Ultra-Rapid UT1 Experiment Using e-VLBI Technique

Shinobu KURIHARA and Kensuke KOKADO

Abstract

Very Long Baseline Interferometry (VLBI) is a space geodetic technique by which Earth orientation parameters (EOP) can be measured. The Tsukuba 32-m VLBI station of the Geographical Survey Institute has been involved in intensive VLBI sessions scheduled by the International VLBI service for Geodesy and Astrometry (IVS) every weekend for measuring the UT1(Universal Time 1), which is an element of an EOP series. In recent years, the latency of UT1 measurement performed by VLBI has been reduced by adopting electronic VLBI (e-VLBI) technology. At the Tsukuba 32-m station, an ultra-rapid UT1 experiment has been performed in collaboration with the Kashima, Onsala, and Metsähovi VLBI stations since 2007 to obtain UT1 results within 30 min of the end of observation sessions. We have shortened the latency of UT1 measurement by carrying out real-time data transfer, automatic data conversion, and correlation processing during the observation session, and we succeeded in obtaining the UT1 result 3 min 45 sec after the end of the session. We plan to introduce the newly developed technology in regular intensive VLBI sessions and 24-h VLBI sessions, and we aim to obtain the UT1 results within 30 min of the end of the session. It is expected that our technique can help improve the accuracy of UT1 data published by the International Earth Rotation and Reference Systems Service (IERS).

1. Introduction

At the Tsukuba 32-m Very Long Baseline Interferometry (VLBI) station, 24-h and 1-h international VLBI sessions known as “Intensive2 (INT2) sessions” are held once a week and on weekends (Saturdays and Sundays), respectively. In these sessions scheduled by the International VLBI Service for Geodesy and Astrometry (IVS), Earth orientation parameters (EOP) such as the earth’s polar motion and UT1 can be determined. EOP results obtained by VLBI techniques can be updated on a daily basis as new VLBI data become available and can be used individually or combined with contributed analysis results that have been obtained using data collected by other techniques, such as the Global Navigation Satellite System (GNSS) and Satellite Laser Ranging (SLR).

UT1 is proportional to the true rotation angle of Earth with respect to the International Celestial Reference Frame (ICRF), whose axis directions are fixed relative to the distant matter in the universe. Therefore, UT1 can be determined only by astronomical observation of extragalactic objects. VLBI is an advanced geodetic technique by which differences in the arrival time between extragalactic radio signals corresponding to pairs of parabolic antennas can be accurately measured. The geometrical VLBI delay model is theoretically based on terrestrial time (TT), while in practice, Universal Time Coordinated (UTC) is used as the time argument for computing the observation epoch in the TT. Using VLBI, the earth’s angle of rotation can be measured with respect to UTC, which corresponds to the value of UT1-UTC. Currently, VLBI is the only space-geodetic technique by which the UT1-UTC can be monitored with long-term stability; the UT1 obtained from periodic VLBI observations helps correlate the Celestial Reference Frame (CRF) to the Terrestrial Reference Frame (TRF).

Since 1985, a series of single-baseline special VLBI sessions known as “intensive sessions” has been conducted by IVS and its predecessor. Single-baseline “intensive sessions” are continuously carried out with the aim of observing UT1 with minimum latency and measuring one value of UT1-UTC daily. In the early years of the sessions, the data were recorded on magnetic media and transmitted to the correlator as data parcels. Subsequently, in the sessions after 2004, data transfer was carried out over broadband networks by using FTP, and this improved the latency. Currently, the minimum latency in the intensive sessions is approximately 3 h. This reduction of the latency has resulted in an improvement in the prediction accuracy of the UT1-UTC solutions by 20–47%.

The goal of our experiment is to obtain UT1 results within the shortest possible time by adopting the e-VLBI technique. The e-VLBI technique developed in this experiment will be regularly introduced in the intensive sessions and is expected to contribute to an improvement in the accuracy of the UT1 data. In this paper, the technical details and results of ultra-rapid UT1 experiments are reported.

2. Current UT1 measurements

2.1 UT1 measurements and predicted UT1 value

Several agencies that serve as analysis centers for space geodetic techniques (VLBI, SLR, and GPS) regularly determine EOP series and submit them to the International Earth Rotation and Reference Systems Service (IERS). The IERS combines various EOP series and publishes the combined EOP in IERS Bulletin-B every month. These data cover the epoch up to one month before the date of issue. Users who require the EOP data during the current or future epochs can obtain the EOP values predicted for the forthcoming year from IERS Bulletin-A, which is published every week. However, currently, prediction of EOP values with sufficient accuracy is difficult. Rapid combined solutions (Rapid-Service) are also published weekly to compensate for the poor accuracy of the predicted EOP values published in Bulletin-A and the latency of the results published in Bulletin-B. These solutions are derived by combining the latest EOP solutions with data obtained by VLBI, SLR, and GPS. Thus, a short latency of the UT1 measurements obtained by VLBI can contribute to the improvement of Rapid-Service.

Table 1 IVS Intensive sessions and ultra-rapid session

Session name	Mode of data transmission	Processing time	Stations	Correlator
INT1	Shipment	3–5 days	Kokee Wettzell	Washington
INT2	Fiber network (BBFTP)	1–3 days	Tsukuba Wettzell	Tsukuba
INT3	Fiber network (TSUNAMI)	<1 day	Wettzell Tsukuba NyÅlesund	Bonn (Germany)
Ultra-rapid UT1	Fiber network (Real-time transfer)	<30 min	Tsukuba Kashima Onsala Metsähovi	Tsukuba Kashima

2.2 IVS Intensive Sessions

The 1-h intensive sessions mentioned previously have been conducted on several baselines since 1985. Currently, these sessions are carried out on three baselines. The first session is known as the “Intensive1 (INT1) session,” and it is conducted on the Kokee (Hawaii, United States)–Wettzell (Germany) baseline from Monday to Friday. The magnetic disk media containing the VLBI data obtained at Kokee station are transported to the Washington correlator by air; therefore, the latency is around 3–5 days. The second session, known as the “Intensive2 (INT2) session,” is conducted on the Wettzell–Tsukuba baseline on Saturdays and Sundays. In this session, the latency is around 1–2 days, as the data are transferred to the Tsukuba correlator via a high-speed network and correlated on Monday. The third session is known as the “Intensive3 (INT3) session” and is conducted on the Wettzell–Tsukuba–NyÅlesund (Norway) baseline. The data obtained during this session are transferred with at the maximum possible rate to the Bonn correlator at the end of the observation session. Therefore, the latency is around 3 h to 1 day. Table 1 lists the details on the 1-h intensive sessions and the ultra-rapid session.

In the regular intensive sessions, data transfer and correlation processing are carried out at the end of the observation session. The latency is expected to decrease if real-time data transfer is carried out and an automatic correlation system is introduced in the sessions.

3. Details of the e-VLBI technique

E-VLBI stands for electronic VLBI, where VLBI antennas and correlators are optically linked for real-time or near-real-time data transfer. The e-VLBI technique has become popular because of recent advancements in network technology and infrastructure. One of the key factors in enabling the high-speed transfer of VLBI data is the choice of the data transfer protocol. The data rate during general VLBI observation is more than 128 Mbps, and the total amount of data at each station is more than 1 TB.

From 2005 to 2007, a TCP/IP-based file transfer software known as BBFTB was used at the Tsukuba 32-m station. TCP/IP is a protocol to guarantee reliable data transfer over a network. However, a drawback of TCP/IP is the decrease in data-transfer rate over a long-distance network. In fact, the maximum data-transfer rate between Wettzell and Tsukuba was 30–50 Mbps, which is far less than the data-acquisition rate. Therefore, we decided to use the “Tsunami” protocol.

The UDP/IP-based protocol “Tsunami” was developed by the Advanced Network Management Laboratory of Indiana University as an experimental high-speed network file transfer protocol for data transfer over very long distances. The Metsähovi Radio Observatory (Finland) has used this protocol for real-time data transfer. In this protocol, a data rate of more than 600 Mbps can be achieved in data transfer across several thousand kilometers over a 1-Gbps network.

4. Ultra-rapid UT1 experiment

The purpose of this experiment is to obtain the UT1 result within the shortest possible time. The key factor in enabling the ultra-rapid UT1 measurement is to process the observed data as fast as possible. We have developed some new programs, whose functions include real-time data transfer and automatic data conversion, as well as an automatic correlation and analysis. The technical details of the ultra-rapid UT1 experiment are described in this chapter.

4.1 Specifications of VLBI stations involved in experiments

The VLBI stations involved in the ultra-rapid UT1 experiments are the Tsukuba station of the Geographical Survey Institute (GSI), the Kashima station of the National Institute of Information and Communication Technology (NICT), the Onsala station of the Onsala Space Observatory (OSO) in Sweden, and the Metsähovi station of the Metsähovi Radio Observatory in Finland. The locations of the VLBI stations are indicated in Fig.1.

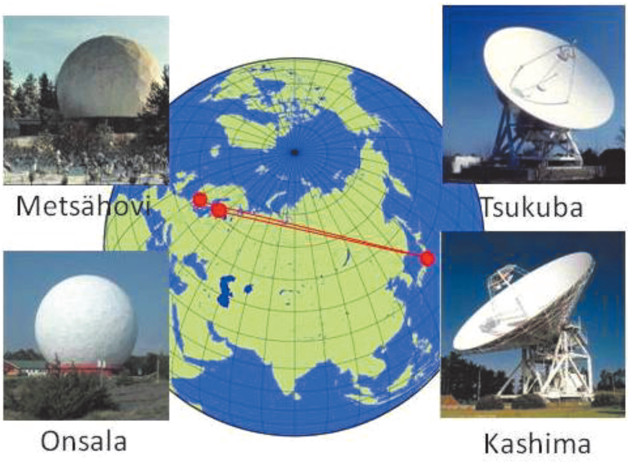

Fig. 1 VLBI stations involved in the ultra-rapid UT1 experiments

The current network speed is 1 Gbps for Kashima, Tsukuba, and Onsala and 10 Gbps for Metsähovi. The Mark 5 VLBI data-acquisition system developed by the Haystack Observatory (Whitney, 2004) is used in the Onsala and the Metsähovi stations. The data captured by Mark 5 are fed to a VSI board (VSIB), which was developed at the Metsähovi observatory (Ritakari and Mujunen, 2004). In the Kashima and Tsukuba stations, the K5/VSSP32 VLBI data acquisition system developed by NICT (Kondo et al., 2006) is used for observation. The main specifications are listed in Table 2.

4.2 Observation scheduling

The precision of the UT1-UTC measurement and its covariance matrix depend on the observation schedule. The schedule is created for each observation session and describes the sequence in which radio sources are observed and the duration of observation for each source. Observation schedules are created by using the automatic schedule generation function of the geodetic VLBI scheduling software “sked.” To obtain precise UT1 results, we have to observe as many radio sources as possible during the observation session. Therefore, the schedules are created by taking into consideration the sensitivity parameter of the antennas and the radio wave strength of the sources. The duration of the observation is 1 h for the IVS regular intensive sessions. Before the beginning of the main session, 30 min are devoted to observation for fringe finding, which is a procedure for fixing the clock parameters by observing the strong radio sources. The clock parameter is the synchronization difference between the atomic clocks at VLBI stations and has to be fixed before correlation processing.

4.3 Data-transfer and processing systems

In the ultra-rapid UT1 experiments, the correlator is located in Kashima or Tsukuba. The total data rate for VLBI observation is 128 Mbps or 256 Mbps. The data transfer from Onsala or Metsähovi station to Japan was carried out in real time during the observation. In the transfer, the data recorded by Mark 5 were fed to VSI board and transmitted to the network in real time. These Mark 5 data are recorded on the transfer server in Japanese stations and automatically converted to the K5/VSSP32 data format after the end of each scan. Correlation processing jobs are shared by a cluster of computers in parallel. The data-format conversion and the correlation processing are performed by using a software package developed by NICT. By using this data-processing system, correlation is completed in a few minutes after the end of the observation session. The data-transfer and processing system is shown in Fig.2.

Table 2 Specifications of each VLBI station

Station name	Diameter	SEFD (Jy)*1		Network speed	VLBI-Data Acquisition System
		X-band	S-band		
Tsukuba 32	32 m	320	360	1 Gbps	K5/VSSP32
Kashima 34	34 m	380	430	1 Gbps	K5/VSSP32
Onsala 60	20 m	1630	1110	1 Gbps	Mark5
Metsähovi	13.7 m	3200	4500	10 Gbps	Mark5

*1: System equivalent flux density (SEFD), expressed in Jy (Jansky), is a non-SI unit of electromagnetic flux density equivalent to 10^{-26} W/m^2·Hz

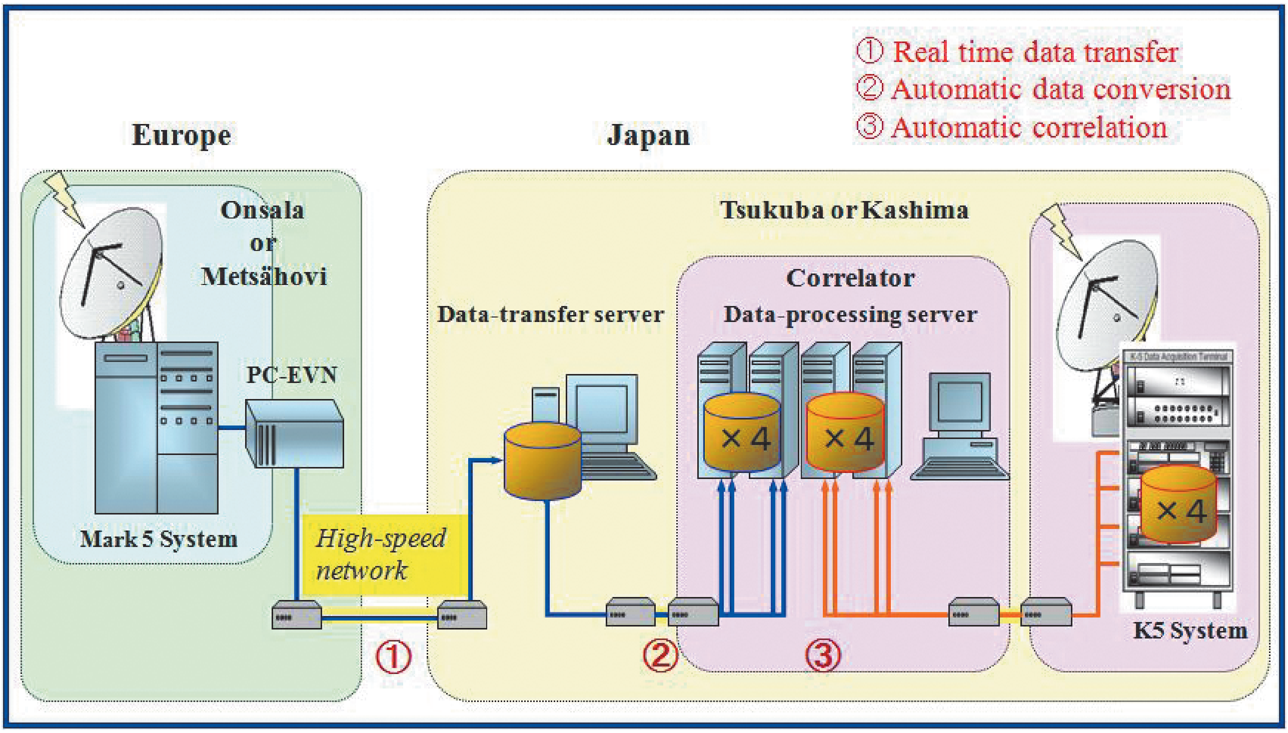

Fig. 2 Data-transfer and processing system for the ultra-rapid UT1 experiments

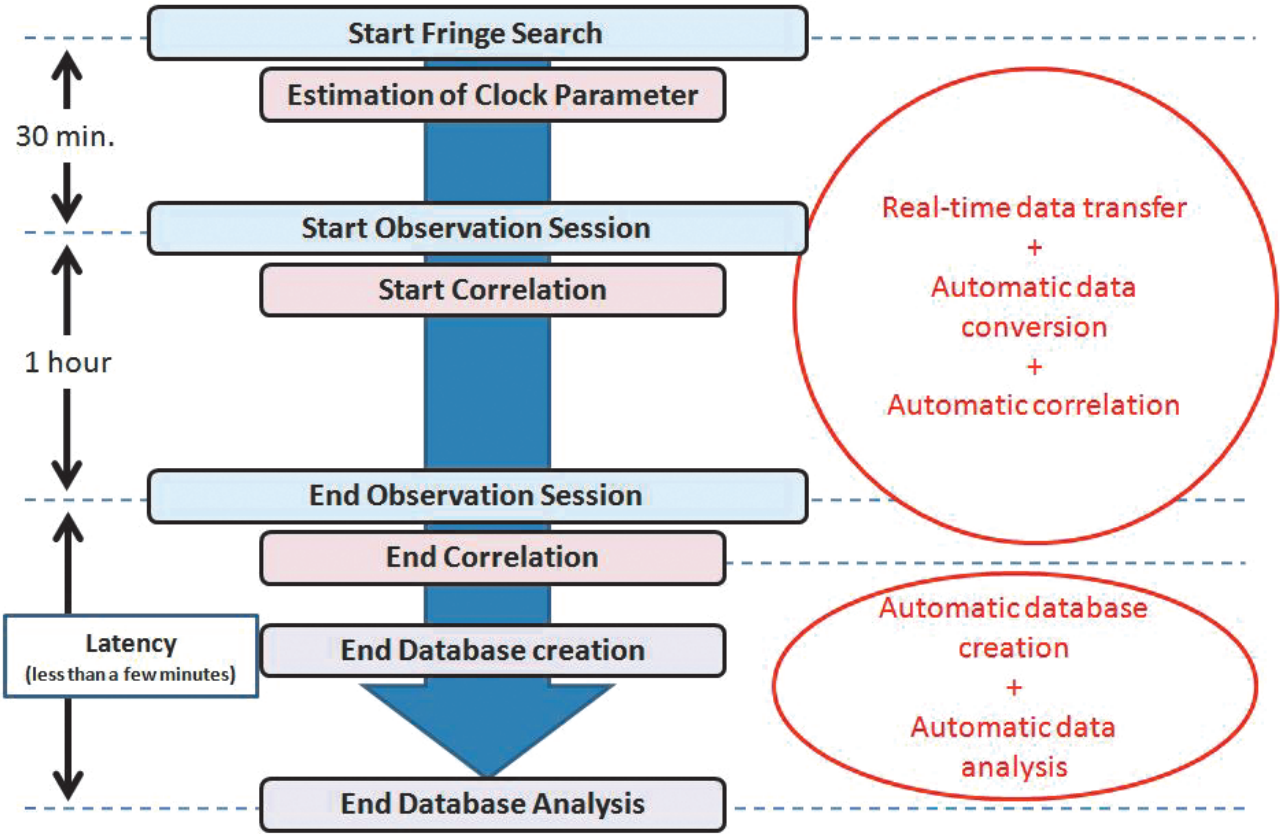

Fig. 3 Typical flow for the ultra-rapid UT1 experiment

4.4 Automatic analysis program

Typically, 20–30 scans are observed in one ultra-rapid UT1 intensive experiment, and the final correlation processing of the last scan is completed within a few minutes of the last observation scan. To obtain the UT1 result as soon as possible, we have to generate the Mark 3 format database for data analysis, and the database should be analyzed automatically and as fast as possible after the correlation processing is complete. However, more than 20 min are required for creating the Mark 3 database and carrying out interactive analysis using the CALC/SOLVE data analysis software, which was developed by the geodetic VLBI group of NASA/GSFC (Petrov, 2007). Therefore, we used the program developed by NICT for automating database creation and analysis.

In this program, a new database based on the Network Common Data Form (NetCDF) architecture has been designed to support both the CALC/SOLVE and OCCAM (Titov et al., 2004) data analysis software improved by the Vienna University of Technology. By using the NetCDF database, it is possible to generate the database files for the CALC/SOLVE and OCCAM software. To obtain the UT1 result, it is necessary to resolve group delay ambiguities caused by bandwidth synthesis processing. The procedure to resolve ambiguities is also automated by integrating the OCCAM data analysis software and scripts used to perform iterative processes for solving ambiguities. Once the ambiguities are resolved, the estimated UT1 result will be sent to the operators by e-mail. The whole processing time is a few minutes. Fig.3 shows the typical flow for the ultra-rapid UT1 experiment.

5. Results of the ultra-rapid UT1 experiments

Our e-VLBI experiments for the ultra-rapid UT1 measurement began in Jul. 2007. We have conducted some observation sessions and found some problems in our newly developed system.

In each session, we changed and improved the programs on the system, and we succeeded in obtaining the UT1 results within 3 min 45 sec of the end of the observation sessions on Feb. 21, 2008, between Onsala and Tsukuba. The latency of the UT1 measurement was remarkably improved in this experiment. In this session, the experimental results and the problems encountered in each experiment are described in Table 3.

Table 3 The results of the ultra-rapid UT1 experiments in which Tsukuba was one of the stations involved

Date	Baseline *1	Success/failure of automatic data processing				UT1 sigma (μs)	Latency *2
		RT Transfer	Conversion	Correlation	Analysis		
14 Jul. 2007	Ts-On	Failure	-------------	-------------	-------------	6.90	-------------
	Kb-On	Failure	-------------	-------------	-------------	10.00	-------------
07 Sep. 2007	Ts-On	Failure	-------------	-------------	-------------	------------	-------------
	Ts-Mh	Success	Failure	-------------	-------------	30.77	-------------
29 Oct. 2007	Ts-On	Success	Success	Failure	-------------	19.47	-------------
22 Nov. 2007	Ts-On	Success	Success	Success	Success	12.86	50 min
22 Feb. 2008	Ts-On	Success	Success	Success	Success	15.00	3 min 45 sec

*1: Station codes are as follows, “Ts”: Tsukuba, “Kb”: Kashima, “On”: Onsala, “Mh”: Metsähovi.

*2: Since the automatic processing environment was not ready in early stage, it took a few days to obtain the analysis result, so the table doesn’t show the latency in the early experiments.

5.1 Details of each UT1 experiment

In the early stages of our experiments, we had to confirm whether the performance of real-time data transfer and the automatic data processing was satisfactory. In the first experiment on Jul. 14, 2007, we attempted simultaneous real-time data transfer from the Onsala station to both the Tsukuba correlator and the Kashima correlator. However, our data transfer was unsatisfactory because the network capacity of the Onsala station was less than expected. Thus, we implemented the data transfer and the correlation processing after the observation session.

In the second experiment, we conducted the observation at Onsala and Metsähovi stations on Sep. 4, 2007. The data observed at the European stations were transferred to the Tsukuba correlator via a high-speed network, but the Onsala data could not be transferred in real time due to the capacity shortage in the Tsukuba network. On the other hand, the Metsähovi data could be transferred to Tsukuba in real time. We carried out automatic data conversion, but the process failed since the program could not read the Metsähovi data because of errors in file naming conventions.

In the third experiment on Oct. 29, 2007, we succeeded in real-time data transfer and automatic data conversion. However, we failed in automatic correlation because of errors in the program setup.

The entire data-processing system worked well in the fourth experiment. We could obtain the UT1 result within 1 h of the end of the observation session. Most of the 1-h delay was devoted to the data-conversion process. Therefore, we upgraded the program to simultaneously convert the data on several servers. At this point, the automatic database creation and analysis program was not yet completely developed, so we manually created and analyzed the database. In the fifth experiment on Feb. 21, 2008, the entire data-processing system was successfully operated. As a result, we could shorten the latency of the UT1 measurement to 3 min 45 sec, though at least one hour or a few hours were required to obtain a solution.

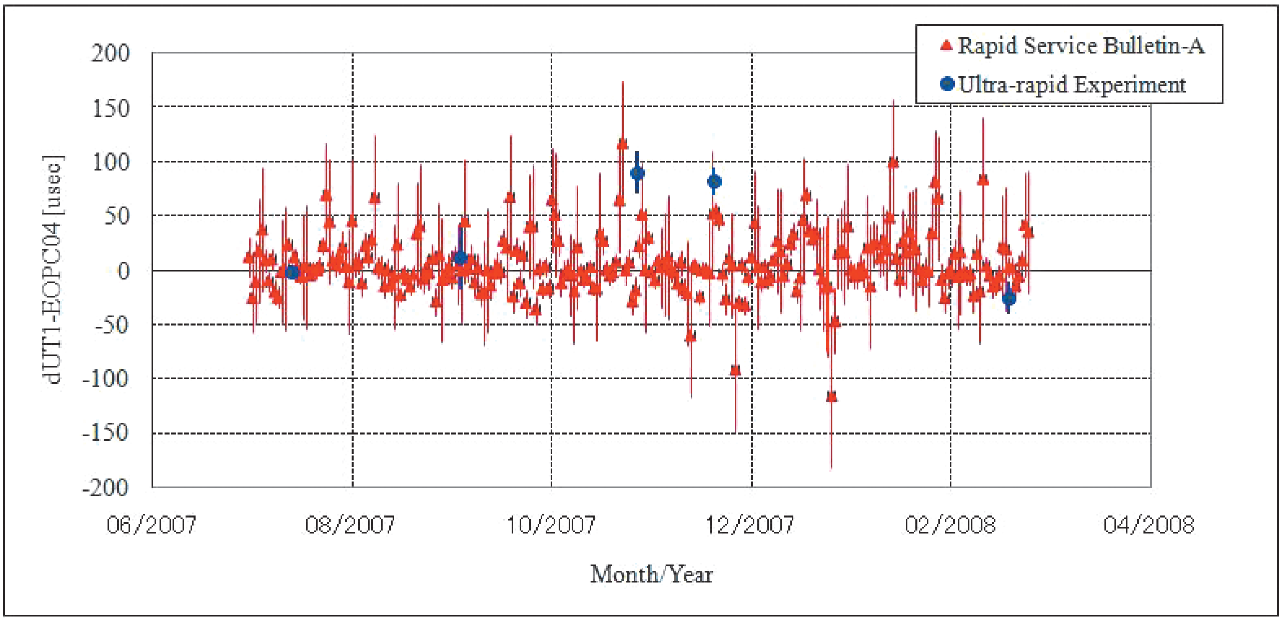

Fig. 4 UT1-UTC data obtained in ultra-rapid UT1 experiments and those reported in the Rapid-Service of Bulletin-A

(These data are plotted after subtraction of the EOPC04 series. The error bars show the formal error for the experiments and uncertainty for the Rapid-Service.)

5.2 Accuracy of UT1 measurement

The UT1-UTC measured in the ultra-rapid experiments and that reported in the Rapid-Service of Bulletin-A are plotted in Fig.4. The standard deviation of the estimated UT1-UTC is approximately a few tens of microseconds. The plot indicates that the accuracy of the UT1-UTC measurement obtained in each ultra-rapid experiment is higher than that of the result reported in the Rapid-Service.

However, the accuracy of the measurements obtained in the ultra-rapid experiment is lower than that of the results obtained in regular UT1 sessions, such as the INT2 session, where the accuracy is less than 10 μs. One possible cause is that the observation schedule is not optimized for UT1 measurement. To prepare the best schedule for UT1 measurement, we have to consider the selection of the radio sources and the conditions with minimum SNR.

6. Future plans

6.1 Increasing data rate in Ultra-rapid experiment

The data rate in our ultra-rapid UT1 experiments was mainly 128 Mbps or 256 Mbps since it was difficult to transfer the data at a rate faster than 500 Mbps because of the low performance of our network environment until summer 2008. Subsequently, we changed the network environment to SINET3, which is operated by the National Institute of Informatics. Recently, the actual transfer rate seems to have become faster than 600 Mbps. If we succeed in the ultra-rapid UT1 session in which the data-transfer rate is 512 Mbps, it is expected that the accuracy of UT1-UTC will improve.

6.2 Ultra-rapid observation in regular observations

The Tsukuba 32-m VLBI station has been involved in IVS UT1 sessions every Saturday and Sunday. The latency is 2–3 days because we correlate the observed data on Monday or Tuesday. Therefore, we have introduced the developed system in the ultra-rapid experiment during the regular session. These regular sessions are conducted over the weekend, and we have to carry out observation by unmanned operation. We have improved the system for ultra-rapid UT1 measurement and performed operation tests in every session. We plan to carry out the ultra-rapid UT1 measurement in all the regular sessions and submit the result to the IVS data center within 30 min of the end of the observation session. The improvement of latency from 2-3 days to 30 min can help improve the accuracy of Rapid-Service results obtained 2-3 days before the date of issue and that of the predicted EOP values published by IERS.

The improved system can be also used in the 24-h regular session. On Jun. 30, 2009, we tried to conduct the ultra-rapid experiment at Onsala station during the 24-h international geodetic session. We succeeded in carrying out the entire data processing. However, we could not obtain the UT1 results because the analysis program did not function well. In the second experiment on Jul. 9, we succeeded in obtaining UT1 results every few minutes, almost in real time. The experiments were carried out on the East–West baseline (Tsukuba–Onsala). The East–West baseline is very sensitive to changes in UT1 but barely sensitive to polar motion. In the future, we would like to carry out the experiment on the North–South baseline and East–West baseline for estimating the UT1 and polar motion almost in real time.

7. Conclusions

The ultra-rapid UT1 experiment has been carried out by adopting e-VLBI technology, and the results become available within a few minutes of the end of the observation session (The best time is 3 min 45 sec.). This has been achieved by exploiting several contributions of advanced e-VLBI technology, such as UDP-based protocol and automatic data processing. The accuracy of our UT1-UTC estimates determined in experiments is higher than that of the results reported in the Rapid-Service of Bulletin-A. However, the accuracy is lower than that in the results of the regular UT1 experiment. The possible cause is that the observation schedule is not optimized for UT1 measurement.

Currently, the ultra-rapid UT1 experiments are being carried out in special 1-h intensive sessions. We plan to perform the ultra-rapid UT1 measurement in the regular INT2 sessions, which are conducted every Saturday and Sunday. The system developed for the ultra-rapid experiment can also be used in the 24-h international session. We plan to improve the system for the ultra-rapid experiment. It is expected that we can obtain the UT1 result within a few minutes of the end of the 24-h or 1-h regular VLBI sessions. If we succeed in ultra-rapid UT1 measurement in the regular sessions, it will greatly contribute to improving the accuracy of UT1 data.

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