MODELING THE POLARIZATION PROPERTIES OF ICY REGOLITH ANALOGS AT OPTICAL AND RADAR WAVELENGTHS.

P. Prem[1]*, D. T. Blewett[1], G. W. Patterson[1], A. K. Virkki[2]. [1]Johns Hopkins Applied Physics Laboratory, 11100 Johns Hopkins Rd., Laurel, MD, US; [2]Arecibo Observatory, University of Central Florida, Arecibo, PR, US; *parvathy.prem@jhuapl.edu.

Introduction: Radar observations of the Moon are one of the few datasets that offer insight into the structure of the lunar subsurface, including the potential distribution of ice at the lunar poles (e.g., [1,2]). Over the past several years, the Mini-RF instrument onboard the Lunar Reconnaissance Orbiter has operated in a bistatic mode, in which the instrument acts as a receiver for signals transmitted towards the lunar surface by the Arecibo Observatory (12.6 cm) and the Goldstone DSS-13 antenna (4.2 cm). This observational geometry allows for unprecedented measurements of polarization properties at radar wavelengths over a range of incidence and bistatic (phase) angles. However, the quantitative interpretation of what these characteristics reveal about the lunar subsurface remains a challenge [2].

In this work, we develop and apply numerical models to investigate how the physical properties of a medium influence its polarimetric characteristics. In particular, we aim to understand the Coherent Backscatter Opposition Effect (CBOE), caused by multiple scattering within a medium, and associated with an opposition surge; i.e., an increase in the intensity and circular polarization ratio (CPR) of backscattered radiation at small phase angles [3]. CBOE is thought to be responsible for the high zero-phase radar CPR of Jupiter's icy moons and Mercury's polar ice deposits [4,5]. On the Moon, some ejecta blankets and the floors of polar craters exhibit opposition surges that vary in nature, and are not yet fully understood [2]. In order to inform the application of our numerical model to the interpretation of radar data, we begin by assessing the ability of the model to reproduce experimentally-observed opposition surges of well-characterized icy regolith analogs at optical wavelengths (e.g. [6,7]).

Numerical Methods: We use an electric field Monte Carlo [8] method to model CBOE at varying incidence angles. This approach is based on tracking the propagation of a large number of "energy bundles" through the medium of interest. Each energy bundle is described by a Jones vector, which defines the polarization characteristics of the electromagnetic radiation represented by the bundle. The two components of the Jones vector are complex electric fields in two orthogonal directions, defined relative to the direction of propagation. Each scattering event modifies the Jones vector; the post-scattering vector is obtained by multiplying the pre-scattering vector by a scattering matrix, the terms of which depend on the properties of the medium at the wavelength of interest. We also account for attenuation of radiation along the propagation path. CBOE arises when time-reversed paths (traveling between the same set of scattering points in opposite directions, as shown in Figure 1) interfere. In an electric field Monte Carlo implementation, interference can be computed by adding the corresponding electric field vectors.

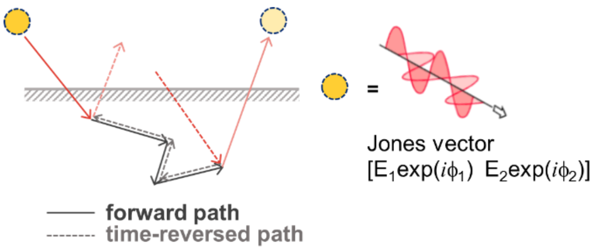

Figure 1. *Schematic view of the electric field Monte Carlo approach used in this work.*

For circularly polarized incident radiation, CPR is defined as the ratio of the same-sense and opposite-sense components of the received signal. Conversely, for linearly polarized incident radiation, the linear polarization ratio (LPR) is defined as the ratio of opposite-sense and same-sense components.

The key inputs to the Monte Carlo code are the complex scattering amplitudes (as a function of scattering angle) for a representative single-scattering event. In the results presented here, we use a Mie code [9] to compute the scattering amplitudes for spherical particles with a specified composition, at wavelengths of interest. We also explore the application of a static structure factor (SSF) correction to the Mie scattering phase function [10] to account for the suppression of forward scattering in a medium where scatterers are not truly isolated, as assumed in the Mie theory calculation. Similar approaches have been adopted to model reflectance and spectral properties in different contexts [11,12,13].

Preliminary Results and Discussion: We apply the methods described above to model an analog regolith composed of 1.2 μm alumina particles (with refractive index, $n = 1.7$) packed with a volume filling factor of 0.2, illuminated by 633 nm light. These parameters were chosen in order to compare model results to lab measurements of such a medium [7]. Figure 2(a) shows the computed scattering phase functions for particles of this nature, with and without the SSF correction.

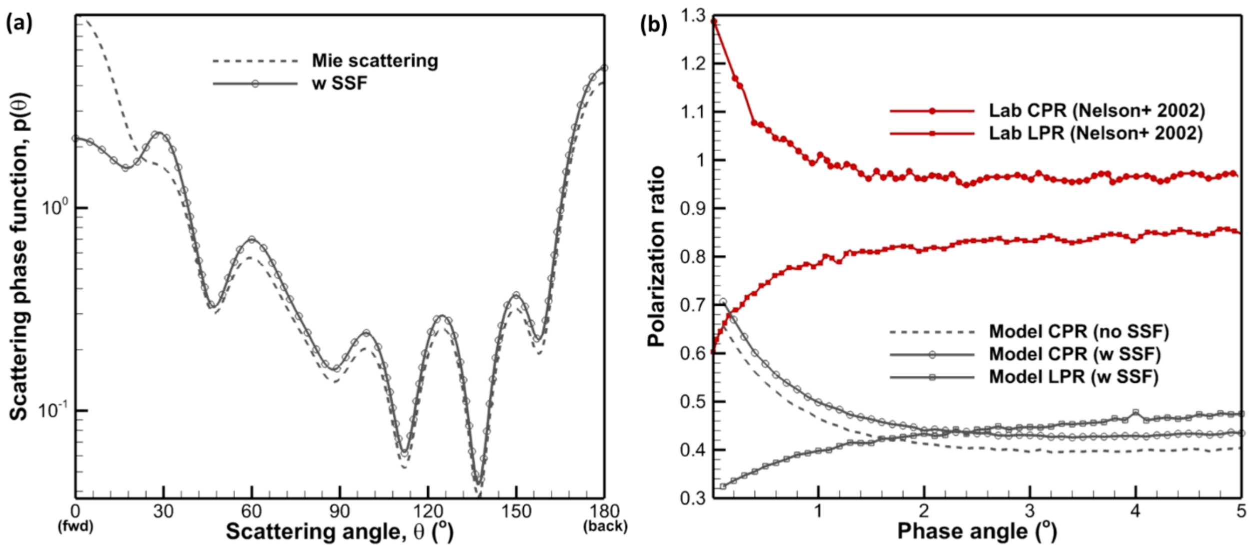

Figure 2. *(a) Scattering phase function for a medium of 1.2 μm alumina particles with a packing density of 0.2 and illuminated by 633 nm light, computed using Mie theory (for isolated spheres) and after application of a static structure factor correction; (b) Circular and linear polarization ratios for such a medium, as measured in lab experiments and modeled in this work.*

Figure 2(b) compares modeled CPR and LPR as a function of phase angle to lab measurements [7]. There are considerable discrepancies between the two: while the shape of the CPR phase curve is qualitatively similar to measurements, the LPR phase curve shows a less pronounced downturn at small phase angles. Most noticeably, modeled polarization ratios are much lower than measured values. The application of the SSF correction has only a modest influence (as illustrated for CPR in Figure 2(b)). We also compared model results (not shown here) to measured polarization ratios for a suspension of polystyrene beads in water (an analog for an icy regolith) [6] and found more severe discrepancies. Previous validation tests found that zero-phase CPR values computed using this model agreed well with analytical solutions [14], but we are currently working to rule out numerical errors, and to identify the factors that drive the differences between modeled and measured polarization properties.

One such contributing factor may be that the scattering properties of the medium are not best represented by those of individual particles [15]. If discrepancies between modeled and measured properties persist after ruling out numerical errors, we plan to investigate the influence of particle size and shape on model results using scattering properties computed for more realistic particle shapes (e.g., [16]). If the electric field Monte Carlo approach can be adapted to reliably reproduce the opposition response of well-characterized media, one of the advantages of the approach is that it can readily be applied to model coherent backscatter from a layered medium (e.g. a layer of dry regolith overlying ice) over a range of incidence angles, potentially providing a means to better understand subsurface stratigraphy at the lunar poles and beyond.

Acknowledgments: This work was supported by NASA Solar Systems Working Grant #NNX15AL58G and through a contract with the NASA LRO mission.

References: [1] Nozette et al. (1996), *Science* 274, 1495-1498. [2] Patterson et al. (2017), *Icarus* 283, 2-19; [3] Hapke (1990), *Icarus* 88, 407-417. [4] Slade et al. (1992), *Science* 258, 635-640. [5] Black et al. (2001), *Icarus* 151, 167-180. [6] Hapke & Blewett (1991), *Nature* 352, 46-47. [7] Nelson et al. (2002), *Planet. & Space Sci.* 50, 849-856. [8] Sawicki et al. (2008), *Optics Express* 16, 5728-5738. [9] Mätzler (2002), *IAP Res. Rep*, 8(1), 9. [10] Mishchenko (1994), *JQSRT* 52, 95-110. [11] Hapke et al. (2009), *Icarus* 199, 210-218. [12] Ito et al. (2018), *JGR: Planets*, 123, 1203-1220. [13] Kolokolova et al. (2020), *PSJ* 1, 74. [14] Prem et al. (2020), *LPSC* 51, #2099. [15] Piatek et al. (2004), *Icarus*, 171, 531-545. [16] Virkki & Muinonen (2016), *Icarus*, 269, 38-49.