Ultra-rapid UT1 measurement by e-VLBI

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(Received xxxx xx, 2007; Revised xxxx xx, 2007; Accepted xxxx xx, 2007)

Using e-VLBI technology, the latency of UT1 measurement with Very Long baseline Interferometry (VLBI) has been greatly improved. VLBI observations on the baseline formed by the Kashima 34 m and the Onsala 20 m radio telescopes achieved ultra-rapid UT1 measurements, where the UT1 result was obtained within 30 minutes after the end of the observing session. High speed network access and the UDP-based data transfer protocol 'Tsunami' assisted the real-time data transfer from Onsala to Kashima. The accuracy of the UT1 value obtained from the 1-hour single baseline e-VLBI experiment has been confirmed to be as accurate as the combined solution of International Earth Rotation Service (IERS) bulletin-A. The developed technology will be transfered to the weekly intensive VLBI sessions, and is expected to contribute to improvements of latency and accuracy of the combined solution of the IERS.

Key words: e-VLBI, UT1

1. Introduction

e-VLBI is a new VLBI technology developed as a fusion with information technology (IT), which includes high speed network and computer technology. Due to the rapid development of the high speed network, it became possible to transfer the large amount of data that is generated by VLBI observations. Furthermore, the increase of computing power and data capacity of personal computers (PC) enabled handling of such a huge amount of data with software program on a cluster of PCs.

The earth rotation angle (UT1) with respect to the celestial reference radio sources is known as a geophysical parameter that is uniquely obtained by VLBI observations. DUT1 (=UT1-UTC) measurements by VLBI observations have a long history. VLBI observations have been organized by the IERS (International Earth Rotation Service) since middle 1980's (Ma et al., 1990; Steppe et al., 1990; Carter and Robertson, 1990; Shifang and Ruexian, 1990; Eubanks et al.,1990) and currently two so-called IVS-Intensive sessions, INT-1 (baseline Wettzell-Kokee) and INT-2 (baseline Wettzell-Tsukuba) (Baver et al., 2004; Fischer et al., 2004), are operated within the IVS (International VLBI Service for Geodesy and Astrometry). These sessions are operated routinely on weekdays (INT-1) and weekends (INT-2) and their latency is about a few days. By using the e-VLBI technology as described in this paper, the latency could be greatly improved.

2. Configuration of e-VLBI Experiments

One of a the key factors to enable the rapid output of results after a VLBI observing session is the choice of data transport protocol over the long distance network. VLBI data convey phase information of the received signal. For interferometry the preservation of this phase information is essential. Thus bit-make or bit-slip must be avoided even for one bit. TCP/IP is a reliable protocol to guarantee the reliable data transport over the network. But its data transport speed is limited by a delay-bandwidth product (e.g. Hirabaru, 2004). The data transfer rate of TCP/IP is theoretically limited by the relation

$$\text{rate(bps)} = 8 \times \text{(Windows size (Byte))}/\text{(RTT (sec))},$$

where, RTT is round trip time between end-to-end of the network. Thus, the transmission rate slows down inversely proportional to the RTT over long distance. This condition can be relaxed by adjusting some kernel parameter to expand the window-size of TCP socket. However, the data rate is affected severely under a network condition with packet loss or congestion. This limitation comes from acknowledgment mechanism inherent to TCP/IP, which enables the reliable packet delivery in communications.

A VLBI dedicated data transmission protocol called VSI-E was proposed by Lapsley and Whitney (2004) for a standard protocol of e-VLBI data transmission. The VSI-E is designed to use the Realtime Transmission Protocol (RTP) based on UDP together with a control protocol (RTCP) based on TCP. It is expected to provide high performance throughput by using the UDP, though its implementation has so far not progressed so rapidly.

Another 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 over very long distance (Meiss, 2004). Wagner and Ritakari of the Metsähovi Radio Observatory applied it for real-time data transfer from their VLBI interface card. This 'Tsunami' protocol was used for our e-VLBI experiments. Fig. 1 shows schematically the e-VLBI observation configuration between the Kashima 34 m, the Onsala 20 m, and the Metsähovi 14 m radio telescopes. The observations were made by using Mark5 data formatter[1] (Whitney, 2004) at Onsala or Metsähovi. The quantized data stream from the formatter were captured by VSI board (VSIB) developed by Metsähovi Radio Observatory (Ritakari and Mujunen, 2004) and transmitted to Japan with the 'Tsunami' protocol. The data stream at the observing date rate of 256 Mbps was transfered from Europe to Japan through the high speed networks SUNET or Funet, NORDUnet, DANTE/GÈANT, Internet2/Abilene, JGN2, and APAN in real-time. Then the data were recorded directly on a disk system at Kashima in the Mark5 data format. The observations at Kashima were made with the K5/VSSP32 system (Kondo et al., 2006). After a scan of data recording was finished, the data were converted automatically from Mark5 to K5 format. Then the observed data sets were ready for both stations, and the cross correlation processing was started. The correlation tasks were shared by processors of a PC cluster at Kashima and processed in parallel by each groups of frequency channels. These data processing scheme from data format conversion to cross correlation processing was performed for every scans, automatically. Each PC of the cluster is a Linux machine running independently, and the data disks are shared via NFS with autofs

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http://www.haystack.edu/tech/vlbi/mark5/

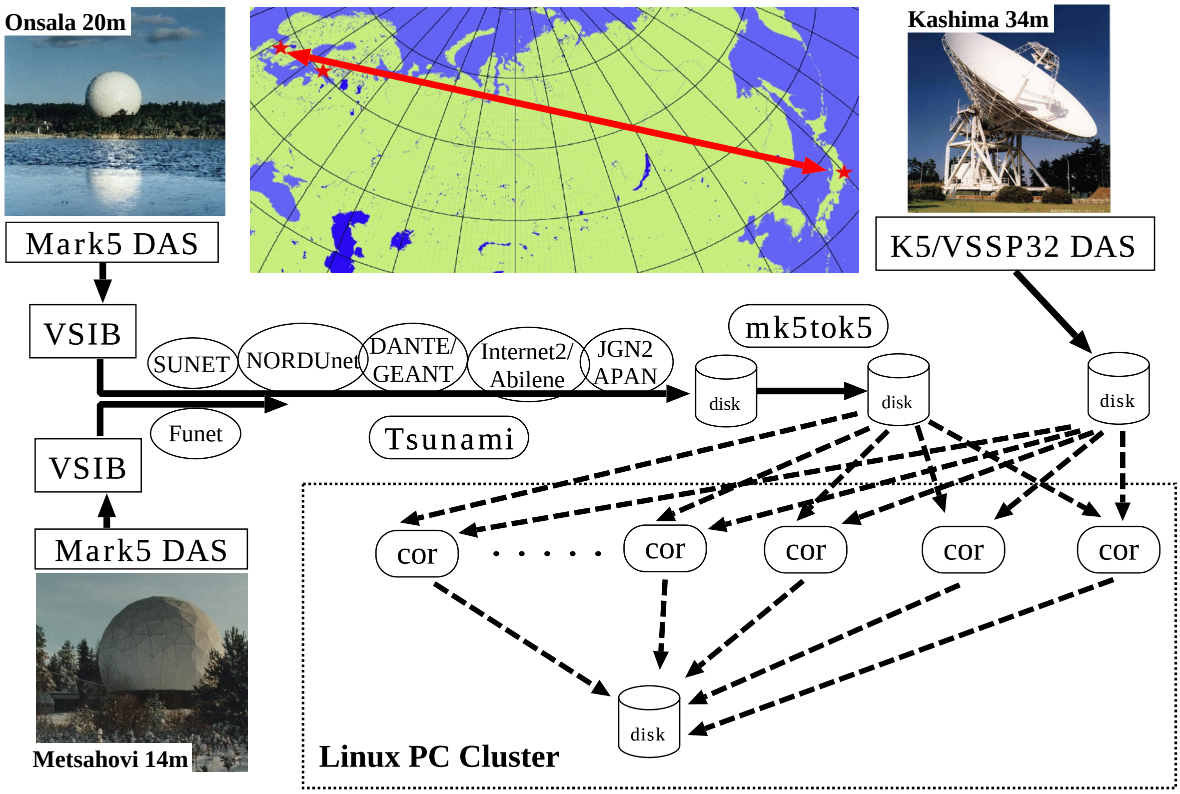

Fig. 1. Overview of the e-VLBI experiment configuration between Kashima (Japan), Onsala (Sweden), and Metsähovi (Finland). Onsala and Metsähovi use a combination of Mark5 formatter and VSI board (VSIB) as data acquisition system (DAS), which were developed by MIT Haystack observatory (USA) and Metsähovi Radio Observatory, respectively. Observed VLBI data (256 Mbps) were transfered through the high speed networks of SUNET (or Funet), NORDUnet, DANTE/GÈANT, Internet2/Abilene, JGN2, and APAN with the 'Tsunami' protocol in real-time. Then, the Onsala or Metsähovi data were directly recorded on a disk system at Kashima. Directly after the recording of each scan, the Mark5 data were automatically converted to the K5 data format and passed to the correlation process running on a cluster of PCs. Observations at Kashima were made with the K5/VSSP32 system. The K5 software package developed by Kondo (NICT) was used as core software for the data format conversion and correlation processing, and the automatic pipeline processing was controlled by a toolkit code by Perl wrapping the core software. The red stars in the map indicates the position of Kashima, Onsala, and Metsähovi.

system. The job control and task management of automated pipeline processing were done by a newly developed set of Perl programs, which communicate with each other with TCP/IP. After the correlation processing, precise group delay observables were derived with the bandwidth synthesis procedure. Then Mark3 database were created and the UT analysis was made with the CALC/SOLVE package, which is a standard VLBI analysis software developed by NASA/GSFC.

The series of e-VLBI observation sessions performed since April in 2007 are listed in Table 1. The table gives information about observation date, baseline, data rate, the DUT1 result, its formal accuracy,

Table 1. e-VLBI sessions for rapid UT1 measurement performed on the Kashima – Onsala or Kashima – Metsähovi baseline since April 2007. After several trials, a pseudo-realtime e-VLBI experiment was successfully performed on 31 May 2007. The DUT1(=UT1-UTC) value was estimated within 30 minutes after the end of the observing session.

Date	**Baseline**	**Data rate** (Mbps)	**DUT1** (ms)	**Uncertainty** (μs)	**Difference from EOP-C04 (μs)**
2007.04.03	Kashima – Onsala	256	-6.96044	8.1	-23.4
2007.04.23	Kashima – Onsala	128	-9.84422	41.0	26.2
2007.05.02	Kashima – Onsala	128	-11.00189	16.0	-18.9
2007.05.18	Kashima – Metsähovi	128	-13.05832	98.0	74.5
2007.05.30	Kashima – Onsala	128	-14.32703	8.5	16.7
2007.05.31	Kashima – Onsala	128	-14.37011	8.1	-72.8
2007.06.04	Kashima – Onsala	256	-14.46447	6.2	-15.1

and its difference to the DUT1 result of the EOPc04 series of the IERS. The observations were made with 8 MHz-1 bit-16 channel or 16 MHz-1 bit-16 channel standard geodetic observation modes. Trials of rapid DUT1 measurements with e-VLBI were made on the Kashima-Onsala and Kashima-Metsähovi baselines several times. Since the automatic processing environment was not ready in the early stage, data processing took time to derive the analysis results. However, the measurements themselves were successful and the DUT1 data were derived with a formal errors of mostly less than 10 μ sec for almost every experiment. The fastest record of rapid DUT1 measurement was achieved in the experiment on Kashima - Onsala baseline in the end of May 2007. The UT1 result was obtained within 30 minutes after the end of the session. The previous record was 4.5 hours of latency achieved by Koyama et al. in 2004 on the Kashima-Westford baseline (Koyama et al., 2004).

Concerning details of the latency of 30 minutes, the correlation processing was finished within 5 minutes after the session, and most of time was spent for creating the Mark3 database and interactive analysis with CALC/SOLVE. Further improvement of latency may be possible by an automation of the

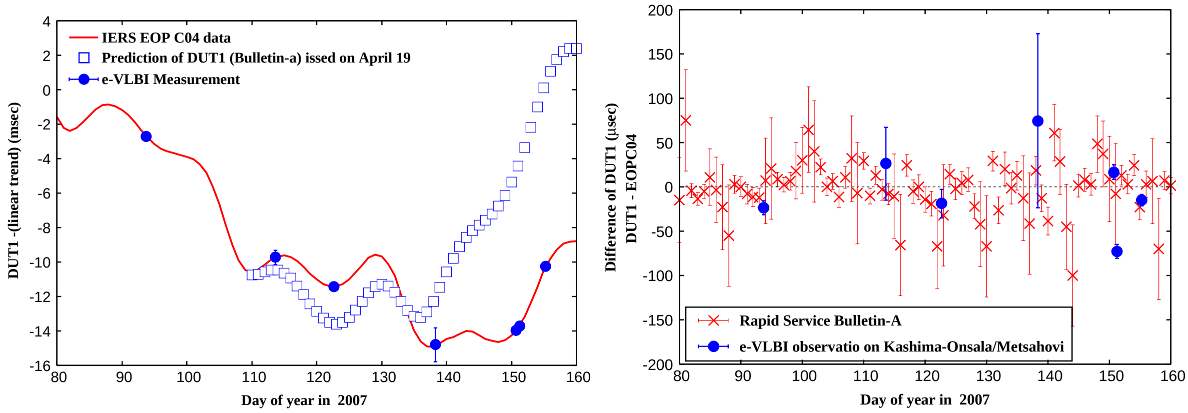

Fig. 2. Left plot: Comparison of UT1-UTC values between e-VLBI measurements('•'), combined solution EOPc04 series (solid line), and UT1 prediction value of Bulletin-A ('*square*'). They are plotted after removal of common linear trend. The prediction data of bulletin-A is the issue on 19 April (Day of year = 109). In comparison with the EOPc04 series, the plot clearly indicates that the accuracy of prediction value degrades rapidly with time. DUT1 data measured by e-VLBI are consistent with EOPc04, which is regarded as the best estimate of DUT1. Right plot: DUT1 data by e-VLBI measurement ('•') and that of Rapid Service in bulletin-A ('$\times$') are plotted after subtraction of EOPc04 series data. The error bars are formal error for e-VLBI and standard uncertainty for bulletin-A.

database creation and analysis. Although secure data quality control may be necessary in the further automated processing to avoid accidental release of a wrong analysis result caused by observation failure or outliers.

3. Comparison of UT1 Results by e-VLBI Observation and IERS Combination Solution

The typical formal error of the ultra-rapid UT1 measurement was less than 10 micro seconds. The IERS routinely publishes DUT1 (=UT1-UTC) and sets of earth rotation parameters (EOP), which are estimated by a combination of observational data of VLBI, Satellite Laser Ranging (SLR), and the Global Positioning System (GPS). The combined solution is published in the IERS Bulletin-B every month, and that data covers the time up to one month before the date of issue. For users who needs EOP data at current or future epochs, prediction values of EOP for one year future are published weekly as IERS Bulletin-A. However, the accuracy of EOP prediction data of Bulletin-A degrades rapidly as a function of temporal distance from the date of issue. For compensation of the accuracy of prediction value, rapid service of EOP solutions are also published as "COMBINED EARTH ORIENTATION PARAMETERS" in the first section of Bulletin-A. These are derived by using the latest observational data of VLBI, SLR, GPS, Lunar Laser Ranging (LLR), and meteorological predictions of variations in Atmospheric Angular Momentum (AAM).

The left plot in the Fig. 2 clearly shows that the IERS Bulletin-A DUT1 prediction degrades rapidly from one day after the issue date. The right plot in Fig. 2 shows that the rapid service of the combined solution has an accuracy on the order of a few tens of microseconds and the DUT1 value measured by e-VLBI can provide the same accuracy with only one single observation session. When Hefty and Gontier (1997) discussed UT1 measurements with intensive VLBI observation data on the Westford-Wettzell baseline, the number of delay observables were only 8 during the 1-hour observation session. Therefore atmospheric parameters were not estimated in the analysis of single sessions. Due to the improvement of sensitivity by increasing data rate with new DAS (Mark5, K5), the necessary integration time to achieve enough signal to noise ratio (SNR) has been reduced, and consequently the number of scans in a 1-hour session has been increased. For example is the number of scans about 14 on Kashima-Onsala/Metsähovi baseline (this experiment) and 28 on intensive-2 session on Tsukuba-Wettzell baseline. Thus, atmospheric parameters were estimated in the current UT1 analysis and more accurate DUT1 data have been obtained from each single sessions.

4. Summary

An ultra-rapid UT1 measurement has been realized using the e-VLBI technology, and DUT1(=UT1-UTC) data could be derived within 30 minutes after the VLBI observation. The success of e-VLBI is due to several key factors: Utilizing of high speed network, choice of an UDP-based protocol enabling high-speed data transfer over very long distance, automation of data processing, and enhancement of compatibility between different sorts of VLBI-DASs. Currently we are organizing rapid UT1 measurements with parallel baselines between Japan and Europe using the Kashima, Tsukuba, Onsala, Wettzell, and Metsähovi stations. The proposal for UT1 measurement sessions with parallel baselines has recently been approved by IVS Observing Program Committee. The simultaneous measurements of UT1 with parallel baselines will be useful for the evaluation of accuracy and stability of the UT1 measurement by VLBI. Also the latency of data processing of the IVS INT-2 sessions, which are routinely observed on the Tsukuba-Wettzell baseline, will be improved by introducing the e-VLBI technique used on these experiments.

Acknowledgments. We thank the network research community of SUNET, Funet, NORDUnet, DANTE/GÈANT, Internet2/Abilene, JGN2, and APAN for providing high speed network connections between VLBI stations in Japan and Europe. Especially Takatoshi Ikeda, Hiroaki Harai, and Masaki Hirabaru in the Network Architecture Group of NICT have been supporting the e-VLBI experiments at view points of the network configuration and giving advices on technique to get high throughput on very long distance network. We thank the Finish Geodetic Institute (FGI) for providing the S/X receiver for Metsähovi. We appreciate contributions by Shinobu Kurihara of Geographical Survey Institute of Japan, and Gerhard Kronschnabl of Wettzell station in Germany for discussion on prospect of rapid UT1 experiments and collaboration. The VLBI experiments were supported by Ryuichi Ichikawa, Eiji Kawai and Hiromitsu Kuboki of Kashima Space Research Center.

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