THE IRREGULAR MARE PATCH EXPLORATION LANDER (IMPEL) SMALLSAT MISSION CONCEPT.

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Introduction: High-resolution, narrow-angle camera (NAC) images returned by the Lunar Reconnaissance Orbiter Camera (LROC) resulted in the identification of more than 70 sites of geologically recent activity interpreted (based primarily on their morphologies) as volcanic eruptions that occurred within roughly the last 100 million years [1]. Such young ages would require significant changes to our understanding of lunar magmatic and thermal history. The sites of these eruptions were termed *Irregular Mare Patches* (IMPs). The formation mechanisms and ages of these deposits, however, remain debated [2-4]. Nonetheless, their occurrences in association with mare basalts and on volcanic shields suggest volcanic activity, likely either as inflated lava flows or lava squeeze-ups.

Our team was funded by the Planetary Science Division (PSD)'s Planetary Science Deep Space Studies (PSDS3) program to conduct a six-month concept study for a SmallSat mission titled the **Irregular Mare Patch Exploration Lander (*IMPEL*)**. The mission is designed to land a small, simple package of science instruments intended to distinguish between competing formation mechanisms for IMPs. The proposed science package will address the relative age and the physical state of one IMP. We focus on one IMP in particular, termed Ina D (Fig. 1), because it is one of the largest IMPs at 2 by 3 km in area, sufficient orbital data have been collected and processed including the topography necessary for landing site assessment, and its geology and landforms have been described previously in detail to the limits of current data sets. However, the other IMPs are also appealing exploration targets, and our *IMPEL* reference architecture is adaptable for exploring other high-priority destinations on the surface of the Moon in addition to the IMPs.

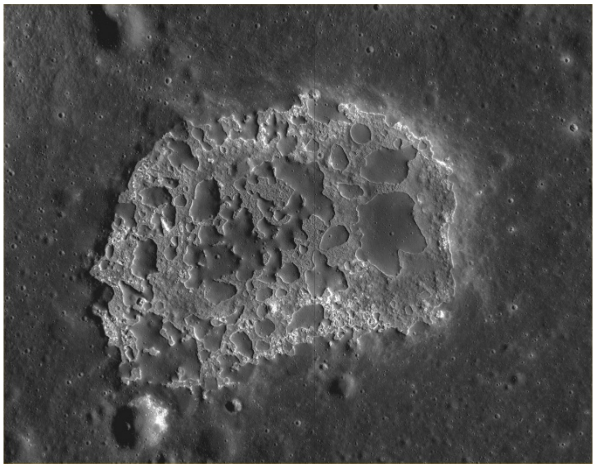

Figure 1. LROC NAC image of irregular mare patch Ina-D. Smooth mounds are topographically higher than rough areas. Feature is ~3km x 2km.

Proposed Landing Site: IMPs such as Ina have two characteristic morphologic types: 1) smooth and steep-sided mounds, and 2) low-relief rougher deposits (Fig. 1). The mounds stand topographically above the rougher deposits. IMP morphology, particularly their crisp and steep margins and lack of superposed impact craters, implies relatively young ages, but whether the related activity is volcanic or erosional is somewhat contentious [5, 6]. It is not currently possible to distinguish whether the volcanic deposits are ~3.5 *billion* years old, or only a few *million* years old. However, the preservation of topographic slopes greater than 45° over distances as short as 5-10 m strongly favors a young age [1, 5]. On the other hand, the IMPs lack the crisp fractures of the kind that typically occur in volcanic deposits [e.g., 7] (Fig. 1). The smooth, particulate deposits on the surfaces of some of the lava flows and mounds instead might suggest an older age or a non-volcanic origin [e.g., 3, 4, 6, 7]. IMPs represent a type of geologic activity not previously understood to occur on the Moon and one that also appears thus far to be unique to the Moon. Understanding the geology of IMPs, and distinguishing whether they are young or old, requires studying them at spatial scales that are presently unavailable.

***IMPEL* concept study:** The guiding philosophy of our approach was to attain a low-mass, low-cost, simplified configuration, dictating a "single-string" approach. We explored two baseline SmallSat mission concepts, landers and impactors, and their potential science instrument trades. The conceptualized mission architectures included single- and dual-stage impactors (the latter with instrument stage), and six different configurations for a powered-descent lander. In addition, three commercial launch vehicles were considered. We found that landed mission architectures have a higher potential to return significant science results than do impactor architectures. Landers allow additional secondary science objectives to be addressed using surface instrumentation and direct measurements of IMP deposits at currently unprecedented spatial scale. These advantages can be achieved only through surface exploration and better address the key, primary question of whether IMPs, and Ina D specifically, are comparatively young (Table 1).

Reference Architecture: The *IMPEL* lander concept employs a dual ESPA class architecture joined by soft tethers. Each spacecraft is 180kg and fits within the ESPA volume of 61x71.1x96.5 cm mounted on a standard C-ring launch adapter as a secondary payload (Fig. 2). The launch vehicle will provide trans-lunar injection and trajectory insertion for direct landing (no lunar orbit). The spacecraft has its own self-contained nano-star trackers and carries two small navigational cameras for terrain-relative navigation during descent and landing, and a primary science imaging system for acquiring high-resolution images of Ina D deposits.

One of the ESPA volumes contains a small solid rocket motor to decelerate; the remainder of the deceleration is carried out by the lander equipped with a hydrazine mono-propellant system. The system of terrain relative navigation combined with cold-gas jets and reaction wheels is expected to provide a landing ellipse of ~100m in longest dimension.

The spacecraft is equipped with body mounted solar arrays for power. A patent-pending Ka-band phased array antenna, which is currently in a certification process with a small software-defined radio, provides radar altimetry and communications during descent and after landing. Communication rates available from use of the Goldstone array are sufficient for landing and surface operations (10 Mbits/sec). Power is provided by a single 204 W-hr lithium-ion battery charged by the body-mounted solar arrays.

Science Instrument Package: We anticipate up to 9 kg of payload; a key objective of this study is determining how to get the most science out of the instrument suite. The science objectives will be achieved primarily through optical imaging. The camera system includes a top-mounted camera with RGB (Bayer pattern) and stereo capabilities. The primary observations to be acquired with this camera include panoramas (to look for fractures and pits nearby; objectives P1&P2) of deposits and outcrops. A side-mounted near-field RGB mirco-imaging camera will acquire up to 10-micron pixel scale images near the lander (to look for regolith agglutinates and allow characterization of surface grain morphologies; objectives S1&S2).

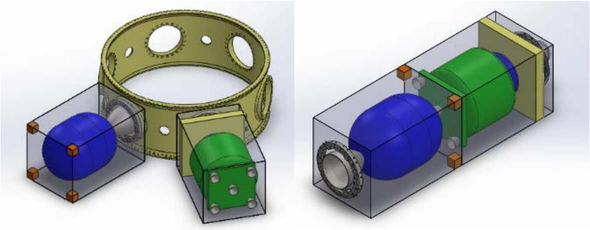

Figure 2. Schematic CAD drawings of IMPEL spacecraft concepts. First (descent) stage (in blue, on left in each image) is STAR 17A solid-rocket motor; lander stage (green, right) uses five Aerojet GR-22 descent engines.

Table 1. *IMPEL* mission concept science objectives

Primary Objectives (impactor or lander mission concept)
P1. Identify any sub-meter-scale fractures within the IMP deposits (to test young volcanic origin theory)
P2. Identify any sub-meter-scale collapse features or pitting within the IMP deposits (test erosional origin theory)
Secondary Objectives (lander mission concept only)
S1. Determine grain size and cohesiveness of the IMP's mounds and associated deposits (to distinguish between volcanic and other regolith deposits)
S2. Determine abundances of agglutinates on surface of the IMP (to further distinguish between volcanic and other regolith materials, and to constrain age by directly determining the maturity of any regolith present)

Surface Operations: *IMPEL* will land 72 hrs after lunar dawn, to mitigate possible effects from shadowing during descent and landing. The lander will have sufficient onboard battery power (recharged from solar panels) to operate past lunar noon. The top-mounted camera can be positioned, powered off, and shielded to reduce maximum temperatures approaching noon. The concept of operations calls for key observations to be collected before lunar noon, and thus the mission duration would be less than one lunar day.

Traceability: The *IMPEL* mission concept targeting Ina D addresses numerous goals enumerated by guidance documents produced since 2004. These include the 2014 NASA Science Plan, Science Goal 5 (especially a, b, d) of the Scientific Context for the Exploration of the Moon (SCEM) report [8], and Objective 5.1.3 of the 2011 Planetary Decadal Survey [9]. Understanding the ages, origin(s), and formation mechanism(s) of Ina and other IMPs will shed light on the origins and variability of lunar basalts, including the structure and evolution of the lunar interior and the generation of lunar magmas over time.

References: [1] Braden, S. E., et al. (2014), *Nat Geosci* 7, 787–791. [2] Wilson, L. & Head III, J. (2017) *Icarus* 283, 146-175. [3] Qiao et al. (2017a) *LPS* XLVIII #1126 [4] Qiao et al. 2017b, Geology 45, 455-458. [5] Schultz, P. H., et al., (2006), *Nature*, 444, 184–186. [6] Qiao, L., et al. (2016), *LPS* XLVII, #2002. [7] Garry, W. B., et al. (2012), *J. Geophys. Res. Planets*, doi:10.1029/2011JE003981. [8] Scientific Context for the Exploration of the Moon, doi:10.17226/11954. [9] Visions and Voyages for Planetary Science in the Decade 2013-2022, National Research Council.