Current Status and Future of OMOTENASHI Trajectory Design

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OMOTENASHI is a Japanese 6U cubesat to be launched by Space Launch System (SLS) maiden flight Exploration Mission 1 (EM1). OMOTENASHI seeks to demonstrate technologies and techniques for future missions in the surface of the Moon, and perform a semi-hard landing after deceleration by a solid rocket motor. This paper presents the current status of OMOTENASHI trajectory design with its most recent developments. OMOTENASHI performs two deterministic maneuvers, DV1 and DV2, plus an stochastic trajectory correction maneuver (TCM) between them. The magnitude and direction of DV1 are chosen based on the designer experience with no measurable performance index. Evaluating the entire trajectory success rate for all samples of the grid searches is not feasible, because it would be computationally too expensive, and the possible candidates chosen by hand are not guaranteed to be better than others. Thus, we propose a novel approach for DV1 stochastic design. We define the total trajectory success rate as objective function, and study its relation with the FPA and the local topography. The latter is quantified for every location on the Moon with the residual of a least-squares fit to a plane of the elevation of the surrounding topography. Using a continuation of solutions method, we generate the families of trajectories that arrive in the lunar surface with constant FPA, and by employing the surface roughness index defined above, we can select several DV1 candidates that lead to landings in smooth topography. Finally, we evaluate the total trajectory mission success rate for the best candidates for different FPA to obtain the optimal trajectory.

Key Words: OMOTENASHI, Lunar landing, Cubesat, stochastic design, SLS

1 Introduction

OMOTENASHI is a 6U cubesat by the Japan Aerospace Exploration Agency (JAXA) that aims to become the smallest lunar lander. [1)] OMOTENASHI features a unique approach to deliver a payload to the lunar surface in which the Lunar Orbit Insertion (LOI), the descend and deceleration maneuvers are combined into a single burn in the proximity of the lunar surface. [2)] This will enable a completely new class of missions by universities and research centers in the lunar surface, as a full-size spacecraft would not be needed if a piggyback opportunity in a translunar orbit is available.

OMOTENASHI will be deployed into a translunar orbit by Space Launch System (SLS), Exploration Mission 1 (EM-1), missing the Moon by a few hundred kilometers if no maneuvers were executed. One day after deployment, a maneuver called DV1 will put the spacecraft in an intercept course, being the FPA at lunar arrival very shallow in order to enable a safe landing. A deceleration maneuver DV2 by a solid rocket motor fired a few kilometer above the lunar surface will reduce the kinetic energy of the spacecraft, which will finally free-fall onto the lunar surface at a speed of about 30 m/s. A stochastic trajectory correction maneuver (TCM) will be performed as needed one day after DV1 to correct its execution errors. The transfer phase of OMOTENASHI is summarized in Fig. 1, where the DV1 and TCM events are indicated. Figure 2 shows an overview of the landing phase, which includes a ballistic approach, the DV2 deceleration maneuver by a solid rocket motor, and the free-fall and final touchdown.

This paper first revisits the trajectory design approach previously developed. [2, 3, 4)] The simplified landing design is presented in section 2.1. The transfer phase design is divided in the DV1 maneuver design (section 2.2) and the TCM design (section 2.3). Finally, the high-fidelity landing-phase analysis

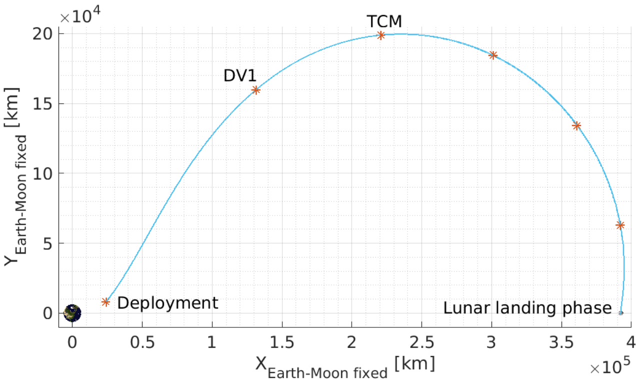

Fig. 1. Overview of the OMOTENASHI trajectory: transfer phase

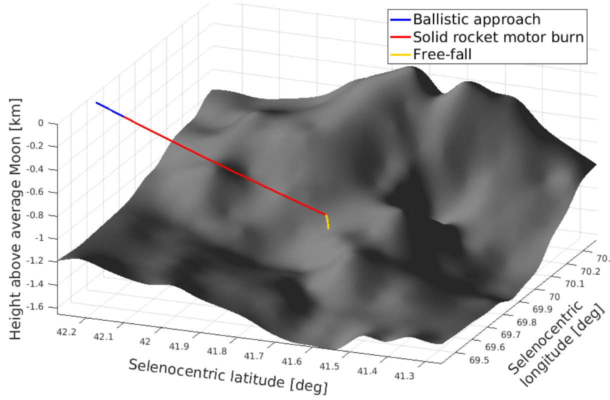

Fig. 2. Overview of the OMOTENASHI trajectory: landing phase.

This note was presented at the 28th JAXA Workshop on Astrodynamics and Flight Mechanics at Sagamihara (Japan), with manuscript number C-2 and design is covered in section 2.4. The drawbacks of the previous approach are highlighted, and the new developments in the design of the trajectory of OMOTENASHI are are presented in section 3. These improvements allow the trajectory design team to better explore the trajectories solution space and estimate their success rate under the presence of navigation and execution errors.

2 Current trajectory design

2.1 Simplified landing design

A simplified model for the landing phase is helpful for the trajectory design, as it gives a first approximation to the sensitivity of the landing with respect to the design parameters as presented by Hernando-Ayuso et al. [4] This analytical model considers a flat Moon with constant gravity during the deceleration maneuver and posterior free-fall. After restricting the motion to the local-vertical plane and by imposing zero vertical velocity at the end of DV2, the only free parameters are the FPA at lunar arrival and the free-fall initial height h_F. When considering errors of the current design (see [4] for reference), the landing success rate and the probability of an early impact with the lunar topography can be calculated for each pair of values (FPA–h_F). The result is shown in Fig. 3.

Furthermore, the analytical solutions allow to easily calculate the sensitivity with respect to each parameter. In particular, in [4] the maximum admissible variation of each parameter for a safe landing was investigated. For instance, Fig. 4 shows the maximum admissible variation of α, the maneuver out-of-horizontal-plane orientation angle, for each pair of (FPA–h_F).

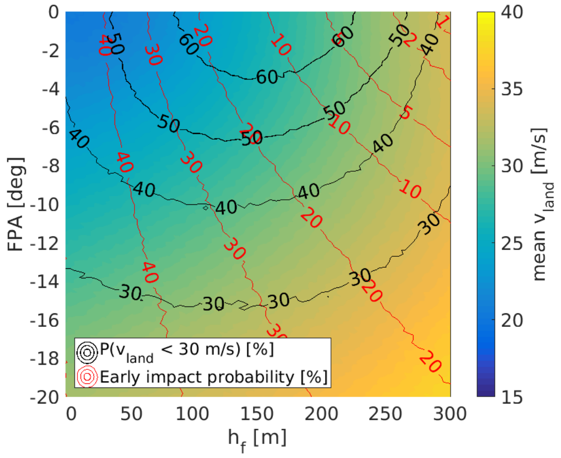

Fig. 3. Results of the simplified landing design

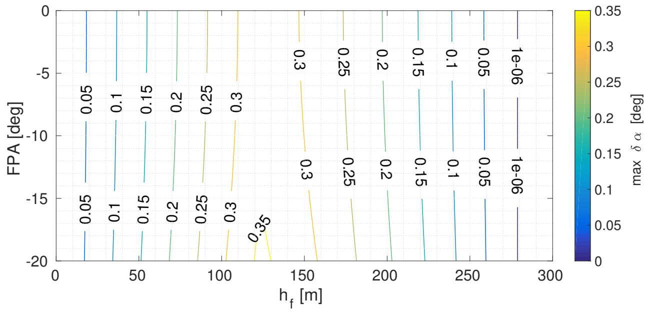

Fig. 4. Maximum admissible α variation.

An important conclusion drawn from the simplified landing model is a navigation requirement, as the position error in the local-vertical direction was identified as a factor potentially critical. For a safe landing, the navigation accuracy on the local-vertical direction should be much lower than the free-fall initial height, but results of covariance analyses revealed that employing only range and range-rate measurements with reasonable tracking by ground stations is not enough for the trajectory of OMOTENASHI. The reason for this lies in the slow evolution of the range in the last 2–3 days of the mission and the usually more effective range-rate measurements have a reduced effect. Requesting additional tracking was determined to be challenging, as 13 cubesats are delivered at the same time by EM-1 and the time to perform orbit determination is very limited. To solve this predicament, it was decided to include D-DOR (Delta Differential One-way Ranging) in the navigation observables. This increases cost and complexity of the mission, but is necessary for its success.

2.2 DV1 design

Under the current design strategy, DV1 is selected as a trajectory that arrives in the Moon with a shallow FPA following the conclusions of the simplified landing design. Furthermore, the DV1 maneuver should be robust with respect to execution errors. There are four degrees of freedom in this maneuver: the epoch, magnitude and two angles for the direction. For simplicity, and for operational purposes, the epoch is fixed as one day after deployment. Then, the question is how to fix the remaining variables. This is currently done with a grid search with iterative refinement and progressive filtering of unpromising solutions, as discussed in detail by Ozawa et al. [3]

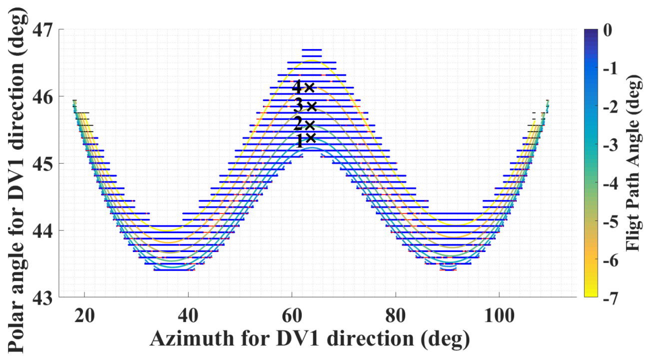

Fig. 5. DV1 orientation angles for the DV1 fine grid search.

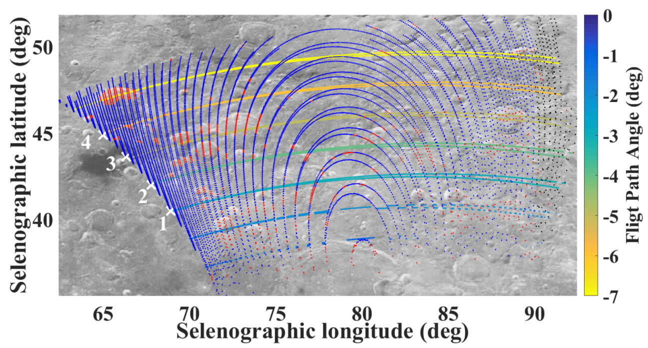

Fig. 6. Landing locations for the DV1 fine grid search.

The results of this design process can be shown in Figs. 5 and 6, in which a large family of feasible maneuvers are presented. It was found that the solutions with constant azimuth in the central region of Fig. 5 have a larger tolerance for errors in the direction, and that their dispersion at lunar arrival was smaller in Fig. 6. Because of that, we employed these solutions to select 4 DV1 candidate maneuvers with different FPA at lunar arrival. For simplicity, we consider that the arrival point lays on a spherical Moon with an average radius equal to 1734.4 km.

2.3 Transfer Error analysis and TCM

The error analysis in the transfer phase and TCM design was discussed in detail by Ozawa et al. [3] He evaluated the effect of the navigation and execution errors of the DV1 maneuver on the lunar arrival. It was found that the navigation errors are not critical for their expected values, but that the DV1 magnitude and orientation errors could jeopardize the transfer phase. On one hand, OMOTENASHI could miss the Moon, failing to land with an acceptable velocity. On the other hand, the FPA could become too steep, which would potentially lead to a very challenging landing.

As an example of the results of the analysis, Fig. 7 shows the transfer success rate as a function of the execution error of the DV1 magnitude. We indicated in red the expected errors (1%), which leads to a transfer success rate lower than 80%. To assure a successful transfer, it was decided to include a TCM in the mission profile. After validating the linearity of the motion for the expected errors, we employed a fixed-arrival-time approach to re-target the original position of the spacecraft. The results can be summarized in Fig. 8, where the dashed black curve corresponds to the trajectory without TCM and the blue one for the one with TCM. The black curve shows a great dispersion and fails to reach the 100% of cases with lunar flybys, but the TCM eliminates the possibility of missing the Moon and effectively controls the FPA to acceptable values.

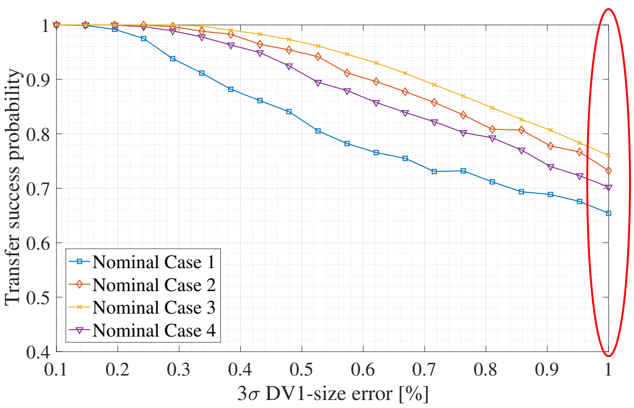

Fig. 7. Transfer success probability as a function of the execution errors of DV1.

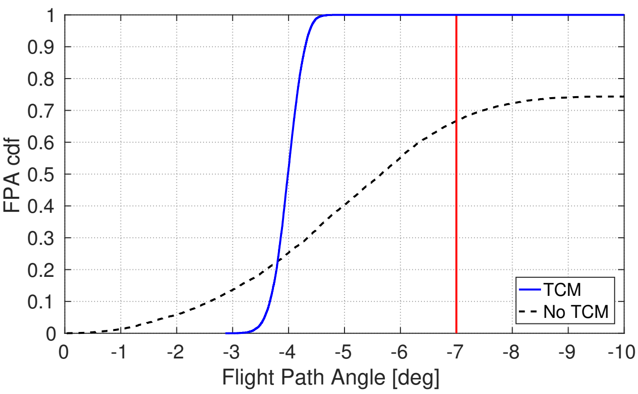

Fig. 8. Cumulative distribution function (cdf) of the FPA at lunar arrival.

2.4 DV2 error analysis (high fidelity)

It is paramount to evaluate the success rate of the landing maneuver presented in section 2.1 with a higher fidelity model. To do so, the OMOTENASHI trajectory team proposed a high fidelity tool [4] that given a DV1 maneuver, simulates the landing on the corresponding arrival location on the real lunar surface, including nonlinear gravity of the Moon, the Sun and Earth, and actual topography using a SELENE DEM model. The landing velocity profiles (see Fig. 9 for an example) and the sensitivity to each source of error were evaluated, and the most critical factors were determined to be the maneuver orientation angle with respect to the local-horizontal plane, and the thrust direction, and feedback to the rest of the OMOTENASHI project team was provided. However, improving these factors may be difficult because OMOTENASHI is a cubesat with limited resources and a short time until launch.

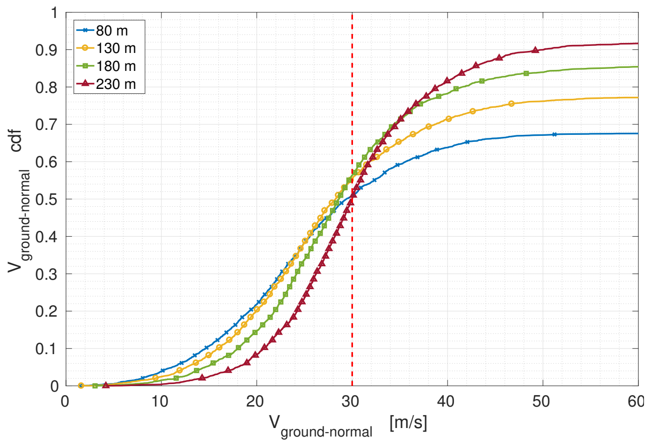

Fig. 9. Cumulative Distribution Function (cdf) for the component of the landing velocity normal to the ground.

2.5 Drawbacks of the current approach

After fixing the DV1 maneuver, the only degree of freedom of DV2 is the free-fall initial height h_f, which in principle can be locally optimized to maximize the landing success rate. This means that in order to design an optimal trajectory for OMOTENASHI, DV1 is key. However, it is hard to optimize this maneuver. First, the magnitude had been fixed *by eye*: not very large because of the fuel budget limitations, but not very low to potentially reach multiple locations on the Moon. Furthermore, the criteria for direction is not clear. The azimuth is chosen for error-robustness of the transfer, while the polar angle is selected to adjust the FPA at lunar arrival. The only a priori clue that the trajectory designer has is that a steeper FPA is associated with a lower landing success rate, and that some topographical features like crater or hills may hinder the landing. After fixing DV1 one still needs to numerically simulate the landing to correctly assess the nonlinear effects and the lunar topography. However, these simulations are numerically expensive and cannot be incorporated into the grid search process while keeping the execution time low. Without the full simulations, the trajectory designer has to rely only on the FPA and on visual

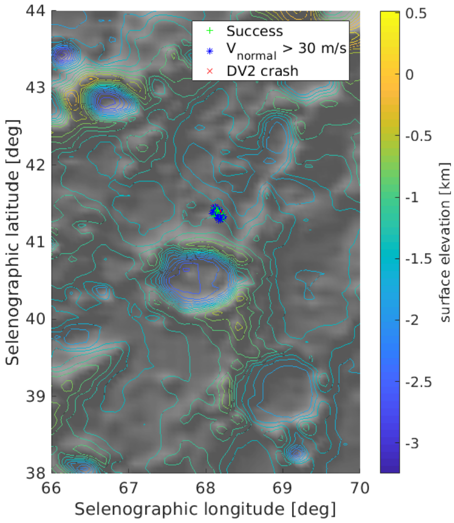

Fig. 10. Landing dispersion with a deterministic transfer phase.

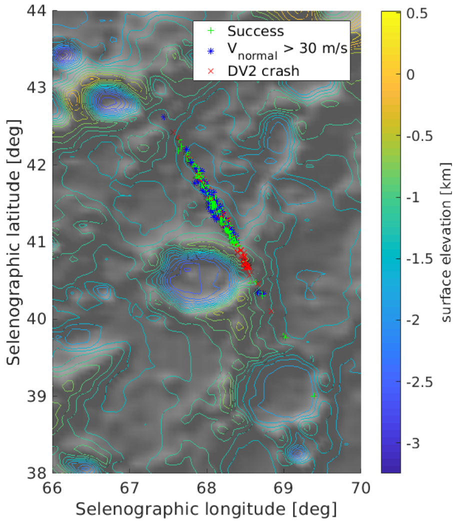

Fig. 11. Landing dispersion considering errors in the transfer phase.

inspection of the landing location to select a reasonable number of candidates for the for the landing simulation.

Another drawback of the current approach is the landing analysis does not consider dispersion caused by DV1 and TCM errors. So far, the tool employed for the landing analysis (see section 2.4) considered a nominal transfer, analyzing only the errors during the landing.

3 New improvements

3.1 Full-trajectory error analysis tool

The first improvement to the tools used by the trajectory design team was to incorporate the errors in the transfer phase to the landing simulations. We created a full-trajectory error analysis tool that considers OD and execution errors at DV1, TCM and DV2 events. Given a DV1, characterized by its magnitude, polar angle and azimuth, and free fall height h, the toolbox provides the perpendicular and ground-tangent impact velocity profiles, the total success rate ($v_{\text{tangent}} < 100\,\text{m/s}$ AND $v_{\text{perp}} < 30\,\text{m/s}$), and visualization of the landing location and the landing trajectory.

With this new analysis tool, we could assess the effect in the landing phase of the errors of the transfer phase. Figure 10 shows the landing dispersion when no errors on the transfer are considered. In this scenario, the success rate is close to 57%, with a 21% early crashes during the solid motor burn. When the newly-introduced errors during the transfer phase are considered, the landing dispersion becomes considerably larger as shown in Fig. 11. In some of these dispersed locations, OMOTENASHI prematurely crashes in the proximity of the rim of a crater, which suggests that landing in non-smooth locations is challenging. The early crash rate increases by 5%, and the success rate decreases by the same amount.

3.2 Considering topography in DV1 design

From the previous improvement, we learned that the local topography has a non-negligible effect in the mission success rate. This implies that the trajectory design team needs a way to *quickly* evaluate the effect of the local topography of the landing area, without resorting to time-consuming simulations of the landing with high-fidelity models.

One way of doing this is to aim for *smoother* areas to maximize the success rate. To this end, we constructed a surface-roughness map of the Moon. For every location on the surface, we sampled the topography in a 50 *km* radius following a Gaussian distribution. This size was chosen to coincide to the along-track dispersion observed in the full-trajectory error analyses. For every sampled point, we retrieved its elevation and performed a least-squares fitting of the all the points to a plane. Then, we considered the root mean square (RMS) error of the fitting as a measure of the *roughness* of the surface. The resulting map is shown in Fig. 12, where the bluish areas are characterized by a smoother local surface than the yellowish regions. A comparison with the map of the Moon shown in Fig. 13, confirms that the lunar maria is smoother than other regions with a larger amount of large craters, as one could expect.

In order to apply this map, we must consider the actual landing location of each trajectory. However, in the design of DV1 we previously defined the arrival points on an average Moon instead of the real lunar surface. This can have important effects as shown in Fig. 14, where the DV1 candidates previously employed are shown. DV1 candidates that arrive in smooth areas can be shifted to rougher regions, so it is important to numerically adjust the arrival points to the actual surface.

3.3 Iso-FPA families of DV1 maneuvers

The FPA at lunar arrival has been shown to be a good indicator of the landing success rate. [4] However, in the previous DV1 design strategy it is a result of the calculations, instead of an input. Furthermore, with the previous strategy it is hard to modify the landing location, because fixing the magnitude limits the locations of the Moon OMOTENASHI can reach.

To circumvent these limitations, we propose a different method to explore the DV1 solution space, in which we fix the azimuth and calculated families of curves with constant FPA by changing the magnitude and the polar angle. The reasoning for fixing the azimuth is that all the candidates with the pre-

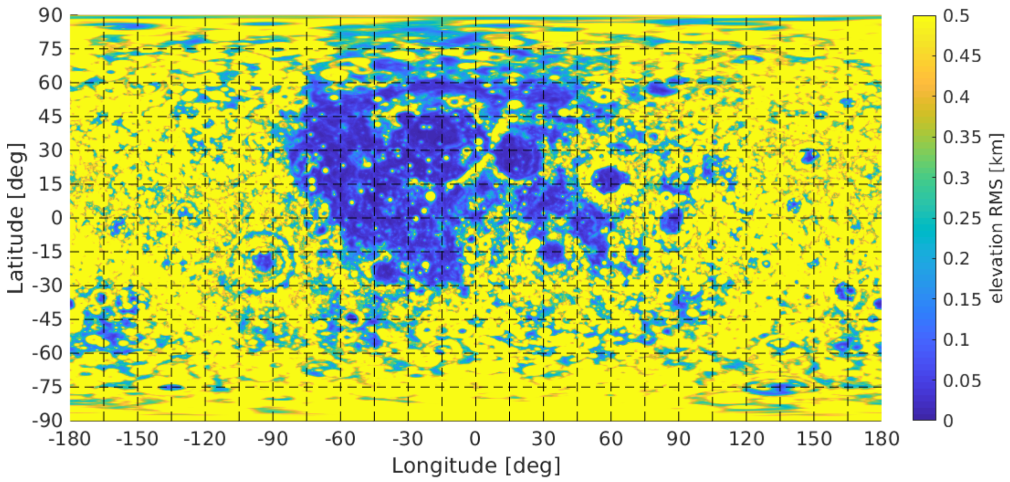

Fig. 12. Lunar surface roughness map.

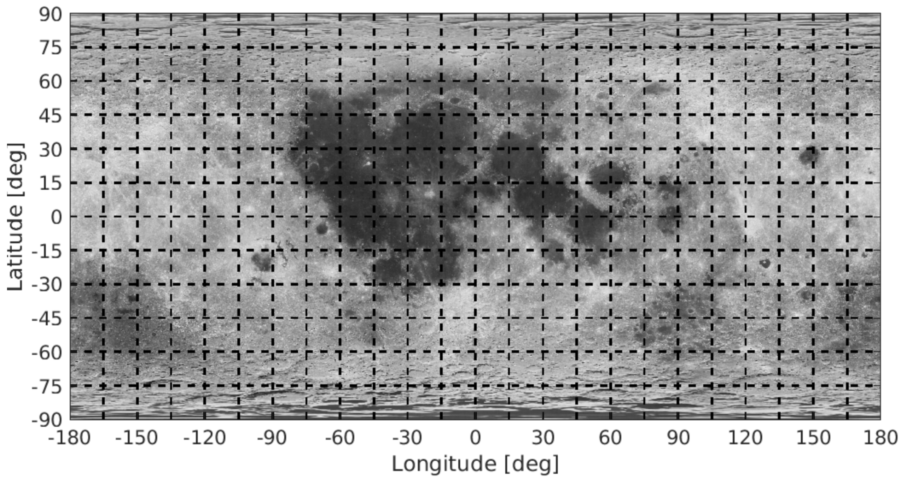

Fig. 13. Lunar surface map.

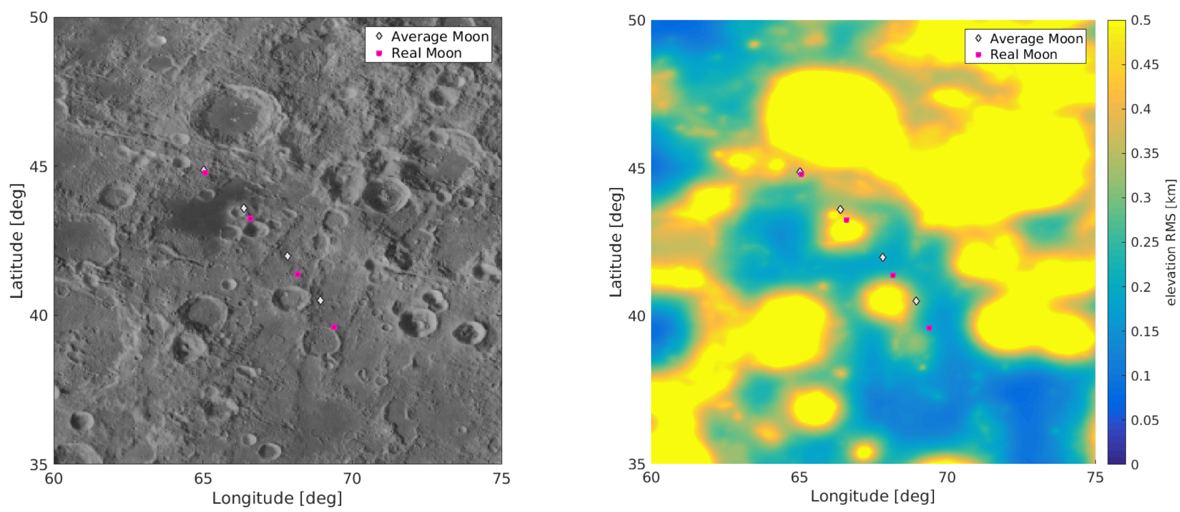

Fig. 14. Arrival locations from DV1 design adjusted to the actual lunar topography.

vious approach were generated for constant azimuth for error-robustness, and further investigation revealed that this azimuth corresponds to the maneuver with minimum ΔV to reach the surface of the Moon. The calculation was performed by first numerically determining a point with the desired FPA, and then applying a continuation method to calculate the whole family.

Figure 15 shows the arrival points on an average Moon of the constant-FPA curves, with FPA between −2.0 and −7.0 deg and with a magnitude smaller than 20 m/s. The minimum magnitude arrival point is on the far side, and the magnitude increases counterclockwise towards the near side. Figure 16 shows these families over the lunar roughness map, whereas in Fig. 17 the

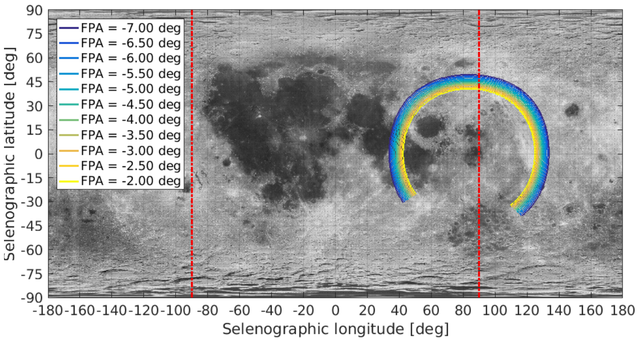

Fig. 15. Arrival points on an average Moon of the maneuvers with constant-FPA

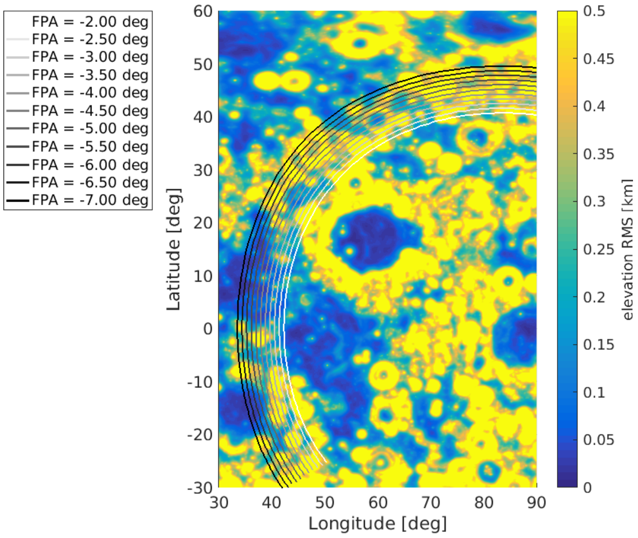

Fig. 16. Surface roughness for iso-FPA families on the average Moon.

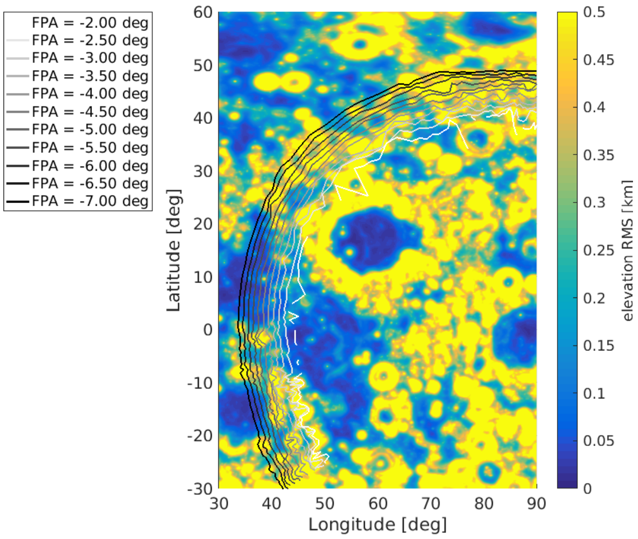

Fig. 17. Surface roughness for iso-FPA families on the real Moon.

landing points were adjusted to the actual topography.

One of the most promising locations in these figures corresponds to a DV1 that arrives in Mare Tranquillitatis, with $FPA \simeq -4.5$ deg, and with longitude and latitude close to 39 and 12 deg, respectively. This location has a very smooth topography (see Fig. 18), and compared to the previous landing locations, the success rate can is increased by 5%, and the early crash rate is reduced by the same amount. The landing velocity cumulative distribution function is shown in Fig. 19/

4 Conclusions

In this paper presented the current status of the OMOTENASHI trajectory design, as well as the new tools and techniques developed in the last year. We considered the ±50 km along-track dispersion on arrival at the Moon in the evaluation of the mission success rate. We determined that the local lunar topography becomes key to the success of the mission and must be considered in the design of the Moon-targeting maneuver. To this end, we presented an estimate of the local surface roughness that allows the trajectory team to easily estimate the quality of a DV1 candidate without performing time-consuming high-fidelity simulations of the landing.

Acknowledgments

The authors are indebted to all the members of the OMOTENASHI team. The Ministry of Education, Culture, Sports, Science and Technology (MEXT) of the Japanese government supported Javier Hernando-Ayuso under its program of scholarships for graduate school students. Stefano Campagnola acknowledges the support from JAXA's International Top Young Fellowship program and from JPL's Raise the Bar funding, and part of this research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

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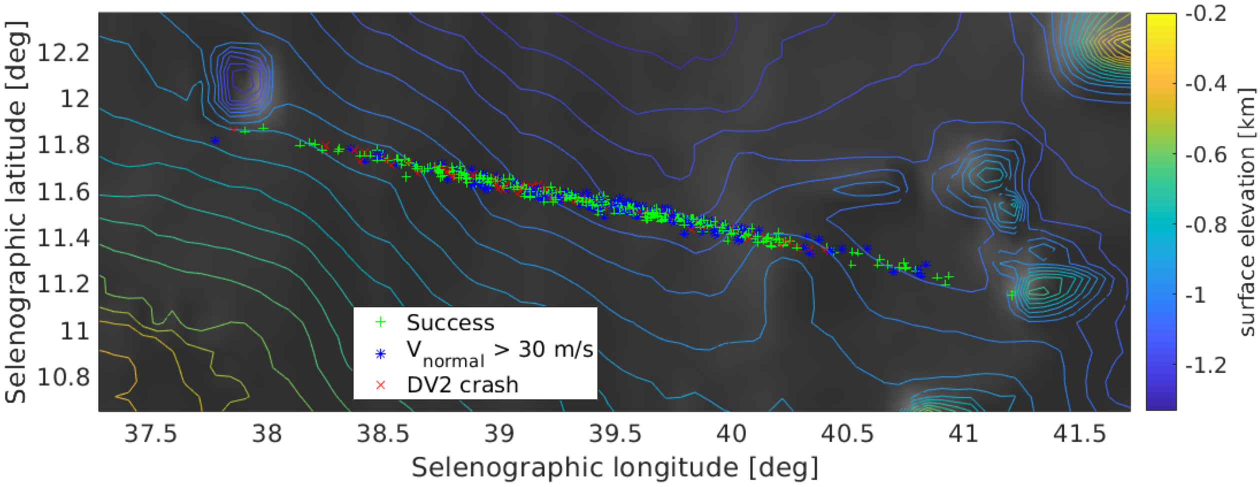

Fig. 18. Landing location in Mare Tranquillitatis with smooth local topography.

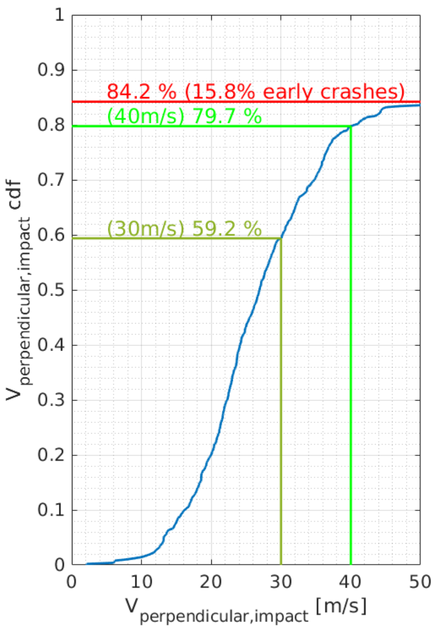

Fig. 19. Landing velocity profile for the landing location in Mare Tranquillitatis with smooth local topography.