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CONTENTS

Research and Developments for the Second NICT Mid-Term Research Plan (2006-2011)

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Abstract:

NICT had completed its first so called 'mid-term research plan' and has just started the new research plan since April 2006. As a technology development center and other various components of the IVS, research and developments plan related with VLBI has been defined by focusing to integration of the space and time standards and their applications for the public life. In the second mid-term research plan, NICT will focus its efforts to realize real-time VLBI observations with large scale observing networks using the e-VLBI methods and to realize accurate baseline length measurements using two small aperture antennas and one large aperture antenna.

1 Introduction

On April 1, 2001, the Communications Research Laboratory (CRL) became an Incorporated Administrative Agency. Before this date, the laboratory was belonging to the Ministry of Internal Affairs and Communications of the Japanese government. On the same date, 57 governmental institutes including many research and development laboratories became the Incorporated Administrative Agency. Unlike the institutes directly belonging to the Japanese government, the Incorporated Administrative Agencies are given certain level of independence from the government for their managements. Foe example, the total number of research staff in the laboratory and allocation of the research resource to each project can be determined without a restriction. Instead of these flexibilities, all agencies have to define the so called 'mid-term plan' and the plan have to be reviewed by the supervising minister of the government. The period of the mid-term plan can be determined by each agency and NICT defined its period as 5 years. After the period of the mid-term plan has past, the achievements and effectiveness of the agency are reviewed by the supervising minister with a help of professional advice from the external reviewing committee. The results of the review process are referred to determine the grant budget for the next mid-term plan of the agency.

Although the CRL was merged with the Telecommunications Advancement Organisation (TAO) in 2004, and the NICT was established as the new Incorporated Administrative Agency, the initial mid-term plan of the CRL was succeeded by the NICT. The first mid-term plan then just completed in March 2006. Since April 2006, a new mid-term plan started for another five years of period.

In this report, the achievements of the first mid-term plan will be summarised and then the outline of the second mid-term research plan related with the VLBI technology will be described in this paper.

2 The first mid-term research plan (2001-2006)

The first mid-term plan of NICT (and CRL) was conducted during the five years of period since April 2001. The research and developments related with the VLBI were conducted in the Radio Astronomy Applications Group of the Applied Research and Standards Department. In the department, three major research fields were defined, i.e. remote sensing technologies, outer space weather forecast, and space and time standards. The Radio Astronomy Applications Group was one of the six research groups in the space-time standards research field.

The VLBI related research and developments were performed to develop elemental technologies required to establish space-time reference coordinate frames on the Earth and in the outer space. The research theme was divided into the two subthemes. One sub-theme was to establish precise ITRF and ICRF reference frames and to determine Earth's orientation parameters in near real-time. For these purposes, the K5 observation and data processing system was developed, and e-VLBI demonstration observations were performed through the cooperations with many research institutes including Haystack Observatory, Joint Institute of VLBI in Europe, Shanghai Observatory, Urumqi Observatory, Australia Telescope National Facility / CSIRO, Swinburne University of Technology, Internet2, Super-SINET, JGN2, NTT Laboratories and TransPAC. In June 2004, one-hour demonstration e-VLBI session was performed and UT1-UTC was estimated within 4.5 hours after the observing session by immediately processing observed data using the K5 software correlator (Koyama, et al., 2003: Koyama, et al., 2006). Dur-

Table 1: Six groups in the space-time standards research field.

Name of the group	Main objective of the group
Atomic Frequency Standard Group	R&D of atomic frequency standard
Time and Frequency Measurements Group	R&D of Precise time and frequency transfer, and highly stable time scale
Japan Standard Time Group	Dissemination of time and frequency standard
Radio Astronomy Applications Group	R&D of precise space measurement
Quasi-Zenith Satellite System Group	R&D of satellite positioning system using Quasi-Zenith Satellite System
Time Stamp Platform Group	R&D of time stamp technology

ing the first mid-term research plan period, various components of the K5 VLBI system have been developed and completed. Various A/D sampling speeds (from 20kHz to 2GHz) are supported by using one of the five different AD sampling units: i.e. K5/VSSP, K5/VSSP32, ADS1000, ADS2000, and ADS3000 systems. Linux or FreeBSD Unix PC system, the data can be recorded up to 2Gbps using single PC system. 2GHz 2bits/sample (4Gbps in total) sampling mode can also be recorded by using two PC systems in parallel. The interface between the AD sampler unit and the PC recording unit is designed to be compliant with the VSI-H (VLBI Standard Interface - Hardware) specifications. K5 software correlator has been used for various observation modes. Currently, the K5 software correlator system is used by Geographical Survey Institute (GSI) at Tsukuba to process Tsukuba-Wettzell baseline weekly intensive VLBI sessions, and domestic geodetic VLBI sessions. The software was also adopted by the National Astronomical Observatory of Japan to develop the backup correalator for their VERA (VLBI Exploration of Radio Astrometry) project (Machida, et al., 2006).

The other sub-theme was to determine precise position of spacecrafts by using VLBI technique. Geotail, Nozomi, and Hayabusa spacecrafts were observed by using the K5 VLBI system through the cooperations with Institute of Space and Astronautical Science / JAXA, National Astronomical Observatory of Japan, Canadian Space Agency, GSI Yamaguchi University, and Gifu University (Sekido, et al., 2005). From the observations of Hayabusa spacecraft during its touching-down operation in November 2005, the phase-delay measurements obtained by the VLBI observations were compared with the calculated predictions using the precise orbit of the Itokawa asteroid, and the consistency between these two values were confirmed. The results presented positive expectations that VLBI observations can improve the position determination of spacecrafts.

3 The second mid-term research plan (2006-2011)

For the second mid-term research plan period, the internal organisations of the NICT were reformed to corresponding to the new research plan. The six research groups listed in the Table 1 were merged into one group and the Space-Time Standards Group. The new group is one of the four groups in the newly established New Generation Network Research Center. The objective if the group it to improve time and frequency standards and spatial reference coordinate frame, and to disseminate benefits from the accurate and reliable space-time standards to the public activities. Developments and improvements of optical frequency standards will be performed in the group. The improvements of reliability of the Japan Standard Time will also be performed. VLBI related research and developments will be performed to improve the spatial reference and standards. In Figure 1, the concept of the space-time standards group is illustrated.

The objective of the group is to support safe and reliable public activities and advanced science and technology R&D by means of precise, accurate, and reliable information of spatial position and time. To achieve this objective, the group will perform various R&D to 'generate', 'measure', and 'disseminate' space-time standards. VLBI or e-VLBI is one of the fundamental techniques which measures the spatial reference coordinate frames, earth's orientation, and the absolute standard of length to be used in the ground survey. In Figure 2, the various research themes of the space-time standards group are illustrated.

R&D related with the VLBI and spatial reference measurements are done under the space-time standards integration project defined under the space-time standards group. At Kashima Space Research Center, e-VLBI R&D will be continued from the previous mid-term research plan to realize real-time VLBI data processing with global scale VLBI network with more than two stations. To realize this target, we are considering to enhance the K5 software correlator capability to make it possible to process the data stream from the observing sites in real-time. By adopting the standardised protocol defined under the VSI-E (VLBI Standard Interface - Electronic) specifications. In addition, we are planning to realize large scale distributed processing using multi-cast of the data stream and the use of high speed network GRID.

In addition to the e-VLBI R&D, we are starting to develop a pair of small aperture antennas to establish absolute standard of length to be used as a reference from other surveying techniques including the GNSS (Global Navigation Satellite System) receivers with a close cooperation with GSI. As the authorised organisation to maintain quality of ground surveys performed in Japan, GSI is responsible to calibrate surveying instruments including GNSS receivers. For this purpose, there are several reference baseline with the typical distance of 10 km to be used to calibrate the ground surveying instruments. The distance of 10 km is too long to be calibrated by direct measurements with laser technique, and VLBI is considered to be the most reliable method as a reference. By using a pair of very small antennas, it is expected we can avoid gravitational deformation and the antenna structures and the two rotation axes (Az&El) to precisely intersect. Since the VLBI measures the baseline length between two reference points geometrically from the frequency standard, the results are considered to be traceable to the fundamental physical standards. To perform accurate baseline length measurements with the two small aperture antennas, we need to use one large aperture sensitive antenna. By subtracting two time delay measurements with large-small pair of the antennas, we can obtain time delay between the two small antennas which is free from the effect of gravitational deformation of the large antenna (Figure 3). Since the sensitivity of the large-small pair of the antennas are not as high as the usual VLBI baselines, it is essential to use high speed AD sampler systems to improve the sensitivity.

Both of the VLBI related R&D described above are challenging research themes. It is obvious they

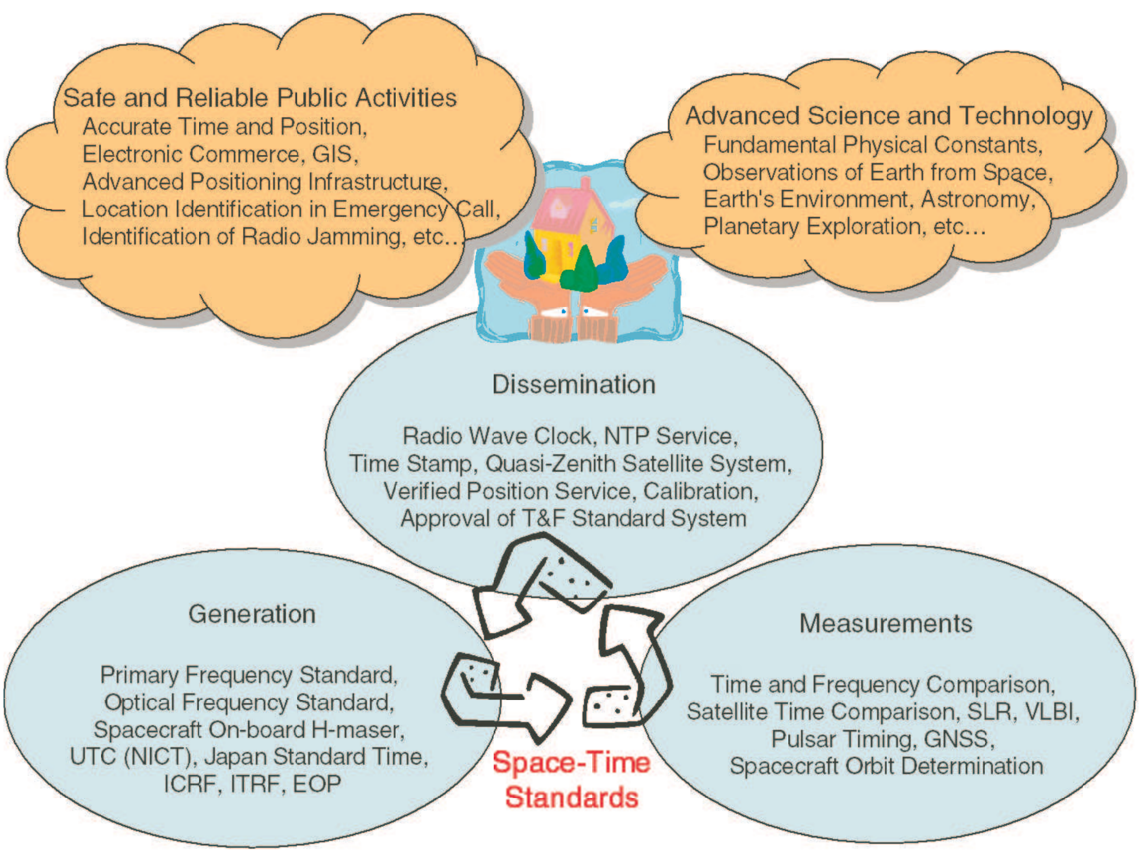

Figure 1: Concept of the space-time standards group.

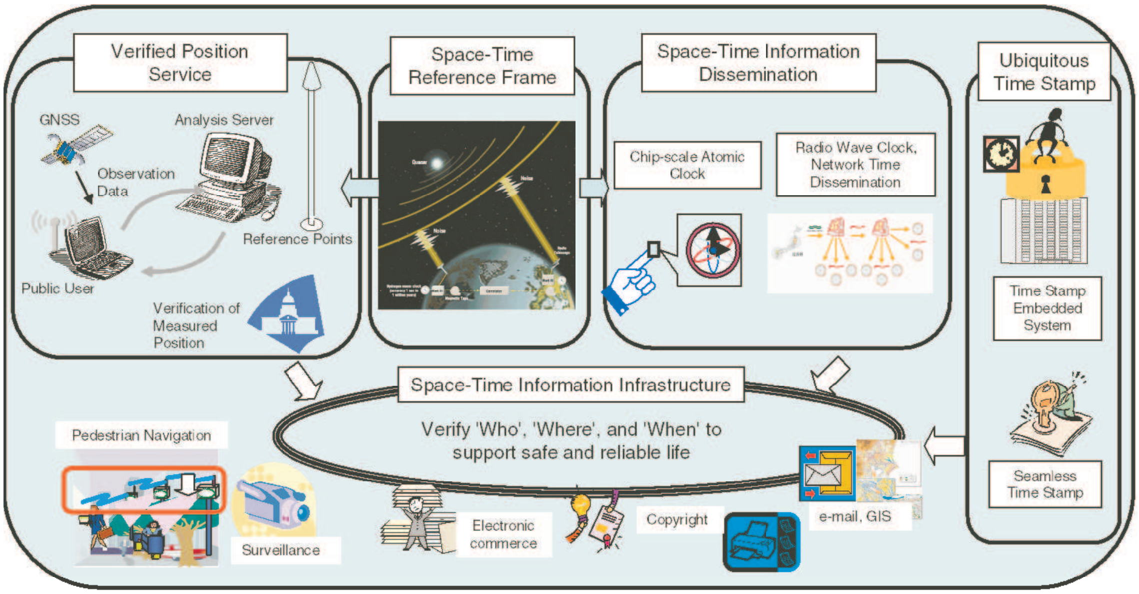

Figure 2: R&D research themes in the space-time standards group.

will not be achieved by NICT alone, but we expect we can achieve the goals by collaborating with many related organisations. We also expect the research and developments we will perform will contribute to realize VLBI2010.

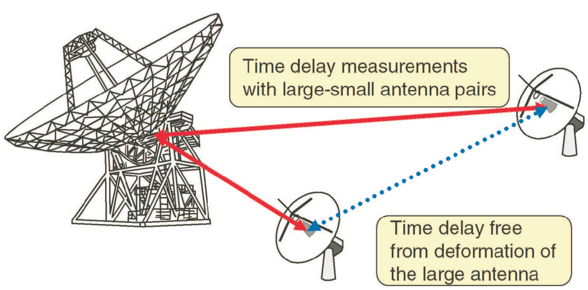

Figure 3: Concept to realize absolute standard of length by VLBI.

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A new VLBI sampler K5/VSSP32 developed by NICT

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[2] *ISAS/JAXA*

Abstract: National Institute of Information and Communications Technology (NICT) has developed a new VLBI sampler unit named K5/VSSP32 dedicated to e-VLBI which is a successor to the K5/VSSP. The new sampler is featured by the use of USB 2.0 interface as well as a faster sampling frequency. It enables us to use a variety of PCs as a host PC for VLBI data acquisition, such as a notebook PC as well as a desktop PC.

1 Introduction

Samplers developed by NICT are categorized into two series: 1) ADS series sampler equipped with a VSI-H interface; 2) VSSP series sampler not equipped with a VSI-H but directly connectable to a host PC. Recently we have developed a new sampler named K5/VSSP32 belong to the VSSP series. We describe the chracteristics of this new sampler and results of fringe test using this sampler.

2 Characteristics

K5/VSSP32 (see Figs.1 and 2) is a successor to the K5/VSSP, but a USB 2.0(Universal Serial Bus specification revision 2.0) is newly adopted as an interface with a host PC instead of a PCI-bus interface adopted in the K5/VSSP. Therefore we can use even a notebook PC or a laptop PC as a host PC of the sampler, if we hope so. Both 5 MHz and 10 MHz are allowed as the frequency of reference signals of the K5/VSSP32 unit, and they are automatically detected and switched by the unit. Maximum sampling frequency per channel is increased up to 64 MHz, which is four times faster than that of K5/VSSP's (16 MHz). Maximum data rate of a unit is increased to 256 Mbps in accordance with the increase of the maximum sampling frequency, which is also four times faster than that of K5/VSSP's (64 Mbps). As a K5/VSSP32 unit has 4 channel analog inputs, 4 units can cover 16 channels which is sufficient number of channels in case of geodetic VLBI. Table 1 summarizes specifications of VSSP series.
The number of bits in a header block in a frame data is increased to 256 bits to accommodate more information in the header, which is four times larger than that of K5/VSSP's (64 bits) and is extendable. Table 2 shows the typical format of the header block. An auxiliary field is a field set from a host PC, so that the content of the auxiliary field is freely definable according to the purpose of experiment.

3 Results of fringe test

A fringe test using a K5/VSSP32 unit was carried out between a 34m antenna and an 11m antenna (baseline length is about 149 m) at Kashima Space Research Center on November 10, 2005. A note PC

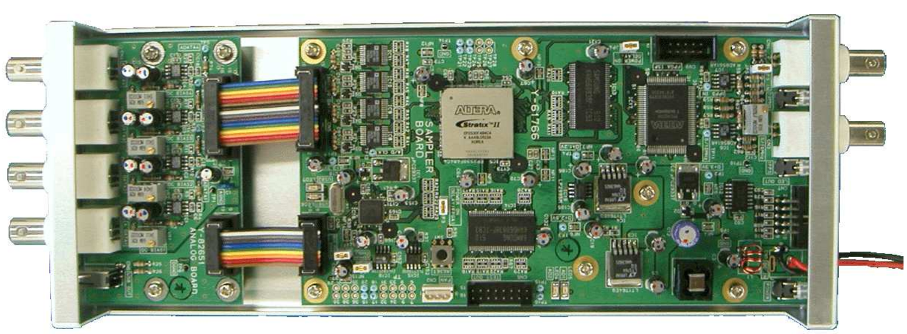

Figure 1: A K5/VSSP32 unit.

Figure 2: A K5/VSSP32 16 ch module.

was used in addition to desk-top PCs in observations. In the fringe test, video output signals with a 32MHz bandwidth are fed to a K5/VSSP32 unit. Five scans were observed with changing both radio stars between 3C345 and 3C84 and the sampling frequencies between 32 MHz and 64 MHz, respectively. Both units used in the fringe test were a prototype model of K5/VSSP32 and were not implemented with a digital filter to prevent aliasing. Thus a low-pass filter with the cutoff frequency of 16 MHz is inserted between a video output and a K5/VSSP32 unit (see Fig.3) to prevent aliasing in the case of a 32 MHz sampling. Observed data were correlated by using K5 software correlator [*Kondo et al.,* 2004], and fringes were successfully detected for all scans as shown in Fig.4. Periodic component with a period of 0.2 μsec seen in the delay direction (seen clearly in Scan #1) is due to the phase calibration (PCAL) signals injected to both antennas. Correlations between PCAL signals appear as periodic signals with the period being inverse of the least common multiple of each PCAL signal's frequency step, i.e., 0.2 μsec(=1/5MHz). Baseline length is short ($\sim$149 m) and expected fringe rate is only 0.1 Hz or less. Moreover integration period is only 5$\sim$6 seconds, so that correlations between PCAL signals are not well-separated from those derived from the radio source on the fringe rate domain. Although correlations of PCAL signals are overlapped with fringes from the radio source, we can see a clear peak at the center on the delay and fringe-rate space for all scans.

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. K5/VSSP32 has the maximum sampling frequency of 64 MHz that is four times faster than that of K5/VSSP's. Adoption of USB2.0 interface enables us to use a variety of PCs as a host PC of the sampler, such as a notebook and/or a laptop PC as well as a desktop PC. Thus K5/VSSP32 can be used for a not only a VLBI observation but also a general-purpose geophysical observation using a notebook PC which requires precise time label.

Reference

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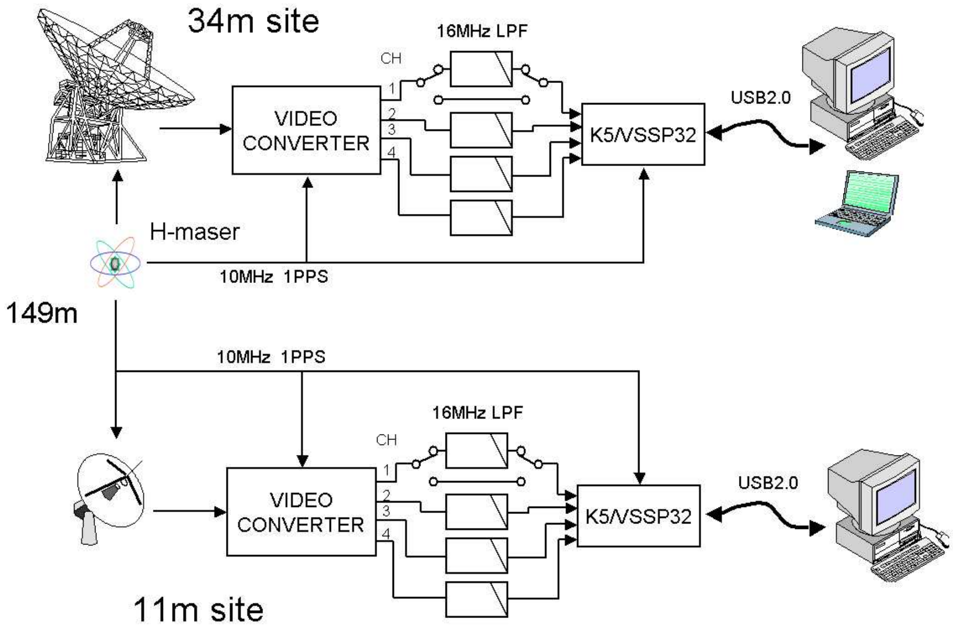

Figure 3: A block diagram of fringe test.

Table 1: Specifications of VSSP series samplers.

	K5/VSSP	K5/VSSP32
Reference Signals	10 MHz, 1 PPS	10/5 MHz, 1 PPS
Number of Input Ch/unit	4	4
A/D bits	1, 2, 4, 8	1, 2, 4, 8
Sampling Freq.	0.04, 0.1, 0.2, 0.5,	0.04, 0.1, 0.2, 0.5,
	1, 2, 4, 8, 16 MHz	1, 2, 4, 8, 16, 32, 64 MHz
Maximum Data Rate	64 Mbps/unit	256 Mbps/unit
	256 Mbps/4units	1024 Mbps/4units
Interface with PC	PCI-bus	USB2.0
Function	—	digital LPF

Table 2: Typical header format (#1) of K5/VSSP32 sampler.

<table>
<tr><th></th><th>15</th><th>14</th><th>13</th><th>12</th><th>11</th><th>10</th><th>9</th><th>8</th><th>7</th><th>6</th><th>5</th><th>4</th><th>3</th><th>2</th><th>1</th><th>0</th></tr>
<tr><td>0x00</td><td colspan="16" rowspan="2">sync pattern （all 0xFF)</td></tr>
<tr><td>0x01</td></tr>
<tr><td>0x02</td><td colspan="16">seconds from 0h UTC (17 bits) (LSB)</td></tr>
<tr><td>0x03</td><td colspan="8">sync pattern 2 (0x8C) (0x8B for VSSP)</td><td colspan="2">AD bits</td><td colspan="4">sampling frequency</td><td>CH</td><td>(M)</td></tr>
<tr><td>0x04</td><td colspan="7">year (3 digits) (7bits： 0-127)</td><td colspan="9">total day (9bits)</td></tr>
<tr><td>0x05</td><td colspan="4">major version #</td><td colspan="4">minor version #</td><td colspan="8">AUX FIELD size (in bytes : default is 20)</td></tr>
<tr><td>0x06</td><td colspan="8">AUX FIELD format # (1)</td><td colspan="8">LPF frequency (MHz: 0 means through)</td></tr>
<tr><td>0x07</td><td colspan="16">station ID (max 2 charcters)</td></tr>
<tr><td>0x08</td><td colspan="16" rowspan="4">station name (max 8 characters)</td></tr>
<tr><td>0x09</td></tr>
<tr><td>0x0A</td></tr>
<tr><td>0x0B</td></tr>
<tr><td>0x0C</td><td colspan="16" rowspan="4">PC host name (max 8 characters)</td></tr>
<tr><td>0x0D</td></tr>
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</table>

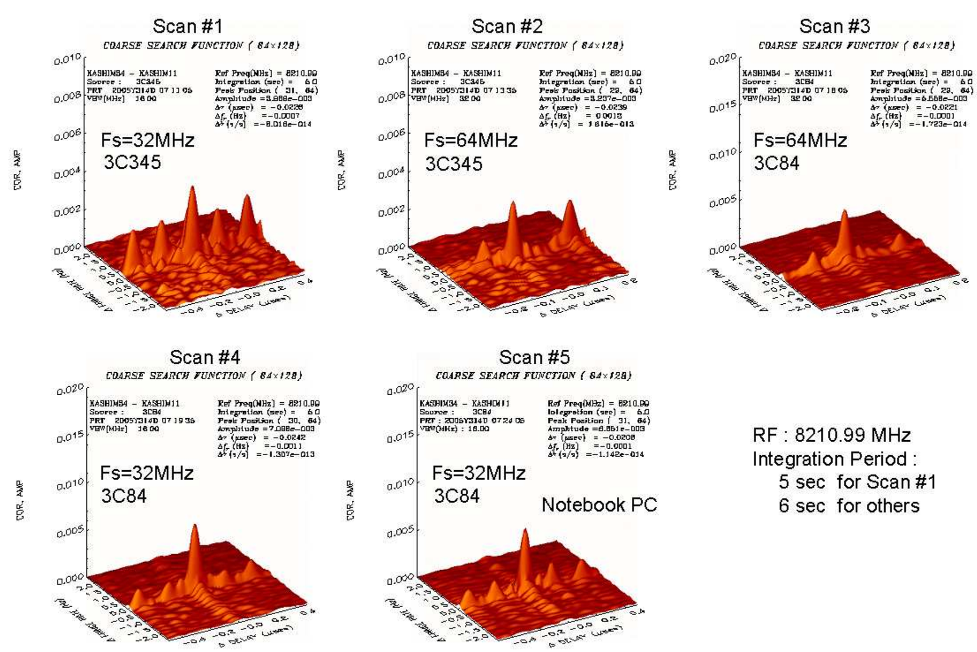

Figure 4: Correlation results for CH 1.

VLBI Experiments Using CARAVAN2400

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1 Introduction

The CARAVAN (Compact Antenna of Radio Astronomy VLBI Adapted for Network) is the series of the small radio telescoped system that is dedicated to mobile e-VLBI measurements. The state of art 'K5 VLBI system' developed by the National Institute of Information and Communication Technology (NICT) [1] enable us to perform e-VLBI measurements with high sensitivity, even if a small dish antenna is used.
We are now developing a compact and geodetic VLBI facility with a 2.4 m diameter dish antenna, which is named 'CARAVAN2400' [2]. Please refer to reference document [2] for details. We expect it will be able to contribute to the high precision co-location survey and the precise positioning of interplanetary spacecrafts. In addition, the research and development results of the CARAVAN2400 will be applicable to validate GPS survey equipments. We have prepared to perform a VLBI measurement using CARAVAN2400 in collaboration with the Geographical Survey Institute (GSI). In order to confirm a performance of the CARAVAN2400, some tests were done. We will present results of these.

2 CARAVAN2400

The CARAVAN2400 consists of an 8 GHz low noise amplifier at normal temperature condition, a frequency converter, an antenna control unit and the K5/VSI giga-bit VLBI system, etc. The dish antenna can be operated at 1.0 degree per second maximum tracking speed for both azimuth and elevation angles. The antenna is equipped antenna control unit (ACU) as shown in the Figure 1. The ACU can be controlled using a software named MAOS (Mobile Automatic Operation Software) on a PC via GP-IB interface. MAOS can control the antenna along a standard schedule file described by the NASA/GSFC document [3]. The specification of CARAVAN2400 is shown in Table 1.

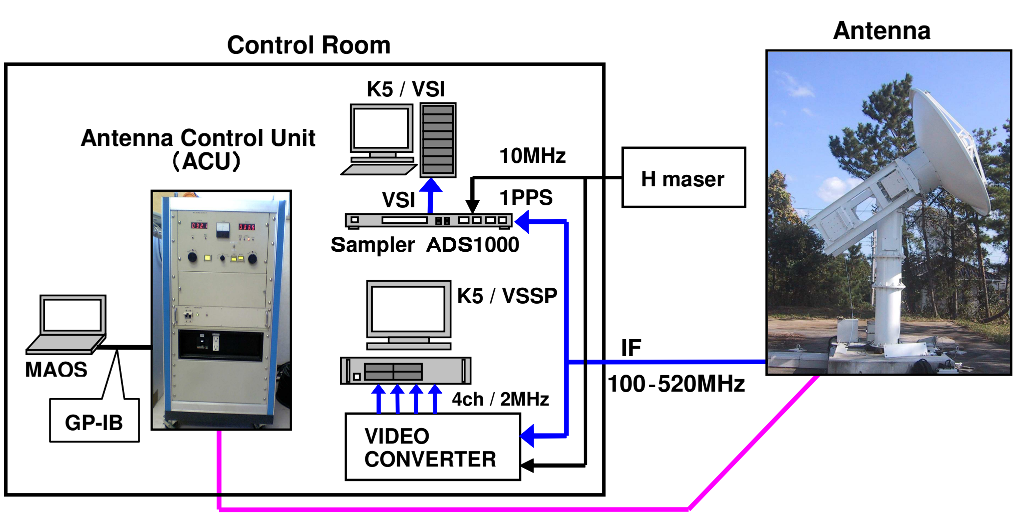

Figure 1: CARAVAN2400 block diagram

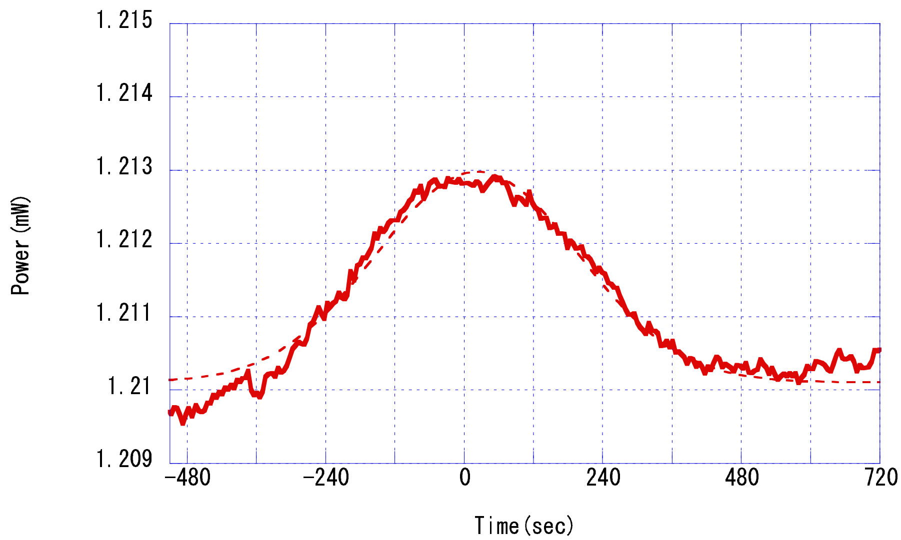

Figure 2: Cas-A signal on December 16, 2005. Origin of the time axis is taken to be the reference time for the observation.

Table 1: The specification of CARAVAN2400

Antenna Type	Cassegrain type
Diameter of Antenna	2.4m
Mount Stile	Az-El mount
Receiving Frequency	8180-8600MHz
Polarization	RHCP
Angle Resolution	0.1deg
Driving Speed	1deg/sec
Weight	640kg(Antenna+Pillar)

Table 2: Summary of first fringe test

Station	Kashima11m	CARAVAN2400
RF frequency	8100-8600MHz	8180-8600MHz
Sampling parameters	1024MHz × 2bit × 1ch	
Sources	Sun	
Scan information	02:18:00-02:18:03(UT)	

3 Performance Evaluation

We quantified the noise temperature of the receiver by measuring differences in receiver response to ambient temperature load (hot load) and liquid nitrogen temperature load (cold load). The loads are made of microwave absorber, a carbon-impregnated foam. The cold load was realized by soaking in a styrene foam box which filled liquid nitrogen. The noise temperature of the receiver was 116K. In addition, we quantified the noise temperature of the system by measuring the background sky temperature. The noise temperature of the system was 127K.

Next, we observed sun, moon, CasA,TauA and OriA by the CARAVAN2400 antenna in waiting observation method. A time variation of the total power of the IF signal was measured in these observation. The half power beam-width(about 1degree) and the alignment of the antenna were confirmed by these observation results. Figure 2 shows the result of observing CasA as one example. In addition we evaluated the aperture efficiency of CARAVAN2400 from this CasA observation result. The aperture efficiency of CARAVAN2400 is 0.42.

4 VLBI Experiments

In order to confirm its performance, we carried out the first fringe test using Kashima 11-m antenna and CARAVAN2400 on December 7, 2005. Then we successfully detected a first fringe of the sun using K5/VSI backend(see Figure 4). Figure 3 and Table 2 show block diagram and sampling parameters on this test respectively.In addition we carried out a second fringe test using Kashima 34-m antenna and CARAVAN2400 on March 15, 2006. Figure 5 and Table 3 show block diagram and sampling parameters on this second test respectively. We detected a fringe of 3C84 using K5/VSSP back-

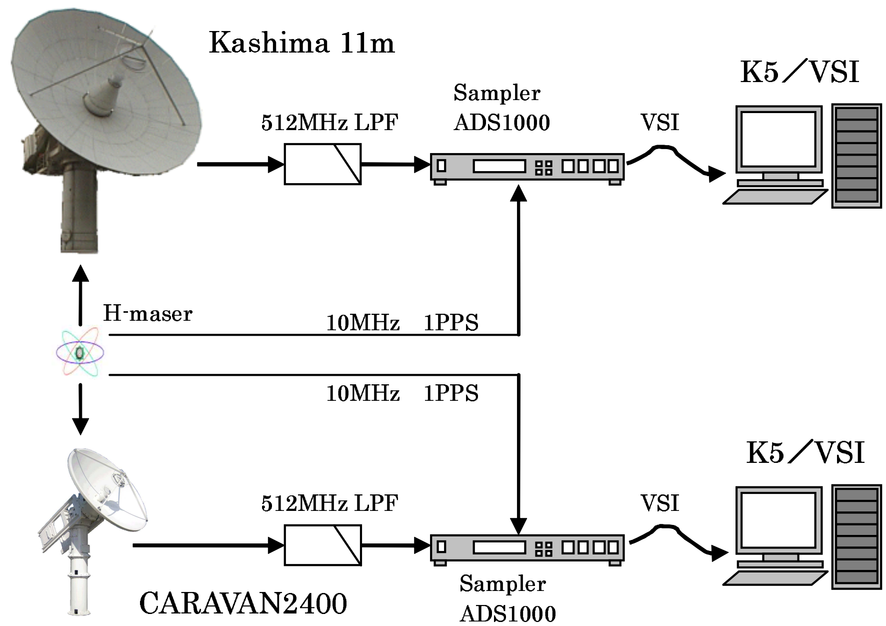

Figure 3: The block diagram of first fringe test

end. Figure 6 shows result of the second test observation. We were able to confirm the performance as the VLBI observation station of CARAVAN from these results. It can be said that there are enough phase stability and sensitivity in a VLBI observation in CARAVAN2400.

5 Conclusion

The performance of CARAVAN240 was evaluated. The evaluated parameters are as follows.

- Receiver noise temperature: 116K
- System noise temperature: 127K
- Antenna aperture efficiency: 0.42
- Half power beam-width(HPBW): $\simeq$1 degree

In addition, We tried the fringe tests, and it succeeded in the fringe detection of the sun and 3C84. The following were confirmed from this.

- CARAVAN2400 have enough phase stability and sensitivity in a VLBI observation.
- There must not be problems in the alignment of the antenna and the antenna control system.

We will carry out a geodetic experiment using CARAVAN2400 to verify the performance as a geodetic VLBI station. Therefore, a preciser correction of the antenna alignment and the arrangement of the backend are needed. Moreover, because CARAVAN2400 is a single frequency antenna of X band, how the delay correction of the ionosphere is done becomes a big problem. In addition, we will advance development of CARAVAN in consideration of the spacecraft tracking too.

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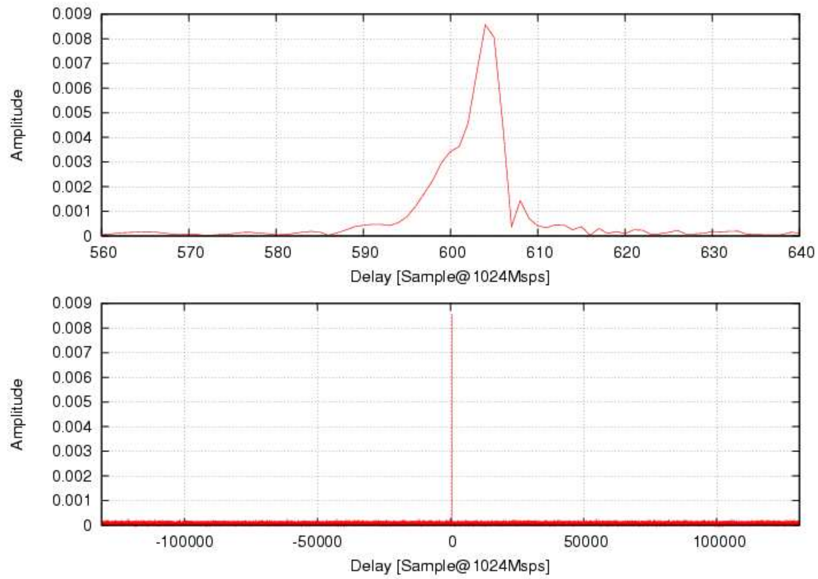

Figure 4: Result of the first fringe test

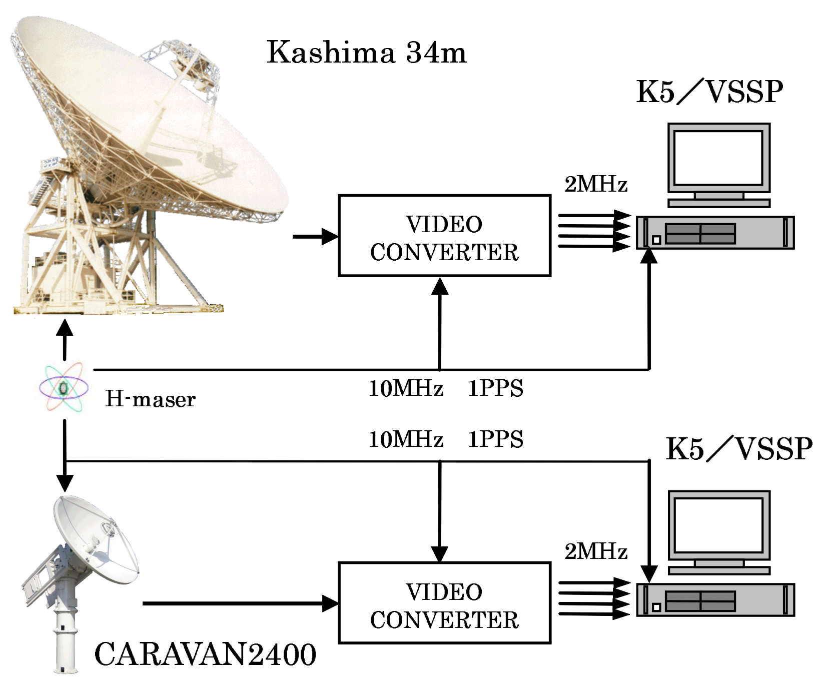

Figure 5: A block diagram of test on March 15, 2006

Table 3: Summary of test observation on March 15, 2006

RF freqency	CH1 8404.9MHz
	CH2 8414.9MHZ
	CH3 8454.9MHz
	CH4 8474.9MHz
Sampling parameters	4MHz × 1bit × 4ch
Sources	3C84
Scan information	04:40:00-04:45:00(UT)

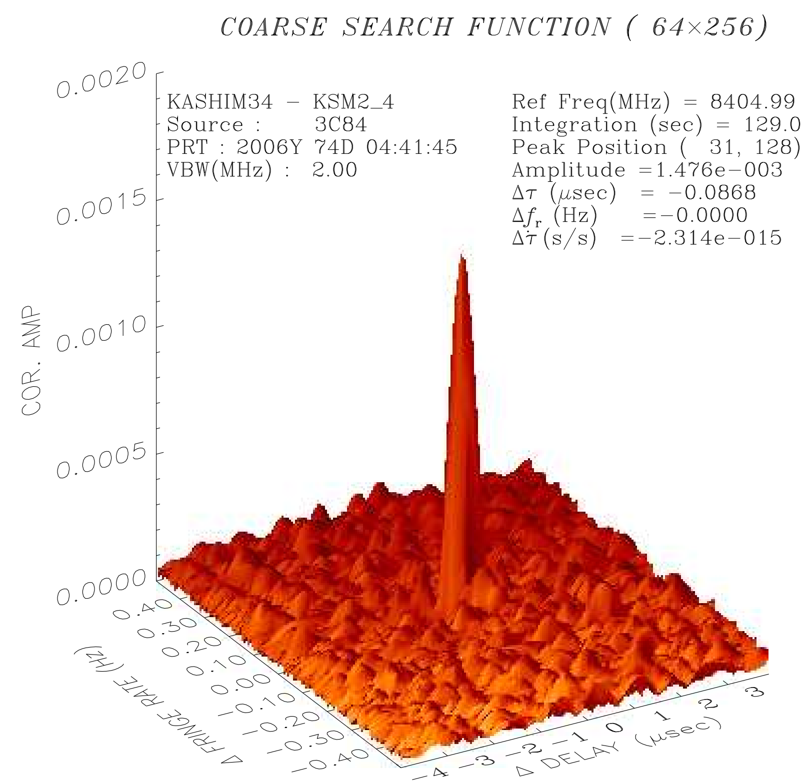

Figure 6: Correlation result for CH1

Phase Delay Δ VLBI Observation of HAYABUSA at its Touchdown to ITOKAWA.

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Abstract

Differential VLBI observations of HAYABUSA were performed with Japanese domestic VLBI stations during a series of its touchdown trials to ITOKAWA in Nov. 2005. Phase delay of main carrier tone signal was used to derive high precision delay observable. It was good occasion to examine the performance of Δ VLBI spacecraft tracking with phase-delay. Reference sources were chosen from ICRF catalog in each session. And group delays of the reference radio sources were used for correction of excess delay and clock parameters due to mis-synchronization of atomic standards at each observation stations.
The post-fit delay residuals of HAYABUSA were distributed around zero within the range about a few hundreds pico seconds, as expected. Although, the distribution of the residual was not uniform, but some systematic trend remained in some cases. Possible causes of the remaining residual are suspected to be some of the followings: (1) short term variation of atmospheric delay, (2) contribution of ionospheric delay, and (3) instrumental phase delay variation of observation equipment.

1 Introduction

VLBI is an important tool for precise orbit determination and navigation of spacecraft in the deep space. JPL/NASA has been using Delta Differential One-way Range (Δ DOR) technique for this purpose. Recently the international interest on this application is increasing. Chinese Space Agency is planning to use VLBI to their lunar mission. European Space Agency (ESA) has demonstrated VLBI activity in tracking of Cassini-Huygens mission in 2005. JPL/NASA and NRAO is developing a technique to use phase delay with VLBA[3][5].
Japanese Space Agency (JAXA) and Japanese VLBI community are collaborating to use VLBI for spacecraft navigation. Several VLBI experiments were performed with Japanese first Mars exploration mission NOZOMI[1] and asteroid exploration mission HAYABUSA[2]. Although those Japanese spacecrafts were not designed to transmit a signal with wide frequency bandwidth for precise group delay measurement of VLBI. NASA's Δ DOR uses several tens of MHz, whereas HAYABUSA's range signal has ± 1 MHz span. Additionally length of Japanese domestic baselines are limited. Therefore to achieve higher angular resolution, higher delay resolution is desirable.
In November 2005, spacecraft HAYABUSA made touchdown to asteroid ITOKAWA. In the period from 4th to 25th in November, a series of touchdown trials were performed and at the same time with these events, we have made VLBI observations of HAYABUSA. Since group delay has not enough delay resolution due to limited bandwidth, we used phase delay, which can achieve much higher delay resolution. Although phase delay has difficulty to get absolute delay measurement due to uncertainty of phase ambiguity, we could prevent this problem with accurate a a priori information of HAYABUSA. The orbit of asteroid ITOKAWA is accurately known within one interferometer fringe spacing of Japanese domestic baseline, and HAYABUSA was in almost the same position in November 2005. Therefore we could assume zero ambiguity in this period, and it was a good opportunity to examine the performance of phase delay Δ VLBI observation of spacecraft.
In the next following section, observation configuration of Δ VLBI observation and scheme of Δ VLBI data processing is described. And remaining residual and its cause are discussed in section 3.

2 Δ VLBI Observation and Data Processing

2.1 Observations

Dates of observation sessions and VLBI stations participated in the experiments are listed in table 1. Time span of observation was about 6 hours for each sessions. HAYABUSA was seen about 6-8 degrees from the sun in this period, then observations were from the morning until late afternoon of each days. Pictures of the antennas are displayed in Figure 1.
The data was acquired with IP-sampler board in 2bit-4Mbps-1channel mode for HAYABUSA

Table 1: ΔVLBI observation sessions in 2005 and stations participated in those sessions. Stations marked with '*' did not perform switching observation, therefore they are excluded in analysis. The codes of each stations are as follows: O:Kashima-34m, T:Tsukuba-32m, C:Chichijima-10m, M:Mizusawa-20m, U:Usuda-64m, V:Uchinoura-34m.

Date	Scan Duration (sec)	Switching Cycle (min.)	VLBI Stations	Reference Sources & Angular Distance
4 Nov.	174	6	O,T,C,U*,V*	1352-104 (3.3 deg.)
12 Nov.	160	6	O,T,U*,V*	1430-178(3.3 deg.) 1443-162 (2.4 deg.)
19 Nov.	160	6	O,T,M,U*,V*	1443-162 (5.5 deg.) 1430-178 (8.5 deg.)
25 Nov.	140	6	O,T,U*,V*	1514-241 (6.8 deg.) 1504-166 (7.1 deg.)

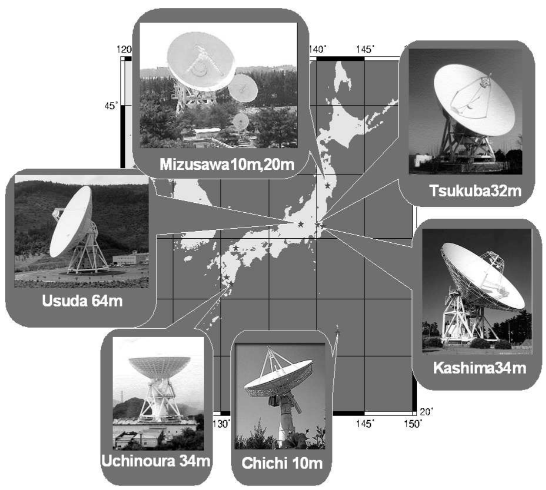

Figure 1: VLBI stations participated in the Δ VLBI observations of HAYABUSA in Nov. 2005.

and 2bit-4Mbps-8channel mode for reference radio sources. Observation radio frequency was 8408 MHz for HAYABUSA. For observation of reference sources, eight data channels were distributed in wide X-band frequency range as the same with geodetic VLBI so that the group delay observable can be obtained by bandwidth synthesis technique of the 8 channels. Phase delay was derived by connecting fringe phase of tone signal for HAYABUSA. Phase connection was successful over the 6 minutes interval of switching cycle.

Calibration of phase delay with group delay of reference radio source has potential problem of contamination with ionospheric delay as discussed in the latter section, although here used conventional group delay obtained by bandwidth synthesis. It was partly because to get high signal to noise ratio (SNR) by using full scan duration for integration time, and to use conventional software.

Reference radio sources are chosen from ICRF catalog[10] so as to use accurate radio source coordinates. The difference between ICRF and dynamical reference frame, where the orbit of spacecraft in the solar system is described, thought to be coincide within 3 mas precision [8].

2.2 Delay Correction with Δ VLBI

Either group delay and phase delay observables includes not only geometrical delay, but also excess delay due to propagation medium, and clock parameters due to mis-synchronization of atomic clocks at each observation stations. Thus each of these observable can be expressed as follows:

$$\tau_{\text{observable}} = \tau_{\text{geo}} + \tau_{\text{atm}} \pm \tau_{\text{ion}} + \tau_{\text{clk}}, \qquad (1)$$

where 'plus' sign is for group delay and 'minus' is for phase delay. We took the following steps of data calibration with Δ VLBI delay data.

1. Correlation processing is performed for reference quasar with software correlator. Then Group Delay observables of reference radio sources are derived by bandwidth synthesis of 8 channels of X-band data.

2. Fringe phase of tone signal of HAYABUSA is derived every 2 seconds with software correlator. VLBI delay model of finite distance radio source[7] is used for correlation processing. Phase Delay observables are derived by connecting fringe phase all over the scans of HAYABUSA by ambiguity editing.

3. Delay residual after subtracting computed delay (O-C) is calculated for reference sources by using VLBI delay model calculation software CALC Version 9. The computed delay is composed of geometrical delay and contribution from dry atmosphere. Dry atmospheric contribution is computed by using ground weather

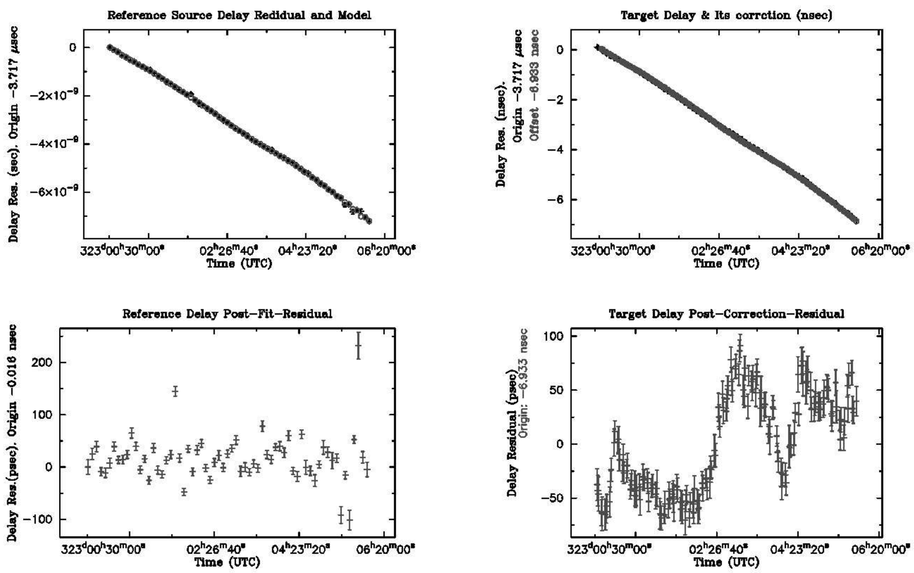

Figure 2: Plot of O-C data of reference radio source for Tsukuba32-Mizusawa20 baseline on 19 Nov. 2005 (left top) is displayed as an example. Symbol of '+' indicates the O-C data and '∘' stands for model of equation (2) fitted to the data. Lower left panel shows the post-fit residual of O-C data of reference radio source. In the upper right panel, O-C data of HAYABUSA is plotted with '+'. The excess delay model estimated with O-C data of reference source are over plotted with '∘'. The residual of O-C data of HAYABUSA after the correction is displayed in the lower right panel.

data and NMF mapping function[9]. Since celestial coordinates of reference sources are known in high accuracy, then O-C of reference source will be modeled by the effect of synchronization of atomic clocks and excess delay residual of propagation medium.

4. Following model was used for O-C delay residual data of reference sources:

$$\begin{aligned}\Delta\tau = &\tau^0_{\rm clock} + \dot\tau_{\rm clock}(t - t_0)\\ &- \{\tau_{\rm atmX,0} + \dot\tau_{\rm atmX,n}(t - t_n)\\ &+ \sum_{i=1}^{n} \dot\tau_{\rm atmX,i}(t_i - t_{i-1})\} fm(Elx)\\ &+ \{\tau_{\rm atmY} + \dot\tau_{\rm atmY}(t - t_n)\\ &+ \sum_{i=1}^{n} \dot\tau_{\rm atmY}(t_i - t_{i-1})\} fm(Ely). \quad (2)\end{aligned}$$

This model is composition of linear clock model and piece-wise linear function of zenith atmosphere at each station. Constraint of rate (1.e-15 s/h) and initial offset of zenith atmosphere (1.e-10 s) are applied to get stable solution least-square estimation. The interval of the piece-wise linear function was set to be 30 minutes. Short interval of atmospheric estimation may be beneficial to absorb short time variation of atmospheric delay, however no further remarkable improvement was not observed with shorter time interval.

These clock and atmospheric parameters obtained by least-square fitting to the O-C data of reference radio sources are used for calibration of delay observable of HAYABUSA.

5. Delay residual O-C is computed for HAYABUSA, where geometrical delay is computed with newly developed VLBI delay model for radio source at finite distance[7]. And delay correction terms derived in step 4 is applied. Then calibrated delay residual of HAYABUSA is obtained.

3 Discussion

The plot of O-C data and model fitting residual is displayed in Figure 2.

After subtracting the a priori delay correction of atmospheric delay, O-C data became almost straight line as seen in the upper left panel of Figure 2. It means the atmospheric delay can be corrected in this level with ground weather data and NMF mapping function. The position of HAYABUSA is given with the orbit of ITOKAWA in the period

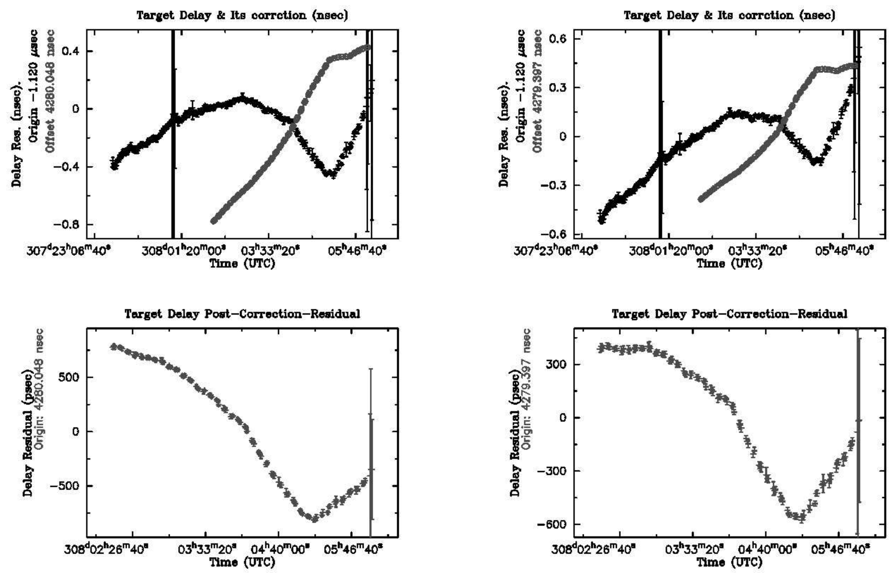

Figure 3: Delay correction error due to ionospheric contribution was observed in Chichijima baseline. In the upper panel, plot with '+' indicates phase delay of HAYABUSA and 'o' is delay correction term derived from group delay of reference source. Residual after the correction is plotted in the lower panel. Ionospheric delay is not taken into account in the left panels. In the right panels, ionospheric delay computed by using global ionosphere map (GIM/CODE, see text) is use for removing ionospheric delay contribution.

of these experiments, residual of O-C data is expected to be distributed around zero and constant with time. Actual residual of HAYABUSA (lower right panel) was almost as expected within the error about 100 ps.

The excess delay behavior is well modeled with piece-wise linear atmosphere of equation (2) as it is seen from the uniform distribution of post-fit residual (lower left panel). Although the residual of O-C of HAYABUSA shows systematic short term variation even after the excess delay correction with reference radio source. Possible reasons of this may be (1) modeling error of atmosphere, (2) ionospheric delay, which is not corrected here and it is contributing twofolds to this calibration procedure, or (3) behavior of instrumental phase of data acquisition system, which cannot be calibrated with group delay of reference radio source.

The reason (1) may become error source when the atmospheric zenith thickness is wrongly estimated in the process with the data of reference radio source. Also short time variation or inhomogeneity of atmosphere which cannot be modeled by mapping function may contribute to the error. The reason (2) is more likely to be responsible here, since we are doing calibration of phase delay of HAYABUSA with group delay of nearby quasars. Excess delay contribution of ionosphere is opposite sign with the same magnitude for phase delay and group delay. Thus if excess delay including ionospheric delay is modeled by neutral atmosphere, the phase delay residual after the delay correction with group delay will be contaminated by the ionospheric contribution by two folds. This was clearly observed in the data of the baselines including Chichijima station (Figure 3) on 4th Nov. The correction term derived from group delay shows delay change of opposite sense with respect to the phase delay of HAYABUSA (upper left panel of Figure 3). It will be due to contribution of dispersive medium, which contribute opposite sense for phase delay and group delay. Then, that effect contributes twofolds after applying the correction term (lower panel). Since Chichijima is located in south part of Japan where geomagnetic latitude is relatively low and dense ionosphere passes by, it is natural that the ionospheric effect is large for Chichijima station. We tested to use global ionosphere map (GIM), which is derived by the Center for Orbit Determination in Europe (CODE) in Bern University from GPS data of IGS (International GPS Service) network. Daily GIM data since 1995 is available from the Internet (http://www.cx.unibe.ch/aiub/ionosphere.html).

We computed ionospheric delay contributions to VLBI delay for each scans by using the GIM/CODE data of the date of VLBI observa-

tions. The data in right panels of Figure 3 are result of applying the ionospheric delay correction with GIM/CODE. We can see the variation range of residual of HAYABUSA has reduced after the ionospheric delay correction with GIM/CODE (lower right panel), though unfortunately that correction is insufficient.
Ionospheric contribution may be removed more effectively if we use phase delay of reference source for excess delay correction. And the systematic post-fit delay residual is caused from the reason (3) instrumental phase change, this error source will be also calibrated. We are going to test this very near future.

4 Summary

Δ VLBI observations of HAYABUSA were conducted with Japanese domestic VLBI stations at the time of its touchdown trials to the asteroid ITOKAWA. Since the orbit of ITOKAWA is know within the fringe spacing of our observation, we could evaluate the precision of Δ VLBI method with phase delay observable by avoiding the issue of phase ambiguity. Fringe phase of tone signal of HAYABUSA was derived every two seconds and they are successfully connected without ambiguity over the scans with 6 minutes intervals.
As the result of delay calibration via Δ VLBI with nearby reference radio sources, phase delay residual for HAYABUSA distributed in the range of a few hundreds pico seconds. Remaining delay residual may be due to the contribution of ionospheric delay, which affect two folds in calibration procedure in this time. Global ionosphere map derived from GPS observation was tested to remove the ionospheric effect. Consequently it showed improvement of calibration, but it was insufficient.
We used conventional group delay derived from bandwidth synthesis for the data of reference source, because of easiness to deal with, and stability to get enough SNR. Using phase delay of quasar for calibration of excess delay may work more effectively to remove excess delay including ionosphere.

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Zenith wet delay comparisons at Tsukuba and Kashima VLBI stations during the CONT05 VLBI campaign

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Abstract: During the CONT05 VLBI campaign we performed the zenith troposphere delay (ZWD) measurements using microwave water vapor radiometer (WVR). The obtained ZWDs were compared with concurrent observations made over a 15-day period by radiosonde, GPS, and VLBI. The agreement of averaged ZWD between the collocated WVR and GPS was within 13 mm, while it between the WVR and VLBI was relatively large more than 20 mm. It is possible that these bias could be caused by mapping function difference between GPS and VLBI processing and WVR retrieval coefficient error. On the other hand, meteorological data implies that large scatters of ZWD differences among these techniques are attributed to the high variability of water vapor content.

1 Introduction

In September 2005, 15 continuous days of VLBI data were observed in the Continuous VLBI 2005 (CONT05) campaign. The Tsukuba VLBI station of Geographical Survey Institute (GSI) is one of the eleven observatories that participated in the campaign as the only one station in the Asia and Oceania region. The Kashima VLBI station of National Institute of Information and Communications Technology (NICT) also participated in the campaign on September 16, 2005. The one of main concerns of the campaign is to investigate atmospheric effects on the estimated station coordinates. Since Tsukuba and Kashima are located in the Asian monsoon region and the campaign was performed in the summer season of Japan, water vapor content was highly variable during the campaign. In this short report, we present a comparison of estimated ZWD derived from an independent analysis of simultaneous radiosonde, WVR, GPS and VLBI observations made over the CONT05 period.

2 Observation

Both Tsukuba and Kashima VLBI stations are co-located with a GPS station and a WVR. Both of these WVRs are Radiometrics^{TM} Corp. WVR-1100 two frequency model. WVR data required a careful correction in order to be consistent with the wet refractivity formulation of the VLBI, GPS, and radiosondes.

Figure 1: WVR (Radiometrics^{TM} WVR-1100) measurements at Tsukuba. The Tsukuba 32-m antenna of GSI is shown behind the WVRs.

At Tsukuba the Tateno radiosonde station of Japan Meteorological Agency (JMA) is located about 9 km south from GSI VLBI station. Thus, simultaneous WVR, GPS and radiosonde observations were carried out from September 6 to October 12, 2005 including the CONT05 campaign period. Our WVRs were measuring in the zenith direction at each station during the whole period.
First, we install two WVRs (WVR26 and WVR28) on a top of the VLBI observation building at Tsukuba approximately 20 m from the Tsukuba 32 m antenna on September 6 (see Figure 1). Both WVRs ran continuously until September 14. WVR26 was moved to Kashima since the Kashima 34 m station participated the CONT05 campaign on September 16. After the one day experiment at

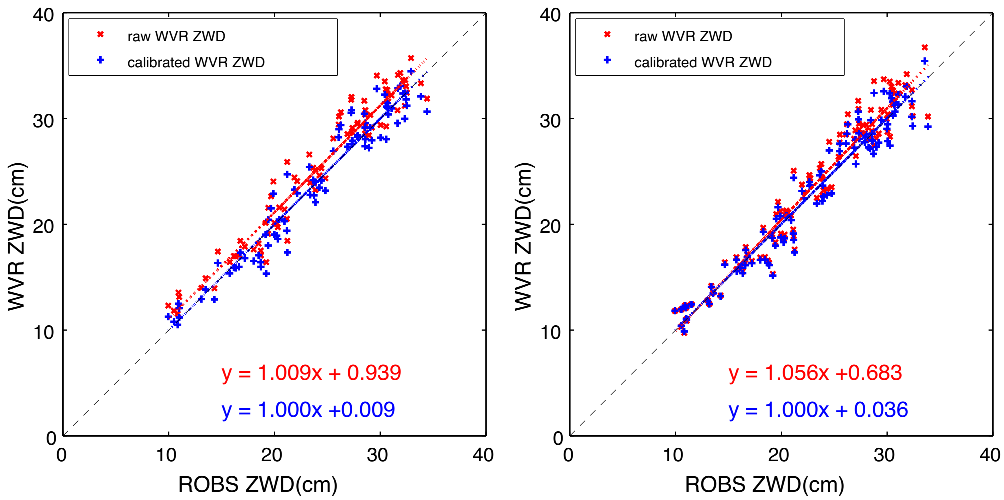

Figure 2: WVR data calibration using the radiosonde observations data derived at Tsukuba (Tateno) station of JMA.

Kashima the WVR26 was moved back to Tsukuba on September 21 and it ran until October 12 with WVR28 at Tsukuba. WVR-based ZWDs were measured every 3 minutes.
We determined corrected WVR-based ZWDs by its linear regression on the estimates derived from the radiosonde observations data as shown in Figure 2. In our report we compare these ZWDs with those obtained by other techniques as a preliminary result. The retrieval coefficients for converting the opacities to ZWD have to be determined in order to obtained more accurate WVR-based ZWD. We will present results based on the determined retrieval coefficients in another paper.
GPS receivers at Tsukuba (TSKB) and Kashima (KSMV) are AOA BENCHMARK ACT and Ashtech Z-XII, respectively. Both of them are connected to Dorne Margolin type antenna with choke rings. The data were sampled every 30 seconds and these were processed using Bernese 4.2 version software[1]. Satellite final orbit and clock files were obtained from the anonymous ftp site of the International GNSS Service (IGS). GPS-based ZWD were estimated using the Niell mapping function (NMF)[2] every 20 minutes and these were corrected by zenith hydrostatic delay calculation based on accurate surface pressure measurements.
In order to comparison we use hourly VLBI-based ZWDs which were estimated from VLBI observations using the OCCAM 6.1 software with Vienna mapping function (VMF)[3, 4] by VLBI data analysis at the Institute of Geodesy and Geophysics, Vienna University of Technology[5]. The VLBI-based ZWD were directly used for the comparisons since the hydrostatic delay used as the a priori value was based on measured pressure at the site.

3 Result and Discussion

The measured ZWDs at Tsukuba are shown in Figure 3. In this figure many brief periods of extremely high scatter in ZWDs due to rain effect are illustrated. We removed such high values contaminated by liquid water on the optics based on the WVR liquid water estimates and surface meteorological data of JMA for the comparisons among different techniques.
The mean and standard deviation values of the differences between the different techniques such as WVR, GPS, and VLBI (with 10° minimum elevation angle cutoff) are summarized in Table 1. For VLBI and for the GPS site, the ZWDs were interpolated to the time of the WVR measurement. After corrections were applied to the WVR and radiosonde measurements, the mean value (bias) between WVR and GPS are less than 13 mm with a standard deviation (scatter) of 17 mm, whereas the those between WVR and VLBI are large up to about 24 mm with a standard deviation of 14 mm.

Table 1: Mean and scatter (standard deviation) values in millimeter between ZWDs derived from different techniques at Tsukuba.

	GPS	**VLBI**
WVR26	12.3 ± 16.5	23.6 ± 13.5
WVR28	6.5 ± 15.2	17.2 ± 12.1
VLBI	-12.1 ± 12.6	—

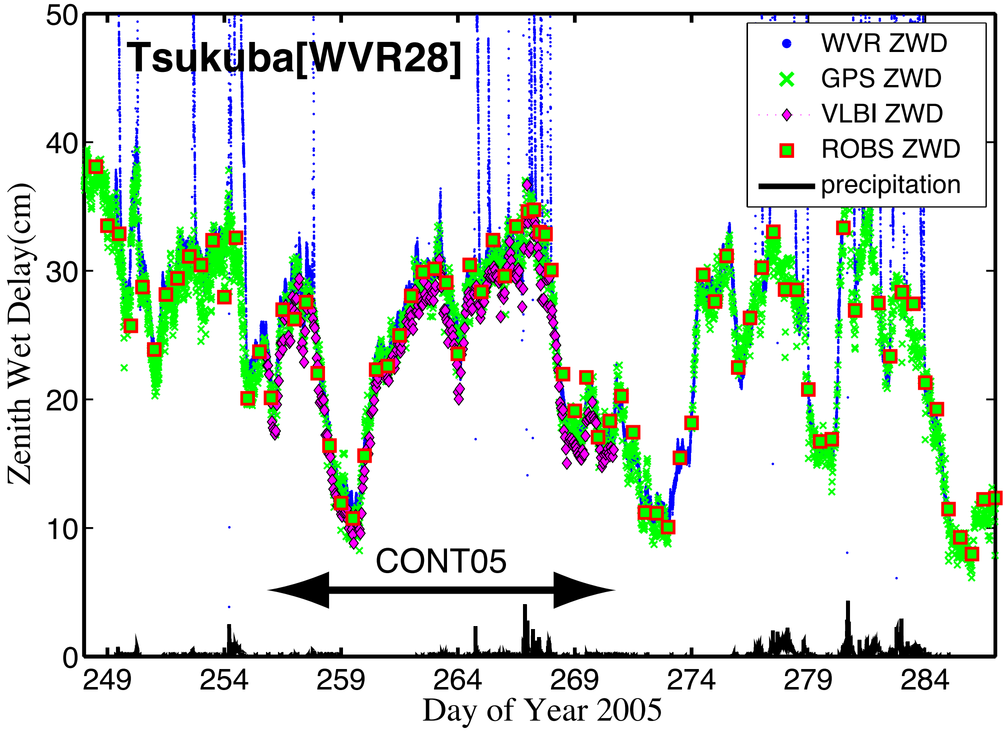

Figure 3: Time series of ZWD derived from the collocated techniques VLBI, WVR, GPS and radiosonde at Tsukuba during September 6 - October 12, 2005. The arrows indicate the period of the CONT05 campaign for which VLBI data were compared.

The maximum value of ZWD was up to 35 cm on September 24-25 (the day of year 267 and 268). These large ZWD values were caused by high water vapor content during the period of the typhoon 0517 (SAOLA) approaching east of Japan island (see Figure 4).

Our results demonstrate relatively degraded agreement of ZWD estimates among the four techniques compared with previous studies(e.g. [8], [9]). These worse agreements in averaged differences are likely caused by to use different mapping functions between GPS (NMF) and VLBI (VMF) and WVR retrieval coefficient error. We expect both error source can be reduced if we process GPS and VLBI data sets using the same mapping function and the WVR retrieval coefficients are calculated using the full wet refractivity obtained from radiosonde data.

On the other hand, the high variability ranges from 20 to 35 cm of ZWD within a few days suggests that the large scatters of ZWD differences is attributed to natural variability of the water vapor fields themselves. Unfortunately, the duration of our experiment including the CONT05 period is in the midst of typhoon season as shown in Figure 4. The WVR rain spikes and sharp rises in Figure 3 are known to have been associated with the passing weather fronts and typhoon. In such cases horizontal variability of water vapor content could cause the uncertainty of WVR-based ZWDs due to errors in the measurement of brightness temperature. We are going to investigate horizontal variation of water vapor using the meso-scale numerical weather model of JMA in order to resolve the large ZWD scatters among different techniques.

Acknowledgement: We thank the RINEX GPS data used in this study were supplied by IGS and GEONET (GPS Earth Observation Network System) of GSI, Japan. We are also deeply grateful to the IVS Special Analysis Center Institute of Geodesy and Geophysics (IGG), Vienna, Austria for providing VLBI ZWD estimates.

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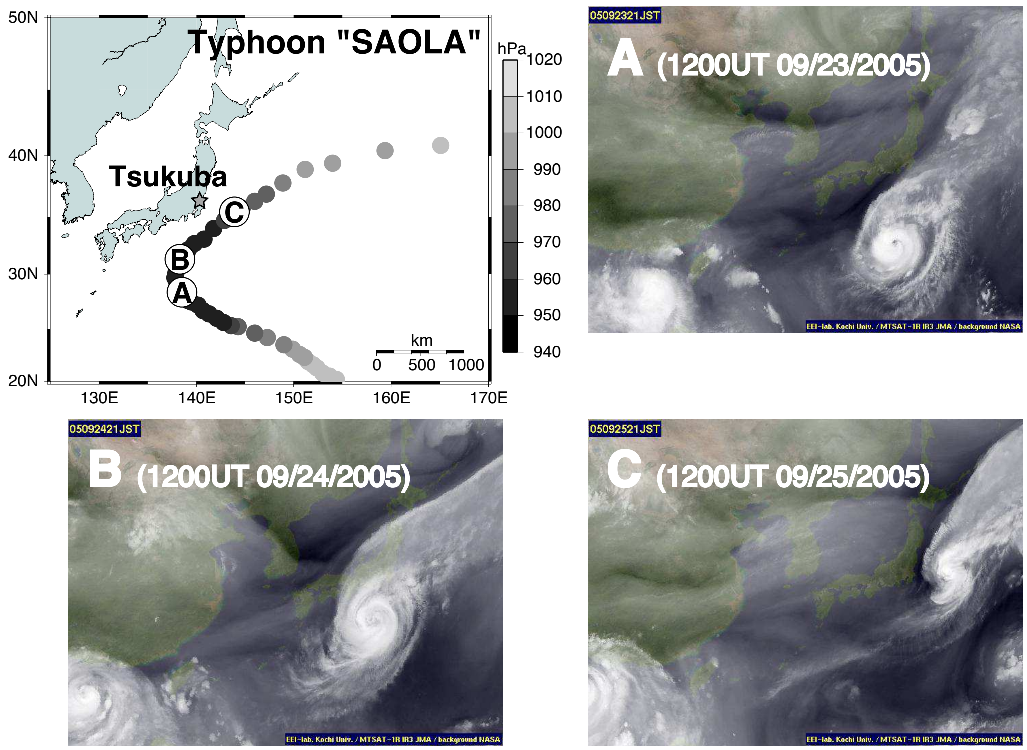

Figure 4: Track map of the typhoon SAOLA. The daily water vapor satellite images from JMA satellite GMS-6 from 23 to 25 September, 2005[6, 7]. Locations A, B, and C in the map correspond the typhoon center in each image.

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An numerical simulation of atmospheric path delay correction in differential VLBI experiments for spacecraft tracking

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Abstract: We numerically simulated the differential path delays over the declination - right ascension field with 0.2° grid step nearby the HAYABUSA spacecraft covering a 4° × 4° region during the $\Delta VLBI$ experiments on October, 2004. Our simulation suggests that the massive amounts of water vapor and its high variability would degrade the effect on cancelling out atmospheric path delay errors at lower elevation angle, whereas this effect is still efficient at the higher elevation angle more than 30 degrees. Such simulation would be also useful to make the most optimize observation schedule.

1 Introduction

We tried to evaluate an effect of cancelling out atmospheric path delay errors on the $\Delta VLBI$ measurements based on the delays derived from geodetic GPS analysis[1]. According to our simple analysis, a large difference value of up to 10 cm of the differential path delay for the Kashima-Uchinoura baseline was estimated in spite of a small separation angle of less than 3 degrees between the Japanese spacecraft "Hayabusa" and quasar. Such large value was mainly caused by the humid condition around Uchinoura due to the typhoon approaching.

The previous result suggests that we need to understand the behavior of the differential path delay to optimize an observation schedule for the $\Delta VLBI$ measurements. Thus, we numerically simulated the differential path delays in order to investigate relationship between the cancel effect and separation angles. In this report, we describe a preliminary result.

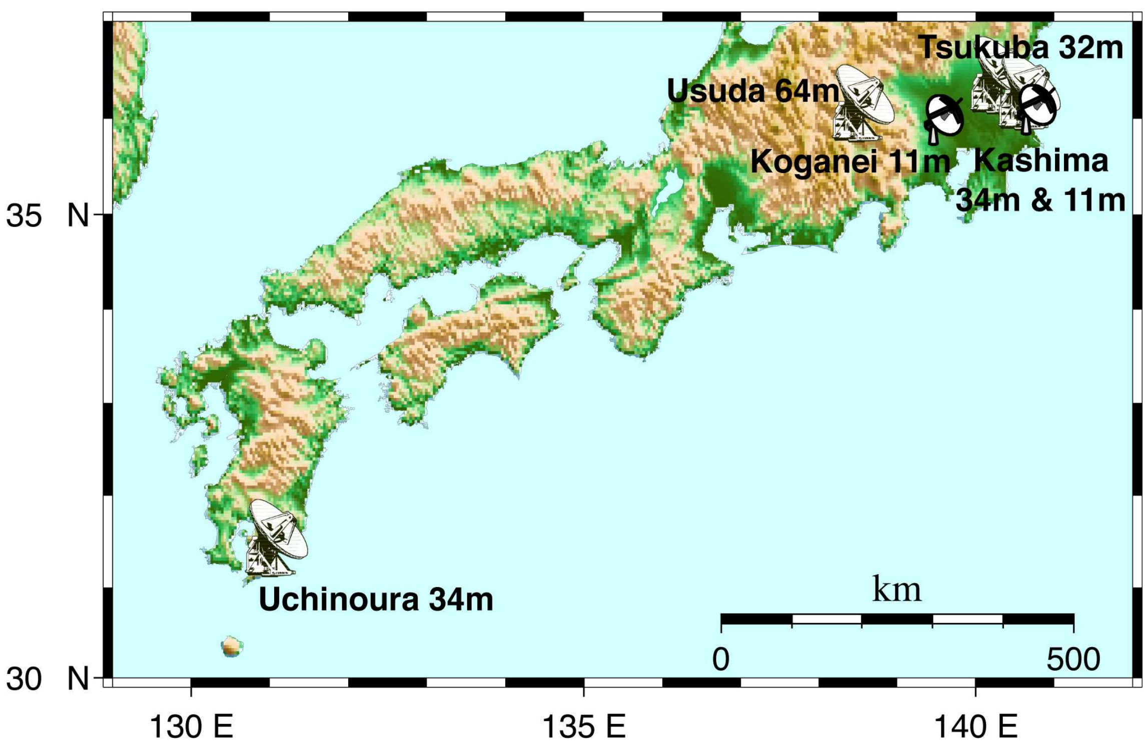

Figure 1: VLBI stations participated HAYABUSA DVLBI experiments

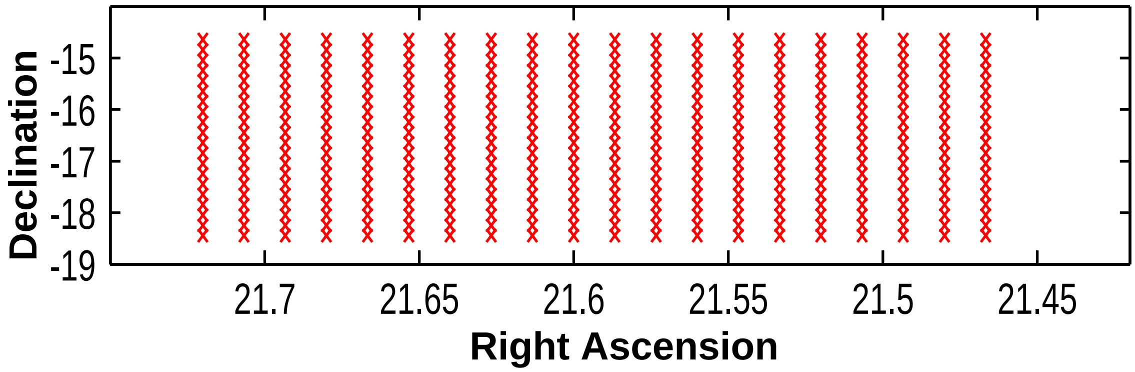

Figure 2: Declination - right ascension grid points nearby the HAYABUSA for the numerical simulation of differential delays.

2 Numerical simulation

Two HAYABUSA $\Delta VLBI$ experiments were carried out in order to evaluate reducing propagation delays due to the ionosphere and neutral atmosphere using $\Delta VLBI$ technique on October, 2004. We numerically calculated differences values between both differential wet delays of the HAYABUSA spacecraft and those of the quasar as described in the previous report based on a conventional manner of the $\Delta VLBI$ technique[1]. Here, we defined "differential wet delay" as path delay differences between the slant delays ΔSLW at the both end of baseline. The calculation procedure is shown by:

$$D\Delta SLW_{AB}^{QH} = D\Delta SLW_{AB}^{Q} - D\Delta SLW_{AB}^{H} \quad (3)$$

where $D\Delta SLW_{AB}^{QH}$ denotes the difference between two differential delays and subscripts A and B denote the station names of the baseline vector. The superscripts Q and H denotes the quasar and the HAYABUSA spacecraft, respectively.

In the previous report, we presented two examples of time series of difference values, which are mentioned in the equation (3). The maximum value of differences for the Kashima-Uchinoura baseline (see Figure 1) was up to more than 10 cm during the $\Delta VLBI$ experiment in spite of a small separation angle of less than 3 degrees between the HAYABUSA spacecraft and quasar. Such large value occurred under the condition of typhoon approach. The detail of the experiments and preliminary calculations are summarized in the previous report[1].

We have carried out new numerical simulation in order to investigate effects of cancelling out atmospheric path delay errors more detail. We focus on to find out upper limit of separation angles in the $\Delta VLBI$ experiment. Figure 2 shows the declination - right ascension grid points nearby the HAYABUSA spacecraft covering a $4° \times 4°$ region during the $\Delta VLBI$ experiments on October, 2004 for the simulation. The grid step size is 0.2°, giving a total of 400 mesh points. We calculate the atmospheric differential delay values at each mesh point and epoch. In this short report, we mainly focus on the case of the longest baseline, which is the Kashima - Uchinoura baseline, as shown in Figure 1[1].

3 Result

Figure 3 represents three sky maps of the simulated differential delays for the Kashima and Uchinoura baseline at 07:16UT(epoch A), 10:48UT(epoch B), and 13:11UT(epoch C) of October 16, 2004. The maximum of the value is up to about 1 cm on the upper right corner of the simulated area, where the HAYABUSA/QSO(2126-158) separation angle in elevation is about 3 degrees. This slight large value is due to lower elevation angle less than 20 degrees at the epoch A. However, such values were only shown in first several minutes. The differences values were less than 0.2 cm during the rest of all over the period under calm weather conditions.

On the other hand, dense contour lines are demonstrated all over the simulated area as shown in the most upper panel of Figure 4. The maximum of the value was up to more than 10 cm at epoch A. As we already mentioned in the previous report, this result is caused by the high water vapor content due to the typhoon approaching at Uchinoura, the constellation of the baseline vector and difference in elevation angle at two stations.[1]. According to this figure, though the separation angle of the most angularly nearby quasar "2135-184", which is listed in the most recent VLBA Calibrator Survey (VCS4) catalogue[2], was only 1 degree at the epoch A, the differential delay value was up to 5 cm. After this epoch, the differential delay values over the area significantly decreased as the elevation angle increased. This result suggests that the massive amounts of water vapor and its high variability would degrade the effect on cancelling out atmospheric path delay errors at lower elevation angle, whereas this effect is still efficient at the higher elevation angle more than 30 degrees.

In addition, we consider that the numerical simulation of the differential delay would be useful to make an observation schedule of the $\Delta VLBI$ experiment in term of choosing the better radio sources to minimize the tropospheric delay error. For example, the ray tracing calculation through the numerical weather prediction (NWP) models is the one of suitable way for the simulation. We have a plan to extend our numerical simulation to include horizontal variability of the water vapor content by using the NWP model. Development of such simulation would be also available to apply it to atmospheric correction of the measurements.

References

[1] Ichikawa et al., An Evaluation of Atmospheric Path Delay Correction in Differential VLBI Experiments for Spacecraft Tracking, *TDC News*, **Vol. 26**, 14-19, 2005.

[2] Petrov et al, The Fourth VLBA Calibrator Survey - VCS4, *Astronomical Journal*, vol. 131, 2006 (in press).

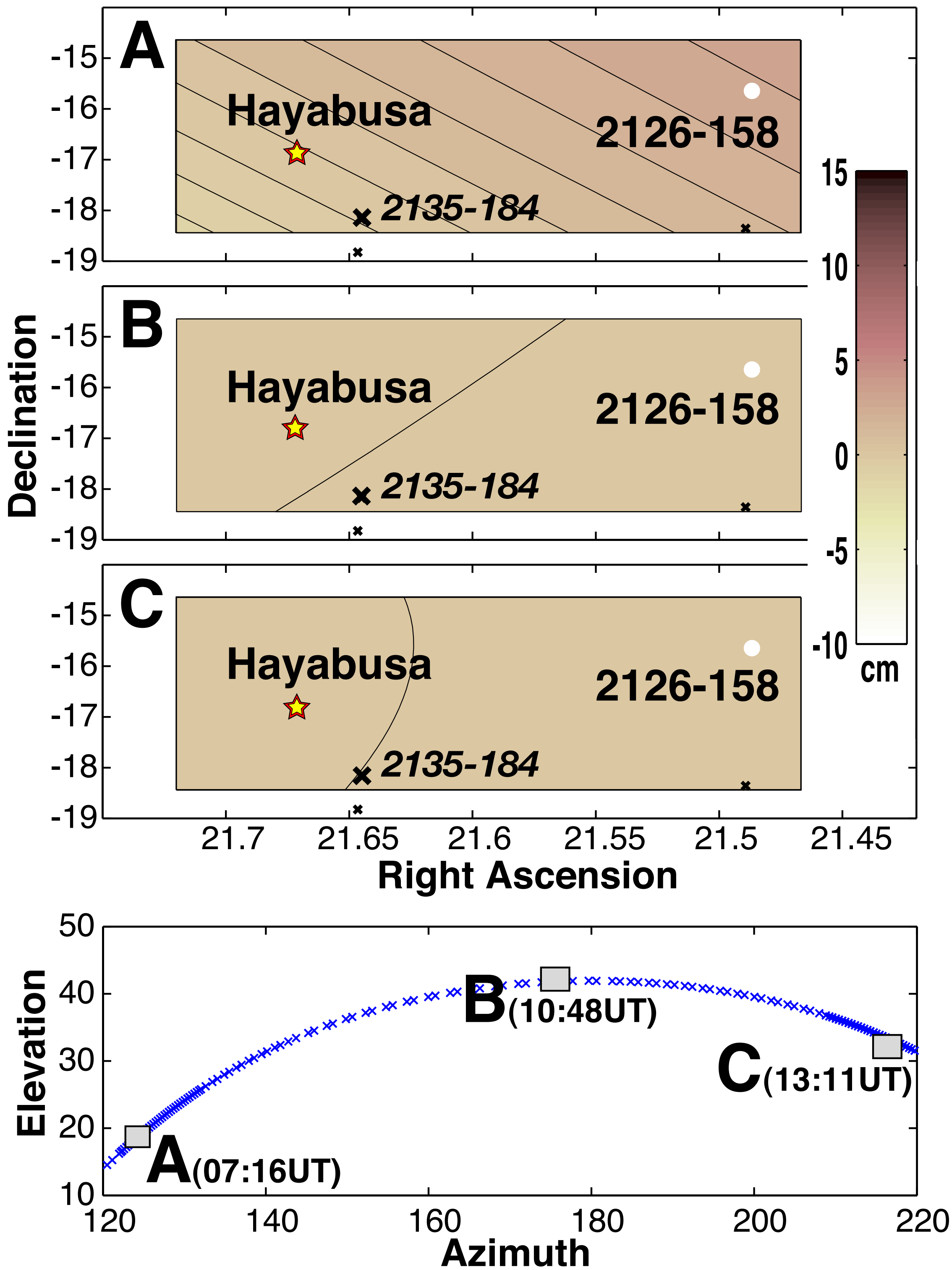

Figure 3: Sky maps of the simulated differential delays for the Kashima and Uchinoura baseline in the three upper panels during the $\Delta VLBI$ experiment on October 16, 2004. Contour interval is 0.2 cm. The quasar "2126-158 (white circle)" were observed as the reference source in the actual experiment. The quasar "2135-184" is the most nearby radio source to the HAYABUSA spacecraft. Black crosses in these panels denote the new radio sources listed in the forth VLBA Calibrator Survey (VCS4) catalogue[2]. Azimuth and Elevation angles of the radio sources at each epoch (A, B, and C) in Kashima are shown in the lower panel.

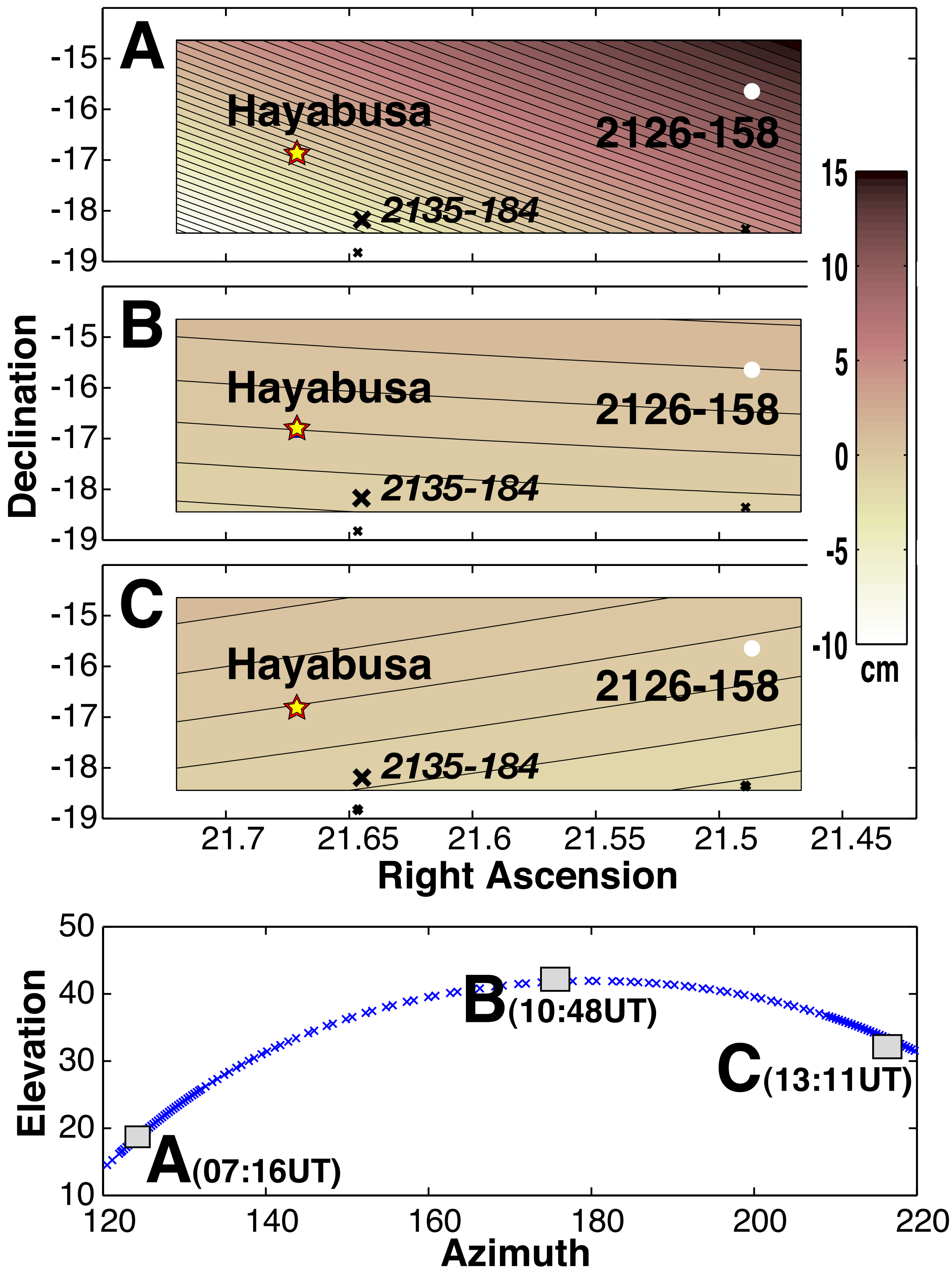

Figure 4: Same plot of Figure 3 but for the second $\Delta VLBI$ experiment on October 18, 2004.

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