VLBI Observation of Spacecraft for Navigation
–Approaches with Group Delay and Phase Delay –

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Abstract

Very long baseline interferometry (VLBI) has high sensitivity in coordinate measurement in the celestial sphere. Joint use of VLBI and range and range rate measurement can enhance the accuracy of the spacecraft navigation. Group delay and phase delay are observables of VLBI observation. The latter has an advantage of better delay resolution than the former, although its drawback is difficulty to get absolute delay due to phase ambiguity. We have observed spacecraft NOZOMI with Japanese and Canadian VLBI stations. As an approach to the phase ambiguity problem, we have successfully connected the phase delay over 24 hours, and celestial coordinates of NOZOMI was estimated by astrometry analysis.

Group delay observable is good at absolute delay measurement even though delay resolution is limited by bandwidth of the signal from the spacecraft. For increasing the delay resolution, spectrum filtering and correlation processing with replica of the signal are tested in VLBI observation of spacecraft HAYABUSA.

1 Introduction

Very long baseline interferometry (VLBI) is a technology of angular measurement with the highest precision. Range observation of spacecraft has been used as a conventional technique for spacecraft navigation in the deep space. The range observable is sensitive in the line of sight (LoS), and VLBI has complementary characteristic with it. Thus joint use with VLBI and range and range rate observables is expected to enhance the precision of the spacecraft navigation.

Group delay measurement of radio signal has been used for spacecraft navigation by JPL/NASA as delta differential one way range (DDOR) technique[1]. Since precision of delay measurement of the DDOR is limited by bandwidth of spacecraft signal, long baseline is required for high angular resolution. Phase delay observable has potential to achieve about 2 orders of higher precision of delay measurement than group delay. However the drawback of phase delay is difficulty to get absolute delay due to phase ambiguity. An approach to this problem is connecting phase continuously for all scans and estimating phase ambiguity together with clock offset on the analysis stage. Here we report on the astrometric analysis of radio source coordinates with phase delays observed for spacecraft NOZOMI.

As another approach, delta-VLBI observation with group delay is investigated. The advantage of group delay is the easiness to get absolute delay than the case of phase delay. Geometrical delay is obtained by calibrating the excess delay due to propagation medium with delta-VLBI technique. Consequently, short time session is enough for astrometric position estimation. Additionally no need for phase connection between scans gives less restriction on switching cycle in delta-VLBI observation. Low delay resolution due to narrow bandwidth of the signal from spacecraft is only its disadvantage. To improve the delay resolution of group delay, signal filtering and correlation with replica signal, are tested by VLBI observation of HAYABUSA.

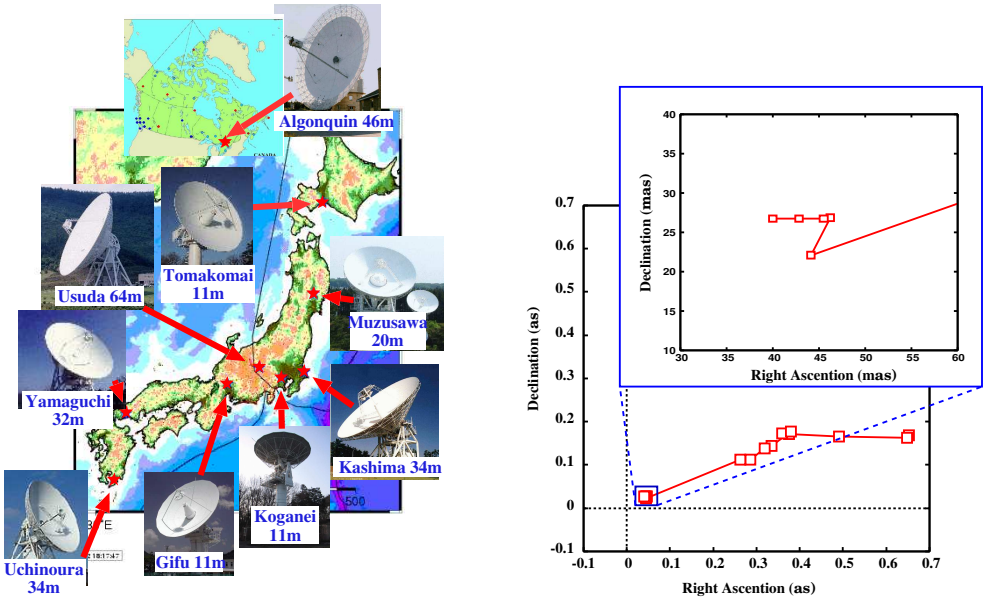

Figure 1: Celestial coordinates of NOZOMI estimated by VLBI observations on 4th June 2003 is plotted. The origin of plot is the orbit determined by R&RR measurements. Atmospheric delay was calibrated by means of GPS observations. Each points of plot are solutions with data sets as including from short baselines to long baselines. Magnified plot superimposed at the top is solutions including Algonquin related baselines.

2 Observations and Astrometric Analysis

NOZOMI, which was the first Japanese Mars mission[2], performed two earth swing-bys in December 2002 and June 2003 to get energy to travel to the Mars. During this period, several VLBI observation sessions are organized. Many Japanese VLBI stations and Canadian Algonquin observatory has joined to the observations (Fig. 1). However, the high-gain-antenna (HGA) of NOZOMI could not face to the earth during this period, group delay of range signal was not obtained with good signal to noise ratio (SNR) except for when NOZOMI was very close to the earth. Therefore we conducted mainly phase delay observations for NOZOMI.

HAYABUSA was launched in May 2003 for asteroid exploration by ISAS/JAXA and it approaches to the asteroid 'ITOKAWA' at the end of summer in 2005. Delta-VLBI observations and some test observations are performed for HAYABUSA with Kashima 34m, Usuda 64m, Uchinoura 34m, Mizusawa 20m, 10m, Tsukuba 32m, and 10m diameter antennas of GSI at Chichijima and Aira stations. Detail of group delay characteristic will be discussed in section 4.

Disk-based data acquisition system (K-5 system)[3] was used for both spacecraft and reference source (quasar) observation. Observed data was transmitted to correlation center through the Internet. Then data reduction was performed by software correlator.

VLBI observation delay model is different from standard VLBI delay model (consensus model) [4][5] mainly due to the effect of curvature of wave front. The magnitude of the effect reaches to order of micro second for distance to Mars and Venus. A new VLBI delay model for radio source at finite distance [6][7] was used for theoretical delay calculation.

Astrometric analysis is based on the assumption that the apparent coordinates offsets (right ascension and declination) of true orbit from the reference orbit seen from geocenter is constant during observation session (normally less than 1 day). Delay model is computed along the reference orbit. Then the residual of delay is analyzed by linearized observation equation by least square.

3 Phase delay analysis

Fringe phase contains the position information of the radio source. However, due to the uncertainty of phase ambiguity, absolute delay measurement is not easy. By means of connecting phase for all scans, which corresponds to reducing the number of unknowns, phase delay can be used for coordinates estimation by least square analysis. Among some VLBI sessions for NOZOMI observation, most of Japanese domestic VLBI stations and Canadian Algonquin observatory have participated in the VLBI session (Fig. 1) on June 4th 2003 over 24 hours. Excess delay due to the atmosphere was calibrated by atmospheric delay obtained by analyzing GPS data of GEONET [8] and IGS sites. Right panel of Fig. 1 shows spacecraft coordinates offset with respect to the reference orbit estimated by astrometric analysis. The origin of plot is the orbit determined by R&RR measurement as reference orbit. The track of the plots indicates the solutions converges

closely to the reference orbit by increasing the data sets of long baselines. However, the error (variation) of astrometric solutions of the coordinates are not comparable with precision of delay observable. Cause of that may be attributed to following error sources. For total phase connection over the scans, continuous spacecraft tracking observation instead of delta-VLBI was employed. Even though the tropospheric delay calibration by GPS data is applied, calibration error caused by interpolation of inhomogeneous atmospheric thickness should remain. Also instrumental phase drift might cause the phase delay error. Each of those error sources are to be diminished by delta-VLBI technique and by using phase calibration signal.

4 Improvement of SNR on group delay observable

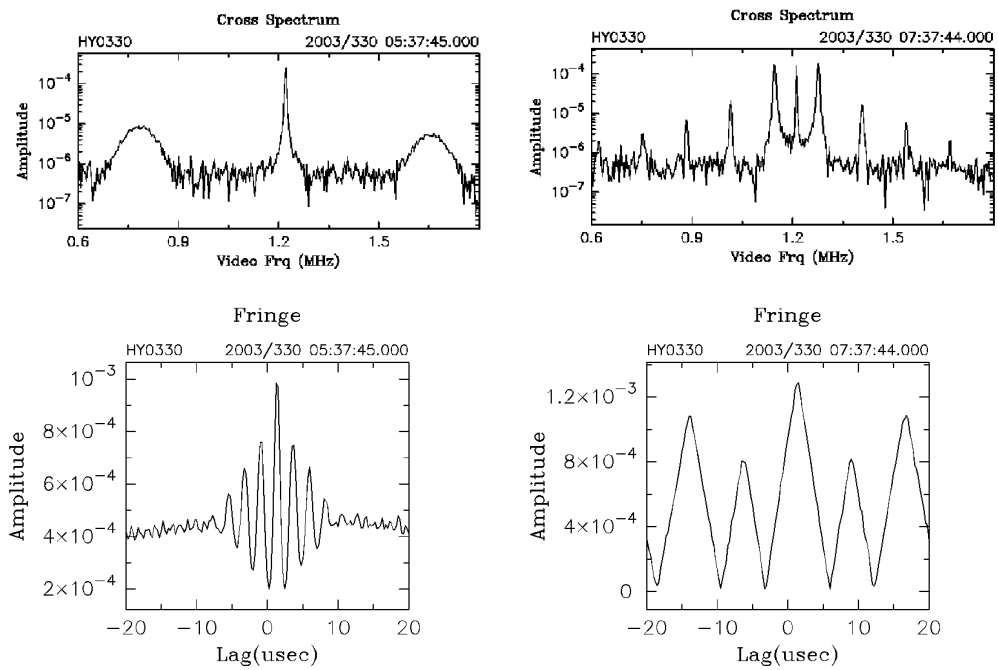

Figure 2: Frequency spectrum (upper panel) and delay resolution function (lower panel) of range signal (left) and telemetry signal (right), respectively.

Group delay of VLBI data has been intensively tested with the signal from HAYABUSA. Precision of group delay measurement depends on the signal characteristic. Fig. 2 shows frequency power spectra and delay resolution functions of range and telemetry signals. Range signal has wider spectrum than telemetry, thus it has higher delay resolution. According to a simulation analysis, one ns or better precision of delay is necessary for contribution to orbit determination. Order of a few ns of precision was actually possible in observation of range signal with large diameter antenna pairs, although medium size antenna pairs such as Chichijima, Aira, Gifu, and Mizusawa did not alway achieved high resolution. Delay resolution is inversely proportional to the effective bandwidth and SNR. Two sorts of technique were tested to increase the SNR. First one is signal filtering in cross correlation processing. Spacecraft signal has power at some portion of frequency spectrum. Therefore by suppression of spectrum where the signal is absent, SNR can be improved. (Fig. 3).

Secondly, the ideal filtering is correlation between observed data and replica of the transmitted signal itself. Range signal is up-linked and sent back from spacecraft after frequency conversion. Up-link range signal was split at ground station and recorded with K-5 disk-based recording system at the same time with range observation. The round trip time for HAYABUSA was about 40 minutes in March 2005. Fringes between observed data and the replica signal were successfully detected with high SNR. Although, since the predicted orbit was not so accurate, the delay model computed from the orbit caused higher order term of fringe rate residual. Consequently data could not be integrated for a long time. We are planning to use observed range rate data for correlation processing to solve this problem.

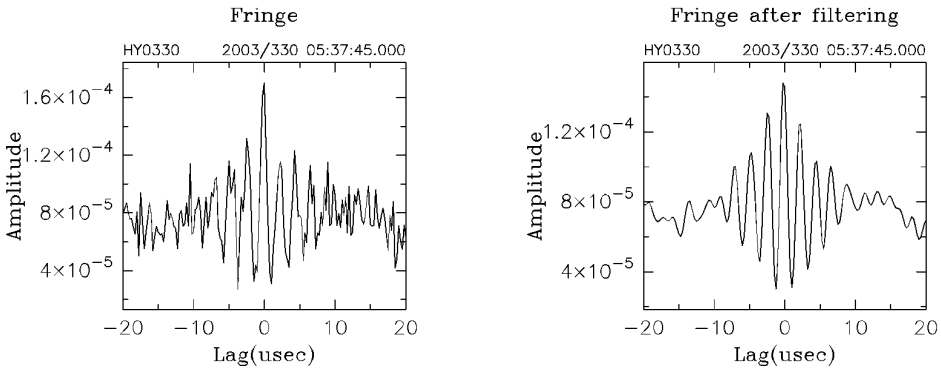

Figure 3: Effect of signal filtering. Signal to noise ratio of delay resolution function was improved by bandpass filtering of range signal (right) than before filtering (left).

5 Summary

Disk-based data acquisition (K-5) system and a new VLBI delay model for radio source at finite distance are used for observation, data processing and astrometric analysis. Phase delay observable obtained by continuous spacecraft tracking was was used for coordinates estimation of NOZOMI.

Delta-VLBI technique was tested with asteroid exploration mission HAYABUSA. Precision of delay measurement is in order of 10 ns or more except for large diameter antenna pairs, at present. Spectrum filtering and correlation with replica of the signal are demonstrated to improve the delay precision.

Acknowledgment

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