MORPHOLOGIC PARAMETERS FOR SUCCESSFUL LUNAR LANDING SITES

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Introduction: The Moon, with its abundant resources, intriguing science questions, and vast unexplored surface area, is the most attainable and useful near-term target for future human exploration [1]. In recognition of this fact, Presidential Space Policy Directive 1 (PSPD-1) has directed the United States to return to the Moon for "long-term exploration and utilization", beginning with the 7th American human lunar landing by 2024 and building to sustainable surface presence by 2028 [2, 3].

Rationale: The NASA Lunar Exploration Analysis Group (LEAG) Lunar Exploration Roadmap (LER), created at the request of the NASA Advisory Council and last updated in 2016, is the definitive strategic plan for incorporating the Moon into Earth's economic sphere [1]. The LER calls for an integrated strategy for lunar exploration that starts with precursor missions, builds to human operations on the surface, and culminates in permanent surface presence at field stations. Achieving the goals of the LER will require a robust cadence of crewed and uncrewed missions to the lunar surface at a variety of geographic locations at both prepared (i.e., outposts) and unprepared locations. Missions called for by the LER include stationary landers, short-duration rovers, extended duration rovers, human missions including rovers (unpressurized and pressurized), and permanent human outposts.

The original purpose of the NASA Lunar Reconnaissance Orbiter (LRO) was to collect the dataset necessary to facilitate future human and robotic lunar exploration [4], and its data is uniquely well-suited to understand the engineering requirements needed to optimize future exploration.

We have updated our previous efforts [5] describing the interpretation and quantification of how LRO observations of legacy lunar landing locations (e.g, Figure 1), including the recent Chang'e-4 landing site, will inform planning for future science and exploration missions. Here, we develop key morphologic and physical metrics

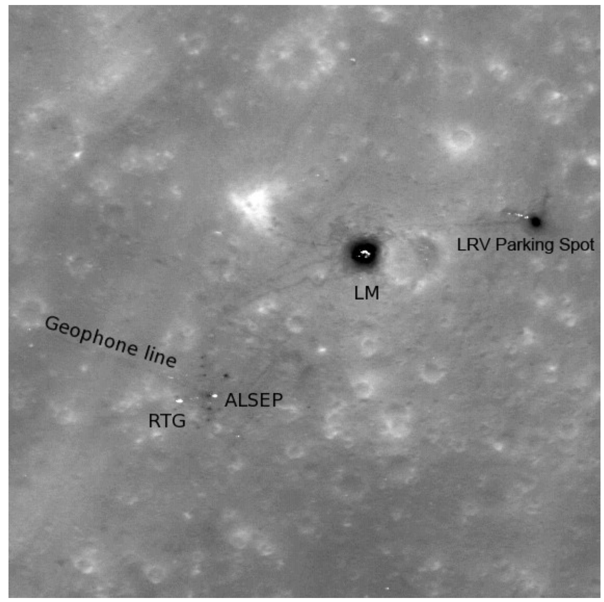

Figure 1: The Apollo 16 Landing Site. LROC NAC image M109134835L, 296 m across [NASA/GSFC/ASU].

that can be straightforwardly calculated for any potential future landing site. This analysis includes sites in a variety of terrains, ranging from ancient mare plains to cratered highlands.

Purpose and Scope: The prerequisite for successful lunar surface operations is a successful landing, defined here as one where the spacecraft is intact, operational, and capable of carrying out its mission. While some areas on the Moon can certainly present challenges for successful touchdowns due to various hazards such as small (<2m diameter) craters and boulders on the surface, the reality is that the vast majority of the lunar surface is accessible provided landing systems have sufficient landing accuracy.

These are metrics that are required to assess landing site suitability from an operational standpoint. This is an important question because many of the highest-priority sites for lunar exploration [6] as well as the target for the Artemis 3 mission [3] are situated in regions that are considered challenging.

Methods: LROC Narrow Angle Camera (NAC) and NAC-Derived Digital Terrain Models (DTMs) are being used to assess the accessibility of each site in terms of the slopes and the Terrain Ruggedness Index (TRI). TRI is the mean elevation difference between the central pixel of interest and its surrounding cells [7]. We also use the Rock Abundance maps produced using LRO Diviner data [8].

Approach: As outlined in [5], to develop a defensible set of parameters for lunar landing site selection we have analyzed each of the landed lunar surface locations for which NAC DTMs (scale 2-m/pixel) and Diviner rock abundance are available. NAC imagery was used to position 200m regions of interest around each landed spacecraft. NAC DTMs were used to calculate the TRI and determine slope distributions. We have quantified the range of morphometric parameters exhibited by locations where lunar landings have been successfully achieved.

Results: Figure 2 summarizes our updated results. The morphometric properties of the landing sites where landings have been successfully achieved are:

- NAC DTM-derived TRI values between 0.077 and 0.462 m
- NAC DTM slopes between 0° and 10°
- Diviner rock abundances between 0.003 and 0.011

Discussion: This analysis establishes an achievability envelope for safe landings. If a given landing site has the morphometric properties derived using LRO's dataset falls within the boundaries established by this analysis, then a lunar landing at the location is likely achievable. Future mission planners can use these updated results to inform site selection activities.

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References: [1] LEAG, Lunar Exploration Roadmap [2] Space Policy Directive 1 [3] Remarks by Vice President Pence at the Fifth Meeting of the National Space Council, 26 March 2019 [4] R. Vondrak et al. Space Sci Rev., 150, 1-4, 7-22, 2010. [5] S. J. Lawrence et al., LEAG 2015, Abstract 2074 [6] Jawin E. R. et al. (2019) Earth and Space Sci., 6, 2-40. [7] M. F. J. Wilson et al., Mar. Geod., 30, 1-2, 3-35, 2007 [8] J. L. Bandfield et al., JGR-Planets, 116, E12, 2011

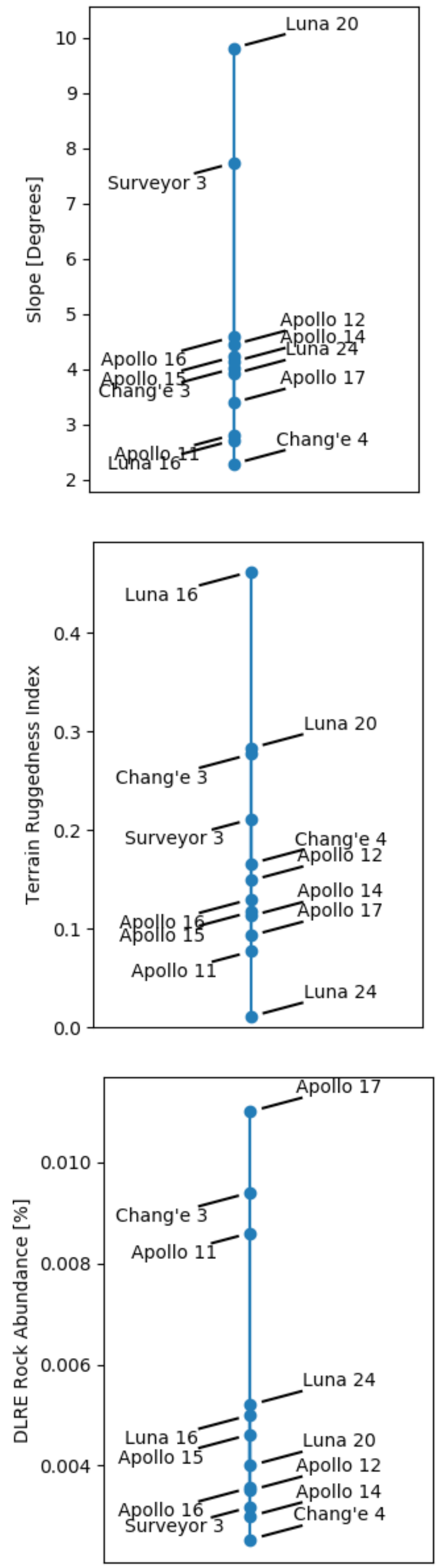

Figure 2: Slope, TRI, and Rock Abundance metrics for historical lunar landings.