MARAUDERS: A SMALL-SAT MISSION TO PROBE THE PHYSICAL PROPERTIES OF VOLATILES IN LUNAR PERMANENTLY SHADOWED REGIONS

S. T. Crites[1], N. Ozaki[1], R.-L. Ballouz[3], N. Baresi[1], S. Arahata[2], R. Bolden, O. Çelik[1,4], R. Funase[2], Y. Himeno[2], A. Parker[5], L. Riu[1], K.J. Walsh[5], [1]ISAS/JAXA, Sagamihara, Japan. [2]University of Tokyo, Tokyo, Japan. [3]Lunar and Planetary Lab, University of Arizona, Tucson, AZ, USA. [4]Sokendai Graduate University, Japan. [5]Southwest Research Institute, Boulder, CO, USA.

Introduction: The Mini lAndeRs And boUncers Deployed for Exploration and Regolith Science (MARAUDERS) is a small satellite concept that aims to characterize the surface and volatile properties of regolith in permanently shadowed regions (PSRs) around the Moon's poles. Large PSRs are cold enough to trap scientifically and economically valuable volatiles such as water ice for geologically long timescales. However, despite ongoing studies, the distribution, abundance, and physical phase of volatiles at the Moon's poles remains elusive [1]. In-situ measurements are required to conclusively determine the geotechnical and physical properties of lunar polar volatiles. To address these needs, the MARAUDERS team is currently developing an *in situ* technique to perform measurements of regolith physical properties--including volatile content--in many locations across one or more lunar polar craters (Fig. 1). Our technique is based on the deployment of small, short-lived, inexpensive probes. Upon impacting the surface, the deceleration data relates the strength and structure of the upper 10-20 centimeters of the surrounding regolith.

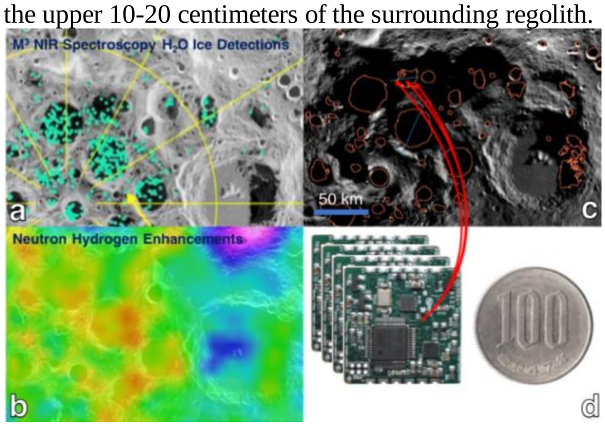

Figure 1 *- The MARAUDERS nano-landers will target regions of permanent shadow that have remote sensing signatures consistent with the presence of water ice (e.g. neutrons, high reflectance, M3 water ice signatures). The simple ground truth measured by MARAUDERS will be highly complementary to remote sensing as well as later, more detailed measurements performed by lunar polar landers and rover elsewhere at the poles, enabling a better understanding of the environmental factors that affect volatile concentration.*

Science and Exploration Objectives: Understanding the physical properties of polar regolith is a priority for lunar science and exploration [2]. Some remote sensing observations [3] are consistent with an extremely high porosity layer of regolith in lunar PSRs, which could make rover locomotion challenging; in contrast, laboratory studies of ice-regolith mixtures at lunar PSR temperatures indicate strengths similar to granite [4], an important parameter for design of drills and sampling mechanisms for future missions. Resolving these uncertainties would be invaluable for future human and/or robotic exploration mission to these volatile-rich regions of the Moon as stated by the Lunar Exploration Analysis Group (LEAG) through the definition of Strategic Knowledge Gaps (SKGs) [5]. MARAUDERS would address two SKGs, namely i) What are the geotechnical properties of lunar polar regolith (including inside cold traps)? and ii) What is the lateral distribution of polar volatiles over 10-100m scales?, by:

1. Providing a direct measurement of the mechanical strength of PSR regolith in order to infer its composition and structure;
2. Deploying nano-impactors in multiple regions of a target PSR to assess the lateral distribution of polar volatiles and estimate the relative heterogeneity of regolith physical properties.

Measurement Technique: Small spacecraft equipped with penetrators or inertial measurement units (IMU) can characterize the strength and structure of the planetary surface that they impact. Early space exploration used penetrometers to determine the surface properties of the Moon and Mars before the arrival of astronauts and rovers. In recent decades, spacecraft equipped with IMUs characterized the surface of Titan [6], and determined the sub-surface stratification of ice and rock on the comet 67P/C-G [7]. While this technique is unable to relay the detailed mineralogical and elemental composition at the impact point, it obtains a first-order structural knowledge of potentially hazardous surfaces and sub-surfaces that cannot be obtained through remote sensing. This is highly relevant for PSRs due to extreme environmental conditions such as the lack of solar illumination, cold temperatures, and challenging communications.

The goal of our deployed nano-impactors will be to relay deceleration and temperature profiles as they penetrate in the lunar regolith of a target PSR. Based on the data volume and data transfer rate of Commercial Off-The Shelf (COTS) communication devices, the total survival time needed after impact is less than 5 minutes. It is also assumed that the nano-impactors will be released from an altitude of ~10 km, reaching free-fall velocities of less than 300 m/s. Preliminary calculations indicate that our probes will be able to withstand such velocities and survive the cold temperatures of PSRs without the need of large batteries.

	Option A	Option B
Deployment from	Lander/Rover	Lunar Orbit
Distribution method	Ascent Vehicle	Mothership
Overall Payload Mass	~15 kg	~40 kg
Volume Estimate	30 x 20 x 20 cm	40 x 25 x 25 cm
Required Power	4 W (Peak: 20 W) Charging Bat. + Comm. + Deployment Mech.	4 W (Peak: 10 W) Charging Bat. + Deployment Mech.
Communication	Probes -> Mothership OR SELENE-R OR Earth	Probes -> Mothership OR Earth

Table 1 *- Payload Deployment Scenario and Mass/Power Budget (Number of Probes: 10)*

Concept of Operations: The next stage of lunar exploration will allow for the deployment of small satellite orbiters (SLS launch opportunities), as well as the delivery of scientific instruments to the lunar surface (through, among others, the Commercial Lunar Payload Services program). A key strength of MARAUDERS is its flexibility to be allocated either as the secondary payload of a large spacecraft / lander or as the primary payload of a standalone small satellite mission. The preliminary system design of the MARAUDERS down-selected the number of candidate architectures to the following two options: Option A is our current baseline and consists of an ascent module to be installed on a lander or rover to be deployed after arrival. Option B considers the separation of a 12U CubeSat from either a launcher or a Moon orbiter to minimize interference with the main mission. Table 1 summarizes the mass, power, and volume estimates produced by our preliminary trade-off analysis for the two candidate mission architectures. Each of the options rely on the assumption that each nano-probe would include at least one accelerometer, a thermometer, power and communication systems, leading to a gross mass estimate of 0.1 kg for each payload.

According to the baseline operation sequence, the MARAUDERS ascent module is launched from the surface of the Moon towards a deep permanently shadowed region. Once over the destination, the probe deploys ~10 nano-landers from an altitude of approximately 10 km. After separation of the nano-landers, the MARAUDERS mothership begins a second vertical burn to remain in sight of the nano-landers until their measurements are complete, at which point the data are relayed back to the polar lander or rover (direct communication with the Earth is currently under investigation). Upon penetration into the PSR regolith, each MARAUDERS nano-lander will return a penetrometry signal. These measurements will be compared with extensive laboratory measurements to determine the presence or absence of water ice mixed with regolith.

Candidate Landing Sites: We are assessing the landing site potential of different PSRs in the lunar poles by considering a number of factors such as

1. Elevation: limited by the threshold impact speed required for nano-impactor survival;
2. Presence of volatile-rich regolith: to correlate our measurements with remote observations, we will attempt to target regions that have had positive detections of hydration at the surface [1][8].
3. Visibility from Earth: desired to ease the communication burden of the mothercraft (optional).

Preliminary analysis reveals that several candidate PSRs would be accessible from an Option A type architecture based on candidate landing sites under study for a JAXA lunar polar lander mission [9] from 50 km with a Delta-V as low as ~ 250 m/s (Fig. 2).

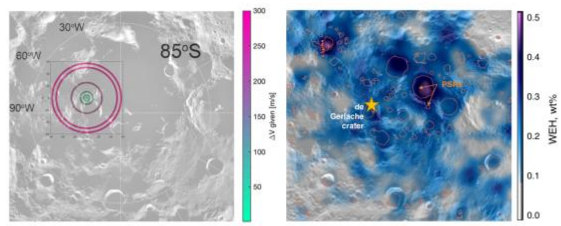

Figure 2 *- Preliminary analysis of accessible PSRs from one example lunar landing site on the rim of de Gerlache crater.*

Summary: Reconnaissance of the lunar polar regions by small satellites/landers would benefit future mission to the Moon by i) linking remote sensing data to ground truth information for identifying volatile-rich sites, and ii) measuring physical properties of remote polar regolith. By providing the first in-situ measurement of regolith structural properties in PSRs, the MARAUDERS mission would provide insights into the mechanism of volatile sequestration in polar cold traps and facilitate landing site selection for future in-depth explorations.

References: [1] Lawrence et al. (2017), JGR-Planets, 122. [2] LEAG Volatiles Specific Action Team Report (2014). [3] Gladstone, G.R. (2012), JGR, 117, E00H04. [4] Gertsch et al. (2008), Internat. Conf. Case Histories Geotechnical Eng. [5] LEAG Strategic Knowledge Gaps - 2: “The Moon First” Human Exploration Scenario (2016) [6] Lorenz, R. et al. (1994) Meas. Sci. Technol. 5, 1033-1041 [7] Biele, J. et al. (2016), Science, 349, 6247. [8] Li et al. (2018), PNAS, 115 (36) 8907-8912. [9] Inoue, H. et al. (2018), 49th LPSC, Abstract #1738.