INTEGRATIVE REGOLITH CHARACTERIZATION FOR SPACE RESOURCES, SURFACE INFRASTRUCTURE, AND PLANETARY EXPLORATION J. M. Long-Fox[1], D. L. Buczkowski[2], I. R. King[3], R. L. McCormick[4], S. J. Moreland[4], D. E. Newill-Smith[4], L. S. Sollitt[5], D. Y. Wyrick[6], and R. C. Anderson[4], [1]University of Central Florida Department of Physics (4111 Libra Drive Room 430, Orlando, FL 32816; jared.long-fox@ucf.edu), [2]Johns Hopkins University Applied Physics Laboratory, [3]Honeybee Robotics, [4]NASA/Caltech Jet Propulsion Laboratory, [5]NASA Ames Research Center, [6]Southwest Research Institute

Introduction: Sustained exploration and utilization of planetary surfaces require quantitative knowledge of regolith physical properties at spatial scales directly relevant to surface operations [1,2,3,4,5]. Resource prospecting, excavation, infrastructure emplacement, landing and launch pad construction, and rover mobility are all governed by the mechanical, thermal, and electrical behavior of near-surface regolith. Uncertainty in these properties propagates directly into system design margins, operational risk, and the efficiency of *in situ* resource utilization (ISRU). At the same time, these properties provide valuable scientific information about regolith formation, compaction history, volatile stability, and surface processes. Despite their importance, many key regolith properties remain poorly constrained because they cannot be reliably inferred from orbital observations and have not been measured *in situ* at high spatial resolution.

To address this gap, the Soil Properties Assessment, Resistance, and Thermal Analysis (SPARTA) probe (Figure 1, [6]) has been developed as a compact, integrated toolkit for in situ regolith characterization. SPARTA combines four high-heritage geotechnical measurement techniques into a single deployable probe head: a Cone Penetration Tester (CPT), Vane Shear Tester (VST), Thermal Conductivity Probe (TCP), and Dielectric Spectroscopy Probe (DSP). Together, these instruments provide co-located measurements of penetration resistance, shear strength, thermophysical properties, and dielectric properties. By acquiring complementary measurements at the same location and depth, SPARTA enables interpretation of regolith properties while reducing ambiguity that would arise from independent measurements. The compact and modular architecture of SPARTA also enables straightforward integration with a wide range of surface mission architectures [7], including astronaut-, rover-, and lander-deployed platforms. This readiness to infuse with other payloads allows SPARTA to complement instruments focused on imaging, spectroscopy, or geophysics, providing the *in situ* physical property measurements necessary to relate remote observations to information for resource utilization, infrastructure development, and planetary science investigations.

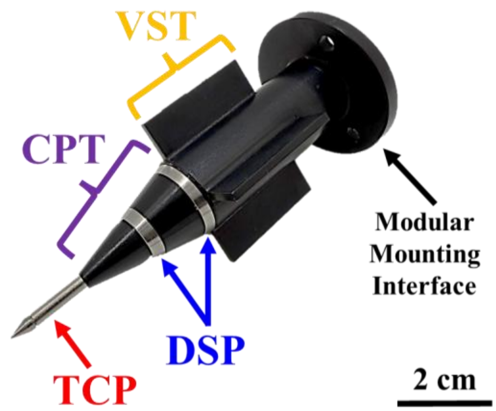

Figure 1. SPARTA probe with component instruments labeled, namely the Vane Shear Tester (VST), Cone Penetration Tester (CPT), Thermal Conductivity Probe (TCP), and Dielectric Spectrometer (DSP).

Regolith Characterization for Resources and Infrastructure: Quantitative knowledge of regolith physical properties is essential for the development of space resource utilization and surface infrastructure systems [5,8].

Mechanical measurements from cone penetration and vane shear testing constrain regolith compaction state, shear strength, and load-bearing capacity [9], parameters that directly influence excavation performance [10], rover trafficability [11,12], and the design of foundations, landing pads, and other structural elements [13]. These measurements also provide insight into regolith mechanical stratigraphy and the variability of subsurface materials that may affect excavation efficiency and construction stability [9,11].

Thermal and dielectric measurements provide complementary information relevant to both resource prospecting and infrastructure design. Thermal conductivity and diffusivity control heat transport in regolith and hence influence the performance of ISRU systems, thermal control strategies for surface assets, and the thermal response of regolith-based construction materials. Dielectric spectroscopy measurements constrain the electrical properties of the regolith and are sensitive to the presence of electroactive components, including water ice and hydrated minerals [14]. These measurements can help validate orbital detections of volatiles and provide site-specific information about the distribution and concentration of potentially valuable resources.

Scientific Value of *in situ* Regolith Property Measurements: Geomechanical, thermophysical, and dielectric measurements of regolith properties provide important scientific constraints on the origin and evolution of planetary surfaces. Mechanical stratigraphy, compaction state, and shear strength contain information about impact gardening, regolith maturity, and subsurface layering. Thermophysical properties reflect particle packing, porosity, and composition, while dielectric properties can reveal the presence and state of volatiles within the regolith. Measurements obtained during physical interactions with the surface, such as penetration, shearing, heating, and electrical excitation and therefore act as scientifically informative, opportunistic experiments. When performed at high spatial resolution and in a co-located manner, these measurements allow the structure and heterogeneity of regolith to be investigated at scales that cannot be achieved through orbital measurements.

Exploration is Science, Science is Exploration: A key advantage of the SPARTA toolkit is the ability to acquire multiple complementary measurements at the same location and depth within the regolith. Relationships between penetration resistance, shear strength, thermal properties, and dielectric properties provide independent constraints on regolith density, particle packing, and volatile content. These relationships enable cross-validation of measurements and improve the reliability of derived regolith parameters, particularly in environments where ground truth data are sparse. Such integrated datasets are difficult to obtain with single-purpose instruments but are essential for reducing uncertainty in both engineering analyses and scientific interpretations.

This capability highlights an increasingly important paradigm in planetary surface exploration: operational activities themselves can serve as scientifically informative experiments. Interactions with the regolith during penetration, shearing, heating, and electrical excitation reveal fundamental physical properties that are directly linked to regolith formation and modification processes. Measurements of strength and compaction constrain the history of impact gardening and surface disturbance, while thermophysical and dielectric properties provide insight into porosity, composition, and the presence or stability of volatiles.

SPARTA enables routine surface activities such as site preparation, excavation, and resource prospecting to generate datasets that simultaneously inform engineering decision-making and planetary science investigations. In this way, exploration activities become opportunities for high-value scientific measurement, while scientific observations directly support safer and more efficient surface operations. This convergence of operational capability and scientific investigation represents a key step toward sustainable exploration and utilization of planetary surfaces [16].

Conclusions: The SPARTA probe is a low mass and low power, multifunctional lunar and planetary regolith characterization toolkit capable of supporting both resource utilization and planetary science objectives. By integrating complementary measurements of regolith mechanical, thermal, and electrical properties into a compact and deployable system, SPARTA enables quantitative characterization of planetary regolith at spatial scales relevant to excavation, infrastructure development, and volatile prospecting. At the same time, these measurements provide new insights into regolith formation processes, subsurface structure, and volatile stability. As lunar and planetary exploration evolves toward long-duration surface operations and resource utilization, integrated regolith characterization tools such as SPARTA will be essential for reducing uncertainty, enabling safe infrastructure development, and advancing scientific understanding of planetary surfaces.

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