Status Report on VLBI application for Space Navigation of HAYABUSA

Abstract

To establish the technical basis of using VLBI for spacecraft navigation, Δ VLBI experiments were performed for spacecraft HAYABUSA. Several domestic VLBI stations are participated in the observation, and range and telemetry signal are observed. Since the lengths of Japanese domestic baselines are not so long, high resolution of delay measurement is required to get high angular resolution. Precision of delay measurement depends on the signal type. And group delay is characterized by signal to noise ratio (SNR) and effective band width (EBW). From the plot of delay precision versus SNR, following things are confirmed. (1) Range signal is about 4 times better precision than telemetry signal. (2) Delay precision better than 1 nano sec is available when SNR is more than 1000 in case of range signal. Therefore it may be necessary to consider to use other type of signal, which has wider EBW, to achieve sub-nano second delay resolution.

VLBI を使った軌道決定に向けたHAYABUSA の観測 -現状報告-

概要

VLBI を宇宙飛翔体のナビゲーションに応用する技術的基礎を確立するため、小惑星探査機　はやぶさ　を対象に相対 VLBI 実験を行ってきた。観測には、日本国内の VLBI 関連研究機関のアンテナが参加し、レンジ信号、及びテレメトリ信号の観測をおこなった。国内基線基線では基線長がそれほど長く取れないため、高い角度分解能を得るためには、高い遅延分解能を必要とする。遅延計測精度は信号のタイプに依存し、信号対雑音比 (SNR) と有効帯域幅で特徴付けられる。これまでに観測を行ったデータの遅延計測精度と SNR の関係を、信号のタイプごとにプロットすると、(1) レンジ信号はテレメトリ信号より約４倍程度遅延計測精度がよい. (2) レンジ信号を使って１ナノ秒以下の群遅延計測精度を達成するためには、SNR が 1000 以上必要である、といったことが明らかになってきた。従って、ナノ秒以下の遅延計測精度を達成するには、信号形態の改善も検討する必要があると考えられる。

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1 Introduction

Observation of spacecraft with very long baseline interferometry (VLBI) is effective to enhance the precision of orbit determination with range and rate measurements (e.g. [1]). Japanese space agency (JAXA) and VLBI community are collaborating to establish technical basis to use VLBI for spacecraft navigation [2, 3, 4, 5, 6]. Two sort of delay observables, group delay and phase delay, are available from VLBI observation. Group delay observable has advantage in operational point of view. Because ambiguity is not the problem in group delay, geometrical delay can be derived by calibrating propagation excess delay width Δ VLBI technique, which observes target radio source and nearby reference radio sources alternatively. Thus the celestial coordinates of target radio source can be determined in a short time observation (for instance 20 min), in principle. Less requirement to keep observation time of each radio telescope is big advantage in operational viewpoint. Although drawback of the group delay observation is limited delay resolution. Delay precision of group delay is characterized by signal to noise ratio (SNR) and effective band width. We have performed several test VLBI experiment for HAYABUSA, while it is operated in telemetry mode and range mode. Comparisons of spectrum and delay measurement precision are described in the sections 3.

Whereas, using phase delay has potential to enable high precision delay measurement. But problem is difficulty to get absolute delay due to phase ambiguity. An approach to use phase delay by connecting phase for long time observation has demonstrated in VLBI observation of spacecraft NOZOMI. Details are described in section 4.

2 VLBI Observations

Spacecraft HAYABUSA is a spacecraft of asteroid exploration mission launched in 2003. It has arrived to the asteroid ITOKAWA in August 2005. Δ VLBI observations of HAYABUSA and nearby quasar were conducted some times from the end of May to beginning of July 2005. VLBI stations participated in the observations were Usuda 64m (JAXA/ISAS), Kashima 34m (NICT), Tsukuba 32m, Aira 10m, Chichijima 10m (GSI), and Mizusawa 20m and 10m (NAOJ) (see Fig. 1). The K5/VSSP disk-based VLBI data acquisition systems placed each VLBI stations were used in 8 MHz sampling 1 bit observation mode. Since the down link signal is about 8408 MHz, HAYABUSA and reference quasar were observed in X-band. Reference quasar was observed with 8 channels and signal of HAYABUSA was recorded in one of those channels. Observed data recorded in the hard disk of K5/VSSP system were transfered from Tsukuba and Usuda to Kashima through the Internet. Hard disks which contains observed data at Aira and Chichijima were sent to Tsukuba by surface mail and transfered to Kashima through the network.

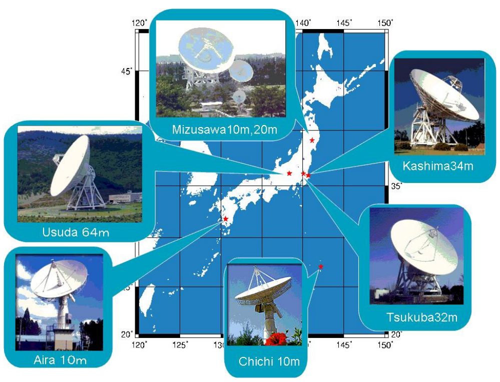

Figure 1: Kashima 34m, Usuda 64m, Tsukuba 32m, Mizusawa 20m, Aira 10m, and Chichijima 10m stations are participated several VLBI observations of spacecraft HAYABUSA in the first half of 2005.

The data were cross correlated by K5 correlation software [7]. Precise group delay were obtained on quasar observation, in which data were recorded with 8 channels distributed over radio frequency range 360 MHz. Bandwidth synthesis method [9] was applied to quasar's data with the software KOMB [8] as in the same way with geodetic VLBI observation. Since the celestial coordinates of reference radio sources are accurately known, residual of delay between observed data and theoretical geometrical delays of reference sources are though to be composed of excess delays of propagation media, hardware offsets, and station clock synchronization error. Thus subtracting the delay residual of reference radio source from target radio source gives calibrated geometrical delay of target radio source. And this data are used for radio source coordinate estimation.

3 Signal Type and Precision of Group Delay

Delay precision of spacecraft observation depends on signal type. It is well known that precision of group delay measurement is inversely proportional to the signal to noise ratio (SNR) and effective

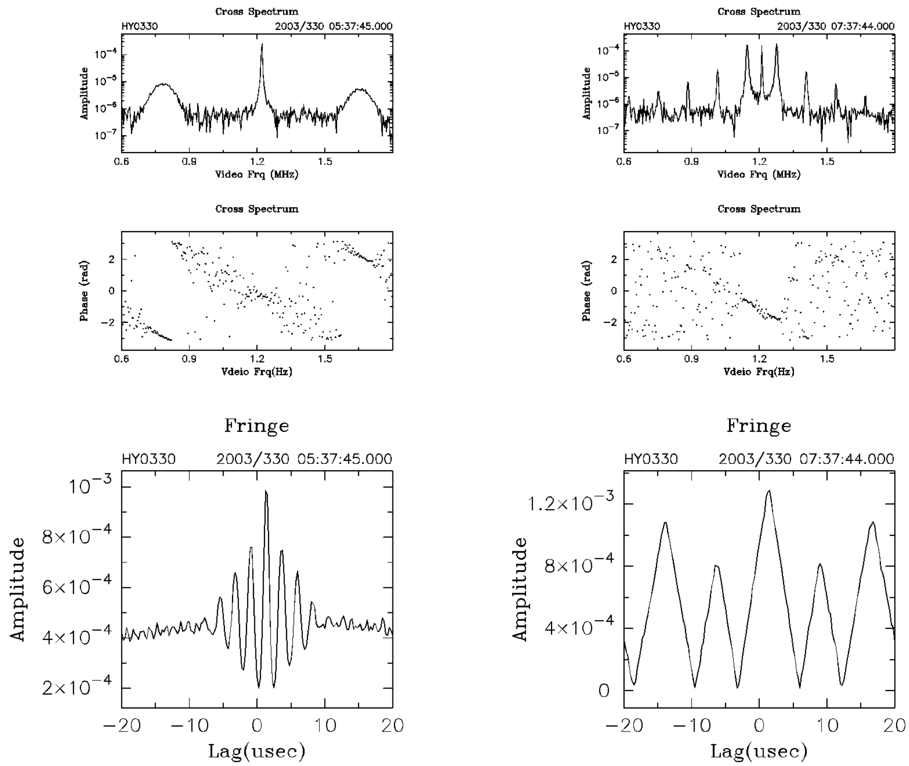

Figure 2: Amplitude (top) and phase (middle) of cross power spectrum of range signal (left) and telemetry signal (right). Correlation functions (delay resolution function) in time domain are displayed in the panels at the bottom. Sharpness of the peak of delay resolution function correspond to the delay precision.

band width (EBW). The EBW is defined by root mean square of signal power spectrum around the mean. Fig. 2 shows the power spectrum and correlation function of range and telemetry signals. Plot of power spectrum indicates that power of telemetry signal is concentrated around the carrier signal then EBW become small and correlation function is broad. On the other hand, range signal has wider power spectrum, then peak of correlation function has better delay resolution than telemetry signal. Actual delay measurement precisions of each VLBI experiments were evaluated by RMS of residual delay around smoothing polynomials fitted to the data. Fig. 3 shows plot of the RMS as a function of SNR for each signal types. Group delays of range signal, telemetry signal, and delay obtained by bandwidth synthesis for quasar data are plotted for VLBI experiments from May to July 2005. Under the comparison of the same SNR, range signal is about 4 times better precision than telemetry signal. And that is corresponding to the ratio of each EBW 100 kHz (telemetry signal) and 450 kHz (range signal). Delay precision of sub nano seconds is desirable to use the VLBI measurement for spacecraft navigation, especially when the baseline length is limited. Although 1 nano sec precision was achieved only when SNR was about 1000 with range signal, it was in quite good signal condition and we cannot expect $SNR \geq 1000$ regularly. RMS delay of quasar signal obtained by bandwidth synthesis is also plotted in the figure. The EBW of eight channels allocated in the radio frequency range from 8196 MHz to 8556 MHz was 140 MHz. Consequently the delay precision become about 3 order of magnitude better than telemetry signal owing to the wider EBW.

Board spectrum such as that of quasar cannot be used in spacecraft signal because of limited power and frequency allocation. One of the best way of signal allocation in frequency domain will be using multiple tones. Because signal power per unit frequency can be made larger than spread

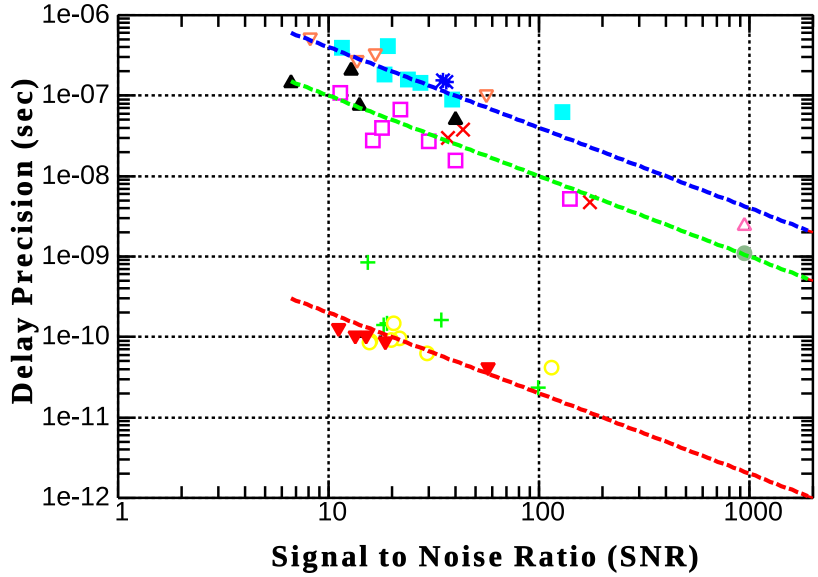

Figure 3: RMS residuals of VLBI delay measurement around low order polynomial fitted to the data are plotted as a function of SNR. RMS of range signal, telemetry signal, and quasar's signal are separately computed. Three lines, which are proportional to the SNR^{-1}, are plotted as reference for each signal types.

spectrum. And by reducing the noise with appropriate frequency filtering, SNR can be improved. Additionally wide EBW will be obtained by allocating tone signals in wide frequency area with appropriate frequency intervals. Actually DDOR (delta differential one way range) signal, which is used by JPL/NASA, is in the form of multiple tones. We are considering using other type of signal rather than range and telemetry signal, but maybe multi-tone signal to get high delay resolution in VLBI group delay observation.

4 Phase Delay

Alternative technique to get high delay resolution in VLBI observation is using phase delay. Although uncertainty of phase ambiguity prevent us to get absolute delay, reducing number of unknowns by phase connection enables us to estimate radio source coordinates via delay variation due to earth rotation. One of the example of such approach was demonstrated in VLBI observation of Spacecraft NOZOMI, which was the first Japanese Mars mission. On 4 June 2003, 7 VLBI stations (Usuda 64m, Kashima 34m, Tsukuba 32m, Yamaguchi 32m, Gifu 11m, Tomakomai 11m, and Algonquin 46m) are participated the VLBI observation. Most of the station observed NOZOMI for 24 hours, because NOZOMI was at high declination differently from standard planetary spacecraft. After connecting fringe phase about 24 hours, spacecraft coordinate offsets $(\Delta\alpha, \Delta\delta)$ from predicted orbit were estimated. Excess delay due to propagation medium was calibrated with Atmospheric delay estimated by GPS observation data at nearby VLBI stations . The estimated celestial coordinate offset with respect to the predicted orbit is plotted in Fig. 5. Three coordinates solutions obtained by different estimation conditions are plotted. Also determined orbit by range and range rate observation is drawn with red line in the same plot. Determined orbit (hereafter OD) is regarded as true orbit within its error of about 1 μ radian ($\cong$ 200 mas). The three solutions given by VLBI observations are distributed around the OD within 100 mas. Note that about 15 arc seconds of offset from predicted orbit was correctly estimated with reasonable precision even only with domestic baseline data. It demonstrates that phase delay observable can

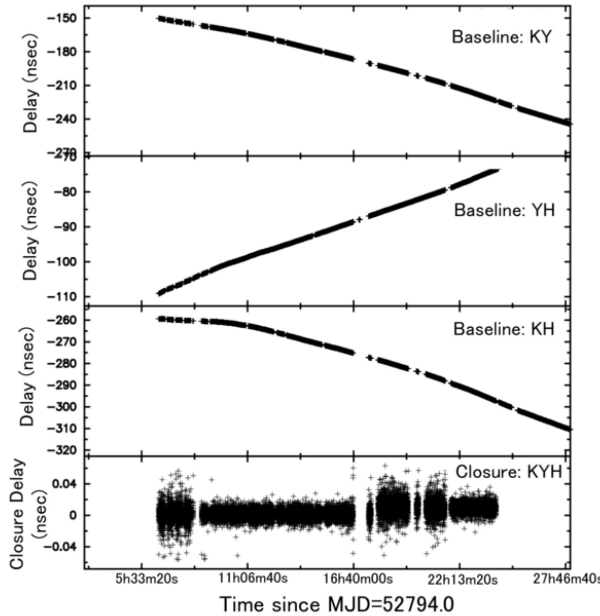

Figure 4: Example of phase delay and closure of phase delays observed at VLBI stations Yamaguchi 32m (K), Gifu 11m (Y), and Tomakomai 11m (H). The bottom panel indicates the closure of phase delay. Precision of phase delay observable is seen from the plot as about a few tens of pico sec.

significantly contribute to orbit determination only with domestic VLBI observations. The reason of no improvement of coordinates even with intercontinental baseline with Algonquin station is to be investigated. Also it is obvious that time derivative of coordinates offsets $(\Delta\dot{\alpha}, \Delta\dot{\delta})$ need to be estimated simultaneously.

5 Summary

Difference of spectrum and delay resolution function between range and telemetry signal of spacecraft HAYABUSA was investigated. Delay precision obtained by several VLBI experiments clearly confirmed the relation

$$\delta\tau \propto (SNR)^{-1}(EBW)^{-1}.$$

It suggest that we need to consider to use alternative signal type to get higher group delay resolution that 1 nano second.

Analysis with phase delay observable of VLBI observation of spacecraft NOZOMI demonstrated the high delay precision of phase delay observable enables significant contribution to orbit determination even with domestic VLBI observations.

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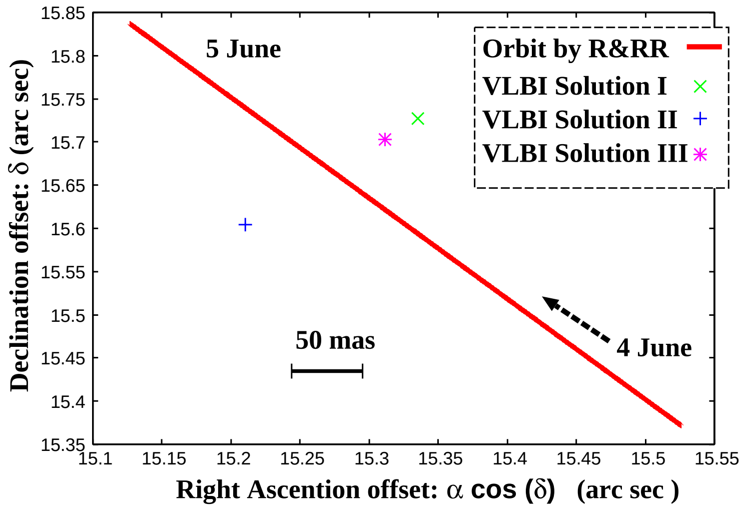

Figure 5: Relative position of determined orbit by R&RR (red line), and estimated coordinates NOZOMI with VLBI data in different three conditions. The origin of the plot is taken at the predicted orbit. The track of red line shows motion of determined orbit with respect to the predicted orbit during 1.5 days from 4 June 0:00 UT. VLBI solution I and II include data of Algonquin baseline, and solution III is by only domestic baselines. Right ascension, declination offsets $(\Delta\alpha, \Delta\delta)$, clock offset, and its rate are estimated in Solution I and III. Only $(\Delta\alpha, \Delta\delta)$ are estimated with fixed clock offset and rate at appropriate values in solution II.

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