SICE Annual Conference 2007
Sept. 17-20, 2007, Kagawa University, Japan

Evaluation of Differential VLBI Phase Delay Observable for Spacecraft Navigation

– ΔVLBI observation of Hayabusa at touchdown to ITOKAWA –

Mamoru Sekido[1],Ryuichi Ichikawa[1], Makoto Yoshikawa[2], Hiroshi Takeuchi[2], Takaji Kato[2],
Nanako Mochizuki[2],Yasuhiro Murata[2], Tsutomu Ichikawa[2]

[1] National Institute of Information and Communications Technology, Kashima Space Research Center.
(Tel:+81-299-84-7146; E-mail: sekido@nict.go.jp)
[2] Japan Aerospace Exploration Agency/ Institute of Space and Astronautical Science.
(Tel:+81-427-59-8341; E-mail: makoto@isas.jaxa.ac.jp)

Abstract: This report describes the evaluation of Δ VLBI delay measurement accuracy for Spacecraft Navigation. At the epochs of Hayabusa's touchdown to asteroid Itokawa, we made Δ VLBI observation for Hayabusa with Japanese domestic VLBI stations. Since the orbit of Itokawa is accurately known, we could use this occasion for evaluation of the delay calibration accuracy by Δ VLBI. By using a calibration technique of modeling the excess delay with group delays of multiple reference sources, calibration accuracy in the order of several hundreds pico seconds are obtained. Further improvements are expected by using dual-band observation for reference sources. As another approach, phase delay data of reference radio sources were applied for calibration with expecting improved precision and temporal resolution, though it did not show significant improvement for calibration in this case.

Keywords: ΔVLBI, Spacecraft Navigation, Bandwidth synthesis, Group delay, Phase delay

1. INTRODUCTION

Very long baseline interferometry (VLBI) is a technique to measure the angular position of celestial radio source with very high resolution (order of a few nano radians). Thus it is useful tool not only for radio astronomy but also measurement of spacecraft orbit. Range and range rate (R&RR) observation is one of the major ground based observables for orbit determination of spacecrafts in the deep space. Though it has sensitivity for spacecraft coordinates mainly in direction of the line of sight (LoS). Especially the radio source is in low equatorial region, its sensitivity to the declination coordinates decreases significantly. Complementarily with R&RR technique, VLBI technique has sensitive to the radio source coordinates in the plane perpendicular to the LoS. For the purpose to improve the precision of orbit determination, NASA/JPL has been jointly using both VLBI and R&RR for orbit determination by so called differential delta one-way range (DDOR) technique[1].

To satisfy the requirements of higher precision of orbit determination in recent space missions, JAXA/ISAS (Japan Aerospace Exploration Agency/ Institute of Space and Astronautical Science), NICT (National Institute of Information and Communications Technology), and NAOJ (National Astronomical Observatory of Japan) have started collaboration to use VLBI for spacecraft navigation. We have made a series of VLBI experiments for Japanese spacecraft Nozomi and Hayabusa[2] with support of Japanese Institutes involved in research work with VLBI (NAOJ, GSI, Gifu Univ. Hokkaido Univ., Yamaguchi Univ.) and Canadian Algonquin Observatory operated by NRCan and Crestech [3][4][5]. The DDOR method is based on group delay observation and its resolution is inversely proportional to both the signal to noise ratio (SNR) and signal bandwidth of the spacecraft signal. However Japanese spacecrafts have not been originally designed for ΔVLBI observation, which requires wide frequency band at their transponders, thus the delay precision is limited. Additionally the baseline lengths, which dominate the angular resolution, among Japanese domestic VLBI stations are one order smaller than those of NASA/JPL. These are disadvantages in our VLBI application to spacecraft navigation.

In November 2005, spacecraft Hayabusa has made touchdown to the asteroid ITOKAWA[6]. In this occasion, we organized ΔVLBI observation of Hayabusa with four Japanese domestic VLBI stations. We used phase delay as observable for the spacecraft observation. Phase delay has advantages of higher delay resolution and free from the requirement of signal bandwidth. Its drawback is uncertainty of phase ambiguity of 2πn. Fortunately at this event, both Hayabusa and ITOKAWA were at the same coordinates within one fringe phase projected on the sky. And the orbit of asteroid ITOKAWA is supposed to be known with enough accuracy owing to optical and radar observations. Therefore the phase delay could be directly used as absolute delay observable with replying on theoretical delay prediction and assumption of zero phase ambiguity. This became a good chance to evaluate the accuracy of the calibration with ΔVLBI technique applied to spacecraft. Inherently VLBI delay observable contains excess delay biases, which is mainly caused from atmosphere and clock-synchronization error between atomic standards at each observation stations. The ΔVLBI is a technique for calibrating the excess delay via frequent switching observation between target radio source and its nearby reference radio sources. By using phase delay observable, we could evaluated the accuracy of ΔVLBI calibration technique with high precision, which was not possible with group delay due to limited delay precision. The algorithm and data analysis procedure are described in section 2.Configuration of ΔVLBI observation of Hayabusa in Nov. 2005 and a relation between angular and delay resolutions are discussed in section 3.Finally the results of Δ VLBI observation are presented and precision of the calibration technique is discussed in section 4.

2. CALIBRATION ALGORITHM WITH ΔVLBI

2.1 Delay calibration by Δ VLBI method

VLBI is a technique of high precision for angular measurement in the celestial sphere, though its fundamental observable is difference of arrival time between a pair of X and Y radio telescopes. Δ VLBI is a method of astrometric VLBI observation by switching between target and reference radio sources alternatively. And its essence is calibrating error of delay observable inherent in VLBI observation such as excess delay due to propagation medium and synchronization error of atomic clocks at each radio telescopes. The angular distance to be estimated is the angular offset of true coordinates of the target radio source from those of a priori, which is so called phase tracking center.

The VLBI delay observable is defined by difference of signal time of arrival to station Y with respect to station X and it is expressed by a equation taking into account the relativistic effect due to the Earth's orbital motion around the sun and gravitational potential[7][8]. And also corresponding observation equation for radio source in the solar system is given by numerical[9][10] and analytical expression[11]. Although, since factor of relativistic corrections to the delay difference between observed delay and theoretical one becomes so small as to be negligible in the difference equation discussed below, when the a priori delay model has enough accuracy. Thus hereafter the VLBI observation equations are expressed in simplified form. Delay observable for quasar is expressed by following formula:

$$\tau_{\mathrm{ref}}^{\mathrm{obs}} = -\frac{\vec{B}\cdot\vec{S}}{c} + \tau_{\mathrm{clk}} + \tau_{\mathrm{atm}} \pm \tau_{\mathrm{ion}} + \tau_{\mathrm{etc}}, \qquad (1)$$

where $\vec{B}$, and $\vec{S}$ are baseline vector and unit direction vector of the reference radio source in the reference frame in the space, respectively. The second and following terms: τ_{clk}, τ_{atm}, τ_{ion}, and τ_{etc} are clock difference between each radio telescopes, contributions of non-dispersive and dispersive delays, and other error source such as instrumental delay and radio source structure. The sign of the dispersive delay is '+' for group delay and '–' for phase delay. We chose reference radio sources from a ICRF (International Celestial Reference Frame) catalog[12][13], whose celestial coordinates are accurate and continuously monitored by IERS. Here we introduce $\Delta\vec{S}$ and $\Delta\vec{B}$ to evaluate the error of reference radio source coordinates and station coordinates. Theoretical prediction of geometrical delay including the error is given by

$$\tau_{\mathrm{ref}}^{\mathrm{th}} = -\frac{(\vec{B}+\Delta\vec{B})\cdot(\vec{S}+\Delta\vec{S})}{c}. \qquad (2)$$

Then, O-C (Observed – Theoretical) delay for a reference radio source is expressed by keeping only the first order of the error $\Delta\vec{S}$ and $\Delta\vec{B}$ as

$$\Delta\tau_{\mathrm{ref}}^{\mathrm{O-C}} = \frac{\Delta\vec{B}\cdot\vec{S} + \Delta\vec{S}\cdot\vec{B}}{c} + \tau_{\mathrm{clk}} + \tau_{\mathrm{atm}} \pm \tau_{\mathrm{ion}} + \tau_{\mathrm{etc}}. \qquad (3)$$

This represents the deviation of observed delay from theoretical one for a reference radio source. And it is thought to be dominated by the non-geometrical excess delay in the term latter than the second, when station coordinates and radio source coordinates information are accurate enough.

For VLBI observation of radio sources in the solar system, observation equation have to take into account the effect of curved wavefront[10][11], which is neglected in VLBI observation for extragalactic radio sources. The delay observable for for spacecraft is expressed by replacing the first term of eqn. (1) with $-\vec{K}\cdot\vec{B}/c$ as

$$\tau_{\mathrm{sc}}^{\mathrm{obs}} = -\frac{\vec{B}\cdot\vec{K}}{c} + \tau_{\mathrm{clk}} + \tau_{\mathrm{atm}} \pm \tau_{\mathrm{ion}} + \tau_{\mathrm{etc}}', \qquad (4)$$

where $\vec{K}$ represents the effect of curved wavefront and it is given by

$$\vec{K} = \frac{\vec{R}_{01} + \vec{R}_{02}}{R_{01} + R_{02}}, \qquad (5)$$

where $\vec{R}_{0\mathrm{i}}$ (i=1,2) is position vector from station i to radio source 0 in the reference frame in the space. Detail of eqn. (5) and $\vec{R}_{0\mathrm{i}}$ is found in reference[11] and its eqn. (13),(14),and (15). The expression of O-C delay of spacecraft is given by using $\vec{K}^0$ vector, which is computed by using predicted orbit of spacecraft, and difference of true orbit from prediction expressed by $\Delta\vec{K}$ as

$$\Delta\tau_{\mathrm{sc}}^{\mathrm{O-C}} = \frac{-\Delta\vec{K}\cdot\vec{B} + \vec{K}^0\cdot\Delta\vec{B}}{c} + \tau_{\mathrm{clk}} + \tau_{\mathrm{atm}} \pm \tau_{\mathrm{ion}} + \Delta\tau_{\mathrm{etc}}. \qquad (6)$$

This observation equation could be used for astrometric position estimation of spacecraft coordinates by least square fitting. Although, since the second and latter terms affect as bias error, thus excess delay data obtained by observation of reference radio source are used for calibration. Subtracting the eqn. (3) from eqn. (6) gives

$$\Delta\tau_{\mathrm{sc-ref}}^{\mathrm{O-C}} = -\frac{\Delta\vec{K}\cdot\vec{B}}{c} - \frac{\Delta\vec{S}\cdot\vec{B}}{c} + \frac{\Delta\vec{B}\cdot(\vec{K}^0 - \vec{S})}{c} + \tau_{\mathrm{err}}. \qquad (7)$$

The first term is the main term for estimation of spacecraft coordinates $\Delta\vec{K}$ in astrometric analysis. The second term is proportional to the error of reference radio source coordinates. The reason of using ICRF radio source, whose coordinates are accurately known, is for the purpose to keep the second term small. When the error of $\Delta\vec{S}$ is order of 1 milli arc-seconds and baseline length is 1000 km, this term reaches 16 pico seconds The third term is proportional to the error of baseline vector and angular separation between target and reference radio sources. Its magnitude is about 10 pico seconds, when angular separation is 5 degrees and baseline error is 3cm, for instance. The last term $\tau_{\rm err}$ represent the other delay errors including imperfectness of delay calibration by ΔVLBI. As seen in eqn. (7), essence of the ΔVLBI method is obtaining accurate geometrical delay by calibrating the clock synchronization error and signal propagation delay common to target and reference radio sources. And the reference radio source have to be chosen within 10 degrees of angular distance from target spacecraft.

2.2 Modeling of Switching Δ VLBI Data

Computing the eqn. (7) is not so simple in practice, because the elevation angles for target and reference radio sources are different at each observation stations. It is optimum if the target and reference radio sources are observed simultaneously within a beam width of radio telescopes. Though the probability of finding reference radio sources close to the target radio source within a beam size is quite low, because of narrow beam size large diameter antenna at X-band and limited number of ICRF radio sources. Currently about 700 of ICRF radio sources are categorized[13]. Usually we have to observe reference radio sources and target spacecraft alternatively by switching in Δ VLBI. Therefore, $\Delta\tau_{\rm ref}^{\rm O-C}$ need to be interpolated not only in the parameter space of elevation angles for X and Y stations, but also in temporal space for the scan epoch of target radio source sandwiched by scans for reference radio sources. For the interpolation of different elevation angles, we used atmospheric mapping function proposed by A.Neil[14]. Mapping function is defined by the ratio of slant propagation path length to that in zenith direction as a function of elevation angle. For interpolation in temporal direction, the delay $\Delta\tau_{\rm ref}^{\rm O-C}$ was modeled by sum of linear trend of clock synchronization difference between two stations and peacewise linear function of atmospheric zenith path length at each stations. Whole data span is divided into n intervals as $(t_0, ..., t_n)$. Then data of $\tau_{\rm ref}^{\rm O-C}$ are parameterized by clock ($\tau_{\rm clk}$,$\dot{\tau}_{\rm clk}$), initial zenith path length ($\tau_{atm,x}^{(0)}$,$\tau_{atm,y}^{(0)}$) and continuous linear time variation at each time interval i with ($\dot{\tau}_{atm,x}^{(i)}$,$\dot{\tau}_{atm,y}^{(i)}$). The model equation is expressed as

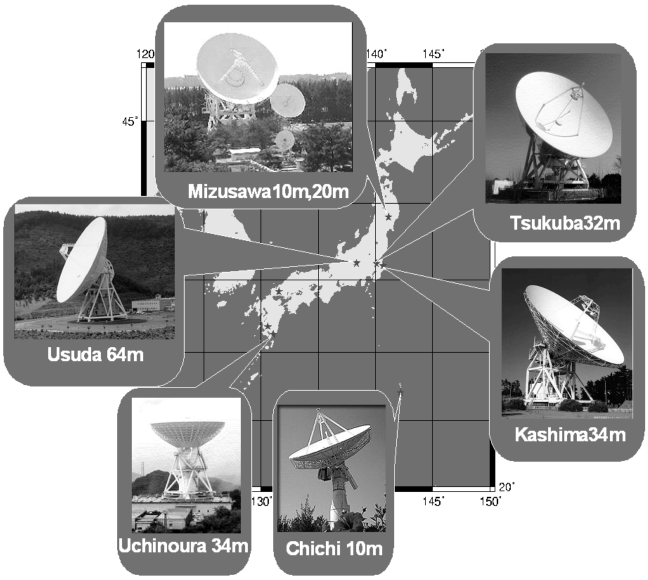

Fig. 1 Japanese VLBI stations participated in the ΔVLBI observations for Hayabusa

$$\begin{aligned}\Delta\tau &= \tau_{clk} + \dot{\tau}_{clk}(t-t_0)\\ &-\left[\tau_{atm,x}^{(0)} + \tau_{atm,x}^{(n)}(t-t_{n-1}) + \sum_{i=0}^{n-1}\dot{\tau}_{atm,x}^{(i)}(t_i - t_{i-1})\right]\\ &\times fm(El_x)\\ &+\left[\tau_{atm,y}^{(0)} + \tau_{atm,y}^{(n)}(t-t_{n-1}) + \sum_{i=0}^{n-1}\dot{\tau}_{atm,y}^{(i)}(t_i - t_{i-1})\right]\\ &\qquad\times fm(El_y), \qquad (8)\end{aligned}$$

where $fm(El)$ is the mapping function of atmosphere. The above mentioned model parameters were estimated by least square fitting of this equation to the data of $\tau_{\rm ref}^{\rm O-C}$. And also a few ps/s of constraint was applied for atmospheric rate parameter for stabilize the estimation. The clock and atmospheric delay parameters obtained for reference radio sources in this fashion are used for computing the calibration data at the epoch and elevation angles of each scans of target spacecraft. Finally the calibration data is subtracted from the delay observable of the spacecraft. These are our procedure for excess delay calibration by ΔVLBI.

3. Δ VLBI OBSERVATION OF HAYABUSA

3.1 Observations

From 4 to 26 November 2005, Hayabusa made four times of touchdown approaches to Hayabusa including rehearsals and real attempts[6]. At each time of these events, we made VLBI observations of Hayabusa with support of Japanese VLBI related institutes. Kashima 34m (NICT), Tsukuba 32m, Chichijima 10m (Geographical Survey Institute:GSI) and Mizusawa 20m (NAOJ) radio telescopes had made ΔVLBI observation. Due to

Table 1 ΔVLBI observations for Hayabusa were made on 4, 12, 19, and 25th of Nov. 2005. Japanese domestic VLBI stations: Kashima 34m (O), Tsukuba 32m (T), Mizusawa 20m (M) and Chichijima 10m (C) are participated the observation. VLBI stations, reference radio sources and their angular distance from Hayabusa are listed.

Date	Reference radio source (Angular distance)	Switching Cycle	Station ID
4th	1352-104 (3.3 deg.)	6 min.	O, T, C
12th	1430-178 (3.3 deg.) 1443-162 (2.4 deg.)	6 min.	O, T
19th	1430-178 (8.5 deg.) 1443-162 (5.5 deg.)	6 min.	O, T, M
25th	1514-241 (5.8 deg.) 1504-166 (7.1 deg.)	6 min.	O, T

the requirement of mission operation of Hayabusa, Usuda 64m and Uchinoura 34m radio telescopes (JAXA/ISAS) had made observation only for Hayabusa and not for reference radio sources, then their data was not used for ΔVLBI analysis. The X-band signal from Hayabusa was recorded with the K5/VSSP data acquisition system [15] at each stations. Eight channels with 4 MHz band width each of X-band signal were observed for reference radio source(quasar) to get precise group delay. And one of these data channels was used for recording the Hayabusa's signal. Data sampling mode of 8MHz-1bit per channel was used for both reference radio source and Hayabusa. Fig.1 shows the VLBI stations participated in the observations. And Table 1 shows the reference radio sources, their angular distance, switching interval and IDs of VLBI stations. Reference radio sources were selected from the ICRF catalog except for 1352-104. As discussed at eqn. (7), since the error of reference radio source coordinates affect to the calibration error, thus it is important to use radio source whose coordinates are accurately known. Uncertainty of these reference radio sources are 1430-178(4mas), 1443-162 (0.5mas), 1514-241(0.3mas), 1504-166(0.3mas)[13]. From viewpoint of choosing reference sources, these experiment were in relatively better condition, since more than one reference radio sources where found within 10 degrees from the Hayabusa. Although angular distance from the sun was relatively small (< 8 deg.), because the Hayabusa was almost opposite side of the sun from the Earth at this time. When radio signal passes close to the sun, not only delay and refraction, but also scintillation effect are caused by dense and inhomogeneous plasma of solar corona and induce degradation of coherence and broadening of the source image. Therefore observation of radio source at solar angle less than 10 degrees is usually avoided in geodetic and astronomical VLBI observation. This hard condition of observing through a dense plasma of solar corona is potential error source of the ΔVLBI observation.

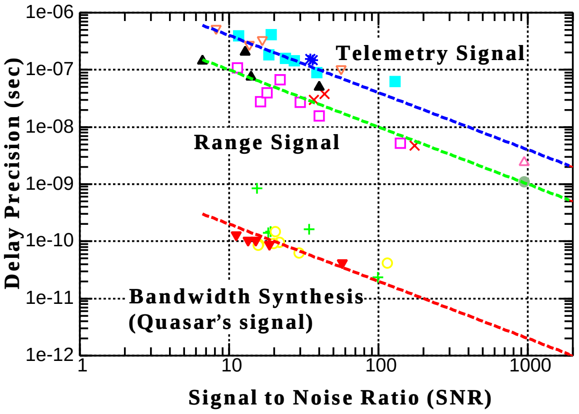

Fig. 2 Precision of group delay measurement (RMS around the mean) for range-signal and telemetry-signal of Hayabusa are plotted with respect to the signal to noise ratio (SNR)). For comparison, the same data for quasar's signal after bandwidth synthesis are indicated at the bottom. effective bandwidths of the signals are 100kHz, 450kHz, and 340MHz for telemetry-signal, range-signal, and bandwidth synthesis of quasar, respectively.

3.2 Delay and Angular Precision

The relation between precision of angular and delay measurement of VLBI observation is expressed by

$$d\theta \sim \frac{c|\delta\tau|}{B}, \tag{9}$$

where B is magnitude of projected baseline vector on a plane perpendicular to the direction to the radio source. As seen from this formula, angular precision is proportional to the precision of delay measurement and inversely proportional to the baseline length. JPL/NASA has been doing DDOR observation with radio telescopes of Deep Space Network located at California (USA), Madrid (Spain), and Canberra(Australia). The baseline length of this network is more than 8000km. In case of our observation, the baseline lengths are from 50km(Kashima-Tsukuba) to 1000km (Kashima-Chichijima). Since our baseline lengths are one to two order smaller than the DSN, we need more than one order better precision of delay measurement to get comparable angular precision with the DDOR observation by JPL/NASA. Let us put a minimum delay precision at 1 nano second (=0.3m), which correspond to a level of angular precision of 1μ radian with 300km baseline. The 1 μ radian is the same level with current orbit determination precision with R&RR measurements. Fig.2 shows plots delay measurement precision with respect to SNR for two sorts of signal (range-signal, telemetry-signal) of Hayabusa. Precision of Group delay measurement is inversely proportional to signal bandwidth and SNR in general. Since range-signal of Hayabusa (effective bandwidth 450 kHz) has wider bandwidth than telemetry-signal (effective bandwidth 100 kHz), then delay precision of range-signal is higher than telemetry-signal.

However, even by using range-signal, SNR greater than 1000 is required to get 1 nano second of delay precision, and it is not always possible. Additionally 1 nano second is a minimum requirement but more higher delay resolution will be necessary to get navigation accuracy comparable with DDOR observation by NASA/JPL. By using wide-band signal, delay precision can be improved with lower SNR. For example, geodetic VLBI observation enables order of a few tens of pico seconds of delay resolution by using more than 300 MHz effective bandwidth (Fig.2). The DDOR signal used by NASA/JPL is composed of multiple tone signal with several to ten several MHz intervals. That enable to keep wide bandwidth to get high delay resolution (1$\sim$ 0.1 ns). Future Japanese space mission have to prepare for such wide bandwidth operation in deep space navigation, though such wide bandwidth of transponders are not equipped on current Japanese space probes. Therefore when group delay is used, VLBI observation with short or middle range of Japanese domestic baselines are not enough to testing the orbit determination improvement by joint use of VLBI with R&RR measurement.

Due to these reasons, we tried to use phase delay observable for evaluation of Δ VLBI calibration. The advantage of phase delay observable is less requirement for the space-prove and ground station. One tone signal from spacecraft is enough for observation thus applicable for any spacecrafts. And its delay resolution is high. Disadvantage of the phase delay is ambiguity uncertainty. But in case of this observation, we could expect the phase ambiguity as zero around the theoretical delay computed by using the orbit of Itokawa, because Hayabusa was at the same position with Itokawa within one fringe projected on the sky. And Itokawa's orbit is accurately known by other optical and radar observations. Consequently the VLBI observations of Hayabusa in November 2005 became a good chance to testing the calibration accuracy of ΔVLBI method in spacecraft observation.

3.3 Data Reduction for Group Delay and Phase Delay

The K5/VSSP data acquisition system is designed to handle the data with computer, data reduction procedure including correlation processing has been done by software correlator developed by NICT. Followings are descriptions of delay observable extracted from the VLBI data.

3.3.1 Group Delay of reference radio Source

Bandwidth-Synthesis (BWS) technique has been used to get precise group delay in geodetic and astrometric VLBI observations[16]. Group delay observables for each scans were obtained by integrating the observed fringe phase in both frequency (BWS) and time directions [17]. Group delay also has a integer number of ambiguity with a interval, which is reciprocal of greatest common measure (GCM) of the frequency interval of observation channels. It was 100 nano seconds in this observation. Since terrestrial coordinates of VLBI stations are known by geodetic VLBI observations within the accuracy better than a few cm, thus the ambiguity of group delay is easily solved when station coordinates and radio source coordinates are accurately known. The order of precision of group delay measurements is about a few tens of pico seconds, when about 500 MHz bandwidth is available. A drawback of the group delay is that the time interval of data points is sparse. Because one group delay is obtained every scan by integrating the data in both time and frequency domain to get high SNR.

3.3.2 Phase Delay of Reference Radio Source

Phase delay is another choice as delay observable of VLBI observations. Its advantage is high delay resolution and continuity of the data. And disadvantage is the uncertainty of integer number of phase ambiguity. Since the signal form quasar is weak in general, thus the signal is integrated coherently in frequency direction (BWS) and also integrated in minimum short interval (2 seconds) in time direction. If radio source coordinates and VLBI station's coordinates are appropriately accurate enough, then fringe phase is expected to be stable within the interval of a few tens to hundreds of seconds. Thus fringe phase could be connected by unwrapping the phase cycle. After the fringe phase connection, phase data is converted to delay by using mean radio frequency of the observation. Since phase-delay data is obtained by correlation process as a residual after subtracting accurate a priori delay, phase-delay data is obtained by adding the theoretical a priori delay. As an tool of finding and correcting mistakes of phase connection, closure delay relation may be used, if more than 3 stations are available, and this was the case.

3.3.3 Phase Delay of Target Radio Source

Phase delay for spacecraft is rather simple than phase delay of quasar's data. In the process of cross correlation of X and Y data, the phase data of main carrier signal are extracted by multiplexing a series of numerically generated sinusoidal data in a software software correlator. Note that the frequency of the carrier signal have to be tracked since it is drifting with time due to instability of oscillator on the spacecraft and relative motion of the spacecraft and observation stations, which is mainly caused by earth rotation and orbital motion around the sun. Since power density of artificial signal of spacecraft is higher than that of quasar in comparison per unit of frequency even though the total power is small, then the fringe phase data are obtained every 2 seconds with enough SNR. Then the fringe phase are connected by unwrapping the phase cycle and converted to delay data by dividing with the frequency of the carrier signal. Finally phase delay of spacecraft is gained by adding the theoretical a priori delay to the fringe phase data.

4. RESULTS AND DISCUSSION

4.1 Results

As discussed in section 2.2, the delay model express by equation (8) was fitted to the VLBI group delay data (sec-

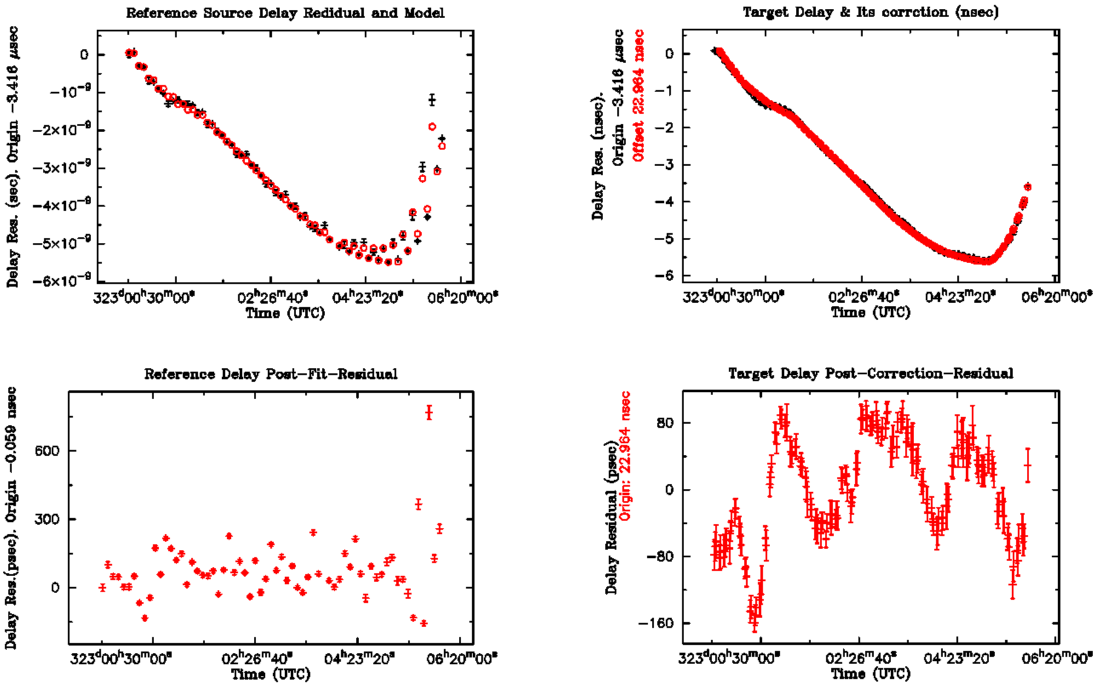

Fig. 3 As an example of delay calibration by Δ VLBI, data of Kashima-Mizusawa baseline observed on 19 Nov. 2005 are displayed. Residual O-C data of reference radio sources are plotted with '+' in upper left panel and delay model obtained by fitting to the data is over plotted with '○'. Lower left is post fit residual of group delay for reference radio sources. Original O-C residual for Hayabusa is plotted in upper right panel and calibration data based on the group delay of reference sources are over plotted with '○. Lower right is post-calibration residual of phase delay of Hayabusa.

tion3.3.1) of reference sources by least square method. Then the derived model parameters are used for calibration of phase delay data for Hayabusa (hereafter referred as 'Group-Phase Calibration'). An example is demonstrated in Fig.3. The excess delay for Hayabusa computed by the model shows good agreement with the O-C phase delay data(Right panels in Fig.3). The post-calibration residuals (lower right panel in Fig.3) are almost constant for the whole span of the observation (about 6 hours.). And they are scattered within ± 100 pico seconds in this case. Scattering of post-calibration residual in the other cases are within ± 100 pico seconds in better case and within ± 1 nano second in the worst case. The residual does not randomly scatted but still unknown systematic variations in around 1 hour time scale remain. The overall correction accuracy was around several hundreds of pico seconds Excess delay correction was made by using group delay of reference radio source (section3.3.1) and it was applied to phase delay of target source (section3.3.3) in this case. Thus the effect of dispersive delay caused by plasma in the ionosphere or solar corona affected two fold in the residual.

As the other choice of delay observable, phase delay of reference radio source(section3.3.2) was used for calibration of phase delay data of Hayabusa (hereafter refereed as 'Phase-Phase Calibration'). The plot of calibration data and post-calibration residual are displayed in Fig.4

4.2 Discussion

The 'Group-Phase Calibration' worked fairly well and overall accuracy in order of sub-nano seconds are obtained. Remaining points to be improved are that the post-calibration residuals are not randomly distributed but they show systematic trend. One of possible cause this may be insufficient calibration model which does not include both neutral and dispersive delay caused by ionized medium. In the group delay based On baselines related with Chichijima station, calibration data showed opposite sense of delay variation to the O-C phase delay data of Hayabusa in 'Group-Phase' calibration. The Chichijima is located 1000km south from Japanese Honshu Island and ionospheric electron density is high above the station, because it is at low geomagnetic latitude. The 'opposite calibration' was explained by opposite sign of dispersive delay for group delay and phase delay. Actually the 'opposite calibration' was not seen in the calibration data of 'Phase-Phase' calibration. This fact indicating that we need to model the dispersive medium separately with neutral atmosphere, especially when using lower latitude station. The mapping function of these two kinds of delay are quite different due to the different altitude of the layer which is substantial source of the effects. As it is used in geodetic VLBI, simultaneous S/X dual band observation for reference radio source will be good solution for separate estimation of the two sorts of propagation delay.

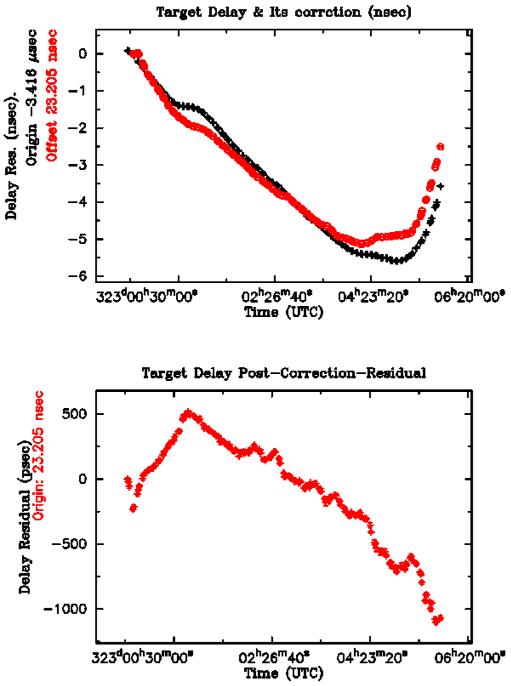

Fig. 4 An example of excess delay calibration by using phase delay of reference radio source. Phase delay data of reference radio sources are obtained by connecting fringe phase of bandwidth synthesis result(see section3.3.2 of text). The mark of '◯' in the upper panel shows the calibration data generated by using the phase delay data. O-C delay data of Hayabusa are superimposed with '+'. Lower panel shows post-calibration residual.

Relatively poor calibration accuracy ± 1 nano second are observed in the experiment on 4th Nov. The main reason of this is that only single reference source was used as the calibrator in the Δ VLBI. The atmospheric thickness and its time variation at each stations are estimated by the difference of delay sampled at different elevation angle. This was a good lessen to learn that we have to use more than one references for calibrator.

The method of 'Phase-Phase Calibration' was expected to have higher delay and temporal resolution than group delay, though the calibration results were even worse than the case of 'Group-Phase Calibration' (see Fig.4). Causes of this result could be (1) Phase connection procedure is taken for each reference sources, then each data set are merged into one file, because phase continuity can be supposed for the same source but not for different source. Thus a it is difficult to prevent the entry of phase ambiguity offset between data set of different sources. Since separation of atmospheric thickness estimation is gained by delay difference and dependency with respect to the elevation angles, uncertainty of delay offset among reference radio sources might have affected the wrong estimation of atmospheric parameters. (2) The scan length of reference radio sources were less than 3 minutes with about 10 minutes of switching cycle for returning back to the same reference source in observation on 19 Nov. 2005, where two reference sources are alternatively switched with target spacecraft. Thus phase connection by extrapolating rely on the phase slope within one scan was marginal. Extension of scan length of reference sources might relax the condition, though it elongate the switching cycle of target source and may affect to the phase connectivity. Optimum compromise of these conditions have to be searched to solve this problem.

5. SUMMARY

We made a series of Δ VLBI observations of Hayabusa with Japanese domestic VLBI stations at the time of touchdown events to asteroid Itokawa. This was a good chance for evaluation of calibration accuracy of Δ VLBI method with known position of the target radio source. One or two reference radio sources were observed by switching with Hayabusa in X-band. Eight channel of 4MHz video signals were observed with the same frequency arrangement of geodetic VLBI to get precise group delay by bandwidth synthesis. Group delay and phase delay data were extracted from reference radio sources and applied to delay calibration for Hayabusa. The calibration accuracy of 'Group-Phase' calibration was found out to be in order of several hundreds of pico seconds. Further improvement is expected by modeling dispersive medium and it will be possible by S/X dual frequency observation. The result of using single calibrator source proved that more that one reference radio sources are necessary for accurate calibration modeling. The 'Phase-Phase' calibration was applied with expecting high delay and temporal resolution. However it did not show better result in this experiments, and it would be due to uncertainty of ambiguity of phase delay for reference radio sources.

REFERENCES

[1] J.S.Border, et al., "Determining Spacecraft Angular Position with Delta VLBI: The Voyager Demonstration", *AIAA/AAS Astrodynamics Conference August 9-11 1982 San Diego CA.*, AIAA-82-1471, 1982.

[2] J.Kawaguchi, K.Uesugi, and A.Fujiwara, "The MUSES-C mission for the sample and return-its technology development status and readiness", *Atca Astronautica*, Vol. 52, pp.117-123, 2003.

[3] M. Sekido, et al., "Astrometry Observation of Spacecraft with Very Long Baseline Interferometry - A Step of VLBI Application for Spacecraft Navigation -", *Proceedings of URSI Commission-F Triennium Open Symposium. 1-4 June 2004 Cairns, Great Barrier Reef, Australia* pp.163-170. 2004.

[4] R.Ichikawa, M.Sekido, H.Osaki, Y.Koyama, T.Kondo, T.Ohnishi, M.Yoshikawa, W.Cannon, A.Novikov, M.Berube, NOZOMI VLBI Group"An Evaluation of VLBI Observations for the Deep Space Tracking of the Interplanetary Spacecrafts" *,in International VLBI Service for Geodesy and Astrometry 2004 General Meeting Proceedings, edited by Nancy R. Vandenberg and Karen D. Baver,* NASA/CP-2004- 212255, pp.253-257, 2004.

[5] M.Sekido, R. Ichikawa, H. Osaki, T. Kondo, Y. Koyama, M. Yoshikawa, T. Ohnishi, W. Cannon, A. Novikov, M. Berube, and NOZOMI VLBI group, "VLBI Observation for Spacecraft Navigation (NOZOMI) - Data Processing and Analysis Status Report",*in International VLBI Service for Geodesy and Astrometry 2004 General Meeting Proceedings, edited by Nancy R. Vanden-*

berg and Karen D. Baver, NASA/CP-2004- 212255, pp.258-262, 2004.

[6] , H.Yano, et al., “Touchdown of the Hayabusa Spacecraft at the Muses Sea on Itokawa”, *Science*, Vol. 312, pp.1350-1353, 2006.

[7] T.M.Eubanks, “A Consensus Model for Relativistic Effects in Geodetic VLBI”, *Proc. of the USNO workshop on Relativistic Models for Use in Space Geodesy*, pp. 60-82, 1991

[8] D.D.McCarthy, and G.Petit, “General Relativistic Models for Propagation” *IERS Conventions 2003, IERS Technical Note* No. 32. pp. 109-116, 2003.

[9] S.Klioner, “General relativistic model of VLBI observables”, *in Proc. AGU Chapman Conf. on Geodetic VLBI: Monitoring of Global Change, (eds. Carter WE) NOAA Technical Report*, NOS 137 NGS 49, American Geophysical Union, Washington D.C: pp. 188-202, 1991.

[10] T.Fukushima, “Lunar VLBI observation model”, *Astron. Astrophys*, Vol. 291: pp. 320-323, 1994.

[11] M.Sekido, and T. Fukushima, “VLBI Delay Model for Radio Source at a Finite Distance”, *Journal of Geodesy*, Vol.80, pp.137-149, 2006.

[12] C.Ma, E.F.Arias, T.M.Eubanks, A.L.Fey, A.-M.Gontier, C.S.Jacobs, O.J.Sovers, B.A.Archinal, and P.Charlot, “The International Celestial Reference Frame as realized by Very Long Baseline Interferometry”, *Astronomical Journal*, Vol. 116, pp.516-546, 1998.

[13] A.L.Feys, C.Ma, D.F.Arias, P.Charlot, M. Feissel-Vernier, A.M.Gontier, C.S.Jacobs, J.Li, and D.MacMillan, “The Second Extension of the International Celestial Reference Frame: ICRF-EXT.1”, *Astronomical Journal*, Vol. 127, pp.3587-3608, 2004.

[14] A.Neill, “Global mapping functions for the atmosphere delay at radio wavelengths”, *J. geophys. Res.*, Vol. 101 No. B2, pp3227-3246, 1996.

[15] Y.Koyama, T.Kondo, K.Takashima, K.Sorai, H.Takaba, and K.Fujisawa, “Evaluation of the K5 system in geodetic VLBI experiments”, *IVS CRL-TDC News*, No.23, pp.26-30, 2003.

[16] T.A.Clark, et al., “A Very-Long-Baseline Interferometer for geodetic applications”, *Radio Science*, Vol. 11, pp.421-432, 1976.

[17] A.E.E.Rogers, “Very Long Baseline Interferometry with Large Effective Bandwidth for Phase-Delay Measurements”, *Radio Science*, Vol. 5, pp.1239-1247, 1970.