SURVEY OF LUNAR PITS AND ANALYSIS OF THEIR POTENTIAL AS HABITAT LOCATIONS.
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Introduction: Even before the discovery of lunar subsurface voids, their existence was hypothesized and it was suggested that they could be utilized as shelters for future habitats [1,2,3]. In 2009, the SELENE mission data revealed the first lunar pit [4]. To date, 268 pits have been discovered, mostly by analysis of Lunar Reconnaissance Orbiter Camera (LROC) images [5,6].

Current formation models suggest that these pits were formed by the collapse of the roof above subsurface voids created by magma chambers, lava tubes, or flow structures in impact melts [6]. The known pits vary in size from 5 m in diameter (lower limit of resolution) to over 100 m. The pits provide access to features and structures of the lunar subsurface as well as to delicate minerals and possibly ancient samples of solar wind stored in paleo-regoliths [6].

The discovery of the pits re-sparked discussions of engineering applications such as potential shelters from the harsh lunar environment in terms of radiation and micrometeorite mitigation [1,2,3]. Protection from dangerous radiation levels in space is one of the major engineering challenges for exploration, for both humans and electronics. Radiation effects increase on the surface of the Moon due to secondary particles created by the interaction of Galactic Cosmic Rays (GCRs) and Solar Energetic Particles (SEPs) with the regolith [7]. Traditional shielding methods do not provide adequate protection and add tremendous mass to the system. Micrometeorites also present a risk on the lunar surface: these particles typically impact at velocities >10 km/s and pose a hazard to any structure. However, lunar regolith provides good shielding against both radiation and micrometeorites [1,2,3], provided it has sufficient thickness. DeAngelis et al. [8] calculate that approximately 7 meters of regolith will protect against high-energy radiation. In this work, we use the geometry of lunar impact melt pits to calculate the radiation shielding that they provide.

Pit Database: Our analysis of the protection afforded by pits uses a database we are developing that lists the physical properties of the currently-known lunar pits:

- length and orientation of the major and semi-major axes of the pit opening
- approximate depth from shadow measurements
- list of images of the pit (noting which were used for measurements)
- description of the pit
- presence of notable common features such as potentially-traversable regolith slopes from surface to floor, nearby depressions or pits, etc.

To gather this information, for each pit we processed all available images (photometric correction and map-projection at native resolution), and selected several of them for making both quantitative measurements of the pit dimensions and qualitative observations of specific pit features and the local geologic context. To minimize depth and diameter measurements errors, we only used images with viewing angles within 3° of nadir, and used the highest-resolution images with a variety of lighting angles wherever possible. For qualitative observations, such as the presence of nearby depressions, we also used stereo and oblique images if they existed.

This database will be publicly released in the first half of 2016.

Approach: The starting point for the project was to calculate the necessary dimensions for a habitat module for a crew of three on the surface. Literature suggests an average of 25 m^3 per crewmember [9,10]; a horizontal cylindrical structure of 3 m diameter with approximately 11 m length provides the necessary volume. Accordingly, 11 m was identified for minimum pit diameter with a depth of at least 10 m for adequate radiation protection. This depth was selected because with a 3 m habitat diameter, there would be at least 7 m of regolith in all directions except for the clear view of the sky.

The second step was the manual inspection of the database described above to identify pits of suitable dimensions. The preliminary version of the database used in this analysis included approximately 170 of the 268 known pits, and of those 170, 41% could accommodate the habitat. The candidate pits were then analyzed with a MATLAB code to calculate how much of the sky the habitat would be exposed (Equation 1; Figure 1). These calculations make a simplifying assumption that all pits are cylinders with flat bottoms, level rims, and a diameter equal to the measured major-axis diameter of that pit, and thus usually over-estimate the sky exposure for a given pit. Additionally, we assume that the habitat module is tucked as close the wall of the pit as possible.

$$\Omega = \frac{A}{r^2} \text{ where } A = 2\pi r^2(1 - cos\theta) \qquad (1)$$

A = spherical cap surface area
r = radius of the unit sphere
θ = angle of the cone created by the lines to the pit edges

Knowing that a structure on the surface would be exposed to 2 steradians (sr) of the sky, it was possible to calculate the percent reduction in exposure to micrometeorites and radiation. We inspected the results to determine which pits provided 80% reduction or more in exposure. This number was selected because a habitat module placed next to a near vertical ridge would have ~50% exposure reduction, therefore it was expected a pit should provide much better protection to be deemed a good candidate. On the other hand, this is a somewhat arbitrary selection and no specific analysis is made to determine desired percent reduction.

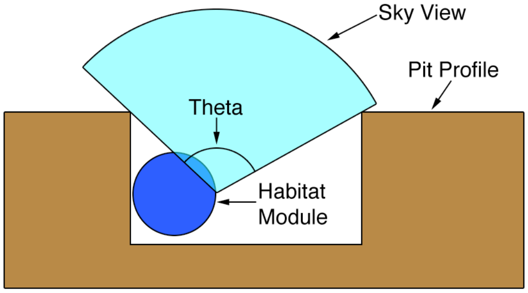

Figure 1: Geometry for Equation 1.

The next step of the procedure was to visually inspect the 32 pits that were identified for their ease of access with a wheeled vehicle. Unfortunately, high enough resolution stereo reconstruction does not exist for most of the pits for a slope analysis at this scale, so the results of this step are qualitative.

Results: Of the 170 pits that were manually inspected, 69 had the necessary dimensions to accommodate a habitat module. These provided various degrees of reduction in exposure to the sky. 32 were identified as reducing the exposure by 80% or more. Unfortunately, most of these pits do not appear suitable for driving into. A visual inspection revealed three that might be accessible by wheeled vehicles (Table 1; Figure 2).

Discussion: The results show that lunar pits can provide significant protection against hazards on the surface of the Moon by limiting the exposure to the sky. This added protection could increase the safety of the crew and/or reduce the amount of material that must be carried to the Moon, reducing the costs for such a mission. Three of the pits are of suitable dimensions and may be accessible with a wheeled vehicle. However a more in depth inspection of some of the other pits may reveal a solution where the pit can provide optimal protection for the habitat and astronauts can walk in and out of the pit. There are still approximately 100 pits that have yet to be analyzed in this study. Looking at the ratio of the suitable pits found in this study, it could be expected that there will be many more that will fit the criteria, perhaps with better accessibility.

Summary and Conclusion: Lunar pits are a relatively new discovery and the number discovered has rapidly increased to 268 since the first discovery in 2009. Lunar pits can provide significant protection for surface assets increasing safety and reducing mission costs. In this study, we analyzed approximately 170 pits for their suitability in protecting a lunar habitat module. Of these 69 were wide and deep enough for a habitat module and 32 provided protection greater than 80%. Three were determined to be possibly suitable for driving in and out with a wheeled rover.

Name	Lat.	Lon.	Avg. Depth	Max. Diam.	% Exp. Reduction
Jackson 1a	22.421	196.287	19 m	13 m	93%
Stefan L 1	44.537	252.030	13 m	~12 m	89%
Tycho 5a	-42.618	348.636	22 m	31 m	85%

Table 1: Three pits that exhibit a high level of shielding and acceptable accessibility by wheeled vehicles.

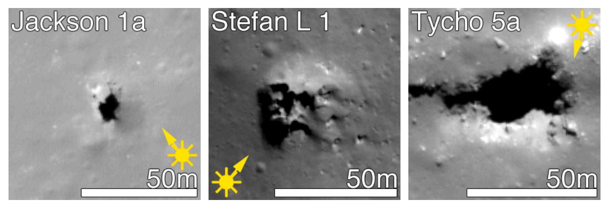

Figure 2: Three pits that exhibit a high level of shielding and acceptable accessibility by wheeled vehicles.

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