Error Sensitivity Analysis for Lunar Semi-Hard Impact Orbit

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This study describes the results of the error sensitivity analysis for OMOTENASHI(Outstanding MOon exploration TEchnologies demonstrated by NAno Semi-Hard Impactor) mission. OMOTENASHI is the 6U CubeSat Lunar semi-hard impactor which is planned to be launched as a secondary payload of NASA's SLS/EM-1 mission. OMOTENASHI executes dV1 1 day after the separation from ICPS(Interim Cryogenic Propulsion Stage) to inject itself into the Lunar impact orbit. Short before the impact, dV2 of about 2.5 km/s is applied to decelerate OMOTENASHI and it semi-hard impacts on the Lunar surface. The dispersion error, navigation error and delta-V control error produces the variation of the impact points hence the orbital parameters such as impact angle should be meticulously assessed considering both of the variation of the impact locations and the Lunar topography. This analysis gives essential information to determine a robust orbital parameters.

月セミハードインパクト軌道における誤差感度解析

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本発表では NASA/SLS 相乗り CubeSat ミッションである OMOTENASHI(Outstanding MOon exploration TEchnologies demonstrated by NAno Semi-Hard Impactor)ミッションに向けた月セミハードインパクト軌道における誤差感度解析の結果を示す．OMOTENAHI は SLS/ICPS(Interim Cryogenic Propulsion Stage)から分離後，一日後に ΔV1 を実施し，月衝突軌道に移行したのち，月表面到達の直前に約 2.5 km/s の ΔV2 を実施し，月表面にセミハード着陸を行う．一方，ΔV1 時における航法誤差，ΔV 制御誤差により着陸点の誤差が生じるため，この着地点分散と月地形を勘案しつつ月進入角度等の軌道パラメータを決める必要がある．その判断材料として，本検討では分離誤差，航法誤差，ΔV 制御誤差による着地点に対する感度評価を実施した．その結果を報告する．

1. Introduction

The "Outstanding MOon exploration TEchnologies demonstrated by NAno Semi-Hard Impactor", OMOTENASHI is one of the thirteen 6U CubeSats being launched with Exploration Mission-1 (EM-1) by NASA's Space Launch System (SLS). The launch is scheduled in the fall of 2018. Fig .1 shows the overview of the SLS and the MPCV Stage Adapter (MSA) on which the thirteen CubeSats are loaded on. MPCV stands for Multi-Purpose Crew Vehicle, in other name, Orion.

OMOTENASHI will be the world first nano-lander to the Lunar surface. OMOTENASHI has solid propellant kick motor with capability of about 2.5 km/s delta-V. OMOTENASHI changes its orbit 1-day after the deployment into the impact orbit to the Lunar surface, and the on-board kick motor is ignited just before the impact to decelerate the spacecraft, and it freely falls onto the surface. OMOTENASHI has a shock absorbing mechanism which protects the Surface Probe (SP) from the impact. Fig. 2 shows the overview of the operation.

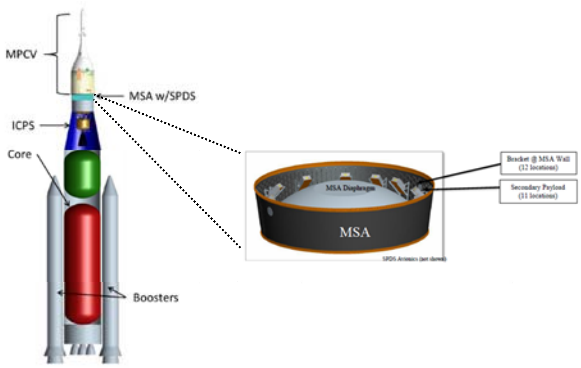

Fig. 1 Overview of SLS and MSA.

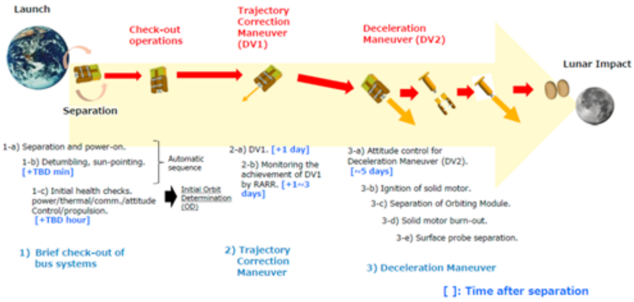

Fig. 2 Overview of the operation

The shock absorbing mechanism is under design, however the maximum allowable impact velocity is tentatively set to be 30 m/s. In the nominal plan, OMOTENASHI is "stopped" after the deceleration delta-V and the spacecraft freely falls onto the Lunar surface. When the free fall from an altitude h is described as the following:

$$V_{impact} = \sqrt{2gh} \tag{1}$$

where g is the Lunar's gravitational acceleration which is about 1.6 m/s^2. From Eqs. (1), the altitude at the burn out of the deceleration delta-V should be less than only 280 m. To achieve this value, precise knowledge and accurate orbit and attitude control will be necessary.

Note that this is preliminary analysis. The detail analysis will be shown in [Ozawa, et al., 2017][1)].

2. Nominal Orbit Design

2.1 Initial Condition at Deployment

In this paper, it is assumed that OMOTENASHI flies along the pre-designed nominal trajectory through implicit guidance scheme. The nominal trajectory is obtained through random search of ΔV_1 which is the delta-V to inject OMOTENASHI into the Lunar impact orbit. Fig. 3 shows the diagram of the random search.

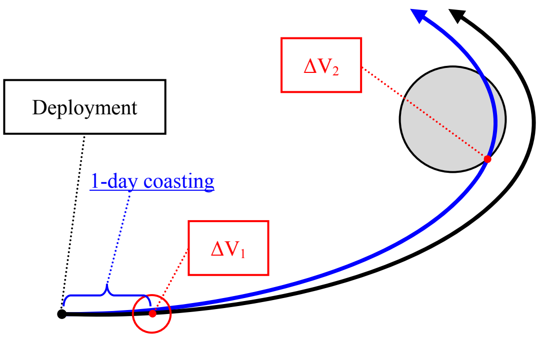

Fig. 3 Diagram of the random search.

Interim Cryogenic Propulsion Stage, ICPS which is the second stage of SLS, is intended to be disposed into a heliocentric orbit via Lunar swing-by i.e., heliocentric disposal. The current condition at the deployment produces the orbit whose perilun altitude is 573 km. Fig. 4 and 5 show the Lunar flyby orbit as viewed in Earth-Moon fixed frame and J2000EQ, respectively.

As aforementioned, ΔV_1, which is applied 1-day coasting after the deployment, is randomly applied within 0~20 m/s, and all directions to obtain candidate nominal trajectories. As described in Fig. 3, ΔV_1 decreases the perilun altitude less than the Lunar radius.

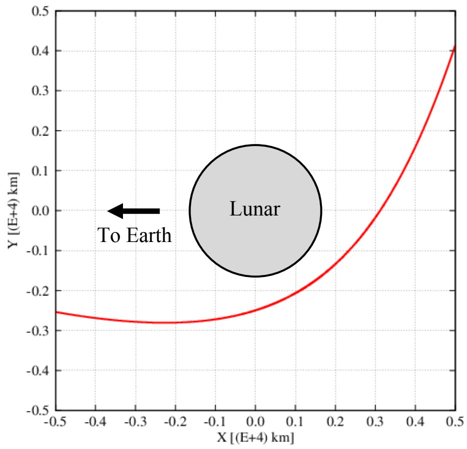

Fig. 4 Orbit of ICPS as viewed in Earth-Moon fixed frame.

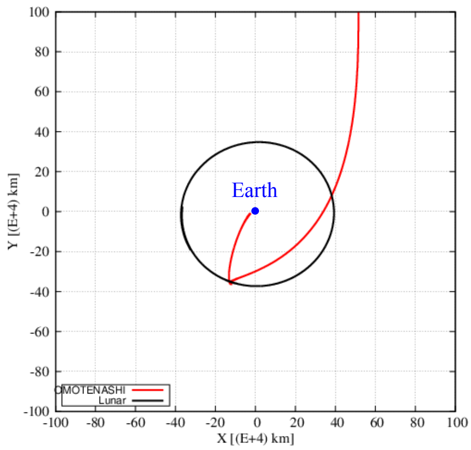

Fig. 5 Orbit of ICPS as viewed in J2000EQ.

2.2 Landing Locations

Fig. 6 shows the landing locations corresponding to 10~20 m/s ΔV_1.

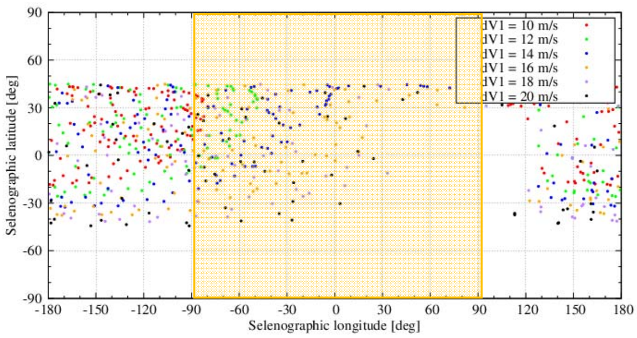

Fig. 6 Landing locations.

Although there are no specific requirements to the landing location of OMOTENASHI, it should land on the near-side the Moon to obtain radio signal from the spacecraft. The area indicates as orange corresponds to the near-side of the Moon. Note that the center of Fig. 6 is Earth-Moon line in this paper.

Also, the flight path angle at ΔV_2 should be shallow to reduce the impact velocity. The detail of the orbital analysis of the landing phase i.e., from the burn start of ΔV_2 to the landing, will be shown in [Hernando-Ayuso, et al., 2017][2]. Fig. 7 shows the variation of the flight path angle at ΔV_2 as a function of the selenographic longitude.

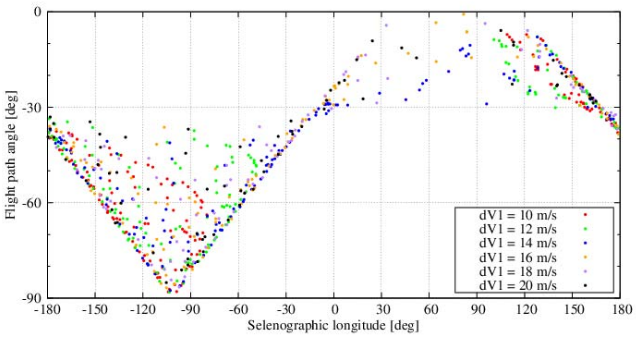

Fig. 7 Flight path angle variation.

From the results shown in Figs 6 and 7, more than roughly 15 m/s ΔV_1 will be required for OMOTENASHI to land on the near-side of the Moon with sufficiently shallow flight path angle.

2.3 Nominal Trajectory

Figs. 8 shows the nominal trajectory as viewed in XY plane of the Earth-Moon fixed frame.

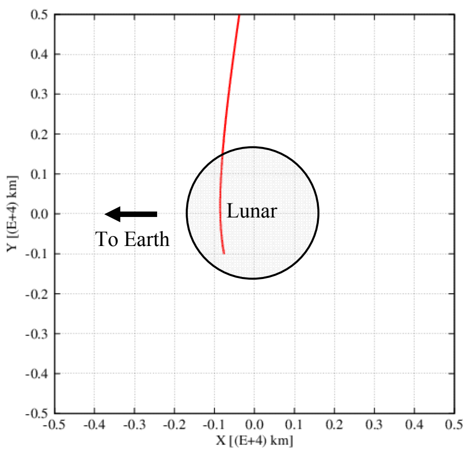

Fig. 8 Nominal trajectory as viewed in XY plane of Earth-Moon fixed frame.

Table 1. Major parameter results of the nominal trajectory

Terms	Values
Deployment epoch [UTC]	2018/Oct/07 15:39
ΔV_1 epoch [UTC]	2018/Oct/08 15:39
ΔV_2 epoch [UTC]	2018/Oct/13 08:23
ΔV_1 [m/s]	15.4
ΔV_2 [m/s]	2515.9
Flight path angle [deg]	-8.3
Landing location [deg]	52.9E, 34.6N

Table 1 summarizes the major parameter results of the nominal trajectory. In the nominal trajectory, ΔV_2 is applied exactly at 200 m above the Lunar surface and the spacecraft falls onto the surface from the point. ΔV_2 vector is defined as the velocity vector w.r.t the Lunar center at the point of interest. The impact velocity of this case is 26 m/s.

3. Error Sensitivity Analysis

In this study, three trajectories are handled i.e. nominal, actual in which the spacecraft flies, and estimated trajectory which is obtained through the orbit determination. Fig. 8 shows the relationship between those three trajectories[3].

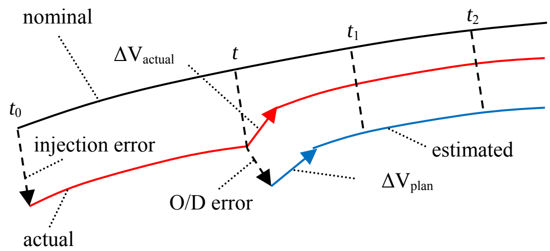

Fig. 8 Diagram of nominal, actual and estimated trajectories

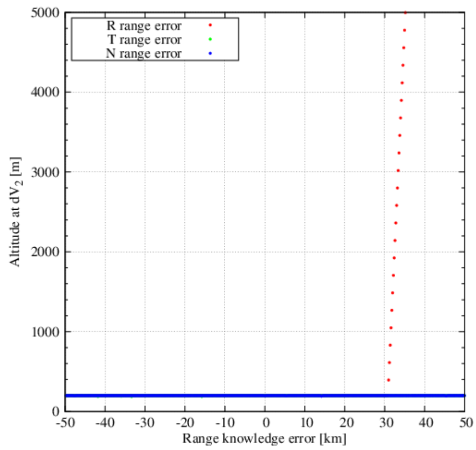

Fig. 9 Variation of ΔV_2 altitude by range knowledge error.

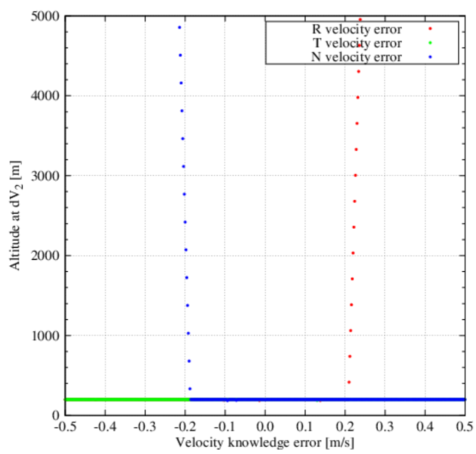

Fig. 10 Variation of ΔV_2 altitude by velocity knowledge error.

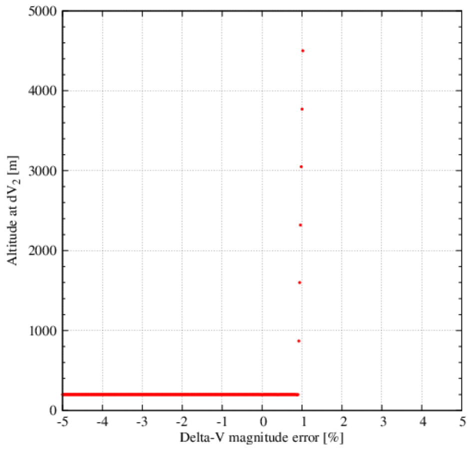

Fig. 11 Variation of ΔV_2 altitude by delta-V magnitude error.

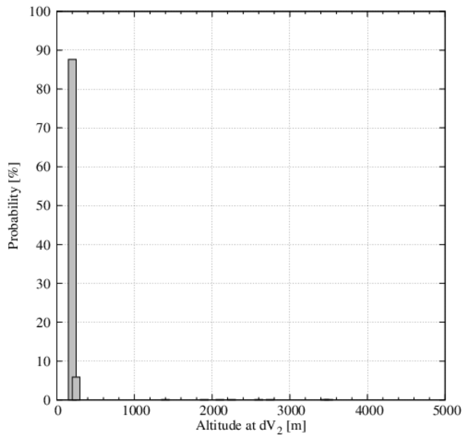

Fig. 12 Histogram of ΔV_2 altitude considering ΔV_1 direction error.

ΔV_1 is planned based on the estimated state values because it is the knowledge for the ground operators in the real situation. In this study, the nominal landing point is pre-defined, thus ΔV_1 is computed to aim the nominal landing location by differential correction.

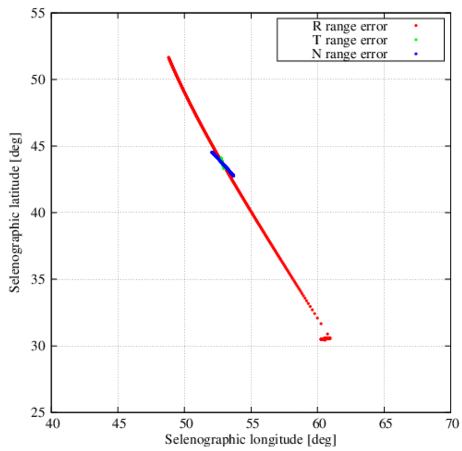

Fig. 13 Variation of landing locations by range knowledge error.

Figs 9~11 show the variation of the altitude where ΔV_2 is applied. Fig. 12 shows the probability of the ΔV_2 altitude varied by ΔV_1 direction error. As shown in the figures, the range knowledge error will not affect to the altitude except more than 30 km radial direction error. On the other hand, the velocity knowledge error, delta-V execution errors will increase the altitude, which means, the spacecraft flybys the Moon. By applying ΔV_2, the spacecraft can reach the surface however the impact velocity will be up to 600 m/s maximum, which is far from acceptable for the shock absorbing mechanism.

Figs 13~15 show the landing locations varied by the navigation and delta-V execution errors. As shown, the velocity knowledge errors and delta-V execution errors produces large variation of the landing locations.

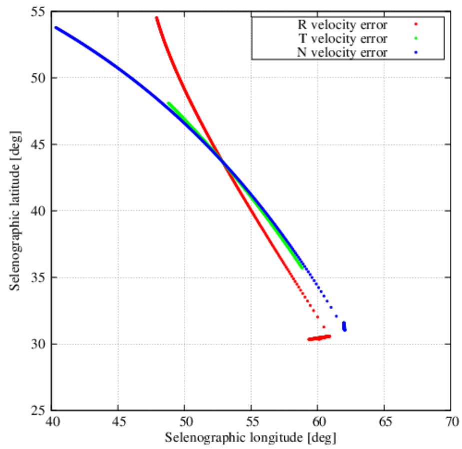

Fig. 14 Variation of landing locations by velocity knowledge error.

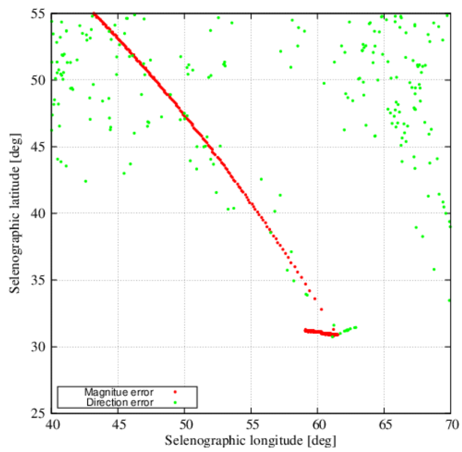

Fig. 15 Variation of landing locations by delta-V execution error.

Finally, the variation assuming realistic errors are evaluated in Fig. 16 which shows the histogram of the ΔV_2 altitude. Also, Table 2 summarizes the knowledge errors at delta=V timings. These knowledge errors are results of navigation analysis assuming realistic situation including DSN support. Note that the knowledge errors can be drastically changed by the initial condition, the available ground stations and so on.

As shown in Fig. 16, about 82 % reaches about 200 m altitude. In other word, OMOTENASHI flybys the Moon with 18 % possibility, which means mission failure for OMOTENASHI.

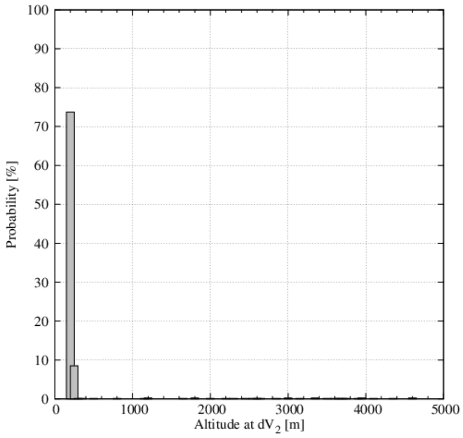

Fig. 16 Histogram of ΔV_2 altitude.

Table 2. Knowledge errors

Terms	at ΔV_1	at TCM
Range error in R (3σ)	1.4 km	3.5 km
Range error in T (3σ)	1.4 km	4.1 km
Range error in N (3σ)	3.8 km	25.1 km
Velocity error in R (3σ)	3.2 cm/s	7.8 cm/s
Velocity error in T (3σ)	2.6 cm/s	15.1 cm/s
Velocity error in N (3σ)	5.4 cm/s	31.4 cm/s

4. Trajectory Correction Maneuver Planning

To avoid the flyby cases, TCM is planned 1 day after ΔV_1 aiming the same nominal landing point. Fig. 17 shows the variation of the landing locations.

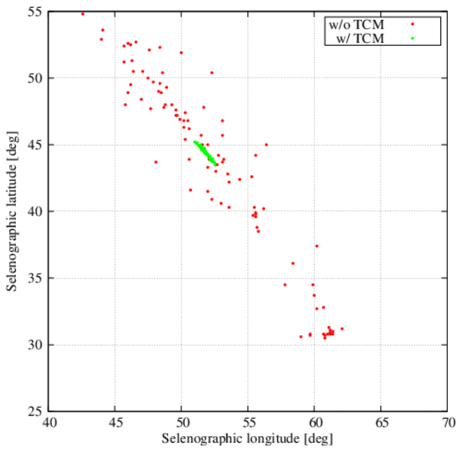

Fig. 17 Variation of landing locations.

As shown in Fig. 17, the variation of the landing locations drastically decreases with TCM, and 100 % reaches the planned ΔV_2 altitude i.e., 200 m. Table 3 summarizes the amount of delta-Vs.

Table 3. Summary of delta-Vs

Terms	average	standard deviation
ΔV_1 [m/s]	15.39	0.15
TCM [m/s]	0.73	0.34

The amount of TCM is 1.75 m/s (3σ), and the total of ΔV_1 and TCM is 17.59 m/s (3σ), which will be acceptable amount for OMOTENASHI.

5. Conclusion

This paper shows the results of preliminary analysis of the error sensitivity and trajectory correction planning. Using the current information such as the initial condition of the deployment, assumed navigation precision shows some reasonable amounts of delta-Vs. However, the landing phase is not fully studied yet, which has possibility to change the conclusion. Also, the initial condition, error budgets will significantly affect to the results, hence further detail study is essential for OMOTENASHI mission.

References

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3) Ikenaga, T., Utashima, M.: *Study on the Stationkeeping Strategy for the Libration Point Mission*, Transaction of JSASS Aerospace Technology, Japan, Vol. 10, No. ists28, pp. Pd_11-Pd_20, 2012