CHARACTERIZING LOCATIONS FOR FUTURE LUNAR EXPLORATION USING RECENT MISSION RESULTS.

S. J. Lawrence[1], J. D. Stopar[1], E. J. Speyerer[1], M. S. Robinson[1], B. L. Jolliff[2]. [1]School of Earth and Space Exploration, Arizona State University, Tempe, AZ, USA (samuel.lawrence@asu.edu) [2]Department of Earth and Planetary Sciences, Washington University in St. Louis, St. Louis, MO, USA

Introduction: The original objective of LRO was to collect observations required to facilitate planning and operations of future human lunar and robotic exploration missions. Recent discoveries have highlighted other sites of high exploration and science value that should also be included in future lunar exploration endeavors [e.g., 1,2].

To address this issue, we are systematically assessing likely locations for near-term robotic precursor missions on the Moon [3,4]. In order to maximize the practical utility of the research, our goals are directly traceable to three examples of robotic missions (short-duration rover, extended operations rover, and automated sample return) that have been recommended as precursor missions [3,5]. However, the results of this study will also be applicable to future human lunar exploration efforts. Here, we present some preliminary results and discuss implications of this study.

Objectives: *Define optimal landing sites for future robotic pre-cursor lunar missions:* Using morphology, topography, temperatures, illumination, roughness, slopes, and rock abundances we are identifying landing sites optimized for scientific exploration of the lunar surface. We are particularly focused on defining landing sites where automated sample returns can obtain high-value samples for terrestrial analysis [6,7].

Identify meter-scale traverses and focused investigation stations: Using LRO NAC images and NAC-derived digital terrain models (DTM), we are identifying outcrops, specific boulders, craters, and other geologic features and evaluating how these locations as traverse stations can be safely reached in terms of slope and surface roughness. Planning at this level was not generally enjoyed by the Apollo missions; however, by beginning the process now, the results of this and similar studies will reduce risk and enhance science return.

Develop Concept of Operations: Our assessments produce results directly addressing critical questions about rover, lander, and/or human exploration concepts of operation, including: distances required to reach scientifically interesting waypoints from landing sites, accessibility, and measurement objectives needed to fulfill investigation goals.

Methods: We are fusing LROC (NAC, WAC, and DTMs), Diviner, and LOLA datasets with Moon Mineralogy Mapper (Chandrayaan-1), Kaguya Terrain Mapping Camera, Clementine derived FeO and TiO_2 mapping products, and Apollo Metric Camera frames. These integrated datasets are then used to determine important lithologies and geologic units, any potential resources, and downselect candidate landing sites and productive exploration locations.

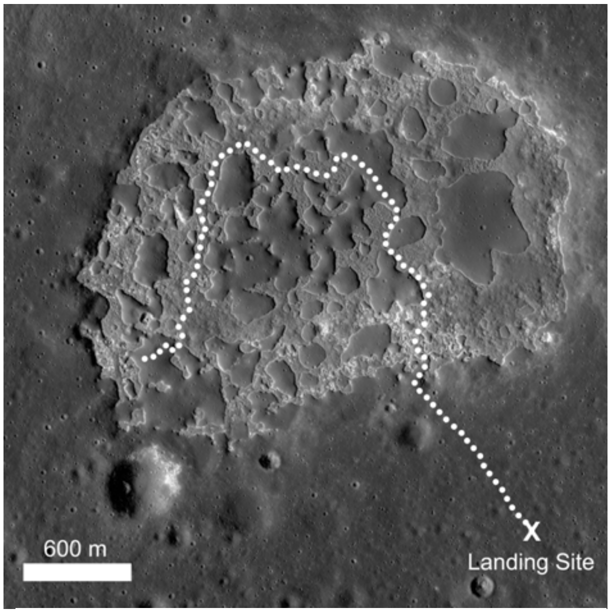

Figure 1. Example path planning algorithm output for Ina on a LROC Narrow Angle Camera image.

LROC NAC map-projected and mosaicked images allow evaluation of meter-scale hazards [8], characterization of surface materials and illumination considerations (including shadow persistence) [e.g., 9]. PDS-archived NAC-derived Digital Terrain Models (DTMs) allow determination of local slopes and surface roughness over a range of scales from meter to decameter.

We have developed a path planning algorithm [10] based on a generalized least-energy model for planetary rovers, altered for the Moon [11]. This algorithm identifies least energy traverse paths (Fig. 1) and allows us to determine capabilities (e.g., rolling resistance, turning capability, maximum slopes) that are required to reach specific targets.

Results and Discussion: Slopes likely encountered, maximum 30-m length scale roughness, potential hazards, and distances between key waypoints are presented in Table 1 for representative sites that include plains units, impact craters, and volcanic terrains. These results are an initial phase of site assessment and our path planning and evaluation processes will continue to be improved and refined.

Limited-Duration Rover: The small areal extent and relative accessibility of Irregular Mare Patches (IMPs) such as Ina (18.5°N, 5.2°E) make them ideal candidates for short-duration rover missions (Fig. 1).

In general, exploration of recent impact craters may best be accomplished from a rover platform by sampling ejected materials scattered near the crater; however, this strategy would preclude exploration of any subsurface voids in impact melt on the crater floor [e.g., 12]. The interiors of fresh craters can also have extensive shadows during significant periods of time.

Extended Operations Rover: Typical lunar mare domes (e.g., Hortensius) have flank slopes of a few degrees (5-7°) with few meter-scale hazards. The steep slopes and irregular topography of other lunar volcanic landforms (e.g., Marius Hills) may require more capable rover hardware at these sites when “rolled boulders” do not provide adequate samples from higher topographic units. Boulder sampling is particularly important for features like the Mairan domes, where flank slopes can exceed 20°.

Regionally smooth units such as regional pyroclastic deposits, mare plains, and other smooth plains units have gentle slopes and few topographic obstacles; however, travel distances between waypoints may be greater. Excavated blocks can potentially provide subsurface samples from geologic materials located beneath a relatively thin plains unit; these blocks are generally derived from small recent impact craters, including secondaries from relatively recent cratering events [e.g., 13-14].

Automated Sample Return: Locations such as the comparatively recent mare basalts south of the Aristarchus Plateau, the Sulpicius Gallus regional dark mantling deposit, and the Imbrium mare flows have relatively uniform compositions, favorable illumination conditions, and smooth slopes. Consequently, these are attractive targets for automated sample return, since mobility will not be required to achieve valuable scientific objectives.

Conclusions: Minimum travel distances, minimum mission duration, wheel slip tolerance, and maximum approach and departure angles for exploration locations are fundamental for defining hardware as well as instrument-suite selection. Understanding the physical properties of the lunar surface as well as the accessibility of desirable exploration locations is critical to maximize the science return from future lunar surface missions.

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TABLE 1. ACCESSIBILITY, NAVIGATABILITY AND HAZARD ANALYSIS FOR DIFFERENT TERRAINS

SITE	DEM RES (MPP)	NOMINAL SCIENCE GOAL	PRIMARY TARGET/FEATURE	AVG SLOPE (DEG)	MAX SLOPE (DEG)	MAX 30-m "ROUGHNESS" (DEG)	POTENTIAL HAZARDS	TRAVEL DISTANCES (KM) BTWN KEY WAYPOINTS
Plains								
Sulpicius Gallus FM	2	Composition and Origin of Pyroclastics	Pyroclastic deposits, vent structure	6	11	4	Descent into "vent" includes slopes greater than 20 deg	~1-10
Imbrium Flows	5	Structure and Composition of Mare Flow Fronts	Flow surfaces	2	9	2	Minimal	~2-10
Craters								
Fresh 2.5-km Impact Crater Near Denning	2	Composition and Distribution of Impact Melt	Impact Melt Deposits	6	13 (rim); 30 (wall)	4 (rim); 13 (wall)	Large dm-scale blocks near rim; 30 deg slope descending into crater; steep slopes near rim	~0.5
Giordano Bruno	2	Age and Composition of Extremely Young Impact Crater	Ejecta, Impact Melt Deposits	4 (melt); 9 (rim)	20 (rim); 35 (wall)	6 (rim); 13 (boulder fields)	Areas along rim with dense boulder populations	~0.1-3
"North Crater"	6	High Latitude Crater Materials	Crater Walls and Floor	27 (wall)	30 (wall)	5 (wall)	Polar illumination; slopes ~30 deg inside crater	~0.5-1
Volcanic Constructs								
Hortensius	2	Composition of Lunar "Mare" Dome	Volcanic Domes and Vents	5 (flank)	9 (flank); 30 (vent)	3 (flank)	Up to 30 deg slopes descending into "vents"	~0.5-10
Isis and Osiris	5	Composition of Lunar Cones	Volcanic Cones	5	23	4	Greater than 20 deg slopes ascending cones	~0.1-5
Marius Hills	2	Composition and Structure of Complex Lunar Volcanism	Volcanic Domes, Cones, and Vents	5	20	3	Minimal	~0.1-5
Ina	2	Properties of Irregular Mare Patches [IMP]	Volcanic Deposits and Structure	4	13	3	Ascent from rille floor includes slopes up to 30 deg	~0.1-0.5
Mairan T	2	Composition and Age of Silicic Volcanism	Volcanic Dome (rolled blocks)	5 (base); 30 (flank)	3 (base); 40 (flank)	6 (flank)	Greater than 30 deg slopes ascending dome	~0.5