ASTROMETRY OBSERVATION OF SPACECRAFT WITH VERY LONG BASELINE INTERFEROMETRY

- A STEP OF VLBI APPLICATION FOR SPACECRAFT NAVIGATION -

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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 an analysis of the VLBI data for celestial coordinates estimation of the spacecraft in two approaches. One is using group delay measurement, which is free of ambiguity problem, but delay resolution is not so high. The second approach is using phase delay, which 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. For correlation processing and analysis of VLBI data, relativistic VLBI delay model for finite distance radio source was developed, and it is 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. 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 were performed for the spacecraft. 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.

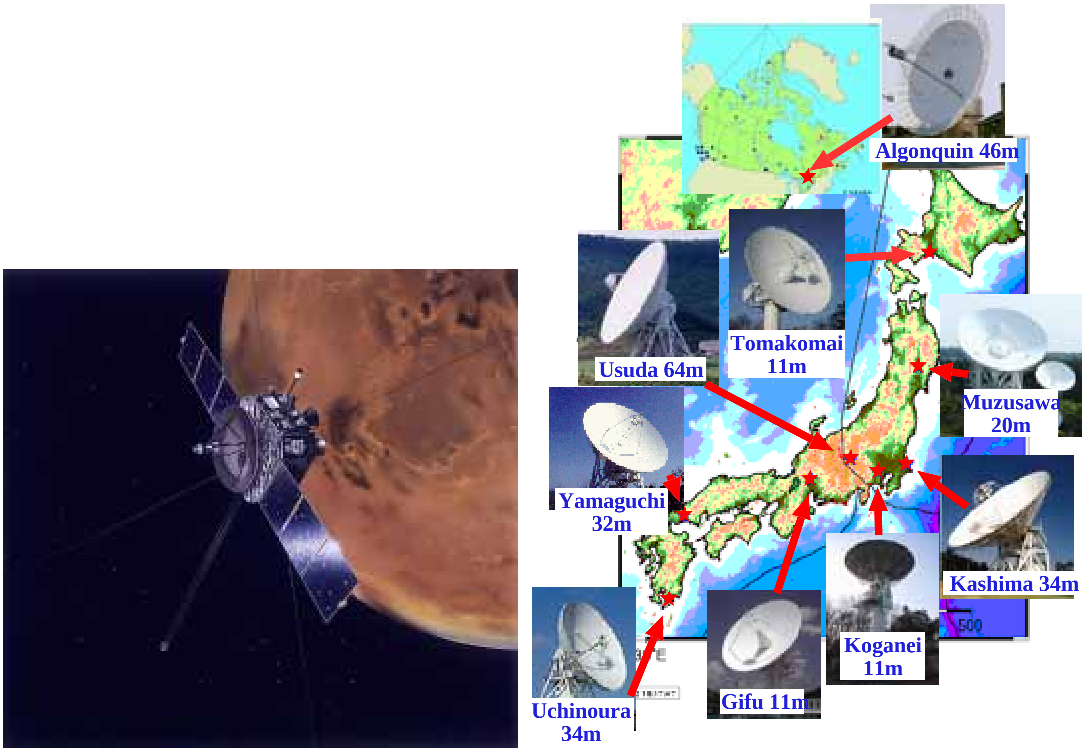

Figure 1: Left:Spacecraft NOZOMI was the first Mars exploration mission of Japanese Space Agency ISAS/JAXA. Right:VLBI stations and antennas participated in the VLBI observations for NOZOMI.

2 VLBI ASTROMETRY OF SPACECRAFT

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 [1], 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 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.

2.1 VLBI NETWORK OBSERVATION OF SPACECRAFT 'NOZOMI'

Spacecraft 'NOZOMI' (left pannel of Fig. 1) is the first Mars exploration mission of the Japanese Space agency ISAS/JAXA. It was launched in July 1998. After some troubles on the spacecraft itself, NOZOMI was planned to changed its orbit to the Mars by two earth swing-bys in December 2002 and in June 2003. There was anxiety of lose of R&RR measurements during the period between the two swing-bys, since the high-gain antenna fixed to the spacecraft did not face to the earth but to the sun to get electricity with its solar paddles. Then orbit determination by support with VLBI observations became important. Besides of those reasons of urgency, orbit determination by joint use of VLBI and R&RR measurements has been planned for more accurate orbit control for future space mission. With help of the request from the ISAS/JAXA for supporting of NOZOMI, a series of VLBI observations have been 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)). Right pannel of Fig. 1 shows the VLBI antennas participated in the VLBI observations for NOZOMI.

2.2 FINITE DISTANCE VLBI DELAY MODEL

VLBI delay model named “consensus model” [1][2] 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 eliminating curvature of wavefront, which have to be taken into account when radio source is closer than 30 light years [3]. Sovers & Jacobs [3] discussed on curvature effect of finite distance radio source. Fukushima [4] 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 [5] 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[6]. Time difference of signal arrival between two VLBI stations measured with time scale on the geoid (TT) is expressed as

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

where $\beta_{02} = \widehat{\vec{\mathbf{R}}}_{02}\cdot\frac{\vec{\mathbf{V}}_2}{c}$, $\vec{\mathbf{K}} = \frac{\vec{\mathbf{R}}_{02}+\vec{\mathbf{R}}_{01}}{R_{02}+R_{01}}$, 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) 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 geocenter 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 precision of less than five pico seconds for the radio source beyond 10^9 m from observer. This VLBI delay model was implemented in modified version of CALC9 (referred as ’CALC9M’) 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[7][8] is a VLBI data acquisition system developed by the NICT with intention to transfer the 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 some points. Firstly the signal from spacecraft is not so wide as that of quasar. Then IP-VLBI sampler is enough at viewpoint of sampling bandwidth and has flexibility to choose the quantization bit up to 8 bit in accordance with the observation requirements. Secondly data stored in hard disk of PC in the form of a binary file can be transfered to correlation center for data processing immediately after the observation. It saves the time and cost of data transportation. Thirdly the data in form of a computer file on HD is appropriate for data processing with software correlator, which has much wider flexibility than hardware correlator. Quasars were also observed at the beginning and end of each VLBI experiments for calibration of clock parameters. And quasar data were sampled in four data channels

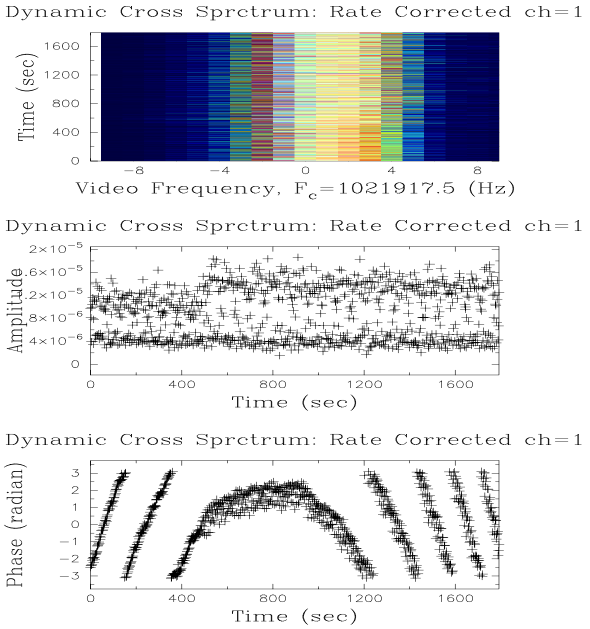

Figure 2: Example of fringe phase extracted from line spectrum correlation. Upper pannel shows contour plot of dynamic cross spectrum beside the main carrier signal. The middle and bottom panels are time line data of correlation amplitude,and fringe phase, respectively.

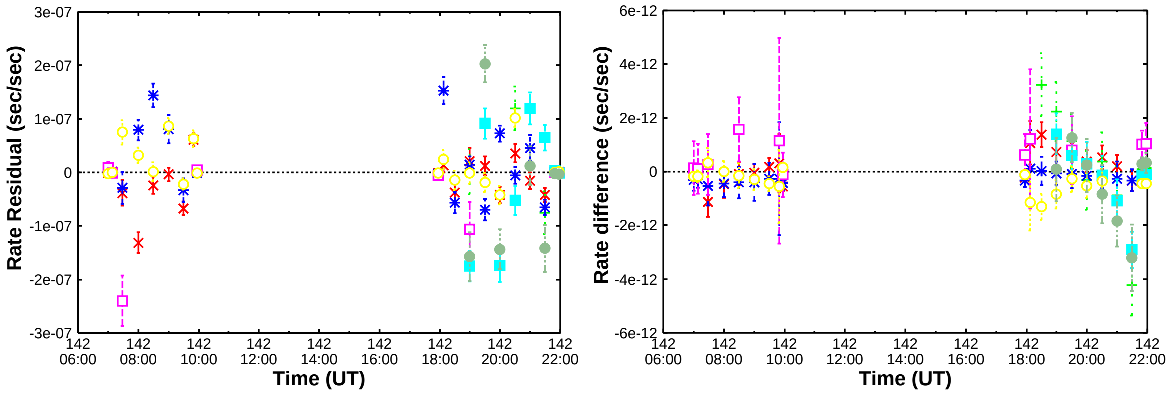

Figure 3: Post fit residual of group delay (left) and delay rate (right) in nz142 (2003/5/22) VLBI experiment. Some Quasars were observed at the beginning and end of sessions.

with two purposes. One is for improving signal to noise ratio (SNR) and the other is to achieve higher delay resolution by using bandwidth (multichannel) synthesis technique[9].

Two sort of software correlator were used to derive group delay and phase delay observables from the data. Group delay was derived by a software correlator, which cross correlates whole bandwidth of the data and derives group delay observable. It was developed for geodetic VLBI for cross correlation of signal from continuum radio source such as quasar.

Since the signal from spacecraft does not have wide band spectrum, but composed from main carrier and some sideband signals separated from the main carrier up to a few Mega Hertz even in case of modulated signal like telemetry and range signal. So correlation processing with narrow bandwidth around the radio frequency of main carrier is good way to get higher signal to noise ratio (SNR) of phase delay observable. Otherwise SNR is smeared by system noise contributed from frequency band where signal from spacecraft is absent. We have developed a correlation software to extract fringe phase from line spectrum data. Fig. 2 shows an example of line spectrum correlation output.

Spacecraft astrometry analysis described here is based on standard linear least square parameter estimation of small-signal analysis. When residual of observed data (O) minus computed value (C) is modeled by a first order Taylor expansion of the observation model function $\vec{\mathbf{f}}(\vec{\mathbf{x}})$ in terms of parameter set $\vec{\mathbf{x}}$ around the a priori parameter set $\vec{\mathbf{x}}_0$ as

$$O - C = \left.\frac{\partial \vec{\mathbf{f}}(\vec{\mathbf{x}})}{\partial \vec{\mathbf{x}}}\right|_{\vec{\mathbf{x}}=\vec{\mathbf{x}}_0} \cdot \Delta\vec{\mathbf{x}}. \tag{2}$$

By using equation (2) as observation equation, parameter set $\Delta\vec{\mathbf{x}}$ can be estimated by weighted least square method. Estimated parameters besides right ascension and declination of the spacecraft were clock offsets, clock rates, thickness of zenith dry atmosphere and its rates at each stations.

3.1 GROUP DELAY

Post-fit-residual-plots of group delay and delay rate of VLBI observation of NOZOMI are displayed in figure 3. The post fit residuals of group delay was scattered in range of several tens of nano seconds. 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 of the spacecraft. Spacecraft coordinates have been obtained from the analysis, however detail of the group delay results is skipped in this paper. Because the accuracy of estimated coordinates did not reach to the level of requirement (1 micro radians) mainly due to low delay resolution. We may need to revise correlation processing to improve the delay resolution and SNR. The SNR can be improved if the transmitted sinal patterns are known and the correlation is taken between data and the signal pattern.

3.2 PHASE DELAY

The main problem of dealing with phase delay is the ambiguity $2\pi n$, 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. Actually, we observed the spacecraft NOZOMI continuously for a long time (from several hours up to 24 hours) in the series of VLBI experiments.

Derivative of phase delay with time (delay rate) is also independent observable in free of the ambiguity. We have tracked the spacecraft for a long time in VLBI observation and from 5 to 30 minutes duration of observation data were stored in a file as one scan. Since the interval between a scan to the next scan was about 10 second or so, fringe phase data derived by correlation processing were connected easily as far as fringes were detected with enough SNR. After the phase connection procedure, data were smoothly approximated by 4th order of polynomial at every 400 seconds intervals, and delay rates were commutated by using the analytical derivative of the polynomial. Then we used these phase delay and phase delay rate for spacecraft coordinates analysis. Fig. 4 shows an example of closure of phase delay among Kashima, Usuda, and Tsukuba stations. It demonstrates that 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 pico seconds. That is about 3 order of precision improvement from group delay measurements.

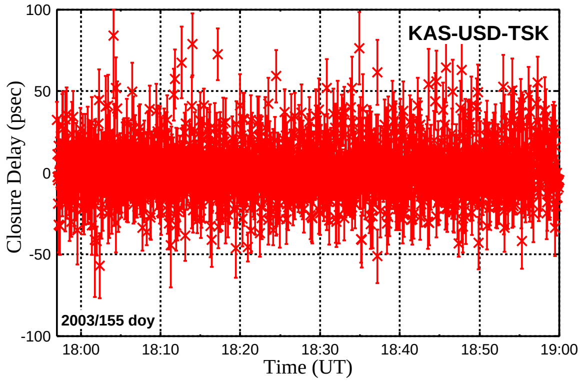

Figure 4: Closure of phase delay among Kashima, Usuda, and Tsukuba stations.

Post-fit residual of phase delay and phase delay rate were compared for two cases where predicted orbit and determined orbit by R&RR were used for a priori data in Fig. 5. In the case where predicted orbit is used for a priori data (left panels in Fig. 5), systematic trends are remain in the residual plot, especially in phase delay rate of long baseline (data of Usuda-Algonquin baseline are plotted yellow open circles). When determined orbit by R&RR is used for a priori data (right panels of Fig. 5), no large systematic trends are seen in residual plots. The small magnitude of behaviour in delay residual plot may be due to change of propagation path length of atmosphere. Since atmospheric delay is modeled simply by offset and rate at one epoch for more than 24 hours of experiment duration, it is natural that more than second order of delay change in order of several hundreds of pico seconds remain in the delay residual. Fig. 6 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 (Red colored plot) and only delay rate (refered as R) was used as the other case (blue colored 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 pannel, 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.

The reason why VLBI solution with predicted orbit does not give correct answer may be understood as follows: True coordinates of spacecraft is more than 10 arc second away from the predicted orbit as seen in Fig. 6. 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 VLBI observation for natural radio sources. However, this order of deviataion of predicted orbit from true coordinates must be inevitable in VLBI application for spacecraft navigation. And we need to estimate true coordinates of spacecraft from the predicted orbit.

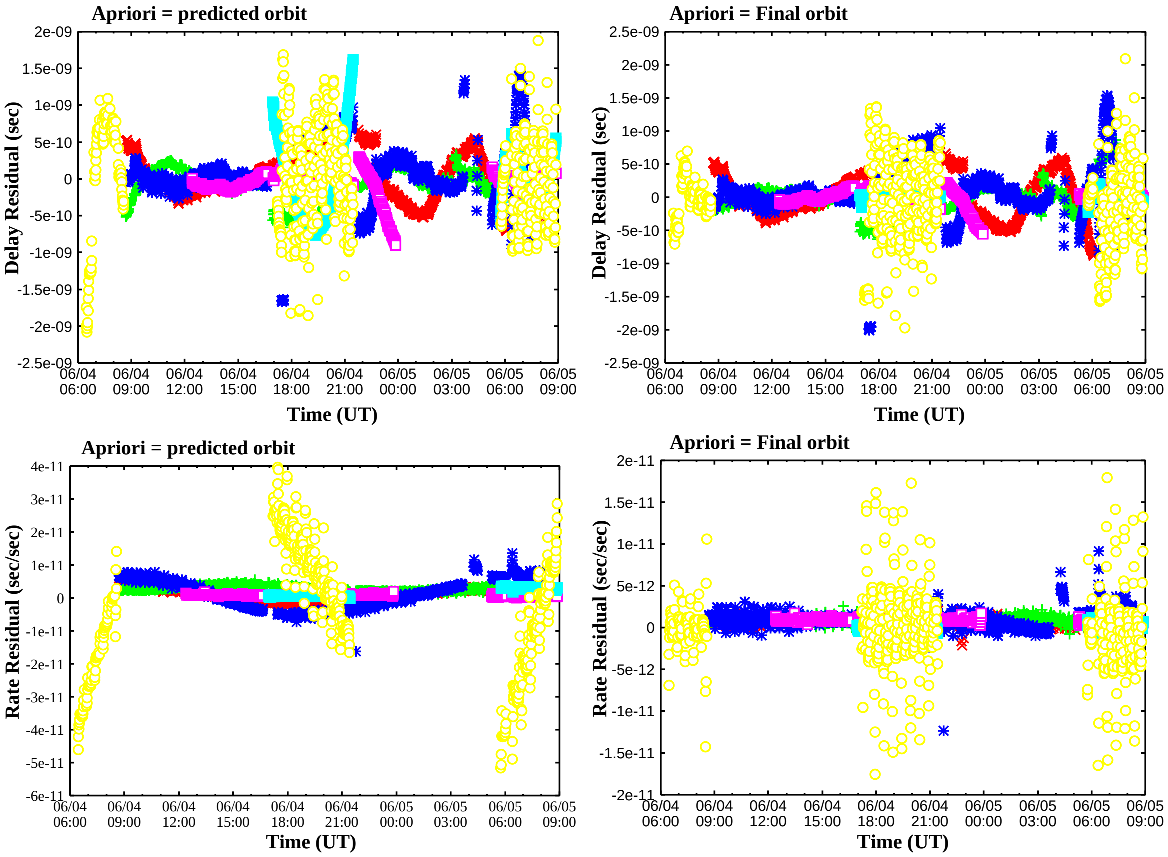

Figure 5: Post-fit residuals of phase delay (upper panels) and phase delay rate (lower panels) in nz155 VLBI experiments on June 4th 2003. Baselines used for analysis were UT, OT, OY, OH, OK, and Uc, where 'U', 'O', 'T', 'Y', 'H', 'K', and 'c' are Usuda 64m, Kashima 34m, Tsukuba 32m, Gifu 11m, Tomakomai 11m, Yamaguchi 32m, and Algonquin 46m, respectively. Two panels in left hand side are result when predicted orbit was used as a priori coordinates of spacecraft. Those in right hand side are in the case that determined orbit by R&RR were used for a priori data.

If our estiamte on the reason why VLBI solutions using predicted orbit did not give correct answer is right, we may be able to approch to the true spacecraft coordinates by means of non-linear least square method: (1)Solving radio source coordinates with least square method starting from predicted orbit. (2)Updating a priori radio source coordinate with the solution of (1). (3)Solving radio source coordinates by least square method by using updated source coordinates as a priori data. Iterative computation of (2) and (3) 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.

4 SUMMARY

We are investigating utilization of both group delay and phase delay of VLBI observation for spacecraft navigation. For this project, we developed an relativistic VLBI delay model for finite distance radio source in the similar form with the consensus model. The model was implemented to a priori computation software CALC9M, and has been used for correlation and data analysis. A series of VLBI observations was made for spacecraft NOZOMI under wide collaboration among Japanese VLBI community and Canadian observatory. Data were taken by PC-based system and processed by software correlators. Least square analysis package, which was newly developed for this project, was used for group delay and phase delay analysis. Due to low delay resolution of group delay, spacecraft coordinates solution at the level of requirement is not derived with group delay yet. Making use of phase delay enables 3-4 order of delay reolution improvement and may give a possibility of VLBI

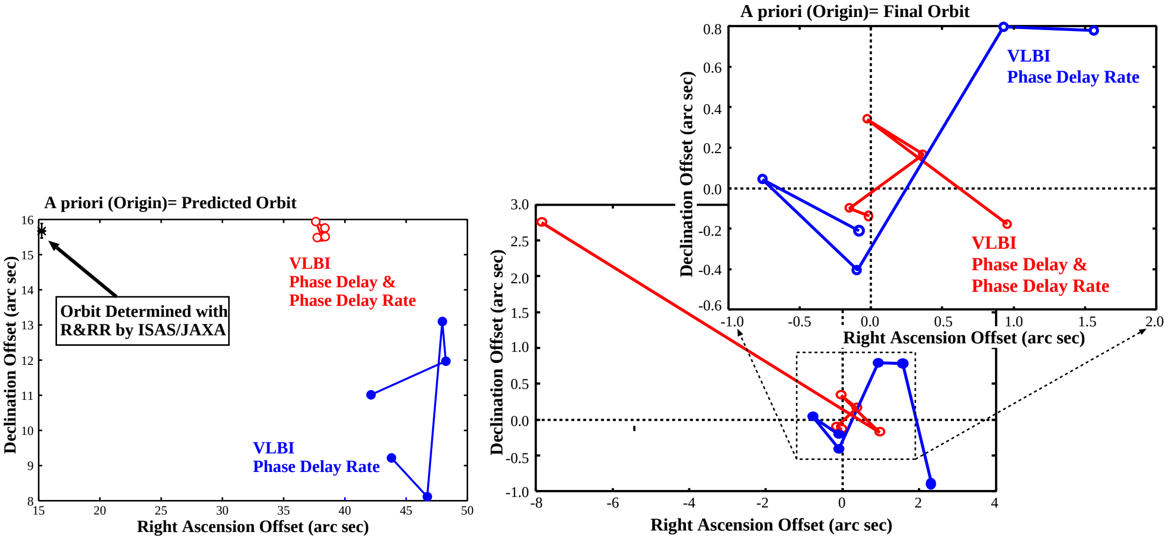

Figure 6: Estimated coordinates of NOZOMI with VLBI data of nz155 VLBI experiment on June 4th 2003. Red open circles are results of joint use with phase delay and delay rate data of VLBI observation, and closed blue circles are estimated coordinates only by phase delay rate data. The lines connecting the circles of VLBI results indicate track of solutions when number of baselines used for the analysis was increased in the order of 'UT', 'OT', 'OY', 'OH', 'OK', and 'Uc' one by one. Left: 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: Orbit determined by R&RR was used for a priori data (origin of the plot).

spacecraft navigation only with Japanese domestic baseline instead of using group delay with intercontinental baseline. We have succesfully estimated spacecraft cooridnates with phase delay and delay rate observables, when determined ornbit by R&RR was used for a priori spacecraft coordinates. When predicted orbit is used as a priori data, however the solution did not converg as increasing number of baselines and two sort (D&R and R) of solutions were not consistent each other. We guess the cause of this probrem would be come from non-liniarity of observables which cannot be modeled by 1st order approximation. If this interpretation is correct, estimation of radio source coordinates will be possible with non-linear least square method.

5 ACKNOWLEDGMENTS

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