Small Lunar Penetrators

Decadal Survey Mission Concept White Paper

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Introduction: Small lunar penetrators are poised to become a valuable new tool for lunar science and exploration during the next decade. These low-cost ballistic probes can be deployed from orbit, or from descending robotic or crewed vehicles in large numbers to explore and characterize the diversity of extreme lunar shallow subsurface environments. In this white paper, we describe the science opportunities for these penetrators, their general characteristics, as well as two mission concepts that employ them to enable ground-breaking lunar science.

Fig. 1. LRO Diviner maximum temperature measurements in the lunar north (left) and south (right) polar regions (Williams et al, 2019). During the next decade, small penetrators are likely to be the best technological option for exploring the diversity of the moon's extensive permanent shadow regions.

Lunar Science in the Next Decade:

Lunar exploration during the next decade will see many opportunities for human and robotic missions. Some key next-decade mission goals currently under consideration include sample return, lunar network science, and exploring extreme environments (LEAG, 2016). The Moon's extreme environments that have thus far been identified through analysis of orbital data include: Permanently shadowed regions at the lunar poles; Steep topographic slopes; Extreme rocky regions; Lunar caves and pits, and the Lunar swirls. These extreme

environments present significant challenges for accessibility, as well as potentially significant rewards for science. Small penetrators hold great potential for precursor and survey missions for the exploration of extreme lunar environments, producing early science data and geotechnic information crucial to science goals and later mission planning.

One of the biggest remaining mysteries about the Moon are its polar volatile deposits. We have several lines of evidence that a range of volatiles are present in the Moon's permanently shadowed regions (Watson et al., 1961; Watson et al., 1962; Stacy et al., 1997, Feldman et al., 1998, Feldman et al., 2000; Campbell et. al. 2006; Paige et al., 2010; Coloprete et al., 2010, Mitrofanov et al., 2010; Spudis et al., 2013; Hayne et. al., 2015; Fisher et al., 2017; Li et al., 2018; Rubanenko et al., 2019), but the nature and distribution of these volatiles is highly uncertain (Lawrence, 2016). During the next decade, exploring and sampling these volatiles could yield to the discovery of enabling resource utilization for future solar system

exploration, as well as fundamental new insights regarding the origin and evolution of volatiles in the inner solar system, including the origin of the Earth's water (Hayne et al., 2020).

Accessing Extreme Lunar Environments: While some extreme environments such as pits and swirls are geographically localized, the permanently shadowed regions at the lunar north and south poles are geographically extensive, comprising ~20,000 km² in area (Paige et al., 2010) (roughly the area of the state of New Jersey). Furthermore, what data we have for these regions suggests that their temperatures (Williams et al., 2010), and the potential abundance of surface and subsurface volatiles (Colaprete et al., 2010), are quite diverse (See Fig. 1). This diversity may exist on scales ranging from centimeters for micro-cold traps, to scales of several tens of km for the floors of large polar impact craters.

The proximity of smaller cold traps to adjacent illuminated terrain provides potential options for access by conventional rovers and landers. However, accessing deep permanent shadow regions, which include no direct solar illumination for 10's of km, cold temperatures of less than 100K, rugged terrain, and unknown surface and subsurface geotechnical and electrical properties, appears outside the capabilities of currently envisioned lunar landers and rovers. What is needed during the next decade is a method to provide in-situ reconnaissance of these unexplored regions to get a first-order understanding of their general characteristics and diversity, followed by more detailed in-situ studies and returned samples.

Penetrators 101: Penetrators, defined as vehicles designed to function after traversing vertically for some distance into their targets, have been in development for planetary missions since the 1970's (Lorenz, 2011). The key potential advantages of penetrators over conventional soft-landers include: low mass and low cost, flexible options for multiple deployments, and the ability to achieve subsurface emplacement. Potential disadvantages include limited mass, high g-loading, and uncertain reliability of emplacement. Penetrators are best utilized as exploration tools in extreme environments where varied and uncertain subsurface conditions are likely to be encountered. By measuring their acceleration during ballistic emplacement, penetrators naturally provide information regarding the vertical density structure of their targets. Subsequent measurements after emplacement can provide a diverse range of thermal, geophysical, and compositional information depending on their payloads, communications capabilities and lifetimes (See Table 1).

Penetrators have been successfully used in military applications, but to date, no planetary penetrators have successfully flown. Between 1993 and 2007, the Japanese space agencies ISAS and JAXA developed the Lunar A mission, which included two 13 kg penetrators intended to impact the lunar farside at a velocity of 305 m/sec (Lorenz, 2011). Unfortunately, the mission and the penetrators were ultimately abandoned due to schedule delays and cost overruns. In 1999, the unsuccessful Mars Polar Lander mission included two 2.4 kg DS-2 penetrators that reached Mars, but subsequently failed due to unknown causes. Today, more than 30 years later, improved technologies for electronics miniaturization and shock tolerance and shock mitigation has once again made penetrators an attractive technical option for planetary exploration. For the case of the moon specifically, a wide variety of next-generation penetrator missions have been advocated (Mosher and Lucey, 2006; Gowen, 2008; Shiraishi, H. et al., 2008; Smith et al., 2012; Riu et al., 2020; Eubanks et al., 2020a).

Penetrator Science Payloads

Small penetrators have the potential to accommodate a wide range of science payloads, which can be tailored to meet specific mission objectives. Table 1 shows examples of penetrator instruments and investigations that have been studied to date, and their potential contributions to lunar science and exploration. Technological advancements in instrument miniaturization enable the deployment of multiple instruments in each penetrator.

Table 1 - Penetrator Payload Element Options

Example Payload Elements	Measurement Goals and Parameters	Key Contributions to Science and Exploration
3-Axis Accelerometers	Regolith vertical density structure, volatiles detection to <1m depth	First-order measurement of general regolith characteristics in polar cold traps
Thermal Probes	Regolith temperature and thermophysical properties	Volatile stability, regolith ice content, heat flow
Seismometers (Active and Passive)	Seismic wave velocity (long period and short period)	Regolith structure, regolith depth, ice content, lunar interior
Dielectric Probes	Dielectric permittivity	Ice content
Neutron Spectrometers	Hydrogen abundance vs. depth	Abundance and distribution of water and other H-bearing species
Gamma Ray Spectrometer	Elemental composition	Major elements, radioactive elements, hydrogen detection
APX Spectrometer	Elemental composition	Formation and evolution of the lunar crust
Oven/Evolved Gas Analyzer	Trace volatile abundances and isotopic ratios, e.g., D/H	Origins and history of lunar volatiles
Radio Science	Low frequency radio - _shallow_ lunar surface science and particles and fields	Lunar librations and existence of liquid or solid core, long-range lunar communications network
Charged Particle Detectors	Cosmic rays and solar wind particles	Solar wind environment in PSR's, Lunar Swirls properties and origins
Heat flow sensors	Subsurface temperature gradient and thermal conductivity	Constraints on the composition and thermal evolution of lunar interior; Proximity of heat generating elements, e.g Thorium in KREEP
Magnetometer	Field strength, direction, and variations with time	Swirls - formation processes Polar - deflection of solar wind [H]
Cavity Ringdown Spectrometer	Detailed volatile composition and variations with depth	Origins and history of lunar volatiles
Microscope	Crystal and grain structure	Nature of volatiles, Regolith properties
Spectrometers	Raman and Heterodyne Fringe Spectrometers	Water composition and chemistry, organics
LIBS/ XRS / Raman type spectrometers	Elemental and molecular composition of subsurface minerals	Lunar mineralogy

Lunar Penetrator Mission Concept Examples: Here we present two examples of lunar penetrator mission concepts that demonstrate the potential utility of this technology to enable and enhance sustained lunar exploration during the next decade through the first in-situ exploration of extreme lunar environments.

Example 1: Small Lander Piggyback Penetrators

During the next decade, NASA plans to deploy a number of large and small soft-landers to the lunar surface. These landers could include multiple small penetrators as piggyback payloads

that could be deployed during terminal descent (Fig. 2) The penetrators would be ballistically emplaced downrange of the lander and be targeted to extend the scientific reach of the landers into extreme environments (Fig. 3) . Data relay can be accomplished through the lander itself, or via direct-to-Earth for longer duration missions.

Fig. 2. Small ~1.5 kg piggyback penetrator design concept.

Fig 3. Penetrator downrange deployment scenario into a permanently shadowed crater.

Depending on their deployment locations and payloads, piggyback penetrators could address a wide range of science and exploration objectives. Possible mission scenarios for short-lived penetrators could include scouting out permanent shadow regions for rovers or astronauts, or exploring the particle and field environments above and below the surface of lunar swirls. There are also opportunities for synergistic observations between landers and a piggyback penetrators emplaced in the surrounding area for conducting studies of lunar regolith composition and structure. The low mass and cost of these probes should make them an attractive complement to most lunar lander missions. On this type of mission the penetrator payload must accept whatever landing site is designated by the primary mission.

Space Initiatives Inc (SII) have designed such a mission where a single 3U sized carrier containing 8 penetrators is ejected from a soft lander 5 to 10 km above the lunar surface. The first short-duration proof of concept mission is to be powered by primary chemical batteries without heater units. The payload bay is 4.5 cm diameter and can accommodate 400 grams of instruments.

Example 2: Dedicated Penetrator Mission

NASA's Discovery and New Frontiers programs provide opportunities for larger-scale science-driven missions that could incorporate sophisticated penetrators aimed at better defining the global distribution and detailed properties of polar ice deposits. Figure 4 shows cutaway views of an advanced Discovery-Class 20 kg penetrator system designed for lunar volatile detection and characterization.

Fig. 4. Advanced 20 kg penetrator system for volatile detection and characterization.

This self-contained mission concept would include an orbiter, two descent vehicles, and approximately four penetrator probes that would be deployed to high-latitude targets in both polar regions (Fig. 5). The descent vehicles would use solid rocket motors to precision target the penetrators at optimum vertical and horizontal velocity, while orbiters would relay data between the penetrators and Earth. The penetrators would be targeted to a range of cold-trap locations to sample the diversity of lunar polar environments, including deep permanent shadow. The number of penetrators and their capabilities are scalable depending on mission cost and mission risk posture. The penetrators shown in Figure 4 are powered by advanced RHU thermo-electric generators, and are capable of data collection and transmission over extended lifetimes. For this mission example, the penetrators are the primary payload and therefore can select the landing site. The Example 1 piggyback mission can be adapted to Example 2 by adding a single solid rocket motor to decelerate a 3U carrier after separating from an orbiter.

L₂ Northern Near Rectilinear Halo Orbit (NRHO)

Fig. 5. Penetrator deployment scenario from lunar orbit.

Conclusions and Future Outlook: Small penetrators represent exciting new platforms for lunar science and exploration during the next decade, providing opportunities for vastly expanded in-situ reconnaissance of extreme lunar environments. Penetrators have the unique potential to overcome obstacles to exploring these scientifically strategic and unexplored regions, and provide a solid basis for the next wave of missions capable of detailed characterization. Because of the diversity and extended geographic extent of these regions, a multiplicity of probe locations is required - a task that is ideally suited to penetrators.

The first wave of lunar penetrators is currently in the early proposal phases. With the infusion of technology development funding for the penetrators themselves and for their instrument payloads, it will be possible to build upon the work of past NASA and military penetrator projects to create full-scale engineering models capable of realistic end-to-end testing. During the next decade, we envision that penetrator systems will take their place along with orbiters, landers, and rovers in NASA's stable of planetary exploration tools - providing access and first-reconnaissance for extreme environments throughout the solar system (Eubanks et al., 2020b)

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