3. KSP VLBI System

3.1 Observation System

3.1.4 Observation and System Management Software

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ABSTRACT

One of the unique characteristics of the Key Stone Project VLBI system is its design for automation. The observation system is highly automated and frequent geodetic VLBI experiments can be performed without the need for human operations. The observation system is designed so that anybody can operate the system with a minimal amount of training. This paper gives an overview of the system and its unique concepts, which improve its reliability.

(Keywords: VLBI, remote control, remote monitoring)

1. Introduction

Before the Key Stone Project (KSP) VLBI system was developed, at least one human operator was required to be at each observation site during a VLBI experiment. The operator had to begin and interact with observation control programs at the site and monitor the system functions repeatedly. These operations have been partially automated for the Very Long Baseline Array system developed by the National Radio Astronomy Observatory,[(1)] but a human operator is still necessary at each site for changing observation tapes. In contrast, the KSP VLBI system realized full automation to the level in which it does not require any human operations at four observation sites. This has been achieved by the automated observation control system and the use of a real-time VLBI system that utilizes a high-speed digital communication network to transfer observed data to a correlator.[(2)]

The highly automated VLBI observation system enables daily or every other day experiments. In each experiment, a series of observations are performed and various parameters are estimated from the set of obtained time delays. Daily experiments were performed until September 1997 with the duration of about 6 hours. Since September 30, 1997, the duration of each experiment was expanded to about 24 hours while the frequency of the experiments was decreased from daily to every-other-day. Such frequent experiments are essential since the main purpose of the KSP network is to investigate the dynamic behavior of a relatively small region around Tokyo associated with seismic activity and deformation of the lithosphere in the area. Continuous monitoring of the region is expected to provide valuable information about the geophysical processes occurring under the region. To achieve this objective, measurements have to be performed as frequently as possible and the results have to be made available with minimum delay. To perform the frequent VLBI experiments with sufficient reliability, the entire system must also be robust. This paper describes the VLBI observation system for the KSP network, focusing on various features that make the automation of operations possible and the system highly reliable.

2. Observation software system

2.1 Observation control and data monitoring systems

At each station, two workstations and one PC system perform all the automated tasks necessary for VLBI observations, as shown in Fig. 1. The PC system, which controls tracking of the antenna system, is called an antenna control PC. When it is given the right ascension and the declination of a celestial radio source, it calculates the azimuth and elevation angles and sends necessary commands to the antenna control unit. The antenna control PC is connected to a Unix workstation, called an observation control workstation, via a GPIB (general purpose interface bus) communication interface. The observation control workstation provides the right ascensions and declinations of target radio sources during a VLBI experiment according to an observation schedule file. Tape changing and data recording are also controlled by the observation control workstation in the tape-based VLBI mode of operations. The observation schedule file also specifies local frequencies and video-bandwidths of 16 observation channels, and necessary commands are sent from the observation control workstation to the data acquisition terminal via the GPIB communication bus to set up observation configurations at the beginning of each experimental session.

In a geodetic VLBI experiment, weather data and cable delay data have to be collected during the experiment for the calibrations required in the data analysis. These data are collected by a different Unix workstation called the monitoring workstation. This workstation also measures and collects many data for monitoring the statuses of many components via a GPIB interface and a parallel I/O interface. These tasks are separated from the observation control workstation so that calibration data as well as monitoring data can be collected continuously regardless of whether the VLBI observations are being performed or not. Separating data monitoring tasks from observation control tasks also reduces the data load on the GPIB line. When one of the status signals collected by a parallel I/O interface indicates a problem, or when one of the monitored data items exceeds a predetermined threshold, the monitoring workstation indicates the problem on the console terminal screen and sends an alarm signal to the central control workstations over the wide area network system.

2.2 Central control systems

At Koganei and Kashima stations, there are additional Unix workstations called central control workstations. Their role is to organize observations performed by the observation control workstations at the four stations and to collect status and monitoring data from the monitoring workstations. The graphical user interface of the central control workstations has been designed to be easy to use so that untrained operators can easily perform remote operations and various checks on the observation systems at remote sites. Observations at remote sites can be started, interrupted, and resumed after an interruption from the central control workstations. Receiving systems and data acquisition systems can be controlled remotely, and the results of the operations can be confirmed with video camera images over the computer network. Any problems detected by an observation control workstation or a monitoring workstation are reported to the central control workstations and such events are logged in a file and sent over the network to pre-registered e-mail addresses to notify the designated persons in charge that there is a problem. Observation programs on the observation control workstations are executed by commands from two central control workstations. These two commands are issued at different times with a certain arbitrarily-chosen interval between them. Usually case, the first command starts the observations at all four sites, and the second command is ignored. However, if the first command fails to reach the observation control workstation at any station for some reason, then the second command becomes effective and prevents the experiment from failing as a result of an unexpected situation.

After all the observations in an experiment are finished, observation log files are transferred and merged with other data files on the monitoring workstation at each site. The merged log files are then used in the data correlation processing and when the database files are created. Before the experiment, the central control workstations perform check routines at all four stations to examine whether the observation tapes are ready. If any of the observation tapes are not properly set in the tape changer unit or have a problem, an e-mail message is sent to the responsible persons to inform them that the station is not ready for the observations. The tapes to be used in the experiment are specified in a master control file stored on each central control workstation. The central control workstations interpret the master control file to determine which stations will participate in the next experiment and which tapes should be used at each station. The master control file is updated every month automatically so that regular experiments can be done without human interaction. The master control file can also be modified at any time by an operator on a central control workstation in order to change the participating stations and tapes to be used. Every time the file is modified, the master control file is sent to the other central control workstation to ensure consistency between these files on the two central control workstations.

2.3 Computer network system

At each station, a TCP/IP local area network over Ethernet connects the observation control workstation and the monitoring workstation; at Koganei and Kashima stations, it also connects the central control workstation. Other computers are connected to the same network to acquire data from a GPS receiver and a seismometer. In addition, at Koganei station, correlator units and additional workstations required for the correlation processing and data analysis are connected to the network. An intelligent network bridge is located between the segment for correlators and the segments for other computers to keep the huge amount of correlated data on one side.

All four VLBI stations are connected together by dedicated computer network lines. The configuration of the network system is shown in Fig. 2. Three dedicated computer network lines connect Koganei to Miura, Koganei to Kashima, and Kashima to Tateyama. Since the amount of data traffic on the computer network is not very high and there are no requirements for high-speed responses between the computer systems, a data capacity of 64 kbps is sufficient for the network system. However, the data rate between Kashima and Koganei is doubled to 128 kbps because most of the communications are done by two central control workstation systems at Kashima and Koganei with other workstation systems and therefore the amount of data traffic on this segment is about twice as high as for the other two segments. In addition to the three dedicated computer network lines, Miura and Tateyema stations are connected by a dial-up packet line, which becomes active if one of the three dedicated lines becomes unavailable. This configuration ensures that each station is always reachable from any other station, so observations can be performed as usual unless two or more network lines fail at the same time.

The network is connected to the Internet through the data analysis workstation at Koganei. This workstation has two network interfaces: one is connected to the KSP network and the other is connected to the laboratory network, which is connected to the public

Internet. This workstation acts as a firewall system. Necessary connections between two network segments can be made through the workstation, but unauthorized access to the KSP network from the public Internet is prevented.

The antenna control PC and observation control workstation at each station have parallel data interfaces, which are connected to an Inter-Range Instrument Group (IRIG) time code signal generator of a GPS receiver. The internal clocks of these computer systems are synchronized to the coordinated universal time (UTC) provided by the GPS receiver every day during the observation preparation procedures. The precise time information maintained in the antenna control PC is necessary to accurately point the antenna in the direction of a radio source. The observation control workstation disseminates precise time information by Network Time Protocol (NTP) as a server. The monitoring workstations and central control workstations are configured as NTP clients and the internal clocks of these systems are always synchronized to the UTC.

2.4 Redundant system design concepts

Since the VLBI observation system of the KSP was intended to be as automated as possible, it was designed with a redundant configuration to improve overall reliability. The network system described in the previous section is one example that has been designed with the redundant concept. Each observation control workstation is also accessible via a public telephone line using a modem, and observations can be controlled remotely even if the network connection to the station is unavailable.

The two central control workstation systems at Koganei and Kashima are identical and operate independently of each other. This dual operation guarantees that regular observations can be made at all stations even if one of the central control workstations malfunctions. The combination of redundant designs makes the entire VLBI observation system robust against many possible irregularities. If any one station goes down for any reason, the other three stations can still continue observations because they are accessible from at least one of the central control workstations via the dial-up packet network line. Some of the software components related to automated experiment management are also written with redundant design. For example, the observation schedule file is created two weeks before each experiment and contains all the information necessary to carry out observations and correlation processing of an experiment. In particular, the sequence of radio sources to be observed can not be the same and a schedule file has to be made each time. Whether the file is actually created or not is checked again on the day of the experiment. If the file is not found, it is created at this time. This way, the schedule file can be replaced anytime during the two weeks before the day of the experiment if a special experiment has to be coordinated. Moreover, the risk of the loss of the experiment because the schedule file was not created can be reduced considerably. This kind of redundancy is quite effective for improving the reliability of the automated observation system.

3. Observations

3.1 Optimized observation time

The KSP VLBI system uses relatively small and fast slewing antennas. Each antenna is equipped with low-noise amplifiers for the X- and S-band frequencies that operate without a cryogenic system. Using non-cryogenic receivers reduces the amount of maintenance and the likelihood of system failure but increases the system noise temperature compared with using cryogenic ones. Both the small antenna aperture and the high system noise temperature contribute to reducing the sensitivity of the receiving system, so only strong radio sources have to be selected for the KSP VLBI experiments. To obtain sufficient signal-to-noise ratio (SNR) R within a reasonable correlation integration time T, the necessary flux density $\mathrm{F_s}(\mathrm{Jy})$ of an observation target radio source after a cross correlation can be determined from the relationship,

$$R < \frac{2}{\pi} \cdot \frac{\mathrm{F_s}}{\sqrt{\mathrm{F_1 F_2}}} \sqrt{2BT}, \tag{1}$$

where B is the total frequency width (Hz) and $\mathrm{F_i}(\mathrm{i} = 1, 2)$ are SEFDs (Jy) of the receiver systems at two stations. The actual SEFD values of the four stations are listed in Table 1. The factor $\frac{2}{\pi}$ is the result of a loss due to the 1-bit sampling digitization error. If we limit the maximum correlation integration time to 320 seconds and minimum SNR to 10, then the minimum flux density of the radio sources with an observation data rate of 64 Mbps is 1.8 Jy in the X-band and 0.57 Jy in the S-band. From the list of radio sources whose positions are known precisely in the International Celestial Reference Frame, 16 strong radio sources that satisfy the requirements were selected. The optimal integration time of cross-correlation processing for each source was then determined to get a sufficient SNR of 20 in both the X- and S-bands for all baselines. The maximum correlation integration time is limited to 320 seconds even if the desired SNR is not obtained and the minimum correlation integration time of 50 seconds is maintained.

To determine an adequate observation time for the target radio sources, a certain amount of time required to synchronize data in correlation processing should be added to the optimized integration time. Fig. 3 shows the distribution of the data synchronization times for two data rates and two observation modes. It reveals a clear difference in the data synchronization times between tape-based and real-time VLBI modes. In the real-time VLBI mode, the data synchronization time is about 10 seconds for data rates of both 256 and 64 Mbps, and more than 95% of the data were less than 12 seconds. In the tape-based VLBI mode, however, data synchronization is achieved by adjusting the data reproducing timing mechanically which takes longer than data synchronization using data buffers as is done in the real-time VLBI mode. The distribution of time required to perform data synchronization in this case has a peak at about 30 seconds, and it takes 40 seconds to cover 95% of all the data. The observation time for each radio source was determined by adding the correlation integration time determined from the SNR requirements and the data synchronization time, which is 12 seconds for the real-time VLBI mode and 40 seconds for the tape-based VLBI mode. The results are shown in Table 2. The maximum number of observations in one experiment is achieved at a data rate of 256 Mbps in real-time VLBI mode. In a typical experiment with a duration of 24 hours, about 600 observations are possible at 256 Mbps in real-time VLBI mode, compared to only about 380 at 64 Mbps in tape-based VLBI mode. The uncertainties of the estimated site coordinates are proportional to the inverse of the square-root of the number of observations if the signal-to-noise ratio is maintained and each measurement can be regarded as independent of other observations. Therefore, making observations at 256 Mbps in real-time VLBI mode instead of at 64 Mbps in tape-based VLBI mode should improve the final results by about 26%. However, the actual improvements were not as good as expected probably because the measurement errors can not be regarded as white noise.

3.2 Optimized channel frequency assignments

The KSP VLBI observation system can perform observations with 16 video channels. Ten channels are assigned for the X-band and the other six for the S-band. The frequency assignments of observation channels were determined to achieve a wide equivalent frequency width after bandwidth synthesis processing while the side-lobe peak height of the bandwidth synthesis function was kept small. Table 3 shows the frequency assignments used at present. The phase calibration signal is injected into the received signal at 5-MHz-frequency intervals, and the local frequency of each channel is chosen to have the phase calibration signal at 10 kHz.

3.3 Automated VLBI Observations

In both tape-based and real-time VLBI experiments, the observations at four stations are performed without any operators. First, the observation schedule file is created by the software SKED using its AutoSKED capability. This software has been developed by NASA's Goddard Space Flight Center and can produce an optimized observation schedule automatically.(3) The software is run by a clock daemon (cron) process of a Unix workstation two weeks before the actual observations. The observation schedule file is duplicated and transferred to two central control workstations. For better reliability, the observation schedule for the day is checked by a different cron process. If the schedule file is not actually prepared two weeks in adnance, the schedule file is newly produced at this time. The observation mode and starting and ending times are specified in a parameter file and the observation schedule is produced according to its contents. These parameters can be easily modified using one of the widely available browsers for the World Wide Web (WWW). If a special observation schedule is required temporarily, an operator at Koganei central station can create the schedule file using a WWW browser.

On the day of the experiment, the two central control workstations independently transfer the observation schedule file to the four observation control workstations. Stations to be included in the session are controlled by the master control files on the central control workstations. Then the observation control program on the observation control workstation is started by a command from the central control workstation. Before the first observation is begun, the internal clock of the observation control workstation is synchronized to UTC using the time code generator of a GPS receiver, and then the input interface units of the data acquisition system are synchronized to the internal clock of the observation control workstation. This step is especially important when a leap second is introduced. The frequency settings of the video converter units and the observation data rate of the data acquisition system are properly set according to the information in the observation schedule file. During an experiment, the status of each site is reported to an operator at Koganei central station by e-mail once every hour. After all observations in the experiment are finished, the log files are transferred to the central control workstations and merged with the weather calibration data file, delay calibration data file, and time difference data files for the correlation processing and the following data analysis procedures.

3.4 Regular observations

The first VLBI experiment with the KSP network was performed for 24 hours on August 29, 1994 with the single baseline between Koganei and Kashima. Daily VLBI experiments began on January 31, 1995 with the same baseline. In the daily experiments, observations were usually performed from midnight for about 6 hours. Full network experiments with the four stations started on September 1, 1996 on a daily basis. Table 4 shows how the reliability of the observation system of the KSP VLBI network has improved since full network experiments began in September 1996. The percentage of the number of days in the month in which successful experiments were conducted is shown in the table for each station. Here, an experiment was considered to be successful for a station if the station position could be estimated from the obtained data. As shown in the table, the ratio gradually improved, and all the experiments were successful for every station in February 1997. This demonstrates the reliability of the observation system designed for the KSP VLBI system.

Until September 29, 1997, daily VLBI observations were performed for about 6 hours in night time. From September 30, 1997, the frequency of experiments was reduced from every day to alternate days and the duration of an experiment was extended to 24 hours in the expectation that this would reduce systematic errors in the data analysis results.

4. Concluding remarks

The KSP VLBI observation system has made fully automated observations possible for the first time. The capability of the system has been demonstrated by more than two years of daily 6 hours VLBI experiments followed by more than one year of 24 hours VLBI experiments conducted on alternate days. Such frequent VLBI experiments could not be achieved without the automated observation system. Redundancy in the system has improved the reliability of the entire system. If any trouble occurs in the observation system, the problem can be found remotely and adequate corrective measures can be applied immediately. As a result, the downtime of the system has been minimized.

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Fig. 1. Schematic diagram of the exchange of data between various equipment and the observation control workstation or the monitoring workstation.

Fig. 2. Configuration of the wide area computer network system for the entire KSP VLBI network. The dial-up network line between Miura and Tateyama stations becomes active when one of the other three networks happens to be unavailable. The high-speed (2.4 Gbps) ATM network lines used to transfer observed data in the real-time VLBI mode are not used for the communications between computer systems and are not shown here.

Fig. 3. Data synchronization time for different observation modes and different observation data rates.

Table 1. System equivalent flux density (SEFD) of four VLBI antennas. These values were estimated from a measurement of the 34-m antenna at Kashima and correlated flux results obtained in a joint VLBI experiment with the 34-m antenna station at Kashima and four Key Stone Project stations.

Station	SEFD (X-band)	SEFD (S-band)
Koganei	6180 Jy	3030 Jy
Kashima	5490 Jy	2830 Jy
Miura	10200 Jy	3350 Jy
Tateyama	16500 Jy	3070 Jy
34-m at Kashima	316 Jy	343 Jy

Table 2. Optimized observation times (seconds).

Radio	Real-time VLBI mode		Tape-based VLBI mode	
Sources	256 Mbps	64 Mbps	256 Mbps	64 Mbps
0059+581	332	332	360	360
3C84	62	62	90	90
0420-014	117	222	145	250
0552+398	62	67	90	95
0727-115	126	239	154	267
4C39.25	62	62	90	90
3C273B	62	62	90	90
3C279	62	62	90	90
1308+326	108	204	136	232
1334-127	62	98	90	126
3C345	62	62	90	90
NRAO530	62	62	90	90
1921-293	62	62	90	90
2134+004	62	62	90	90
2145+067	62	94	90	122
3C454.3	62	62	90	90

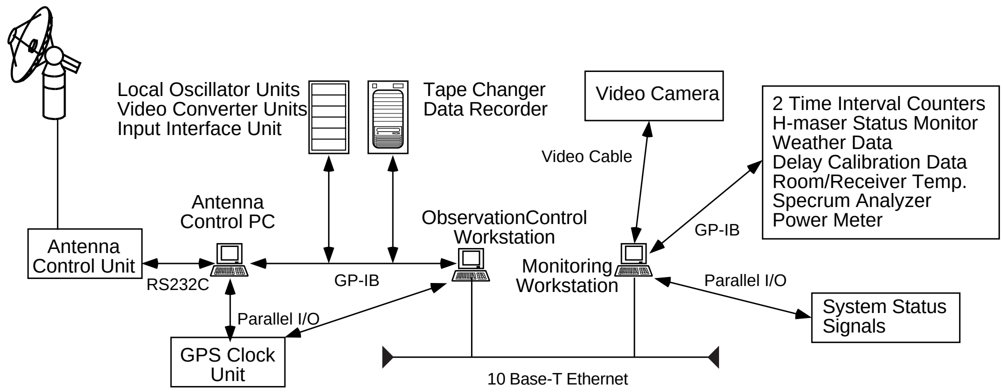
Table 3. Frequency assignments.

X-band		S-band	
Ch. No.	Local Freq. (MHz)	Ch. No.	Local Freq. (MHz)
1	7714.99	11	2154.99
2	7724.99	12	2164.99
3	7754.99	13	2234.99
4	7814.99	14	2294.99
5	8034.99	15	2384.99
6	8234.99	16	2414.99
7	8414.99		
8	8524.99		
9	8564.99		
10	8584.99		

Table 4. Percentage of total number of days in a month in which successful experiments were conducted summarized for every month from September 1996 through March 1997. An experiment was considered successful for a specific station if the station coordinate was estimated or used as a reference in the data analysis.

		Koganei	Kashima	Miura	Tateyama
1996	September	96.7	96.7	83.3	93.3
	October	96.8	93.5	96.8	93.5
	November	93.3	80.0	93.3	83.3
	December	96.8	90.3	100.0	100.0
1997	January	90.3	96.8	100.0	100.0
	February	100.0	100.0	100.0	100.0
	March	90.9	100.0	100.0	86.4

Fig. 1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Video Converter Units
Input Interface Unit
Tape Changer
Data Recorder
Video Camera
2 Time Interval Counters
H-maser Status Monitor
Weather Data
Delay Calibration Data
Room/Receiver Temp.
Specrum Analyzer
Power Meter
Video Cable
GP-IB
Antenna
Control PC
ObservationControl
Workstation
Antenna
Control Unit
RS232C
GP-IB
Monitoring
Workstation
Parallel I/O
System Status
Signals
Parallel I/O
GPS Clock
Unit
10 Base-T Ethernet

Fig. 2

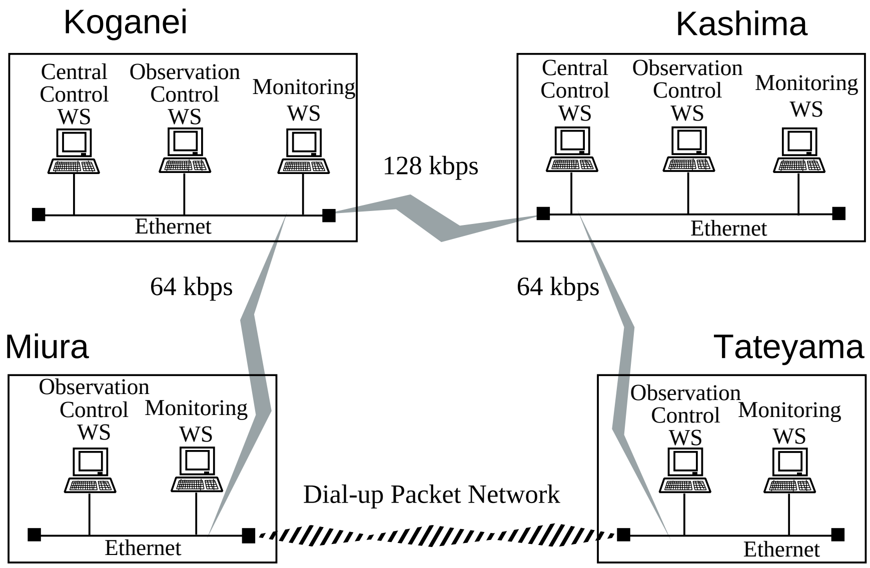
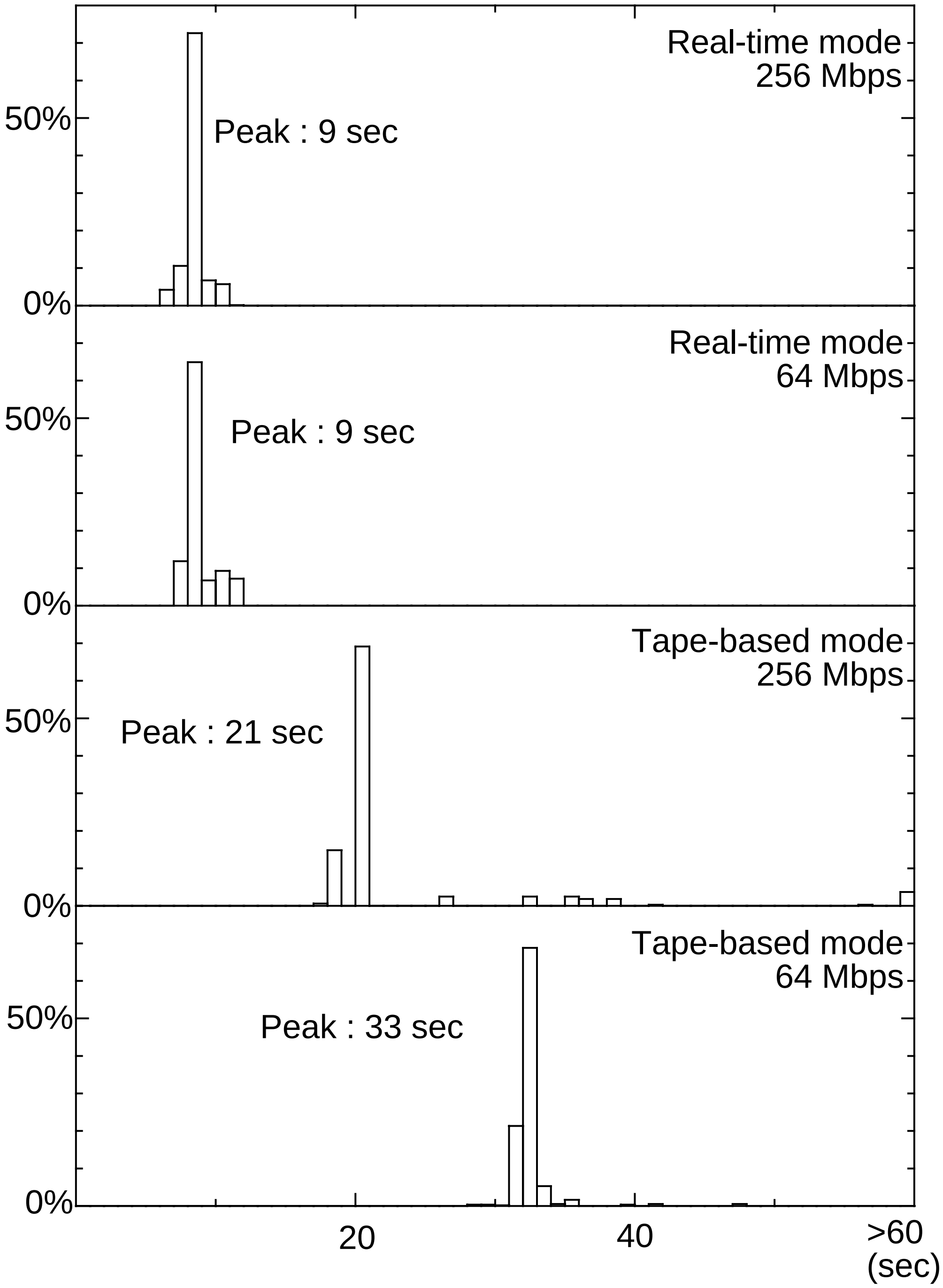

Koganei
Central Control WS
Observation Control WS
Monitoring WS
Ethernet
Kashima
Central Control WS
Observation Control WS
Monitoring WS
Ethernet
128 kbps
64 kbps
64 kbps
Miura
Observation Control WS
Monitoring WS
Ethernet
Tateyama
Observation Control WS
Monitoring WS
Ethernet
Dial-up Packet Network

Fig. 3


Real-time mode
256 Mbps
Peak : 9 sec
Real-time mode
64 Mbps
Peak : 9 sec
Tape-based mode
256 Mbps
Peak : 21 sec
Tape-based mode
64 Mbps
Peak : 33 sec
50%
0%
20
40
>60
(sec)