ABSTRACT
Japanese first Mars explorer NOZOMI, which was launched in July 1998, suffered several problems during the operation period of more than five years. It reached near Mars at the end of 2003, but it was not put into the orbit around Mars. Although NOZOMI was not able to execute its main mission, it provided us a lot of good experiences from the point of the orbit determination of spacecraft. The related issues are the spin modulation, the solar radiation pressure, the small force related to the attitude change, the solar conjunction, and the orbit determination by the side lobe of the high gain antenna without the telemetry. We tried to solve these issues by the conventional way using range and Doppler data. We also tried the orbit determination by using the Delta-VLBI method (VLBI: Very Long Baseline Interferometry). In addition to this, we tried optical observations of NOZOMI at the earth swingbys.

1. Introduction

The Japanese Mars explorer NOZOMI (Figure 1) was launched in July 1998. It was planned to arrive at Mars in October 1999 (Figure 2). However, when NOZOMI left form the earth to Mars, a problem occurred and the orbit plan was changed so that it would reach Mars at the end of 2003 or at the beginning of 2004 (Figure 3). In addition to this problem, NOZOMI suffered several difficulties, such as the loss of S-band downlink, the solar conjunction, and the loss of the telemetry. Particularly the damage related to the power supply unit, which occurred at the end of April 2002, was very serious. We were not able to get the telemetry
data after that and the radio link was completely lost for about two months. However, we were able to control NOZOMI by using very special method and we carried out two earth swingbys in December 2002 and June 2003 successfully. NOZOMI was put into the orbit that goes near Mars in the middle of December of 2003. But we were not able to solve the trouble related the power supply unit and NOZOMI did not become the orbiter of Mars. This trouble of the power supply unit occurred just after strong solar flare, but the direct relationship between the trouble and the solar flare is unknown.

Although NOZOMI was not able to execute its main mission, from the point of the orbit determination of spacecraft it provided us a lot of good experiences. The most difficult work was, of course, the orbit determination for the period without the telemetry. Fortunately it was possible to get the tracking data (range and Doppler) in this period. But most of this period, the high gain antenna did not point to the earth because of a constraint of the attitude of the spacecraft. Therefore the quality of the tracking data was not good, and for some period it was impossible to get the tracking data at all. Under such critical condition, we managed to get the solution of the orbit, and we were able to carry out two earth swingbys successfully as mentioned above.

There are several other issues related the orbit determination of NOZOMI and they are the spin modulation, the solar radiation pressure, the small force related to the attitude change, and the solar conjunction. We tried to solve these issues by the conventional way using range and Doppler data. However, we also tried the new method, that is the orbit determination by using the Delta-VLBI method (VLBI: Very Long Baseline Interferometry). In addition to this, we tried optical observations of NOZOMI when it approached the earth at the earth swingbys.

Up to now, we have carried out many studied about the orbit determination of NOZOMI. In this paper, we summarize all the issues related to the orbit determination of NOZOMI especially from the point of what we have done. The quantitative results such as the accuracy of orbit determination will be reported in separate papers.

2. Orbit Determination in Normal Period

In this section, we summarize the orbit determination in the normal period. The words "normal period" mean the period when we could get the telemetry and when the high gain antenna could be pointed toward the earth. These analyses are also discussed in previous papers. The orbit determination in the critical period is discussed in the next section.
2.1 Software
We have been developing software for orbit determination of spacecraft from more than 20 years ago. This software is called ISSOP (ISAS Orbit Determination Program). It was first used for the mission of SAKIGAKE and SUISEI, which were launched in 1985 to the comet Halley. And then it was used for HITEN, which was launched 1990 for experiments of swingbys. As for NOZOMI, we tried to modify ISSOP in several points to carry out much accurate orbit determination. And also we are modifying this software in order to include VLBI data.

2.2 Spin modulation
Since NOZOMI was rotating about 7 rpm, there were spin effects in the observed data of range and Doppler. In order to carry out the accurate orbit determination, we should remove the effects of spin. We obtained a function that simulated the effects of spin, and eliminated them. For example, Doppler data of LGA-B shows spin modulation with the amplitude of about 20 cm/s, and after the elimination of spin modulation, the amplitude becomes about 1 mm/s. After the elimination of spin effect, the accuracy of orbit determination became a little better.

2.3 Solar radiation pressure
As for the solar radiation pressure, we modified our previous model largely. In our new model, the geometry and material properties of the spacecraft are taken into consideration. The spacecraft is treated as a combination of a spinning box and two flat plates, representing the spacecraft body, solar panels, and HGA dish respectively. The surface properties are area, reflectance, diffused reflectance, transparency, and direction against the spin axis. Daily change of the spacecraft orientation is also taken into account. By these modifications, the accuracy of our orbit determination became better. However, we should still improve our model to achieve much better accuracy.

2.4 Small force caused by re-orientation maneuvers
When re-orientation maneuvers were carried out, we found that there are variations about 1 mm/s in the Doppler. This means that there exists acceleration in the orbital motion at re-orientation maneuver. Such acceleration was not expected before the launch. After the trouble of S-band downlink, the re-orientation maneuvers are executed much more frequently, because X-band, which has narrower beam size, was used for downlink. This acceleration acts as perturbations of several $10^{-12}$ km/s$^2$ acceleration. It corresponds to several percent of solar radiation pressure, which has a significant influence on the orbit determination results. We tried to estimate this acceleration, but the estimated values seemed to be not accurate enough. Such estimation of small forces remained as one of the future problems.

2.5 Solar conjunction
At the beginning of the year 2001, the angle of Sun-Earth-NOZOMI became very small. This meant that NOZOMI was observed very close to the sun. When such conjunction occurs, we cannot establish the link between spacecraft and the ground stations. Actually for NOZOMI the communication was stopped for about three weeks around the conjunction. In addition to this, the range and Doppler data were affected by noise. Especially the noise level of Doppler became very large near the conjunction. As for the range, the effect of conjunction was small. The accuracy of orbit determination became worse around the conjunction.

3. Orbit Determination in Critical Period
After the loss of telemetry from NOZOMI, we could not get range and Doppler data stably. Figure 4 shows O-C of Doppler just around the telemetry loss. Until 27 April 2002, the Doppler data were normal. But the data shows strange behaviors after this. This is because the beam of HGA was straying off from the direction of the earth. Since the heater also stopped, the fuel on board was frozen. Therefore it was impossible to control the attitude and orbit of NOZOMI. In order to operate NOZOMI without telemetry, we established a special method by using an autonomous function. And we used the sunlight to melt a part of the fuel. Thus we succeeded to control of attitude and orbit of NOZOMI without telemetry and heater.

However, a big problem remained. That was
that the high gain antenna could not always point toward the earth. In fact, we used the side lobe, which was perpendicular to the direction of the main beam of the high gain antenna.

The range rate data taken under this situation showed strange biases. The typical two cases are shown in Figures 5 and 6. Figure 5 shows O-C of Doppler in November and December 2002, just before the first earth swingby. Some passes have a bias in the unit of about 0.4 cm/s. Figure 6 shows O-C of Doppler in June 2004. In this case, one pass splits into several bands. This feature can be seen only when the integration time of Doppler is the same as the spin period of NOZOMI. If the integration time is different from the spin period, we would see O-C with very large noise.

When we carried out the orbit determination, we selected Doppler data only around 0 in such figures of O-C. As for the range there was no such strange bias. However, when we use the side lobe of the high gain antenna, the range data can be obtained up to the distance of about six million km. This means that we must determine the orbit of NOZOMI in the period of about one month before and after the earth swingbys.

In this critical situation, we carried out the orbit determinations for the two earth swingbys. The results of the covariance analysis shows that the accuracies of orbit determination is about one or several km in position and several or 10 mm/s in velocity just before the swingbys. Just after the swingbys, the accuracies are about ten km and several cm/s. Jet Propulsion Laboratory (JPL) supported the orbit determination of NOZOMI by using the tracking data of Deep Space Network (DSN), and we compared the results of our orbit determination with those of JPL. The differences were typically several km in the position and 1 cm/s in the velocity. We think the agreement of the results is satisfactory under such unusual and critical conditions. Based on these orbit determinations, we were able to perform the two earth swingbys successfully.

4. Delta-VLBI and Optical Observations

In the period around the two earth swingbys, we tried observations of Delta-VLBI to back up the orbit determination by range and Doppler. The Delta-VLBI method is to observe NOZOMI and Quasars by using two or more antennas simultaneously and derive the delay time. This method itself is not new in Japan. Theoretical studies have been done for many years, and there were several trial observations, too. However, for NOZOMI, we carried out quite extensive attempt in collaboration with many organizations, such as NICT (National Institute of Information and Communication Technology), NAO (National Astronomical Observatory of Japan), GSI (Geographical Survey Institute of Japan), Gifu university, Yamaguchi university, Hokkaido university,
and Canada (CRESTech/SGL). These organizations have facilities of VLBI for astronomy and/or geodesy.

We carried out the Delta-VLBI observation of NOZOMI more than 30 days. And after various works, we were able to derive the delay time by carrying out correlation analysis. The results of the Delta-VLBI observation are consistent with those of range and Doppler. However, the derived delay time shows rather large scattering (about several 10 to 100 nsec). We tried to determine the orbit of NOZOMI by including these Delta-VLBI data to the range and Doppler data, but the results were not good. We think the reason is the large scattering of the data. We are now trying further analyses to solve this problem.

On the days of the first (Dec. 2002) and second (June 2003) earth swingby, we tried optical observations of NOZOMI from ground-based observatories. The purpose of this optical observation is mainly the public outreach, but observed data can be used to check the result of orbit determination. We asked several observatories in Japan to observe NOZOMI, and 14 observatories or groups tried to observe NOZOMI at the swingbys. However, the weather was not good on both days of the first and second earth swingbys, and most observations were unsuccessful. Only the observation from Kuma Kogen Astronomical Observatory was successful at the second earth swingby, and two images of NOZOMI were taken.

We compared the observed position with the results of the orbit determination by ISAS and JPL. The results of optical observation are among the determined values and we can say that the agreement is quite good. Thus, the results of the orbit determination were confirmed by this optical observation.

5. Conclusions

We have done many analyses for the orbit determination of NOZOMI, such as the spin modulation, the solar radiation pressure, the small force caused by re-orientation maneuver, and the solar conjunction. We have reached a certain technical level to achieve accurate orbit determination of spacecraft in the deep space. Moreover, we could manage the orbit determination under such critical situation that there was no telemetry and the range and Doppler data were unusual. As the result, NOZOMI was finally put on the orbit that goes to Mars.

Fig. 7: O-C of Doppler data for all the mission period
In this plot, the range rate bias is not eliminated.
As for the Delta-VLBI observations, we have achieved the technique of Delta-VLBI for spacecraft in deep space. But we should continue our work much further to make it possible to carry out orbit determination with the Delta-VLBI data. The optical observation at the earth swingbys was optional, but it was successful, too.

In conclusion, NOZOMI gave us a lot of experience related to the orbit determination, and in this point, we can say the mission was quite valuable. At the end of this paper we show O-C of Doppler data for all the mission period in Figure 7. This figure is the landmark of what we did for NOZOMI. NOZOMI was the first Japanese spacecraft that went near the planet Mars. It was a quite pity that NOZOMI could not carry out scientific observations. We do hope that we can try the mission to Mars again in the near future.

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References