MODELING RADAR SCATTERING FROM THE LUNAR SURFACE AND ANALYSIS OF THE EFFECT OF ROUGHNESS AND ICE INCLUSIONS ON CPR VALUES. Wenzhe Fa, Essam Heggy, Mark A. Wieczorek Institut de Physique du Globe de Paris, France (wzfa@ipgp.fr).

Introduction: The unambiguous detection of possible ice inclusions in the lunar regolith at the poles of the Moon using polarimetric radar signatures remains a challenging task. The Clementine bistatic radar experiment reported finding evidence of ice in the vicinity of Shackleton crater [1], while Earth-based Arecibo radar observations suggested no significant differences between the sunlit and permanently shadowed walls of this crater [2]. In an attempt to reduce the ambiguities on such observations, two orbital miniature synthetic aperture radars (Mini-SAR) on Chandrayaan-1 and Lunar Reconnaissance Orbiter (LRO) have imaged the lunar surface (and will continue to do so over the next 2 years for LRO) with the main purpose of detecting the polarimetric signature of ice in the shallow lunar subsurface in the lunar polar areas [3].

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 ice deposits. In this study, we have developed a quantitative model for radar scattering from the lunar reoglith layer using vector radiative transfer (VRT) theory of random media. From this model, both the radar backscattering coefficient and the circular polarization ratio (CPR) can be predicted analytically as a function of regolith parameters. We also discussed the possibility for ice detection using radar data.

Radar Scattering Model: Radar backscattering from the lunar regolith can be described mainly as a function of frequency, incidence angle, surface slope and roughness, regolith thickness, dielectric permittivity and the rock size distribution in the regolith. Figure 1 shows a schematic diagram of our two-layer model of the lunar regolith that is described by a homogeneous fine-grained regolith layer of thickness *d*, rough relief at the surface and bottom on the regolith layer, and buried rocks. In this study, a parameterized model using vector radiative transfer theory [4] is used to give quantitative relations between radar echoes 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 two rough interfaces [5]. Non-spherical particles are used to model the buried rocks, and their scattering properties depend upon the rock shape and size frequency distributions. An iterative method is used to obtain the Mueller matrix solution of the 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 surface and the rough interface between the regolith and bedrock, direct scattering from suspended rocks, and the interaction of scattering between rocks and the rough surfaces. Multiple scattering between rocks is not yet taken into consideration, but this will be included in our future modeling.

Model Validation: Prior to applying our model to analyze CPR data, we validated the output of the VRT method to polarimetric calculations using the finite-difference time-domain (FDTD) method [6]. FDTD is a full-wave approach that directly solves Maxwell's equations of wave propagation in discrete time and space steps, and it allows us to use complex surface and subsurface geometries as well as to implicitly account for volume scattering from the buried rocks. Special boundary conditions and absorbing layers were used to eliminate the clutter from the edges of the simulation domain. Figure 2 shows the comparison of bistatic scattering coefficient between FDTD simulations and the VRT model. To better interpret the statistical properties of rough surface scattering, the FDTD simulation results were averaged over 10 different realizations of random rock orientations and surface roughness. It can be seen that the VRT model matches the FDTD simulation results reasonably well given the computational limits of our small box size (1.5 by 1.5 meters).

Simulation Results and Analysis: Both polarized (opposite sense) and depolarized (same sense) radar echoes as well as the CPR are calculated using the VRT model as a function of incidence angle, layer thickness, surface and subsurface roughness, surface slope, size and population of buried rocks, and $FeO+TiO_2$ content. Our preliminary results imply the following:

(1) Polarized radar echoes at S and X band are mostly dominated by scattering from the surface and buried rocks, while the depolarized radar echo is domintated by scattering from the buried rocks.

(2) Both the polarized and depolarized radar echoes increase as the regolith thickness increases, while the CPR decreases with an increase of regolith layer thickness. As a result of this, the lunar highlands, whose regolith thickness is greater by about a factor of two than the mare, should have relatively strong radar echoes and a relatively small CPR when compared to the mare.

(3) The loss tangent of the lunar regolith increases as the abundance of $FeO+TiO_2$ increases, and this causes a decrease of the radar echoes and an increase in the CPR. Therefore, the mare, with high $FeO+TiO_2$ content, will have lower radar echoes and high CPR value.

(4) Under the condition of single scattering from rocks, radar echoes increase as the abundance of buried rocks increase, while the CPR decreases as rock abundances increase.

(5) Areas with regional tilts toward the radar antenna primary lobe will have stronger echoes and smaller CPRs than regions that are titled away from the radar antenna.

(6) Both radar echoes and CPR increase as surface roughness increases.

Implications for Ice Decetction Using Radar Data: To explore the expected polarimetric signature of ice in the polar permanently shadowed areas using radar, four parametric regolith models are considered. The first model contains a desiccated regolith with buried rocks and no ice inclusions, the second contains an ice layer of thickness *d* with buried rocks, the third contains a desiccated regolith layer with buried ice inclusions, and the last contains a regolith layer with buried rocks that overlays a pure homgenous ice layer. Both radar backscattered echoes and CPR values are calculated for each model. Figure 3 shows the CPR values versus radar incidence angle of the four different models. For LRO, the incidence angle is 49°, whereas for Chandrayaan-1, the incidence angle is 35°.

Simulation results suggest that it will be a difficult task to identify ice in the lunar regolith given the small contrast of dielectric permittivity between the ice and silicate regolith. This result assumes the validity of the current state of knowledge of lunar dielectric properties as reported in Olhoeft et al [8]. Nevertheless, if ice exists as buried particles with a sizes larger than that of regolith particles, radar echoes will decrease while the CPR will increase, which might provide an approach for identifying ice deposits.

We are currently applying the validated VRT model to assess ice enrichement in the mini-RF data and results will be compared to models performed by Thompson et al [7]. Results of this analysis will be discussed at the conference.

References: [1] Nozette S. et al. (1996) *Science, 274,* 1495-1498. [2] Campbell B. A. et al. (2005) *Icarus, 180,* 1-7. [3] Bussey D. B. J. et al. (2008) *LPS XXXIV,* Abstract #2389. [4] Jin Y. Q. (1994) Singapore, World Scientific. [5] Fung A. K. (1994) Boston, Artech House. [6] Yee K. S. (1966) *IEEE Trans. Antennas Propag., 14,* 302-307. [7] Thompson T. W. (2009) *JGR,* 2009JE003368. [8] Olhoeft G. R. (1973) *LPS IV,* 3133–3149.

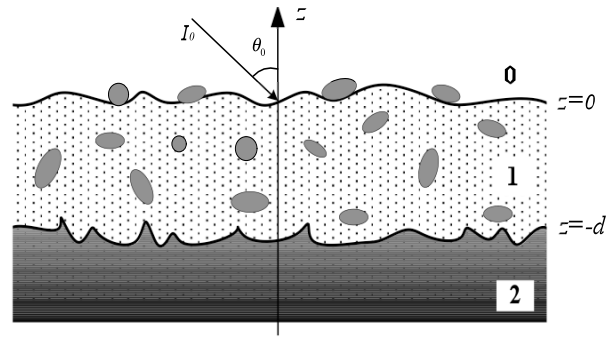

Figure 1. A two-layer model of the lunar regolith. Model parameters include the regolith thickness, abundance and size distribution of buried rocks, and rough relief at the surface and bedrock.

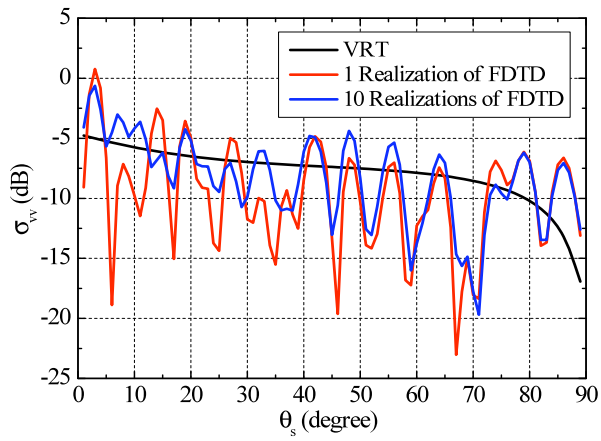

Figure 2. Comparsion between a VRT model and FDTD simulation. As the number of random realizations in the FDTD simulations increase, the average is seen to approach the VRT predictions.

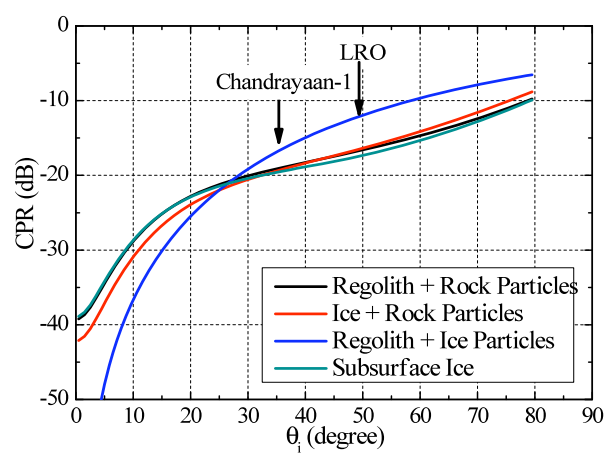

Figure 3. Circular polarization ratio (CPR) variations as a function of radar incence angle for difference regolith models.