An Evaluation of VLBI Observations for the Precise Positioning of the NOZOMI Spacecraft

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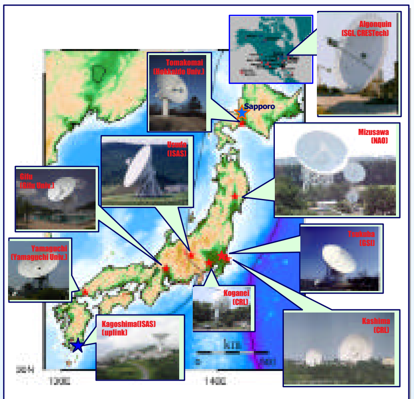

Figure 2: VLBI stations participating to DVLBI experiments

1. Introduction

Precise spacecraft positions (5-10 nrad) can be obtained with differential spacecraft-quasar VLBI (DVLBI) observations that directly measure the angular position of the spacecraft relative to nearby quasars. We performed more than 30 VLBI experiments for the two Japan's spacecrafts, NOZOMI and HAYABUSA from September 2002 until November 2003. These VLBI experiments are aimed to establish the positioning technology for the interplanetary spacecrafts in realtime. In this poster we describe the preliminary results of the VLBI experiments and future plans.

2. NOZOMI VLBI experiments

NOZOMI mission sequence

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). 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 (see Figure 1).

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.

VLBI experiments

We use nine VLBI antennas in Japan to perform the VLBI experiments at X-band as shown in Figure 2. Algonquin 46-m of Natural Resources Canada (NRCan) also participate in several experiments in collaboration with the Space Geodynamics Laboratory (SGL) of CRESTech. We equipped **the state of the art "K5 VLBI system"** to these stations as shown in Figure 3. 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. 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.** 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.

We detected fringes of NOZOMI range signal for several baselines using software correlation in spite of weak and narrow-bandwidth signal. On the other hand, we could not detect group delay fringes on intercontinental baselines (Algonquin and Japanese domestic baselines). We will discuss this issue in the next subsection.

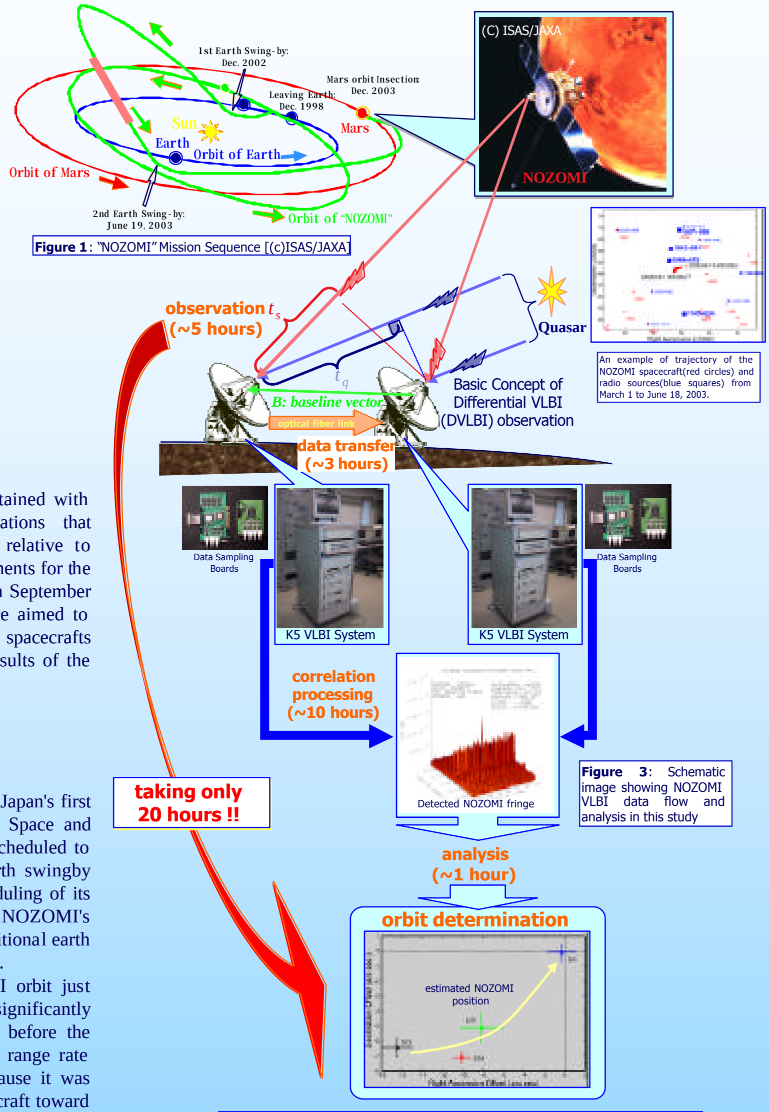

Figure 1: "NOZOMI" Mission Sequence [(c)ISAS/JAXA]

Figure 3: Schematic image showing NOZOMI VLBI data flow and analysis in this study

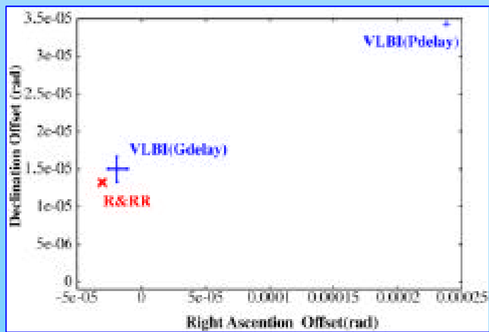

Figure 4: Comparison of Estimated NOZOMI position on January 10, 2003

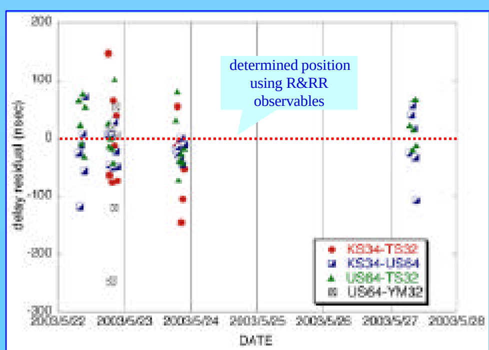

Figure 5: Residual delays between determined position using R&RR data by ISAS and VLBI group delay observables

The final products obtained from the VLBI experiments were available with approximately 20 hours latency as shown in Figure 3. 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 less than 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 hour 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.

Results

The obtained group delays were compared with the NOZOMI orbit using range and range rate (R&RR) observables as shown in Figure 4. 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 5. The unresolved trend for the Kashima (CRL) - Tsukuba (GSI) baseline are also represented. One candidate possibility of the trend is uncertainty of the a priori delay value predicted by the VLBI model.

A 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. We could not detect NOZOMI group delay fringes for the intercontinental baselines during the NOZOMI VLBI experiments. 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. Then, we reprocessed the data sets using calibrated delay rate values which were computed by doppler frequency measurements, came from deviation of prediction orbit of NOZOMI (see Figure 6). As a result, we could successfully detect group delay fringe for the intercontinental baselines. Figure 7 shows an example of fringe for the Kashima - Algonquin baseline. To enable stable fringe detection under large delay rate offset, we need to expand rate window by reducing the integration duration of each bin.

Eventually, we provided 15 DVLBI 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. 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.

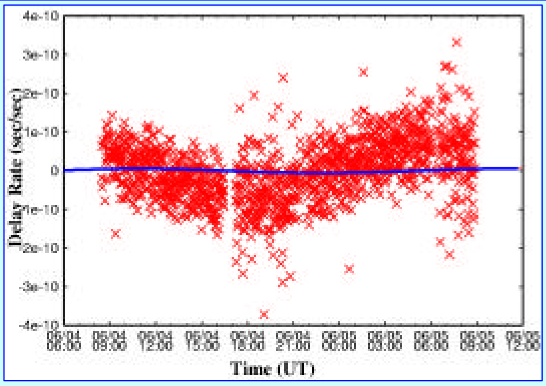

Figure 6: Difference of delay rate between observed by Doppler frequency measurements and theoretical calculation by CRL based on finite distance VLBI model (cross mark). The data is on Kashima - Algonquin (9000km) baseline on June 4 2003. Solid line indicates difference of delay rate between predictions of CRL and ISAS.

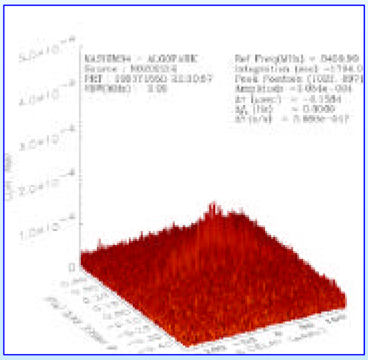

Figure 7: An example of NOZOMI range signal fringe for the Kashima - Algonquin baseline on June 4 2003. This fringe can be detected using calibrated a priori delay rate value obtained by Doppler frequency measurements.

3. HAYABUSA VLBI experiments

NOZOMI VLBI experiments are insufficient to develop the VLBI tracking technique due to some problems such as signal weakness, narrow band width and so on. Thus, we perform another VLBI experiments. The one of the candidate targets is HAYABUSA, which was developed to investigate asteroids (see Figure 8). 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 [JAXA, 2003].

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 5 degrees at each epoch. A source geometry of the HAYABUSA spacecraft and nearby quasars are illustrated in Figure 9. The first HAYABUSA VLBI experiment was successfully carried out November 26, 2003. Figure 10 shows two examples of group delay fringes of HAYABUSA range and telemetry signals for the Kashima-Usuda baseline. We are now evaluating the obtained HAYABUSA group delays by comparing with the R&RR results.

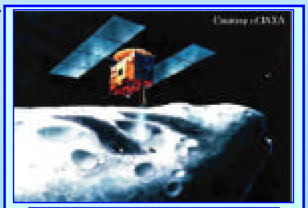

Figure 8: HAYABUSA image (ISAS/JAXA)

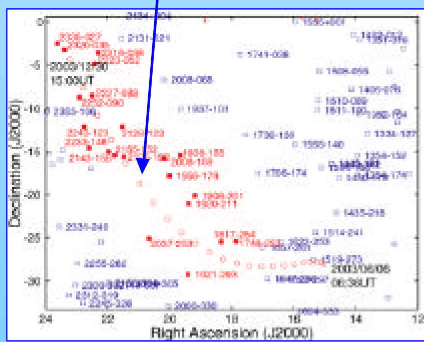

Figure 9: Trajectory of the HAYABUSA spacecraft (red circles) and nearby radio sources (red squares) from September 1 to December 31, 2003.

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*

◆*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.*

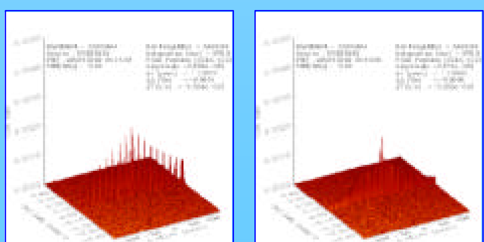

Figure 10: Detected HAYABUSA group delay fringes for the Kashima 34m -Usuda 64m baseline on November 26, 2003.
Left: range signal
Right: telemetry signal

5. Reference

JAXA web site, http://www.muses-c.isas.jaxa.jp/English/index.html, 2003.