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Modeling Radar Scattering From the Lunar Regolith: Parametric Study on the Effect of Roughness and Ice Inclusions on CRP Measurement

Wenzhe Fa, Essam Heggy and Mark A. Wieczorek

Institut de Physique du Globe de Paris (wzfa@ipgp.fr, heggy@ipgp.fr, wieczor@ipgp.fr / Fax: +33-0145114147)

Since the Moon's axis of rotation is almost perpendicular to the ecliptic plane, the crater floors at lunar polar areas are permanently dark and very cold, receiving heat only from space and the interior of the Moon. As a consequence, this forms a "cold trap", where ice can remain stable for geological time span. Over the long geological history of the Moon, significant quantities of water could accumulate in this "cold trap" due to water-bearing cometary debris and meterorites strikes the Moon [1]. The Clementine bistatic radar experiment has been reported to find the evidence of ice deposits in the vicinity of Shackleton crater [2], while earth-based Arecibo radar found on significant differences between the sunlit and permanently shadowed walls of Shackleton crater [3]. The debate on the presence of ice deposits at the poles of the Moon still remains as a controversy.

To resolve this controversy, two orbital miniature synthetic aperture radars (Mini-SAR) on Chandrayaan-1 and Lunar Reconnaissance Orbiter (LRO), will be imaging the lunar surface over the next 2 years with the purpose of studying the physical properties of the lunar surface and to search for ice deposits in lunar polar areas [4][5][6]. Knowledge about the propagation, scattering, penetration and reflection of radar waves in the lunar reoglith layer is critical to deciphering the received radar echo and identifying the ice deposits. In this study, a quantitative model for radar scattering from the lunar reoglith is developed using vector radiative transfer (VRT) theory of random media, which is a physical-mathematical method for studying scattering and multiple scattering, absorption and transmission of polarized electromagnetic intensity through random scatters or continuous random media [7].

Radar backscattering from the lunar regolith can be described mainly as a function of frequency, incident angle, surface roughness, dielectric permittivity and the rock size distribution in the regolith layer (among other acquisition orbital parameters). Figure 1 is an idealized model of the lunar regolith that is described by a homogeneous fine-grained layer of thickness *d* possessing a roughness for both the upper and lower interfaces, and buried rocks within the regolith layer. In this study, a parameterized model using vector radiative transfer theory [7] is employed to give quantitative relations between radar echo and the physical properties of the regolith layer. The integral equation method (IEM) for rough surface scattering is utilized to calculate radar wave scattering and penetration at the top and bottom rough interfaces [5]. Non-spherical particles are employed to model the buried rocks, and this effect depends upon the rock shape and size frequency distributions. An iterative method is used to obtain the Mueller matrix solution of VRT equation, which gives the fully polarimetric backscatter coefficients for any transmit/receive polarization state. The derived Mueller matrix contains five scattering terms for the regolith layer: diffuse scattering from both the rough top and bottom surfaces, direct scattering from suspended rocks, and the interaction of rocks with rough surfaces.

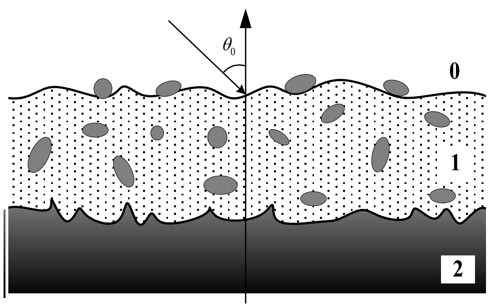

Figure 1. Idealized model of lunar regolith

Both polarized and depolarized radar echos are simulated as a function of incident angle, layer

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thickness, roughness of surface and subsurface, size and population of buried rocks, and FeO+ TiO_2 content (among others). Our results show that radar backscattering coefficient increases as frequency, surface roughness, rock size and its population increase. High FeO+TiO_2 content increases the imaginary part of the dielectric permittivity and causes more attenuation, therefore the scattering from buried rocks and underlying rough surface is shadowed. Simulation results show that polarized radar echos at S and X band are mostly dominant by the surface scattering and buried rock scattering, while the depolarized radar echo is mostly dominated by the buried rocks (Figure 2).

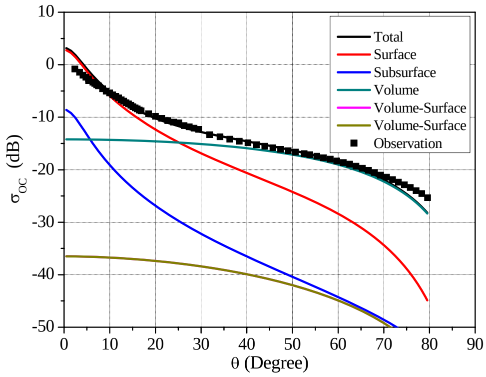

Figure 2. Polarized, opposite-sense-circular radar echoes of the five different scattering mechanisms (diffuse scattering from both the rough top and bottom surfaces, direct scattering from suspended rocks, and the interaction of rocks with rough surfaces) accounted in the model and comparison with earth-based radar observations at 3.8-cm wavelength given by *Hagfors* [9].

Finally, the possibility to detect ice deposits at lunar polar areas by radar circular polarization ratios (CPR) was also simulated and discussed. Results show that CPR increases as incident angle, FeO+TiO_2 content, surface roughness increase (Figure 3), while CPR decreases as regolith layer increases. Under the specific configuration of Mini-SAR, both surface roughness and ice particles can enhance the CPR values, and that double scattering causes CPRs greater than unity.

The simulation approach used in this study will be useful as a tool for data and image evaluation, feature identification and information extraction in future radar exploration of the Moon using the mini-SAR experiment on board Chandrayaan-1 and LRO.

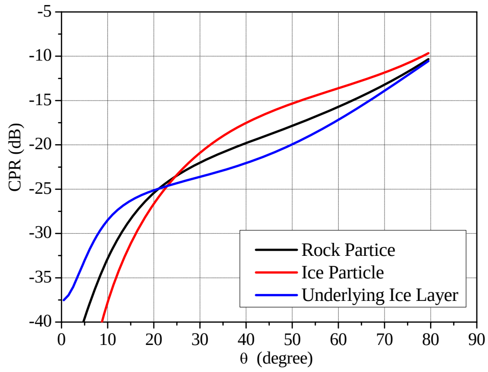

Figure 3. CPR varies with radar incident angle. The black line indicates a regolith layer with buried rock particles and the underlying subsurface is rock, the red line indicates a regolith layer with buried ice particles and the underlying subsurface is rock, and the blue line indicates a regolith layer with buried rock particles and the underlying subsurface is ice.

Acknowledgments

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