VLBI Application for Spacecraft Navigation

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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 $\pm$ 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

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.)

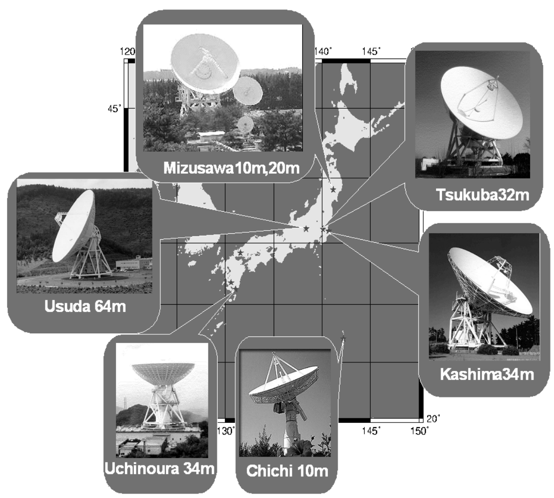

Figure 1: VLBI stations participated in the Δ VLBI observations of HAYABUSA in Nov. 2005.

2bit-4Mbps-1channel mode for HAYABUSA 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:

$$\tau_{\mathrm{observable}} = \tau_{\mathrm{geo}} + \tau_{\mathrm{atm}} \pm \tau_{\mathrm{ion}} + \tau_{\mathrm{clk}}, \tag{1}$$

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 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:

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

   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

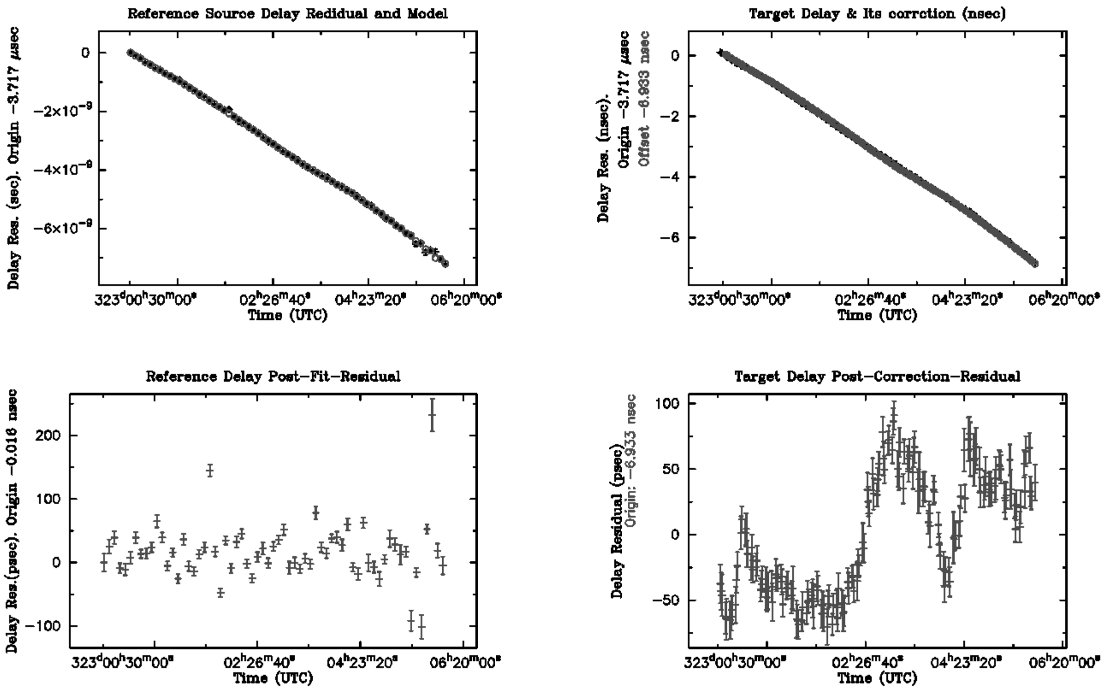

Figure 2: Plot of O-C data of reference radio source for Tsukuba32-Mizusawa20 baseline on 19 Nov. 2005 (left top) is displayed as an example. Symbol of '+' indicates the O-C data and '○' stands for model of equation (2) fitted to the data. Lower left panel shows the post-fit residual of O-C data of reference 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.

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 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

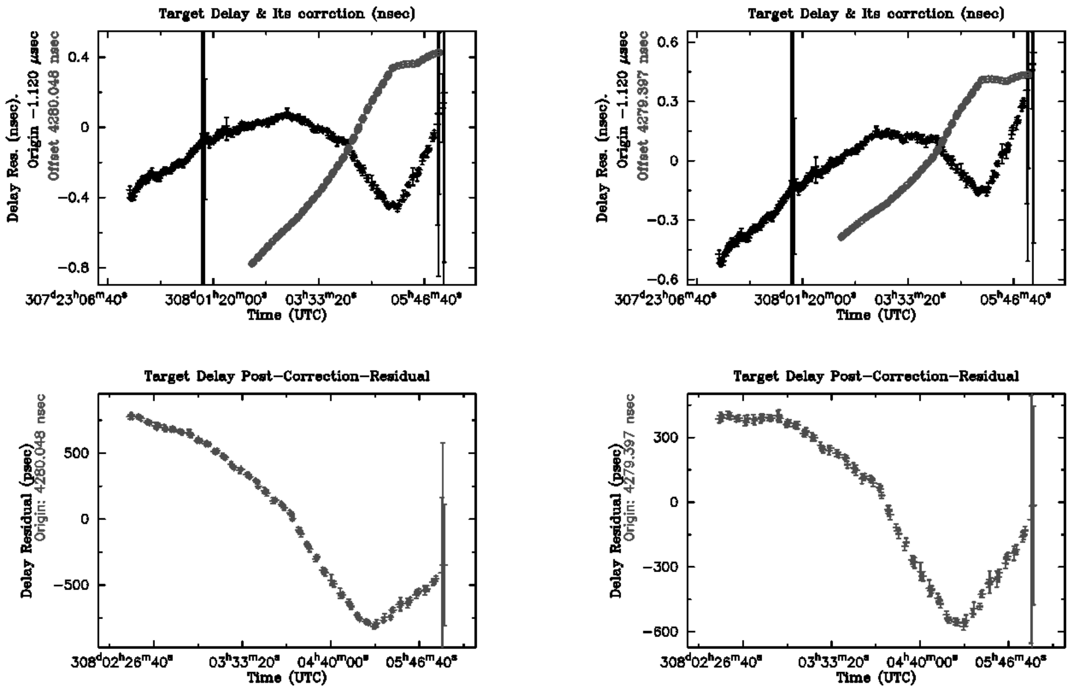

Figure 3: Delay correction error due to ionospheric contribution was observed in Chichijima baseline. In the upper panel, plot with '+' indicates phase delay of HAYABUSA and '◦' is delay correction term derived from group delay of reference source. Residual after the correction is plotted in the lower 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.

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 observations. 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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