ON THE LUNAR AND HELIOCENTRIC GRAVITY ASSIST EXPERIENCED IN THE PLANET-B (“NOZOMI”)

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Abstract

The PLANET-B spacecraft of the Institute of Space and Astronautical Science (ISAS) of Japan was successfully launched on July 4, 1998 and currently on the journey to the Mars. It was renamed “Nozomi” (Hope) after the launch. It so far performed two lunar swingbys together with the solar gravity assist to accelerate its speed to save the fuel onboard. This escape scheme was firstly taken by the spacecraft and exhibits the new path to the interplanetary flight widely available for the smaller spacecraft. Eventually it saved 120 m/sec ΔV that is converted to 24 kg dry payload, whereas the scientific payload carried by the Nozomi is about 30 kg. The spacecraft executed the powered swingby to kick itself to the interplanetary flight on December 20, 19998, however, an incompletely opened latching valve prevented it from generating the ΔV as planned. The paper also describes the alternative strategies developed immediately after this incident happened and present the newly updated orbital sequence to the Mars. ISAS decided to shift the sequence and make Nozomi arrive at the Mars at the end of 2003 to the beginning of 2004.

Introduction

The PLANET-B spacecraft that weighs about 540 kg including the bi-propellant fuel of 285 kg was launched from Kagoshima Space Center of Japan by the Institute of Space and Astronautical Science (ISAS) on July 4 in 1998. The spacecraft was renamed later as “Nozomi” (Hope). Nozomi is the Mars orbiter for the plasma physics observation carrying the international payload of about 30 kg aiming at disclosing the solar interaction with the Martian intrinsic magnetic field. The spacecraft is illustrated in Fig. 1.

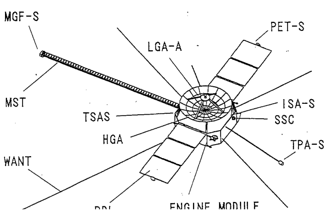

Fig. 1 The PLANET-B “Nozomi”

Spacecraft

Originally it was planned to be launched in 1996, however, owing to the delayed launcher development, it was slipped to 1998. The window in 1996 was the best window among several years and the alternative trajectory sequence had to be introduced to compensate for the payload capability deficit. What ISAS devised for this purpose was to utilize the lunar and solar gravity assist to boost its speed up beyond the escape velocity from that corresponding to the trans-lunar trajectory. This pumping mechanism accelerates the spacecraft velocity by almost 120 m/sec that deserves to 24 kg of the dry spacecraft mass. In view of the total spacecraft mass, it is well understood how the use of this scheme is advantageous. The subsequent sections present the essence of the idea and how Nozomi has performed this sophisticated trajectory maneuvers.

The initial trajectory of Nozomi was the trans-lunar ellipse on which the spacecraft was injected through a short low-Earth parking as shown in Fig. 2.

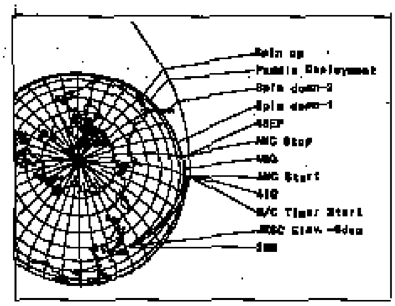

Fig. 2 Injection to Trans Lunar Trajectory

The spacecraft was not visible from Japan and for the launch and early orbit operation, ISAS requested NASA DSN and JPL MMNAV to provide us with the tracking and navigation information. This time, Santiago site of Chilly University had the best location to track Nozomi flying outward around the zenith there and the spacecraft was acquired at Usuda Deep Space Center (UDSC) of ISAS almost half a day later. Ground trace as presented in Fig. 3.

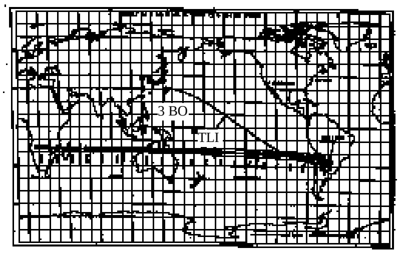

Fig. 3 Ground Trace of the Launch and Early Operation

After the two lunar swingbys, Nozomi conducted the powered swingby to finally kick it out to the interplanetary field, when it returned to the perigee point of 1,000 km altitude on December 20th last year. About 420 m/s ΔV was planned during while it was not visible from the Japanese site. It was the bi-propellant burn for about seven minutes long. An incident took place during the maneuver. Since the oxidizer latching valve was not fully open, the bi-propellant engine could not produce the enough thrust, which resulted in 100 m/sec ΔV deficit with respect to that anticipated. The energy sensitivity reduced quite rapidly from the perigee passage and when it was acquired from the Japanese ground station, the ΔV required for compensation had already grown up to more than 350 m/sec. The total ΔV capability given to Nozomi was approximately 2,000 m/sec among which fixed amount ΔV for both escape and capture burn is for the most part 1,800 m/s. The rest of it 200 m/sec was reserved for injection error correction and trim maneuvers and the attitude reorientation etc. Therefore, the extra fuel consumption to compensate for the escape burn threatened the completion of the original scenario. Immediately after the incident, ISAS started the alteration of the orbital sequence to make the Nozomi spacecraft to accomplish the science mission. There were several alternative strategies proposed, among which the option of making it experience two more Earth gravity assists to the Mars was decided to be taken. The details will be descried later.

Launch to the Escape Burn Maneuver

Eighteen trajectory maneuvers were so far done. The number of it was more than expected before launch. This time, the launcher injection error was extraordinary large and the compensation took some extra fuel. But this is within the correction capability that the spacecraft was designed equipped with. Table-1 below summarizes the Trajectory Correction Maneuvers (TCMs) so far performed. Note July 4 is the launch date and December 20 is the escape burn date.

Table-1 TCM History from Launch

ΔV 1-1	17.25[m/sec]	7/4	OMS
ΔV 1-2	18.52[m/sec]	7/4	OMS
ΔV 1-3	18.52[m/sec]	7/4	OMS
ΔV 2	7.82[m/sec]	7/11	Ax
ΔV 3	8.65[m/sec]	7/19	Ax
ΔV 3c	1.39[m/sec]	7/19	Ax
ΔV 4	5.16[m/sec]	7/31	Ax
ΔV 5	49.98[m/sec]	8/16	OMS
ΔV 5c	13.41[m/sec]	8/28	Ax
ΔV 6	3.34[m/sec]	9/7	Ax
ΔV 6c	0.019+0.013[m/sec]	9/16	Ax + Rd
ΔV 6c2	0.60[m/sec]	10/1	Rd
ΔV 7	7.65[m/sec]	11/4	OMS
ΔV 7c	0.188+0.430[m/sec]	12/4	Ax + Rd
ΔV 7c2	0.103+0.279[m/sec]	12/16	Ax + Rd
ΔV 8	327.25[m/sec]	12/20	OMS(TMI)
ΔV 8c	317.30[m/sec]	12/20	OMS
ΔV 8c2	127.11[m/sec]*	12/20	OMS

The orbital sequence taken by Nozomi was very unique in its boosting mechanism. The primary mechanism is briefly described here. First of all, ISAS intended to make the use of the lunar swingby to accelerate it. As obviously a single lunar swingby is not adequate for increasing the orbital energy required for the journey to the Mars. Just the repetition of the lunar swingbys does not help in pumping the energy up. The relative velocity to the moon needs to be higher so that the another advantage can be extracted from the swingby. To this end, the spacecraft trajectory was designed to be thrown away once to the Earth gravity field boundary region where the solar gravity affects the trajectory around the Earth. The effect is so big as to make the orbit retrograde resulting in the higher swingby velocity at the second encounter with the moon. The effect is from dynamics point of view the same contribution as that employed in our LUNAR-A mission where the solar gravity effect was utilized to lower the encounter velocity to the moon when it is captured around it. The idea was actually demonstrated in our Hiten mission in which the spacecraft took the advantage of the solar gravity assist having enabled it orbit around the moon with less fuel. The details of these ideas on how the trajectory can be synthesized are presented in the reference[1]. There was also shown Three lunar swingby strategy to escape, which may interest the reader.

The firs swingby took place on September 24 and the second one on December 18th in 19998. When Nozomi finished its second lunar swingby, the orbital energy had already exceeded well beyond the escape level and the last perigee passage is therefore Earth swingby with ΔV, in other word, the Earth powered swingby. The swingby is relatively tight swingby in which the lowest altitude was 1,000 km above the surface. In order not only to add the velocity but also to bend the escape direction in compliance with the flight to the Mars, the escape (not really for escape) maneuver of 420 m/sec was attempted carried out on Dec. 20th last year. The plan view of the launch to escape is shown in Fig. 4.

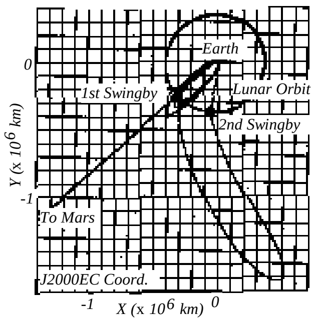

Fig. 4 Lunar Swingbys to Escape for Mars

Up to the first swingby, ISAS adopted the six and half revolution transfer scheme this time. In ISAS Hiten and Geotail missions, the window expansion scheme with less fuel reserve was developed. In those past missions, four and a half revolution transfer scheme was adopted but taking the much more rigorous flight anticipated for Nozomi during its energy pumping phase, the safer approach of six and half revolution transfer was utilized. Fig. 5 below schematically shows the scheme that was perfectly traced by the actual flight.

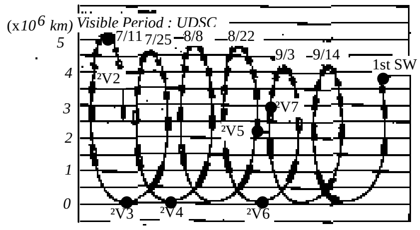

Fig. 5 Trans-Lunar Orbit Operation

The flight between two swingbys is the one of the most characteristic points in the paper. Fig. 6 below shows the trajectory of it followed by the Earth powered swingby. As a matter of fact, the trajectory does not lie on the ecliptic plane. And the trajectory was the first one that has changed its flight direction from direct to retrograde. It might be also noticed that the outbound trajectory is inclined and that the interplanetary orbit plane is inclined with respect to the ecliptic plane. It is illustrated in Fig. 8.

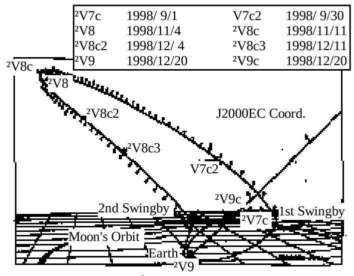

Fig. 6 Utilizing Solar Gravity Perturbation to Accelerate s/c Speed

The second lunar swingby was the important point which governs the Earth perigee height as well as the escape outgoing asymptote direction. Fig. 7 below shows the orbit determination results obtained from both MMNAV/JPL and ISAS. The agreement is satisfactory and both indicate the swingby point accuracy in the B-plane was well within one kilometer.

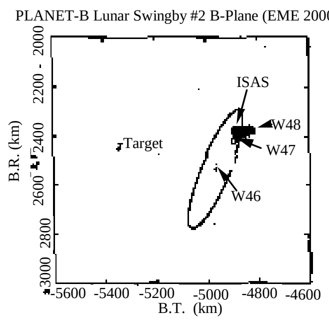

Fig. 7 Orbit Determination Accuracy @2nd Lunar Swingby

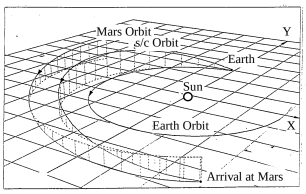

Fig. 8 Interplanetary Trajectory to Mars

On Dec. 20th in 1998, Trans-Mars Insertion (TMI) maneuver was attempted. It planned 420 m/sec ΔV at the perigee passage. It occurred in the midst of Pacific ocean followed by the flight over the northern America and European continent. (see Fig. 9) The spacecraft was not visible and was not controlled from ISAS for almost half a day. As mentioned above, when ISAS had AOS, the energy sensitivity had reduced greatly and this lead to the extra fuel consumption. The troubled latching valve makes the thrust dwindled and the burn did not give the exact speed to the spacecraft toward the Mars. ISAS anyhow performed the compensation maneuver to make it reach the Mars this October, even though the fuel shortage was anticipated.

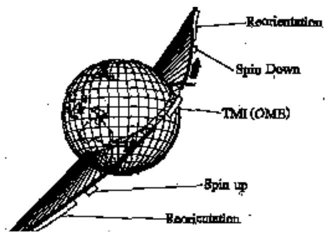

Fig. 9 Trans-Mars Insertion Earth Powered Swingby

After the compensation maneuver finished, ISAS set about devising the orbital sequence that may be substituted with. During two weeks, there were found calculated four ideas to it. They are listed in Table 2 below.

Table-2 A List of Alternative Sequence

MOI Date	Swingbys	Type	ΔV(m/s)
1. Oct, ‘99	No SW		1180
2. Aug, ‘00	1 Mars SW	Pwrd	1080
3. July, ‘02	1 Mars SW	Pwrd	1020
4. Jan. 1, ‘04	2 Earth SW	No Pwrd	840
5. July 20, ‘06	1 Mars SW	No Pwrd	960

After the TMI ended, the remaining fuel available was estimated 1,060 n/sec including that for the attitude and trim maneuvers. The idea 3 may have been thought what barely satisfies the fuel budget. But it was turned down by taking any compensation maneuvers into account. As clearly understood by the above Table, the proposal 4 was decided to be taken. It did nit assume any powered swing by that must be performed accurately and a little tough specification for the RCS aboard not in perfect condition. The fourth idea only postulates the bi-propellant burns at the TCM scheduled at the end of February and at the MOI. Therefore, it is a safer way. Besides, the fuel amount required for it is surprisingly low and good enough for the whole science missions. The idea 1 trajectory is shown below in Fig. 10.

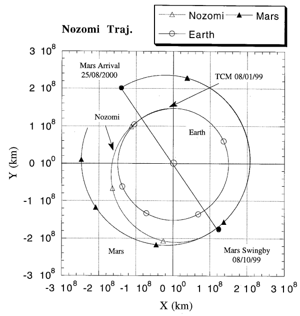

Fig. 10 Mars Swingby to Reach Mars in 2000

The idea 4 orbital plot is on Fig. 11 below. The essence lies in arrival position at the Mars is shifted closer to the aphelion. The ratio of the relative velocity to the Mars orbital velocity is frozen, while the difference between them is diminished, so that the MOI deceleration requirement is loosed. Suppose the relative velocity at MOI on October of 1999, it is 3.4 km/sec, on the other hand, it is down to 2.7 km/s for the idea 4. It saves almost 300 m/sec. The Table-3 lists the ΔVs scheduled.

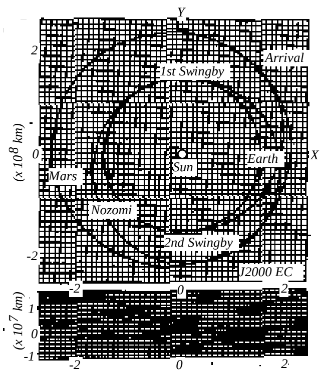

Fig. 11 Double Earth Swingbys to reach Mars in 2003-2004

Table-3 Altered TCM History

ΔV1	79.74 [m/sec]	2/27/99	OME
ΔV2	754.05 [m/sec]	1/ 1/04	OME

The flight connects two swingbys is the highly inclined with respect to the ecliptic plane. It is the synchronized swingbys with the period ratio of 1.0 making the encounter again half a year later exactly. Both swingbys are polar flybys flying over the Antarctica. Primary purpose of these swingbys is to alter the ellipse axis direction opposed to the original arrival point.

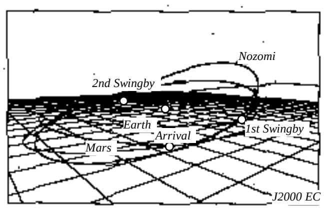

Fig. 12 Bird View of the New SOE

When the orbit is plotted against the Sun-Earth line fixed coordinate, it is drawn as in Fig. 13. As recognized, the flight back to the Earth in 2002 is the synchronous recurrent trajectory whose period ratio is 1:3. It is not shown well on the figure, but the trajectory is elevated and downed just above the Earth for half a year and flies to the Mars.

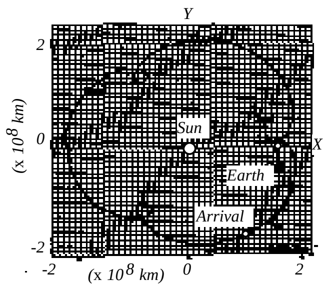

Fig. 13 New SOE in Sun-Earth Fixed Coord.

Associated with this alternative scenario, the angles properties and distance information were examined, which appears in Fig. 14. Fortunately as viewed, even under the attitude which points the HGA toward the Earth, the Sun angle does not exceed 45 degrees except for the flight between the Earth swingbys. It indicates no solar power availability.

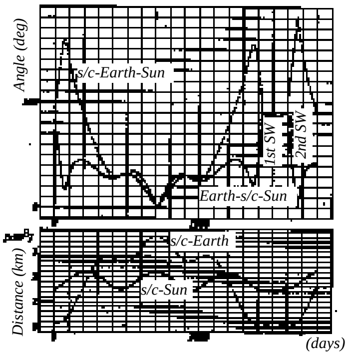

Fig. 14 Angle/Distance Properties in New SOE

The swingby information and MOI parameters are listed in Table-4.

Table-4 Swingbys Parameters

	1st SW	2nd SW	MOI	
Min. Dist.:	35557	15075	3547	[km]
Relative Vel.:	5.757	7.933	5.607	[km/s]
V-infinity:	3.275	3.169	2.699	[km/s]
SW Pl. Phase:	-86.62	-89.33	90.00	[deg]
Closest Pass.:	20/12/02	19/6/03	1/1/04	[UTC]

Remarks

The use of lunar and solar gravity assist demonstrated by Nozomi is viable in the other interplanetary missions. Discovery class smaller spacecraft missions are proposed recently and this new way for the planetary flight will make up for the launcher transportation they may assume. A mishap experienced by Nozomi when it departed from the Earth was recovered by the alternative sequence using two more Earth swingbys. It did not give up any portion of the original missions. ISAS is sure Nozomi continues and accomplishes its journey to the Mars by the year of 2004.

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