In Situ 3D Microscopy of Undisturbed Lunar Regolith to Validate Lunar Surface Features

T. A. Livengood (UMD), M. K. Barker (NASA/GSFC), D. M. Bower (UMD), T. Hewagama (NASA/GSFC)

Systematic and coordinated 3D microscopy and photometry of lunar regolith in its natural state is needed to understand the top layer's structure and its effects on remote sensing measurements. Remote photometry and spectroscopy of airless bodies throughout the Solar System are primary sources of information on the shape of unresolved bodies, topographic changes, dynamical properties, composition, and impact history of asteroid and satellite surfaces. Remote sensing studies of the Moon regularly invoke micro-structural changes to the regolith related to its porosity, surface roughness, and elaborate grain structures to explain remote sensing data over a range of wavelengths, but these hypotheses have never been directly tested on the lunar surface. Microscopic measurement of undisturbed lunar regolith is needed to test and validate microphysical models for planetary surface phenomena and thereby calibrate measurements throughout the Solar System.

Figure 1. Opposition surge effect at the lunar surface. Microscopic measurements of undisturbed regolith at micron scale are essential to understand and account for optical phenomena such as the opposition effect seen here in the bright reflectance centered on Apollo 17 astronaut Gene Cernan's head with the Sun directly behind him.

Regolith on the Moon and asteroids develops in the absence of familiar weathering processes that alter grain shape, orientation, and accumulation patterns. Validating properties of natural regolith surface structure that are derived from observed optical phenomena requires microscopic-scale 3-D imaging of pristine and undisturbed lunar regolith outside the blast zone of landing rockets and other surface disturbances. The investigation itself requires imaging resolution on the order of 10 µm or finer to resolve regolith grains and their arrangement, with comparable vertical resolution. A particularly challenging surface feature is the possible presence of so-called "fairy-castle" structures [2], microscopic towers of regolith grains that are impossible to replicate in the laboratory but which may be ubiquitous on airless rocky surfaces. The breakdown of the fairy-castle structure has been hypothesized to explain the anomalous photometric behavior of lunar lander blast zones and magnetic anomalies ('swirls') whereas enhanced fairy-castling has been invoked to explain the decreased far-UV reflectance in permanently shadowed regions (PSRs) [2-6].

Fairy-castles are a fundamental ambiguity in interpreting optical phenomena observed from space (*SCEM* Concept 7 [1]), including the "opposition surge" effect in photometry at low phase angle (Fig. 1). The opposition surge is a steep non-linear increase in brightness at small phase angles, particularly significant in characterizing surface texture as it is thought to result from interference phenomena as well as inter-particle shadow-hiding [9]. The relative proportions of these phenomena and their relation to grain and soil properties are hotly debated [10].

Investigations of PSRs have yielded challenging results that invoke a range of poorly constrained surface properties and processes [4,5]. Surface microscopy within a **permanently shadowed region (PSR) would address multiple PSDS questions related to the distribution, sources, and sinks of lunar volatiles** (PSDS, Ch. 5, p. 118). Three-dimensional (3-D) microscopy of the lunar surface thus addresses a diverse set of goals in the Planetary Science Decadal Survey (PSDS Ch. 5, p. 116; *SCEM* Science goal 7c [1]). Such measurements would also provide key constraints on the physical properties and transport processes of lunar dust particles with important application to the area of human health and safety.

What is lacking is direct in situ validation of the physical structure of untouched regolith at relevant resolution, as well as sampling the diversity of the surface over a transect comparable to orbital pixel scales. Such an investigation requires high mobility to get far from the landing vehicle and to investigate a range of sites. Apollo and Luna regolith samples, while revolutionizing our view of the Moon, were fundamentally altered by collection, transport, and storage in Earth's gravity [3,7]. Interpretation of the highest-resolution Apollo photographs with ~100 µm pixel scale (Fig. 2) is hindered by their close proximity to the lunar landers [6,8]. A suitable microscopy apparatus should contain its own light source to control illumination as well as to investigate shadowed locations that could host volatile frosts. A condensation-sublimation cycle of frosts is a possible contributor to the formation of surface textures.

Figure 2. State-of-the-art from Apollo does not meet the need. This image shows a photomicrograph of lunar regolith taken within 15 m of the Apollo 11 lunar module [8], about 10 cm square. Orbital imaging from Lunar Reconnaissance Orbiter shows measurable blast effects from the descent engine at comparable range [6]. Measurements must be acquired far from chemical and mechanical alteration by landing and EVA activities.

References:

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