 4MHz, 8MHz, 16MHz

In the mean time, fringe test using data transmitted by FTP has been already realized. We call this "FTP-VLBI" or "e-VLBI" to distinguish it from "IP-VLBI".

2. IP-VLBI System

Figure 1 shows a block diagram of the IP-VLBI system. We use an existing facility to receive radio signals and to convert them into BBS. Each BBS is sampled and converted to digital signals by using a PCI-bus Versatile Scientific Sampling Processor (VSSP) board developed for the IP-VLBI system. Sampled signals are stored on hard disk drives (HDD) and/or transmitted to a remote PC where software correlation processing is carried out. Correlated data are further processed to get multi-band group delay etc.

2.1. A Versatile Sampling Processor Board (VSSP)

A sampler board we have developed is a PCI-bus board (Figure 2) and is designed for use of general purpose data acquiring as well as VLBI data. Table 1 summarizes specifications. The board has two reference signal inputs (10 MHz and 1 PPS signals). A maximum analog input channel of four is possible by adopting an auxiliary board. Sampling frequency is from 40 kHz up to 16 MHz and A/D conversion resolution is from 1 bit to 8 bits. They are all programmable but maximum data rate is limited by a combination of CPU motherboard and PCI bus performance. So far we have attained the data rate of 64 Mbps stably. It corresponds to 4ch×1bit×16MHz sampling or 4ch×4bit×4MHz sampling, and so on. We are expecting increase of the maximum data rate optimistically, because the evolution of PC and peripherals are very quick these days. Base band signals output from a VLBI back-end are converted to digital signals by a VSSP board then a header block of 64 bits including time tag is inserted into the data stream every second (Figure 3). Driver software for VSSP board was first developed for FreeBSD system, but now it is available for Linux and Windows 200 system.

2.2. K5 system

A PC can be a 4-channel data acquisition terminal by use of a VSSP board, so that four PCs can form a 16-channel data acquisition terminal that is compatible with a KSP terminal in terms of the number of channels. The system assembled this way is named "K5". A block diagram of K5 is shown in Figure 4. Each PC has four 120 GB HDDs for data storage, then total storage size is 1.92 TB. This corresponds to a 60000 sec scan length with 256 Mbps observation and is

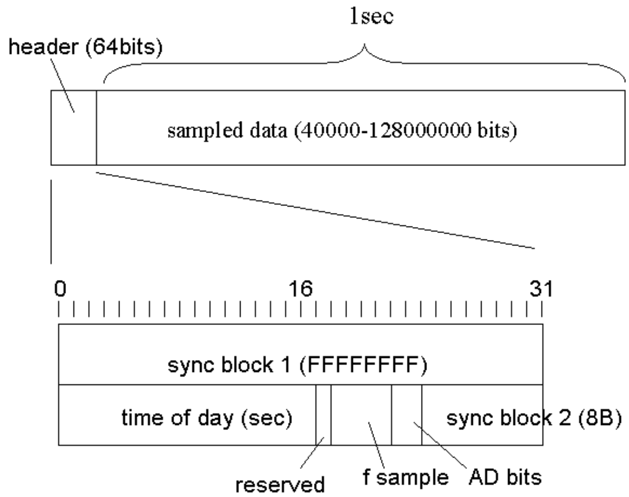

Figure 3. Data format of VSSP board output. Every one second a header block of 64 bits is inserted in a data stream.

usually enough volume to store a 24-hour (86400 sec) geodetic VLBI session, because antenna slewing time to switch radio sources is excluded. A picture of prototype K5 is shown in Figure 5.

2.3. Operation Software

Supposed operational mode of IP-VLBI system is summarized in Figure 6. Although our final goal is real-time operation, off-line operation (FTP-based operation) and/or quasi real-time operation are the first target of system development. Regarding off-line operation, full automatic observation is available now with K5. We have developed various kinds of utility software on FreeBSD and Linux to operate the system (see Table 2).

2.4. Real-time Operation

Real-time operation is carried out through the Internet connection using server and client software. There are two ideas regarding which takes a server between observation site and correlation site. One is that an observation site is a server and a correlation site is a client. The other is the contrary. Both are possible to realize a real-time operation. We have developed prototype server software for an observation site and prototype client software for a correlation site as a start of development. TCP/IP protocol is tested first because it is easy to handle and is reliable for data transmission. The function of server and client software is also summarized in Table 2. By using this server and client software, real-time data transmission up to 64 Mbps (corresponding to 16 Mbps$\times$4 ch) is attained stably through local area network (100BASE-T) at present.

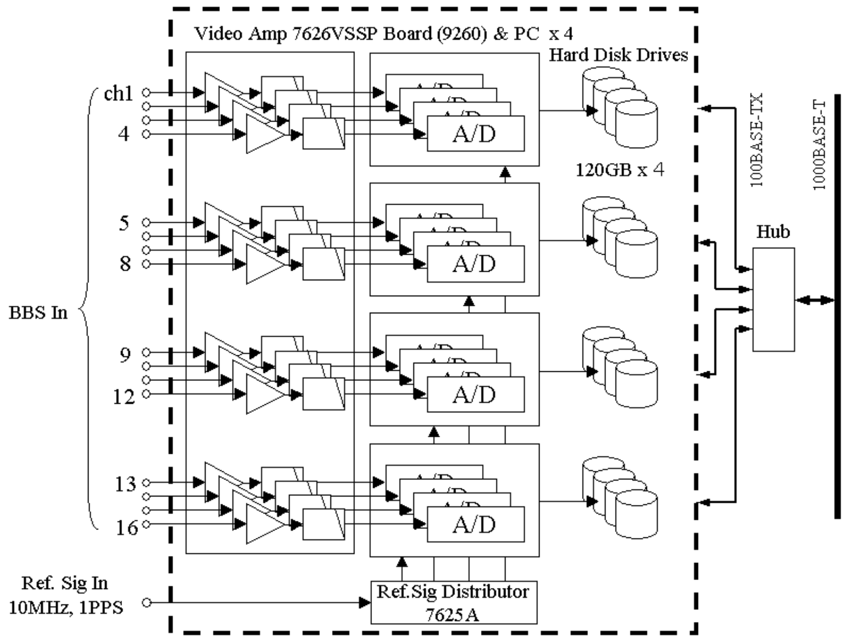

Figure 4. A block diagram of K5 system.

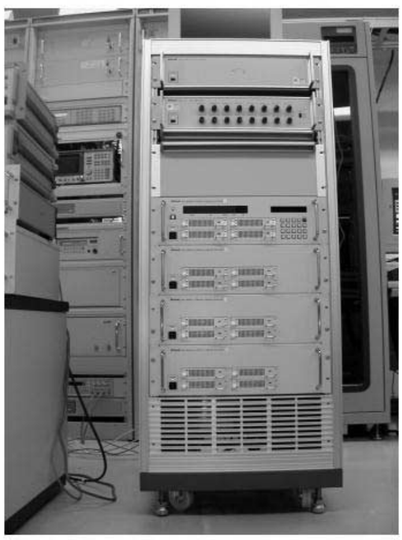

Figure 5. Prototype K5 system. From top to bottom, a reference signal distributor, 16-ch video amplifiers with low-pass filters, and 4 PCs for VSSP boards.

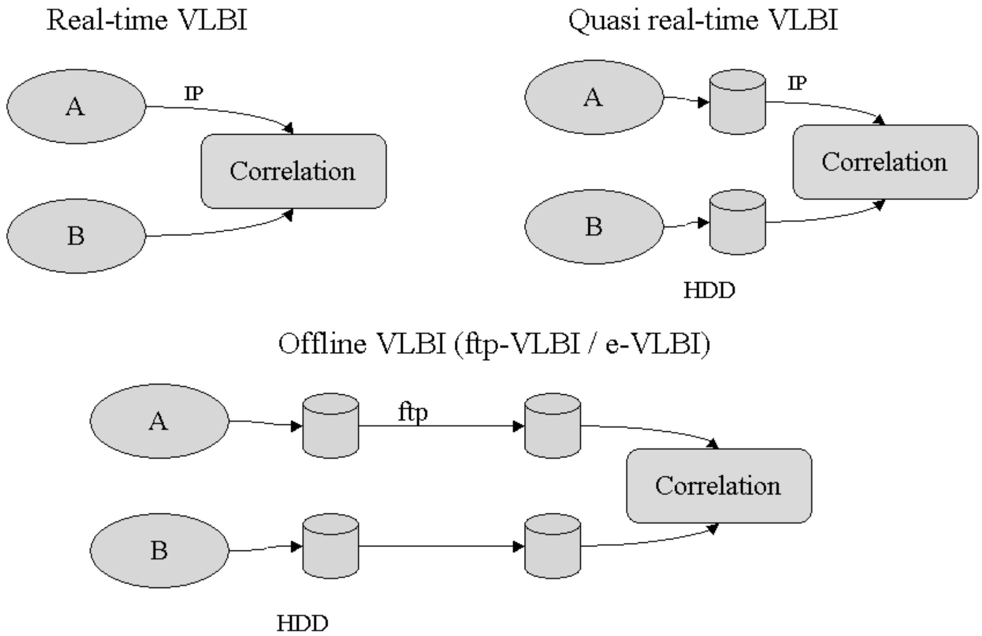

Figure 6. Supposed operational mode of IP-VLBI system. Real-time operation is our goal. Off-line operation is available now.

2.5. Software Correlator

We consider that the software-correlation processing is a key technology to generalize the IP-VLBI system, because it is easy to handle both network data and local disk data. If we read the data on local disk, it will be an off-line processing. If we get the data through the Internet, it will be real-time processing or quasi-real time processing or FTP processing. Thus we are developing software to correlate two data streams without any use of dedicated hardware. The fastest version of SC can process 4 MHz sampling data in real-time when it runs with the Pentium III 1GHz processor.

In order to achieve further speed up, distributed processing software is under development. One example is shown in Figure 7. This shows an idea of time distributed processing. Data stream is divided into a short time segment, and correlation is made for each pair of segmented data.

3. "NOZOMI " Delta VLBI Observations

The NOZOMI is a Japanese spacecraft for exploring Mars. The determination of spacecraft position is usually made on the basis of range and range rate measurements using a two-way telemetry link. However this range measurement is supposed to be difficult during several months before the 2nd Earth swingby of NOZOMI planned on June 19, 2003 to cruise to Mars, due to the geometrical relation between spacecraft attitude and earth position, i.e., high-gain antenna of NOZOMI does not point the Earth. To succeed the 2nd swingby, it is very

Table 2. Utility Software for K5 (including under development)

Utility Name	Function
autoobs	do observation (data acquisition) according to a schedule file (SKED format)
datachk	check data validity
extdata	extract one channel data from a VSSP out
monit	monitor signal input level
sampling	make observation for one scan
signalcheck	check reference and 1PPS signals
skdchk	check schedule file and to calculate required storage size
speana	display spectrum
timedisp	display VSSP board time
timesettk	set VSSP board time
timesync	synchronize board time to 1PPS signal
vlbitkc	client program for real-time operation (not completed)
	send command to server (set sampling frequency, A/D resolution, data span etc.)
	gather VSSP out data
	measure network data transfer speed
vlbitks	server program for real-time operation (not completed)
	do offline observation
	do remote observation
fx_cor	FX type software correlation
ipxros_c	XF type software correlation (fastest version)
m5tok5	Mark5 to K5 format conversion

important to navigate the NOZOMI precisely. CRL and the Institute of Space and Astronautical Science (ISAS) started collaboration to determine NOZOMI position (orbit) using a delta VLBI technique. We adopted the IP-VLBI system for the observations. Test observations have been conducted several times and data reduction software is developed at a quick pace. Examples of fringes observed for NOZOMI telemetry signals are shown in Figure 8. Figure 9 also shows fringes for NOZOMI, but telemetry signal was very weak at that time and it is thought to simulate the period when actual delta VLBI is necessary. In any case, we succeeded in determining group delay without ambiguities.

4. First US-Japan e-VLBI Experiment

We have conducted the first US-Japan e-VLBI experiment in collaboration with the Haystack Observatory VLBI team on October 15, 2002. Kashima 34m antenna and Westford 20 m antenna were used for this experiment. We carried out observations using the K5 at Kashima. After observations, K5 data files were FTPed to Haystack Observatory. From Japan to US, the GEMnet owned by NTT was used then connected to Abilene to reach Haystack. At Haystack observatory K5 data file was converted to Mark 5 data format file, then correlated with Westford data using a Mark 4 correlator. On the other hand, Mark 5 data observed at Westford were FTPed to Kashima followed the reverse net-

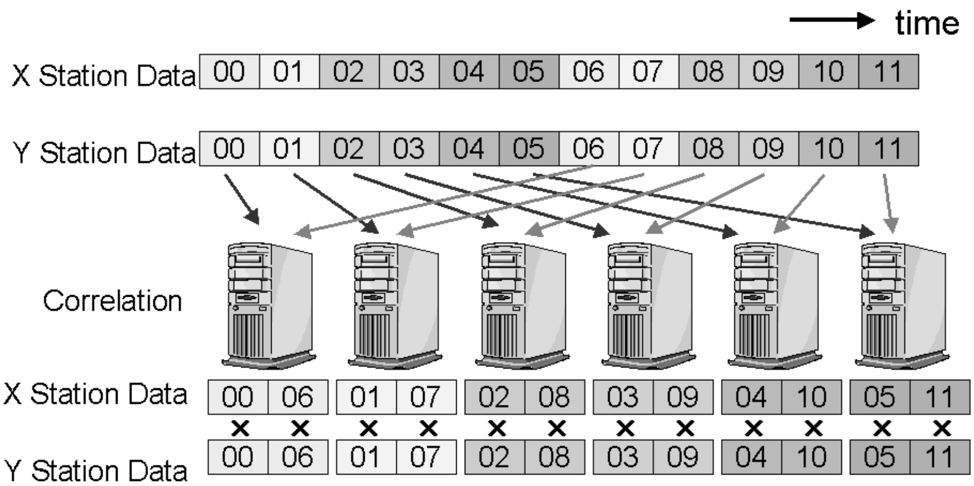

Figure 7. An idea of time distributed correlation processing.

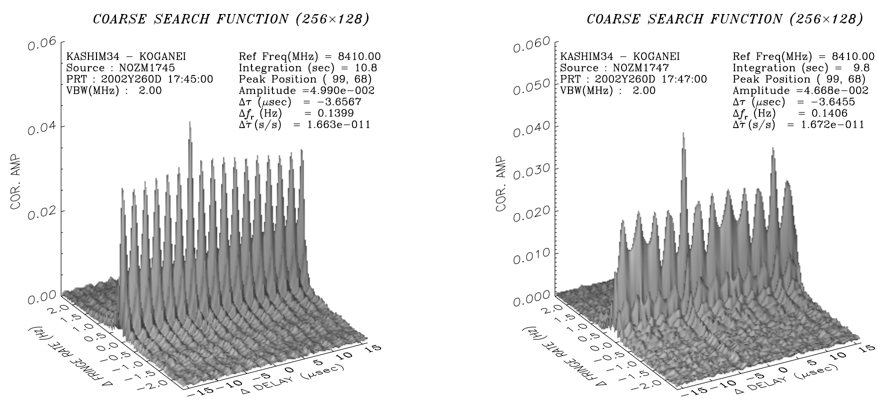

Figure 8. NOZOMI fringes for two different epochs. Telemetry mode changed slightly between two epochs, however group delay without ambiguity is easily determined for both cases.

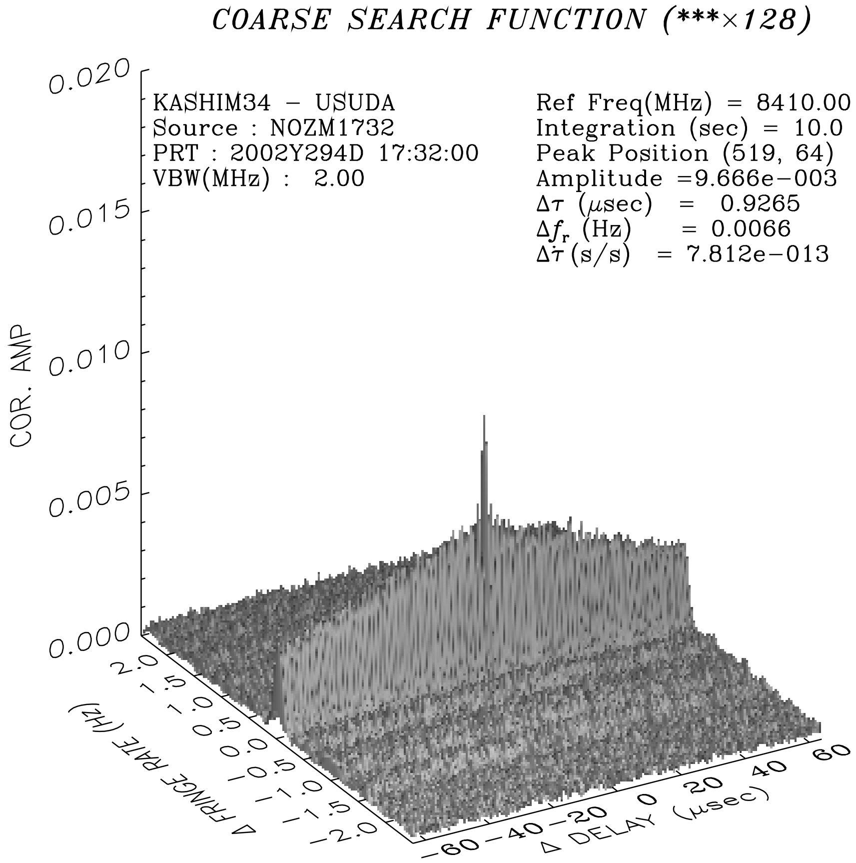

Figure 9. NOZOMI fringes for very weak signal case detected on Kashima 34m - Usuda 64m baseline.

work route. At Kashima Mark 5 data were converted to K5 data format file then they were correlated with Kashima data using software correlator. At both team, good fringes were successfully detected. Figure 10 shows fringes detected by Kashima team.

5. Conclusions

The development of the Internet VLBI system based on the PC-VSSP (IP-VLBI) board has been going well. Various kinds of utility software including correlation processing for FreeBSD/Linux operating system have been developed and automatic observation and FTP-VLBI (e-VLBI) are possible now. First US-Japan e-VLBI was succesfully carried out on Kashima-Westford baseline on October 15, 2002. As for the real-time VLBI operation, prototype server and

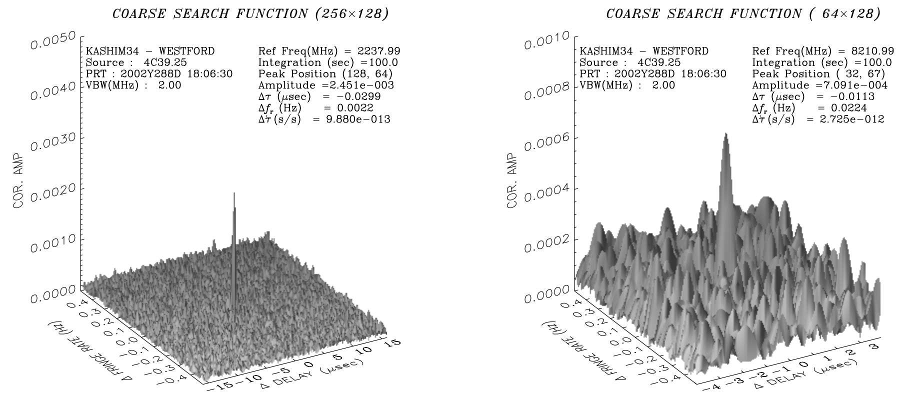

Figure 10. First US-Japan e-VLBI fringes. Left panel is for S band and right is for X band. Observation is made on October 15, 2002.

client software has also been developed, and real-time data transmission up to 64 Mbps (corresponding to 16 Mbps×4 ch) under 100BASE-T condition is attained stably through local area network at present. However, transmission test using the global Internet shows more low performance even if network speed itself is much faster than measured value. Maximum data rate may be limited for each port connection by some gate machine elsewhere in the network. We might introduce multiple port connection to improve performance. This should be considered in the server and client software.

In the meantime, IP-VLBI system is gradually distributed in Japan. We will make delta-VLBI observation of NOZOMI using IP-VLBI system several months before the 2nd Earth swingby planned on June 19, 2003 to determine orbit and to lead a Mars exploring project to a success.

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