Marius Hills Skylight hazard characterization as a possible landing site for lunar subsurface exploration

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Introduction: The renewed interest in the crewed and robotic exploration of the surface and subsurface of the Moon has significantly increased over the past few years among the scientific community and space agencies. The NASA Artemis program and the ESA EL3 (European Large Lunar Lander) represent new steps in this direction. Such exploration requires further technology developments in parallel with new landing sites characterization. In particular, the exploration of the lunar subsurface by accessing lava tubes from skylights has been subject for ESA call for ideas in its Open Space Innovation Platform in the SysNova Lunar Caves system studies framework. In this light we present some preliminary landing site assessments performed as a support for the DAEDALUS (Descent and Exploration in Deep Autonomy of Lava Underground Structures) [1] mission design proposal, to be deployed in the Marius Hills region where a lunar skylight with underlying void has been discovered [2]. The exploration of the Marius Hills lava tube is tied to the possibility to land, rove and safely approach the skylight. Therefore, it is pivotal to characterize in high detail the terrains surrounding the skylight both in terms of science and hazard/safety. In terms of accessibility, the skylight should be surrounded by obstacle-free terrains presenting a relatively low number of boulders, while the regolith should be able to sustain inertial platforms with a relevant mass. In addition, the location should guarantee an easy approach to the pit up to a location where the DAEDALUS sphere will be deployed. Therefore, in order to characterize the feasibility of landing, approach and deployment of the DAEDALUS sphere several aspects of the terrains surrounding the pit must be investigated considering several morphometric parameters:

- flat surface over steep overhanging pit margins, with a slope safety margin of 15°;
- hazard-free or low-hazard trafficability from landing ellipse to the pit;
- hazard free landing area (low crater density, low slopes, boulder-free);
- closest access point to the skylight edge.

Geologic context: Marius Hills region is among the largest volcanic complexes on the Moon and is located in the Oceanus Procellarum. Beside the presence of multiple monogenic cones set on a ~300 km shield, this location is characterized by widespread mare basalt and very large rilles at its flanks, namely “Rille A” and “Rille B” [3]. The selected skylight is a nearly circular hole of ~65 m in diameter, located at 303.3°E, 14.2°N in the Marius Hills region in the middle section of the Rille A. The first detection was achieved via SELENE-Kaguya Terrain Camera images [1] whose first depth estimate was of ~80 m, subsequently refined to be ~45 m [4].

Data and methods: The landing site has been characterized on a bundle-adjusted LROC NAC [5] stereo DEM (4 meters of resolution) refined with the shape from shading technique. This allowed us to retrieve the highest possible detail in the topography and detect small features at high resolution.

We refined the DEM and focused our attention in an area of 1 km^2 centered on the pit.

Hazard characterization: We performed morphometric analyses on the refined DEM using the multi-scale TPI (Topographic Position Index), that allows to extract raised and depressed areas with respect to the surroundings. In this way, together with LROC NAC orthoimage analysis, we were able to characterize the following hazards:

- _Crater density:_ Of all craters we identified, some of them are not hazardous as they may be very shallow (few decimeters per meter in diameter, slopes being negligible);
- _Slopes:_ slopes thresholds represent the major trafficability constraint on the area. Based on both HERACLES [6] and MSL Curiosity we selected a maximum slope safety threshold to be <15°. A safer buffer in slope threshold was set at <10°
- _Craters’ depths:_ craters shallower than 1 m and with inner slopes <15° are considered safe.
- _Boulder abundance:_ less than 50 boulders are present in the area, none implying any hazard.

The final result is a hazard map (see fig. 1) with safe areas for landing and trafficability, low hazard and no-go areas.

Skylight characterization: Since the objective of the SysNova system study call is the deployment of a robotic device inside the lunar cave for horizontal exploration, we attempted to characterize also the cave floor. In order to identify the sizes of the boulders located on the floor of the sinkhole (remnants of the collapsed ceiling) we made use of an LRO/LROC-NAC image (M155607349RE) with a spatial scale of 0.42 m and with a solar incidence angle of ~12°. We were therefore able to map and evaluate the boulder abundance and size [7] (up to ~1.5m also in elevation) with the same methodology. Overall, our preliminary results found the best sector to deploy a device in the NW of the skylight floor (white square in fig. 2).

Results and Discussion: From our analysis of the Marius Hill skylight surroundings it appears that trafficability is not affected by whatsoever obstacles such as boulders, and landing should be sufficiently safe in terms of engineering constraints: the slopes are <10° in most of the area and the no-go zones are limited to few impact craters and depressions apart from the skylight itself and secondarily by the rim of the Marius Hills Rille A. By using low incidence and low phase angle LROC NAC images we were able to observe and characterize the bottom of the cave and retrieve the boulder abundance and their size. Although most of the floor is characterized by a pile of large boulders and regolith, the northwestern portion should be sufficiently safe to be approachable from above and to deploy a robotic device with chances of navigation and mapping.

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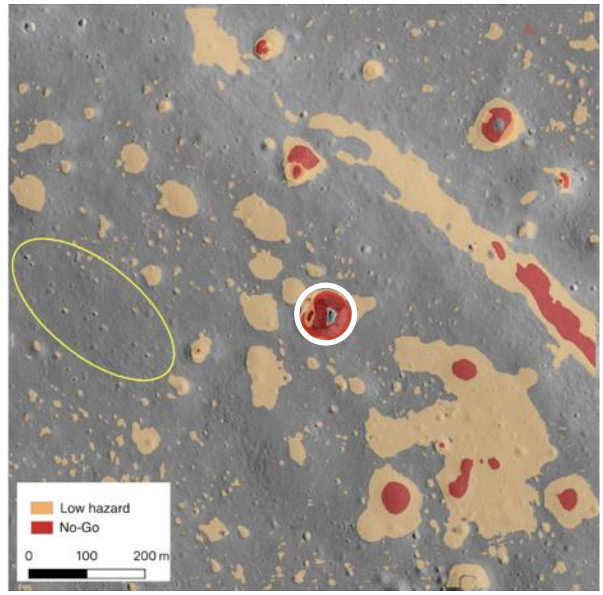

Figure 1: Hazard analysis preliminary map characterized on shape from shading refined DEM. A putative landing ellipse is placed in the safest possible area and the low hazard are highlighted (in orange and red respectively). The skylight is highlighted in white.

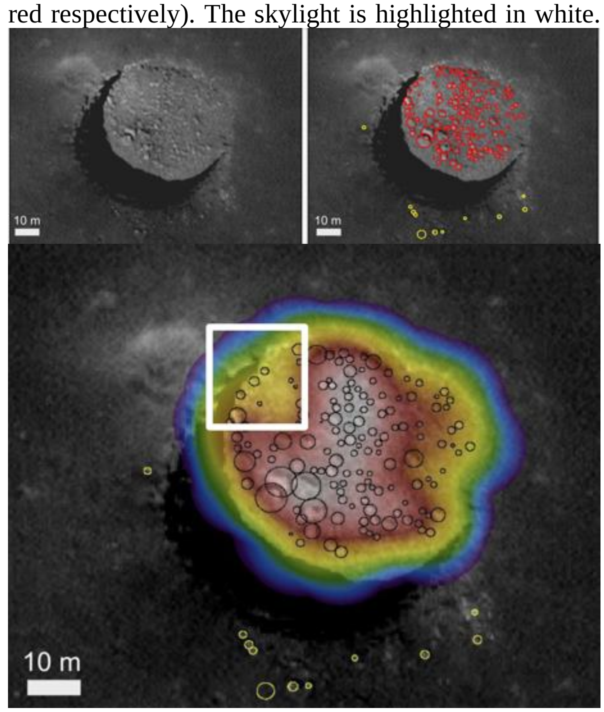

Figure 2: LROC NAC image (M155607349RE, 0.42 m/pixel) with visible boulders on the floor mapped with circles (in red in image 2 and black in image 3). The heatmap highlights the boulder density weighted on their diameter. The yellow circles mark the boulder presence on the surface. The white square marks the area where it is possible to deploy a device with acceptable hazard.