THE LUNAR REGOLITH AS A REMOTE SENSING TARGET FOR THE LUNAR RECONNAISSANCE ORBITER (LRO)

W. W. Mendell, NASA Johnson Space Center, Houston, TX 77058, <wendell.mendell@nasa.gov>.

Introduction: Of the 6 instruments and one technology demonstration aboard the LRO, only CRaTER does not measure some kind of interaction of particles with the lunar regolith. LEND detects neutron fluence that contains information about the number density of protons in the upper regolith. To infer the presence of protons, the PI must assume a model that characterizes the surface as a collection of atoms. Thus, LEND does not sense the regolith as a structure.

LROC, LOLA, and LAMP sense reflected photons whose wavelength is much shorter than the median particle size in the regolith. The photons inteact with electrons, either in atomic shells or in chemical bonds. These intractions occur within a nanometer or so of the surface of a particle. Thus, the particles are macroscopic objects and models of the reflection process invoke ray-tracing optics.

DIVINER senses photons that have been emitted by surface particles through thermal phonon processes. The wavelengths detected by the instrument are of the same order as the median particle size, and the photons contain information on particle dimensions as well as the molecular bonds in the constituent compounds.

The Mini-RF synthetic aperture radar generates and detects photons of a few centimeters wavelength that interact with the regolith as a dielectric, the dielectric properties of the particulate component being described through effective medium theory. However, the interaction with “rocks” (macroscopic objects of interest to geologists) can be characterized using Fresnel or Mie models of electromagnetic properties.

Regolith Structure: The great majority of lunar scientists come from geologic sciences and gravitate to the LROC images for their data on the regolith. These cameras are surrogates for our eyes, and the morphologies and textures in the images can be interpreted in terms of canonical geologic process models.

On the Moon, rocks have a significance in the process of regolith formation and maturation. The textbook narrative of regolith formation starts with a large impact that buries pre-existing regolith under an ejecta blanket. Large boulders are deposited on the rim and smaller blocks go larger distances. One of the attributes of a “fresh” crater is a blocky ejecta blanket; and conversely a surface block population is usually taken as evidence for a fresh ejecta blanket.

Over geologic time, the blocks are fractured and comminuted until, over time scales of hundreds of millions of years, the blocky ejecta blanket is transformed into a mature regolith.[1]

A block on a particulate surface will maintain a positive thermal contrast after lunar sunset. Large blocks are positive thermal anomalies throughout the lunar night, but rocks on the order of 10 cm will become indistinguishable from background by midnight.

The Apollo 17 Infrared Scanning Radiometer (ISR) detected these thermal enhancements, which provide a measure of the level of degradation (i.e., age) by the level of enhancement.[2] DIVINER should be able to provide an approximate age sequence for Copernican Age craters., analogous to, but more quantitative than, the Pohn and Offield [3] visual degradation scheme.

The ISR and the Apollo X-ray spectrometer showed that the tops of massifs such as the Apennines are rocky even though they are old. This mass wasting phenomenon may imply that regoliths on basin and (large) crater rims evolve differently from regoliths on flat plains. DIVINER should provide information on this phenomenon, which might have implications for potential outpost sites.

The Epiregolith: Rarely considered are the variations in regolith properties more closely associated with the physics of the photonic interactions sensed by the LRO instruments. Can non-trivial differences be detected in the *epiregolith*, the term I use for the interaction zone at the upper surface of the Moon? To discuss this possibility, I will discuss the history of the current knowledge base.

Scientific literature on optical and thermal properties of the pre-NASA Moon was written by astronomers using techniques, instruments, and concepts from stellar astronomy. Radio technology from the Second World War led to passive microwave thermal measurements and radar probing of the surface. The combination of these observations produced mathematical models of the upper meter of the surface and of the epiregolith. The model of the upper meter was a reasonable representation of the physical reality, but the epiregolith has never really been studied *in situ*.

Prior to 1960, the source of the lunar photometric function was an enigma. All Earth-based data indicated that the lunar surface reflected sunlight in an odd manner at all locations. In 1963, Bruce Hapke [4] published a model that reproduced the photometric function mathematically and that gave some insight into the physical mechanism responsible for it. Starting from the Lommel-Seeliger 19th-Century model for reflectance from collections of particles, Hapke postulated a complex, highly porous, interconnected surface configuration that allowed reflected photons to escape the surface preferentially if they happened to reflect back along the path by which they entered the structure. He referred to the structure as a “fairy castle”. Hapke further refined his model in later years, and it survived at least two major challenges from competitors. Although the reflectance spectroscopy community resisted employing the Hapke concepts for at least two decades, the model is now regularly cited and utilized.

In 1930, Pettit and Nicholson [5] demonstrated that thermal emission from the Moon was directional in the infrared. Sinton [6] and Montgomery, et al. [7] confirmed the behavior decades later. Bastin and Gough [8] first modeled the directionality successfully with a completely artificial geometric construction. The model consisted of thermally isolated elements exchanging heat only by radiation, and the temperature of each class of element was determined by its view factor of space. The important characteristic of the construction was that the spacing between the elements was about the same dimension as the elements themselves. A Hapke fairy castle fits this description, and Winter and Saari [9] succeeded in matching the directionality using sparse arrays of cubes. In these particulate constructs, the particles perched at the very top have a large view factor of space and are cooler than particles one or two layers down. A detector looking straight down at the collection sees a mixture of temperatures and overestimates the average temperature of the collection because of the Planck function nonlinearity. Conversely, a detector looking along a slant path at the exact same surface element at the exact same time will see more of the cool particles on top and report a lower temperature.

I plan to discuss other observations consistent with this conception of the epiregolith. In particular, the directionality effect should decrease with wavelength throughout the thermal infrared to the submillimeter because the median particle size in a mature regolith is about 50 micrometers. At longer wavelengths, the thermal contrasts become averaged out, and the indivicual particles become more transparent to the radiation. I think data exists in various places that could test this prediction.

Enigma of the Epiregolith: As far as we know, the epiregolith exists everywhere on the Moon, a belief consistent with the idea that regolith processes are the same everywhere. The directionality of reflected and emitted radiation was documented by Earth-based observations of low spatial resolution. However, the photometric function appears to apply at scales appropriate to orbital imaging and to surface operations.

The fairy castle structure described by Hapke need not be more than several particles (~mm) thick and must be quite fragile. How does it survive over geologic time? It must regenerate after being disrupted. Why is it so tenuous, modeled at 90% porosity?

I suggest it has something to do with the charging of the surface. The local charge densities do not generate fields large enough move “average” particles in a regolith, but the accumulation of like charge on the surface particles should produce a repulsion that could result in a fairy castle. If that is so, then the surface structure may change near the terminators and may be different on the day and night sides. Such shuffling among the surface particles would have significance for thermal models because the upper layer dictates the directionality of emissivity and is important in the coupling to the solar insolation.

Thre may be regions of the surface where this effect is muted or enhanced for some reason. Such regions could show unusual thermal behavior. The ISR data detected a small region near the craters Bessarion A and B that was anomalously cool during the lunar night. [2] Positive nighttime thermal anomalies are easy to explain; negative ones are not in the context of a mature regolith.

In principle, DIVINER might detect a rearrangement of the surface particles. In practice, it almost certainly will not because the thermal modeling is not at the correct level of accuracy. Nevertheless, scientists ought to be alert to optical or thermal measurments that seem unusual.

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