An Evaluation of Atmospheric Path Delay Correction in Differential VLBI Experiments for Spacecraft Tracking

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Abstract

We evaluate an effect of cancelling out atmospheric path delay errors on the HAYABUSA differential VLBI measurements based on the delays derived from geodetic GPS analysis. The experiments were carried out on October 16 and 18, 2004. A large difference value of up to 10 cm of the differential path delay for the Kashima-Uchinoura baseline was estimated based on the analysis. It is consider that this large value 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. Introduction

We perform differential VLBI ($\Delta VLBI$) experiments for tracking of the interplanetary spacecraft. Our main goal is to obtain the precise and quasi-realtime navigation technique of the spacecraft using VLBI. With VLBI time delay measurements, differenced between the spacecraft and angularly nearby quasars to cancel common measurement errors such as the propagation delays due to the ionosphere and the neutral atmosphere. However, we can't always observe desirable quasars. It is possible that they have no enough intensity of the source flux to detect fringes. Unfortunately, sometimes we have no choice but to use quasars which are angularly far from the spacecraft. Then, we tried to evaluate the effects cancel by subtracting the group delays of the reference radio source from those of the spacecraft. In this short report, we focus on the issue of the path delay due to the neutral atmosphere estimated by geodetic GPS measurements.

2. VLBI and GPS measurements

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. The experiment IDs of October 16 and 18 are "hy4290" and "hy4292", respectively. We use Kashima 34-m, Kashima 11-m and Koganei-11m of NICT, Usuda 64-m and Uchinoura 34-m of ISAS/JAXA, and Tsukuba 32-m of GSI antennas for the experiments at X-band. The VLBI stations in this study are shown in Figure 1. We acquire the VLBI data using both K5/VSSP system.

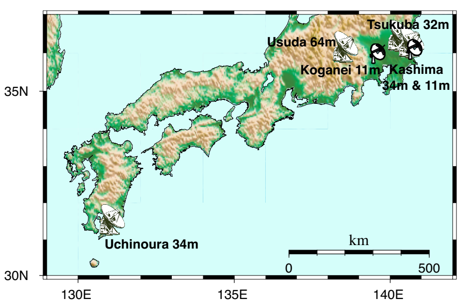

Figure 1. VLBI stations participated HAYABUSA DVLBI experiments

Table 1. Geodetic GPS stations nearby VLBI stations

VLBI station name	**corresponding GPS station ID**	**Agency**
Kashima 34-m and 11-m	KSMV (IGS)	KSRC, NICT
Koganei 11-m	KGNI (IGS)	NICT
Tsukuba 32-m	TSKB (IGS)	GSI
Usuda 64m	USUD (IGS)	ISAS/JAXA
Uchinoura 34-m	940099 (GEONET of GSI)	ISAS/JAXA

The observing time for each day was 7 hours during 0700 to 1400UT. The HAYABUSA spacecraft and an angularly nearby quasar "2126-158" were observed sequentially, not simultaneously, during each period with various time intervals of data acquisition (i.e. 50 seconds, 110 seconds, and 170 seconds). These switching intervals are chose in order to investigate an effect on the phase delay analysis. A result of the investigation will be described in the another report. Two quasars, "NRAO530" and "3C454.3", were also observed at the beginning and the end of the experiment period as a reference source for determining a clock offset. For example, the maximum angular separations of the spacecraft from the quasar "2126-158" are less than 3 degrees on 18 October 2004 at Uchinoura.

In addition, we also acquire the data sets of the corresponding GPS stations nearby the each VLBI station (Table 1). The GPS station "940099" is one of the GPS Earth Observation Network (GEONET), Geographical Survey Institute (GSI) in Japan and it is located at about 1 km northeast from Uchinoura 34-m antenna. Other GPS stations are registered with the International GPS Service for Geodynamics (IGS) and all of them are adjacent to each VLBI antenna.

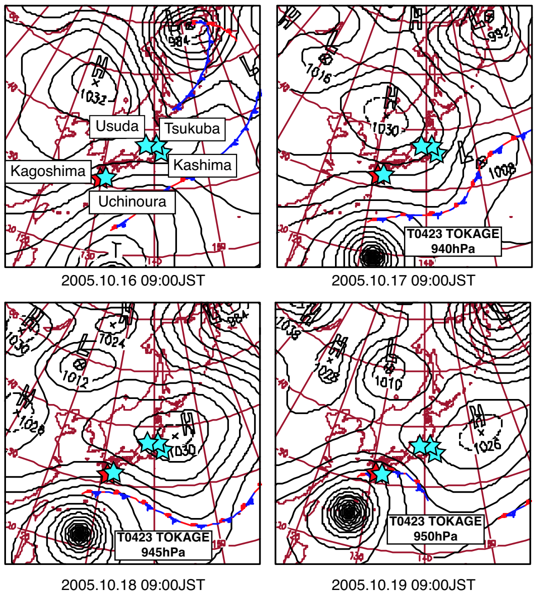

Figure 2. Synoptic weather charts around Japan from 0000UTC of 16th to 0000UTC of 19th October, 2004. Dark gray star and bright gray stars indicate the location of Kagoshima meteorological observatory, Japan Meteorological Agency (JMA) and the VLBI stations, respectively.

3. Meteorological condition

Figure 2 shows synoptic weather charts around Japan from 0000UTC of 16th to 0000UTC of 19th October 2004. During the first experiment (hy4290), it was sunny and calm weather around Japan islands. After the 17th October, the strong typhoon 0423 (TOKAGE) was approaching south of Kyushu island, where Uchinoura station is located. The significant pressure depression at Kagoshima meteorological observatory of Japan Meteorological Agency (JMA), which is located about 100 km west of Uchinoura, is indicated in Figure 2 (lower panel). So, we unfortunately have to interrupt the hy4292 experiment around 0600UTC. The typhoon center was passed about 100 km east of Uchinoura on 20th October and it hit the central Japan with severe damage caused by heavy rainfall and strong wind.

4. Estimation of atmospheric delay by GPS measurements

4.1. Zenith wet delay

First, we estimate path delay due to the neutral atmosphere at zenith direction (ZTD: Zenith Total Delay) for each station through the double-difference procedure using the Bernese GPS software version 4.2[4]. Next, we calculate the zenith path delay due to the water vapor (ZWD: Zenith Wet Delay) by subtracting the zenith hydrostatic delay (ZHD: Zenith Hydrostatic Delay) from the ZTD. The ZHD which is mainly caused by the dry components of the atmosphere is determined by surface pressure measurements[5]. Time series of ZWD values at Kashima, Tsukuba, Usuda, and Uchinoura during 15 to 19 October 2004 are shown in Figure 3. On October 16th, which is the day of the hy4290 experiment, the ZWD values at all stations are less than 10 cm and it is consistent with the calm weather as shown in Figure 2.

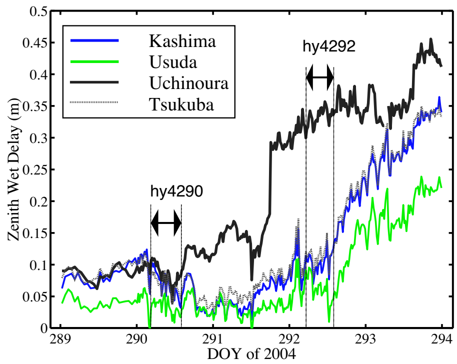

Figure 3. ZWD time series derived from GPS data sets at Kashima, Tsukuba, Usuda, and Uchinoura.

The ZWD value at Uchinoura dramatically increased from 15 cm to 27 cm within one hour on October 17th with the approach of typhoon TOKAGE. The ZWD values at Kashima and Tsukuba gradually increased up to 35 cm after October 18. At Usuda, where station altitude is above 1500 m, the ZWD value is relatively small compared with the values at other stations because of a low water vapor content at high altitude. However, even at Usuda the ZWD value was up to 25 cm until the end of October 19th. As shown in Figure 2 and 3, since meteorological conditions were significantly different between two experiment periods, we consider that those experiments are very suitable for our study.

4.2. Slant delay and differential delay

Conventionally, the slant-path wet delay ΔSLW_i at i_{th} epoch can be computed from the ZWD via

$$\Delta SLW_i = NMF(\theta_i) \times ZWD_i \tag{1}$$

where $NMF(\theta_i)$ is the Niell mapping function[6] and θ_i is an elevation angle of the HAYABUSA spacecraft or nearby quasar at at i_{th} epoch. Next, we calculate resampled slant-path wet delay values $\Delta SLW'$ over the whole experiment period at all stations using piecewise cubic spline interpolation. A principle observable feature of VLBI is the difference in arrival times of radio signals between two stations. Then, we calculate differences between the values $\Delta SLW'$ at each station. We define this "differential wet delay".

The differential wet delays for the HAYABUSA spacecraft ($D\Delta SLW^H_{AB}\prime$) and for the quasar ($D\Delta SLW^Q_{AB}\prime$) are shown by:

$$D\Delta SLW^H_{AB}\prime = \Delta SLW^H_A\prime - \Delta SLW^H_B\prime \tag{2}$$

$$D\Delta SLW_{AB}^{Q}\prime = \Delta SLW_{A}^{Q}\prime - \Delta SLW_{B}^{Q}\prime \quad (3)$$

where the A and B denote stations at the both ends of the baseline.

Finally we calculate differences between both differential wet delays of the HAYABUSA spacecraft and those of the quasar:

$$D\Delta SLW_{AB}^{QH}\prime = D\Delta SLW_{AB}^{Q}\prime - D\Delta SLW_{AB}^{H}\prime \quad (4)$$

where $D\Delta SLW_{AB}^{QH}\prime$ denotes the difference between two differential delays.

If the angular separation is sufficiently small, the differential wet delays for both radio sources are almost equal. Then, these are canceled out by the difference procedures written in the equation (4). However, if these are different, the differences between them is added directly to the observables as an error source.

5. Results

Figure 4 shows time series of difference values, which are mentioned in the previous section (equation (4)), between two differential delays during the hy4290 experiment (a) and the hy4292 experiment (b).

The ZWD time series at all stations as shown in Figure 3 are consistent well each other in both amplitude and phase through the first experiment period. Thus, the differences values are almost equal zero. It suggests that the difference procedure is efficient to correct the errors due to the atmospheric path delay under calm weather conditions. On the other hand, the characteristics of the time series for the Kashima-Uchinoura baseline as shown upper and lower panels are very different each other. The maximum value of differences is less than 1.5 cm over the first experiment period (upper panel), whereas the maximum value of differences is up to more than 10 cm during the second experiment period (lower panel).

The primary cause of the large difference value is a significant difference in water vapor content during the second experiment at Uchinoura and Kashima. We can infer from a experiment schedule and a baseline azimuth that the effect is emphasized by the difference in elevation angle of radio source at both stations.

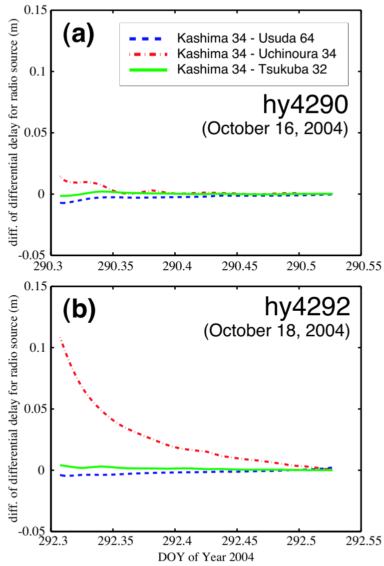

Figure 4. Upper: Difference between the differential delays during the first experiment hy4290; Lower: Same plot but for the second experiment hy4292.

Since the baseline vector between both stations is toward the west and the radio sources were in the southeastward direction, about four degrees in the elevation angle at Uchinoura is smaller by comparing with that at Kashima at the beginning of the second experiment period.

In general, we can estimate an atmospheric path delay as the one of unknown parameters from the VLBI observables only. However, it is essentially difficult to perform the same way in the $\Delta VLBI$ measurement analysis. Because the elevation and azimuth angles of the radio sources are not homogeneously distributed in the sky, a least square estimation becomes unstable due to the mutual distinguishability among the parameters.

In this report we mention about to use the GPS-based ZWD estimates to evaluate the effects of atmospheric correction on the $\Delta VLBI$ measurements. At present, these estimates for each station have enough precision to improve the numerical weather prediction (NWP) models[7], [8]. The recent studies indicate that the GPS-based ZWD estimates agree well with those obtained by radiosonde data sets or a water vapor radiometer (WVR) at a few millimeter rms level(ex. [10], [11]). Therefore, we are going to develop a new correction method based on the estimates in order to remove the atmospheric path delay error from the VLBI observables.

6. Summary

We performed two $\Delta VLBI$ experiments for the HAYABUSA spacecraft on October 16th and 18th, 2004. In these experiments we acquired the geodetic GPS data sets from the IGS stations and one GEONET GPS station of the GSI, Japan. These GPS stations are adjacent to the each VLBI station participated the experiments. We evaluate an effect of cancelling out atmospheric path delay errors on the $\Delta VLBI$ measurements based on the delays derived from geodetic GPS analysis. According to our 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 HAYABUSA spacecraft and quasar. Such large value was mainly caused by the humid condition around Uchinoura due to the typhoon approaching. Moreover, the east-west direction of the baseline vector and the large difference in elevation angle of radio source between both stations helped to enlarge the difference value.

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