Ultra-rapid UT1 measurement by e-VLBI

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By using e-VLBI technology, latency of UT1 measurement with VLBI has been greatly improved. VLBI observations of UT1 organized between Kashima 34m and Onsala 20m radio telescopes achieved ultra-rapid UT1 measurement, where UT1 result was obtained within 30 mintutes after the observation. High speed network access and UDP-based data trasnfer protocol 'Tsunami' assisted the real-time data transfer from Onsala to Kashima. The accuracy of the UT1 value obtained from the 1-hour sinle baseline e-VLBI experiment has been confirmed to be accurate as combined solution of bulletin-A. The developed technology will be transfered to weekly operated intensive VLBI session, and expected to contribute improvement of latency and accuracy of the combined solutioin of IERS.

Key words: e-VLBI, UT1

1. Introduction

e-VLBI is a new VLBI technology developed as a fusion with information technology (IT), which include high speed network and computer technology. Owing to the rapid development of the high speed network technology, transferring large amount of data generated by a VLBI observation became possible. Also increase of computing power and enlargement of data capacity of personal computers (PC) enabled handling of such 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

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geophysical parameter uniquely obtained by VLBI observation. DUT1 (=UT1-UTC) measurement by VLBI observations have long history. VLBI observation campaign has been organized by 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 Intensive session 1 (Wettzell-Kokee) and 2 (Wettzell-Tsukuba) (Barver et al., 2004; Fischer et al., 2004) sessions are operated under the IVS (International VLBI Service for Geodesy and Astrometry). These sessions are operated routinely every week and their latency is about a few days. By using the e-VLBI technology, the latency could be greatly improved.

2. Configuration of e-VLBI Experiments

One of a key factor to enable rapid output of result after a VLBI observation is choice of data transport protocol over the long distance network. Since VLBI data conveys phase information of received signal and preservation of it is essential for interferometry. 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. Though its data transport speed is limited by a delay-bandwidth products (e.g. M.Hirabaru, 2004). Data transfer rate of TCP/IP is theoretically limited by a 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 transmission rate get slow down inversely proportional to the RTT of long distance. This condition can be relaxed by adjusting some kernel parameter to expand the window-size of TCP socket, though that limitation affects 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 communication.

A VLBI dedicated data transmission protocol called VSI-E was proposed by D.Lapsley and A.Whitney (2004) for a standard protocol of e-VLBI data transmission. The VSI-E is designed to use Realtime Transmission Protocol (RTP) based on UDP and its control protocol (RTCP) based on TCP in tandem.

It is expected to provide high performance throughput by using the UDP packet, though its implementation has not so rapidly progressed, yet.

One of the other UDP/IP based protocol, 'Tsunami' was developed by Advanced Network Management Laboratory of Indiana University as an experimental high speed network file transfer protocol over very long distance (Meiss,2004). Then J. Wagner and J.Ritakari of Metsähovi radio observatory of Helsinki university of technology applied it for real-time data transfer from their VLBI interface card. This 'Tsunami' protocol was used for our e-VLBI experiment. Fig. 1 shows the overview of the e-VLBI observation configuration between Kashima 34 m, Onsala 20 m, and Metsähovi 14m radio telescopes.

The observation was made by using Mark5 data formatter[1] (Whitney,2004) at Onsala or Metsähovi radio telescopes. 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 Tsunami protocol. Data stream of the observation date rate at 256 Mbps was transfered from Europe to Japan through the high speed network NORDUnet, DANTE/GÈANT, Internet2/Abilene, JGN2, and APAN in real-time, Then it was recorded directly in a disk system at Kashima in the Mark5 data format. Observation at Kashima 34m telescope was made by using K5/VSSP32 system (Kondo et al.,2006). After one scan of data recording has finished, format conversion from Mark5 to K5 performed automatically. Then observed data set are ready for both stations, cross correlation processing is called. The correlation tasks are shared by processors of the PC cluster and processed in parallel by a unit of scan and group of frequency channels. Each PC of the cluster is a Linux machine running independently, and the data disks are shared via NFS with autofs system. These job control and task management of automated pipeline processing are done by newly developed a set of Perl program, which are communicating each other with TCP/IP.

The e-VLBI observation sessions performed since April in 2007 are listed in Table 1. The observations were made with 8MHz-1bit-16channel or 16MHz-1bit-16channel of standard geodetic

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[1] http://www.haystack.edu/tech/vlbi/mark5/

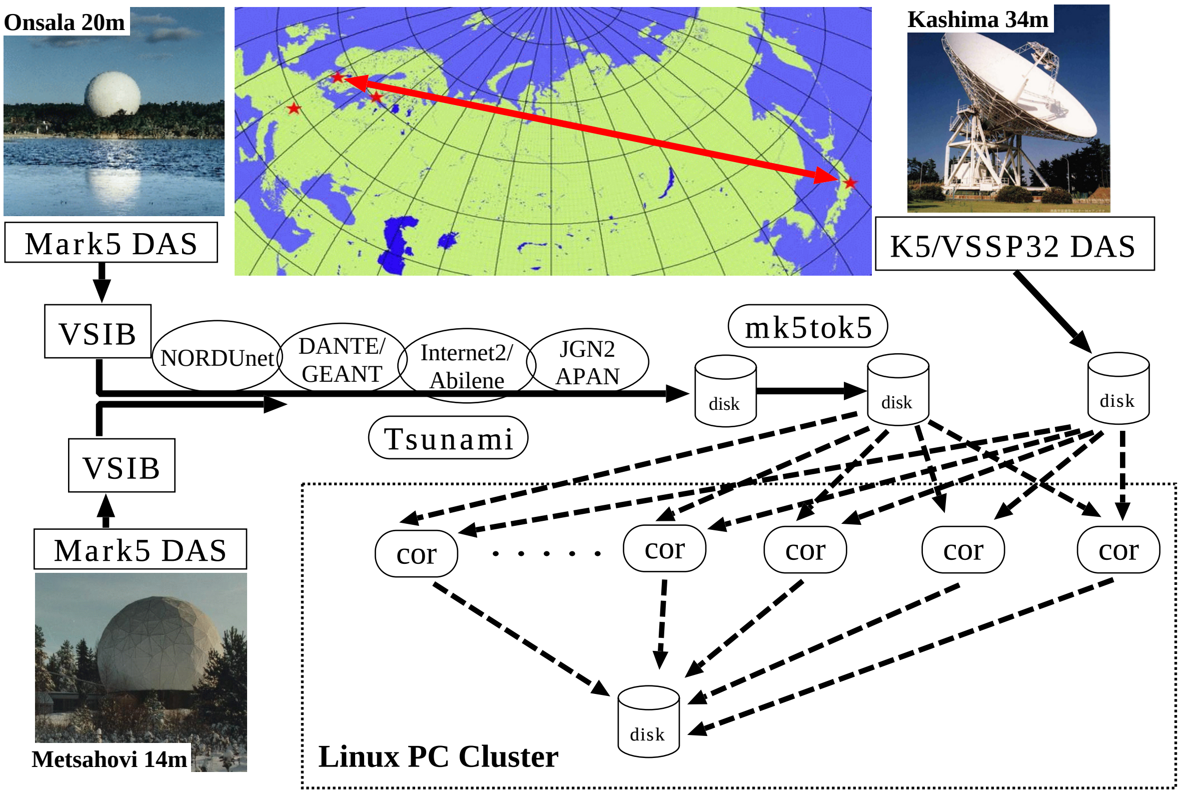

Fig. 1. Overview of the e-VLBI experiment configuration between, Kashima (Japan), Onsala (Sweden), and Metsähovi (Finland) stations. Onsala and Metsähovi observatories are using combination of Mark5 formatter and VSI board (VSIB) for data acquisition system (DAS), which are developed by MIT Haystack observatory (USA) and Metsähovi observatory, respectively. Observed data (256 Mbps) were transfered through high speed network of NORDUnet, DANTE/GÈANT, Internet2/Abilene, JGN2, and APAN with Tsunami protocol in real-time. And the Onsala or Metsähovi data are directly recorded in a disk system at Kashima. Soon after the recording of each scan, Mark5 data was converted to K5 data format automatically and passed to correlation process running on a cluster of PCs. Observation at Kashima 34m telescope was made by using K5/VSSP32 system. The K5 software package developed by T.Kondo (NICT) was used as core software of 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, Metsähovi, and Wettzell (Germany).

observation mode. After the correlation processing, precise group delay observables are derived with bandwidth synthesis procedure. Then Mark3 database has been created and UT analysis was made by CALC/SOLVE package, which is a standard VLBI analysis software developed by NASA/GSFC. Trials of rapid DUT1 measurements with e-VLBI had been made between Kashima-Onsala/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 measurement itself was made successfully and DUT1 data were derived with a formal error of mostly less than 10 μ sec in almost

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

Date	**Stations**	**Data rate** (Mbps)	**DUT1** (sec.)	**Uncertainty** (μ sec.)	**Difference from EOP-C04 (μ sec.)**
3 Apr.	Kashima 34m, Onsala 20m	256	-0.0696044	8.1	-23.4
23 Apr.	Kashima 34m, Onsala 20m	128	-0.0984422	41	26.2
02 May	Kashima 34m, Onsala 20m	128	-0.1100189	16	-18.9
18 May	Kashima 34m, Metsähovi 14m	128	-0.1305832	98	74.5
30 May	Kashima 34m, Onsala 20m	128	-0.1432703	8.5	16.7
31 May	Kashima 34m, Onsala 20m	128	-0.1437011	8.1	-72.8
04 Jun.	Kashima 34m, Onsala 20m	256	-0.1446447	6.2	-15.1

every experiments. 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 session. Former record was 4.5 hours of latency achieved by Y.Koyama et al. in 2004 on Kashima-Westford baseline. As for the detail of the latency of 30 minutes, the correlation processing has been finished within 5 minutes after the session, and most of time was spent for creating Mark3 database and manual analysis with CALC/SOLVE. Further improvement of latency may be possible by automation of 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

Typical formal error of the ultra-rapid UT1 measurement was less than 10 micro seconds. The IERS has been routinely publishing UT1-UTC and set earth rotation parameters (EOP) estimated by combination of observation data of VLBI, Satellite Laser Ranging (SLR), and the Global Positioning

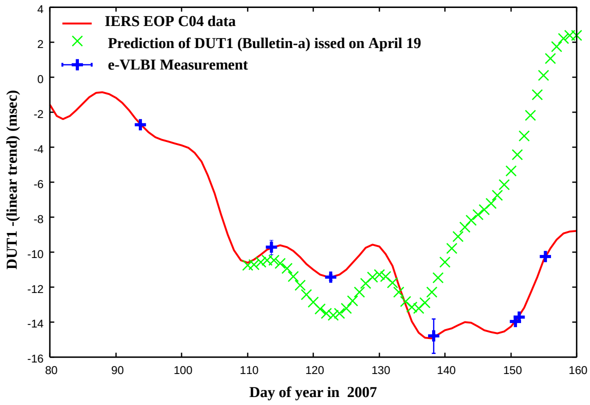

Fig. 2. Comparison of UT1-UTC values between e-VLBI measurements('+'), combined solution EOP-C04 series (solid line), and UT1 prediction value of Bulletin-A ('×'). They are plotted after removal of common linear trend. The prediction data of bulletin-A is the issue on 19 April (Day of year = 109). In comparison with EOP-C04 series, the plot clearly indicates the accuracy of prediction value degrades rapidly with time. DUT1 data measured by e-VLBI is consistent with EOP-C04, which is regarded as the best estimate of DUT1.

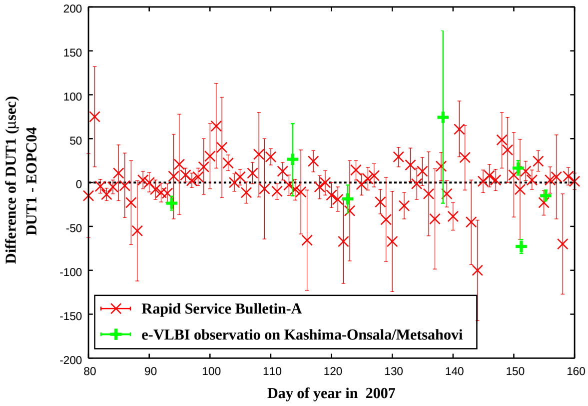

Fig. 3. DUT1 data by e-VLBI measurement ('+') and that of Rapid Service in bulletin-A ('×') are plotted after subtraction of EOP-C04 series data. The error bars are formal error for e-VLBI and standard uncertainty for bulletin-A.

System (GPS) satellites. The combined solution is published in Bulletin-B every month, and the time coverage of the data is up to one month before the date of issue. For users who needs EOP data for current or future epochs, prediction values for one year future are published every week as Bulletin-A. Though the accuracy of EOP prediction data of Bulletin-A degrades rapidly as distant in time 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. That is derived by using the latest observation data of VLBI, SLR, GPS, Lunar Laser Ranging (LLR), and meteorological predictions of variations in Atmospheric Angular Momentum

(AAM). The plot in the Fig. 2 clearly shows that the prediction value of DUT1 degrades rapidly from the next day of the issue. Fig. 3 shows the rapid service of combined solution has accuracy in order of a few tens of micro seconds and the DUT1 value measured by e-VLBI can provide the same accuracy only with single session of observation. When Hefty and Gontier (1997) have discussed about UT1 measurement with intensive VLBI observation data of Westford-Wettzell baseline, number of delay observables were only 8 in 1-hour observation session, thus atmospheric parameters were not estimated in the single session. Owing to the improvement of sensitivity by increasing data rate with new DAS (Mark5, K5), integration time to be necessary for enough signal to noise ratio (SNR) has reduced, and consequently number of scans in a 1-hours session have been increased, for instance the number of scans is about 14 on Kashima-Onsala/Metsähovi baseline (this experiment) and 28 on intensive-2 session on Tsukuba-Wettzell baseline. Thus atmospheric parameters are estimated in current UT1 analysis and more accurate DUT1 data have been obtained from each single sessions.

4. Summary

The ultra-rapid UT1 measurement has been realized by e-VLBI technology, and DUT1(=UT1-UTC) data could be derived within 30 minutes after the VLBI observation. The success of e-VLBI are achieved by several key factors: Utilizing of high speed network, choice of 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 among Kashima, Tsukuba, Onsala, Wettzell, and Metsähovi stations. The proposal of this UT1 measurement with parallel baselines has been approved by IVS stealing committee. The simultaneous measurement of UT1 with parallel baselines must be useful for evaluation of accuracy and stability of the UT1 measurement by VLBI. Also the latency of data processing of the Intensive-2 session, which is routinely observed by Tsukuba-Wettzell baseline for UT1 measurement, will be improved by introducing the e-VLBI technique used on these experiments.

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