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VLBI Observation for Spacecraft Navigation (NOZOMI) - Data Processing and Analysis Status Report

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Abstract

We started investigation and development of VLBI application for orbit determination. Under the collaboration of Japanese VLBI community and Canadian VLBI team, a series of VLBI observation was performed for spacecraft NOZOMI, which was Japanese first Mars mission. PC-based data acquisition system and software correlator was used for observation and data reduction. Relativistic VLBI delay model for finite distance radio source and analysis software package were developed for this project. We are taking approach with group delay and phase delay in parallel. Current accuracy of delay measurements are order of several tens of nanoseconds and a ten picoseconds for group delay and phase delay, respectively. Preliminary result of estimated spacecraft coordinates are obtained.

1. Introduction

Range and Range rate (R&RR) measurements, which have been traditionally used for Spacecraft navigation in deep space, has sensitivity in direction of the line of sight (LoS). Complimentarily, VLBI is sensitive in direction perpendicular to the LoS. Thus joint use of these two techniques is expected to enhance the precision of spacecraft navigation. And JPL/NASA has been using this technique sometimes for planetary missions since 1980s. Requirement of navigation accuracy is increasing in recent and in future space missions for precise landing and orbiting other planets and for saving energy for orbit correction. Due to these reasons, Japanese space agency JAXA, CRL (NICT from April 2004), and NAOJ have started collaboration on VLBI application for spacecraft navigation. In 2003, first Japanese Mars mission “NOZOMI” was planned to do two earth swingbys for changing its orbit to Mars. During the period between two swingbys (Dec. 2002 and Jun. 2003), a series of VLBI observations were performed for the spacecraft by wide support of Japanese VLBI community across different institutes and Universities, and Canadian VLBI team (SGL/CRESTech, NRCan, and CSA). Detail of the VLBI observation of NOZOMI is described in the other article of this issue [3]. Currently CRL is doing analysis of celestial coordinates (α, δ) estimation of spacecraft (hereafter Spacecraft (SC) Astrometry) as one of the steps for spacecraft navigation.

2. Tasks to be Done for Spacecraft Astrometry

VLBI observation for spacecraft in the solar system is different from normal VLBI in some points. Firstly curvature of wavefront have to be taken into account in the delay model, which was ignored in standard VLBI model [1]. As second point, the signal from spacecraft is normally narrow band signal as wide as a few MHz. Thus group delay resolution is in order of a nanosecond in best case. To achieve high angular resolution with group delay observable, intercontinental baseline is inevitable. As another choice, phase delay has potential of 3 - 4 order better delay resolution than group delay if ambiguity problems can be solved. We are taking both approaches in parallel for the SC astrometry.

2.1. Finite Distance VLBI Model

VLBI delay model named "consensus model" [1] is used as standard VLBI delay model in world wide VLBI community. However this model assumes the radio source is at infinite distance and ignoring curvature of wavefront, which have to be taken into account when radio source is closer than 30 light years [10]. Sovers & Jacobs [10] discussed the curvature effect of finite distance radio source. Fukushima [2] proposed useful expression of VLBI delay model for finite distance radio source. However, alternative formula corresponding to the consensus model was not presented in those papers. Moyer [7] has derived an expression of VLBI delay model for finite distance radio source with solution of light time equation. Although, iterative computation is needed to solve the light time equation. Since we intended to use the CALC9 as the base of a priori computation software, then author has developed a formula for finite distance radio source[8].

$$\tau_2 - \tau_1 = (1+\beta_{02})^{-1} \left\{ \Delta t_g - \frac{\vec{\mathbf{K}}\cdot\vec{\mathbf{b}}}{c}\left[1-(1+\gamma)U - \frac{V_e^2 + 2\vec{\mathbf{V}}_e\cdot\vec{\mathbf{w}}_2}{2c^2}\right] - \frac{\vec{\mathbf{V}}_e\cdot\vec{\mathbf{b}}}{c^2}\left(1+\beta_{02} - \frac{\vec{\mathbf{K}}\cdot(\vec{\mathbf{V}}_e + 2\vec{\mathbf{w}}_2)}{2c}\right)\right\}, \quad (1)$$

where $\beta_{02} = \hat{\vec{\mathbf{R}}}_{02}\cdot\frac{\vec{\mathbf{V}}_2}{c}$, $\vec{\mathbf{K}} = \frac{\vec{\mathbf{R}}_{02}+\vec{\mathbf{R}}_{01}}{R_{02}+R_{01}}$, and $\vec{\mathbf{R}}_{\mathrm{ij}} = \vec{\mathbf{X}}_{\mathrm{i}} - \vec{\mathbf{X}}_{\mathrm{j}}$. Indexes 0,1,2 indicate respectively radio source, station1, and 2. Variables of large capital indicate quantities in frame of Solar System Barycenter (SSB), and small ones are those in geocentric reference frame. $\vec{\mathbf{V}}_2$ and $\vec{\mathbf{w}}_2$ are velocity vector of station 2 in SSB frame and geocentric frame, respectively. This formula has precision of less than five picoseconds for the radio source beyond 10^9 m from observer.

2.2. Data Processing and Analysis System

IP-sampler system [4][5] was used for data acquisition. The data were sampled at 4 MHz with 2 bit quantization per channel. The PC-based data acquisition system has some advantages for spacecraft observation. Since sampled data is directly stored in hard disk of personal computer, it is suitable for data transfer through the Internet and for processing with software correlator, which has wider flexibility than hardware correlator. Additionally one data channel is enough for sampling narrow band signal from the spacecraft. Quasars were also observed at the beginning and end of experiments for calibration of clock parameters. Quasar data were sampled in four data channels, for improving signal to noise ratio (SNR) and for getting higher delay resolution by using bandwidth synthesis technique.

Since we are taking both approaches using group delay and phase delay, two sorts of software correlator were used to derive those observables. Group delay was derived by the same correlation software used in K5 system, and phase delay was derived by another correlation software for line spectrum signal.

A priori delay, delay rate, and partial derivatives were computed by modified version of 'CALC9', which was originally developed by GSFC/NASA and we modified it for our purpose (hereafter we call it 'CALC9M'). New VLBI delay model of finite distance radio source mentioned above section was implemented in this software[1].

From observables (O) derived by correlation processing and a priori values (C) computed with 'CALC9M', residuals (O-C) were computed and analyzed by least square parameter fitting with partial derivatives. Least square analysis package was also developed for this project.

3. Least-Square Analysis Results

3.1. Group Delay

Post fit residual plots of group delay and delay rate of VLBI observation of NOZOMI are displayed in figure 1. The post fit residuals of group delay were scattered in range of several tens

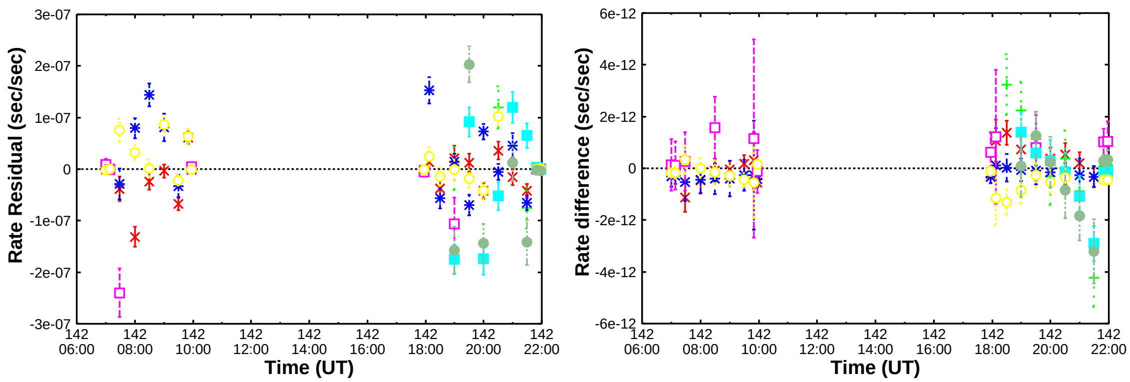

Figure 1. Post fit residual of group delay (left) and delay rate (right) in nz142 (2003/5/22) VLBI experiment. Some Quasars were observed at the beginning and end of sessions.

of nanoseconds. This seems to be current accuracy of group delay measurement, since scattering range of closure delay data was in the same order. The reasons of this large error of group delay observable will be due to low SNR and narrow bandwidth of signal from the spacecraft. The disadvantage of low SNR can be overcomed if correlation is taken with signal itself, which is transmitted from the spacecraft. This technique is used by JPL/NASA.

3.2. Phase Delay

Phase delay can be used as an observable if fringe phases between scans can be connected without ambiguity for a long time interval. Since we took conservative observation strategy in NOZOMI observation, namely tracking the NOZOMI continuously for a long time, phase connec-

[1]The delay model expressed by formula (1) is derived from framework of TCB, however JPL ephemeris and spacecraft orbit is usually given in TDB frame. Thus another modified version of formula (1) (Sekido & Fukushima 2004) was actually implemented in 'CALC9M'

tion between scans were not so difficult in this case as far as fringes are detected with enough SNR. Phase delay was extracted by line-spectrum software correlator. Figure 2 shows an example of closure of phase delay among Kashima, Usuda, and Tsukuba stations after the phase connection. It demonstrates phase connection is performed successfully without any ambiguity jump, where three scans are included in the time span of the figure. The closure plot indicates that the delay measurement accuracy is around a few tens of picoseconds. Figure 3 shows preliminary result of phase delay analysis. Left panel is post-fit residual plot of phase delays on several baselines and right one indicates coordinates of NOZOMI estimated with phase delay measurements. The right panel indicates the VLBI solutions converge to a certain points as the number of baselines data sets increases. Declination of the VLBI solution almost coincides with that of orbit determination (OD) by ISAS with R&RR measurements. Although, there is a large offset in right ascension between two sort of measurements. We need further check of software to make practically reliable output.

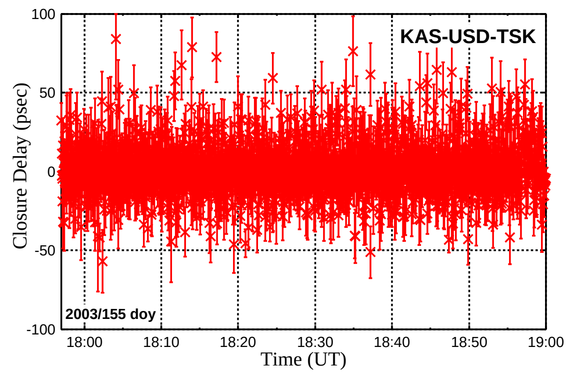

Figure 2. Closure of phase delay among Kashima, Usuda, and Tsukuba stations.

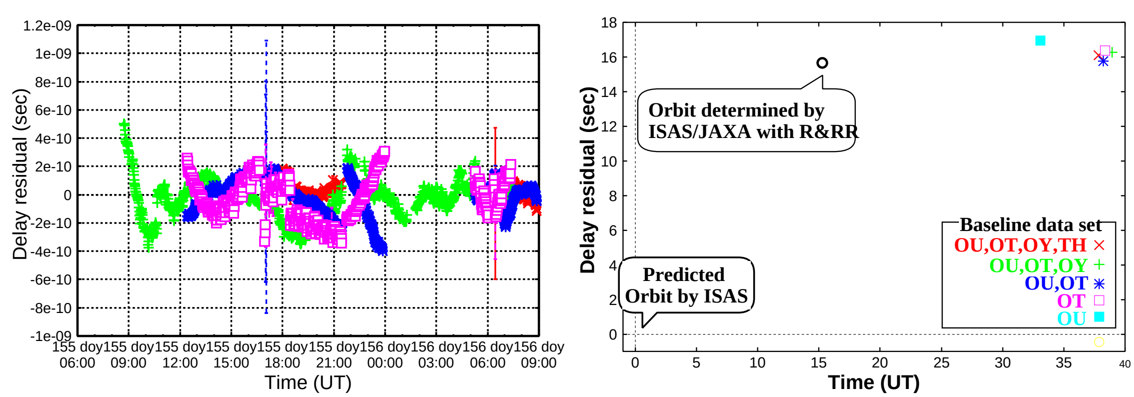

Figure 3. Post-fit residual of phase delay (left) and celestial coordinates of NOZOMI estimated from VLBI phase delay measurements in nz155 (2003/6/4) VLBI observation (right). Origin of the plot is the predicted orbit of NOZOMI. ○ mark indicates the coordinates determined by R&RR measurement by ISAS. Other marks are estimated coordinates of NOZOMI by VLBI phase delay observation with different baselines data sets. Each characters “O”, “U”, “T”, “Y”, “K”, and “H” represents VLBI stations Kashima 34m, Usuda 64m, Gifu 11m, Yamaguchi 32m, and Hokkaido 11m, respectively.

4. Acknowledgments

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