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“Land & Fly” Methods for Effective, Future Lunar Exploration

A “Mission Concept” White Paper Submitted to The Decadal Survey in Planetary Science and Astrobiology 2023-2032

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1 MOBILITY IN THE CONTEXT OF LUNAR EXPLORATION

Planetary exploration has been benefiting substantially from post-landing mobility. Surface missions to the Moon, Mars and Near-Earth asteroids have seen various implementations of mobility to permit field geology to be performed, to allow controlled approach to outcrop and other targets of interest for in situ analysis and sampling (e.g. Arvidson et al., 2000; Squyres et al., 2004; Arvidson et al., 2014), and to enable efficient geology investigations by humans in the case of the final three Apollo missions to the Moon. Traditionally, post-landing mobility is realized via ground vehicles, also referred to as rovers. For very low gravity environments as found on small bodies, mobility by hopping using an internal momentum mechanism has been pioneered on the Japanese Hayabusa-2 mission to near-Earth asteroid 162173 Ryugu. The current, new era of lunar surface exploration is presently led by China which succeeded in landing two lander and rover missions on the Moon between 2013 and 2019, including the first ever farside landing, with the Chang'e 5 sample return mission ready for launch in the fall of 2020.

Surface mobility with uncrewed rovers provides comprehensive science capabilities and access to compelling scientific features that are identified by science and operations team on the ground. Surface rovers can also enable "Go-To mobility" where the rover's delivery location (mission landing site) is carefully selected such that it is safe for landing but within reasonable driving range from the chosen prime science target that itself may be hazardous for the lander to reach in the first place, such as is the case for the MSL and Mars 2020 Mars roving missions. On the downside, however, uncrewed surface rovers suffer from several shortfalls:

- All ground vehicles are subjected to limits in mobility that vary depending on the exact vehicle configuration: performance characteristics such as gradability and obstacle negotiation capability will always be limited, preventing access of ground vehicles to particularly steep or rough terrain. In addition, terrain with low bearing strength represents a mobility hazard.
- Effective speed of uncrewed rovers, i.e. ground covered vs. time, is typically very low; this is primarily driven by limited on board autonomous capability for long range driving; the tele-operated (by humans on the ground using real-time, slow-scan video) Lunokhod 1 and 2 rovers covered 10.5 km and 42 km over 10 and 4 lunar days, respectively, but China's Yutu-2 – operated mostly through command loads and on board autonomy rather than by tele operation – to this day has traversed just short of 0.5 km over a period of 20 lunar days (corresponding to ~1.5 years), thus typically covering 10…40 m per lunar daytime period; the astronaut crews of Apollo 15, 16, and 17 on the other hand traversed total distances of 28 km, 27 km, and 36 km, respectively, over 3 EVAs each, with total drive durations per mission of typically ~10 hours (Carrier et al., 1991).

Several lunar rovers are currently in flight development for uncrewed landing missions to the Moon over the next several years, primarily as part of NASA CLPS mission opportunities: the small, ~18 kg MoonRanger vehicle to fly on the CLPS 19C high Southern latitude mission to the Moon and the NASA VIPER lunar polar rover mission with a ~450 kg vehicle for volatiles prospecting through sampling and analyses in the vicinity of Permanently Shadowed Regions (PSRs) near the lunar South pole. Also for these vehicles, strict performance limitations apply: for MoonRanger primarily through its exceedingly small physical dimensions that constrain rough terrain mobility, and for VIPER because of the complex lighting situation at polar latitudes which restrict the operations and solar occultation survival scenarios for the rover (A. Colaprete et al., 2020).

In this White Paper, we are advocating another method of post-landing mobility in lunar exploration which we refer to as "land & fly" mobility. Benefiting from the modest gravitational acceleration of the Moon, thruster propelled vehicles carrying out powered or ballistic flight arcs are a feasible way of achieving regional exploration and vehicle relocation. Already in the 1960's, early studies were investigating free flying vehicles on the Moon for larger scale mobility (Kaplan and Seifert, 1969).

Some of the authors of the present White Paper – LR and BO of OHB System, Germany, and SS of Blue Origin, USA – have been studying two different types of free flying vehicles that could be delivered to the lunar surface as fueled spacecraft by some of the upcoming, larger lunar landers that are currently in flight development, such as Blue Origin's "Blue Moon". The free flyer vehicles would take off after landing of the main spacecraft and carry out their own assignments. Several advantages are attached to such vehicles:

- If the landing site has been selected to be in the vicinity of a science target which itself would be unsafe for landing in terms of topography or other terrain conditions, free flying vehicles as studied by us would provide "go to" mobility or "last-mile access" to that target for at least close-up remote sensing studies that exceed spatial resolution obtainable with lunar orbital assets.
- Free flying vehicles can cover kilometer-scale distances in a matter of minutes as opposed to uncrewed surface rovers that require at least several weeks to achieve similar ranges.
- Mobility is not hampered by rough or otherwise unsafe terrain conditions.

Science rationale, concepts, and suggested instrumentation of our free flying vehicles are discussed below.

2 LUNAR SCIENCE QUESTIONS BENEFITING FROM POST-LANDING MOBILITY

The Moon has been used for decades as a Rosetta stone by planetary scientists, bringing crucial information on key planetary processes. In addition, its accessibility and resource potential make it an excellent platform for future space exploration. Still, despite decades of exploration, a number of science questions pertaining to the Moon's formation, evolution and surface environment remain. These questions are listed in several reference documents such as the NRC report (2007), LEAG Lunar Exploration Roadmap (2016), or more recently ESA's strategy for Science at the Moon (2019). Table 2-1 illustrates the list of science themes or concepts (lines) and corresponding goals (columns) which are listed in the NRC report "The Scientific Context for the Exploration of the Moon".

Several studies have been carried out in the past years in an attempt to identify where and how these science questions could be addressed (e.g., Kring and Durda, 2012; Flahaut et al., 2012, 2020; Pernet-Fisher et al., 2019). It became clear that the open issues could not be addressed at a single location or by a single mission to the lunar surface, illustrating the necessity for access to unexplored locations, mobility and for multiple exploration vehicles.

We argue that post landing mobility using the novel "land & fly" drones and hoppers we are putting forward here could resolve this problem by very quickly covering ground from the original landing site irrespective of terrain conditions, and by allowing close approach to otherwise inaccessible features. This will yield remote sensing data products of as yet unmatched spatial resolution and SNR but will also permit multiple in situ measurements at different sites with the same instrument suite.

The potential for addressing Scientific Knowledge Gaps (SKGs) with the suggested vehicles is extremely high, as can e.g. be judged from the Lunar Polar Prospecting Workshop findings and recommendations (Morris and Sowers, 2018). One of the outstanding open lunar science issues is the unequivocal identification and characterization of sites that contain water ice and other volatiles, having also a bearing on future commercial aspects of lunar exploration (ISRU). With the clear potential to shed light on the evolution of the Earth-Moon system and the role that the volatile elements played during the evolution of our Solar System, this question is the clear focus of many upcoming lunar missions.

As there are many different potential sources for hydrogen-bearing volatiles (dependent also on their exogenic and / or endogenic origin, e.g. Anan, 2010; Prem et al., 2020) it is – despite many existing mapping efforts - by no means obvious where and in what physical state the near surface hydrogen-bearing volatiles are going to be found. One class of feature that is implicated by available observations to harbor elevated volatile abundances is Permanently Shadowed Regions (PSRs) near the lunar poles. PSRs are associated with topographic lows which, due to the orientation of the Moon's rotational axis and orbital plane, are not exposed to direct sunlight over geologic timescales and that can thus act as cold traps for volatiles.

Table 2-1: Summary table of the NRC science concepts and goals for the exploration of the Moon. Orange coloured boxes indicate goals which would strongly benefit from post-landing mobility, remote sensing and/or in situ analyses or the deployment of a science package

NRC Concept/Goal	a	b	c	d	e
1: Bombardment history of the inner solar system	***Test cataclysm hypothesis***	***Age of South Pole-Aitken basin***	***Establish absolute chronology***	Recent impact flux	Secondary craters
2: Structure and composition of lunar interior	***Thickness/ variability of lunar crust***	***Stratification of mantle***	***Size, composition, state of core***	Thermal state of interior	N/A
3: Diversity of lunar crustal rocks	***Differentiation products***	***Age, distribution, origin of rocks***	Composition of lower crust	Complexity of lunar crust	Extent/structure of megaregolith
4: Lunar poles and volatiles	***State and distribution of volatiles***	Source of volatiles	Transport, alteration, loss processes	Properties of polar regolith	Polar regolith and ancient solar environment
5: Lunar volcanism	Origin/variability of basalts	Age of mare basalts	Range/extent of pyroclastic deposits	Lunar volcanic flux	N/A
6: Impact processes	Melt sheet differentiation	Structure of multi-ring impact basins	Crater formation	Mixing of local and ejecta material	N/A
7: Regolith processes	Characterize ancient regolith	Physical properties of regolith	Regolith modification processes	Rare minerals in regolith	N/A
8: Atmosphere and dust processes	***Characterize the fragile lunar atmosphere***	***Physical properties of dust***	Time-variable gas release from the lunar interior	Volatile migration and trapping	N/A

Willl be addressed with surface mobility (human or robotic exploration)

May be addressed with human/robotic exploration

Would greatly benefit from post-landing mobility (drones or hopper)

Searching for deposits of lunar volatiles at ground level may require repeated attempts to investigate many possible candidate sites in situ. On the other hand, the ideas proposed in the present paper would not only resolve uncertainties regarding the distribution and physical nature of volatiles at 10 to 100 m scales as relevant for their comprehensive study and possible exploitation, but they also allow for an efficient search strategy within a single mission. This would strongly impact scenarios for future polar missions and ISRU perspectives, and address concepts 4 and 8 of the NRC report (e.g., LEAG VSAT report, Lucey et al., 2014).

The concepts outlined here further offer the possibility to explore diverse and regionally complex locations away from the poles that could not be efficiently visited with a large surface rover mission, such as volcanic plateaus with domes, cones, Irregular Mare Patches (IMP) (Schnuriger et al., 2020), lava tubes, ancient crust from the highland terrains, interior and exterior of impact craters (including melt sheet and ejecta blanket, which are largely inaccessible to rovers), interior and exterior of lunar swirls, etc., therefore addressing most concepts (2, 3, 4, 5, 6, 7, 8) of the NRC report.

An additional benefit from the multi-lander or hopper as one of two of the vehicle types suggested here is its capability to deploy long-lived science packages at various locations, such as seismometers and other geophysical experiments (required to address NRC concept 2), dust and atmospheric monitor package (concept 8), volatile cycle monitoring station (concept 4), biological or fundamental physics experiments (see ESA, 2019) or even small autonomous rovers (<20 kg). A self-sustained, long-lived, deployable geophysics package that includes a Very Broadband Seismometer similar to the one flown on InSight to Mars is being studied by a joint European-US team and amounts to a mass of ~75 kg.

3 TWO SUGGESTED TYPES OF FREE FLYING VEHICLES

Two types of post-landing mobility vehicles are proposed by us to provide last-mile access to otherwise difficult-to-access regions. These vehicles would be transported to the lunar surface by larger lunar landers. They would also use the carrying lander, or “mothership”, as a base during their own missions, including as a communications relay back to Earth.

3.1 Multipoint Surface Measurement Platform (MSMP)

The first vehicle concept we propose to provide post-landing mobility on the lunar surface is a Multipoint Surface Measurement Platform (MSMP), also referred to as a “hopper”. An MSMP will be able to reposition itself using its on-board propulsion system in order to access multiple surface sites over the course of a single mission. An MSMP will be able to perform both in-situ and remote sensing experiments during and in-between “hops” to acquire data related to e.g. geophysics, volatile composition, surface topography, as well as radiation / plasma monitoring.

Regions of Interests (RoIs) would be identified based on the intended landing site of the mothership lander, and a notional roadmap of hops would be planned out for an individual MSMP prior to launch.

Hops may be performed purely for transit purposes, i.e. to reach a new surface site, but they can also be taken to perform remote sensing “fly-over” measurements of a RoI below the hop-trajectory, which may otherwise be inaccessible by conventional means. Such sites may include Permanently Shadowed Regions (PSRs), skylights of lava tubes, central massifs / melt sheets / ejecta of craters, volcanic dome cones, IMPs and rilles. Suitable science instruments for such “fly-over” observations include: 1) laser reflectometer to study exposed volatile deposits through surface albedo, 2) VIS / NIR / TIR imagers (the latter to indicate exposed ices), 3) scattering radar, for capturing the CPR (circular polarization ratio) signature of terrain below in search for volume scatterers such as ices.

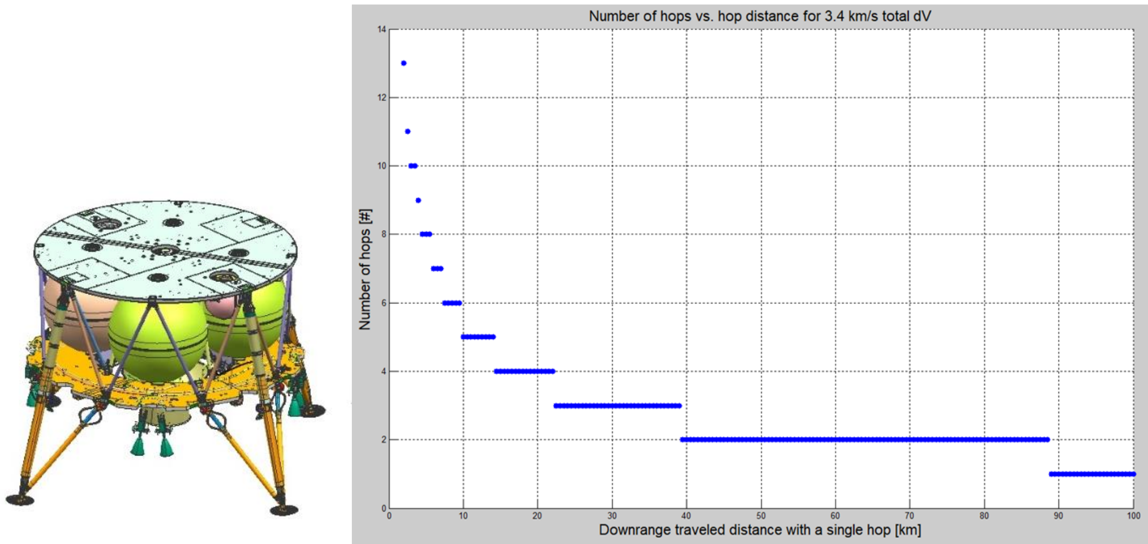

Figure 3-1: Left: MSMP hopper design derived from the OHB-IAI Lunar Surface Access Service (LSAS) vehicle; right: MSMP range per hop vs. number of hops, for a total delta-V of 3.4 km/s

The proposed MSMP design is derived from the upcoming OHB-IAI Lunar Surface Access Service (LSAS) spacecraft, itself drawing heritage from the SpaceIL Beresheet mission, the first privately funded lunar lander mission, which launched early 2019. The hopper would have a wet mass of roughly 600 kg, and could carry around 25 kg of payload if the original delta-V capacity of about 3.4 km/s were retained. For a reduced delta-V of 2.0 km/s, payload mass increases to ~140 kg. The on board delta-V may be flexibly spent on several shorter hops, fewer longer hops, or a mix in between.

The envelope of the hopper is roughly 2 meter in diameter, and 1.5 m in height. Its indicative accommodation on Blue Origin's "Blue Moon" lunar lander, assumed as the mothership for purposes of this White Paper, has been studied by us and would be on the lander's top deck, with appropriate thruster plume deflection shields to minimize damage to the host vehicle as the MSMP takes off.

3.2 Low-Altitude Free-Flying Measurement Platform (LAFFMP)

The second vehicle concept we propose to provide post-landing mobility on the lunar surface is a Low-Altitude Free-Flying Measurement Platform (LAFFMP), i.e. a free-flying drone.

Since our suggested drones would nominally *not* be designed to land once they take off, they would primarily be used for remote sensing measurements above lunar surface features that they are sent to inspect. Our drones as studied by OHB have been defined to be relatively lightweight, at below 200 kg including propellant. A payload capacity of at least 10 kg has been allocated. Candidate instruments could be identical to the remote sensing "fly-over science" instruments on the MSMP hopper, thus being: 1) laser reflectometer to study exposed volatile deposits through surface albedo, 2) VIS / NIR / TIR imagers (the latter to indicate exposed ices), 3) scattering radar, for capturing the CPR (circular polarization ratio) signature of terrain below in search for volume scatterers such as ices. The drone may also carry a mass spectrometer to test the local environment while in flight for e.g. presence of volatiles offgassing from the terrain below. All candidate instruments have integration times short enough to be compatible with expected lateral motion speeds and descent rates of the drone over the RoI.

A simple monopropellant propulsion system is implemented, capable of about 1300 m/s delta-V. This delta-V may then be flexibly spent, either prioritizing RoIs far away, or maximizing the measurement acquisition time by increasing the descent duration for close-up observations above an RoI. For example, the delta-V required by the proposed drone to reach an RoI 10 km away is about 370 m/s and takes three minutes to reach, while an RoI 30 km away takes just over five minutes to reach and requires 640 m/s of delta-V.

Each drone's envelope is roughly a box with sides of 1 meter each. Also for the LAFFMP vehicles, we found a feasible accommodation on Blue Origin's "Blue Moon" lunar lander, by enclosing drones in lidded containers on the lander's top deck.

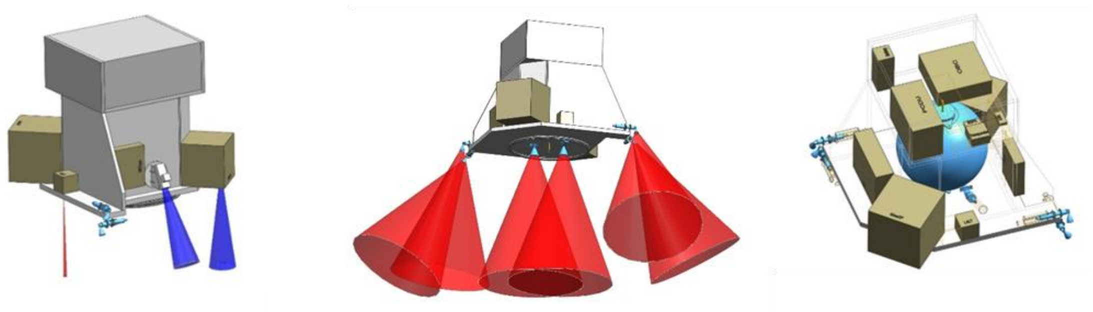

Figure 3-2: Left: LAFFMP drone with indicative FOV's (blue) of candidate instruments; center: thruster plumes (red); right: drone configuration with internal items shown

4 EXAMPLE: "LAND & FLY" CONCEPTS FOR EXPLORATION OF LUNAR POLAR COLD TRAPS

We suggest that our proposed Multipoint Surface Measurement Platform (MSMP) or hopper can be brought to bear for the study of the lunar polar volatiles inventory. The general mission concept for the MSMP was described above.

Whereas the MSMP will not be able to be directed to land inside a PSR – due to low temperature and largely unknown topography and thus terrain hazards – it offers the capability for multiple relocations before its delta-V capacity is expended. Relative to the study of lunar polar volatiles, this can be exploited in several ways:

- Choosing a number of Regions of Interest (RoIs) in the vicinity of the mothership lander such that landed locations of the hopper are in the vicinity of PSRs but outside permanent shadow; in-situ measurements at such locations would then include analyses of the local regolith for abundance of volatiles (by e.g. an instrumented, shallow drill or a LIBS instrument) to contribute to mapping the small scale nature of volatiles in the polar regions.
- Choosing some of the hop trajectories such that they pass over selected PSRs, allowing the hopper to act as a platform for relatively low altitude remote sensing observations of the interior of the PSR in what we refer to as “fly-over” science.

As an example, for a lateral hop range of 10 km, maximum altitude of the vehicle would be of the order of 150 m while a 30 km hop would reach a peak altitude of about 300 m. This is more than a twentyfold reduction of the minimum observational altitude achieved with NASA’s Lunar Reconnaissance Orbiter (LRO), and suitable on board instrumentation on the MSMP hopper promises significant improvements in both ground resolution and SNR of remote sensing measurements above a PSR.

On the other hand, activities at each landed location of the hopper would not be limited to volatile-specific in-situ measurements but are suggested to include geophysical investigations, ISRU demonstrations and, optionally, the deployment of one or more self-sustained instrument packages that would be left behind before the hopper departs.

The MSMP would nominally not be designed to survive lunar nights on its own, limiting its useful surface operation time to roughly 14 Earth days. However, it may be feasible to plan a hop-roadmap so that an MSMP continuously tries to outrun the solar terminator, in particular if the operating zone is at lunar polar latitudes. This would allow for the mission to be long-lived, as the MSMP would be avoiding local dusk and hopping further into local daylight.

We consider our second type of free flying vehicle, the Low-Altitude Free-Flying Measurement Platform (LAFFMP) or lunar drone, as particularly attractive for the study of PSRs. The general mission concept for the LAFFMP was described above. Such a drone can be directed to traverse to a PSR as a Region of Interest (RoI) a number of km away from the mothership’s landing site and to then descend into the shadowed envelope of the topographic low constituting the PSR while taking measurements ever closer to the ground and transmitting the data in real time.

The cold thermal environment at ground level of a PSR is of little concern for the drone design as radiative exposure to this cold background is of short duration (of the order of minutes or less), and there is no landed mission phase for the vehicle in which there would be conductive ground contact. Once the on board propellant is expended, the vehicle would impact the ground but may continue measurements and data transmission up to that point. We suggest a multi-drone mission to study topographic lows such as PSRs simultaneously with more than one drone where at least one drone will have to keep a high altitude to maintain a line-of-sight communication link with the lander, to act as a data relay for the drones that have disappeared from the lander’s field of view due to terrain features.

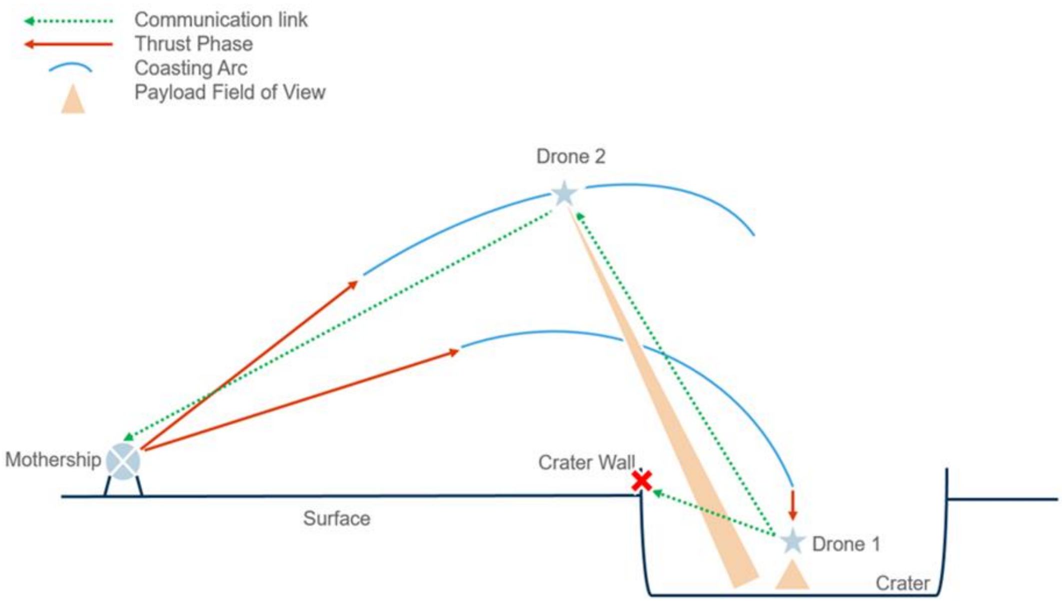

Figure 4-1: Schematic of two LAFFMP drones operating in concert to explore the interior of a lunar PSR

For a 200 kg wet mass drone, it would take 188 seconds and cost 370 m/s delta-V to cover a lateral range of 10 km. During the final approach to the RoI, the drone may restart its main thruster to slow down its descent. This final thrusting phase allows the vehicle to spend more time acquiring data during its mission than it would if it just fell freely into the RoI. The flight and thrust profile of this final approach can be flexible depending on the needs of the individual payloads on board, and the interaction of the exhaust plume with the payload FoVs. For payloads that need a more unperturbed environment, the drone could potentially schedule its thruster firings to maximize uncontaminated data acquisition. For this final phase, the propellant costs involved are relatively high. Hovering (thrust-to-weight ratio of 1) for 30 seconds costs 295 m/s delta-V, and does increase linearly with time. Again, as described above in section 3.2, on board delta-V capacity of the LAFFMP drone is 1300 m/s which comfortably envelopes the here outlined PSR exploration scenario.

For the drone "diving" into the PSR, measurements would improve in ground resolution while descending (with concurrent reduction of observational footprint on the ground), with the most valuable observations made just 10's of meters above the ground with low vertical velocity (respecting the need to transmit the data). This is a ~200-fold reduction of the minimum observational altitude achieved with NASA's Lunar Reconnaissance Orbiter (LRO), and suitable on board instrumentation on the LAFFMP drone promises significant improvements in both ground resolution and SNR of remote sensing measurements above the floor of a PSR.

5 REFERENCES

[1] Allender et al, 2019 [2] Anand, 2010. [3] Arvidson et al, 2000 [4] Arvidson et al, 2014 [5] Carrier et al, 1991 [6] Chevrel et al, 2009 [7] Colaprete et al, 2010 [8] Colaprete et al, 2020 [9] ESA Strategy For Science at the Moon, 2019 [10] Feistel & Wagner, 2007 [11] Flahaut et al, 2012 [12] Flahaut et al, 2020 [13] Hayne et al, 2015 [14] Arvidson, 2008 [15] Hess et al, 2020 [16] Kaplan & Seifert, 1969 [17] Kramer et al, 2013 [18] Kring & Durda, 2012 [19] LEAG, 2016 [20] Li et al, 2018 [21] Lucey et al, 2014 [22] Mazarico et al, 2011 [23] McClanahan et al, 2018 [24] Moriarty & Pieters, 2018 [25] Morris & Sowers, 2018 [26] NRC, 2007 [27] Paige et al, 2010 [28] Pernet-Fisher et al, 2019 [29] Potts et al, 2014 [30] Prem et al, 2020 [31] Schnuriger et al 2020 [32] Waydo & Voorhees, 2006