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CONTENTS

The 6th NICT IVS-TDC Symposium

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As a Technical Development Center (TDC) of IVS (International VLBI Service for Geodesy and Astrometry), Kashima Space Research Center (KSRC) of NICT is hosting the annual symposium focusing on the up-to-date research and developments related with the VLBI technologies. The 6th symposium was held on March 9, 2007 at a conference room of KSRC. In total, 18 presentations were given by researchers from NICT, Geograhical Survey Institute, Japan Aerospace Exploration Agency, National Astronomical Observatory, and Yokohama National University. The presentations covered all range of the technical developments of VLBI including the developments of the very small aperture antenna system for the measurement of standard length, precise orbit determinations of spacecrafts, e-VLBI, an idea to establish a service to provide precise ray-tracing results of the atmospheric delay using numerical weather model, development of high speed software correlator and K5/VSSP32 system. The materials of these presentations are available on the web at `http://www.nict.go.jp/w/w114/stsi/ivstdc/sympo070309/twmemo.html` (*in Japanese*). In this issue of NICT IVS TDC News, the proceedings from the symposium are included.

Development of a compact VLBI system for a length examination of a reference baseline.

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Abstract: We started to develop a compact VLBI system with 1.5m diameter aperture antenna which is planned to be used for examination of reference baseline. Reference baseline is used for validating of surveying instruments and maintained by Geographical Survey Institute (GSI). Since the reference baselines lie in various places in Japan, the antenna system must be transportable. Therefore the diameter of the antenna has to be very small. We also considered another requirements for the VLBI system, and designed the concept of the system that fulfilled the requirements. The concept is to measure the 10km distance with two small antennas and one conventional large-size antennas. We estimated the diameter of a small antenna that be able to achieve this system to be 1.5m. Moreover, the front end of this system was designed. In the design, the radio wave is received with a wide-band feed antenna, and it divides into two frequency bands with a diplexer.

1. Introduction

National Institute of Information and Communication Technology (NICT) is collaborating with GSI in the development of a compact VLBI system with a 1-m diameter aperture antenna to examine a reference baseline length. Since GSI is responsible to calibrate and validate survey instruments, GSI is maintaining several reference baselines up to 10km in Japan. One of this baseline is located around GSI Tsukuba as shown in Figure1. Reference baseline consist of a series of fixed pillars made of stainless steel. GPS receiver and EDM can be installed on top of the pillar. To guarantee the quality of validation, the baseline length has to be measured routinely. However, the entire distance of 10km is too long to be measured by a EDM directly. Therefore, the 10km reference baseline is examined only by GPS receiver at present. Moreover, though a measurement method that can tie to a national standard through the traceability is required for this measurement, it is difficult to tie the GPS measurement to a national standard directly.

On the other hand, Geodetic VLBI technique can give an independent measurement to examine this baseline. Measuring the 10km reference baseline by a method independent of GPS becomes a reliability improvement of the GPS validation. VLBI measurement can also tie to the national time standard through the traceability system.

Technical requirement, system concept, and feasibility study of VLBI system dedicated to 10km measurement will be described below.

2. System requirement

The system aims to measure 10km with the accuracy of 2mm to surpass the measurement accuracy of GPS. Antenna system must be transportable, because the reference baseline lies in various places in Japan. Moreover transportation should be carried out without a heavy machine like a crane etc. The repeatability of relocation is also required with the accuracy of several milli-meters. This system should be able to receive two frequency bands to correct ionospheric delay because it plans to be used also for the precise time transfer[1].

3. System concept

Our concept of this VLBI system is using a pair of very small antennas combined with a large aperture antenna. Time delay between small antennas is directly undetectable due to their low sensitivity. However their time delay can be obtained from delays observed with a large antenna(Figure2). Since the sensitivity of the large-small pair of the antennas are still not enough. We have to plan to include high speed AD sampler into our system to improve the sensitivity.

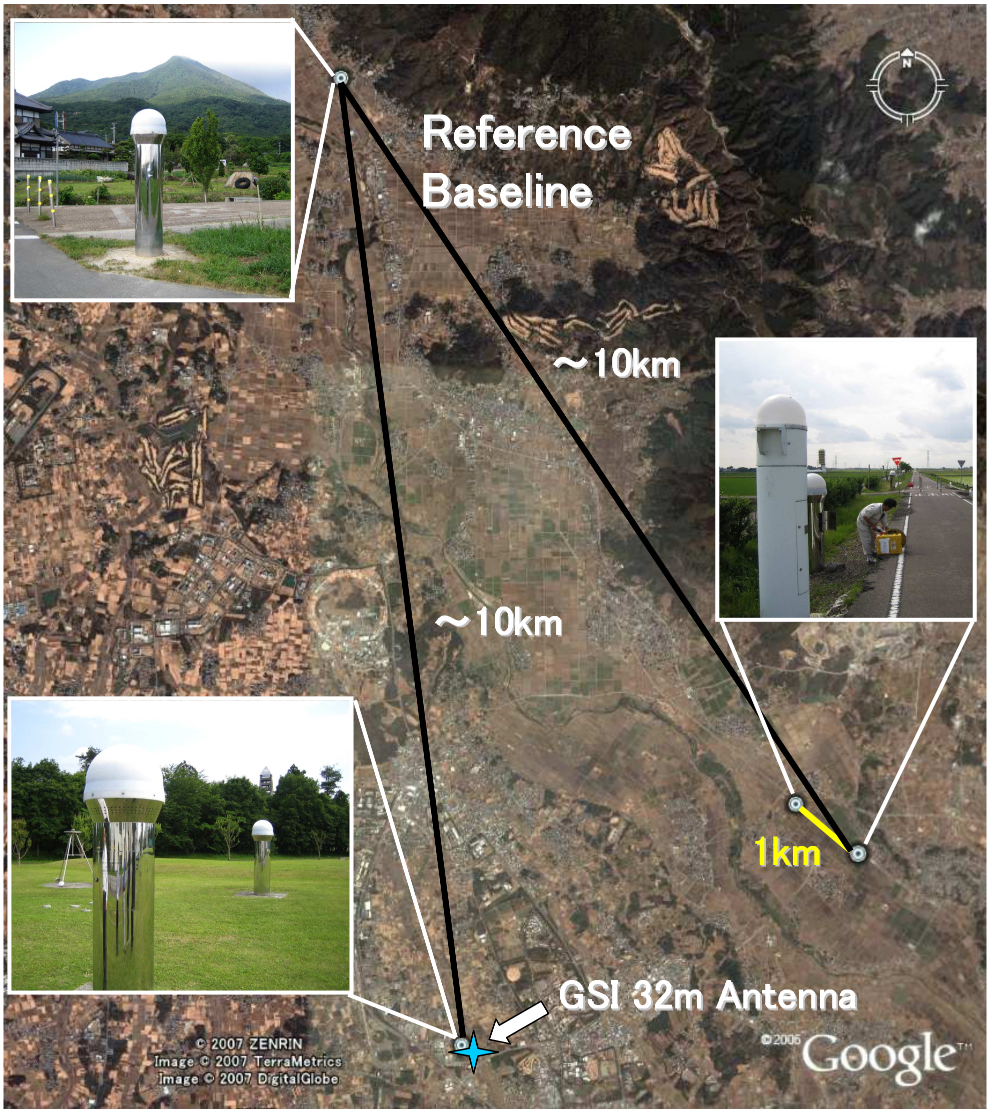

Figure 1. Reference baseline (This figure is modified image from Google Earth.)

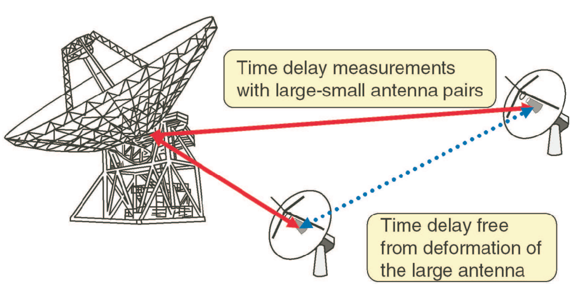

Figure 2. Concept of the length examination for the reference baseline using VLBI technique.

4. Antenna diameter and sampling rate

We estimated the minimum antenna diameter of this VLBI system. The estimation was carried out by evaluating a signal to noise ratio (SNR) under certain assumptions. Parameters used for SNR estimation are summarized in Table 1. Station X is assumed as the Tsukuba 32m antenna of GSI. Sampling rate is assumed to be like ADS1000 and K5/VSI system [2]. Results of the calculations are shown in Figures 3 and 4. In general, geodetic VLBI needs SNR 20 for S-band and SNR 30 for X-band. From the result, this requirements can be achieved using the pair of X and Y2 stations, namely minimum diameter of antenna is about 1.5m.

5. Design for a prototype

We are planning to use CARAVAN2400 as a prototype of this VLBI system [3], [1]. The sub reflector of CARAVAN2400 will be removed, and

Table 1. The assumption parameter of the calculation

Source flux	1.5 Jy				
	Band width		Sampling rate (1bit 2-level)		
S-band	150MHz		300Mbps		
X-band	512MHz		1024Mbps		
Station	Diameter of antenna(m)	Aperture efficiency		System noise temperature(K)	
	D	S-band	X-band	S-band	X-band
X(large antenna)	32.0	0.60	0.65	80	60
Y-1(small antenna)	1.0	0.45	0.50	150	120
Y-2(small antenna)	1.5	0.45	0.50	150	120
Y-3(small antenna)	2.0	0.45	0.50	150	120

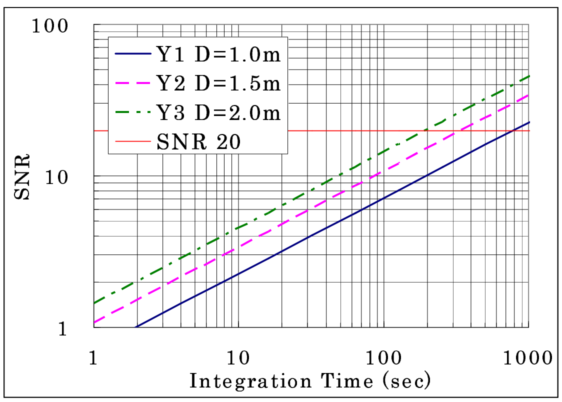

Figure 3. Result of S-band SNR calculation

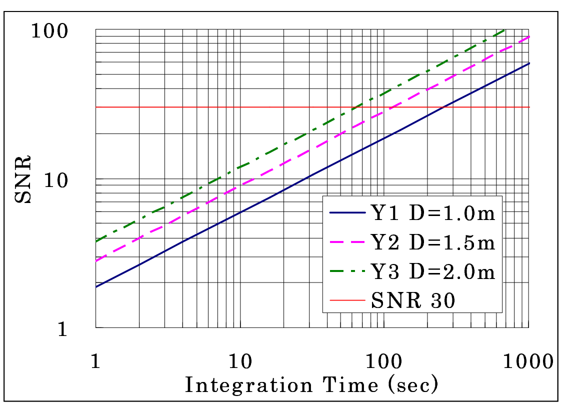

Figure 4. Result of X-band SNR calculation

a new feed antenna and a front end will be put at the prime focus of the antenna. Moreover, in order to receive two frequency bands we are going to use a wide-band feed antenna. Received signals are divided into two frequency bands (S-band and X-band) using a diplexer. Figure 5 shows a designed front end. We had already selected parts and bought them. The receiver noise temperatures are estimated to be 124K and 131K for S-band and X-band from the specifications of those parts.

6. Summary and Outlook

We started to develop a compact VLBI system with a 1.5m diameter aperture antenna dedicated to a precise 10km measurement. We showed a concept that will be able to achieve the goal. We have estimated the minimum antenna diameter and the appropriate frequency band width of the system. We are designing the prototype now, in particular wide band feed adoption is not fixed yet. We intend to decide an appropriate feed antenna by a computer simulation and actual measurements in an anechoic chamber. The proof experiment will be made by using remodeled CARAVAN2400. We will proceed the design work of other parts by repeating an examination and a proof experiment.

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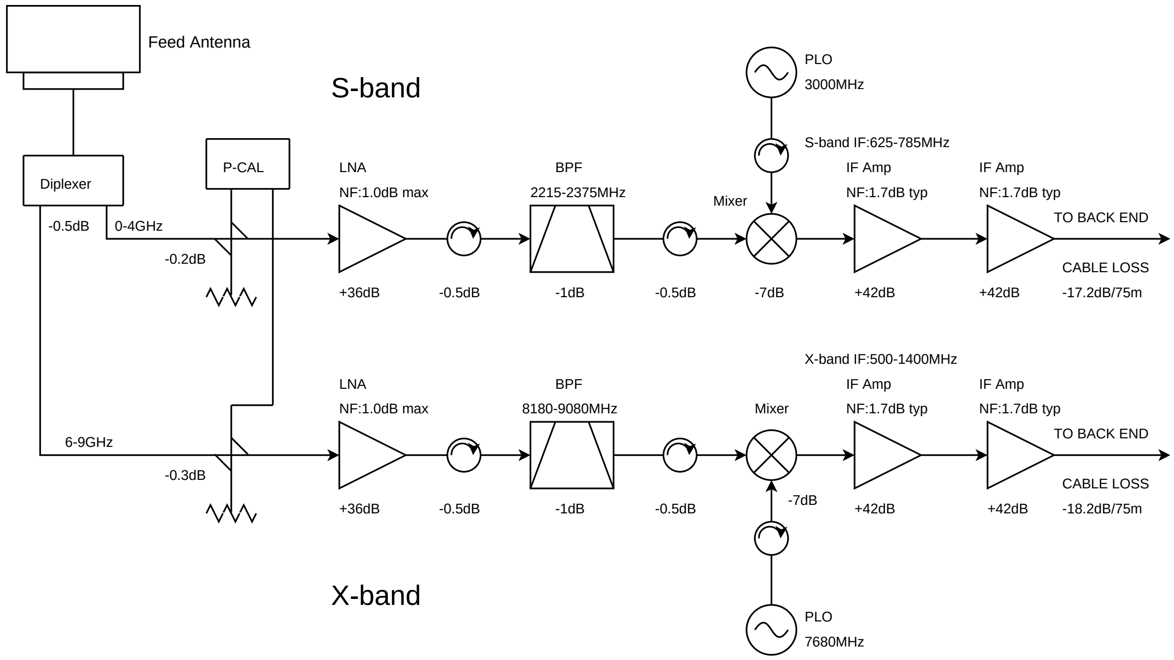

Figure 5. Designed front end block diagram

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Developments of the Evaluation System for the Verified Position Service

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Abstract: As one of the useful applications of the precise and accurate spatial reference frame, we have started to develop an evaluation system for the Verified Position Service. The service is intended to provide best accurate position of a GPS receiver by analysing the data provided to the server, and to archive the results and the original data with a verification ID. By specifying the ID to the server, anyone can access the analysed results and thus the ID can be used as the verification to the position of the GPS receiver. In this report, the concept of the Verified Positioning Service will be explained and the outline of the developed evaluation system will be introduced.

1. Introduction

Since April 2006, NICT started the 2nd Mid-Term research plan for the term of 5 years (April 2005-March 2011) (Koyama, 2006 [2]). As one of the research projects in the Space-Time Standards Group, we have been performing research and developments to improve spatial and time standard of reference and to make the reference easily available to the public community. In this way, we consider we can demonstrate the usefulness and importance of the space and time standards. The activities of the e-VLBI research and developments are performed to develop a method to improve the accuracy of the Earth Orientation Parameters especially for the current values to the predictions time range. The e-VLBI developments are also considered to improve the Terrestrial Reference Frame and Celestial Reference Frames by realizing the next generation international geodetic VLBI system, called VLBI2010 (Niell et al., 2006 [3]). Another new project has been started to establish standard of length in the range of more than 1km by means of two small aperture antennas and one large aperture antenna. Although the standard of length is established by using lasers up to a few hundred meters, the length standard is not well established for the long distance above 1km. These is a high demand to calibrate the geodetic survey instruments including geodetic GPS receivers, and NICT and Geodetic Survey Institute of Japan started cooperations to establish such a standard of length of typically 10km.

These projects are considered as the major research themes to establish or to improve spatial standards. On the other hand, there is a demand to our group to develop a method to disseminate the high quality spatial standard to the wider community. The concept of the Verified Position Service was brought out from this requirement. Similar concept for the verification of the time is known as the time stamp. The concept of the time stamp has been established by operating Time Stamp Authority which authorise the validity of the time information on the network. By using the time stamping services, anyone can obtain a time stamp on any data files. Since the time stamp is stored in the data file with the hash value calculated from the contents of the data file, it can be used as a proof that the data file has not been changed after the time stamp was included in the file. Although such a scheme to verify the validity of the information is available for time (when) and individual (who), there has not been any methods to provide verification to the information of the position (where). If the scheme to verify the position is available, many applications can be considered. For example, it can be used to protect legal rights for individuals for their personal real property, and also it can be used as a proof that the person was present at given location at certain time.

2. Developments of the Prototype Test System

With the scope explained in the previous introduction, we have developed a prototype system for the evaluation system for the Verified Position Service (VPS). The VPS is a new concept we defined as a service to verify the positions of arbitrary locations upon requests from arbitrary users. The prototype test system has been developed as an example to technically demonstrate concept of the VPS. It is also expected to identify operational requirements and difficult problems which have to be solved to realize the service in practice. The developed system uses the Advanced Precise Positioning System (APPS) to automatically analyse the observation data recorded by precise geodetic GPS receivers. APPS has been developed through collaborations with NICT and Nippon GPS Solutions Corporation (NGS). In the APPS, users of

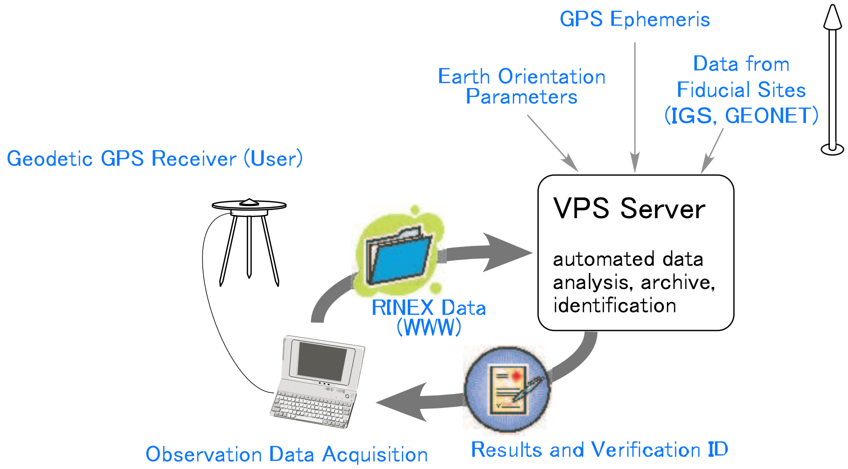

Figure 1. Conceptual illustration of the test evaluation system of the VPS.

the system obtain the RINEX GPS observation data with geodetic GPS receivers and send them to the analysis server as attachment files to an e-mail message. The server then extract the observation data and automatically analyse the data with a-priori information of Earth Orientation Parameters and satellite ephemeris. In addition, RINEX observation data at other fiducial sites either in the IGS network or in the GEONET network are automatically retrieved and analysed together with the user's provided observation data to obtain accurate position of the user site referenced to the fiducial sites (Ichikawa, et al., 2001 [1]). The fiducial reference sites can be selected and specified by the user, but if the sites are not specified, three sites are selected close to the user site and the data will be used to analyse the entire data. The data analysis are done with the GARD system which was developed by NGS to automate the data analysis and the core part of the analysis is done by the Bernese GPS data analysis software package version 4.2.

The prototype evaluation system for the VPS has been developed based on the APPS. The concept of the system is illustrated in the Figure 1. A WWW interface was developed to accept RINEX data files from the users. The users are expected to obtain the RINEX GPS data files by using their own geodetic GPS receivers. Then the user can access the server at http://vps.nict.go.jp/ and upload the RINEX data files. Once the observation data is obtained for about 24 hours by using a static geodetic GPS receiver, the data file saved in the RINEX format is uploaded to the prototype test server through the WWW page interface, and then the data is passed to the APPS server and is automatically analysed. As soon as the data files are uploaded, a unique identification number is issued to the user. The data are then provided to the APPS server and the data will be analysed automatically, After the data are analysed and results are obtained, the results are archived on the VPS server associated with the identification number. The user can access the results by using the identification number with the standard WWW browser applications. The prototype evaluation system for the VPS acts as an interface for users to obtain the analysed results of the GPS data from the APPS server, and in parallel, the analysed data and the observation data are archived in the database system and it provides the function for any users to browse the results upon requests. Figures 2 through 4 show the WWW interface of the prototype evaluation system.

The user can use the accurate position information as the verified position. The user can also tell the ID information to other people and the others can confirm the information by browsing the results on the prototype evaluation server. As the results, the position can be used as officially verified information. By realizing such system, it is expected to be used for basic or public surveys, investigations of the land history, establishing reference points in the geographic information infrastructure, and various other applications. The prototype evaluation system is only designed to provide positions in WGS84 reference frame, but we are planning to improve the system to adequately convert the position information to any reference frames. We are also planning to improve the accuracy and precision by using numerical weather model and ionospheric models to introduce better compensation for the propagation delay. In addition, in the future, we want to develop a method to evaluate the precise error under the multi-path environment, and a method to pro-

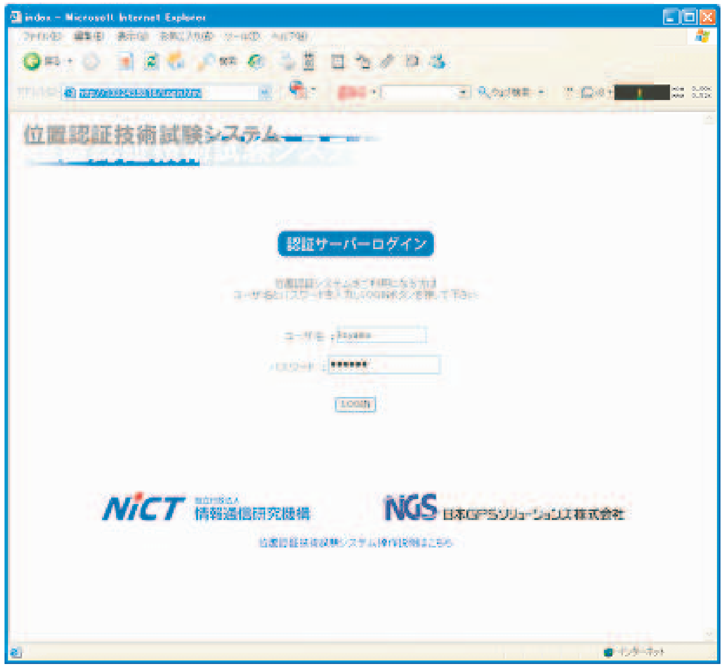

Figure 2. Log-in window for the prototype evaluation system of VPS <http://vps.nict.go.jp/Login.html>.

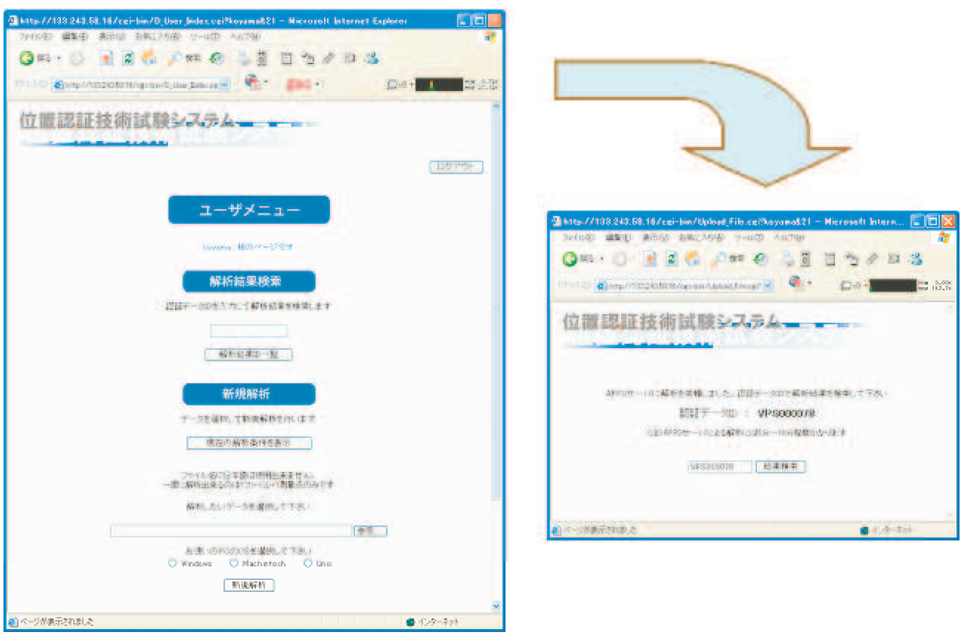

Figure 3. R&D research themes in the space-time standards group.

tect inappropriate usages.

3. Discussions and Future Ideas

To establish the robust and reliable system to verify any information, it is very important to prevent unfaithful usage of the service. At present, there is a risk of flaw in the system because the observation RINEX data can be generated by using GPS signal simulators. However, to imitate the GPS RINEX observation data with the GPS signal emulator, it is necessary to use predicted GPS satellite ephemeris. But the estimated ephemeris have a larger error in the file compared with the accurate ephemeris which will become available after a certain days. By developing an algorithm to

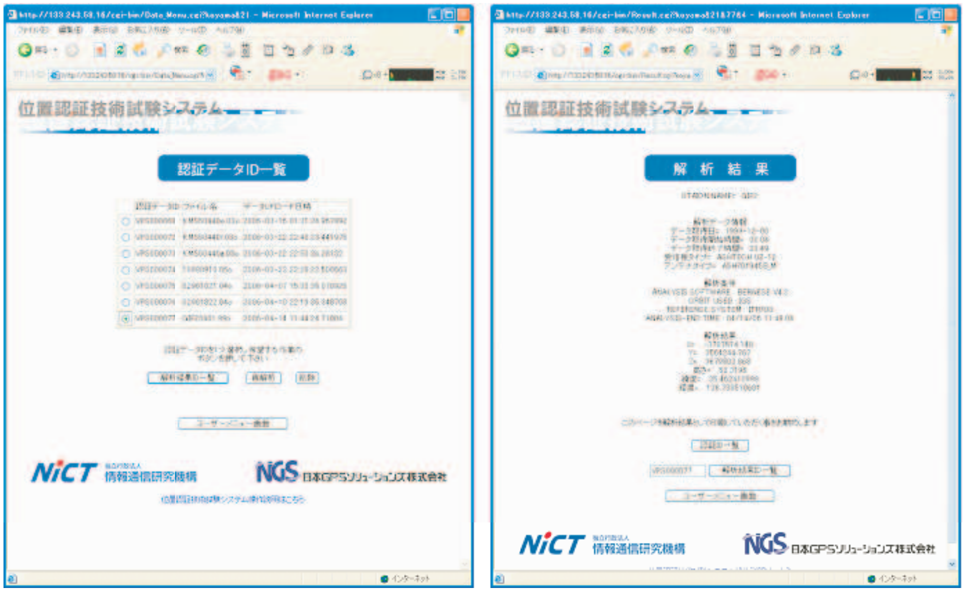

Figure 4. Concept to realize absolute standard of length by VLBI.

investigate the residual of the data analysis, it is considered possible to judge if the data were generated from actual observations or from the GPS signal generators.

The prototype evaluation system is relying the geodetic GPS receivers and the data have to be acquired for typically one day. If we can develop methods to provide verification to the position information within shorter period of time, if will be more preferable. Also, this method is only applicable to the locations from where many GPS satellites can be tracked. If we can develop methods to verify position information without visibility of the GPS satellites, it will expand the usefulness of the system. One of the ideas which will solve these problems, is to identify the position of the signal transmitter by means of interferometric data processing to the multiple antenna system surrounding to the radio transmitter, such as mobile phones and RFID.

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Comparison with GPS Time Transfer and VLBI Time Transfer

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Abstract: To compare the results with Global Positioning System (GPS) Time Transfer and Very Long Baseline Interferometry (VLBI) Time Transfer, we carried out the geodetic VLBI experiments for four times. The averaged formal error (1σ) of the clock offsets that were estimated every one hour in the geodetic VLBI analysis procedure (CALC/SOLVE), was 33 picoseconds. Especially, in the case of using K5/VSSP32 system, the averaged formal error was 29 picoseconds. The results of the VLBI time transfer were very consistent with the results of the GPS time transfer. The difference of both results was about ± 500 picoseconds. In term of frequency stability, the Allan deviation showed that VLBI time transfer is more stable than GPS time transfer between 2000 seconds to 60000 seconds (uncertainty of under 3×10^{-14}).

1. Introduction

Universal Time Coordinated (UTC) is computed and maintained by the International Bureau of Weights and Measures (BIPM) using a weighted average from about 250 atomic clocks located in about 50 national laboratories to construct a time scale called International Atomic Time (TAI). National Institute of Information and Communications Technology (NICT) is a one of the laboratory contribute to the UTC maintenance. NICT have 18 sets of cesium atomic clocks and 4 sets of hydrogen-maser clocks, and also generate Japan Standard Time (JST). And also, NICT is research and development of the next-generation frequency standards. One of the products of the primary frequency standard called "NICT-O1" is capable of realizing the definition of the second with an uncertainty of 6×10^{-15}. In addition, the atomic fountain frequency standard and optical frequency standard under development aim at an uncertainty of 1×10^{-15}. To realise such an uncertainty, it is necessary to compare regularly with these clocks and domestic and foreign research laboratories with precision and accuracy. These comparison are commonly undertaken through time transfer methods using GPS (GPS Time Transfer, Common-View method or Carrier Phase method) or communication satellites (Two-way Satellite Time and Frequency Transfer: TWSTFT), with an inaccuracy of the order of several hundreds picoseconds. In the future, it will be necessary to improve present comparison accuracy of time transfer greatly.

In the usual geodetic VLBI analysis, the clock offsets and their rates of change at all stations except for the reference station are estimated. The averaged formal error (1σ) is about 20 picoseconds in the International VLBI Service (IVS) general experiments. This accuracy is more accurate than GPS time transfer and TWSTFT. In addition, VLBI community are improving VLBI system and they aim about 4 picoseconds of the formal error with a per-observation (VLBI2010; Niell et al., 2007 [2]).

Because of the current VLBI system need large antenna and frequency standard, VLBI time transfer isn't practical use though the high accuracy. However, it begins to solve the problem by the ongoing research. For example, the development of a compact VLBI system by NICT (Ishii et al., 2007 [1]) and the above mentioned work of VLBI2010. In this study, to confirm the potential of the VLBI time transfer aiming at the practical use of the VLBI time transfer in the future, we compared the results of the VLBI time transfer and the GPS time transfer.

2. VLBI Experiments for Time Transfer

The details of performed VLBI observation are listed in Table 1. GPS observation was also carried out at the same time near the VLBI station. Until the k07059 experiment, we used the receiver for time transfer (KOGANEI: Septentrio PolarRX2 TR, KASHIMA: Ashtech Z-XII3T Metronome with a choke ring antenna). But, we replaced them with the geodetic receivers (KOGANEI and KASHIMA: Ashtech Z-XII3 with a choke ring antenna) before the k07166 experiment, and moved KASHIMA GPS station from near the Kashima 11m to near the Kashima 34m. Figure 1 is the map of the KASHIMA station that show the layout of VLBI antennas, GPS antenna and the frequency standard (hydrogen maser). The distance from the Kashima 11m to the frequency standard is about 200 meter.

The VLBI observations were made with standard geodetic observation mode. Then we analyzed that data by CALC/SOLVE software, which is a standard VLBI analysis software developed by NASA/GSFC. The averaged formal errors (1σ) of

Table 1. Details of the VLBI observations

Code	Term (UT)	Baseline	Mode	Sysetm
k07011	Jan.11 09 - Jan.12 15	KASHIM11-KOGANEI11	4Mbps/ch,1bit,16ch,64bps	K5/VSSP
k07022	Jan.22 10 - Jan.23 16	KASHIM11-KOGANEI11	4Mbps/ch,1bit,16ch,64bps	K5/VSSP
k07059	Feb.28 15 - Mar.03 15	KASHIM11-KOGANEI11	4Mbps/ch,1bit,16ch,64bps	K5/VSSP
k07166	Jun.15 02 - Jun.23 03	KASHIM34-KOGANEI11	16Mbps/ch,1bit,16ch,256Mbps	K5/VSSP32

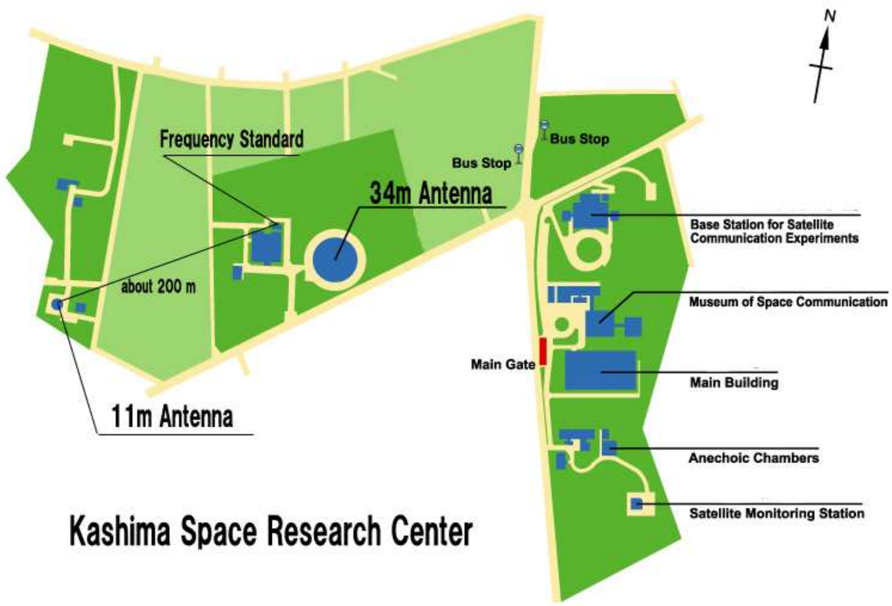

Figure 1. Layout map of KASHIMA station

the clock offsets at KOGANEI station referred to KASHIMA station are listed in Table 2. In the k07166 experiment, the data was split into the 3 parts because of the operation mistake. So we analyzed that data individually (k07166A, k07166B and k07166C). The result of the k07011 experiment was not shown after here, because of the enough data was not able to be acquired by the trouble of HDD.

Every after the experiment, we evaluated the schedule and SNR of the obtained data and improved the schedule for the next experiment. In addition, we changed the VLBI system of both of the stations from K5/VSSP to K5/VSSP32 that is more sensitive (about 4 times) and the antenna of KASHIMA station from Kashima 11m to Kashima 34m in the k07166 experiment. The averaged formal errors have decreased by the experiment. Finally, the averaged formal error of all experiment is 33 picoseconds. Especially, in the K5/VSSP32 system case, the averaged formal error was 29 picoseconds.

Table 2. The averaged formal error (1σ) of the clock offsets at KOGANEI station referred to KASHIMA station

Code	Formal Error [ps]
1) k07022	51
2) k07059	36
3) k07166A	28
4) k07166B	40
5) k07166C	23
average all	33
average K5/VSSP	39
average K5/VSSP32	29

3. Comparison with VLBI Time Transfer to GPS Time Transfer

3.1 Time Series of the Time Transfer

Figure 1 shows the difference time series between GPS and VLBI clock offsets at KOGANEI station

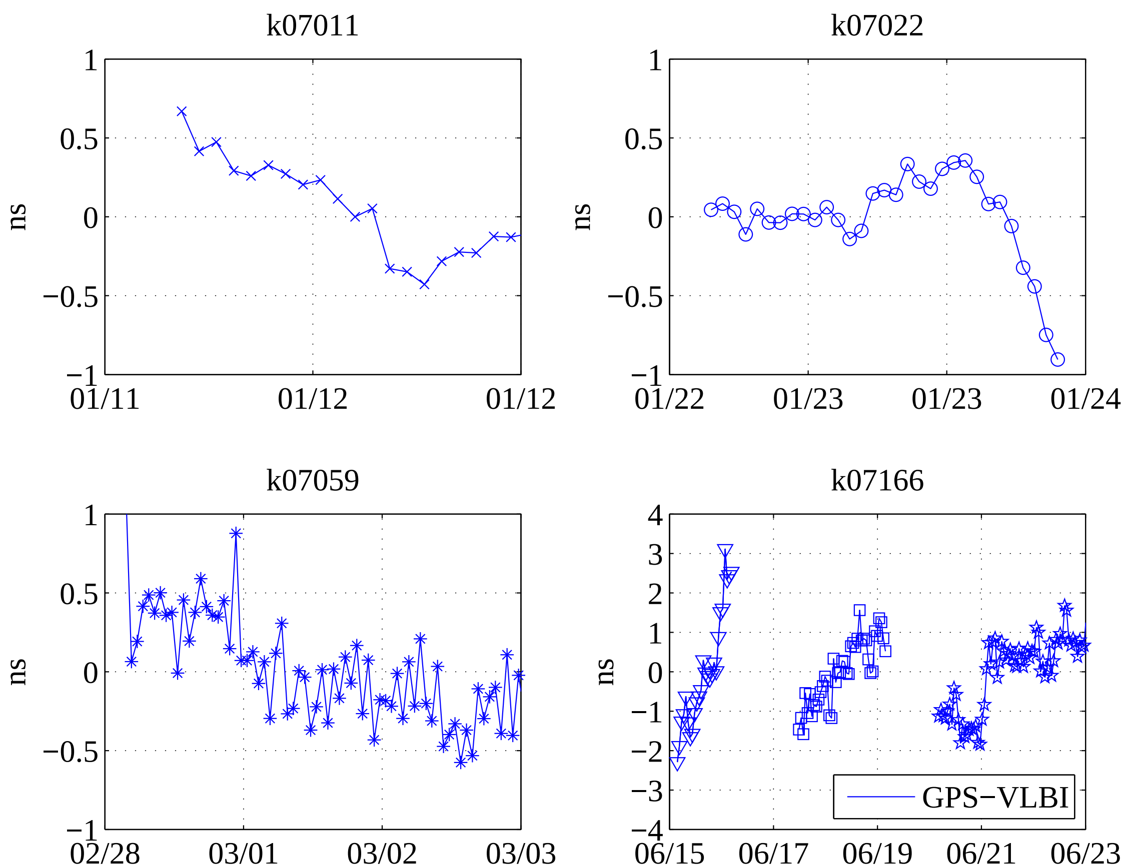

Figure 2. Time series of the difference between GPS clock offsets and VLBI clock offsets at KOGANEI station referred to KASHIMA station

referred to KASHIMA station. We extracted the GPS clock offsets every 1 hour to compare with the VLBI clock offsets, even though GPS clock offsets were estimated every 5 minutes (Carrier Phase method).

The results of the VLBI time transfer were very consistent with the results of the GPS time transfer, in the case of using the receiver for time transfer. The difference between both results were about ±500 picoseconds. In the case of using the geodetic receiver (k07166), the difference between GPS and VLBI were over ±1 nanoseconds. We confirmed that the geodetic receiver is unsuitable for high accuracy time transfer.

3.2 Stability of VLBI Time Transfer

Figure 3 shows the Allan deviation that were calculated from the clock offsets of VLBI (blue), GPS (red), "GPS-VLBI" (light blue) and frequency standard (green and pink).

3.2.1 Kashima 11m - Koganei 11m Baseline

About the Kashima 11m and Koganei 11m baseline (k07011, k07022 and k07059), the stability of the VLBI time transfer (blue dotted lines) are stable than GPS time transfer (red lines) in the period from 3600 seconds to 10000 seconds. But, after 10000 seconds, both stabilities were tended to be unstable. It seems that that change has peak at 30000 seconds. The results of the GPS minus VLBI (the stability of measurement system that removes common noise) were change along the $1/\sqrt{\tau}$ (frequency noise). It means that that peaks were not caused by noise of the measurement system. The first candidate is the distance from the frequency standard to the antenna at KASHIMA station, if except the noise of the measurement system. The distance from the frequency standard to the Kashima 11m antenna is about 200 meter. We calculated the stability of the frequency standard at the recorder of Kashima 11m antenna using

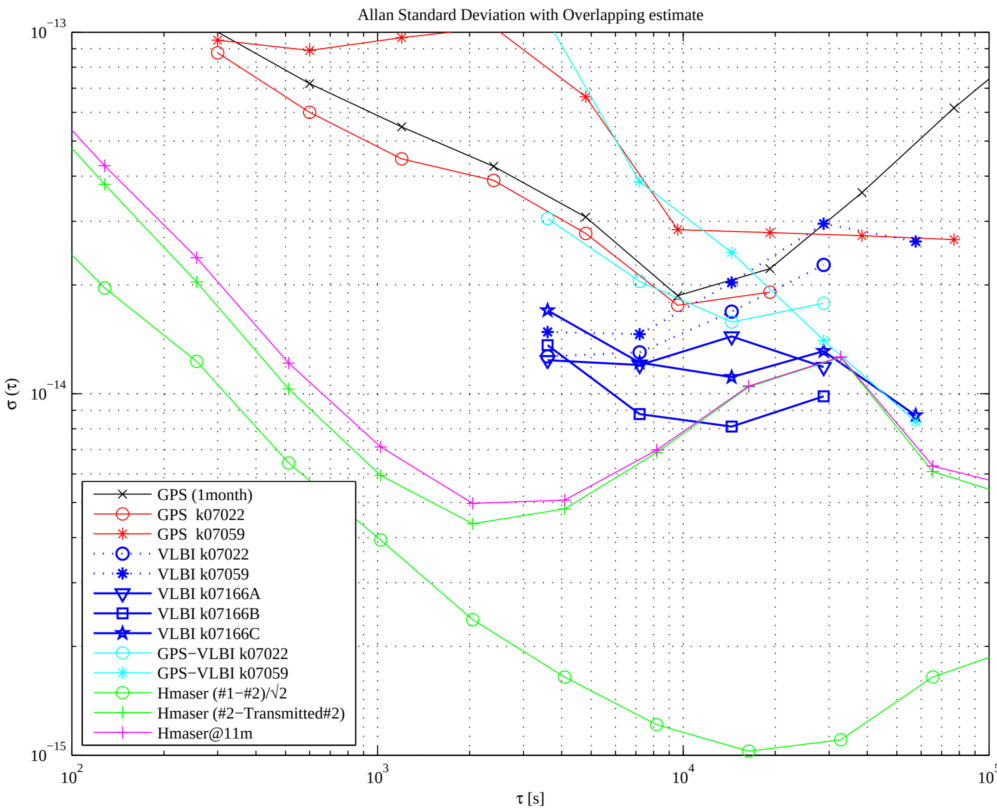

Figure 3. Frequency stability comparison (in term of Allan deviation) between VLBI solution (blue), GPS solution (red), "GPS-VLBI" solution (light blue) and frequency standard (green and pink)

two hydrogen masers (pink line and crosses). The green line and circles in Figure 3 are the stability of the frequency standard in the maser room, the green line and crosses are the stability of the signal turned back from Kashima 11m antenna. The frequency standard at the recorder of Kashima 11m antenna has peak at 30000 seconds like the results of VLBI. It means that the baseline with Kashima 11m is unsuitable for time transfer.

3.2.2 Kashima 34m - Koganei 11m Baseline

The blue lines in Figure 3 are the results in the baseline of Kashima 34m and Koganei 11m (k07166). These stabilities are more stable than the baseline of Kashima 11m and Koganei 11m. And it seems that these stabilities have also small peak at 30000 seconds, but it's not clear. The distance of the frequency standard and the recorder for Kashima 34m antenna is about 10 meter. We can't conclude from only these experiments, it might appear the peak at 30000 seconds (periods of about 16 hours), if the recorder is far some distance from the frequency standard. These results shows that the VLBI time transfer is more stable than GPS time transfer, especially between 3600 seconds to 60000 seconds.

3.2.3 Stability Calculated from the Delay Residuals plus Clock Offsets

We evaluated the stability calculated from the data that added the clock offsets to the delay residuals which were obtained from every scan. Because of the data (delay residuals + clock offsets) is not equal interval, we interpolated that to calculate the Allan deviation. To verify the validity of this interpolation, we extracted the equal interval data and calculated the Allan deviation. Figure 4 shows the results of the k07166 experiment (k07166C, blue crosses). The black line that is Allan deviation calculated from clock offsets, traced the average of distribution of Allan deviation calculated from equal interval data. It shows that Allan deviation calculated from interpolated data like clock offsets and "delay residuals + clock offsets" is appropriateness. The Allan deviation calculated from the data interpolated every 60 seconds is shown in Figure 4 (red line) and Figure 5.

The stability of VLBI changed from stable to unstable between 1000 seconds to 2000 seconds in

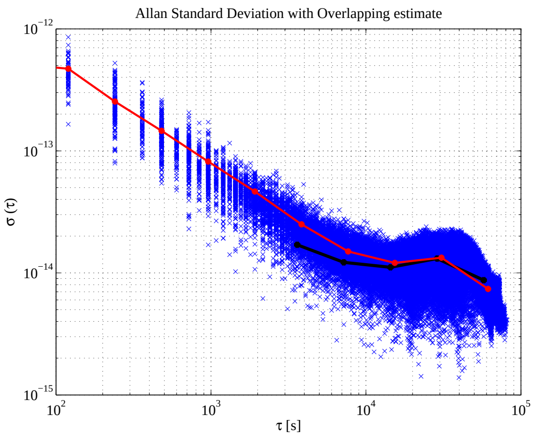

Figure 4. Allan deviation calculated from equal intervals data (blue crosses) and interpolated data every 60 seconds (red line) of the k07166 experiment (k07166C). The black line is the Allan deviation calculated from the clock offsets estimated by CALC/SOLVE.

Figure 5. Synthetically, in term of frequency stability, the Allan deviation showed that VLBI time transfer is more stable than GPS time transfer between 2000 seconds to 60000 seconds (uncertainty of under 3×10^{-14}).

4. Conclusions

To compare the results with GPS Time Transfer (Carrier Phase) and VLBI Time Transfer, we carried out the geodetic VLBI experiments for four times. The averaged formal error(1σ) of the clock offsets when estimated every one hour in the geodetic VLBI analysis procedure (CALC/SOLVE), was 33 picoseconds. Especially, in the K5/VSSP32 system case, the averaged formal error was 29 picoseconds. The results of the VLBI time transfer were very consistent with the results of the GPS time transfer. The difference of both results was about ±500 picoseconds. In term of frequency stability, the Allan deviation showed that VLBI time transfer is more stabile than GPS time transfer between 2000 seconds to 60000 seconds (uncertainty of under 3×10^{-14}). And we confirmed that the "delay residual + clock offsets" estimated from the VLBI analysis software could use for evaluation of frequency stability in term of the Allan deviation. These results are meaningful that we confirmed the stability of the VLBI time transfer in actual exper-

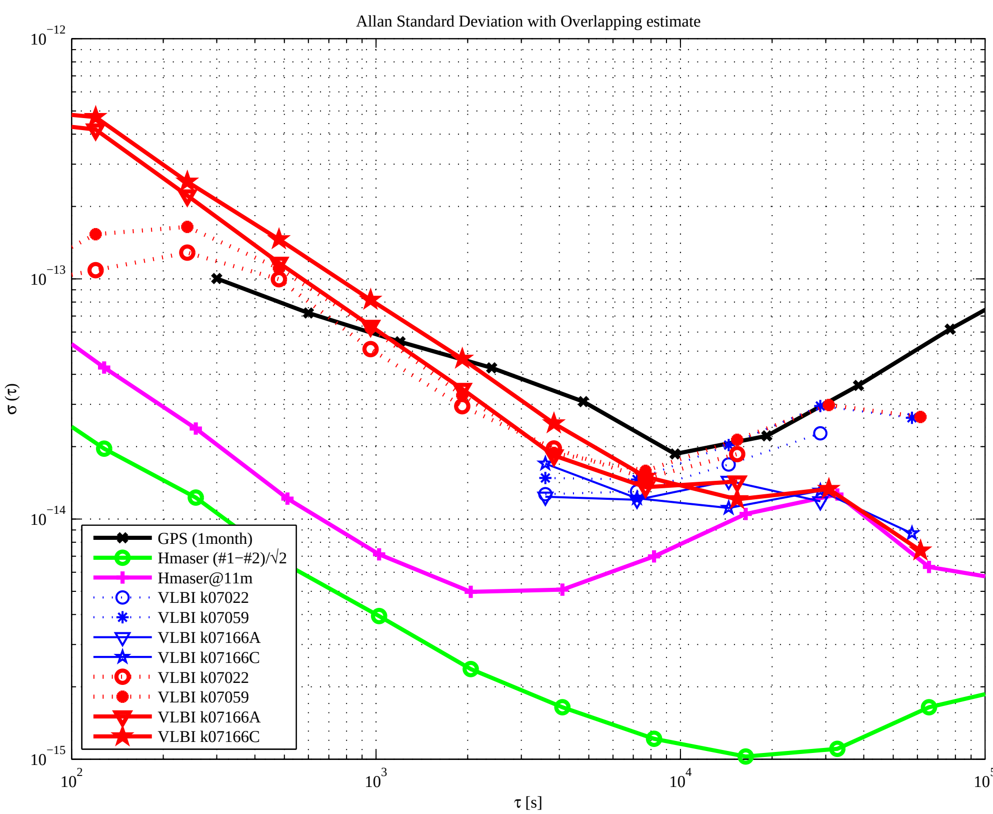

Figure 5. Allan deviation calculated from data that interpolated "delay residuals + clock offsets" every 60 seconds

iment though can expect from the potential of the VLBI system. We will improve the VLBI system aiming at practical use in the future.

Acknowledgments: We would like to thank T. Gotoh and J. Amagai of NICT for their help of GPS observation and analysis. The VLBI experiments were supported by M. Sekido, E. Kawai and H. Kuboki of Kashima Space Research Center.

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Kashima Ray-Tracing Service (KARATS) — Fast ray-tracing through numerical weather models for real-time positioning applications

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Abstract: Numerical weather models (NWMs) have undergone a significant improvement of accuracy and spatial resolution. Therefore such models can be used to correct for the excess delay which is caused when signals are propagation through the troposphere. The Kashima Ray-Tracing Service (KARATS) is capable of reading, re-griding and ray-tracing NWMs which cover East Asia countries including Japan, Korea, Taiwan and parts of China and Russia. Optimized algorithms and the upcoming multi-core technology permit real-time computation of troposphere corrections. First tests have shown that KARATS is capable to remove nearly all of the tropospheric delay and that precision and accuracy of estimated station coordinates are improved significantly.

1. Introduction

The tropospheric delay is still one of the limiting factors that restricts accuracy of space geodetic techniques. But recent investigations (Hulley and Pavlis, 2007 [3]) have shown that the introduction of ray-traced delays from numerical weather models improves the results and helps to remove systematic errors. With the introduction of the 10km mesoscale model by the Japanese Meteorological Agency (JMA) is became feasible to start the development of a ray-tracing service for East Asia which does not only provide tropospheric corrections in real-time but also supports post-processing requests.

2. Ray-tracing through the 10km JMA mesoscale weather model

The 10km JMA mesoscale weather model is utilized to obtain all the necessary information for the correction of tropospheric delays using ray-tracing techniques.

2.1 Tropospheric delay

Electromagnetic signals propagating through the (neutral) atmosphere are delayed since the refractivity index of the gases inside the media is greater than one. E.g., Smith and Weintraub (1952) [6] report that the atmospheric refractivity N (respectively the index of refractivity n) can be computed by

$$N = (n-1)\cdot 10^{-6} = k_1\frac{P_d}{T} + k_2\frac{P_v}{T} + k_3\frac{P_v}{T^2} \quad (1)$$

where P_d and P_v are the partial pressure of dry air and water vapor and T represents the absolute temperature. The physical constants are set to $k_1 = 77.604$, $k_2 = 70.4$ and $k_3 = 373900$, in accordance with (Bevis et al., 1994 [1]). Since numerical weather models provide only values of total pressure P one has to compute the water vapor pressure and thereafter derive the pressure of dry air by applying $P_d = P - P_v$. In an intermediate step the coefficient f, which only depending on the temperature T, can be computed. Finally P_v can be obtained from

$$P_v = \frac{RH}{100}\cdot 10^{\,f} \quad (2)$$

where RH is the relative humidity (in percent), which is also provided from the numerical weather model. When the index of refractivity $n(\vec{r})$ is known along the the ray-path, the atmospheric delay $\Delta\tau_a$ can be denoted by

$$\Delta\tau_a = \underbrace{\int_{atm} (n(\vec{r})-1)\,ds}_{\Delta\tau_e} + \underbrace{\int_{atm} ds - \int_{vac} ds}_{\Delta\tau_g} \quad (3)$$

The first integral in equation 3 is evaluated along the ray from the transmitter through the atmosphere until it reaches the receiver and yields the so-called electromagnetic delay $\Delta\tau_e$. The second term denotes the geometric excess which is caused by a difference of the ray-path when passing the atmosphere compared to vacuum propagation. The integral expression in equation 3 has to be approximated as a finite sum for the case of ray-tracing through a numerical weather model.

2.2 Transformation of the data

Datasets from the JMA are used to compute values of refractivity N at the original grid points. But these points are located on a equally spaced grid whose axes are not parallel to the geographic grid. Moreover a constant grid spacing of about 10km is used, what causes a variation of the geographic distance (in degrees) in dependency of the latitude. Additionally one has to consider that vertical slices of the NWM are provided for constant pressure rather than constant geopotential height. In order to run fast ray-tracing algorithms which utilize these weather models it is necessary to transform, respectively interpolate, the data to an equally spaced geographical grid with height slices given at selected (i.e. constant geopotential) heights. Therefore a sophisticated re-griding algorithm (considering also the ground topography during interpolation) is applied and the data-slices are stored as binary files for follow-on ray-tracing.

2.3 Ray-tracing through the NWM

The ray-tracing class is implemented in "C++" and supports two modes. The first one assumes straight propagation of the ray between two consecutive height levels and computes bending only at the intersection with the height slices. The second mode solves the Thayer (1967) [7] partial derivative equations by an iterative algorithm and thus considers bending all along the ray-path. Table 1 summarizes the height levels used for the computation of the delay. Since the JMA model provides

Table 1. Height slices used for ray-tracing computations

from	to	height steps	Lat/Lon res.
topo.	—	—	$0.01° \times 0.01°$
—	3 km	30 m	$0.1° \times 0.1°$
3 km	10 km	100 m	$0.1° \times 0.1°$
10 km	30 km	500 m	$0.1° \times 0.1°$
30 km	86 km	2000 m	$0.1° \times 0.1°$

only values up to the 10hPa level (i.e. about 32km height) the model is extended by the U.S. Standard Atmosphere (1976) [8] up to 86km. Due to this large number of height-slices the differences between both approaches do not exceed 6 mm at 10 degrees of elevation. Details of the algorithms will be given in Hobiger et al. (2007) [2].

2.4 Performance and results

All necessary routines are coded in "C++" and condensed to a package called Kashima ray-tracing tools (KARAT). It contains all the necessary functions to re-grid the NWM and to carry out the ray-tracing. Moreover a class for manipulating RINEX data has been added and a module for the computation of the observing geometry, using GNSS orbits, has been included. The main ray-tracing class has been prepared for processing on multi-core machines using memory sharing. First tests on a Pentium D, 3GHz using only one core have yielded a ray-tracing though-put of 1200 observation per second. Additionally the time for reading the binary slices has to be considered,too. At the same machine it takes about 3 seconds to load the re-sampled refractivity grids into memory before the ray-tracing can start.

KARAT does not only provide the ray-traced total delay but also gives total bending angle and ground refractivity as output. Figure 1 shows the ray-traced total zenith delays for a selected region around Japan on July 23rd, 2006 at 0h UT. The

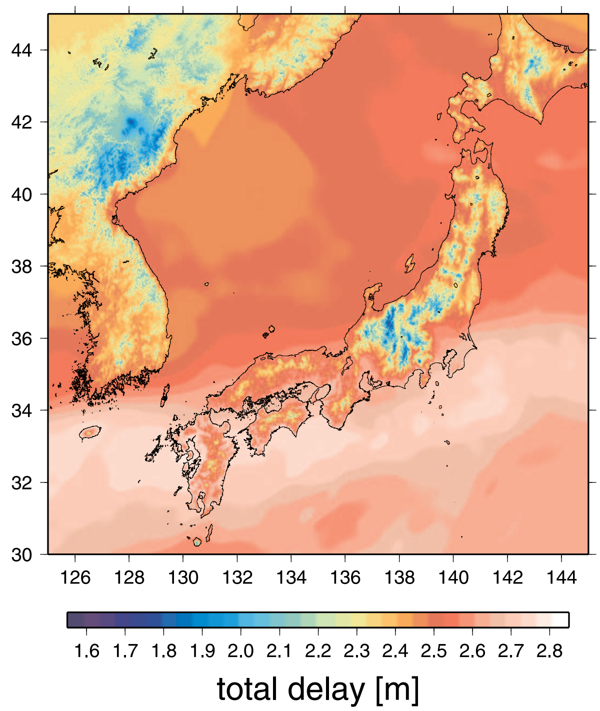

Figure 1. Total zenith delay on July 23, 2006 0UT obtained from ray-tracing through the 10km mesoscale model.

obtained delays do not only reflect the complex weather situation (multiple rain-fronts crossing the South of Japan) but also show that the topography is considered well in the ray-tracing process. The latter model refinement has been achieved by introduction the topography from the Space Shuttle Radar Topography Mission (Rabus et al., 2003) instead of the sparse data given from the JMA. In order to reveal how the ray-traced delays differ from model assumptions used in common analysis strategies GPS station AIRA ($\lambda = 130.5996$, $\varphi = 31.8241$) which is located in the center of maximum rainfall has been selected. The residual delay, i.e. the delay differences between the exact ray-tracing and a symmetrical approximation have been computed for all directions on July 23rd, 2006 at 0h UT at that station. Figure 2 shows the result of this evaluation. Due to the fact that there

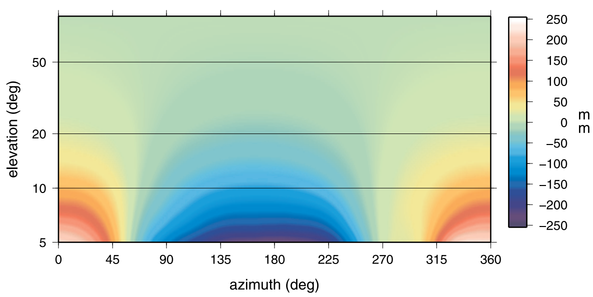

Figure 2. Resid. delay (i.e. the delay excess due to the neglection of asymmetry) at station AIRA on July 23rd, 2006, 0h UT. The elevation axis has been chosen to be of logarithmic scale for better readability.

is a strong North-South gradient of water vapor, caused by the rain fields in the Northern parts, the residual delay characteristics are dominated by this behavior too. Thus the excess delay is positive (i.e. the ray-traced delay is larger than the symmetric delay) in North direction and negative when looking Southwards. Since the residual delays reach values up to ± 25 cm at lowest elevations a noticeable effect of the estimated station coordinates is expected. Ichikawa et al. (2007) [4] have investigated how the site coordinates of AIRA are affected when a symmetrical atmosphere was assumed instead of considering the true weather situation. Thorough investigations about the effect of introduction of ray-traced delays in GNSS analysis are currently ongoing.

3. Kashima Ray-Tracing Service – KARATS

Since the first tests with ray-traced slant delays have shown that station position accuracy and precision can be significantly improved it has been decided to open a service that does the ray-tracing for the user. Thus the ray-tracing tools will be embedded in an automatic processing chain, called Kashima Ray-Tracing Service (KARATS), which can be started via a web-interface. Figure 3 shows how KARATS is going to be working. Once a user (from the GPS or VLBI community) has taken his observations, he can send the data in a common format (which will be RINEX for GPS and MK3/FITS for VLBI at first) via Internet to KARATS. Thereafter the web-server will do a rough data-check and compute the geometry from the observation file. As soon as a ray-tracing client becomes available it will send the geometry file to that machine. The client performs the ray-

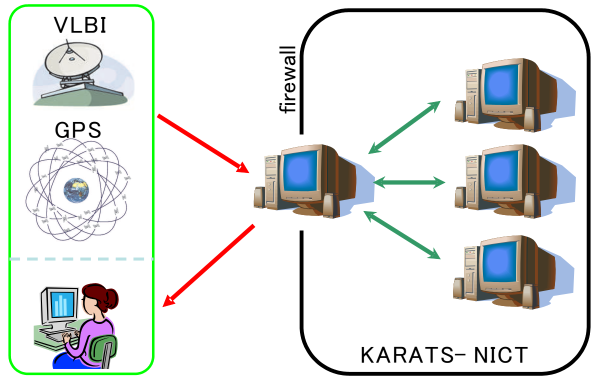

Figure 3. Flow chart of the KARATS processing chain.

tracing through the weather model and sends the tropospheric delays back to the server. Thereafter the ray-traced delays are subtracted from the user's data and a "reduced" observation file is sent back to the user. Thus the analyst can estimate his target parameters without spending too much effort on estimating tropospheric delays. First tests have shown that about 99% of total tropospheric delay are removed by KARATS. Moreover it was found out that it is sufficient to use a simple mapping function, which is independent of any external parameter, to model the remaining atmospheric delay. The KARATS post-processing mode will be free of charge and an turn-around time of one minute per file is aimed at. In the case that VLBI observations are submitted it is checked that both stations lie within the boundaries of the NWM and thereafter the tropospheric delays are computed at each station. In a final step the server will compute the differenced corrections and apply them to the VLBI observations. Up to now it is not planned to support the case that only one station lies within the region supported by KARATS.
Moreover it is planned to run KARATS for real-time applications. Since this mode needs weather prediction data from the JMA it will be limited to a selected user group. In order to determine the maximum load that can be caused by the users it was assumed that 1300 GEONET receivers are streaming their data every second and that on average 12 satellite are tracked by each receiver. This sets the specifications of the data-throughput to about 15000 observations per seconds. Considering that 1200 rays can be computed on a single core machine already, it was concluded that 4 quad-core machines can fulfill the needs of 1Hz GEONET data streams. The real-time mode of KARATS is currently being coded using OpenMP to parallelize the necessary routines. Undertakings to obtain the

NWM forecasts from JMA are ongoing.

4. Outlook

KARATS ray-tracing routines are currently going to be optimized to increase the data throughput. Moreover multi-core support via OpenMP is being implemented and the web-interface and the control scripts are being coded. Currently the 10km mesoscale models cover one year of data starting from April, 2006. Before that epoch only models with a coarser grid width are provided for the whole region covered by KARATS. KARATS is already prepared to treat even finer mesh NWMs, if access is granted by JMA. Additionally it is planned to support other observing formats and techniques, as well as offer the user to analyze the data automatically and send back the results.

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KARATS post-processing mode is planned to be available in the second half of 2007.

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An Evaluation of Geodetic Position Error Simulated using the Fast Ray Tracing Algorithms through the JMA Mesoscale Numerical Weather Data

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Abstract: We simultaneously calculate atmospheric parameters (zenith total delay and a gradient vector) and position errors estimated from atmospheric slant path delays obtained by new ray tracing technique [Hobiger et al., 2007 [1, 2]] through the meso-scale numerical weather data with 10 km horizontal resolution. In this numerical calculation we find that the large horizontal position errors up to 40 mm associated with severe rain fall event.

1. Introduction

We have developed new tool to estimate atmospheric slant path delays by ray-tracing through the meso-scale analysis data for numerical weather prediction developed by Japan Meteorological Agency (JMA) with 10 km horizontal resolution[1, 2] (hereafter, we call this "JMA 10km MANAL data").

The JMA 10km MANAL data which we used in this study is operationally used for the purpose of weather forecast. We have named the tool "KAshima RAytracing Tools (KARAT)"[1, 2]. We evaluate atmospheric parameters (equivalent zenith wet delay and linear horizontal delay gradients) derived from slant path delays using the KARAT.

We also numerically estimate position changes caused by the horizontal variability of atmosphere by means of simulation analysis using the ray-traced slant delays in order to examine the position error magnitude and its behavior under meso-scale atmospheric disturbances. In this short report we describe the preliminary results of our numerical simulation.

2. Numerical simulation

The JMA 10km MANAL data provides temperature, humidity, and pressure values at the surface and at 21 pressure levels (which are equal to steps of several tens meters to kilometers up to about 38 km), for each node in a 10 km by 10 km grid that covers all Japanese islands, the surrounding ocean and Eastern Asia[1]. We first resample the original JMA grid to a modified grid which allows to run the new ray tracing algorithms using analytic expressions. The other details about KARAT are described in an another article of this issue[2].

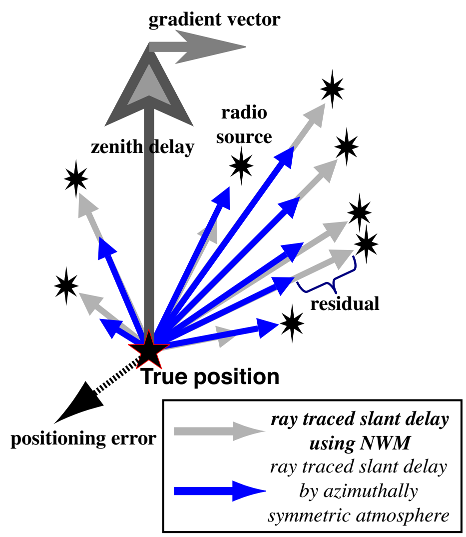

Figure 1. Schematic image showing estimations of atmospheric parameters and position error.

For each virtual receiver location we invert the simulated slant delays using an isotropic and an anisotropic delay model. The isotropic model has only one parameter - the zenith total delay (ZTD). The anisotropic delay model [e.g. Chen and Herring, 1997 [3]] has two additional lateral gradient parameters. We compare the 'true' ZTD, computed by directly integrating the atmospheric refractivity field of the grid data, with the ZTD estimated by least squares inversion of the 'observed' slant delays obtained by ray tracing. We did this using the isotropic and the anisotropic delay model.

In addition we also numerically estimate atmospheric parameters, and site position changes simultaneously from the ray-traced slant delays, assuming single point positioning without coordinate constraints. We consider the vector between the true position and estimated position to be the position error. This estimation is performed to investigate the behavior of the position errors generated by local atmospheric disturbances, the relation between the slant delay errors and the vertical position errors. Our calculation scheme is illustrated in the Figure 1.

At present the 3-hourly operational products are only available by JMA. Thus, a linear time interpolation is used to obtain results at arbitrary epochs what allows also to evaluate temporal change of estimates.

3. Result

We obtain snapshot images of varying position errors for a JMA 10km MANAL data field every three hours. These are quite good for animating ZTD fields and estimated errors. In the west region of Japan islands, heavy rainfall events occurred during July 18-24, 2006. The hourly rain gauge data over southern Kyushu island recorded more than 50 mm. In addition, total rainfall amounts around Kagoshima area during 10 days exceeded 1000 mm.

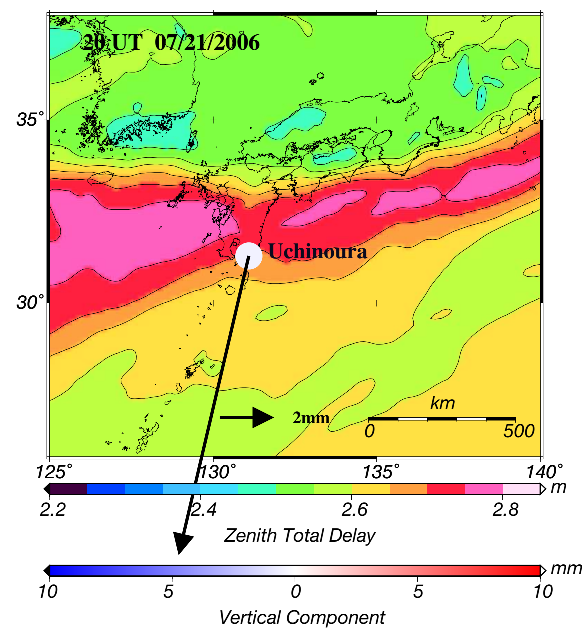

Figure 2. Zenith total delay field and simulated position error at Uchinoura retrieved by the JMA 10km MANAL data at the 2000UT of July 21, 2006.

Figure 2 shows an example of such images showing the estimated error obtained at Uchinoura GPS station, which is located south of Kyushu island, Japan, at 20:00UT of July 21, 2006. We have detected large horizontal position error. The error vector shown in the figure pointed SSW and its magnitude is up to 2 cm. This error is caused by steep water vapor gradient associated with a EW rain band which lies north of Uchinoura. The rain band location coincides a high ZTD band shown in Figure 2. Highly variable position errors associated with same phenomena are also presented after July 19, 2006 (see Figure 3). Especially, a remarkable drop of ZTD and north error component up to 10-40 mm within 10 hours on July 23 is due to a northward moving of the rain band.

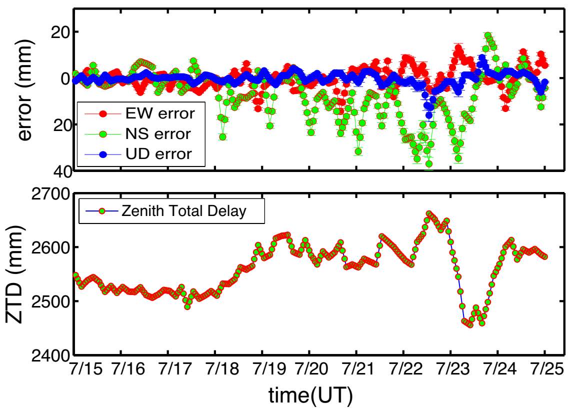

Figure 3. Time series plot of simulated position error (upper) and zenith total delay (lower) at Uchinoura from 14 to 24 July 2006.

4. Outlook

We are now preparing other works to validate an accuracy of the JMA 10km MANAL data and to compare typical mapping functions through one year data sets. We expect such works will help us to improve an accuracy of space geodetic techniques such VLBI, GNSS, and In-SAR.

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Development of the software correlator for the VERA system II

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1. Introduction

The National Institute of Information and Communications Technology (NICT) and the National Astronomical Observatory of Japan (NAOJ) are developing a new software correlation system for the VLBI Exploration of Radio Astrometry (VERA) project. It is constituted combination of the PC-VSI and the software correlator named GICO3. This is a three-year plan and it will have finished at the end of next year. Essential development have finished last year and the first fringe have been detected [1]. The function of handing the multi-beam correlation was installed in the GICO3 system this year, because the two-beam correlations was required for the VERA project. This function can perform processing efficiently for radio sources like maser spots distributed widely and correlation processing time can be reduced drastically. We have verified results of the GICO3 with that of the Mitaka-FX this year. Consequently, there was a good accordance between both correlators. This paper reports the works in this year and current status of the software correlator for VERA system.

2. Software Correlation System for the VERA

Since this software correlation system was designed as a new correlation system for the VERA project, the basic specification were almost the same as that of the Mitaka-FX correlator. However, number of stations, number of FFT points, correlation output speed and number of fringe tracking centers can be set up freely. Since, the Mitaka-FX correlator can handle five VLBI stations at once, the software correlation system have been consisted of five sets of the PC-VSIs (Figure 1). The PC-VSI is one of the VLBI system having the function of recording the VSI signal and correlation processing. It consists of a standard PC , disk arrays and a special PCI board. In the present system, it can record 2Gbps VLBI data for 16 hours using sixteen 1TB hard disks. The VLBI-data recorded in magnetic cassettes are coped into disk arrays of the PC-VSIs and time-division distributed processing are performed at each processors in the PC-VSIs. When correlation processing are completed, correlation results are gathered to one PC-VSI and written in the local file system.

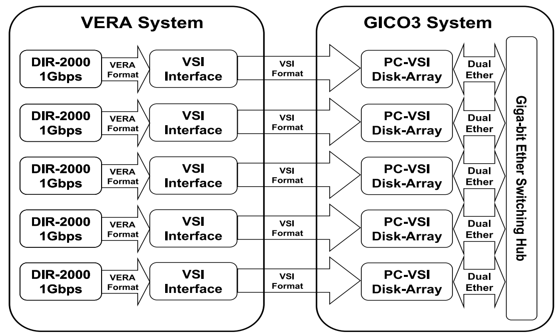

Figure 1. Configuration of the software correlation system

3. Current Component of the PC-VSI and Performance

High performance can be got by using standard PCs, without paying any development cost. Therefore many components of the PC-VSI are general-purpose products except special PCI-board named VSI2000DIM. Present components of the PC-VSI for the VERA system are described in the Table 1. Although expensive parts for the server system are used in this system, one set of the PC-VSI can be bought for about 2.5 million yen. The GICO3 correlation system is designed that can use several sets of PC-VSIs. Usually, the number of the PC-VSI is equal to the number of the observation stations. As a result of performance test in such case, it confirmed that this system had achieved enough processing speed for the VERA project (Figure 2).

Table 1. Current components of the PC-VSI

VSI2000DIM	Digital-Link corp.
CPU	Intel Xeon X5355 × 2
Mother Board	Super Micro X7DBE
Raid Card	High Point RR2340
Hard Disk	SATA 500GB ×16
Memory	FB-DIMM 667MHz 2GB × 2
Case	T-Win RMC3E2-PI-XPSS
OS	CentOS 4.4 for x86-64

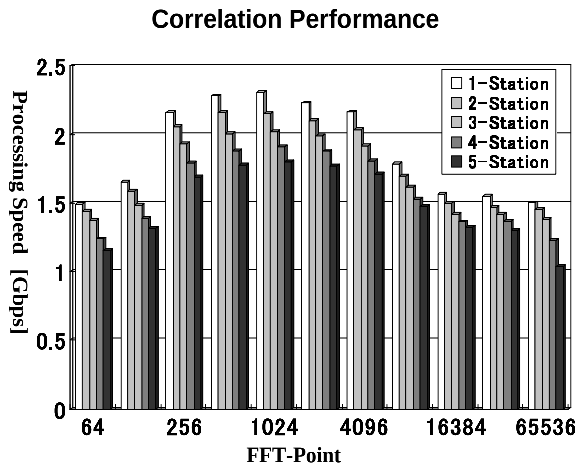

Figure 2. Performance of the multi-baseline correlation by the current PC-VSIs

4. Verification of the Correlation Results

High determination accuracy of correlation-phases and group-delays are required for the VERA project. Therefore, the difference of the correlation system should not change analysis results. In order to confirm whether there are any differences between the GICO3 and the Mitaka-FX, correlation processing was performed on the same conditions and the result were verified.

4.1 Verification of the Regular Correlation

One of the regular observation described in the Table 2 was used for this verification. Figure 3 - 6 show correlation amplitudes, correlation phases, group delays and SNRs of correlation amplitudes of the MIZUSAWA-IRIKI baseline. Although only one baseline was plotted, other baseline were almost the same results. Those figure shows that there was no large difference in the correlation results obtained by the GICO3 and the Mitaka-FX.

Table 2. Information of the observation

Stations	Mizusawa Ogasawara Ishigaki Iriki
Date	2003/328 01:34:00-02:40:00
Mode	VERA-1 (256Msps/2bit/2channel)
Source	A:3C345 B:NRAO512 (dual-beam)
Frequency	A:22.22 GHz / B:22.22GHz

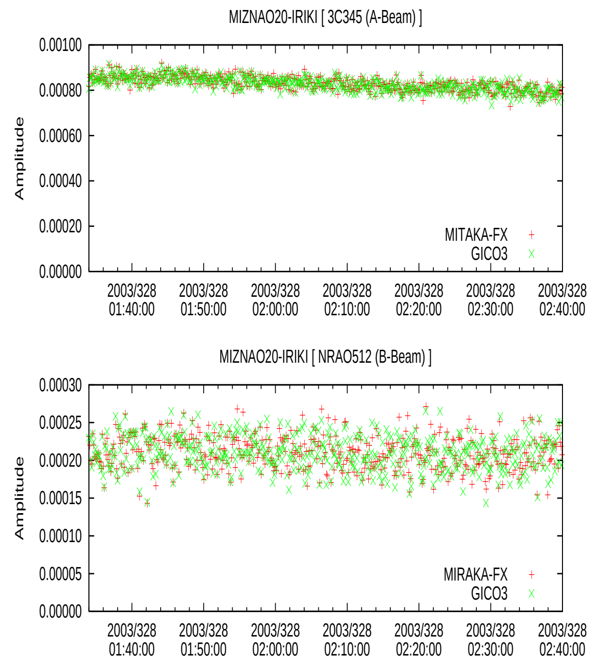

Figure 3. Upper plot shows the correlation amplitudes of 3C345 , lower plot shows that of NRAO512. All integration time is 8 seconds.

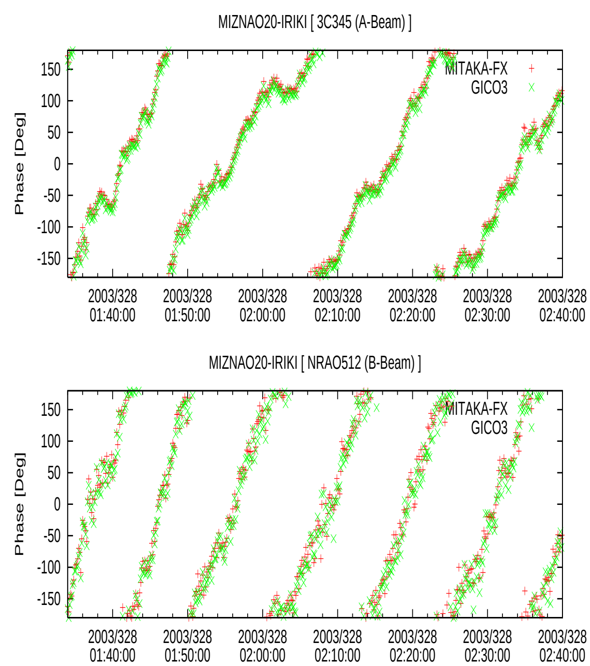

Figure 4. Upper plot shows the correlation phases of 3C345 , lower plot shows that of NRAO512. All integration time is 8 seconds.

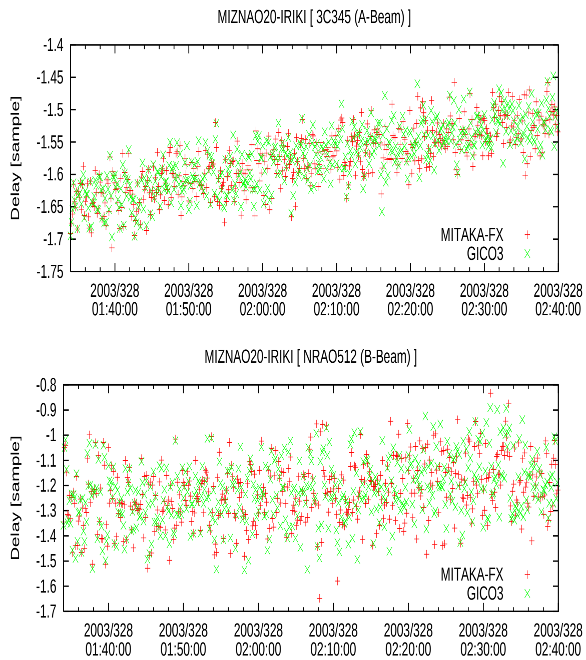

Figure 5. Upper plot shows the group delays of 3C345 , lower plot shows that of NRAO512. All integration time is 8 seconds.

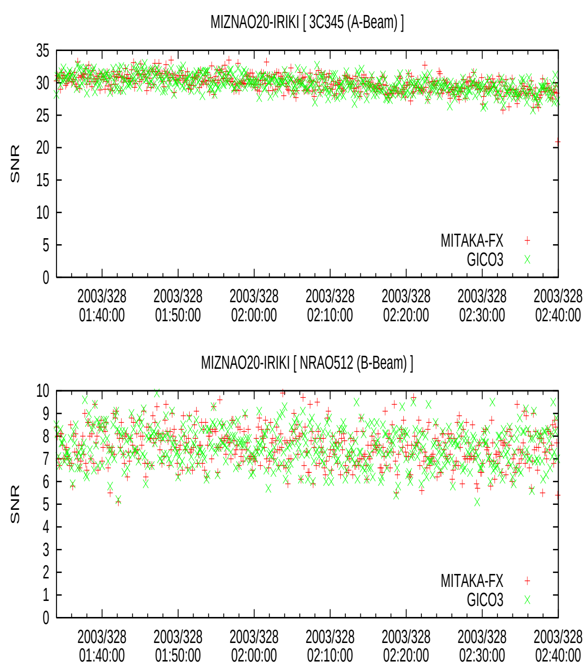

Figure 6. Upper plot shows the SNRs of the correlation amplitude of 3C345 , lower plot shows that of NRAO512. All integration time is 8 seconds.

As described above, group delays and correlation phases are the most important values for the VERA project. Averaged values of the difference between the GICO3 and the Mitaka-FX are described in the Table 3. It cannot be declared that there is a significant difference in the group delay, however, significant difference exists in the correlation phase. In the analysis of the VERA project, radio-sources positions are determined from the phase differences between two sources. In this case, the differential-error occurred by difference correlator is about 1 degree between the GICO3 and the Mitaka-FX, it is an amount which can be ignored for VERA project.

Table 3. Averaged differences between the Mitaka-FX and the GICO3

	Difference Delay [sample]	Difference Phase [Deg]
3C345	+0.0014	-7.45
NRAO512	+0.0031	-8.50

4.2 Verification of the Special Correlation using the Duplicated Tapes

Since correlation results are fluctuated by some observation noises, accuracy of the verification tests between two correlators using regular radio source are limited. If correlation amplitude approaches to 100%, more detailed comparisons will be possible. Therefore, the special correlation was performed using three duplicated tapes and a master tape. In this correlation, some clock offsets and rates as shown in the Table 4 were added each stations. All station positions were changed to the position of the Iriki station and correlation was processed in the same situation as Table 2. Correlation result are shown in the Figure 7.

Table 4. Clock parameters at the each stations

Station	Clock Offset [nsec]	Clock Rate [psec/sec]
IRIKI [Master]	0.0	0.0
IRIKI [Copy-1]	0.0	+1.0
IRIKI [Copy-2]	0.0	−1.0
IRIKI [Copy-3]	+0.1	0.0

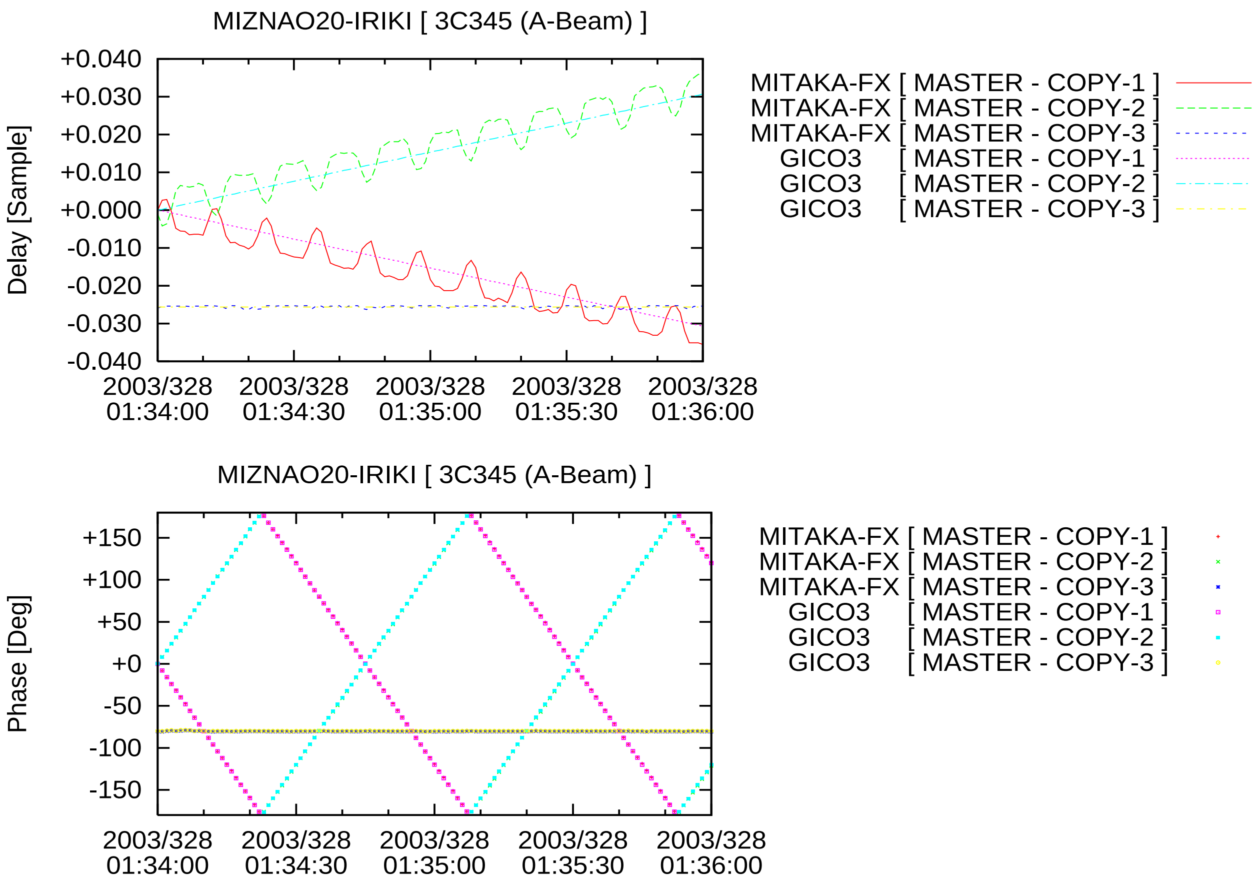

Figure 7. Upper/lower plots shows the group-delays/correlation-phase using the duplicated VLBI tapes. All integration time is 1 seconds.

The characteristic results were obtained about the group delays. The group delay processed by the Mitaka-FX correlator were waved periodically. In contrast, result of the GICO3 located on the straight lines. It was thought that internal operation accuracy cause this difference. Since the real number handled in the Mitaka-FX is expressed with the small number of bits, accurate tracking cannot be performed. Almost all processing in the GICO3 are performed in the 32-bit floating point. In addition, smooth tracking can be possible using the table referencing algorithm which consist of 256 elements of trigonometric functions and random dithering algorithm. However the difference of the correlation phase were not found clearly, the difference will be found by correlation process which gives more smaller rates .

5. Summary and Future

Results of the Mitaka-FX correlator and the GICO3 had been compared intensively this year, almost all results of both correlator were in agreement. Further, it was confirmed that delay tracking accuracy of the GICO3 was higher than that of the Mitaka-FX. Since , there are some processing which are not automation in the software correlation system for the VERA, we will be developing for automation processing in the software correlation system.

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[1] Kimura, M. , Development of the software correlator for the VERA system, *IVS NICT-TDC News*, No.26, pp.26-27,Sep 2005

e-VLBI Demonstration in the JGN2 Symposium

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Abstract: Real-time correlation processing with software correlator was demonstrated in JGN2 symposium held in Hiroshima Japan in January 2007. The e-VLBI demonstration on a intercontinental baseline was realized under the collaboration between MIT Haystack observatory and NICT Kashima. This report describes the e-VLBI demonstration in the symposium and software modules used for data transport and processing. Finally, ultra-rapid UT1 measurement as an application of e-VLBI will be introduced very briefly.

1. Introduction

The e-VLBI has been appeared as a fusion of VLBI and development of computer and network technology. Impact of of e-VLBI is not only quick turn around, but also multiple synergy effect has been induced.

One of the significant points is the improvement of compatibility among different VLBI data acquisition systems. It is caused from the rapid growth of computer technology, which enabled to handle large amount of VLBI data in a personal computer (PC). The easiness to get compatibility among different VLBI system means radio telescopes in the world can be connected more easily to form a synthesized Earth diameter radio telescope. And it will encourage mutual collaborations between international VLBI institutes.

The second point is that software correlation processing has gotten reality to be replaced with hardware correlator. Owing to rapid growth of computational power of personal computer, correlation processing of VLBI data can be finished within a reasonable time or even faster than the recording data rate. Data processing with software correlator gives (1) freedom of designing and chance of implementation of experimental new technique in processing, (2) cutting off the cost and time for development of hardware of the correlator, and (3) broadening the base of research community. As an example of the point (3), we know some groups of universities in the area of computer science are participating the VLBI data processing even if they don't have radio telescope.

NICT is a unique institute, in which VLBI group and network researchers are collaborating together. From viewpoint of network research, VLBI is one of the interesting network contents, which requires high data rate with guaranteed bandwidth. Development of GMPLS (Generalized Multi-Protocol Label Switching) technology is one of the targets in the field of network research. In this report, we introduces the e-VLBI demonstration in JGN2 Symposium as recent our e-VLBI activity and we will present a plan of ultra rapid UT1 measurement as application of the e-VLBI technology.

2. e-VLBI as a Solution of Compatibility

Compatibility among international VLBI systems used to be an issue in the world VLBI community. There are mainly three sorts of VLBI systems: (1) Mark-4, Mark-5, VLBA (2) S2 (Canadian and Australian), and (3) K4, K5, and VSOP system. Copying the data from one format to the other one or mixed correlation processing of data in different formats have been realized in some institutes. Though the compatibility has been still an obstacle for co-observation between observatories equipped with different VLBI systems.

In late 1990's, the idea of VLBI standard interface (VSI) has been proposed by A. Whitney of MIT. And hardware specification (VSI-H)[1] and its software version (VSI-S)[2] have been established under the consensus of world VLBI community. MIT/Haystack and NICT have actively contributed to the establishment of the VSI-H and VSI-S. The essential point of these specification is dividing the data flow from observation to the correlation processing into abstract modules by functions of data input (Data Input Module :DIM), data output (Data Output Module :DOM) and data processing system(DPS). Since VSI specification only defines the interface, then freedom of design was remained in hardware implementation for DIM, DOM, and DPS, where system developers could implement their own idea and skills. As similar with success of OSI's 7-layers network model, the separation of essential functions of VLBI data flow and definition of interfaces between them enabled development of e-VLBI by employment of the latest technology in realization of those abstract modules. As a VSI standard specification for network data transport protocol, VSI-E has been proposed by D. Lapsley and A.Whitney. Since VLBI data can be now handled by software running on PC, data format conversion is no more problem as it was when only hardware could treat such high data rate. Now VLBI data flow from data sampler to the correlation processor may be implemented in transport and application layer of the OSI network model.

3. Real-time Software Correlation Demonstration on the Intercontinental Baseline

We demonstrated a real-time VLBI experiment with software correlator in JGN2 symposium held in Hiroshima city in Japan during 13-14 Jan. 2007. The observation was performed between Kashima 34m telescope of NICT and Westford 18m telescope of MIT Haystack observatory. Mark5-B data sampler was used at Westford and ADS-2000 was used at Kashima 34m.

Since the output interface of the both samplers Mark5-B and ADS-2000 are compliant with VSI-H specification, either of them can be connected to K5/VSI pc-card, which is developed by NICT[3].

This was the first test to confirm the compatibility of hardware connection between Mark5-B and K5/VSI, which are developed by MIT Haystack and NICT, independently. Thanks to accurate implementation of the VSI-H specification, the connection test between different VLBI system was successful and there were no problem in physical, electrical, and data assignment in the connection.

Since data transport tool by means of VSI-E was not fully available at this time, we made some TCP/IP based software for this demonstration. They are composed of VLBI data sender, (VDS), Channel decomposition server (CDS), data distribution server(DDS), and software correlator for real-time data processing. The communication of request and data provision have been made by using TCP/IP. Schematic diagram of the software is displayed in Figure 1. The data request arising from software correlator is passed to the DSS in a binary format of "Payload", which looks like

```
 struct Payload {
// total seconds since 1970/1/1
  uint64_t  epoch;
                 // bits/wire-sream/sec
  uint64_t  length;
  uint64_t  offset; // Bytes
  uint32_t  clock; // Hz
  uint32_t  bit_mask;
}.
```

presented in C source code. The Payload contains time epoch when the data transfer to be started and data length, number of quantization bit, and clock rate. Then the "Payload" is forwarded up to the VLBI data sender. The software in the downstream side works as client and upstream side does

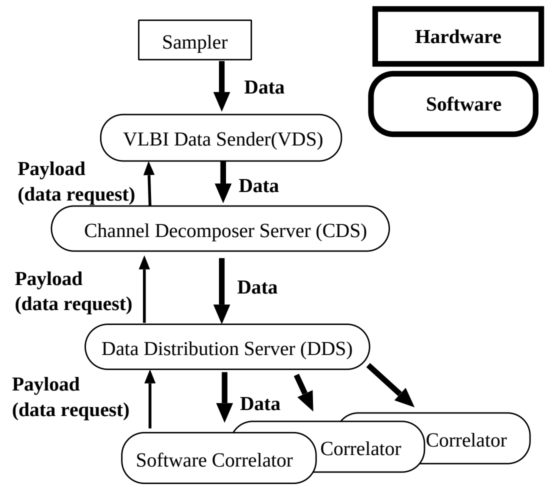

Figure 1. Schematic diagram shows the data flow for one station and relation of software modules. Software correlator sends a request of data to the Data distribution server(DDS) in the "Payload" format. The "Payload" is forwarded up to VLBI Data Server (VDS). The data stream flows in the opposite direction to the path of request coming up. The upstream side works as server and downstream side works as client.

as server. When requested time has come, the VDS start to sending the VLBI data to CDS. The data acquisition mode used in the e-VLBI demonstration was 16channel-1bit-32MHz sampling mode. Totally 512Mbps data rate was sent from VDS to CDS. The CDS extracts specified one channel of data stream from 32 parallel bit-streams, and sends it to DDS after re-packing the data. The DDS was running on a PC at Otemachi in Japan in the e-VLBI demonstration, and the data were distributed to software correlators. Functions of each software modules are listed in Table 1 One of a notable benefit from unification of the interfaces of these modules is that they can work with any different combinations of the modules. For example, Software correlator can receive the data stream directly from CDS by skipping DDS in case of no need of data distribution. Other example is exchanging the position of CDS and DDS. When the capacity of network and that of network interface card (NIC) of PC is high enough to handle multiple VLBI data streams, DDS can be used for multiple distribution of the high bit-rate original data stream.

The route of the data from Westford in Massachusetts was coming to Chicago through the Internet 2 Abilene network. Then it comes through Chicago Starlight connection point to Otemachi in Tokyo via JGN2 network.

The theme of our demonstration in JGN2 sym-

Table 1. Software modules used for the e-VLBI demonstration in JGN2 symposium in Jan. 2007

Module	Function
VLBI Data Sender (VDS)	The VDS works as server waiting for connection. When connection is established from a client and a "Payload" is accepted, it setup its output mode and wait for the starting time of data transfer.
Channel Decomposer Server (CDS)	The CDS works as a server waiting for connection to receive a "Payload". When a "Payload" is received, setup-information such as clock rate and bit mask is set. Then it tries making connection to a specified VDS as client. When the upper connection is established, the same "Payload" is forwarded to the VDS and waits for the data stream will be provided.
Data Distribution Server (DDS)	The DDS works as a server waiting for connection at ports X and Y. When connection is established with port X, the DDS expect to receive a "Payload" from the client. The client connecting to port X is called "master client". The payload accepted at port X is use for setup and it is forwarded to a specified CDS by making connection as client. Clients connecting to port Y is called "dummy clients". When the DDS receives a data stream from the CDS, data stream is provided to the Master client. If some dummy clients are connected as well, the copy of the data stream is provided to the 'dummy clients' in the same way.
Software Correlator	The software correlator generates the "Payload" and sends it to two DDSs for X-data and Y-data. When data stream have come from both stations, time tags of data stream are synchronized and correlation processing is performed.

posium was real-time software correlation via distributed computing. The cluster of PCs were connected with network established by GMPLS. Overview of the network in our demonstration is shown in Figure 2. The e-VLBI demonstration in the JGN2 symposium was successfully finished. The set of server software, which shared the job of data relaying and transformation, worked properly on the intercontinental network. The data stream coming from Kashima and Westford were processed with software correlator in real-time and the plot of interferometric fringe was displayed at venue of the JGN2 symposium at Hiroshima. A brief report of the e-VLBI demo in JGN2 symposium is also on a web[1]. The software modules CDS and DDS are freely available by request(sekido@nict.go.jp). These modules are developed by using "c++" class-library, which was originally developed by D. Lapsley of MIT for VSI-E.

4. Future Plan

As on of the application of e-VLBI, we are challenging pseudo real-time data processing and analysis for ultra rapid UT1 measurement. UT1 is one of the earth rotation parameters, which is uniquely obtained by VLBI observation. And it is important for connecting terrestrial reference frame and the celestial reference frame. Data transfer with high speed network enables to get quick result just after the observation, even the counterpart is as far as opposite side of the Earth. NICT has started joint e-VLBI experiment with Onsala space observatory of Sweden and Metsähovi radio observatory of Finland for ultra-rapid UT1 measurement. In the end of May 2007, we have successfully estimated UT1 within 30 minutes after the end of VLBI observation on Kashima-Onsala baseline. More detail of ultra-rapid UT1 measurement with e-VLBI will be described in the other article.

Acknowledgments: We appreciate many network researcher and engineer of JGN2, Internet2, and Dragon project for cooperated preparation of the e-VLBI demonstration focused on the JGN2 symposium. We thanks to Jerry Sobieski, Chris Tracy, Tom Lehman, (Mid-Atlantic Crossroads), Brian Cashman, Chris Robb, Chris Small, and Rick Summerhill (Internet 2) for supporting this project. We thank Michael Poirier, Mike Titus, Eiji Kawai, and Hiromitsu Kuboki for operation of the radio telescopes at Westford and Kashima.

References

[1] A.Whitney, "VLBI Standard Interface Specification VSI-H" Rev. 1.0 7 Aug. 2000.[2]

[1] http://www2.nict.go.jp/w/w114/stsi/research/e-VLBI/e-VLBI-frame.html

[2] http://www.haystack.edu/tech/vlbi/vsi/docs/2000_08_07_vsi-h_final_rev_1.pdf

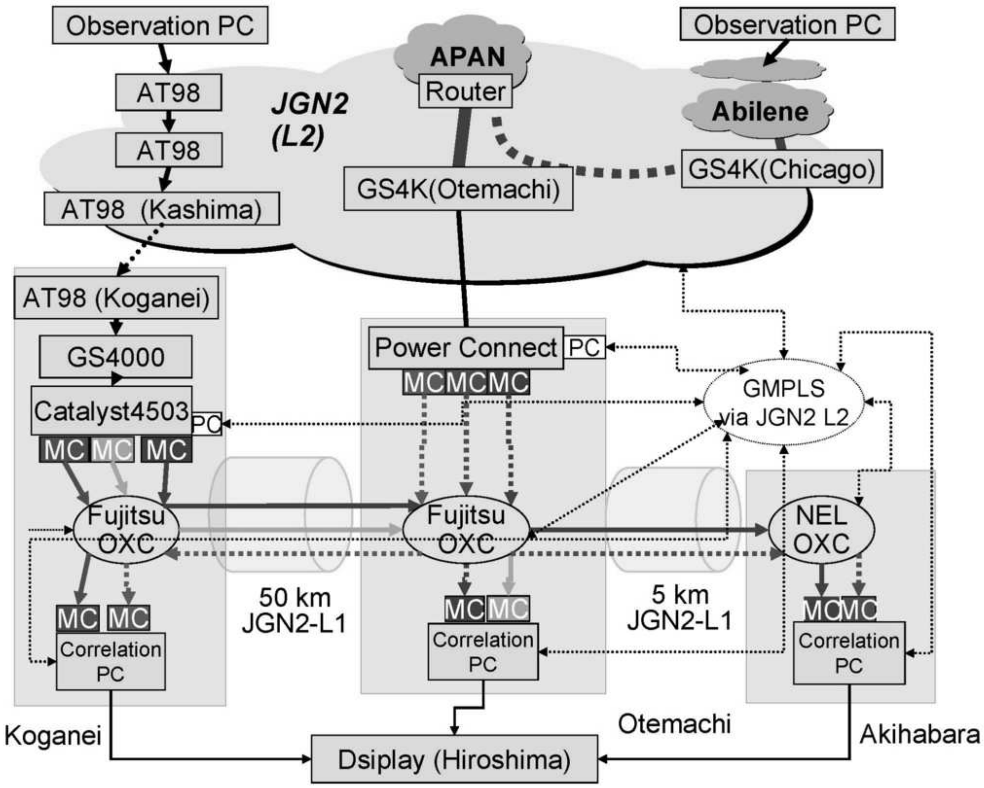

Figure 2. Overview of the network configuration used in the e-VLBI demonstration. The observed data at Westford were transfered to Koganei through the network Glownet-Abilene-StarLight-JGN2. The data from Kashima was transfered to Otemachi through the JGN2. Then data were distributed by the DDS server and correlation was performed at each PC located at Koganei, Otemachi, and Akihabara. These PCs were connected via optical network with different wavelengths. The network paths for data processing were set up by using GMPLS technology. The data stream coming from the two stations were correlated with software correlator in real-time. Then correlation results was displayed at symposium venue at Hiroshima.

[2] A.Whitney, "VLBI Standard Software Interface Specification - VSI-S" Rev. 1.0 13 Feb. 2003.,[3]

[3] M.Kimura, and J. Nakajima, "The Implementation of the PC based Giga bit VLBI system", *IVS CRL-TDC News* No.21,pp.31-33, 2002.

[3]http://www.haystack.edu/tech/vlbi/vsi/docs/2003_02_13_vsi-s_final_rev_1.pdf

Current status of K5/VSSP32 sampler

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Abstract: K5/VSSP32 is a new VLBI sampler unit dedicated to e-VLBI which is a successor to the K5/VSSP unit developed by National Institute of Information and Communications Technology (NICT). Various kinds of check has been finished and it becomes available to use VLBI observations.

1. Introduction

National Institute of Information and Communications Technology (NICT) has developed a new VLBI sampler named K5/VSSP32 equipped with the USB 2.0 interface. After the succession of fringe test using a prototype of K5/VSSP32 [Kondo et al., 2006 [1]], we have been working to improve reliability of sampler and to upgrade software to support K5/VSSP32. This report shows results of some sampler tests and also reports some comparison results between K5/VSSP and K5/VSSP32 through VLBI observations.

2. Observation software

All utility programs developed for K5/VSSP have upgraded to support K5/VSSP32. Some have been newly developed for K5/VSSP32. They are summarized in Table 1 with a brief explanation of function. The software is free and downloadable through our Web site (http://www2.nict.go.jp/w/w114/stsi/K5/VSSP/install_obs_e.html). The software is written by "C". So far it is confirmed that observation software controling K5/VSSP32 can run on the following distribution of linux, i.e., Debian, Cent OS, and Fedra Core.

3. Sampler Check

A coherence check between 4 input channels has been carried out. Common video signals are fed to 4 inputs of K5/VSSP32 (see Figure 1). Sampled data gathered by a host PC through USB 2.0 interface are cross-correlated among channels by using a software correlator. An example of obtained correlation amplitude and delay among channels for five different sampling frequencies from 4 MHz to 64 MHz are shown in Figure 2. As shown in the figure, coherence is kept higher than 0.95 in all cases.

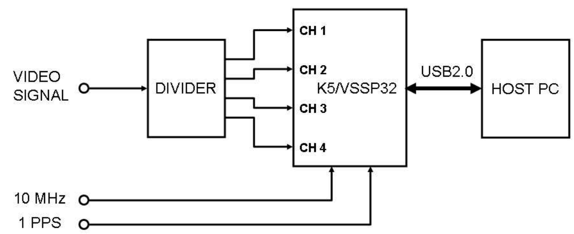

Figure 1. A block diagram for coherence check between channels.

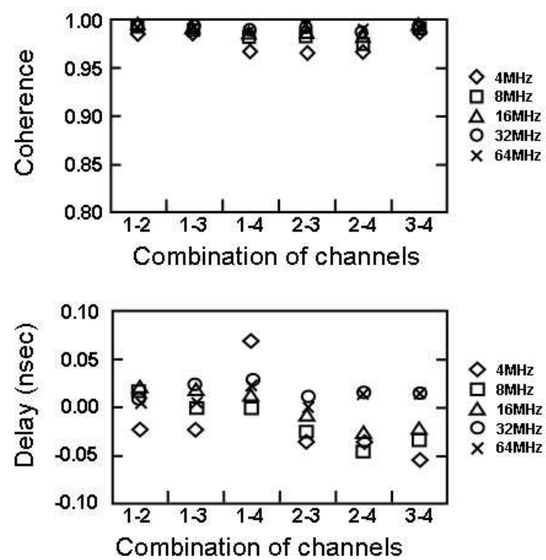

Figure 2. An example of the results of coherence check between channels, CH1, CH2, CH3, and CH4. Coherence (upper panel) and delay (lower panel) among channels.

Instrumental delay of K5/VSSP32 (sampler delay) was measured by using K5/VSSP as a reference. A block diagram of signal connection is shown in Figure 3. Common video signals are fed to both K5/VSSP32 and VSSP which are driven by common 10 MHz and 1 PPS signals. Sampled data are cross-correlated like the case of coherence measurements. Observed sampler delays against

Table 1. K5 observation software.

Sampler Dependent Software	
signalcheck	check reference and 1PPS signals supplied to a sampler
timesettk	set time of a sampler
timeadjust	adjust time of a sampler by 1 sec step
timedisp	display time of a sampler
timesync	synchronize sampler time to 1PPS signal
sampling	triger sampling start and acquire data
sampling2	as same as "sampling" but higher functional capability
autoobs	perform automatic observation using a sampler
monit	monitor input signal level of a sampler
monit2	monitor occurence of error of a sampler for initial checking
setdcoffset	set DC offset of a K5/VSSP32 sampler
pctimeset	set host PC time using sampler time
timesetpc	set sampler time using host PC time (for checking)
timecheck	check false operation in time reading from a sampler (for initial checking)
Sampler Independent Software	
datachk	check sampled data
speana	display spectrum
speana2	display spectrum (higher functional capability)
skdchk	check an observation schedule
extdata	extract data from a sampled data file and output as an aschii file
four2one	convert data file format from 4ch mode to 1ch mode
datacut	extract data for a given period from a data file
adbitconv	convert AD bit resolution of a sampled data file
one2four	combine 4 1-ch data files to a 4-ch data file
data_half	half the samplig frequency by thinning sampled data
data_double	double the sampling frequency by repeat a sample twice
k5v32tok5	convert K5/VSSP32 format data to K5/VSSP format
k5tok5v32	convert K5/VSSP format data to K5/VSSP32 format
data_recov	recover K5/VSSP data header
vssplogana	analyze a log file of "sampling" or "autoobs" and a summary file of "datachk"
aux_recov	recover an auxiliary field of K5/VSSP32 data header
Format Converter between K5 and Mark5	
k5tom5	convert K5VSSP or K5/VSSP32 format to Mark5 format
m5check	analyze Mark5 format data
m5time	display time label in Mark5 format data
m5tok5	convert Mark5 format to K5/VSSP format
m5vex_ana	analyze a VEX schedule file

K5/VSSP at three sampling frequencies, 4, 8, and 16 MHz, are plotted in Figure 4 for the case when an internal LPF (antialiasing filter) is on and off. Sampler delays at sampling frequencies of 32 and 64 MHz can not be measured by this method because the highest sampling frequency of VSSP is 16 MHz. As shown in the figure, sampler delay depends both on sampling frequency and on the use of LPF. The largest sampler-delay reaches about 550 nsec in case of 4 MHz sampling with the use of LPF. The difference in delays between LPF on and off seems to be constant and is about 300 nsec. This delay is caused by a digital filtering processing in a sampler. These sampler delays are constant values if sampling parameters are fixed.

Comparison of VLBI observables, such as delay, delay rate and correlation amplitude, between K5/VSSP and VSSP32 have been made using actual geodetic VLBI observation data provided by Geographical Survey Institute. The data used are those conducted as one of UT1 monitoring experiments on the Tsukuba-Wettzell baseline on April 7, 2007. K5/VSSP and VSSP32 samplers were operated simultaneously at Tsukuba while Mark5 ter-

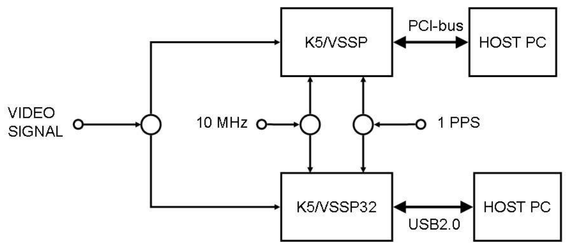

Figure 3. A block diagram for sampler delay check.

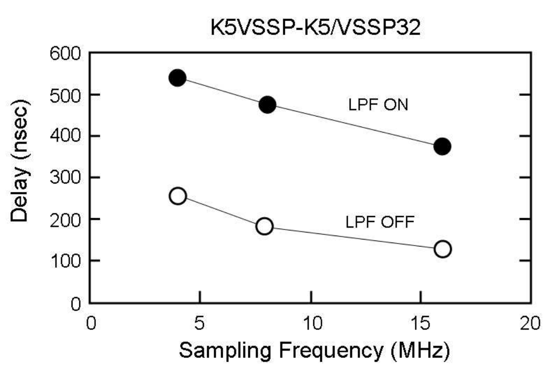

Figure 4. Sampler delays measured relative to K5/VSSP at sampling frequencies of 4, 8, and 16 MHz for the case when LPF (antialiasing filter) is on and off.

Table 2. Summary of comparison results

X-band	Average	One sigma	χ^2
Fine delay	44.2 ps	7.80 ps	0.49
Coarse delay	-20.0 ns	6.74 ns	0.47
Delay rate	0.00 ps/s	0.02 ps/s	0.42
S-band	Average	One sigma	χ^2
Fine delay	12.8 ps	50.3 ps	0.20
Coarse delay	-21.8 ns	2.59 ns	0.89
Delay rate	0.02 ps/s	0.13 ps/s	0.78

minal was operated at Wettzell. Therefore we can compare observables obtained by the combination of VSSP32 at Tsukuba and Mark 5 at Wettzell with those by the combination of VSSP at Tsukuba and Mark 5 at Wettzell. Figures 5 and 6 shows results of comparison for fine search (multi-band) delay, coarse search (single-band) delay, and delay rate as function of time. Table 2 summarizes the average, standard deviation, and χ^2 of differences. Average in difference is not an important factor in this study because it will be removed as a clock offset. An important factor is the scatter of differences that can be evaluated by a χ^2 value. They are less than unity, it is therefore concluded that no serious scatter exceeding thermal noise remains between differences of observed values.

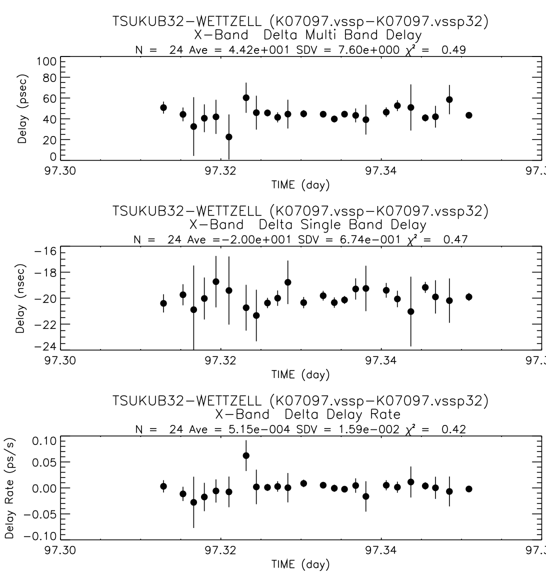

Figure 5. Comparison results of VLBI observabales, fine search (multi-band) delay (top panel), coarse search (single-band) delay (middle), and delay rate (bottom) at X band, between K5/VSSP and VSSP32. The data observed on Tsukuba-Wettzell baseline on April 7, 2007 were used for comparison.

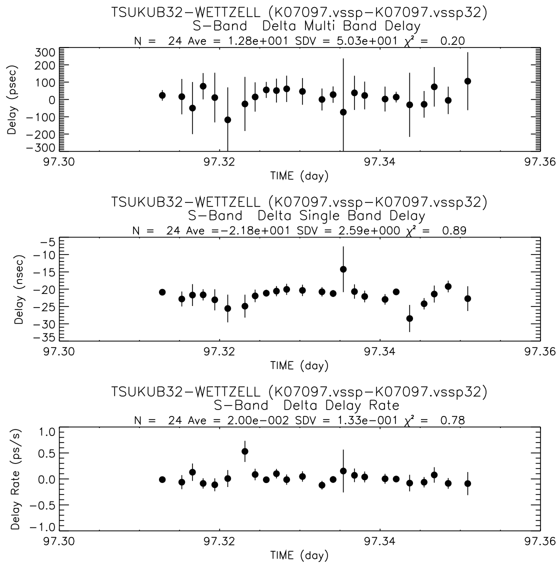

Figure 6. Same as Fig.5 but for S band.

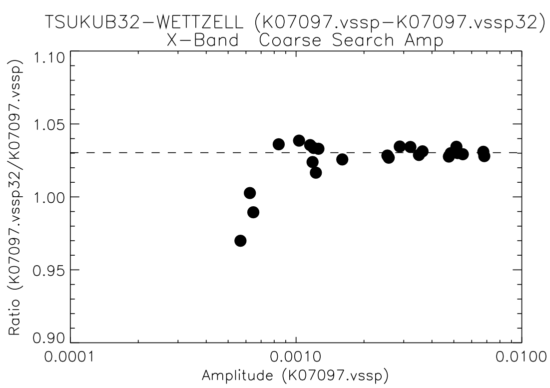

Figure 7. Comparison results of correlation amplitude at X band.

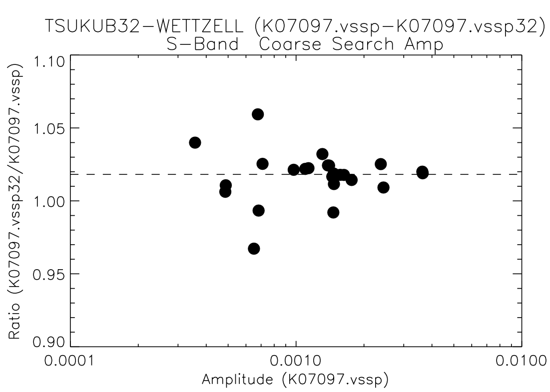

Figure 8. Same as Fig.7 but for S band.

In Figures 7 and 8 the ratio of correlation amplitude observed by K5/VSSP32 and VSSP is plotted as function of VSSP's correlation amplitude. As shown in the figures, correlation amplitude observed by K5/VSSP32 is about 3 % lager than that of VSSP at X band and about 2 % at S band. This means that coherence loss of K5/VSSP32 is less than that of VSSP.

4. Conclusion

A new sampler K5/VSSP32, which is a successor to the K5/VSSP and is equipped with a USB 2.0 interface, has been developed. Coherence check and comparison study with K5/VSSP have demonstrated that K5/VSSP32 has a sufficient (or better) performance as a VLBI sampler. Regarding a clock offset arising in a sampler, K5/VSSP32 has a larger clock offset than VSSP. Even though the offset is a fixed value and can be compensated later, it is desirable to be removed in advance in a sampler. This improvement will be made in near future.

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[1] Kondo,T., Y. Koyama, H. Takeuchi, and R. Ichikawa, A new VLBI sampler K5/VSSP32 developed by NICT, *IVS NICT-TDC News*, No.27, 5–8, 2006.

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