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VLBI Application for Spacecraft Navigation (NOZOMI) Part I – Overview –

ICHIKAWA, R.[1] (*richi@crl.go.jp*), **SEKIDO, M.**[1], **OSAKI, H.**[1], **KOYAMA, Y.**[1], **KONDO, T.**[1], **and NOZOMI VLBI group**[2]

[1] *Kashima Space Research Center Communications Research Laboratory 893-1 Hirai, Kashima, Ibaraki 314-8501, Japan*
[2] *ISAS, NAO, GSI, NASDA, Gifu Univ., Yamaguchi Univ., Hokkaido Univ., and SGL/CRESTech*

Precise spacecraft positions can be obtained with differential spacecraft-quasar VLBI observations that directly measure the angular position of the spacecraft relative to nearby quasars. We performed more than 30 VLBI experiments for the NOZOMI spacecraft navigation from September 2002 until June 2003. NOZOMI, which means "Hope" in Japanese, is the Japan's first Mars probe developed and launched by the Institute of Space and Astronautical Science (ISAS) (see Figure 1). NOZOMI was originally scheduled to reach its destination in October 1998, but an earlier Earth swingby failed to give it sufficient speed, forcing a drastic rescheduling of its flight plan. According to the new trajectory strategy, NOZOMI's arrival at Mars is scheduled early in 2004 through two additional earth swingbys in December 2002 and June 2003 as shown in Figure 2 [*ISAS web site*, 2002].

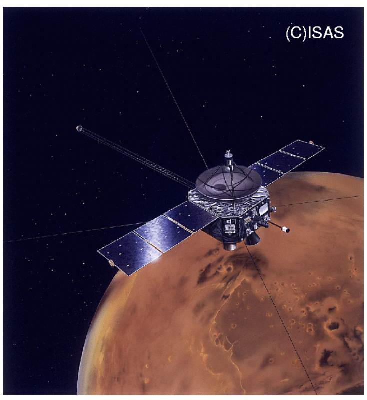

Figure 1. NOZOMI image.

Our main concern was to determine the NOZOMI orbit just before the second earth swingby on June 19, 2003. It was significantly important to get the timing to maneuver the NOZOMI before the swingby. ISAS scientists were afraid that the range and range rate (R&RR) orbit determination might not be available because it was difficult to point the high-gain antenna mounted the spacecraft toward the earth during the period between two swingby events. So we started to support the orbit determination of the NOZOMI using VLBI technique since September 2002. These experiments are also aimed to establish the positioning technology for the interplanetary spacecrafts in realtime.

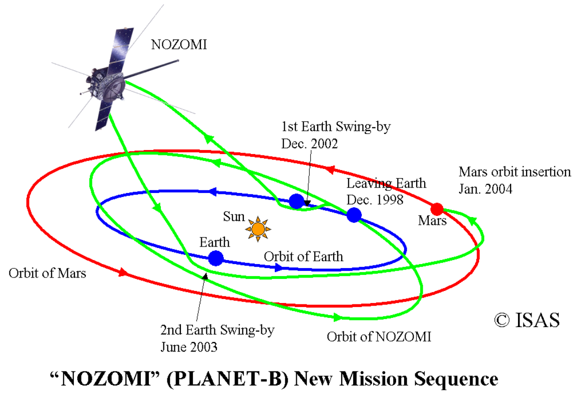

Figure 2. NOZOMI mission sequence toward Mars.

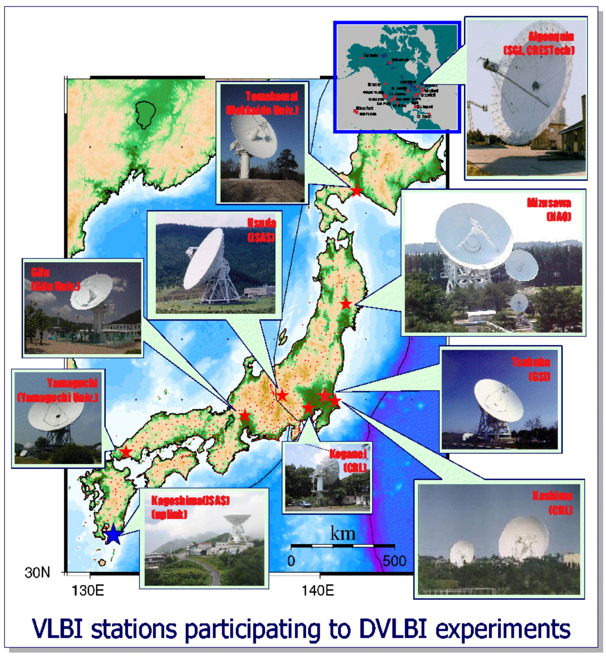

Figure 3. VLBI stations participating to NOZOMI experiments.

We use nine VLBI antennas in Japan to carry out the NOZOMI VLBI experiments at X-band.

Algonquin 46-m antenna operated by Natural Resource Canada and the Space Geodynamics Laboratory (SGL) of the CRESTech also participated in the several experiments. The VLBI stations are shown in Figure 3. In each experiment, several quasar VLBI obsevables are obtained in conjunction with NOZOMI VLBI observations in order to determine the clock offset. We equipped the state of the art "K5 VLBI system" to these stations. The K5 system is the multiple PC-based VLBI system equipped with a PCI-bus Versatile Scientific Sampling Processor (VSSP) board on the FreeBSD and Linux operating system [*Osaki,* 2002; *Kondo et al.,* 2002]. The K5 system includes the original software packages which are data sampling and acquisition, real-time IP data transmission, and correlation analysis. For the purpose of analyzing the VLBI observables we are developing the specific VLBI delay model for finite distance radio source [*Sekido and Fukushima,* 2003; *Sekido et al.,* 2003]. The model is already implemented in the VLBI software package. The package will include the VLBI observation scheduling to take account of the passage of the spacecraft near the quasar line of sight and the propagation delay estimating for the ionosphere and the neutral atmosphere.

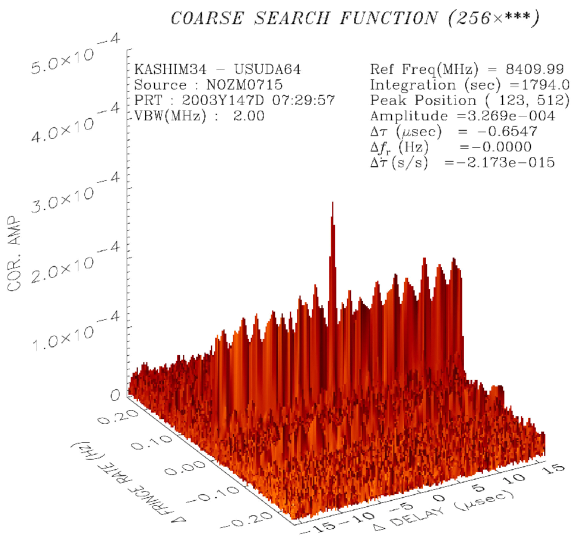

Figure 4. Detected fringe of NOZOMI range signal.

We could successfully detect fringes of NOZOMI range signal for several baselines using software correlation in spite of weak and narrow-bandwidth signal. An example of NOZOMI fringe is shown in Figure 4. We provided 15 VLBI group delay data sets to ISAS to support the orbit determination at the end of May 2003. On the other hand, ISAS scientists have fortunately succeeded to determine the NOZOMI orbit using R&RR observables at the end of May 2003. Preliminary results demonstrate that the VLBI delay residuals are consistent with R&RR observables. However, the rms scatter between them are relatively large up to several tens nanoseconds. We are now evaluating our VLBI data sets in more detail by comparing with the R&RR results.

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VLBI Application for Spacecraft Navigation (NOZOMI) Part II – Delay Model and Analysis –

Mamoru Sekido (*sekido@crl.go.jp*),
Ryuichi Ichikawa, Hiro Osaki,
Tetsuro Kondo, and Yasuhiro Koyama

Kashima Space Research Center
Communications Research Laboratory
893-1 Hirai, Kashima, Ibaraki 314-8501, Japan

1. Introduction

VLBI is one of the most precise technology to measure angular distance in the celestial sphere. It is not only tool for astronomy but also is quite useful in engineering application such as spacecraft navigation. VLBI is good at measurement in coordinates perpendicular to the line of sight. It has complementary sensitivity with that of range and range rate (R&RR) measurement, which is commonly used for spacecraft navigation in deep space. Thus a combined analysis is expected to increase accuracy of orbit determination of spacecraft.

Pioneering work in spacecraft navigation with VLBI has been performed by JPL [*Border et al.,* 1982] with group delay (Delta Differential One way Range). Institute of Space and Astronautical Science (ISAS) in Japan and CRL is collaborating to use VLBI for Japanese space mission. A spacecraft NOZOMI launched by ISAS was going to do two earth swingbys in the period of December 2002 and June 2003 [*Yoshikawa et al.,* 2001]. And a request for support the orbit determination with VLBI data arose. Orbit determination of NOZOMI has been performed by the ISAS and we provided VLBI data delay for supporting their work. On the other hand, our group is planning to develop a tool for spacecraft navigation with VLBI independently from the ISAS. Here we introduce some points in data reduction and analysis procedure of spacecraft coordinates estimation.

2. VLBI Delay Model for Finite Distance Radio Source

The standard VLBI delay model so called 'consensus model' [*Eubanks,* 1991] uses plane wave approximation based on a assumption that a radio source is at infinite distance from observer. When the distance is less than 30 light years, however, curvature of wavefront of the signal from radio source is not negligible as pointed out by Sovers and Jcobs [*Sovers and Jacobs,* 1996]. They and Fukushima [*Fukushima,* 1994] argued about finite distance VLBI model, but an expression including coordinates transformation of general relativity have not been given. Sekido and Fukushima [*Sekido and Fukushima,* 2003] have derived a expression of VLBI delay for finite distance radio source corresponding to the 'consensus model' by taking into account relativistic effects. That form is

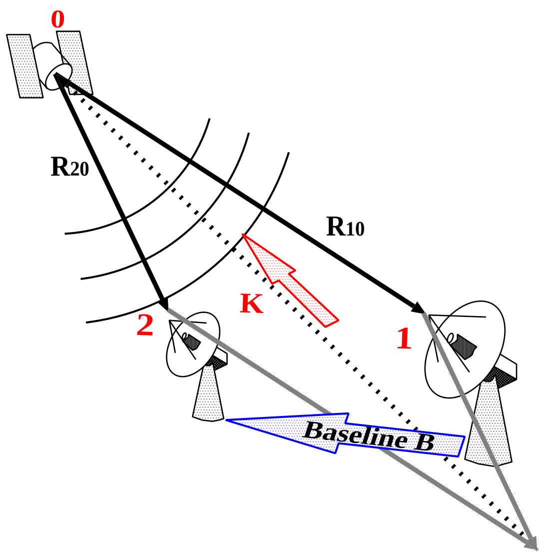

Figure 1. Schematic diagram of pseudo source vector $\vec{\mathbf{K}}$. The vector $\vec{\mathbf{K}}$ is on the diagonal line of parallelogram composed from vector $\vec{\mathbf{R}}_{10}$ and $\vec{\mathbf{R}}_{20}$.

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

where valuable in large capital indicates quantity in barycentric reference frame and that in small capital is that of geocentric frame. $\vec{\mathbf{R}}_{ij} = \vec{\mathbf{X}}_i - \vec{\mathbf{X}}_j$ and $\vec{\mathbf{X}}_i$ is position vector in barycentric reference frame. Suffix 0,1, and 2 respectively indicate radio source, station 1, and 2. $\vec{\mathbf{b}}$ is baseline vector on the geoid, $\vec{\mathbf{V}}_e$ and $\vec{\mathbf{w}}_2$ are barycentric velocity of geocenter and geocentric velocity of station 2, respectively. And pseudo source vector $\vec{\mathbf{K}}$ and parameter β_{20} are defined as :

$$\beta_{02} = \hat{\vec{\mathbf{R}}}_{02}\cdot\frac{\vec{\mathbf{V}}_2}{c} \quad (2)$$

$$\hat{\vec{\mathbf{R}}}_{02} = \frac{\vec{\mathbf{R}}_{02}}{R_{02}} \quad (3)$$

$$\vec{\mathbf{K}} = \frac{\vec{\mathbf{R}}_{02}(T_1) + \vec{\mathbf{R}}_{01}(T_1)}{R_{02}(T_1) + R_{01}(T_1)}. \quad (4)$$

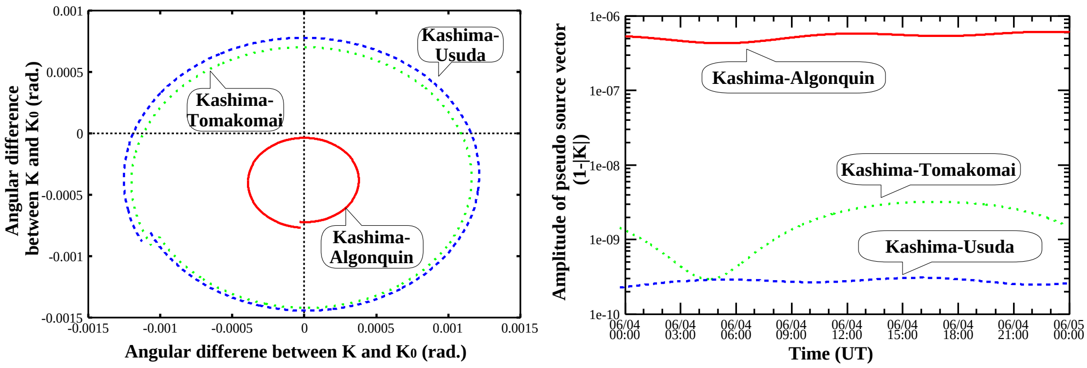

Figure 2. Behavior of pseudo source vector $\vec{\mathbf{K}}$ *in comparison with geocentric source unit vector* $\vec{\mathbf{K}}_0$*. Left panel shows changes of the direction of* $\vec{\mathbf{K}}$ *vector during 24 hours. The origin of the plot is the direction of* $\vec{\mathbf{K}}_0$ *vector. Right panel shows change of the magnitude of* $\vec{\mathbf{K}}$ *vector. Three lines on both two panels correspond to Kashima-Algonquin, Kashima-Tomakomai, and Kashima-Usuda baselines. Predicted orbit of NOZOMI on 4th-5th June 2003 was used for computation of the vectors here. Distance to the NOZOMI was* $4. \times 10^9$ *m from the geocenter in this period.*

The formula of (1) is very similar with that of 'consensus model' and both formulae become identical when the radio source is at infinite distance from observer. In this sense, our formula (1) will be regarded as expansion of 'consensus model'. The main difference between them comes from definition of source vector $\vec{\mathbf{K}}$. Actually, that vector must be called as pseudo source vector, and is neither unit vector nor constant vector as defined in equation (4). The schematic view of pseudo source vector $\vec{\mathbf{K}}$ is displayed in Figure 1. It changes the magnitude and direction with baselines and with time. Figure 2 demonstrate the behavior of $\vec{\mathbf{K}}$ vector during 24 hours in comparison with geocentric source vector to the spacecraft (NOZOMI) on Kashima-Algonquin (9109 km), Kashima-Tomakomai (750 km), and Kashima-Usuda (208 km) baselines. The $\vec{\mathbf{K}}$ vector was computed with based on predicted coordinates of NOZOMI in 4th-5th June 2003. Left panel in the figure shows deviation of the pseudo source vector from the direction to the source from geocenter. The deviation is larger as baseline is shorter. It is because parallax affect more directly to $\vec{\mathbf{K}}$ vector on shorter baseline. Since the NOZOMI is moving, the track of the vectors are not closed curves in 24 hours. Right panel indicate magnitude of the vector $\vec{\mathbf{K}}$. In contrast to the direction of $\vec{\mathbf{K}}$ vector, the magnitude deviates from unity more significantly as baseline becomes longer. Since the (pseudo) source vector affects directly to VLBI delay, change of its direction and magnitude cause change of delay in the same order. We implemented this model in our software by modification of CALC ver.9. Apriori delay, delay rate, and partial derivatives computed by this software was used in correlation processing and astrometric analysis of the spacecraft.

3. Correlation Processing and Difference from Normal VLBI

Observation and correlation processing of the VLBI data has been performed with PC-based system [*Osaki,* 2002; *Kondo et al.,* 2002]. We are seeking for better approach in both group delay and phase delay. In case of group delay, we used range signal to measure group delay for NOZOMI. Since the bandwidth of signal from the spacecraft is in order of 1 MHz when it is modulated, the delay resolution of group delay is in order of one nano second. To increase the spatial resolution of VLBI observation, we have asked to Algonquin observatory to join NOZOMI observations sometimes besides Japanese domestic VLBI stations [*Ichikawa et al.,* 2003]. The delay model for spacecraft is different from normal VLBI observation even on domestic baseline in Japan, since the radio source changes its position in the celestial sphere during observation. Moreover curvature of wave front affect significantly to the delay especially in intercontinental baseline. Figure 3 shows the delay rate derived from observation data and that of VLBI delay model of equation (1). We used following way to get continuous fringe rate for comparison here. We observed NOZOMI for almost 24 hours in the experiment of 4 June. Frequency of tone signal from NOZOMI was extracted every 2 seconds with 1 Hz resolution from observed 2bit-4MHz sampling VLBI data of each station via Fast-Fourier Trans-

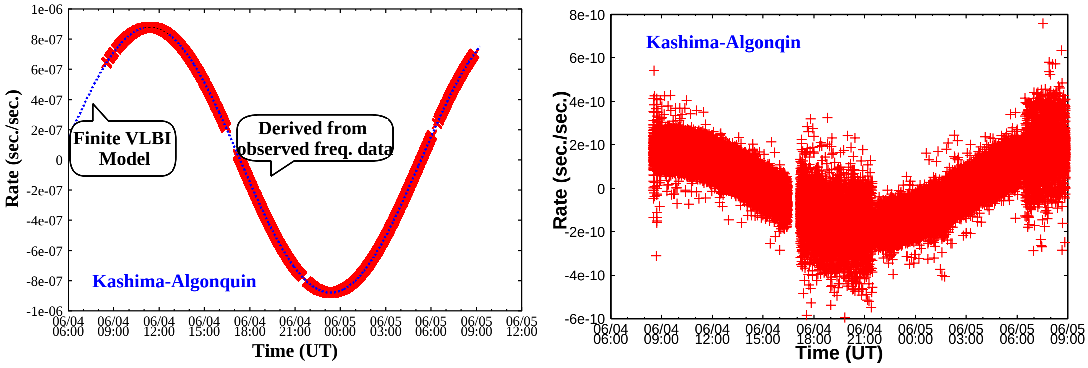

Figure 3. Delay rate derived from Doppler frequency (left) and Residual of delay rate(right) on Kashima-Algonquin baseline. In the left panel, $\times$ *mark indicates derived delay rates and broken line indicate VLBI delay model of finite distance radio source. Plot in the right panel indicates residual of (observed) - (delay rate model).*

form (FFT). Then delay rate including clock rates of VLBI stations was derived by a relation

$$\frac{d\tau}{dt} = \frac{f_x - f_y}{f_x}, \tag{5}$$

where f_x, and f_y is frequency of tone signal of NOZOMI observed at x and y station. Plot in Figure 3 scattered in range of $\pm 10^{-10}$ (sec/sec) because precision of frequency measurement was 1 Hz, then resolution of delay rate measurement here was 1(Hz)/8.4 (GHz) $\sim 1.2 \times 10^{-10}$. This order of delay rate resolution was not enough to compare rate residual precisely, but increasing the frequency resolution was limited due to some technical reasons (Number of FFT points, drifting frequency with time, and etc...). Delay rate resolution is low though number of data points is huge, so we can clearly recognize large systematic change of residual in Figure 3. It indicates apriori delay rate is not accurate enough, and consequently fringe rotates more than 1 turn in integration period (1 second was normal integration time in correlation process here). We think main reason of the rate residual may comes from difference between predicted coordinates and true ones of NOZOMI. Generally, this sort of error in predicted coordinates is supposed to be usual in also other spacecraft observation. Thus we need to establish stable procedure to detect fringe by searching wide range of fringe rate. One solution will be enlargement of rate window via decreasing integration period. Although increase of file size of intermediate correlation output (several tens of Mega Bytes to a few Giga Bytes per file) will accompany with it. The other solution will be searching fringe by repetition of correlation processing with changing rate parameter.

4. Analysis Software for Finite VLBI Astrometry

Observed VLBI delay data set obtained in series of NOZOMI VLBI observations [*Ichikawa et al.,* 2003] were submitted to ISAS for orbit determination analysis with joint data set with R&RR data. Independently from ISAS, we have been constructing our own software for coordinates estimation of spacecraft. Our analysis system is composed from two parts: precise apriori and partial derivative computation package 'calc_skd' and least square analysis package 'lsq_src', as similar with CALC/SOLVE system. We wanted to make platform independent system rather than using Mark-III database binded with HP computer, so most of the data used in the analysis are in form of ASCII text files. We may use PIVEX format [1] [*Gontier and Feissel,* 2002] as data system in future. The CALC version 9 was used as base to implement finite VLBI delay model. The analysis system runs on FreeBSD PC-unix system. The calc_skd computes apriori delay/rate and partials by following a file of scan list and with using a set of parameter files (planetary ephemeris DE405/DE406, EOP, and etc...) as the same with the CALC/SOLVE. The lsq_src is a simple multi-baseline least square analysis software with minimum functions. It use observed delay/rate, apriori delay/rate, partials, and constraints for estimating a subset of the parameters (source coordinates, proper motion, clock offset/rate, dry atmospheric zenith delay/rate, delay gradient of dry atmosphere, wet atmospheric zenith delay/rate). Since spacecraft may move rapidly on the celestial sphere, proper motion of the radio source may be included in estimation pa-

[1] http://lareg.ensg.ign.fr/feissel/pivex.html

rameters.

5. Summary

We are investigating a VLBI technique for application of spacecraft navigation. As a first step, we have developed a finite VLBI delay expression with taken into account relativistic effects, and are developing analysis software packages. We will be able to report more detailed result of the analysis in future issue.

Acknowledgement: We thank members of the NOZOMI VLBI observation working group in Japan and W.Cannon, B. Mario, and S. Novikov for supporting series of VLBI observation for NOZOMI. We also thank VLBI group of Goddard/NASA for providing us CALC 9 package and permission of modification.

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Kashima 34m radio-telescope annual maintenance (*cont. from page 4*)

Photo. 34m telescope and a crane truck. Elevation motors are removed and sent back to the factory for overhawl. *(see topics on page 4 for details)*

TECHNOLOGY DEVELOPMENT CENTER NEWS

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Evaluation of the K5 system in geodetic VLBI experiments

Yasuhiro Koyama[1] (*koyama@crl.go.jp*), **Tetsuro Kondo**[1], **Hiro Osaki**[1], **Kazuhiro Takashima**[2], **Kazuo Sorai**[3], **Hiroshi Takaba**[4], and **Kenta Fujisawa**[5]

[1] *Kashima Space Research Center Communications Research Laboratory 893-1 Hirai, Kashima, Ibaraki 314-8501, Japan*
[2] *Geographical Survey Institute*
[3] *Hokkaido University*
[4] *Gifu University*
[5] *Yamaguchi University*

1. Introduction

After the prototype models of the K5 VLBI system were developed, the systems are beginning to be used for various VLBI observations such as the precise orbit determination of the spacecrafts Nozomi and Geotail [Kondo, et al., 2002; Ichikawa, et al., 2003; Sekido, et al., 2003] and the demonstration of international e-VLBI observations through close cooperations with Haystack Observatory [Koyama, et al., 2003]. Therefore, it is very important to ensure that there is no problem with the performance of the K5 VLBI system by comparing the results from the K5 VLBI system with the results from the conventional VLBI systems such as the K4 VLBI system. For this purpose, two geodetic VLBI sessions were carried out to evaluate the performance and functions of the K5 VLBI system. The first session was performed for about 24 hours from January 31, 2003 by using Kashima34-Koganei baseline. The second experiment was performed for about 24 hours from July 14, 2003 by using five VLBI stations at Kashima (34m), Tsukuba (32m), Tomakomai (11m), Gifu (11m), and Yamaguchi (32m). The details and results of these experiments will be reported in this paper.

2. K5 VLBI system

The K5 VLBI system is designed to perform real-time or near-real-time VLBI observations and correlation processing using Internet Protocol over commonly used shared network lines. Various components are being developed to realize the target goal in various sampling modes and speeds. The entire system will cover various combination of sampling rates, number of channels, and number of sampling bits by selecting subset of the available systems shown in Figure 1. For observations with low data sampling rates, the output signal of the base-band converters are sampled with the IP-VLBI board and the sampled data are directly processed with the PC system to which the IP-VLBI board is installed.

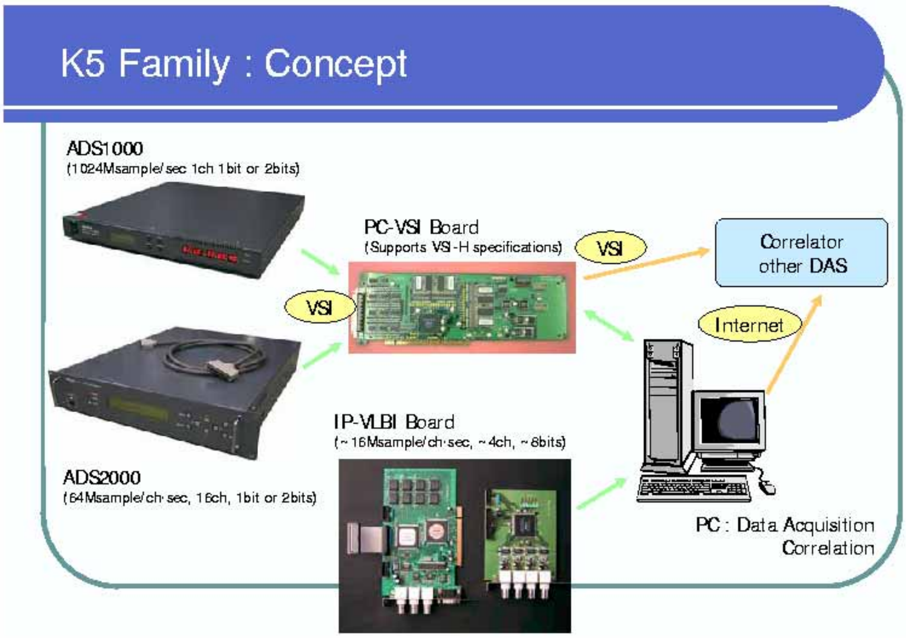

Figure 1. Concept of the entire K5 System.

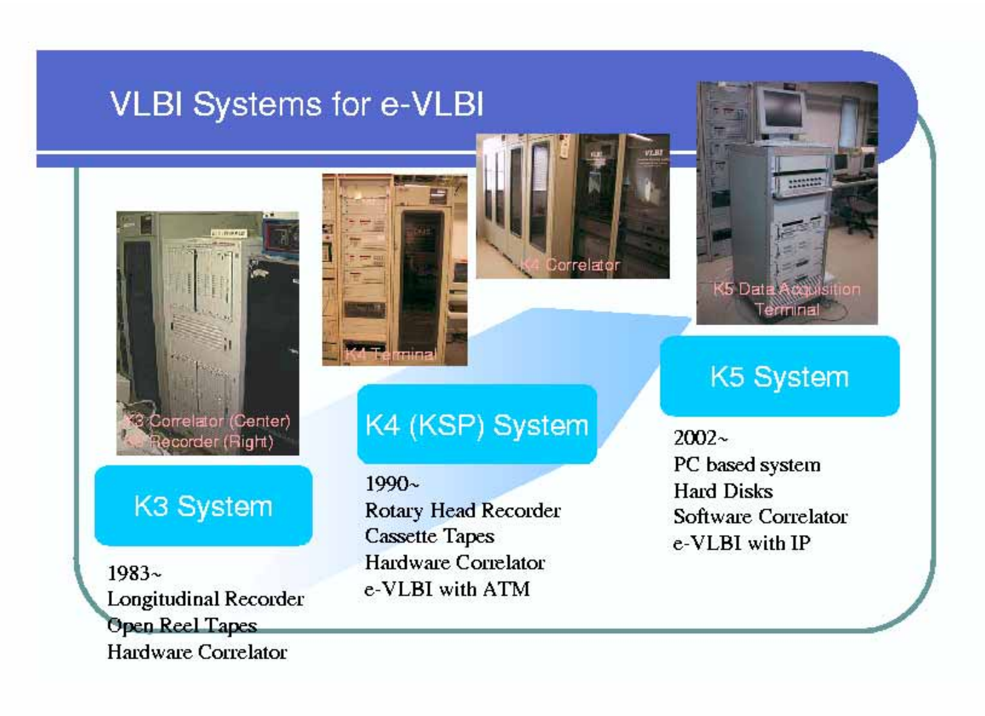

Figure 2. Developments of K3, K4 and K5 VLBI systems.

All the conventional geodetic VLBI modes of total data rate up to 512 Mbps with 16 channels are covered with this configuration. For a single wide frequency band (512 MHz) observations, ADS1000 data sampler unit is used as an A/D sampler and the sampled digital data are transferred to the PC system through VSI-H (VLBI Standard Interface - Hardware) interface with the PC-VSI board. ADS2000 data sampler unit is used for 16 channel observations with the total data rate of 1024 Mbps with 1 bit sampling mode or 2048 Mbps with 2 bits sampling mode. The sampled digital data from ADS2000 are also transferred to the PC system through VSI-H interface with the PC-VSI board. The same PC-VSI board will support data output function from the PC systems. Both IP-VLBI board and PC-VSI board is installed in the PCI (Peripheral Component Interconnect) bus of the PC systems.

As shown in the Figure 1, the K5 system is characterized by the use of conventional PC systems and the shared network based on IP (Internet Protocol). The data correlation can be performed by hardware correlators which support VSI-H specifications, but the target will be to perform correlation processing by the PC systems using software correlator programs. Similarly, the K4 system can be characterized by the use of rotary-head, cassette type magnetic tape recorders and the dedicated network based on ATM (Asynchronous Transfer Mode). Similarly, the K3 system can be characterized by the use of open-reel magnetic tape recorders (Figure 2).

The name of the K5 system is frequently used for the Versatile Scientific Sampling Processor (VSSP) system which is designed for geodetic VLBI sessions. Figure 3 shows the picture of the prototype system of the VSSP. It is consist of four UNIX PC systems. Each UNIX PC system has one IP-VLBI data sampling board, or also called as a VSSP board, on its PCI interfacing bus. Table 1 lists the specifications of the board. The board can sample 4 channels of base-band signals at various sampling rates ranging from 40kHz to 16MHz. The timing of the sampling is controlled by the provided 10MHz and 1-PPS reference signals so that precise timing information can be reproduced from the sampled data. Quantization bits can be set from 1, 2, 4, and 8. Because the board has these many sampling modes, it has many possibilities to be used not only for VLBI observations but also for various other scientific researches which require precise timing information in the data. Device driver software of the board has been developed on LINUX, FreeBSD, and Windows2000 operating systems, and FreeBSD is used in the prototype K5 data acquisition terminals. Two prototype K5 data acquisition systems have been configured. Four PC systems are mounted in the lower part of the 19-inch standard rack. A signal distributor unit for 1-PPS and 10 MHz signals and 16-channel base-band signal variable amplifier unit are mounted in the upper part of the rack. The monitor and the key-board on the top of the rack are connected to the four PC systems by using a four-way switch. Each PC system is equipped with four removable hard disk drives of the data capacity of 120 GBytes each. The sampled data can be transferred to the network by using TCP/IP protocol or can be recorded to internal hard disks as ordinary data files. The maximum recording speed is currently restricted by the speed of the CPU and the speed of the PCI internal bus. Currently, the total recording speed of 512 Mbps has been achieved. It can be expected to record data up to 1024 Mbps by using faster PCI bus and faster CPU in near future. To process the data sampled with the K5 data acquisition system, software correlation processing program is also under development on FreeBSD and Linux PC systems. The correlation processing program receives data from K5 data acquisition systems over the network using TCP/IP protocol and then calculates cross correlation functions in real-time. It can also read data files on internal hard disks. These capabilities allow to transfer observed data in real-time if the connecting network is fast enough, or in near real-time if data buffering is required. Since easily re-writable software programs and general PC systems are used, the processing capacity and the function of the correlator can be easily expanded and upgraded.

Table 1. Specifications of the IP-VLBI (VSSP) board.

Reference Signals	10 MHz (+10 dBm) and 1-PPS
Number of Input Ch.	1 or 4
A/D bits	1, 2, 4, or 8
Sampling Freq.	40 kHz, 100 kHz, 200 kHz, 500 kHz, 1 MHz, 2 MHz, 4 MHz, 8 MHz, or 16 MHz
Bus Interface	PCI
Operating System	FreeBSD, LINUX, or Windows2000

3. Experiments

After completing two prototype K5 VLBI data acquisition terminals, 24 hours of geodetic e-VLBI experiment was performed using two 11-m antennas at Kashima and Koganei from January 31 to February 1, 2003. Eight channels were assigned to both X-band and S-band and the total data rate was 64 Mbps. Observed data were stored in the internal hard disks as the data files. The data files were read by the software correlation program and the cross correlation processing was performed after all the observations finished. Then the bandwidth synthesis processing was performed and the obtained data were analyzed by CALC and SOLVE software developed by Goddard Space Flight Center of National Aeronautics and Space Administration. During the observations, tape-based K4 data acquisition systems were used at both sites in parallel to compare the results. The data obtained with the K4 systems were processed with the K4 correlator at Kashima and analyzed similarly with the data obtained with the K5 systems. The results are compared in Figure 4 and Table 2.

Figure 3. Picture of the prototype K5 VLBI system (VSSP) configured with IP-VLBI boards.

Table 2. Comparison of baseline lengths estimated from the data obtained with K4 and K5 systems.

	No. of valid data	Baseline Length (mm)	RMS Residual Delay (psec)	RMS Residual Rate (fsec/sec)
K4	112	109099657.0 ± 6.7	76	136
K5	159	109099641.2 ± 3.2	33	92

Figure 4 shows the difference in group delay and delay rate obtained by the K4 VLBI system and the K5 VLBI system. The constant offset of the group delay can be absorbed as a part of the clock difference estimated through the data analysis processing and therefore it does not cause any problem in the data analysis. The RMS of the difference is calculated as 72.7 psec for delay rate and 118 fsec/sec for delay rate, and it can be concluded that the K4 and K5 systems are consistent with each other. Table 2 shows the estimated results from the data analysis. From these comparisons, it can be concluded that the estimated baseline lengths are consistent with each other within two time the estimated uncertainties. In addition, the comparison of the RMS residuals of delay and delay rates suggests the performance of the K5 systems is better than the K4 systems. The part of the reason of the improvement can be considered that the phase calculation of the phase calibration signals by the software correlation processing uses precise formula whereas the K4 hardware correlator uses a three level approximation for sine and cosine functions for faster processing and to make the design of the hardware correlator very simple.

Then the opportunity of a domestic regular geodetic VLBI experiment performed by Geographical Survey Institute (GSI) was used for the evaluation of the K5 VLBI system. The experiment JD0306 was performed for 24 hours from July 16, 2003. As a regular domestic experiment, four VLBI stations operated by GSI at Tsukuba (32-m), Shintotsukawa (3.8-m), Chichijima (10-m), Aira (10-m) participated with the K4 VLBI systems. At Tsukuba station, K5 VLBI system was used in addition to the K4 VLBI system. By using the same observing schedule, Kashima (11-m), Tomakomai (11-m), Gifu (11-m) participated in the experiment by using K4 VLBI system and K5 VLBI system in tandem. In addition, at Yamaguchi (32-m) station, K5 VLBI system with two PC units were used to perform observations only in X-band with 8 channels. At three stations (Kashima, Tomakomai, and Tsukuba), K5 prototype models shown in Figure 3 were used while PC systems configured with IP-VLBI boards were used at Gifu and Yamaguchi stations. Table 3 shows the comparison between results obtained from K4 VLBI system and K5 VLBI system for six baselines. Since the K5 VLBI system at Kashima and Gifu stations stopped recording for about six hours and 12 hours respectively during the observations, the number of valid data for baselines including Kashima and Gifu stations are fewer than the data from the K4 VLBI system. The comparison suggests that the estimated error obtained from both systems are comparable considering the number of available data and the estimated baseline lengths are consistent with each other considering the estimated error.

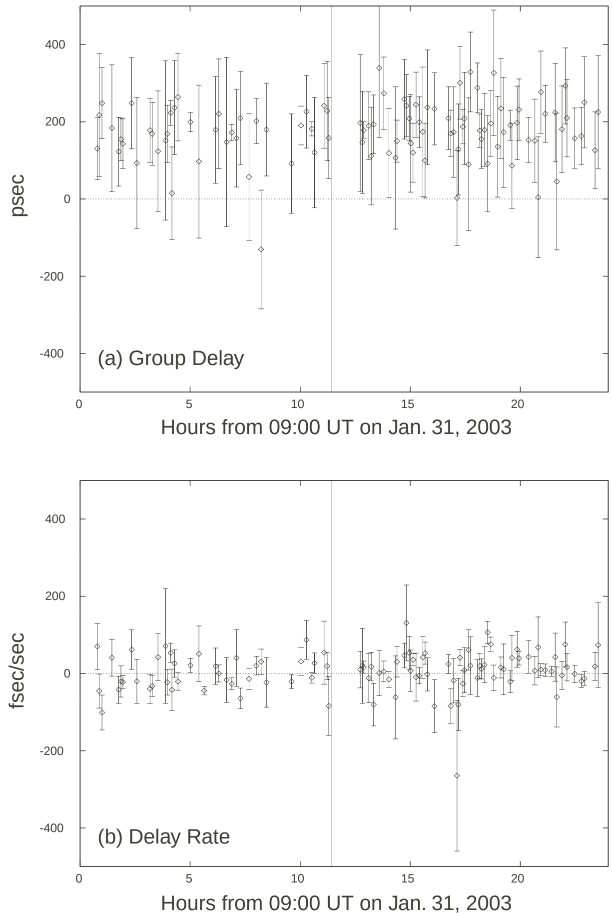

Figure 4. Difference of (a) group delay and (b) delay rate obtained from K4 and K5 systems. Horizontal axis is the time of the scan in hours from the beginning of the session while the vertical axis is the difference of group delay and delay rate. The error bars are one-sigma errors evaluated from $(s_K4^2 + s_K5^2)^{1/2}$ *where* s_K4^2 *and* s_K5^2 *are standard deviations of the data estimated from K4 and K5 systems, respectively.*

In Table 4, preliminary results of estimated coordinates of the Yamaguchi 32-m station based on the ITRF97 reference frame are presented. In the data analysis, site coordinates of the Tsukuba 32-m station was used as the reference and the X-band group delay data between Tsukuba-Yamagichi baseline were used. Since ionospheric correction can not be performed because only X-band data were taken at Yamaguchi station, it have to be noted that there might be a systematic error in the estimated coordinates.

Table 3. Comparison of baseline lengths estimated from the data obtained with K4 and K5 systems.

Baseline	System	No. of valid data	Baseline Length (mm)	RMS Residual Delay (psec)	RMS Residual Rate (fsec/sec)
Tsukuba-Kashima	K4	176	53811894.9 ± 2.1	53	158
	K5	130	53811891.6 ± 3.1	81	121
Tsukuba-Gifu	K4	184	311067474.0 ± 2.9	98	189
	K5	55	311067483.3 ± 4.0	58	136
Tsukuba-Tomakomai	K4	124	740526116.3 ± 4.4	103	165
	K5	169	740526119.4 ± 5.1	103	146
Kashima-Gifu	K4	174	358799168.6 ± 2.8	72	191
	K5	48	358799174.7 ± 4.5	92	144
Kashima-Tomakomai	K4	171	749810979.9 ± 4.4	115	125
	K5	108	749810985.5 ± 5.5	106	143
Gifu -Tomakomai	K4	154	902668931.2 ± 4.8	135	125
	K5	49	902668930.6 ± 6.1	116	138

Table 4. Estimated coordinates of the Yamaguchi 32-m VLBI station.

X :	-3502544258.3 ± 22.1
Y :	3950966396.9 ± 25.8
Z :	3566381164.9 ± 22.0

4. Conclusions

The results from two geodetic VLBI experiments between K4 and K5 VLBI systems were compared to ensure that the K5 VLBI system has expected capability and performance similar or better than the K4 VLBI system. The results from two different systems are consistent with each other considering the estimated error. From these comparisons, it can be concluded that there is no problem in using the K5 VLBI system for precise VLBI observations.

Acknowledgment: The authors would like to express sincere appreciation to many members of Geographical Survey Institute, Hokkaido University, Gifu University, Yamaguchi University, and Communications Research Laboratory for supporting observations of the VLBI experiments described in this report. We also would like to thank Geographical Survey Institute for allowing us the other stations to participate in the JD0306 session.

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An evaluation of VLBI observations for the positioning of the NOZOMI Spacecraft and the future direction in research and development of the deep space tracking using VLBI

Ichikawa, R.[1] (*richi@crl.go.jp*), **Sekido M.**[1], **Osaki H.**[1], **Koyama Y.**[1], **Kondo T.**[1], **Ohnishi T.**[2], **Yoshikawa M.**[3], **and NOZOMI DVLBI group**

[1] *Kashima Space Research Center*
Communications Research Laboratory
893-1 Hirai, Kashima, Ibaraki 314-8501, Japan
[2] *Fujitsu Limted*
1-9-3 Nakase, Mihama-ku, Chiba 261-8588, Japan
[3] *Japan Aerospace Exploration Agency*
Institute of Space and Astronautical Science
3-1-1 Yoshinodai, Sagamihara,
Kanagawa 229-8510, Japan

1. Introduction

We preliminary reported the results of the VLBI experiments for the NOZOMI spacecraft navigation before the second earth swingby on June 19, 2003 [see Ichikawa et al., 2003[1] and Sekido et al., 2003[2] in detail]. NOZOMI is the Japan's first Mars probe. In these experiments, we successfully detected group delay fringes of NOZOMI range signal for several baselines using a software correlation procedure. We provided 15 VLBI group delay data sets to the Institute of Space and Astronautical Science (ISAS). In this short report we describe the results of the experiments and future plans.

2. NOZOMI VLBI experiments

The final products obtained from the VLBI experiments were available with approximately 20 hours latency as shown in Figure 1. The several tens of gigabytes data sets were acquired at each station on the K5 system within 3-5 hours VLBI experiment. After the completion of each VLBI experiment, the data sets at Usuda, Gifu, and Koganei were transferred to the Kashima using a high-speed optical fiber network on TCP/IP protocol in under 3 hours. Correlation processing was completed at Kashima about 10-15 hours later. The estimation of clock parameter based on the quasar group delays was completed at Kashima 1 hours later. On the other hand, the removable data hard disks at other stations (Tomakomai, Tsukuba, Yamaguchi, and Algonquin) were mailed to Kashima. Thus, the latency to product the group delays using these satation data were up to several days.

The obtained group delays were compared with the NOZOMI orbit using range and range rate (R&RR) observables. Preliminary results demonstrate that the VLBI delay residuals are consistent with R&RR observables. However, the rms scatter between them are relatively large up to several tens nanoseconds as shown in Figure 2. The unresolved trend for the Kashima (CRL) - Tsukuba (GSI) baseline are also represented. One candidate

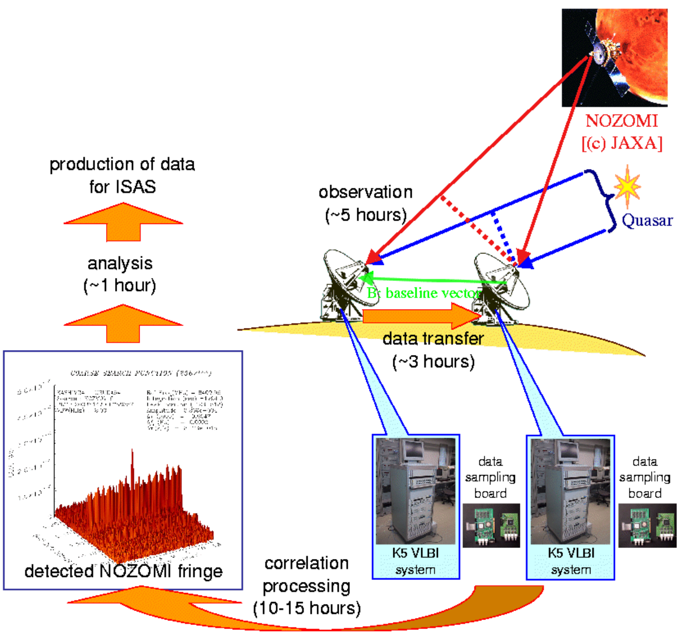

Figure 1. Schematic image showing NOZOMI VLBI data flow and analysis.

possibility of the trend is uncertainty of the a priori delay value predicted by the VLBI model. We are now evaluating our VLBI group delays by comparing with the R&RR results more deeply.

According to the ISAS announcement the NOZOMI completed its final Earth swingby operation on June 19 2003, and is on its way to Mars. NOZOMI passed within 11,000 km of the Earth in a manuever. NOZOMI's arrival at Mars is scheduled in the middle of December 2003.

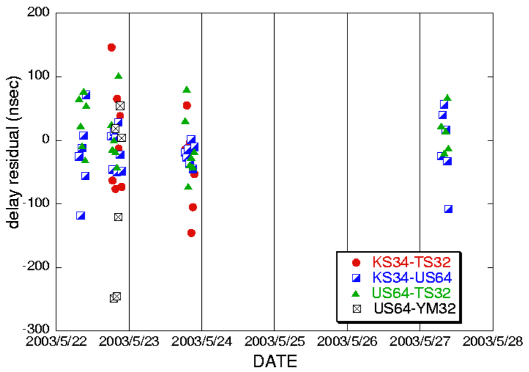

Figure 2. Residual delays between determined position using R&RR data by ISAS and VLBI group delay observables

3. Preparation of HAYABUSA VLBI experiments

Our main concern is to establish the differential VLBI positioning technique for the interplanetary spacecrafts in realtime. However, NOZOMI VLBI experiments are insufficient to develop the technique due to some problems such as signal weakness, narrow band width and so on. Thus, we are now preparing to perform another VLBI experiments. The one of the candidate targets is HAYABUSA, which was developed to investigate asteroids (see Figure 3).

HAYABUSA was launched on May 9 2003, and has been flying steadily towards an asteroid named "Itokawa," after the late Dr. Hideo Itokawa, the father of Japan's space development program. HAYABUSA is traveling through space using an ion engine. It will orbit the asteroid, land on it, and bring back a sample from its surface[3].

First, we evaluated the signal intensities of the candidate quasars to perform the differential VLBI experiments. We selected 24 quasars from the ICRF catalog considering the HAYABUSA trajectory during September 1 to December 31, 2003. The separation angles between the HAYABUSA and the quasars are less than 10 degrees at each

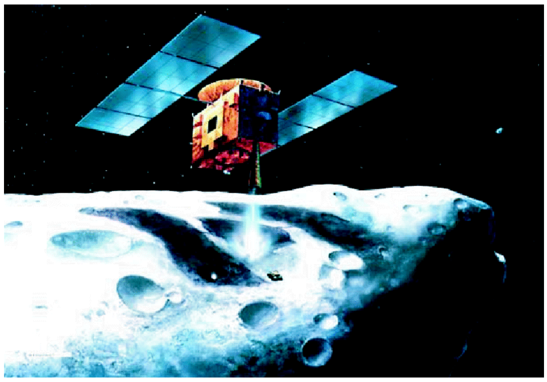

Figure 3. HAYABUSA Image (after JAXA/ISAS)

epoch. A source geometry of the HAYABUSA spacecraft and nearby quasars are illustrated in Figure 4. The signal to noise ratios of the detected quasar fringes are shown in Table 1. We are now planning to perform a first HAYABUSA VLBI experiment based on the signal intensity result.

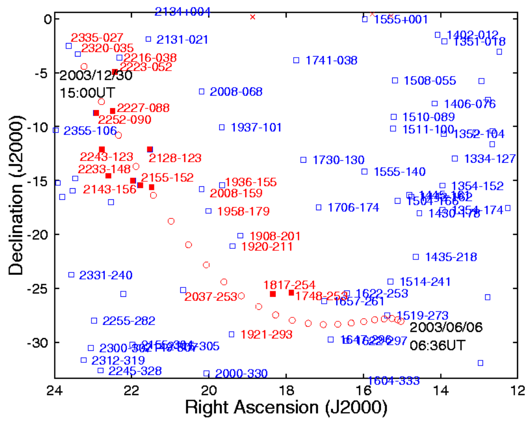

Figure 4. Trajectory of the HAYABUSA spacecraft (circles) and nearby radio sources (solid squares) from September 1 to December 31 2003.

4. Planed Activities

We have to carry out additional works to achieve our final goal as follows:

- Development of the analysis software for the spacecrafts positioning using phase delay observables
- Improvement of the finite distance VLBI model to expand its capability in a positioning of the low earth orbit satellites

Table 1. Signal to noise ratio of the detected quasar fringes nearby HAYABUSA spacecraft during Sep. 1 to Dec. 31, 2003. 3C454.3 and 3C84 are reference sources to check the quasar fringe.

source name	integ. time (sec.)	CH1	CH2	CH3	CH4
3C454.3(Ref.)	60	18.6	19	21.2	21.3
1748-253	600	8.9	8.8	8.6	8.2
1817-254	600	8.4	8.7	8.6	8
1908-201	600	14.9	16	10.3	12.3
1921-293	600	57	59.2	53.7	57.3
1920-211	600	19.9	13.6	13.8	12.3
1936-155	600	7.7	8	9.2	8.5
1958-179	600	16.4	19.5	16.4	15.3
2008-159	600	15	12.8	13.9	15.3
2037-253	600	8.5	8.4	8.4	8.3
2126-158	600	8.8	9.9	8.5	9.5
2128-123	600	27	28.6	26.4	25.7
2143-156	600	8.7	8.4	7.7	8.5
2155-152	600	16.9	14.3	13.3	15.4
2229-172	600	9.8	8.4	8.9	8.7
2216-038	600	20.4	21.6	22	22.5
2223-052	600	29.3	28.8	27.4	31
2227-088	600	20.9	19.3	19.2	21.7
2233-148	600	10	8.2	7.8	7.9
2243-123	600	12.9	14.7	14	12.9
2252-090	600	8.3	7.9	8.5	8.7
2254+024	600	9.1	8.2	8.3	8
2318+049	600	10.8	9.6	8.9	9.4
2320-035	600	10.7	8.3	8.6	8.7
2335-027	600	8.3	9.4	8	8.2
3C84(Ref.)	60	37.1	35.7	29	32.8

- Improvement of processing speed and efficiency for the VLBI data correlation using multiprocessor and high speed network
- Development of the differential VLBI software package such as the antenna tracking for the spacecraft, the automatic scheduling of the VLBI observation, the propagation delay estimation, and so on
- Validation of the NOZOMI VLBI experiments by comparing with R&RR data obtained by ISAS.

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VLBI Application for Spacecraft Navigation (NOZOMI) – follow-up on Model and Analysis –

M. Sekido[1] (*sekido@crl.go.jp*), **R. Ichikawa**[1], **H. Osaki**[1], **T. Kondo**[1], **Y. Koyama**[1], **M. Yoshikawa**[2], **and NOZOMI VLBI Observation Group**[3]

[1] *Kashima Space Research Center*
Communications Research Laboratory
893-1 Hirai, Kashima, Ibaraki 314-8501, Japan
[2] *Institute of Space and Astronautical Science*
Japan Aerospace Exploration Agency
3-1-1 Yoshinodai, Sagamihara,
Kanagawa 229-8510, Japan
[3] *JAXA, CRL, NAO, GSI, Gifu Univ.,*
Yamaguchi Univ., Hokkaido Univ.,
and CRESTech/SGL

1. Introduction

Establishment of VLBI application technique for spacecraft navigation is one of our target of current projects, as we reported in previous issue of IVS CRL-TDC news [*Ichikawa et al.*, 2003; *Sekido et al.*, 2003]. We are going to briefly introduce current problems to be solved.

2. Delay Observable

For the VLBI experiments of spacecraft NOZOMI, several Japanese domestic VLBI stations and Algonquin observatory in Canada had joined in the observations. The modulated signal (range signal) transmitted from NOZOMI spacecraft has not so wide bandwidth inherently. Consequently, the accuracy of its group delay observable is not so high, and long baseline observation is one of the ways to increase the angular resolution of the observation.

Longer baseline VLBI observation requires higher accuracy in a priori delay/rate predictions, since fringe rotates faster and deviation of source coordinates affects to delay/rate more greatly than shorter baselines. Actually stable detection of fringes on intercontinental baselines (Algonquin and Japanese domestic baselines) suffered from some difficulty as reported previously [*Sekido et al.*, 2003]. We will discuss more on this problem in the next section. One of the causes of the problem was deviation of predicted orbit from true one, although it is inevitable for spacecraft differently from normal astrometric VLBI. To enable stable fringe detection under large delay rate offset, we need to expand rate window by reducing the integration duration of each bin.

Even the bandwidth of radio signal from spacecraft is narrower than that of quasar, its phase delay observable can be measured with high resolu-

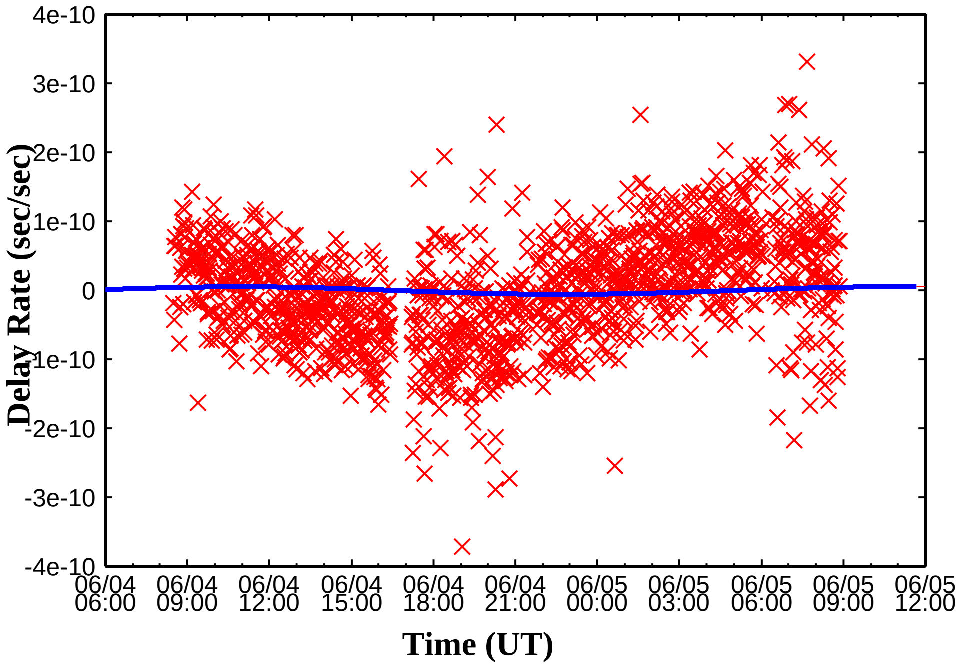

Figure 1. Difference of delay rates between observed by Doppler frequency measurements and theoretical calculation by CRL based on finite distance VLBI model (cross mark). The data is on Kashima - Algonquin (9000km) baseline on June 4 2003. Solid line indicates difference of delay rate between predictions of CRL and ISAS.

tion if we could resolve the ambiguity. It will provide a benefit to achieve high angular resolution even with combination of Japanese domestic VLBI stations. Domestic VLBI stations do not always have large diameter dishes, so signal to noise ratio (SNR) is not so high. To get higher SNR with weak line spectrum signal, frequency resolution has to be increased. The simplest way to increase frequency resolution is extending the time span in Fourier transformation, although it takes longer time for Fourier transformation to get higher resolution no more than one Hertz. In addition, The frequency received at observatory is drifting due to relative motion of the spacecraft and observer, and this effect cannot be eliminated at such high frequency resolution. For this purpose, we are developing a correlation software specific for line spectrum to measure fringe phase.

3. Delay rate comparison –CRL,ISAS, and Doppler measurements–

One of the caused of difference on delay rate between prediction model and observed delay rate, which is computed by Doppler frequency measurements, had come from deviation of prediction orbit of NOZOMI. The orbit data we used in the previous report (Figure 3 of *Sekido et al.* [2003]) was prediction orbit, which was propagated from determined orbit by range and range rate (R&RR) measurements in February 2003. So the prediction orbit at this time had larger error. Determined orbit by R&RR measurements in June was provided afterward. The geocentric angular distance between predicted and determined spacecraft coordinates differed by around twenty arc seconds. After using the determined trajectory of spacecraft, the discrepancy of delay rates between observed by Doppler measurements and the theoretical one has reduced to the half of that before (Figure 1). However the rate residual still remains about 1.e-10 sec/sec on 9000 km baseline.

ISAS also computed delay rate of VLBI observation based on numerical solution of light time equation for two legs from spacecraft to two observation stations. The difference of delay rate between ISAS and CRL is superimposed with solid line in Figure 1. These independent computations of delay rate coincide within the order of a few psec/sec. Since the theoretical computation of delay and delay rate are only for geometrical component, delay due to radio wave propagation medium will me remain as residual. Although, the difference of observed delay rate and theoretical one at order of 1.e-10 sec/sec is too large to be explained by propagation medium. It may suggest that determined orbit still might have error in order of several arc seconds.

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VLBI Observation by Receiving Narrow Bandwidth Signal from NOZOMI

Fuyuhiko Kikuchi (*fuyuhiko@miz.nao.ac.jp*), **Yusuke Kono, Ping Jinsong, Liu Qinghui, Kazuyoshi Asari, Koji Matsumoto, Seiitsu Tsuruta, Hideo Hanada, Nobuyuki Kawano, and NOZOMI VLBI group**

Earth Rotation Division,
National Astronomical Observatory of Japan (NAOJ)
2-12 Hoshigaoka, Mizusawa,
Iwate 023-0861, Japan

1. Introduction

An orbit of a spacecraft (s/c) is usually determined by using coherent 2-way range and range-rate (R&RR) measurements. The range observables are obtained by measuring the round trip light time between the s/c and the ground tracking station. On the other hand, the range-rate observables are obtained from measurements of the Doppler shift of the radio signal on coherent 2-way links by using an onboard transponder. In addition to R&RR, the VLBI (Very Long Baseline Interferometry) technique can be also used for positioning of the s/c. By measuring the difference of arriving time of same wave front of radio signal from the s/c at two separated antennas, VLBI can determine the angular position of the s/c in space. VLBI is sensitive to the direction perpendicular to line-of-sight (LOS) direction to the s/c from the tracking station in contrast to the R&RR. Combination of two kinds of observations can improve the accuracy of orbit determinations.

The VLBI technique has been adopted for the s/c positioning in the early stage of VLBI. JPL/NASA VLBI group used VLBI for tracking Apollo lunar missions and VEGA probes [1]. In Japan, VLBI method was used to track the geosynchronous satellite in the 1980 's. Recently, in order to improve this technique and to make it a common method for the s/c orbit determination, we observed the first Japanese Mars explorer "NOZOMI" by using a regional VLBI network and a new s/c VLBI tracking method. NOZOMI had two swing-bys by the earth in Dec. 2002 and June 2003 so as to be injected into a Mars orbit in 2004. During the period between these two swing-bys, the onboard high gain antenna could not point to the earth due to some operational problems. In this period, R&RR measurements cannot be obtained with sufficient SNR. To overcome this problem, the NOZOMI team of ISAS (Institute of Space and Astronautical Science) and the VLBI group of CRL (Communications Research Laboratory) collaborated to determine the NOZOMI orbit by using VLBI technique [2][3]. The s/c VLBI tracking group of NAOJ (National Astronomical Observatory of Japan) also took part in the observation from 13 to 27 in May 2003. The radio telescopes involved in this mission are listed in Table 1. In this paper, the results of the analysis by the method of correlating the NOZOMI carrier waves are shown.

Table 1. List of radio telescopes involved in the VLBI observation of NOZOMI.

Station	Antenna diameter (m)
USUDA	64
KASHIMA	34
MIZUSAWA	10
MIZUSAWA	20

Table 2. The narrow bandwidth VLBI sampling and recording system (S-RTP station).

Sampling rate:	200 kHz
Quantization:	6 bits
Number of channels:	4

2. Back-end system and correlation software

In radio astronomical and/or geodetic VLBI surveys, usually wide bandwidth signals (from several MHz to GHz) are recorded by fast sampling-rate systems, especially for obtaining the accurate group delay, which depends on signal bandwidth. In contrast with above systems, when applying the VLBI technique for the s/c orbit determination, it is not effective for the s/c to generate and emit such a wide bandwidth signal or for ground system to record and real-time process such a wide bandwidth signal. Usually, the s/c transmits narrow bandwidth downlink carrier wave and/or the modulated carrier wave. The group delay and delay rate should be obtained from the narrow bandwidth signals so as to get the instantaneous angle of the s/c and the angle variation in space. For this reason, we have developed a narrow bandwidth VLBI sampling and recording system, called S-RTP station, for the s/c VLBI tracking [4][5]. The detail performances of this system are listed in Table 2. This system has been used for NOZOMI observations.

The sampling rate of our system is very slow, therefore the amount of sampling data is small enough for correlation by a common used PC. For this system, correlation software has been also developed. The software is composed of modules of VLBI delay estimation and cross-correlation which includes the bit-shift and fringe- stopping. In a conventional correlator, delay is calculated on an assumption of plane wave coming from the radio sources. We modified the delay model of plane wave by spherical one for tracking of the s/c near from the earth [6]. The predicted propagation time from the s/c to the reference station is expressed by following equation.

$$\tau_{ref}(t) = \frac{|R_{sc}(t - \tau_{ref}(t)) - R_{ref}(t)|}{c} \quad (1)$$

where $R_{sc}(t)$ is the predicted position vector of the s/c every 1 minute which was distributed by ISAS, and $R_{ref}(t)$ represent the position vector of the reference station. t is the time based on the reference station, and c is the velocity of light. $\tau_{ref}(t)$ is obtained in iterative procedure as follows.

$$\tau^{i+1}_{ref}(t) = \frac{|R_{sc}\left(t - \tau^{i}_{ref}(t)\right) - R_{ref}(t)|}{c} \quad (2a)$$

$$\tau^{0}_{ref}(t) = \frac{|R_{sc}(t) - R_{ref}(t)|}{c} \quad (2b)$$

$\tau^{0}_{ref}(t)$ is an initial value of $\tau_{ref}(t)$. On the other hand, the propagation time from the s/c to the slave station is expressed by following equation.

$$\tau_{slv}(t) = \frac{|R_{sc}\left(t - \tau_{ref}(t)\right) - R_{slv}\left(t - \tau_{ref}(t) + \tau_{slv}(t)\right)|}{c} \quad (3)$$

where $R_{slv}(t)$ is the position vector of the slave station and $\tau_{ref}(t)$ is given from the Eq.(1). $\tau_{slv}(t)$ is obtained in iterative procedure as well as $\tau_{ref}(t)$. Finally the geometric delay between the reference and the slave station is obtained as follows.

$$\tau_g(t) = \tau_{slv}(t) - \tau_{ref}(t) \quad (4)$$

3. Signals of NOZOMI

Between two swing-by events, the downlink signal from NOZOMI was modulated for R&RR measurements. In ranging mode, downlink signal was consist of a carrier wave, two range tones, and some ambiguity tones. The carrier frequency $f_{carrier}$ of NOZOMI is 8411MHz. The range tone frequencies are $f_{carrier} \pm f_{carrier}/2^{12}$ ($f_{carrier}/2^{12}$ is about 515kHz). The ambiguity tones whose frequencies are $f_{carrier} \pm f_{carrier}/2^{n+12}$ (n =1,2$\cdots$) are added every 100 seconds for 60 seconds to solve the ambiguity of the range tones. In order to resolve the ambiguity of phase measurement by using group delay, the carrier wave and two range tones were separately recorded in 3 channels of S-RTP station. Moreover, to compensate the phase difference between channels of the video converter, the phase calibration signals at every 60kHz were mixed with the IF signals in front of the video converter. For calibrating the clock offset and clock rate between two VLBI stations, several QSOs with position precisely known were also observed before and after the tracking of NOZOMI. The signals were also recorded with IP-VLBI system at the same time [2][3]. Block diagram of narrow bandwidth receiving system is shown at Figure 1.

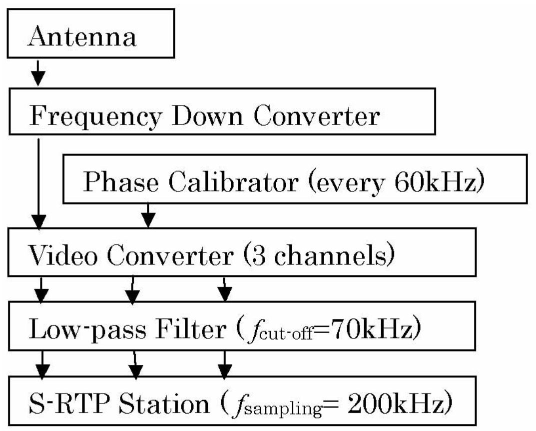

Figure 1. Block diagram of narrow bandwidth receiving system.

4. Results of Correlation

4.1 Estimation of Residual Fringe Phase

The correlation was done by software of FX mode. At first, the signals of the slave station were bit-shifted and fringe-stopped by using the delay predicted by Eq.(4). Then, the signals of the reference and the slave stations were cross-correlated during each parameter period (PP). In NOZOMI mission, a C/N of the signal recorded at the ground station was too low, so we use only $\pm$ 30Hz around the center frequency of the signals to increase the signal-to-noise ratio (SNR). The resulted residual fringe phases of the carrier waves and two range tones for USUDA64-KASHIMA34 baseline are shown in Figure 2. The residual fringe phases of carrier wave were obtained every 1.3 second PP, and SNR was 21. Its standard deviation was 10 degrees, which means that the position of NOZOMI can be determined with an accuracy of 30m assuming that the baseline is 200km and the distance between NOZOMI and ground station is 6×10^6 km. However, an ambiguity of $2n\pi$ (n is integer) is still included in the residual fringe phase. On the other hands, because the C/N of the range tones were less than carrier wave, we could obtain the residual fringe phase only for the USUDA64-KASHIMA34 baseline. Moreover, the transmission of NOZOMI was divided into 2 modes, A and B. In the mode A, the ambiguity tones were added to the range tones and decreased the C/N. So the residual fringe phases of range tones were not obtained for this period of 60 seconds (see A of Figure 2). On the contrary, the ambiguity tones were not added in the mode B and the residual fringe phases of range tones were obtained in this period of 40 seconds, and SNR is 13. Therefore the group delay analysis could only be done during the mode B.

4.2 Estimation of Group Delay

Before analyzing group delay, the effect of the separate band has to be removed from the residual

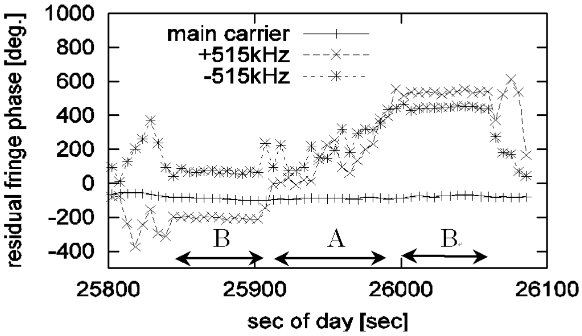

Figure 2. Residual fringe phases of the carrier wave and two range tones.

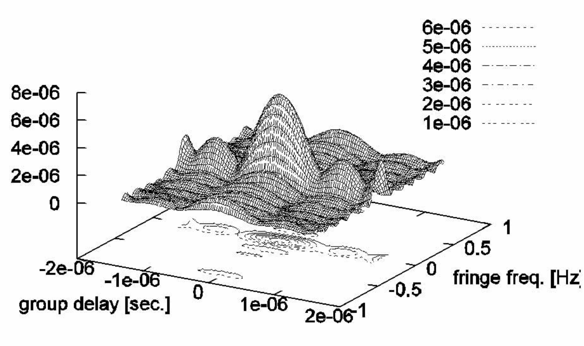

Figure 3. Detected fringe of NOZOMI.

fringe phase as following,

$$\Delta\phi_i' = \Delta\phi_i - \left(\phi_{pcal,i}^{ref} - \phi_{pcal,i}^{slv}\right) \quad (i = 1, 2, 3) \quad (5)$$

where $\Delta\phi_i$ is the residual fringe phase of ith channel and $\phi_{pcal,i}^{ref}$ and $\phi_{pcal,i}^{slv}$ are the phase of phase cals of the channel, respectively. The group delay of the signals are given by,

$$\Delta\tau_{group\ delay} = \frac{\Delta\phi_{i+1}' - \Delta\phi_i'}{2\pi(f_{i+1} - f_i)} \quad (6)$$

where f_i is the carrier frequency of ith channel. The result of group delay is shown in Figures 3 and 4. Its standard deviation was about 41 nsec. This error could be caused by the thermal noise of all the R&RR systems including the low-pass filter. The clock offset and clock rate were estimated from the observation of some QSOs by IP-VLBI through the conventional correlation. The estimated clock offset was 8.1×10^{-7} seconds and clock rate was -2.6×10^{-13} seconds/second. After the corrections of clock offset and clock rate, we compare the geometric delay obtained by above group delay analysis with the result of the VLBI group of CRL [2][3]. It was noticed that an average difference of delay was 58 nsec. This difference may result from the difference of video converter used at KASHIMA station and the different geometric delay models used by different groups.

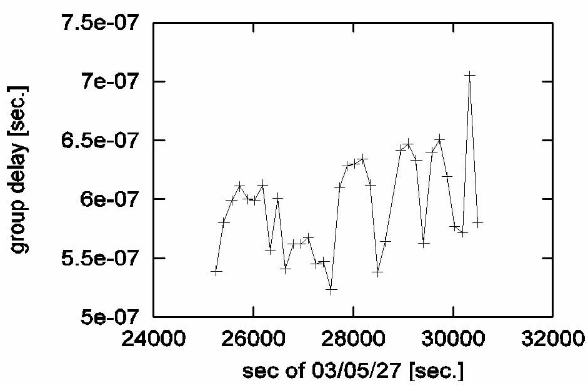

Figure 4. Group delays of NOZOMI signal.

The NOZOMI signal was too weak in this observation, however, it can be expected that the accuracy of the group delay would be improved to 9nsec when the SNR of received signal is 100.

5. Conclusion

The s/c VLBI tracking group of NAOJ participated in the VLBI observation of NOZOMI. In this mission we recorded three carrier wave signals by using narrow bandwidth sampling and recording system, and correlated these signals by using software method. The group delay was obtained every 100 seconds with standard deviation of 41 nsec. Due to the very low C/N, this result is not accurate enough for orbit determination of NOZOMI precisely, but we confirmed the validity of our new hardware and software VLBI systems. It is also confirmed that our new VLBI system has a capability of precise s/c tracking within the error of a few nsec when SNR is about 100.

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Orbit determination of spacecraft in deep space by Delta-VLBI technique: current situation and future

Makoto Yoshikawa[1] (*makoto@pub.isas.jaxa.jp*), **Takaji Kato**[1], **Tsutomu Ichikawa**[1], **Hiroshi Yamakawa**[1], **Jun'ichiro Kawaguchi**[1], **Yasuhiro Murata**[1], **Takafumi Ohnishi**[2], **Shiro Ishibashi**[2], **Shigeo Tsujimoto**[2], **Katsutoshi Kurosu**[2], **and NOZOMI Delta-VLBI group**[3]

[1] *Japan Aerospace Exploration Agency Institute of Space and Astronautical Science 3-1-1 Yoshinodai, Sagamihara, Kanagawa 229-8510, Japan*

[2] *Fujitsu Limted 1-9-3 Nakase, Mihama-ku, Chiba 261-8588, Japan*

[3] *JAXA, CRL, NAO, GSI, Gifu Univ., Yamaguchi Univ., Hokkaido Univ., and CRESTech/SGL*

1. Introduction

At present, we are operating two interplanetary spacecrafts. They are "NOZOMI", Mars explorer of Japan and "HAYABUSA", an asteroid sample return mission. In order to determine their orbits, we use a conventional method using range and range rate (RARR). In addition to this method, we have strong hope to use Delta-VLBI technique for the orbit determination.

The orbit determination by using Delta-VLBI technique is very promising, because the accuracy of the orbit determination will be much better and because we can plan more flexible missions. Moreover, NOZOMI has a serious trouble since April 2002, and we are under the situation that we have to establish a new method for orbit determination for NOZOMI. That is the method using Delta-VLBI technique.

In this paper, we show the results of Delta-VLBI observations for NOZOMI, and we mention about our future plans.

2. Delta-VLBI observation for NOZOMI

The Japanese Mars Explorer NOZOMI was launched in July 1998. In the original plan, it would have arrived at Mars in October 1999. The original orbit plan is shown in Fig.1. However, when the spacecraft left from the earth to Mars, there occurred a problem and the orbit plan was forced to change (Fig.2). In this new plan, NOZOMI will arrive at Mars at the beginning of 2004 after two earth swingbys. Anyway, at this schedule change, there was no problem for the orbit determination of NOZOMI, and we were going to determine its orbit by the conventional RARR method. (At present, NOZOMI is on the orbit that arrives at Mars at the middle of December 2003.)

Another problem occurred in July 1999. The S band down link was stopped. NOZOMI has S and X bands, so X band was used for down link since then. Therefore, this trouble was not so serious for the communication with NOZOMI, but from the point of the orbit determination, this trouble causes some problems. One of the problems is a small acceleration associated with the reorientation of NOZOMI. X band uses the high gain antenna, so we need rather frequent attitude maneuvers to point it to the earth. Acceleration occurs at each attitude maneuver, and it makes the orbit determination rather difficult.

There is another problem, which is much more difficult. We found that in some period between the

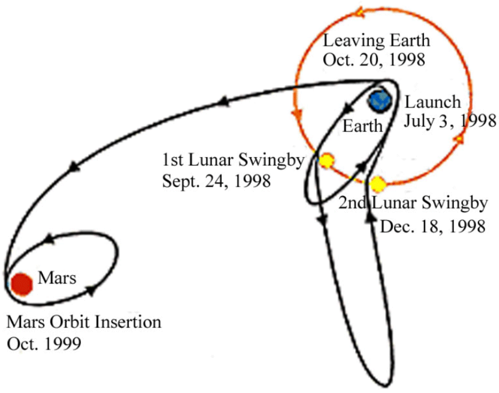

Figure 1. Original orbit plan of NOZOMI.

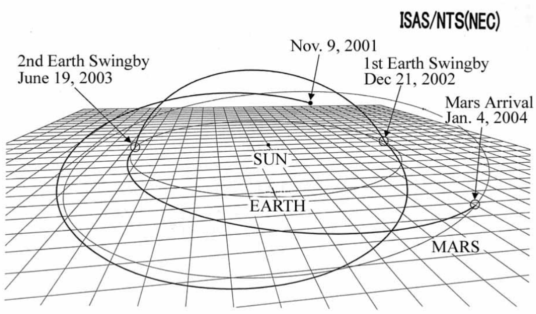

Figure 2. New orbit plan of NOZOMI.

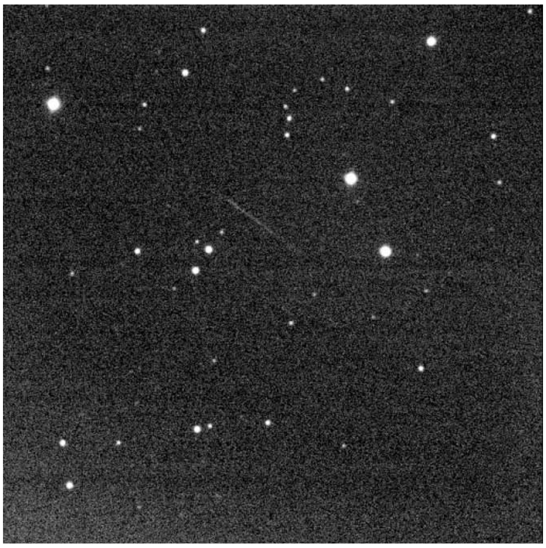

Figure 3. The trail of NOZOMI at the second earth swingby. This photograph was taken at June 19, 2003, 11:39:16 UTC by Mr. Akimasa Nakamura at Kuma Kogen Astronomical Observatory in Ehime prefecture in Japan. The trail of NOZOMI is seen faintly at the center. The field of view is 12 arc seconds, and the exposure time is 12 seconds. The magnitude of NOZOMI is about 15 or 16.

two earth swingbys it is difficult to get the range data, because we cannot make the attitude of NOZOMI to point its high gain antenna to the earth. This is one of the reasons why we started to consider the use of Delta-VLBI technique to the orbit determination of NOZOMI.

And then the most serious problem occurred in April 2002. By strong solar flare one of the power units was stopped, and we could not get the telemetry from NOZOMI. Moreover we could not control its attitude and orbit. After this trouble, many attempts were done and finally we were able to get some information from NOZOMI and to control the attitude and orbit by some special methods. But we could not put the attitude of NOZOMI at the desirable one to get range and Doppler data. So sometimes we could not get range and/or Doppler data, and this made the Delta-VLBI method much more important.

Under this very critical situation, the two earth swingbys (on 21 December 2002 and 19 June 2003) were carried out successfully. At the earth swingbys, we asked several observatories in Japan to observe NOZOMI. And at the second swingby, one of the observatories succeeded to take the image of NOZOMI. Fig.3 shows the trail of NOZOMI, which was taken at the predicted time and position (Fig.3).

We tried both RARR method and Delta-VLBI method for the orbit determination for these two swingbys. As the result, we managed to determine the orbit of NOZOMI by RARR method accurate enough to carry out these swingbys. Because of the constraint of the attitude control of NOZOMI, the tracking data was taken by using not main beam of the high gain antenna but its side lobe for the most time. Therefore the Doppler data was not normal and it has strange bias. We developed a special technique to use such unusual Doppler data for the orbit determination by RARR.

As for the Delta-VLBI, we did many observations. And we were able to derive the delay time by carrying out correlation analysis. However, the results have rather large scattering (about several 10 nsec) and systematic error as shown in Figs.4-7. These figures show the O-C of the delay time, where "O" is Delta-VLBI observation results which were analyzed by Communications Research Laboratory (CRL) and "C" is calculated values based on the orbit determination result by RARR method.

We tried to determine the orbit of NOZOMI by using these Delta-VLBI data, but the results were not good. We think the reason is the large scattering of the data. We will carry out further analyses to solve this problem.

3. Future plans

Although the attempt to carry out the orbit determination of NOZOMI by Delta-VLBI technique has not been successful yet, we would like to continue to try this method much further. Of course firstly we are going to analyze the data for NOZOMI further. In addition to NOZOMI, we have another spacecraft, that is HAYABUSA (Fig.8).

HAYABUSA, which is the spacecraft for the asteroid sample return mission of Japan, was launched on 9 May 2003, and it will arrive at an asteroid in 2005. It has a special engine called "ion engine". The thrust level of the ion engine is not large but it works continuously. Such low continuous thrust makes the orbit determination rather difficult. We would like to try Delta-VLBI technique for the orbit determination of HAYABUSA as well as the RARR method.

We have another plan related Delta-VLBI. In Japan, a new organization for space activity has started since October 2003. This organization is called Japan Aerospace Exploration Agency (JAXA). In JAXA, there is only one VLBI station, that is Usuda Deep Space Center. Up to now, Delta-VLBI observations for spacecraft have been carried out in collaboration with other organizations, such as CRL, NAO (National Astro-

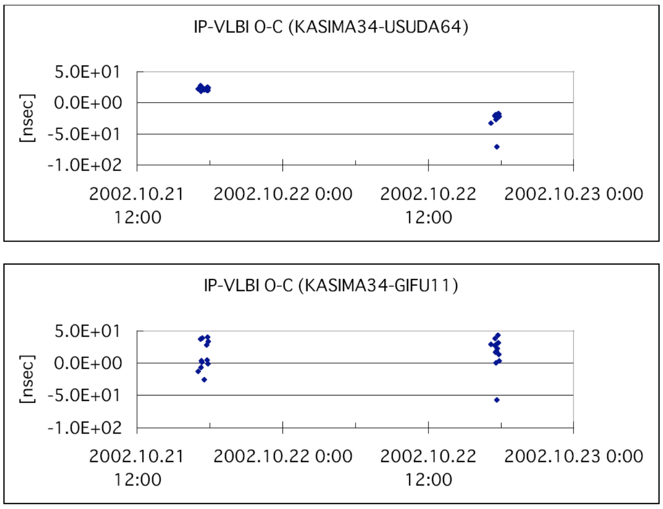

Figure 4. O-C of delay time taken by IP-VLBI system on Dec. 21-22, 2002. The baseline is Kashima-Usuda (above) and Kashima-Gifu (below).

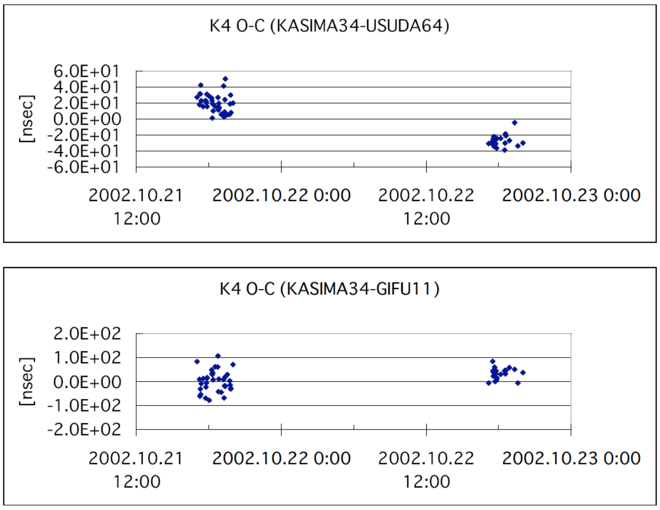

Figure 5. O-C of delay time taken by K4 system on Dec. 21-22, 2002. The baseline is Kashima-Usuda (above) and Kashima-Gifu (below).

nomical Observatory of Japan), GSI (Geographical Survey Institute of Japan), Gifu university, Yamaguchi university, Hokkaido university, and Canada (CRESTech/SGL). Such collaboration is very important and we would like to continue this wide collaboration. However it is also important to have Delta-VLBI facilities in JAXA itself, because Delta-VLBI should be used in the daily tracking as well as emergency tracking. Therefore, at present we have just started to consider the possibility of installing the Delta-VLBI facilities at Uchinoura Space Center. If this is possible, JAXA has two VLBI stations, Usuda and Uchinoura.

We studied how much the Delta-VLBI between Usuda and Uchinoura can make the accuracy of the orbit determination better. One of the results is shown in Fig.9. This is for a certain period of HAYABUSA, where Doppler data is not effective for the orbit determination. This result shows that the Delta-VLBI with the baseline of Usuda-Uchinoura is quite effective for the orbit determination.

As a summary, we say again that the Delta-VLBI method is very promising for the orbit determination of spacecraft in deep space. We have done many Delta-VLBI observations for NOZOMI, and we were able to get delay time as the result. However, we have not been successful to use the Delta-

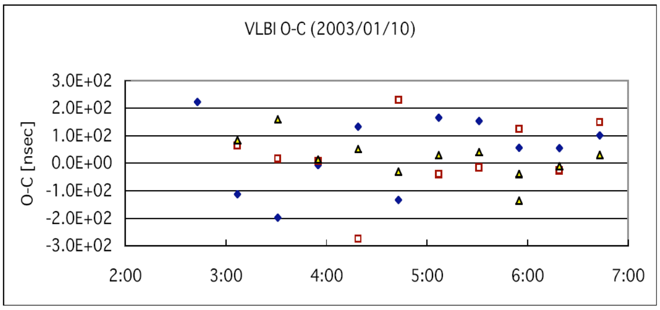

Figure 6. O-C of delay time taken by IP-VLBI systemt on Jan. 10, 2003. The baseline is Usuda-Koganei(◆),Usuda-Gifu(□), and Kashima-Usuda (△).

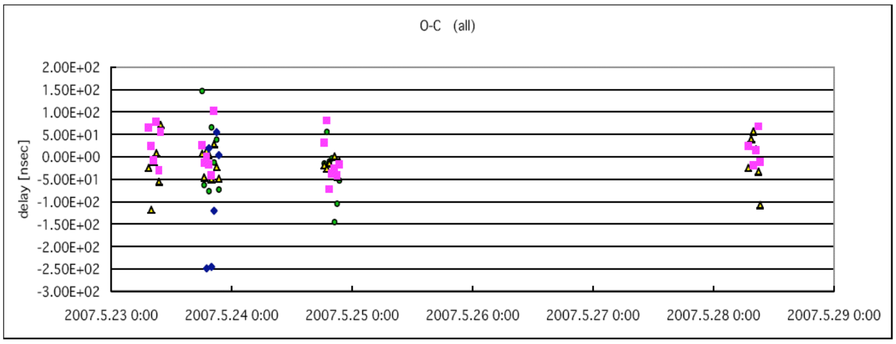

Figure 7. O-C of delay time taken by IP-VLBI system on May 22-27, 2003. The baseline is Kashima-Tukuba (●), Kashima-Usuda (△), Usuda-Tsukubai (■),Usuda-Yamaguchi (◆).

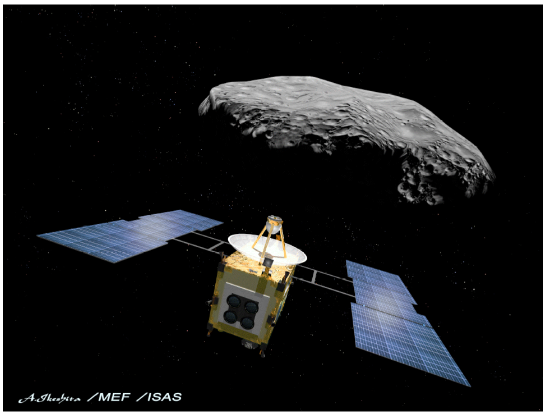

Figure 8. HAYABUSA (MUSES-C) mission. (by A. Ikeshita / MEF / ISAS).

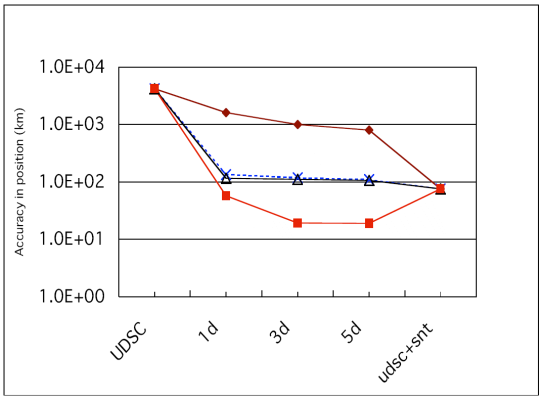

Figure 9. Analysis of position accuracy. The data labeled "UDSC" indicates the accuracy obtained by RARR method using only Usuda station. The data labeled "1d", "3d", and "5d" mean that Delta-VLBI data is also included for the RARR orbit determination and the number is the number of data passes of Delta-VLBI observation. The data labeled "udsc+snt" indicates the accuracy by RARR method using Usuda and Santiago stations. Four different baselines were analyzed: Usuda-Kashima (◆), Usuda-Mizusawa (×), Usuda-Uchinoura (△), and Usuda-Canberra (■).

VLBI data for the actual orbit determination. We will continue our work and we hope we can establish new orbit determination method by using Delta-VLBI technique.

We are grateful to the many people and organizations for their kind and devoted help.