SELENE TRANSLUNAR TRAJECTORY AND LUNAR ORBIT INJECTION

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Abstract

This paper deals with the three topics related to the translunar trajectory and lunar orbit injection of SELENE. The first is the midcourse maneuver on the translunar trajectory. Two midcourse maneuvers are scheduled to achieve the sufficient accuracy in lunar closest approach under the assumed condition of various errors. The second is the lunar orbit injection strategy. Deployed Two large structures restrict the lunar orbit injection acceleration. To avoid the severe gravity loss due to this low acceleration, the injection maneuver is divided into six small maneuvers. The third topic is the analysis as to the eclipse on the translunar trajectory. The eclipse on the translunar trajectory, which could be the restriction to the launch window, turn out not to be the problem as the result of the analysis.

Keywords: SELENE, midcourse correction, lunar orbit injection, launch window.

Introduction

SELENE (SELenological and Engineering Explorer), the first ISAS & NASDA joint mission to the moon is scheduled to be launched by H-IIA rocket in summer, 2003. SELENE is a lunar polar orbiter of 100km altitude with a relay satellite for far-side tracking coverage. Mission overview of SELENE is shown in Fig. 1 and precisely described on Ref. 1. As is shown in Fig. 1, the mission profile of SELENE is unique. Therefore, the design of SELENE includes many items in the field of trajectory design. The major items related to trajectory design of SELENE are listed in Table 1. Items 1), 3) are precisely described in Ref. 2 and items 5), 6), 7) are described in Ref. 3.

This paper deals with the translunar trajectory and lunar orbit injection of SELENE. Three major topics which we are to mention are “midcourese correction maneuver”, “lunar orbit injection”, and “eclipse on translunar trajectory”. Details of these topics are described from the next section.

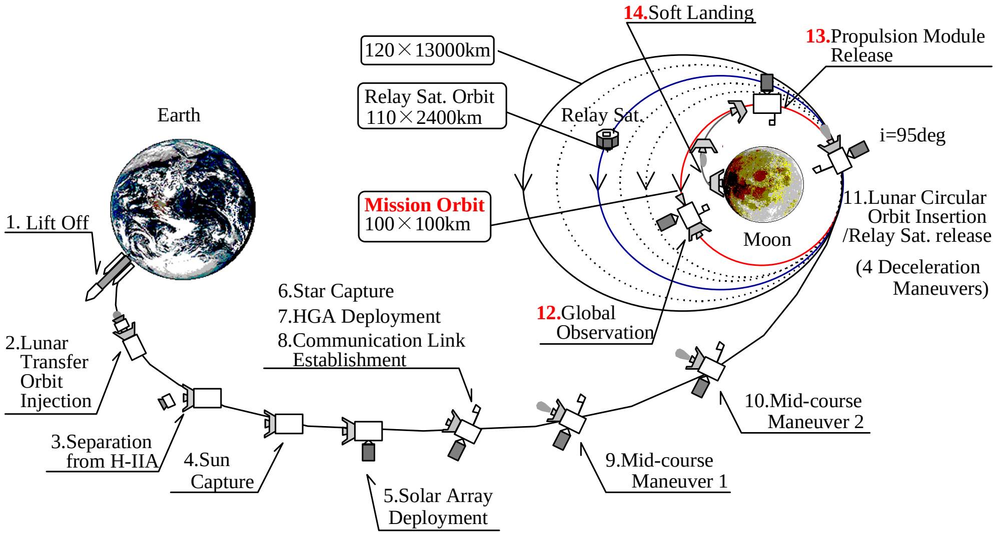

Figure 1 SELENE Mission Overview

Table 1 Trajectory Design Item of SELENE

1) Nominal trajectory design
2) Midcourse Correction Maneuver
3) Launch Window
4) Lunar Orbit Injection
5) Lunar Orbit Maintenance
6) Relay Satellite Orbit
7) Landing Trajectory

Midcourse Correction Maneuver

Two midcourse maneuvers are scheduled to be executed on the way of translunar trajectory. The timing of the maneuvers and their correction objectives are shown in Table 2. Details of each maneuver and their Δv estimation process are shown in the followings.

Table 2 Midcourse Correction Maneuvers

No.	Timing*	Correction objectives
1	24 hours	(Launch delay) Injection error
2	96 hours	Navigation error at the first maneuver Maneuver error at the first maneuver

*from translunar trajectory injection

Midcourse Maneuver 1

The first maneuver, which is scheduled at the 24 hours after translunar trajectory injection, is executed to correct the error caused by the H-IIA rocket injection error.

Error covariance of the translunar trajectory injection is shown in Table 3. The values are expressed in J2000 coordinate system, and they are for the case of the launch in July 14, 2003. If the error is propagated along the translunar trajectory until the lunar orbit injection without midcourse correction, the error covariance ellipse on the lunar impact plane (B-plane) results in the size shown as Fig. 2. The objective of the first midcourse maneuver is to correct the actual impact point (somewhere in the ellipse) to the nominal impact point (the center of the ellipse).

Table 3. Lunar Transfer Injection Error (J2000)

	x(km)	y(km)	z(km)	vx(km/s)	vy(km/s)	vz(km/s)
x	1.27e+1					
y	-1.37e+2	1.92e+3				
z	-6.75e+0	6.67e+2	1.42e+3			
vx	1.03e-1	-1.67e+0	-1.10e+0	1.68e-3		
vy	2.21e-2	-3.02e-1	-7.95e-2	2.51e-4	4.88e-5	
vz	-2.06e-3	-8.71e-2	-2.55e-1	1.73e-4	8.98e-6	4.75e-5

Figure 2. Error covariance on B-plane (Lunar Transfer Injection Error)

The Δv required for this correction is estimated for the worst case. Four points are selected (CASE 1 to 4 in the figure) from Fig. 2 for the Δv estimation. Δv required for the correction differs with the timing when the correction maneuver is executed. Fig. 3 shows the results of the Δv estimation. The horizontal axis indicates the timing of the maneuver by the hours past the lunar transfer injection (LTI). Δv is calculated under the condition of the arrival time fixed for each CASE.

Figure 3. Midcourse Correction Δv (Lunar Transfer Injection Error)

Though we have minimal Δv point before 12 hours past LTI, those timings are not adopted from the point of view of the orbit determination accuracy. 24 hours past LTI is selected as the timing of the first midcourse maneuver and 48m/s correction Δv is estimated for the worst case.

Launch delay is allowed to be up to 20 minutes in the launch date. Originally, the error in lunar transfer injection caused by the launch delay is also treated as the error source to be corrected in the first midcourse maneuver. However, it is made clear that the error caused by the launch delay is corrected sufficiently by the rocket's guidance, midcourse Δv for the launch delay correction is not summed up.

Midcourse Maneuver 2

The second midcourse maneuver is scheduled at 96 hours past LTI. This maneuver aims to correct the error caused in the first midcourse maneuver. The error sources of the first midcourse maneuver are the orbit determination error and maneuver error.

The orbit determination error at the first midcourse maneuver is shown in Table 4. The values are expressed in J2000 coordinate system and assuming the use of single domestic ground station. The error is propagated along the translunar trajectory and projected on the lunar impact plane as the case of injection error mentioned previously. The Δv required for the worst case is estimated as 5m/s.

If NASA Deep Space Network ground stations can be used for the tracking support, more accurate orbit determination can be made at earlier timing. It contributes to reduce the Δv for injection error correction by shifting the first maneuver timing. At the same time, it reduces the Δv for the first maneuver orbit determination error correction by its fine accuracy.

Table 4. Orbit Determination Error (J2000)
(at the first midcourse maneuver)

	x(km)	y(km)	z(km)	vx(km/s)	vy(km/s)	vz(km/s)
x	1.96e+3					
y	-3.21e+2	5.28e+1				
z	9.23e+3	-1.51e+3	4.35e+4			
vx	-8.77e-3	1.43e-3	-4.13e-2	3.92e-8		
vy	3.64e-2	-5.98e-3	1.72e-1	-1.63e-7	6.79e-7	
vz	2.43e-2	-3.97e-3	1.14e-1	-1.09e-7	4.51e-7	3.01e-7

The maneuver error at the first midcourse maneuver is shown in Table 5. The error is again propagated along the translunar trajectory and projected on the lunar impact plane as the case of other errors mentioned previously. The Δv required for the worst case is estimated as 48m/s. Values of the assumed maneuver error are now under re-estimating based on the midcourse guidance and control analysis.

Table 5. Maneuver Error
(at the first midcourse maneuver)

Tail off impulse	200Ns (0.8m/s)
Attitude error	1 deg

The results of the midcourse correction maneuver analysis are listed in Table 6. Δv of 68m/s in total (RSS of three elements) is prepared for midcourse correction maneuver on translunar trajectory.

Table 6. Midcourse Maneuver Analysis Results

Item		Δv
1st	Injection error	48m/s
2nd	Navigation error at 1st maneuver	5m/s
	Maneuver error at 1st maneuver	48m/s
RSS		68m/s

Lunar Orbit Injection

Two large structures, the solar paddle and the high gain antenna, are deployed on the translunar trajectory (Fig. 4). Not to damage these deployed structures, lunar injection maneuver have to be executed with low acceleration. This means eight 40N bi-propellant thrusters are used for lunar injection maneuver instead of the large 1700N thruster which will be used in the landing sequence. The acceleration in this maneuver is approximately 320N/2000kg.

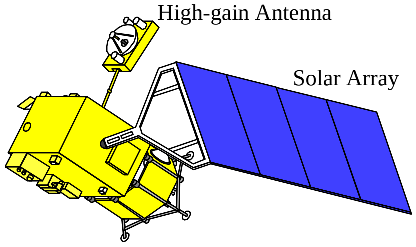

Figure 4. Lunar Orbit Injection Configuration

Δv is estimated as approximately 800m/s in impulsive for the injection to the 100km altitude lunar circular orbit. The Δv value depends on the launch date. Direct injection to this mission circular orbit causes severe gravity loss because of the long low acceleration maneuver. The injection maneuver is divided into six small maneuvers to restrain the effect of gravity loss to the level which is acceptable from the system's point of view. The sequence of these maneuvers are shown in Table 7. Top view of the injection trajectory and the history of perilune altitude during the maneuvers are shown in Fig. 5 and 6 respectively.

Table 7. Lunar Orbit Injection Sequence

Orbit	Altitude	Cycle	Δv	Maneuver
Approach	perilune 150 km			
			292m/s	LOI1
LO1	91 x 13024 km	2		
			133m/s	LOI2
LO2	96 x 5003 km	7		
			127m/s	LOI3
LO3	99 x 2400 km	5		
			110m/s	LOI4
LO4	103 x 1203 km	8		
			100m/s	LOI5
LO5	101 x 503 km	11		
			79m/s	LOI6
LO6	100 x 100 km	12		

Figure 5. Top view of injection trajectory

Figure 6. History of perilune altitude

Maneuver direction is assumed to be tangential and total required Δv for this case is 840m/s, which is 2.9% larger compared to ideal impulsive Δv. As mentioned before, the injection maneuver is executed by eight 40N thrusters. Supposing one thruster failure, at the same time the opposite thruster is stopped for balancing, injection maneuver with six 40N thruster (240N) is investigated. The loss in this case is 4.9% and this value is acceptable from the system point of view.

The loss depends largely on maneuver Δv and the loss in LOI1 is the largest in six maneuvers. Therefore, the best way to reduce the total loss is to separate the LOI1 maneuver into two division. However, this separation is not adopted from the following reason. The separation of the LOI1 means the raising of the apolune altitude of the initial elliptical orbit. The effect of the earth's gravity is large at high altitude and perturb the orbit seriously. Increasing of the perilune altitude in Fig. 6 is one example. We set the tolerable apolune altitude to 13000km for avoiding the serious perturbation and didn't select the option of LOI1 separation.

LO3 is the orbit where the relay satellite is to be released. Since the relay satellite has no maneuver capability, the initial orbit setting must be done carefully to complete its mission. The detail of relay satellite orbit design process is described in Ref. 2.

Cycles in each orbit is temporalily set as "1 day stay" in each orbit for orbit determination. However, these "cycles" must be determined by considering many aspects, such as orbit determination accuracy, visibility from ground station, orbit perturbation. The investigation is now under execution for this point.

Eclipse on Translunar Trajectory

The launch window of SELENE is analyzed considering four restrictions (Table 8). Detail about this analysis is precisely described in Ref. 2. Considering first three restrictions, 13 days in one month remain for the launch window assuming the launch in summer, 2003 . What we want to introduce here is the result of the re-estimation of the eclipse on the translunar trajectory.

Table8. Constraints as to launch window

1) translunar trajectory injection point
2) lunar orbit injection Δv
3) relay satellite altitude during mission
4) eclipse on translunar trajectory

SELENE is designed to survive during its stay in eclipse by onboard battery. The longest eclipse that is expected on one year lunar orbiting phase is lunar eclipse (the moon in shadow of the earth). The duration of this eclipse is about 300 minutes and the battery is sized to survive this duration.

The length of the eclipse on the translunar trajectory differs with the launch date. The reason is that the geometric relation between the translunar trajectory and the earth's shadow or moon's shadow differs with the launch date. If the duration of the eclipse exceed the battery capacity for some launch date, it results in the reduction of the launch window.

The positional relation of the sun, the earth and the moon is shown in Fig. 7.There is two cases that the long eclipse duration is expected. The first case is that SELENE go into the shadow of the moon (CASE 1 in Fig. 7). The low velocity of spacecraft may cause the long eclipse duration. The worst case occurs in the launch date of July 2, 2003 and the eclipse duration is approximately 180 minutes. This duration is acceptable. The second case is that SELENE go into the shadow of the earth just after launch (CASE 2 in Fig. 7). Though the spacecraft velocity is high and the eclipse duration is expected to be short, the battery is partially consumed during the launch process. The worst case occurs in the launch date of July 12, 2003 and the eclipse duration is approximately 90 minutes. This duration is also acceptable.

Figure 7. Positional Relation of Sun, Earth, Moon

Consequently, it is confirmed that the eclipse on the translunar trajectory does not restrict thelalaunch window.

Conclusion

Three topics related to the translunar trajectory and lunar orbit injection of SELENE are introduced. The first is the midcourse maneuver on the translunar trajectory. Two midcourse maneuver are planned to correct the error caused by three sources. Midcourse correction Δv is estimated as 68m/s for 3 s. The second topic is the lunar orbit injection strategy. Lunar injection is separated into six maneuvers. This is to avoid the effect of gravity loss caused by low acceleration. As a result, the Δv loss compared to impulsive Δv is suppressed to 2.9%. The third topic is as to the eclipse on the translunar trajectory. It is confirmed that the eclipse on the translunar trajectory does not restrict the launch window.

SELENE project is now in phase B (definition design) and is phased up to phase C (preliminary design phase) this spring. More detailed studies, tests and simulations will be done to confirm system feasibility.

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