A SEQUENCE FOR FUTURE LUNAR LANDINGS TO ENHANCE SCIENTIFIC RETURNS. J. Mehta[1], A. Kothandhapani[1], V. Vatsal[1], J. Head[2], U. Shah[3], [1]TeamIndus - Axiom Research Labs, Bangalore, Karnataka, 560092, India. [2]Department of Earth, Environmental and Planetary Sciences, Brown University, Providence RI 02912, USA, [3]OrbitBeyond Inc. Edison, NJ 08837. USA.

Introduction: A lunar science community consensus for many high scientific value lunar landing sites was a product of the Lunar Science for Landed Missions Workshop (NASA Ames, January 2018).[1] The authors of this paper, a mix of scientists and research engineers at commercial space companies, present a report addendum, addressing the engineering capabilities required to meet the scientific goals at each site.

The emerging capabilities of commercial entities developing lunar landing and exploration systems will act both as a constraint and an enabler. The intention of this report is to (1) identify the capability requirements to meet the scientific objectives (2) illustrate how capabilities hence developed can be harnessed to enhance scientific returns.

Landing Sites: The reference landing sites[1] taken from the workshop report, to assess engineering requirements and constraints are as follows:

Nearside	
Aristarchus plateau	50 W, 25 N
Gruithuisen Domes	40.5 W, 36.6 N
Ina	5.3 E, 18.66 N
Marius Hills	56 W, 14 N
Pits in Mare Tranquillitatis	33.2 E, 8.3 N
Reiner Gamma	59 W, 7.5 N
Farside	
Compton-Belkovich Volcanic Complex	99.5 E, 61.1 N
Moscoviense	147 E, 26 N
South-Pole Aitken Basin	170 W, 53 S
Antoniadi crater	172 W, 69.7 S
Shackleton plateau/ridge	125 E, 88 S

Engineering Requirements: Requirements that dictate the engineering solution necessary to access each landing site can be broadly categorized as follows:

1. Landing accuracy: Pinpoint landing accuracy (1 to 10 m) might be the ultimate capability required, highly desired for sites like Ina. This requires terrain-relative navigation with features identified from surface maps actively during descent.[2][3]

Medium accuracy landings (10 m to 1 km) enable touchdown adjacent to features like lunar pits or caves, ensuring a short traverse to required regions of interest. These landings may require camera based navigation to correct for position errors.

Coarse accuracy landings (dispersions >1 km) may be done with good quality standalone Inertial Measurement Units propagating state knowledge through the descent. A wide variety of landing sites can be effectively targeted at lower costs with this strategy.

2. Terrain knowledge: A Digital Terrain Model of the landing site at a high resolution (<=5 m/pixel) is necessary to evaluate safe landing spots and identify local hazards. Hazards include regions contained within craters, shadowed areas, high slopes or areas that violate traversability constraints for mobile platforms. A spot within the region of interest which maximizes the landing probability of success is chosen as the targeted set of coordinates.

3. Hazard avoidance and terrain relative navigation: The use of LiDAR sensors would be popular for applications like altimetry, velocimetry, terrain relative navigation and hazard detection and avoidance. Technologies involving Flash LiDARs are essential for night landing and where visible spectrum camera systems may not be useful for navigation. Polar sites and targets in or near Permanently Shadowed Regions will benefit from the same.

4. Orbital approach: Safe descent conditions are necessary to target a landing site. This includes the descent trajectory maintaining a safe distance from lunar terrain till touchdown, adequate illumination of the site during descent, and ability to target a backup landing site if needed.

5. Communication (Nearside): Communication visibility <70 N/S latitudes is good even when accounting for local topography that can occult line of sight. For sites >70 N/S, low Earth elevation combined with terrain features limit visibility. For such sites, local slopes towards the equator are preferred, an example being the southern ridge of Malapert Mountain.[4] Such regions demand pinpoint landing.

6. Surface temperatures: For sites >70 N/S, temperatures are much lower[5] and Radioisotope Heater Units may be needed to keep the electronics and mechanical joints functional, even when there is solar power availability. Moreover, the physical and thermal properties of the soil at these sites need to be better understood, before risking deployment of an exploration platform.

7. Power requirements: The limitations of solar power are tied to the relative motion of the Sun at the landing site. Sizable power requirements can justify the use of deployable and Sun-tracking solar panels, as opposed to fixed ones, thus making the Lander configuration independent of the landing site latitude. For sites >70 N/S, despite low temperatures and long shadows, there is scope to operate across short lunar nights (24 to 48 hrs) using commercially accessible technologies.[6]

8. Farside constraints: Farside missions will require an in-space communications relay, for example at EM-L2.[7] Depending on the orbit of the relay system, surface operations will either be continuous, or intermittent (e.g. orbiting relay). The cost of such a system, if dedicated only for this purpose, is also a consideration. Additionally, higher knowledge errors exist in the farside terrain and gravity models as opposed to the nearside, decreasing farside landing accuracy[7][8] for the same spacecraft configuration.

Enhancing Technological Capabilities: These represent capabilities that enhance scientific return, but are treated as optional in the near-term to core engineering requirements discussed earlier.

1. Sample acquisition and return: For unique sites like Gruithuisen Domes, Ina, Moscoviense, etc., sample return is highly desired.

For returning the sample to Earth, an ascent module can be injected into a Direct-to-Earth trajectory but the time margin for liftoff is small. This method also constrains the reentry coordinates for sample return, akin to the Luna sample return missions[9]. Having the ascent module in a lunar parking orbit and then performing a Trans-Earth Injection does away with the time margin constraint, but at a cost of some increased lander system and fuel mass.

Alternately, the module can dock with an orbiter and then send the capsule to Earth, freeing up both time and mass constraints, but requiring autonomous rendezvous and docking capabilities and increased costs. Operational availability of NASA's Lunar Orbital Platform-Gateway will accelerate possibilities of sample return, not just in terms of logistics, but also enhancing flexibility of the reentry site on Earth.

2. Lunar Night Survival: Purely solar-powered systems are limited to within a lunar day to complete mission objectives, limiting the returns on a single launch. To date, radioisotope-based (e.g. Pu-238) power sources have been used to keep systems warm during the lunar night. But this solution is not sustainable for long durations or for increased power needs, due to low efficiency and hazardous nature of the power source.

The need for sustainable and scalable methods to enable lunar night survival and possible operations is apparent when compared to the discoveries made by the long-duration MERs and Curiosity on Mars. The methods currently under study and prototyping are: a) Regenerative Fuel Cells[10] b) Low-temperature high energy density chemical batteries and c) Use of lunar regolith as thermal wadis to store heat/generate power[11].

Mobility: Mobile platforms add greatly to the scientific return from landing missions.

1. Roving platform: For an exploratory Rover, a Direct-to-Earth communication link, long traverse range and ability to rove on irregular terrain is desirable to meet objectives at many of the high-value landing sites. For smooth, mare-like terrain, wheeled or tracked Rovers are prefered. For rocky, uneven/rigid terrain like that of Marius Hills, rovers that can negotiate >20° slopes[12], or legged rovers are required.

Long traverse capability would greatly benefit sites like Aristarchus, Reiner Gamma, Moscoviense, etc. where studying lateral variability is highly desired.

2. Hopping: The lander can also have the capability to hop to another location post-landing. This may be desirable for sites with highly rocky terrain or steep slopes like Ina, where rover mobility is difficult.

Hopping capability can also add value to a nominal mission scenario in the following ways: a) Study lateral variability on a geologically diverse site or a site with a large feature b) carry larger payloads (as compared to on a rover) to achieve more/better scientific measurements c) Examine far field features of interest.

Conclusion: The output from the Workshop at Ames presented a high-level requirements matrix for each landing site. We have extended this to outline the engineering considerations and developed a notional sequence in which the landing sites may be targeted. This enables a campaign of scientific missions driven by technologies currently within reach of, and planned by commercial spaceflight companies. Understanding the technology progression that such a sequence demands from developers of commercial lunar landing and mobility systems will aid science planners and agency programs in maximizing scientific returns.

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