Δ VLBI Test Observation at HAYABUSA's approach to ITOKAWA

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Abstract

In November 2005, spacecraft HAYABUSA has made touchdown approaches to the asteroid ITOKAWA. In this occasion, we organized Δ-VLBI observation of HAYABUSA with six Japanese domestic VLBI stations. We used phase delay, which has higher resolution that group delay, as observable for this experiments. This was a good chance to evaluate the accuracy of Δ VLBI delay measurement for spacecraft. Excess delay was modeled by clock and atmospheric delay and the correction accuracy was found to be around several hundreds of pico seconds.

ハヤブサのイトカワ接近時の Δ VLBI 評価実験

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摘要

2005 年 11 月、ハヤブサが小惑星イトカワにタッチダウンを行なった時期に合わせて、国内の VLBI 観測局６局を使ってハヤブサの相対 VLBI 観測を行なった。これは飛翔体の VLBI 観測における、相対 VLBI による遅延補正の精度/確度を検証する絶好の機会となった。この観測では、群遅延量より精度の高い位相遅延量を観測量として使い、原子時計の同期誤差と大気に起因する遅延量を数百ピコ秒の精度で補正できることが確認された。本文では相対 VLBI による遅延補正のアルゴリズムについても述べる。

1 Introduction

Joint use of range and range rate (R&RR) measurement and VLBI measurement of spacecraft can enhance the precision of spacecraft navigation (e.g. [1][2]), and it is becoming more important for the success of recent space mission. We have been investigating Δ VLBI technique for application to spacecraft navigation of Japanese space missions[3] [4] [5]. In November 2005, Japanese spacecraft HAYABUSA made touchdown trials to asteroid Itokawa. In this occasion, we organized Δ VLBI observation of HAYABUSA with Japanese domestic VLBI stations. Δ VLBI is a technique to calibrate excess delay of VLBI observable by switching observation of target radio source and its nearby reference radio sources. The excess delays are caused from imperfectness of synchronization of atomic clock standards of each VLBI stations and atmospheric delay. This excess delay is inherent to VLBI observation, though pure geometrical delay is desirable for the purpose of spacecraft navigation. Therefore Δ VLBI technique is used for calibration of those excess delay. The celestial coordinates of reference radio sources are required to be accurately known in Δ VLBI. Then reference radio sources are chosen from ICRF (international Celestial Reference frame) catalog. In the process to calibrate the excess delay in Δ VLBI, difference of ray paths due to the difference of elevation angles for target and reference radio sources are taken into account by using mapping function of atmosphere. Although it is not perfect, then evaluation of delay correction accuracy and understanding of still remaining delay error after the correction is important for further improvement.

Two sorts of observables, group delay and phase delay are obtained from VLBI observations. Due to the limited bandwidth of the signal from HAYABUSA, group delay precision was limited to the order of several tens of nano seconds[6]. For evaluation of the accuracy of Δ VLBI delay correction, higher delay resolution is necessary. Thus we used phase delay observable. Drawback of phase delay is difficulty of absolute delay measurement due to integer number of phase ambiguities. However in this case, the orbit of asteroid Itokawa has been known by optical and radar measurements. And the position of HAYABUSA, which stayed with Itokawa during that period, is also supposed to be known within the one fringe ambiguity. Therefore we could use phase delay by avoiding the phase ambiguity problem.

A series of VLBI experiments in Nov. 2005 for HAYABUSA were a good occasion to evaluate how much accurately Δ VLBI technique can calibrate the excess delay due to atomic clocks and propagation medium. In this paper, we present the algorithm and result of delay correction with Δ VLBI technique in spacecraft VLBI observation for HAYABUSA in Nov. 2005.

2 Algorithm of Excess Delay Correction with ΔVLBI

2.1 Excess Delay Correction with Δ VLBI

VLBI is a technology for angular measurement, though the primary observable is delay time. Δ VLBI is sometimes told as a method to measure the angular distance between target and reference radio sources, although Δ VLBI is essentially a technique to calibrate excess delay inherent to VLBI caused from imperfectness of synchronization of atomic clocks and radio wave propagation medium. The angle to be estimated in the analysis is that between real position of target source in the plane of sky and phase tracking center, which is given as a priori position.

By using baseline vector $\vec{B}$ and unit direction vector $\vec{S}$ of quasar in the quasi-inertial coordinate system in the space, VLBI delay observable for quasar is given by

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

where τ_{clk}^{ref}, τ_{atm}^{ref}, τ_{ion}^{ref} and τ_{etc}^{ref} represent respectively imperfectness of synchronization of atomic clock, contribution from atmosphere, ionosphere, and other delays caused from hardware , structure of radio source and so on. Sign of ionospheric delay is '+' for group delay and '−' for phase delay. Here we suppose the delay observable is represented in coordinate time (TDB) and eliminating the effect of earth motion with respect to the solar system barycenter and relativistic effects. Strict expression of VLBI delay for natural radio source and spacecraft are given in IERS conventions[7] and by Sekido and Fukushima [8]. The magnitude of the error caused by this simplification is order of $V_E/c \sim 10^{-4}$, where V_E is the velocity of earth's motion around the sun. Thus less than 10^{-12} seconds when O-C is less than 10^{-8} seconds.

Reference radio source coordinates are supposed to be accurately known. Here we express the given source direction vector by $\vec{S}+\Delta\vec{S}$ with true source vector $\vec{S}$ and its error $\Delta\vec{S}$. And given baseline vector $\vec{B}+\Delta\vec{B}$ is sum of true baseline vector $\vec{B}$ and its error $\Delta\vec{B}$. Then geometrical delay of theoretical prediction is given as

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

O-C (Observed - Theoretical) for reference radio source is expressed by remaining the first order of the error as

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

Observation equation for spacecraft have to be taken into account the curvature of wavefront. It is given by replacing $-\vec{B}\cdot\vec{S}/c$ of equation (1) with $-\vec{B}\cdot\vec{K}/c$ as

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

where the vector is given by $\vec{K}$ [9][8]

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

where $\vec{R}_{01}$ and $\vec{R}_{02}$ are vectors from station 1 and 2 to 0, respectively.

Let us suppose $\vec{K}^0$ as the vector of equation (5) computed with predicted orbit and suppose $\Delta\vec{K}$ as difference between $\vec{K}$ of true orbit and predicted $\vec{K}^0$. Then O-C of delay for spacecraft is given as

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

The first term of $\Delta\vec{K}$ contains the information of spacecraft coordinates. And other term need to be calibrated via Δ VLBI with reference radio sources.

Subtracting equation (3) from equation (6) becomes,

$$\Delta\tau_{sc}^{obscrr} = -\frac{\Delta\vec{K}\cdot\vec{B}}{c} - \frac{\Delta\vec{S}\cdot\vec{B}}{c} + \frac{\Delta\vec{B}\cdot(\vec{K}^0-\vec{S})}{c} + \tau_{err} \quad (7)$$

The first term of right hand side is the main term to be used for the astrometric VLBI data analysis for spacecraft. The second term is propotional to the position error of reference radio source. Due to this term, the coordinates of reference radio source need to be accurately known. The third term is in proportion to both error of station coordinates and angular distance between target and reference radio sources. This term is generally small., e.g. it is less than 8 pico seconds, when angular distance is less than 5 degrees and baseline vector error is less than 3 cm. Though, note that this term is not neglisible in case baseline error or angular distance of raference sources are larger or precision of the requirement is high. The term τ_{err} represents other errors such as excess delay of propagation medium which could not be properly removed by Δ VLBI technique. In the analysis described in section 5, the ionospheric delay affects two folds since group delay is used for calibration of phase delay. Magnitude of ionospheric delay contribution to VLBI delay in X-band is order of several pico seconds for 50km baseline and about one hundred pico seconds for 300km baseline. When station at low geomagnetic latitude, such as Chichijima, is included, the magnitude reaches to half a nano second or so.

2.2 Modeling of switching Δ VLBI data

At the stage computing the equation (7), a modeling for interpolation of delay in time and elevation angles are necessary, since target and reference radio sources are not observed simultaniously but by switching. Mapping function of the atmosphere is use for calibration of atmospheric delay of target source from that of reference sources observed at different elevation angles. Mapping function is defined by the ratio of a delay along the ray path with respect to that in zenith direction. We used NMF mapping function[10].

Excess delay due to atmosphere and difference of atomic standards are respectively modeled by first order polynomial and continuous piece-wise linear function. Detail of the atmospheric delay model with piece-wise linear function is as follows: Whole period is divided into n intervals by epochs $(t_0, ..., t_n)$. Rate of atmospheric thicknesses of X and Y stations for each intervals $(\dot{\tau}^{(i)}_{atm,x}, \dot{\tau}^{(i)}_{atm,y},$ i=0,...,n-1) and initial zenith delay parameters $(\tau^{(0)}_{atm,x}, \tau^{(0)}_{atm,y})$ are used for modeling of atmonospheric delay in the observables. The excess delay model including clock parameters at t $(t_j \leq t < t_{j+1})$ is expressed as follows:

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

where $fm(El_x)$ is mapping function of atmosphere for station X. As it is for Y station. Parameters $(\tau_{clk}, \dot{\tau}_{clk}, \tau^{(0)}_{atm,x}, \tau^{(0)}_{atm,y}, \dot{\tau}^{(i)}_{atm,x}, \dot{\tau}^{(i)}_{atm,x})(i = 0, ..., j)$ are obtained by fitting the model to the delay residual of reference radio sources.

In the analysis in section 5, time interval was set equally 30 min. And constraint of 18 pico sec/hour for the rate of atmospheric zenith delay are added for estimation of those parameters for each stations. The obtained parameters of atomosphere and clock are used for prediction of excess delay in each scans of HAYABUSA. Finally accurate geometrical delay is obtained by correction of excess delay. These are the procedure of excess delay correction with $\Delta VLBI$ technique.

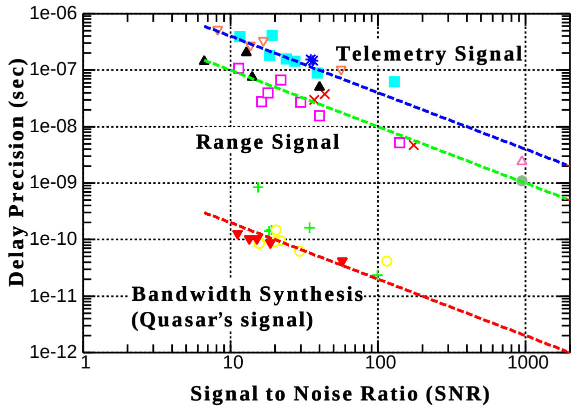

Figure 1: Delay measurement precision of group delay for range and telemetry signal of HAYABUSA are plotted as a function of singl to noise ratio (SNR). Delay precision of group delay derived by bandwidth synthesis (effective band width $\sim$ 300MHz) for quasar's signal is plotted for comparison.

3 Measurement precision for delay and angular resolution

Angular precision of VLBI measurement is evaluated by

$$d\theta \sim \frac{c|\delta\tau|}{B}, \quad (9)$$

where $\delta\tau$ is delay precision and B is baseline length projected to the plane perpendicular to the source vector. Angular precision is in proportion to the delay precision and inverse of baseline length. The JPL/NASA has been doing DDOR observation of spacecraft with intercontinental baseline of Deep Space Network: California (USA), Madrid (Spain), and Canberra (Australia). Since our baselines among domestic VLBI stations are shorter than JPL/NASA by one order or more, thus we need higher delay resolution to achieve comparable result with them.

The accuracy of orbit determination only with R&RR for deep space is about 1 μ radian, and it correspond to delay precision of 1 nano second with 300 km baseline. Thus we put 1 nano second delay accuracy as a mile stone of our observation. We have made several VLBI test experiments with range and telemetry signal of HAYABUSA. Figure 1 indicates the root mean square (RMS) of group delay residual of those experiments with respect to the signal to noise ratio (SNR). Here we regard the RMS of the residual as indicator of delay precition. Theoretically, delay precision is inversely propotional to the bandwidth and SNR. Since bandwidth of range signal ($\pm$ 1MHz) is wider than that of telemetry signal ($\pm$ 74 kHz), then actually delay precision of former signal is better than the latter as seen in figure 1. Although the plot indicates that SNR higher than

1000 is required to achieve 1 nano second of precison. In case of geodetic VLBI, about 10 signal channels are distributed over 500 MHz bandwidth in X-band (8 GHz) and precise delay measurement is performed via bandwidth synthesis technique. Delay precision obtained in observation of quasar is superimposed in the figure 1 for comparison. It shows that two order of higher precision can be achieved due to wider bandwdith. The JPL/NASA is making use of multi-tone signals in several MHz frequency span for DDOR observations. And 1 $\sim$ 0.1 nano second of delay precision is obtained. Of course similar multitone technique will be used in future Japanese space mission for precise group delay measurement, though such operation is not being planed with HAYABUSA at present. For evaluation of Δ VLBI's correction accuracy, group delay observation of HAYABUSA was though to be insufficient. Thus we used phase delay obsevable for the evaluation of Δ VLBI. The advantages of phase delay are as follows: (1) Single tone signal is sufficient for phase delay measurement. (2) No paticular requirements for space proves are needed. (3) precision of delay measurement is high. A draw back is the difficulty of ablolute delay measurement due to phase ambiguity. Though in this case, HAYABUSA was almost in the same orbit with ITOKAWA, whose orbit is known in sufficient accuracy. Then HAYABUSA's position was supposed to be available within one fringe ambiguity, and ambiguity probrem was avoided.

4 Δ VLBI observation of HAYABUSA

From 4th to 26th Nov. in 2005, HAYABUSA performed touchdown trials to asteroid Itokawa. In accordance with these events, VLBI observations of HAYABUSA was made by the colaboration among Japanese VLBI related institutes (JAXA/ISAS, NICT, GSI, and NAOJ). Figure 2 shows the radio telescopes patricipated in the experiments. Table 1 lists reference radio sources, their separation angles from HAYABUSA, switching intervals, and observation station IDs for each experiments. We selected reference sources from the ICRF catalog [11] except for 1352-104. The accuracy of reference source position is important due to the term of equation (7). The uncertainty of the radio source coordinates are respectively 1430-178 (4 mas), 1443-162 (0.5 mas), 1514-241
(0.3 mas), and 1504-166 (0.3 mas). It was fortunate that multiple reference radio sources are found within 10 degrees of separation angle from HAYABUSA. Though it was unfortunate regarding sun angle, since sun angle of HAYABUSA was 4 $\sim$ 5 degrees during the experiments. Then effect of solar corona could be larger than standard VLBI observation. Usually

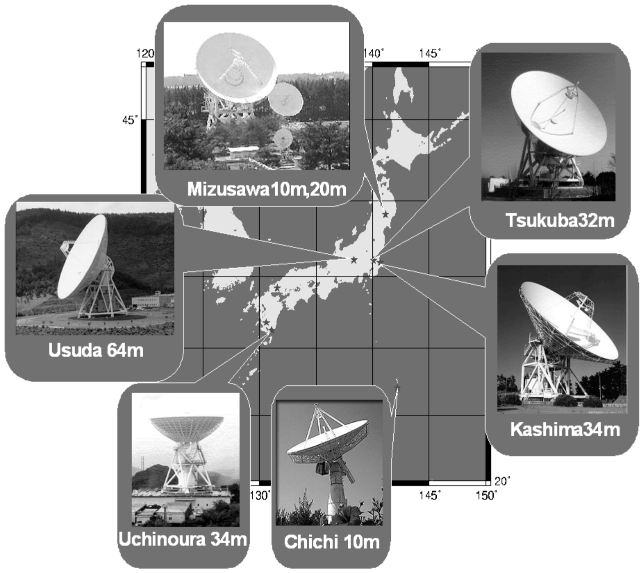

Figure 2: Radio telescopes participated in the VLBI experiment in Nov. 2005 for HAYABUSA.

geodetic and astrometric VLBI prevent observation closer than 10 degree away from the sun to avoid additional error caused from solar corona.

5 Accuracy of Differential VLBI

The delay correction procedure described in section 2 was applied to phase delay observable of HAYABUSA. Figure 3 displays an example of delay correction results by Δ VLBI. Since a priori orbit of HAYABUSA is given accurately, the residual after the correction is expected to be constant around zero. And actually, the behavior of the residual was almost constant for 6 hours within $\pm$ 0.1 nano seconds. It indicates that the delay correction by Δ VLBI is successfully removing the excess delay due to clock and atmosphere. Delay correction accuracy in the VLBI observation of HAYABUSA in Nov. 2005 was around $\pm$ 100 pico seconds on the baselines among Kashima, Tsukuba, and Mizusawa, stations. The residual increased to about 1 nano second for the baselines including Chichi-jima station. Possible reasons of the large delay residual for Chichi-jima baselines are (1) ionospheric delay, which affected two folds due to the procedure of phase-delay correction using group delay in this time, and (2) effects of solar corona. We think the former reason will be main cause of the large correction residual of Chichi-jima baselines. Ionospheric delay correction by using Global Ionospheric Map of Center for Orbit Determination in Europe (GIM/CODE) [12] was tried to improve the residual. It actually reduced the residual about 40 %, though still peak-to-peak 900 pico seconds of variation remained. It might be due to lack of spatial and temporal resolution of the GIM/CODE[13]. We are

Table 1: Reference radio sources, their separation angles from HAYABUSA, and VLBI station ids are listed for each experiments. Station IDs are as follows: O:Kashima 34m station, T:Tsukuba 32m station of GSI, M:Mizusawa 20m VERA station of NAOJ, C:Chichi-jima 10m station of GSI. Uchinoura 34m and Usuda 64m stations were use for spacecraft operation, thus they are not used for Δ VLBI observation.

Date	Reference Radio Source	Angular Distance	Switching Cycle	Station ID
11/4	1352-104	3.3 (deg.)	6 min.	O, T, C
11/12	1430-178 1443-162	3.3 (deg.) 2.4 (deg.)	6 min.	O, T
11/19	1430-178 1443-162	8.5 (deg.) 5.5 (deg.)	6 min.	O, T, M
11/25	1514-241 1504-166	5.8 (deg.) 7.1 (deg.)	6 min.	O, T

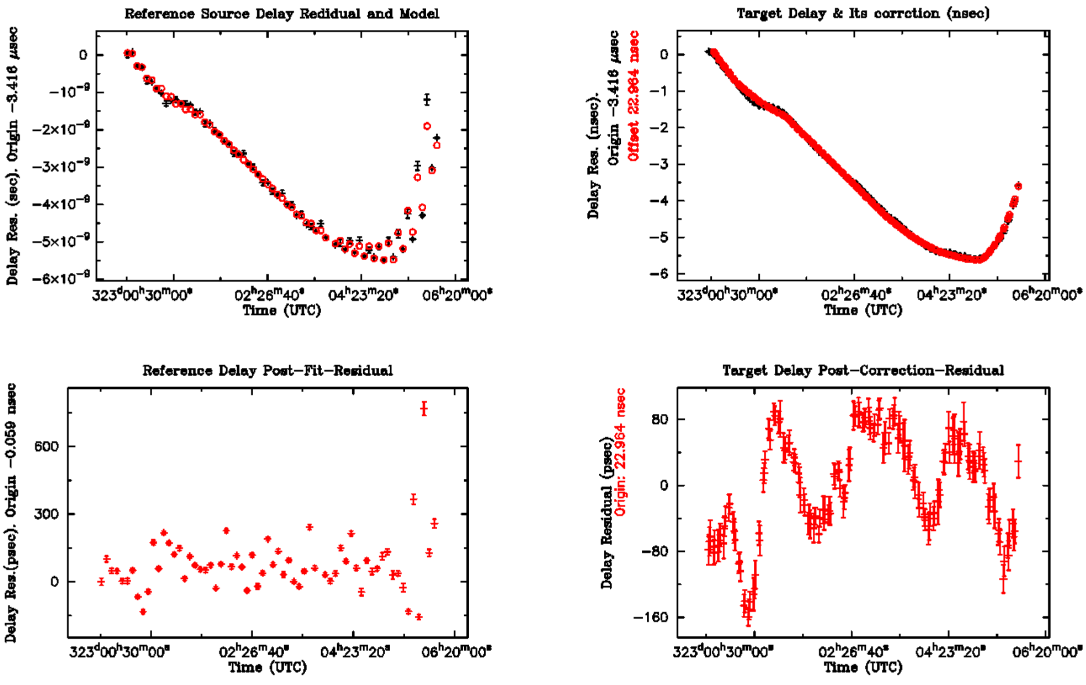

Figure 3: An example of Δ VLBI delay correction. Left panels are the data of quasar and right ones are those of HAYABUSA. In the left upper panel, '+' mark shows delay residual (O-C) of reference quasar corresponding to the equation (3). And '○' indicates best fit of the equation (8) to the data. Left lower panel indicates its post-fit residual. Mark '+' in the upper right panel is O-C data of HAYABUSA and '○' is correction model computed with the parameter obtained from reference quasar data. Right lower panel shows residual after the correction. Except for 23 nano seconds of offset, the residual after of correction is approximately within ± 0.1 nano seconds.

expecting that further improvement might be possible by using fringe phase of quasar's data for the correction procedure in Δ VLBI. We are going to evaluate this near future.

Even for more shorter baselines among Kashima, Tsukuba, and Chichi-jima stations, systematic delay behaviors are still remain in the delay correction residual and improvement will be possible.

6 Summary

We performed Δ VLBI observation of HAYABUSA in accordance with the events of its touchdown to the asteroid Itokawa in Nov. 2005. This observations were quite valuable for evaluation of the accuracy of Δ VLBI delay correction. And we confirmed that excess delay can be calibrated by Δ VLBI (phase delay correction with group delay) with accuracy about ± 0.1 nano seconds. Larger delay correction residual of Chichi-jima baseline is thought to be due to larger ionospheric delay contribution at low geomagnetic latitude. It will be improved by using phase delay of reference quasar in the delay correction procedure of Δ VLBI.

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