VLBI Application for Spacecraft Navigation

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Abstract

Using high angular measurement of VLBI observations for space craft orbit determination is effective to increase the accuracy of spacecraft navigation. Investigation of VLBI application for spacecraft navigation is in progress under the collaboration between Japanese Space Agency and VLBI community. ΔVLBI observation between target spacecraft and its nearby quasar with group delay observable is being tested with spacecraft HAYABUSA. Also alternative approach using phase delay has potential to achieve 2 -- 3 order of higher delay resolution than group delay; however its problem is uncertainty of phase ambiguity. We took continuous phase tracking technique for spacecraft NOZOMI to enable using phase delay observable. The estimated coordinates of NOZOMI by using VLBI observation were in good agreement with those of orbit determination with traditional radio metric observation. We are taking approaches from two ways; using group delay and phase delay. This report describes the current status of our astrometric analysis of spacecraft coordinates with VLBI observations.

1. Introduction

Very long baseline interferometry (VLBI) is the technique with the highest angular resolution in the celestial sphere. Thus VLBI is quite useful tool not only for astronomy and geodesy, but also spacecraft navigation as one of the engineering applications. The JPL/NASA has been using ΔVLBI observation of spacecraft as delta differential one-way range (ΔDOR) (e.g. Border et al., 1986), in which switching observations of spacecraft with nearby quasars are performed.

For the purpose of assisting orbit determination of Japanese spacecraft NOZOMI, which was the first Japanese Mars mission, and for establishing technical basis to use VLBI for orbit determination with VLBI observation of spacecraft, Japanese space agency (JAXA) and Japanese VLBI community have started collaboration. Also Canadian space sensor for Mars was equipped on the NOZOMI spacecraft, so the Canadian space agency and 46 m diameter radio telescope at Algonquin observatory had joined the VLBI observations for supporting NOZOMI. Fortunately earth swing-bys were successfully performed and NOZOMI went to the Mars. Now asteroid exploration mission HAYABUSA launched by JAXA/ISAS is flying with asteroid ITOKAWA at 2 AU away. Several ΔVLBI experiments were performed with group delay observable. In the following sections, VLBI delay model for radio source in the solar system, disk-based data acquisition system, and analysis scheme with group delay and phase delay observable are described.

2. VLBI Delay Model for Finite Distance Radio Source

Accurate VLBI delay model is essential for the VLBI data analysis. Several VLBI delay models were proposed in terms of theory of relativity from late 1980s to beginning of 1990s. Finally, they are unified as the standard VLBI delay model (consensus model) by Eubanks (1991) and it is widely used in the world VLBI community as conventions (McCarthy, and Petit, 2003). Although it was developed for radio source at infinite distance with plane wave approximation, thus use of the consensus model for radio source at finite distance is inaccurate and it causes intolerable error if the target is in the solar system. VLBI delay models for finite distance radio source were proposed by Fukushima (1994) and Sovers and Jacobs (1996) however delay of those models were presented by Barycentric Dynamical Time (TDB) instead of Terrestrial Time (TT), which is actually measured with atomic clock on the earth. Moyer (2000) has developed the delay model based on the light time equation. However it was described in purely numerical procedure. Delay model in similar form with the consensus model is more preferable for implementation to current VLBI analysis software. Thus we have developed an analytical VLBI delay model for radio source at finite distance as an expansion of the consensus model (Sekido and Fukushima, 2004, 2005).

$$TT_2 - TT_1 = \frac{\Delta t_g - \frac{\vec{\mathbf{K}} \bullet \vec{\mathbf{b}}}{c}\left[1-(1+\gamma)U - \frac{V_e^2 + 2\vec{\mathbf{V}}_e \bullet \vec{\mathbf{w}}_2}{2c^2}\right] - \frac{\vec{\mathbf{V}}_e \bullet \vec{\mathbf{b}}}{c^2}\left(1+\vec{\mathbf{R}}_{02} \bullet \frac{\vec{\mathbf{V}}_2}{c} - \frac{\vec{\mathbf{K}} \bullet \left(\vec{\mathbf{V}}_e + 2\vec{\mathbf{w}}_2\right)}{2c}\right)}{\left(1+\vec{\mathbf{R}}_{02} \bullet \frac{\vec{\mathbf{V}}_2}{c}\right)(1+H)}. \quad (1)$$

In this formula, delay expressed in TT is related with baseline vector on the terrestrial reference frame (TRF) and pseudo source vector ***K.*** The vector $\mathbf{K} = (\mathbf{R_1} + \mathbf{R_2})/(R_1 + R_2)$ is composed from station coordinates and radio source coordinates in TDB-frame, because positions of most of spacecrafts and plants are described on the dynamical coordinate system of JPL ephemeris such as DE406 (Standish, 1998). Precision of the delay model is better than 1 ps for ground-based VLBI observation of radio sources from 100km altitude to infinite away (Sekido and Fukushima 2005). Since the effect of the curved wave front is so large as order of 1 μsec for the case of Mars as an example (Fig. 1), this model is used not only for accurate analysis but also correlation processing.

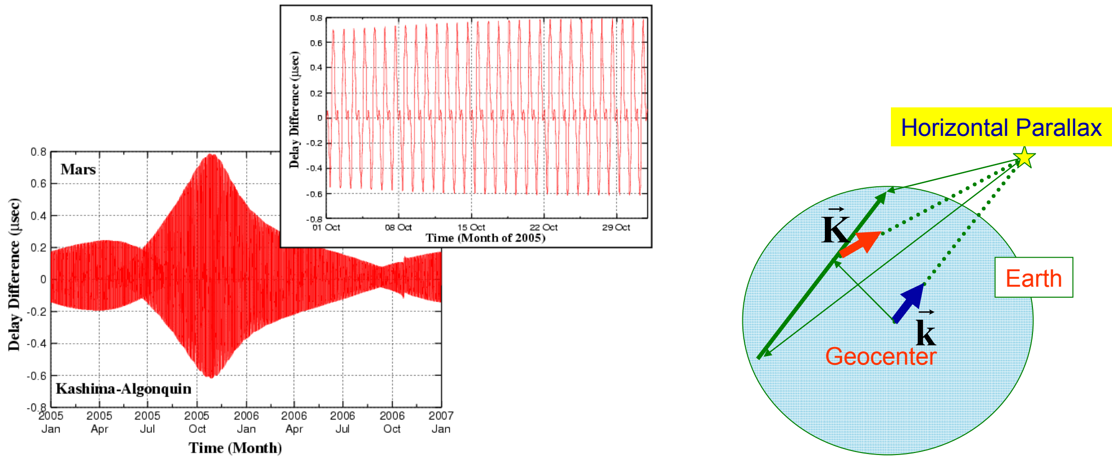

Fig. 1 Delay effect of curved wave front is demonstrated for target radio source at Mars with Kashima-Algonquin (9000 km) baseline. Difference between the finite-VLBI delay model and consensus model is plotted for the period 2005-2007 (left). Geocentric direction vector to the radio source was taken as source vector in the consensus mode. Feature of daily variation in Oct. 2005 is superimposed at upper right of the left panel as an example.

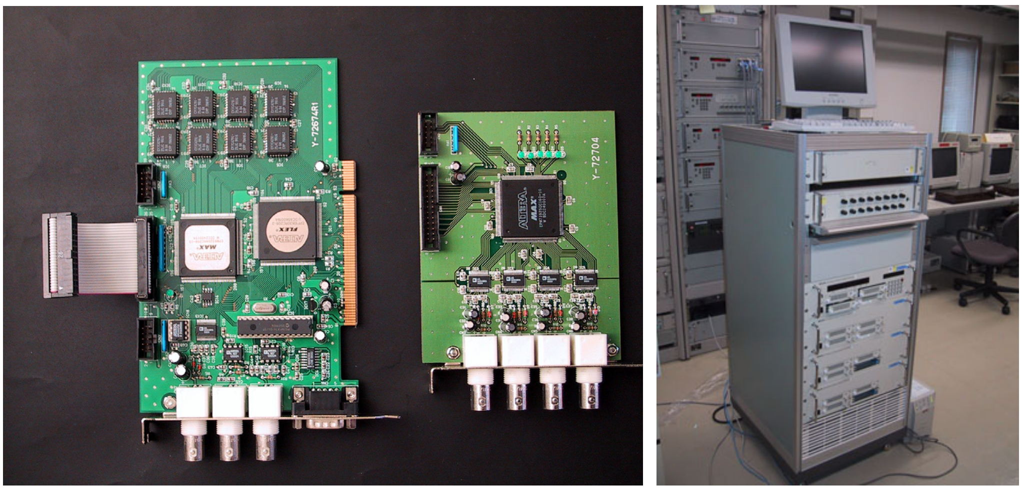

Fig. 2 IP-VLBI sampler board (left) and K5/VSSP VLBI data acquisition system (right). K5/VSSP system is composed of 4 PCs, and each PC has one IP-VLBI board installed at PCI-BUS

Table 1. Specification of IP-VLBI board

Reference Signal Input	10MHz, +10dBm 50 Ohms Impedance
1PPS	TTL level plus, pulse width 1-500μs
Data channels	1ch on main board, 4ch on daughter board
A/D quantization bit	1/2/4/8 bit
Sampling frequency	0.04/0.1/0.2/0.5/1/2/4/8/16 MHz
Data buffer	8Mbits
Maximum data output rate	64Mbps

3. Data Acquisition System and Data Processing

VLBI data for quasar and spacecraft observation was performed with K5/VSSP VLBI system (Fig. 2 right), which is a disk-based VLBI data acquisition system developed by NICT (Osaki, Kondo, and Kimura, 2002). VLBI data sampler board called IP-VLBI board (Fig. 2 left) is installed in each personal computer (PC). The specification of the sampler board is listed in Table 1. Since the data is recorded on the hard-disk of PC, it can be easily transferred to remote station for correlation processing. Also owing to the rapid growth of CPU performances, the correlation processing task, which had to be processed dedicated hardware correlator, can be performed software correlator with general purpose PCs. Wide flexibility of software correlator is also a great benefit to process narrow bandwidth signal of spacecraft. Because implementation of some signal processing techniques such as spectrum filtering or correlation with replica signal are effective to increase the signal to noise ratio (SNR) and those modifications are relatively easy in software correlator.

4. Group Delay Observation

Three sorts of observables, group delay, phase delay, and phase delay rate, are obtained in VLBI observations. The advantage of group delay observable is that the geometrical delay for spacecraft can be derived in a short time by means of ΔVLBI technique, which can calibrate clock synchronization offset and excess delay due to propagation media. Drawback of the group delay is the lower delay resolution cause by limited bandwidth of the spacecraft signal. Delay measurement precision depends on the characteristic of the observed signal. Currently we are testing switching observation of spacecraft HAYABUSA (e.g. Fujiwara et al., 2000), which is Japanese asteroid exploration mission, with nearby quasar. Fig. 3 shows the observed group delay by switching observation of HAYABUSA and quasar 0440+345. Examples of cross spectrum and delay resolution functions for range signal, which is used for range observation, and telemetry signal of HAYABUSA are demonstrated in Fig. 4. It indicates that signal with wider bandwidth has sharper peak of delay resolution function. Range signal observed with large diameter antenna pairs shows thermal error in order of a few ns. Although it is not enough level of delay precision for steady use of VLBI in spacecraft navigation. We are considering the other signal pattern instead of range signal for improvement of delay resolution.

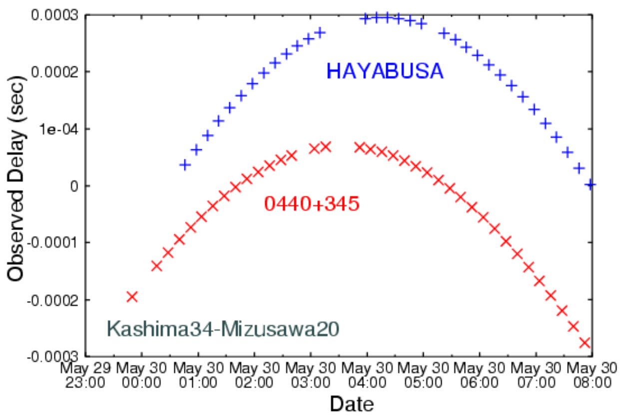

Fig. 3 Observed group delay of spacecraft HAYABUSA and nearby quasar 0440+345. Switching cycle was about 12 min at this time.

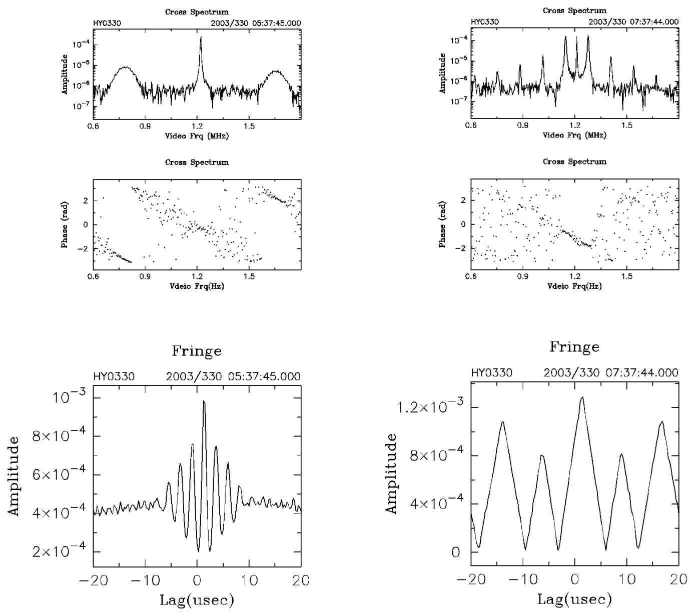

Fig. 4 Examples of cross spectrum (top: amplitude and middle: phase) and delay resolution function (bottom) are displayed for range (left) and telemetry signal (right).

5. Phase Delay Observation

Alternative choice to get higher delay resolution is using phase delay. The advantages of phase delay are its potential to get high delay resolution and fewer requirements to spacecraft signal. Phase delay needs that just tone signal is transmitted from spacecraft, thus it can be applied to any spacecrafts. Disadvantage is difficulty of absolute delay measurement due to the unknown offset of phase ambiguity. One of the solutions to use the phase delay is observing the target radio source for a long time and obtaining the delay variation pattern of the delay caused by the motion of baseline with respect to the radio source. This strategy was taken for observations of NOZOMI spacecraft, which was the first Japanese Mars mission (Yamamoto and Tsuruda, 1998). Due to some troubles in the mission, NOZOMI’s final orbit to the Mars was designed as displayed in Fig. 5 to save fuel of the spacecraft. After the earth swing-by in Dec. 2002, NOZOMI rose up to north hemisphere, then it came down and encountered the second earth swing-by in Jun. 2003.

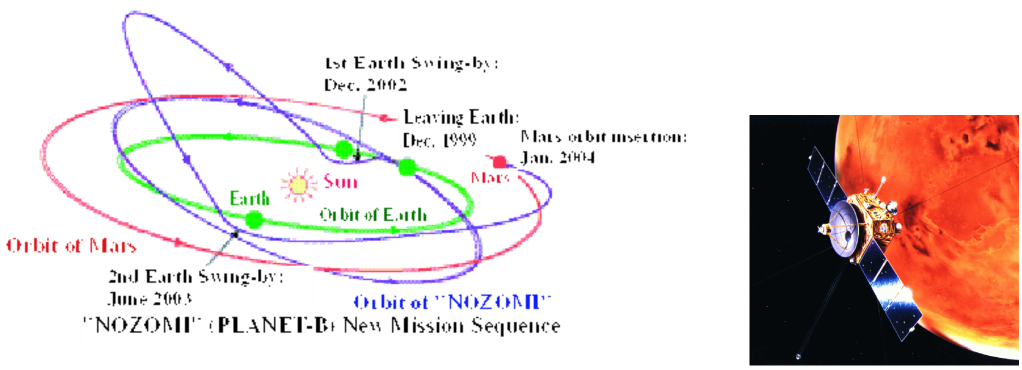

Fig. 5 Orbit of NOZOMI (left) and spacecraft NOZOMI (right). Several VLBI observations were conducted between two earth swing-bys of Dec. 2002 and Jun. 2003.

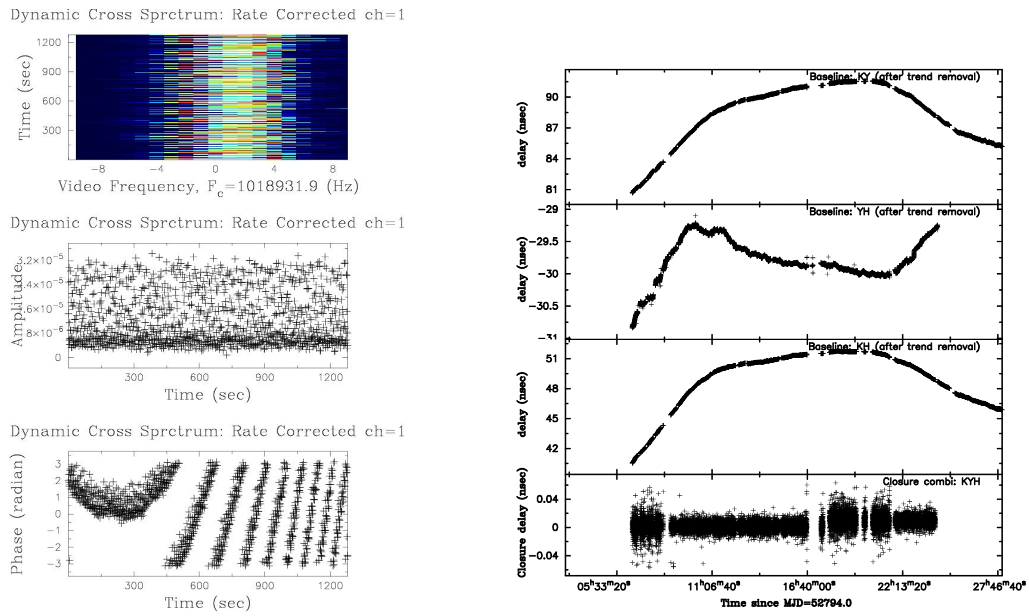

Fig. 6 Example of fringe phase observed for spacecraft NOZOMI (left) and closure delay (right bottom) of the connected fringe phase over 22 hours on Yamaguchi 32m – Gifu 11m – Tomakomai 11m baselines observed on 4 June 2003. The plot of closure delay is indicating the precision of the delay is around 10 ps.

During this period, the solar paddle had to be face to the sun for survival of the spacecraft, then the high gain antenna fixed to the main body of the spacecraft cannot directed to the earth. Due to this condition, signal to noise ratio of group delay was suspected to be insufficient. That was one of the reasons of using phase delay for NOZOMI VLBI observations.

Fringe phase was extracted by cross correlation of carrier signal (Fig. 6, left). We took conservative strategy at this time. The NOZOMI was tracked continuously during the observation, because failure of phase connection might make the data useless. Thus fringe phase could be connected and the signature of delay variation caused by the relative motion between baseline and the radio source was observed with high precision for a long time span. Right panel of Fig. 6 indicates plots of (Observed phase delay) – (Theoretical delay) for baselines among Yamaguchi, Gifu, and Tomakomai stations. Plot of closure delay of those baselines shows that the precision of phase delay observation is order of 10 ps. In the observation of NOZOMI on 4th June 2003, Kashima 34m, Usuda 64m, Algonquin 46m, Tsukuba 32m, Yamaguchi 32m, Gifu 11m, and Tomakomai 11m are participated the observation. Since NOZOMI was at high declination in north hemisphere, most of these stations tracked NOZOMI about 24 hours. Since this was not switching observation, the data contains excess delay caused from atmosphere and atomic clock synchronization errors. Here we used GPS (Global Positioning System) data for estimating the atmospheric excess delay at each station. About a thousand of GPS stations, so called GEONET, are distributed on Japanese islands (Miyazaki et al., 1997) and operated daily by Geographical Survey Institute (GSI) of Japan. By using the GPS data provided from GEONET and IGS stations, atmospheric thickness in zenith direction was analyzed with GPS analysis software *Bernese*, and used for the correction of VLBI data.

Astrometric analysis of the spacecraft coordinates was performed by estimating the coordinate offset from the reference orbit with least square procedure, where the difference of coordinates between true obit and reference orbit was assumed to be constant during one observation session. Consequently coordinates offset (42.4 mas,30.2 mas) from the reference orbit was estimated for the epoch of 4th June 2003. Here we used the orbit determined by range and range rate observation as reference orbit for comparison.

6. Summary

Investigation on application of VLBI for spacecraft navigation is in progress under the collaboration between Japanese space agency JAXA and VLBI community. The newly developed the K5/VSSP disk-based VLBI data acquisition system is used for observation both wide band signal of quasars and narrow bandwidth signal of spacecraft. Relativistic VLBI delay model for radio source at finite distance was developed as an expansion of the consensus model. And it is used for a priori delay computation for correlation processing and astrometric analysis. Two choices of observables, group delay and phase delay, are under investigation for use. Since delay resolution of group delay is highly depend on the spectrum shape of the signal, suitable signal type need to be investigated from view point of less hardware requirement to the spacecraft and wider frequency spectrum with limited power resource. The advantage of group delay is that geometrical delay can be obtained relatively easily by calibrating excess delay error with ΔVLBI technique in a short time observation. And we have been testing ΔVLBI technique with spacecraft HAYABUSA. Phase delay observable has a potential to get higher delay resolution without particular requirement on the signal. To solve problem of phase ambiguity, continuous phase tracking was performed for observation of NOZOMI spacecraft. And excess delay by atmosphere was calibrated with GPS technique. Other approach for the ambiguity problem with short baselines and using phase delay rate are also under investigation.

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