Astrometric VLBI Observation of Spacecraft with Phase Delay

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Abstract

A series of VLBI observations for spacecraft NOZOMI was performed in the period between the end of 2002 and July 2003 with aim of supporting the orbit determination. We have made astrometric analysis of the VLBI data for celestial coordinates estimation of the spacecraft with phase delay observables. Phase delay has potential to give 3 - 4 orders of improvement of delay resolution than group delay measurement, whereas main difficulty in using phase delay is ambiguity problem. We observed the spacecraft NOZOMI continuously for a long time with multiple VLBI stations, and we avoided the problem of phase ambiguity by connecting the phase delay. For correlation processing and analysis of VLBI data, relativistic VLBI delay model for finite distance radio source was developed, and it was used for the analysis. Coordinates of spacecraft in celestial sphere were estimated by least-square parameter fitting technique.

1 Introduction

Measurements of round trip time (range) from ground station to a spacecraft and its time derivative (range rate) (hereafter refereed as R&RR) have been traditionally used for spacecraft navigation in deep space. The R&RR measurements has sensitivity in direction of the line of sight (LoS), but in direction perpendicular to the LoS. Complimentarily, very long baseline interferometry (VLBI) is quite sensitive in the plane perpendicular to the LoS. Thus joint use of these two techniques is expected to enhance the precision of spacecraft navigation. The JPL/NASA has been using this technique sometimes for planetary missions since 1980s[1]. Requirement of navigation accuracy is increasing in recent and in future space missions for precise landing, precise orbiting other planets, and for saving energy for orbit correction. Due to these reasons, Institute of Space and Astronautical Science (ISAS) of Japan Aerospace Exploration Agency (JAXA), National Institute for Information and Communications Technology (NICT), and National Astronomical Observatory of Japan (NAOJ) has started collaboration on VLBI application for spacecraft navigation. In 2003, first Japanese Mars mission “NOZOMI” was planed to do two earth swing-bys for changing its orbit directing to the Mars. During the period between two swing-bys (Dec. 2002 and Jun. 2003), a series of VLBI observations for the spacecraft were performed by wide support from Japanese VLBI community across different institutes and universities (ISAS/JAXA, NICT, National Astronomical Observatory of Japan (NAOJ), Geographical Survey Institute (GSI), Gifu Univ., Yamaguchi Univ., and Hokkaido Univ.) and from Canadian VLBI community (Space Geodynamics Laboratory/CRESTech, Natural Resources Canada (NRCan), and Canadian Space Agency (CSA)). Currently we are working for analysis of celestial coordinates (α, δ) estimation of spacecraft (hereafter astrometry of spacecraft) as one of the steps for spacecraft navigation. VLBI observation for spacecraft in the solar system is different from normal VLBI in some points. Firstly curvature of wavefront, which was ignored in standard VLBI model [2], have to be taken into account in the delay model. 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 nano second in best case. To achieve high angular resolution with group delay observable, intercontinental baseline is inevitable, as the JPL/NASA is doing. 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 astrometry of spacecraft and here will introduce the case of phase delay measurements.

2 Finite Distance VLBI Delay Model

VLBI delay model named “consensus model” [2][3] has been used as standard VLBI delay model in world wide VLBI community. However this model is assuming radio source is at infinite distance and is eliminating curvature of wavefront, which have to be taken into account when radio source is closer than 30 light years [4]. Sovers & Jacobs [4] discussed on curvature effect of finite distance radio source. Fukushima [5] proposed useful expression of VLBI delay model for finite distance radio source. However, alternative formula corresponding to the consensus model has not presented in those papers. Moyer [6] has derived an expression of VLBI delay model for finite distance radio source with solution of light time equation. Although, iterative computation is required to solve the light time equation. Since we intended to use the CALC9, which is standard VLBI delay model computation software developed by the Goddard Space Flight Center of the NASA, as the base of our delay model computation software, then we have developed a formula of VLBI delay model for finite distance radio source corresponding to the consensus model[7][8]. Time difference of signal arrival between two VLBI stations measured with time scale on the geoid (TT) is expressed as

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

where $\alpha = (\beta_2^2 - \beta_{02}^2)\frac{\vec{\mathbf{K}}\cdot\vec{\mathbf{B}}}{2R_{02}}$, $\beta_{\mathrm{ij}} = \widehat{\vec{\mathbf{R}}}_{\mathrm{ij}} \cdot \frac{\vec{\mathbf{V}}_j}{c}$, $\beta_2 = V_2/c$, $\vec{\mathbf{K}} = \frac{\vec{\mathbf{R}}_{02}+\vec{\mathbf{R}}_{01}}{R_{02}+R_{01}}$, and $\vec{\mathbf{R}}_{\mathrm{ij}} = \vec{\mathbf{X}}_{\mathrm{i}} - \vec{\mathbf{X}}_{\mathrm{j}}$. Indexes 0, 1, and 2 indicate respectively radio source, station1, and 2. Variables of large capital indicate quantities in frame of Solar System Barycenter (SSB) in terms of TDB, and small ones are those in geocentric frame of reference. $\vec{\mathbf{V}}_e$ and $\vec{\mathbf{V}}_2$ are velocity vector of geo-center and station 2 in the frame of SSB, respectively. $\vec{\mathbf{w}}_2$ is velocity vector of station 2 in geocentric frame. This formula has a pico second accuracy for most of any radio sources in the solar system in ground-based VLBI observations. This VLBI delay model was implemented in modified version of CALC9 and used for a priori delay / delay rate, and partial derivative computation in correlation processing and data analysis.

3 Data Processing and Analysis

Observed radio signal with large diameter antenna were converted to video frequency band and sampled and recorded by PC (Personal computer)-based data acquisition system named IP-VLBI system. The IP-VLBI system[9][10] is a VLBI data acquisition system developed by the NICT with aim of transferring VLBI data through the Internet in real-time. The data were sampled by 4 MHz with 2 bit quantization per channel and stored in hard-disk (HD) of the PC. The IP-VLBI data acquisition system is suitable for spacecraft observation in several view points. (i) Compactness of the observation data corresponding to the narrow band signal from spacecraft. (ii) Data in form of computer file is suitable for data transfer to correlation center through the Internet. (iii) Software correlator used for PC-based VLBI system has much wider flexibility than hardware correlator.

We have developed a correlation software to extract fringe phase from line spectrum data. The main problem of dealing with phase delay is ambiguity 2π n, where n is integer number. Although, if phase delays of the VLBI observable are connected without ambiguity for a long time interval, the radio source coordinates can be estimated by using the time variation of the phase delay observables. Following this strategy, we observed the spacecraft NOZOMI continuously for a long time (from several hours up to 24 hours) in the series of VLBI experiments. Duration of each scans were about 30 minutes, and the data were stored in each files. Since the interval between a scan to the next scan was less than 1 minute in most cases, fringe phase could be connected easily as far as the fringes were detected with enough SNR. Phase delay rate is also an independent observable with advantage of ambiguity free and disadvantage of less sensitivity than phase delay itself. After the phase connection procedure, data were smoothly approximated by 4th order of chebyshev polynomial at every 400 seconds intervals, and delay rates were computed by using the analytical derivative of the polynomial. Then these phase delay and phase delay rate were used for spacecraft coordinates analysis. Fig. 1 shows an example of closure of phase delay among Kashima, Usuda, and Tsukuba stations. It demonstrates that phase connection was performed successfully without any ambiguity jump, and the delay measurement accuracy is around a few tens of pico seconds. That is about 3 order of precision improvement from group delay measurements.

Fig. 2 shows the estimated coordinates of NOZOMI with phase delay and phase delay rate measurements with VLBI data on June 4th 2003. Two cases, where phase delay and rate (refered as D&R) were jointly used in one case (open circle plot) and only delay rate (refered as R) was used as the other case (close circle plot), of solutions tracks are plotted as a function of number of baselines used for the analysis. In the plot of left hand side, the track of solution as increasing the number of baselines looks like a random work rather than converging to a certtain solution. And solutions of two cases D&R and R are not consistent. In the right pan-

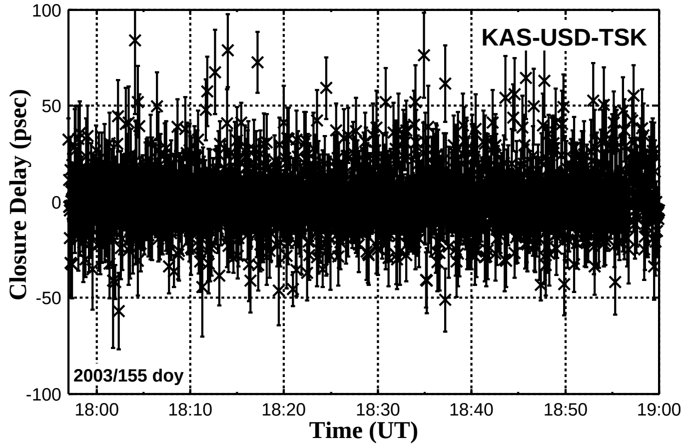

Figure 1: Closure of phase delay among Kashima, Usuda, and Tsukuba stations.

nel, the both of two sorts of solutions (D&R and R) converged close to the origin (determind orbit by R&RR) as increasing the number of baselines. If we believe the determined orbit by R&RR measurement is almost true coordinates of the spacecraft, this plot indicates that our VLBI solutions gives the true coodinates within error of 1 micro radians, which was the requested accuracy for spacecraft astrometry by VLBI at present.

4 Discussion

The reason of the discrepancy among VLBI solutions with predicted orbit might be understood as follows: True coordinates of spacecraft is more than 10 arc second away from the predicted orbit as seen in Fig. 2. Then non-linearity of VLBI observable may come out significantly especially in long baseline, whereas our approach is using least square estimation of linearized model. Consequently, true radio source coordinates were not estimated with partial derivative at the predicted orbit. This 10 arc seconds of angular distance between a priori source coordinates and true coordinates is quite exceptional in ordinary VLBI observation for natural radio sources. However, this order of deviataion of predicted orbit from true coordinates must be inevitable for the case of spacecraft. And we need to estimate true spacecraft coordinates from the predicted orbit.

If our estimation on the reason of the discrepancy in the results mentioned above is correct, we may be able to approch to the true spacecraft coordinates by means of non-linear least square method. In other words, iteration of least square solution and updating the a priori coordinates may converge to a plausible radio source coordinates. We need to test this approach as the next step to derive true spacecraft coordinates from predicted orbit.

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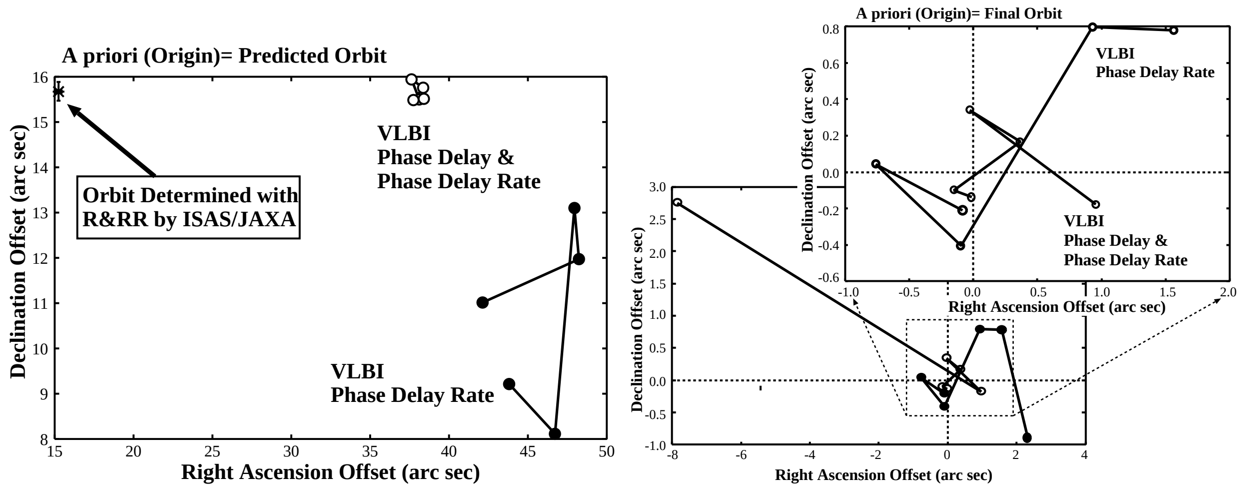

Figure 2: Estimated coordinates of NOZOMI with VLBI data of nz155 VLBI experiment on June 4th 2003. Open circles are results of joint use with phase delay and delay rate data of VLBI observation, and closed circles are estimated coordinates only by phase delay rate data. The lines connecting the circles of VLBI results indicate track of solutions when number of baselines used for the analysis was added in the order of 'UT', 'OT', 'OY', 'OH', 'OK', and 'Uc' one by one. Left panel: Predicted orbit was used for a priori data (origin of the plot). Orbit determined by ISAS/JAXA with R&RR measurements is plotted by black astrisk mark. VLBI solution of only one baseline 'UT' was omitted, since it was out of plot area. Right panel: Orbit determined by R&RR was used for a priori data (origin of the plot).

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