5-2 Research and Developments for e-VLBI Utilizing Global High Speed Network Connections

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Rapid developments of the Information and Communications Technology have been so remarkable and as the results it is becoming possible to transfer enormous amount of data over long distances which could not be considered before. It is not only causing many and large innovations in social life styles and economic activities, but also various and variety of applications are expected to be realized in the field of scientific research and developments. The main theme of this paper, e-VLBI, can be said as a typical example of such applications which requires high speed network. To realize e-VLBI, it is necessary to transfer enormous amount of data between many sites around the world, and it requires effective usage of the network and calculation resources by using multi-cast and distributed computing to realize high speed computing upon high volume of digital data arising from multiple places in the global scale. Therefore, e-VLBI is considered as a unique and quite suitable theme for network technology research and developments. Solving problems and fulfilling unique requirements which e-VLBI presents, we are expecting that it will accelerate further progress for the network technology.

Keywords
Very Long Baseline Interferometry, e-VLBI, Space geodesy, Radio astronomy, High speed network application

1 Introduction

Very Long Baseline Interferometry (VLBI) observation technology applies the principles of interferometry to celestial radio signals received by multiple radio telescopes, enabling high-resolution imaging of celestial radio sources received by multiple radio telescopes and high-precision determination of the time delay between received signals. Figure 1 shows a photograph of a radio telescope with an aperture of 34 meters, located at the Kashima Space Research Center. Large radio telescopes of similar dimensions located around the world are linked to carry out international VLBI observations for a variety of purposes. Although each radio telescope features relatively coarse resolution, limiting its ability to obtain a brightness distribution for a given celestial radio source, the formation of an array of multiple telescopes spaced far apart can provide resolution corresponding to a telescope with an aperture comparable to the distance between two telescopes in the array. This allows for imaging of celestial bodies at resolutions surpassing those of the Hubble Space Telescope or large ground-based optical telescopes.

Furthermore, it is possible to construct a terrestrial reference frame and a celestial reference frame and to make high-precision measurements of earth orientation parameters by

Fig.1 Radio telescope with an aperture of 34 meters in diameter, located at the Kashima Space Research Center (Kashima City, Ibaraki Prefecture)

analyzing VLBI observation data, since the time delay between the received signals are expressed as functions of the relative positions of the reference points of each radio telescope, the position of the celestial radio source, and the earth orientation parameters which describe the direction of the earth's rotational axis and variations in rotation velocity. These parameters include precession and nutation, which represent the direction of the earth's rotational axis in the celestial reference frame; polar motion, which represents the inclination of the earth's rotational axis in the terrestrial reference frame, and universal time (UT1), defined by the earth's rotation (Fig. 2). These parameters constantly display irregular variations resulting from the gravity of bodies in the solar system acting on the earth, the motions of the atmosphere and ocean, and the fluid motions in the earth's interior. In contrast to the terrestrial reference frame constructed by combining the data obtained by space geodetic techniques such as the VLBI, GPS (Global Positioning System), and SLR (Satellite Laser Ranging), the celestial reference frame is constructed by combining the positions of celestial radio sources measured by VLBI. Therefore, VLBI is the only choice for direct high-precision measurements of all earth orientation parameters describing the rotation between the terrestrial and celestial reference frames. However, in past international VLBI observations, observation data had to be recorded on magnetic tapes and transported to facilities (correlators) for correlation processing of the observation data stored in magnetic-tape format. Thus, several days to weeks were required before the results of the processing and analysis of observation data became available, and applications requiring real-time earth orientation parameters had to use values predicted by extrapolation of past observation data, which led to inevitable errors in measurement.

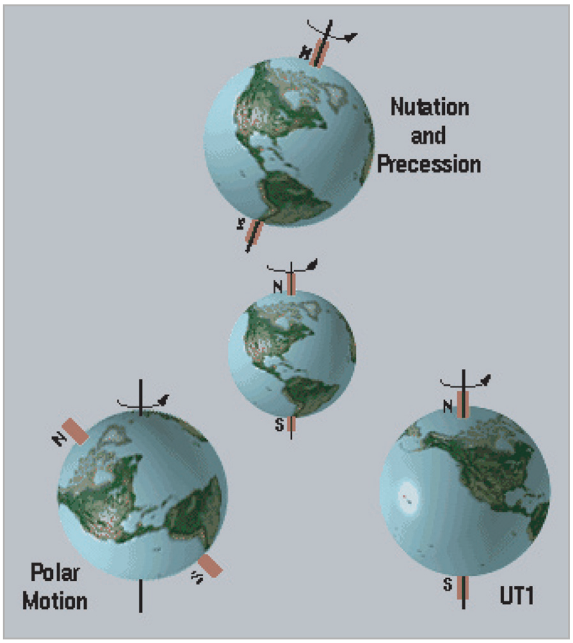

Fig.2 Earth orientation parameters

The term e-VLBI has recently arisen to describe a system that uses high-speed network connections to transmit observation data electronically to correlators, reducing the time required for data processing and analysis relative to existing VLBI observations. With the near-real-time processing of VLBI observation data enabled by e-VLBI, high-precision estimation of the irregular variations of earth orientation parameters becomes theoretically possible, which in turn can lead to improved precision in tracking deep-space probes and more precise determination of the satellite orbital information required for high-precision GPS measurements. These developments are expected to make a significant overall contribution to the fields of space exploration and geodesy. With VLBI, it is necessary to enhance the signal-to-noise ratio by employing as broad a frequency band as possible in order to detect extremely weak signals. Thus, the observed analog data must be converted into digital data and processed as rapidly as possible. Increasing the data-sampling rate is expected to prove particularly effective for VLBI observations in radio astronomy, since this will enable observations of weak radio bodies previously inaccessible to researchers due to the limited data-recording rate of magnetic data recorders used in conventional VLBI observations. Recent R&D in network technology have resulted in an environment in which the network data-transmission rate far exceeds the data-recording rate of magnetic tape recorders (typically 1,024 Mbps). Therefore, significant improvement in the sensitivity of VLBI observation can be expected if real-time correlation processing of observation data can be performed without the magnetic tape-recording procedure; this in turn would drastically reduce the minimum value of observable radio-source intensity. Such a leap in sensitivity would enable the observation of weak celestial radio sources (such as the thermal radio emissions of stars) otherwise impossible with existing VLBI technology; in short, these developments would together represent a breakthrough in radio astronomy.

Nevertheless, technical problems remain in high-speed transmission of massive volumes of data over the Internet—for example, the data collected by the international VLBI experiment carried out in March 2004, which totaled approximately 18 TBytes for five observation stations situated in different countries throughout the world. Some of these problems form interesting themes for R&D in network technology, with topics including maximizing use of available data-transmission capacity in the presence of other types of traffic or effective congestion control in the event of significant network transmission delay. Accordingly, numerous researchers are currently focusing concerted efforts on these and similar challenges.

2 History of e-VLBI

If the term e-VLBI is not limited strictly to a form using high-speed networks but instead is broadened to include all systems for the electronic transmission of data observed by the VLBI, then the first experiment in e-VLBI can be dated back to 1976. In that experiment, VLBI observations at a data rate of 20 Mbps were carried out at the Algonquin station in Canada and the Greenbank station in the U.S. through linkage of these facilities via satellite[1]. In Japan, real-time VLBI observation was carried out in 1977 by transmitting data at a rate of 4.096 Mbps through a microwave link between the Hiraiso Branch of the Radio Research Laboratories (RRL) (presently the Hiraiso Solar Terrestrial Research Center of the National Institute of Information and Communications Technology (NICT)), and the Kashima Branch of the RRL (presently the Kashima Space Research Center of the NICT)[2]. Although these two experiments were revolutionary at the time, the lack of available high-speed satellite communication links and the rapid progress in digital data recording technologies on magnetic tape that followed made it generally more favorable to record observation data on magnetic tape and to perform the correlation processing after transportation to a correlator facility. Since electronic data transmission technologies were limited to those using satellite communications and public telephone lines offering limited data-transmission rates, electronic transmission was used only to validate observation data in preliminary processing; this approach continued until the recent wide availability of high-speed networks[3]. The Tokyo Metropolitan Wide Area Crustal Deformation Monitoring Project (also known as the Keystone Project, or KSP) launched by the Communications Research Laboratory (the CRL; presently the NICT) represented the first efforts at full-fledged introduction of the e-VLBI. System development for the project had as its goal high-precision, high-frequency measurements of the relative positions of four VLBI stations, and was structured to override the existing framework of VLBI observation systems at several points[4]. One such innovation involved the realization of real-time VLBI observation data processing for the four-station, six-baseline array via an ATM (Asynchronous Transfer Mode) network. In this system, the interface for recording data on magnetic tapes was used as is, and the digital data output from the interface was converted into ATM cells and transmitted from each observation station to a data receptor installed at the Koganei Correlator. On the receiving side, the data was fed to the correlator via a buffer unit to absorb the difference in network transmission delay among the stations, followed by real-time correlation processing. This system, developed under the auspices of collaboration between CRL and NTT Communications, Inc., dramatically reduced the time required for data processing relative to existing systems, which relied on magnetic tape recording. Further, this was the first system of its kind to be completely automated—from observation to data processing and analysis—with the results of analysis of nearly non-stop VLBI observation automatically available to the public on the Internet[5]. The development of this system proved that e-VLBI technology could enable near-real-time data processing with virtually no delay between observation and processing.

3 Development of the K5 observation and processing system

In the KSP, a real-time VLBI observation processing system was developed using an ATM network featuring a data-transmission rate of 2.4 Gbps; continuous real-time VLBI observation was realized in 1998 for the four-station, six-baseline array. However, this observation and processing system dedicatedly used an ATM network. As such, the system could not be used to connect multiple VLBI stations throughout the world since it was not feasible to construct an international dedicated ATM network just for e-VLBI. To increase the versatility of this system, development of the K5 observation and processing system began in 2000, eventually resolving earlier problems by enabling data transmission via IP (Internet Protocol), under Internet network conditions involving the presence of other types of traffic. Figure 3 shows the data sampling board developed for the K5 system and Fig. 4 shows a photograph of the K5 observation and processing system now being put to initial use in a variety of observations.

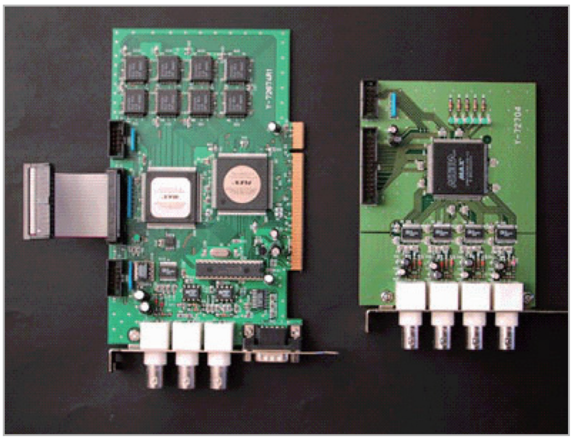

Fig.3 Data sampling board developed for the K5 system

The prototype K5 system for geodetic VLBI observations consists of four PC units operating on FreeBSD or LINUX; each PC system is equipped with a data-sampling board that can sample signals in four channels. The sampled data is recorded on the internal hard disk and may also be transmitted in real time via IP network interface. The K5 system is being developed to process data stored on the hard disk as well as data received in real time through the network, such that it should eventually be possible to form a system accommodating both near-real-time VLBI data processing (in which observed data is transmitted before processing) and real-time VLBI data processing. The data-sampling board uses a highly stable reference frequency signal and a time-pulse signal per second; both of the signals are provided by a hydrogen

Fig.4 K5 VLBI observation and processing system, currently in use in various observations

maser, recording a precise time stamp in the header of the data file and maintaining accuracy of phase information corresponding to the received signal. One of the features of this board is that the sampling rate (from 16 MHz to 20 kHz) and the quantization number (selectable from 1, 2, 4, and 8 bits) may be selected according to the target and purpose of observation. Since existing VLBI systems attempted to improve the S/N ratio by maximizing the data rate of the magnetic tape-recording process, the quantization number was limited to 1 bit or to a choice between 1 and 2 bits, while the K5 system allows multi-bit quantization of up to 8 bits, enabling more accurate recording of waveforms. This feature renders the K5 system suitable not only for e-VLBI applications but also in a range of fields of scientific instrumentation requiring sampling based on an accurate and stable time system.

In contrast to the real-time correlation-processing unit developed for the KSP, which realized high-speed digital data processing through the use of the FPGA (Field Programmable Gate Array), a software correlator has been developed for the K5 system to perform distributed processing using a PC running on a versatile operating system. While a hardware correlator lacks flexibility due to the extended required development time, a software correlator may be modified flexibly to add new functions or to revise processing modes. In addition, development is also underway of software required to enable distributed processing using available computer resources (consisting of multiple CPUs) to the maximum extent, in order to provide the needed processing capacity for data collected at numerous VLBI stations in the context of large-scale VLBI experiments (Fig. 5).

4 UT1 estimation experiment

Using the K5 observation and processing system described in the previous section, test observations began in 2003 for rapid estimation of UT1 using the Kashima 34-m station and the Westford 18-m station at the Haystack Observatory of the Massachusetts Institute of Technology[6]. Unlike other earth orientation parameters, UT1 can be estimated from observations as brief as one hour in duration. Further, as only one baseline is required for estimation, this method is extremely suitable for obtaining rapid analysis results via e-VLBI. Observation at the Westford station was performed using the Mark-V observation system[7] developed mainly by the Haystack Observatory, while the Kashima station employed the K5 system. Like the K5 system, the Mark-V system is designed to store observation data on hard disks using a commodity PC and can also perform real-time data transmission via the Internet. The input for the system is output from a unit referred to as the Mark-IV formatter, which allows observation data to be divided and stored on multiple hard disks. In an experiment conducted on June 30, 2004, multiple data files collected over the course of one hour of observation from 4:00 to 5:00 a.m. (JST) at the Westford station were

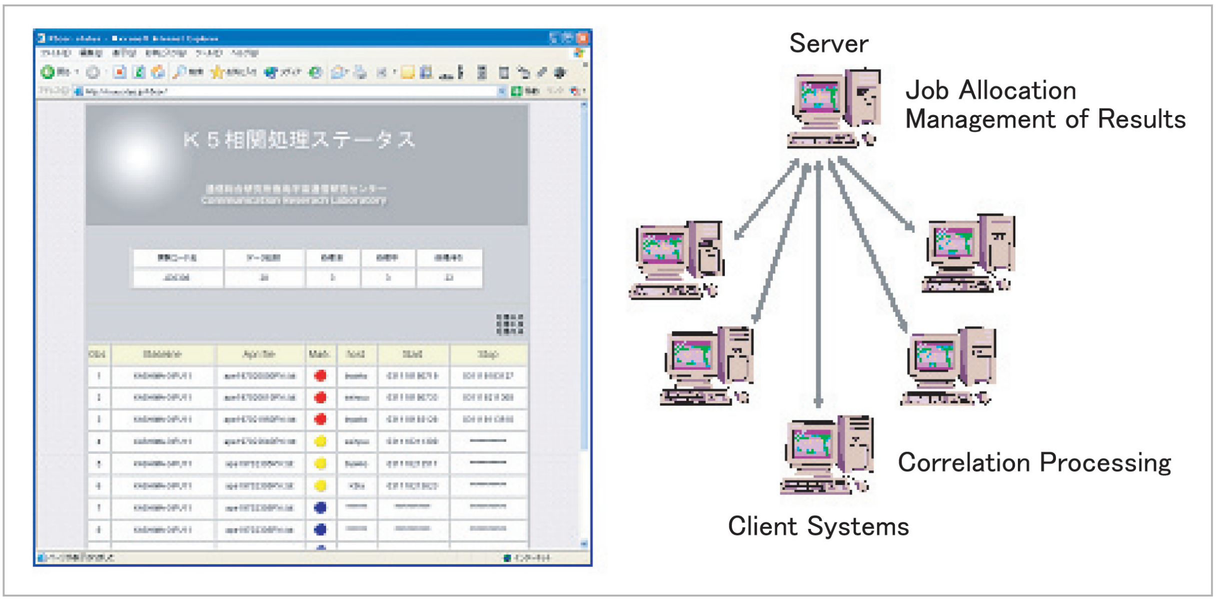

Fig.5 *Scheme for distributed processing (right) and a control screen for distributed processing under development (left)*

sent to the Kashima Space Research Center via a high-speed research-dedicated Internet network. Figures 6 and 7 show the network connections used for file transmission. Inside the U.S., the Abilene network managed by Internet2 was used as the backbone, and the connection from the Westford station to Abilene was performed through two networks, BOSSNET and GLOWNET. The Kashima station established connections to the Otemachi access point using the JGNII, which began operations in April 2004, and from there was connected to the Abilene network in the U.S. via the JGNII /TransPAC network.

Immediately after observations were complete, transmission of approximately 13.5 GBytes of data was initiated, ending 1 hour and 15 minutes later. Thus, the average transmission rate was calculated at approximately 24 Mbps. The transmitted data file was converted into K5-system data-file format and correlation processing was performed by distributed correlation-processing software within the K5 system using a total of 21 CPUs. After correlation processing, database files were created and the data were analyzed using the geodetic VLBI data analysis software programs SOLVE and CALC. As a result of these operations, we succeeded in estimating the UT1 approximately 4 hours and 30 minutes after observation, as opposed to the minimum of one-week period previously required, demonstrating that the use of a high-speed Internet can dramatically reduce the time required to obtain data-processing results.

5 Conclusions

The UT1 estimation experiment conducted by the Westford and Kashima stations resulted in the gradual reduction of the time required for UT1 estimation; this was accomplished by improving the processing rate of the software program for correlation processing, developing software for efficient distributed processing, and automation of the procedures involved. In the future we plan to continue with similar test observations and to develop related software, in addition to increased efforts at reducing processing time—by investigating effective methods to use the available bandwidth of the network under various conditions of the shared network and further automation of the processing system. We are also pursuing methods of establishing a standard data-transmission format, which will

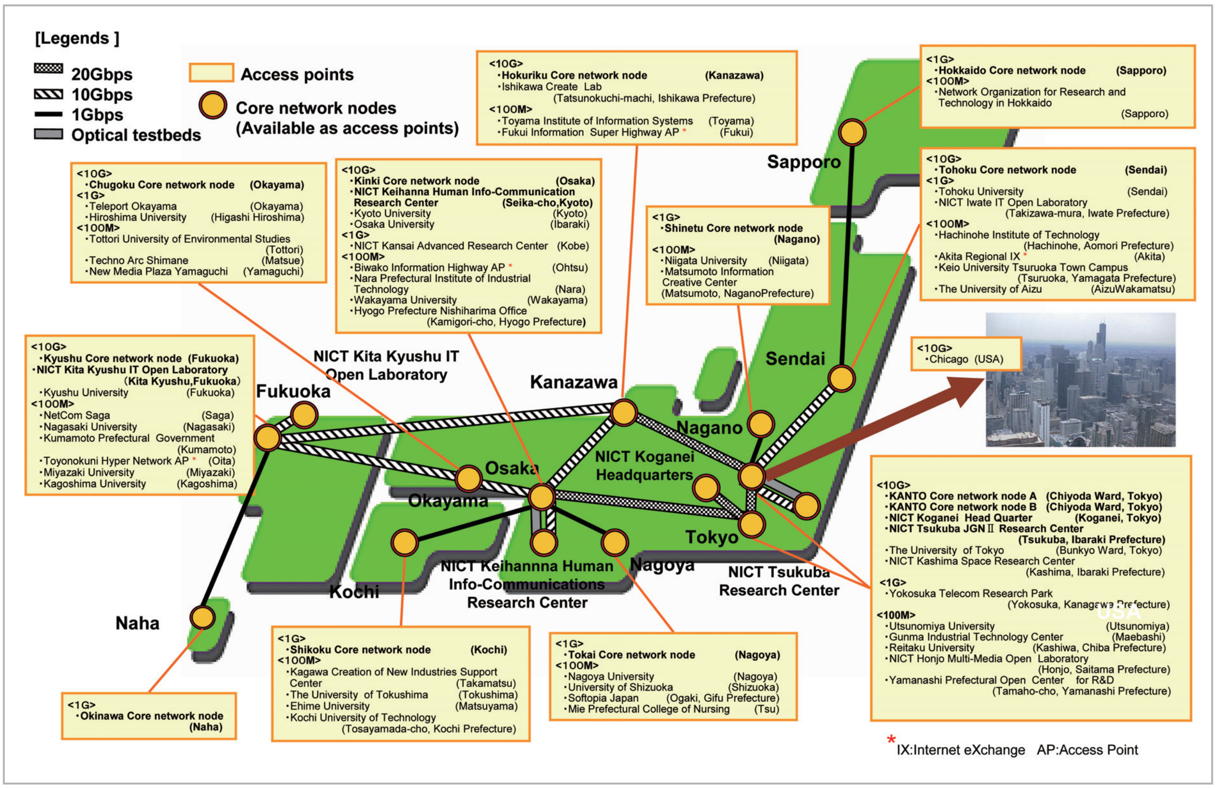

Fig.6 Structure of the JGNⅡ network (from the website of JGNⅡ)

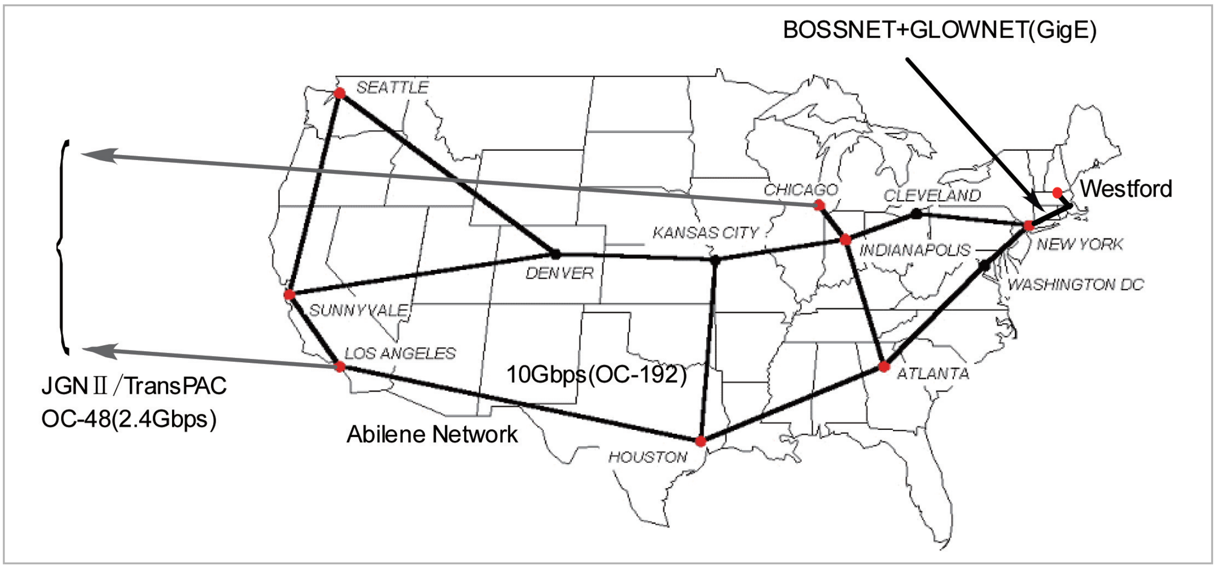

Fig.7 Network connections from the Abilene network to the Westford station

reduce the time required to convert the various file formats of the different observation systems. Our goal is to enable estimation of all earth orientation parameters, not only UT1, instantaneously after observation through the development of a real-time correlator system offering increased processing speed, allowing observation data to be transmitted in real time, and through correlation processing that does not require prior hard-disk storage. To accomplish this goal, technologies must be established for high-speed transmission of wideband e-VLBI observation data over extremely long distances between points featuring large time delays. Thus, it is important to promote research on the application of a research-dedicated high-speed Internet to studies on scientific instrumentation such as advanced congestion-control technologies, and dynamic control technologies to ensure efficient use of transmission bandwidth in these applications without inhibiting concurrent network traffic. Additional associated themes for future R&D include the development of a system for distributed and time-sharing processing of observation data to maximize use of available computer resources as well as the development of a distributed multicast processing system capable of sending identical sets of data to multiple CPUs for distributed processing, in order to perform large-scale e-VLBI experiments (where multiple stations perform observations at the same time). Such R&D efforts are ultimately expected to produce new technologies not only useful in e-VBLI development, but also in the application of research-dedicated high-speed networks to various fields of scientific instrumentation and further areas of R&D.

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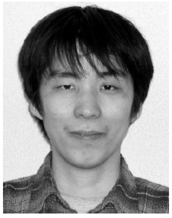

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