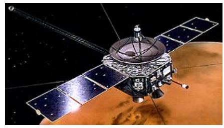
URSI 2005, New Delhi

VLBI Observation of Spacecraft for Navigation

--Approaches with Group Delay and Phase Delay --



M. Sekido[1] (sekido@nict.go.jp), R. Ichikawa[1], H. Takeuchi[1], Y. Koyama[1], E. Kawai[1], T. Kondo[1], M. Yoshikawa[2], N. Mochizuki[2], Y. Murata[2], T. Kato[2], T. Ichikawa[2], H. Hirabayashi[2], T. Ohnishi[3], F. Kikuchi[4], K. Takashima[5], K. Fujisawa[6], H. Takaba[7], K. Sorai[8], W. Cannon[9], S. Novikov[9], and M. Berube[10]

1:National Institute of Information and Communications Technology, Japan
2:Japan Aerospace Exploration Agency, Institute of Space and Astronautical Science., Japan
3:Advanced Science Solutions Group/Fujitsu Limited., Japan.
4:Graduate University of Advanced Studies, Japan
5:Geographical Survey Institute, Japan.
6:Yamaguchi University, Faculty of Science , Japan.
7:Gifu University, Faculty of Engineering, Japan.
8: Hokkaido University, Faculty of Science, Japan.
9: York University, Department of Physics and Astronomy York University, Canada.
10:Geodetic Survey Division/Natural Resources Canada, Canada.

Abstract For using VLBI to improve the precision of spacecraft orbit determination in Japanese space missions, VLBI observation of spacecraft NOZOMI and HAYABUSA have been organized and Japanese domestic VLBI stations and Canadian Algonquin observatory have participated. Disk-based VLBI observation system K5/VSSP has been used for data acquisition system in the observation. Approaches with two sorts of VLBI observables, group delay and phase delay are investigated. Advantage of group delay is easiness to obtain absolute delay but its precision is limited by band width of the spacecraft signal. Phase delay has potential to enable high precision delay measurement, but absolute delay is difficult to get due to phase ambiguity. This paper reports current problem in group delay measurement, the astrometry analysis of spacecraft coordinates with phase delay data.

1. Introduction

Very long baseline interferometry (VLBI) is a powerful tool with the highest angular resolution in space geodesy and astronomy. And it is also quite effective in engineering applications such as spacecraft (S/C) navigation (Border et al. 1982) and precise tracking of space prove (e.g. Gurvits 2004). To utilize the VLBI observation for S/C navigation, Japanese space agency (JAXA/ISAS) and Japanese VLBI community have started collaboration. Especially for supporting earth swing-bys of the S/C NOZOMI, which was the first Japanese Mars mission (top right corner of this poster), most of Japanese VLBI stations and Canadian Algonquin observatory has participated the observation (Fig. 1). Tree sorts of VLBI observables: group delay, phase delay, and phase delay rate can be derived from VLBI observation. Group delay is good at absolute delay measurement, but its precision is limited by signal to noise ratio (SNR) and bandwidth of the signal. Phase delay has potential to enable high precision delay measurement but a difficulty is absolute delay measurement due to phase ambiguity. The third observable, phase delay rate is free of ambiguity, but its drawback is lower sensitivity. Currently JPL/NASA is using group delay measurement, so called DDOR, with intercontinental baselines of the deep space network. Our present target is to enable the same level of precision with Japanese domestic baselines.

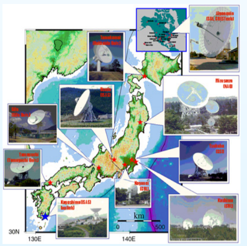


Fig. 1 VLBI stations participated in VLBI observations of NOZOMI in 2003.

2. Observation system

Differential VLBI observation by switching target S/C and nearby quasar is the basic strategy for calibrating the systematic delay error due to propagation medium, clock synchronization error, and instrumental delays. For that purpose, the K5/VSSP system equipped with IP-sampler board (Fig.2) is used for VLBI data acquisition. The system has 4 data channels in one PC (personal computer). One channel is used for S/C signal and 8 channels are used for reference radio sources. Radio frequency of S/C VLBI observations was X-band for both NOZOMI and HAYABUSA. Since observed data are stored in the file system of the computer, data is easily transferred to correlation center through the Internet. And data were processed with software correlator.

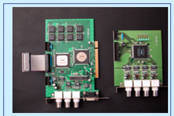


Fig. 2 IP-sampler board is used for both observations of S/C and quasar.

3. Group delay

Group delay observable is free of ambiguity or discrimination of true delay from ambiguity is easy even if it exists. Therefore using group delay has great operational advantage, because radio source coordinates are immediately determined by observation with multiple baselines of different UV components. Delay precision is inversely proportional to SNR and frequency bandwidth. Thus delay precision of S/C is not so high, since bandwidth of S/C signal is restricted by some factors.

$$\delta\tau \propto \frac{1}{(SNR)} \times (\text{Band width})$$

Fig. 3. Spacecraft HAYABUSA

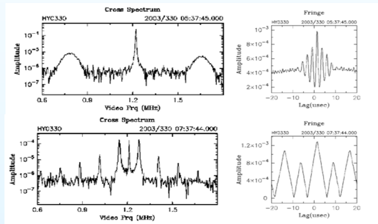


Fig. 4 Correlated spectrum (left) and delay resolution function (right) of range signal (upper) and telemetry signal (lower).

Δ VLBI observation has been tested with the S/C HAYABUSA (Fig.3), which is Japanese asteroid exploration mission launched by JAXA in May 2003. Range and telemetry signals are available from HAYABUSA. Correlated power spectrum and delay resolution function of these signals are presented in Fig. 4. That figure indicates that range signal with wider frequency bandwidth gives sharper peak of delay resolution function. However delay precision is not enough even in the case of range signal, because the signal power is distributed only ±500kHz range. RMS of delay measurement in VLBI observation for HAYABUSA is plotted as a function of SNR in Fig.5. Range signal shows 4 times better precision than telemetry signal. And it corresponds to ratio of effective band width (EBW) 450kHz (range) and 100kHz (telemetry). Reference radio source was observed with 8 data channels distributed in the range 8196-8556 MHz. Its EBW was 140 MHz. The ratio of delay precision of each signal in the figure correspond to the ratio of the EBW in fact. To achieve 1-10 mas precision with about 1000 km domestic baseline, we need 17-170 ps of delay precision. Thus we are considering alternative signal type to get more fine delay resolution.

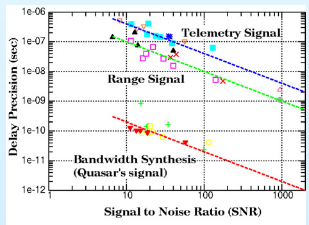


Fig. 5. RMS of delay measurements in VLBI observation of HAYABUSA are plotted as a function of SNR. Telemetry, range signal, and bandwidth synthesis result of reference radio source are compared. Lines in the plot have slope of ∝1/SNR.

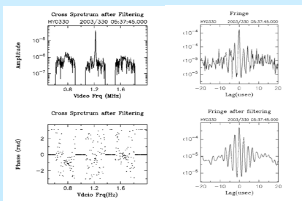


Fig. 6. SNR improvement with spectrum filtering. Cross power spectrum after the filtering (left) and delay resolution function before filtering (upper right) and after the filtering (lower right) are presented.

Farther efforts to improve the delay precision have been made by increasing the SNR. One of the techniques is **signal filtering** (Fig. 6). SNR can be improved by suppression of noise component in the frequency spectrum. Fig. 6 shows the example of signal filtering applied to the data of HAYABUSA observation.

Another approach was **correlation processing with replica signal**. Unfortunately, the signal pattern was not given, then we recorded the spitted uplink data at Usuda uplink station and correlated with observed data. Although correlation processing with replica data is fairly different from standard correlation processing at following points. (1) The round trip time between the earth and the S/C was about 40 minutes. Thus such a large time difference have to be shifted for synchronization of the data. (2) Deviation of radio source orbit from the predicted one affects to the delay residual by two folds, whereas common mode error of arrival time is eliminated in standard VLBI. (3) Unlinked signal is re-transmitted from S/C by converting the frequency. Although the local oscillator on HAYABUSA is running without reference. Thus instability of local oscillator causes a fake Doppler shift and increases rate residual. In fact, the fringe between observed data and the replica signal was successfully detected, but non-linearity of delay and delay rate residual introduced complexity in integrating the data.

4. Phase delay

Main problem in phase delay is the uncertainty of ambiguity. One approach is reducing number of unknown ambiguities by connecting the phase for a long time. Phase variation pattern due to the earth rotation contains the information of radio source coordinates. This approach was taken in VLBI observation of NOZOMI. One reason was the signal of the S/C was too weak to detect group delay at that time. Since it was continuous observation instead of ΔVLBI, atmospheric delays estimated by GPS observations were used for calibration. Coordinates offset (Δα, Δδ) of the S/C from the predicted orbit in the celestial sphere were estimated with least square analysis. Fig.8 shows the solution and residual plot. **Note that S/C coordinates can be estimated at an accuracy of about 100 mas only with Japan domestic baselines (solution III).** The line in Fig.8 (up) is the motion of S/C during 4th and 5th of June on the orbit determined by range and range rate measurement (R&RR). Since the radio source is moving during the observation period, motion of radio source need to be simultaneously estimated. Although those derivative parameters was correlated with the offsets and could not be appropriately estimated at present. This is one of the issues to be resolved.

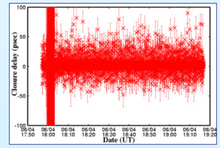


Fig. 7. An example of closure phase delay of NOZOMI VLBI observation. Phase delay measurement error in a few tens of ps is seen.

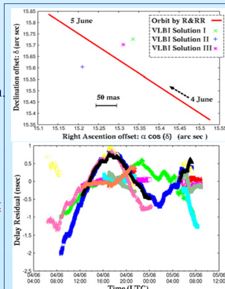


Fig.8. Estimated coordinates of NOZOMI with VLBI phase delay data on the coordinate system co-moving with the predicted orbit (upper) and delay residuals for domestic baselines (lower). The origin of the upper plot is predicted orbit of the S/C. VLBI solution I and II include Algonquin baseline, but solution III is only with Japan domestic baselines.