MODELLING THE PHYSICAL NATURE OF LUNAR REGOLITH AT S-BAND AND L-BAND WAVELENGTHS USING THE CHANDRAYAAN-2 DFSAR AND LRO MINI-RF RADARS.
S. Shukla[1,2], A. Maiti[2], G. W. Patterson[3], P. Prem[3], S. S. Bhiravarasu[4,5], V. A. Tolpekin[6], and S. Kumar[1], [1]Indian Institute of Remote Sensing, ISRO, Dehradun, India (sshashwat93@gmail.com), [2]Faculty ITC, University of Twente, Enschede, The Netherlands, [3]Johns Hopkins University Applied Physics Laboratory, Laurel, MD, [4]Lunar and Planetary Institute, USRA, Houston, TX, [5]Space Applications Centre, ISRO, Ahmedabad, India, and [6]ICEYE, Espoo, Finland.

Introduction: Identifying target regions for In-Situ Resource Utilization (ISRU) will be important for enabling future human exploration of the Moon. For instance, understanding the abundance and physical form of water has significant implications for developing new exploration strategies. Other volatiles of possible economic value, such as Helium-3 (^{3}He), may also be of importance. Radar has a unique capability for identifying these volatiles and both the NASA LRO Mini-RF [1] and ISRO Chandrayaan-2 DFSAR [2] instruments in orbit around the Moon have the characterization of volatiles as a primary objective. Prospecting the tonnage and grade of potential volatile deposits with these radar instrument requires an understanding of the interactions of radar waves with lunar regolith. Here, we propose a quantitative radar scattering model that, coupled with a deep learning inversion algorithm, is capable of retrieving the dielectric constant of regolith from radar data. This information can be used to search for regions with a high probability of harboring near-surface reservoirs of volatiles such as ice and ^{3}He.

Model Description: The radar backscatter is mainly governed by frequency, incidence angle, roughness, dielectric constant, regolith thickness, $FeO+TiO_2$ content, and buried rock abundance [3, 4].

Two-layer Lunar Regolith Model. We consider the regolith to be a homogenous fine-grained layer with buried inclusions between the top surface and bottom subsurface of well-defined roughness and dielectric constant. We describe five basic mechanisms through direct scattering from the regolith and bedrock, diffuse scattering from the buried inclusions, and scattering from the interaction between bedrock and buried inclusions [5]. In this study, we parameterize the Integral Equation Model (IEM) for rough surfaces [3] and derive the scattering contribution from a low dielectric layer of Rayleigh spheres with irregular regolith-bedrock boundaries. We further account for differences in the concentration of volatiles in the regolith by modeling the dielectric constant of silicate/ice/^{3}He mixtures. Our model does not consider coherent backscatter opposition effect (CBOE) and multiple scattering between the buried inclusions.

Deep Learning based Dielectric Inversion Model. Deep learning algorithms are known to be effective when the given system is of multivariate, complex, and non-linear nature [5]. Since the relation between radar backscatter and physical parameters is strongly dominated by such characteristics, we prefer to design and develop a deep learning architecture over traditional empiric/semi-empiric approaches [5]. However, one of the important requirements is large amount of training data for achieving reliable inversion results. In this context, we use the simulated data from our proposed regolith model benchmarked against lunar sample data by adopting multilayer perceptrons for dielectric inversion [5]. The model inputs are horizontal and vertical radar albedo, incidence angle, and frequency whereas the outputs comprise of real and imaginary part of dielectric constant. Before training, the data is rigorously shuffled and then split into two parts with 20% for validation and the other 80% used for actual training.

Results and Discussion: For both S- and L-bands, we observe a major contribution from the top surface (regolith) at lower incidence angles, whereas diffuse scattering from the buried inclusions remains predominant at steeper angles. The polarimetric response of the regolith layer mixed with ice particles suggests enhancements in the diffuse scattering power for S-band compared to L-band, possibly due to the initial assumption of smaller sized inclusions that may be invisible at longer wavelengths. Moreover, the lower dielectric gradient and inhomogeneities significantly reduce the contribution from ice scatterers in contrast to the regolith media with buried rocks. Within the incidence angle range of DFSAR, the subsurface scattering is found to be even more important than buried ice scattering mainly because of shorter path of radar wave that is expected at lower incidence angles. Such a response is not noted in case of buried ^{3}He regolith grains. There is a strong dependence of loss tangent on the ^{3}He abundance from lunar sample data. As the abundance increases, the radar wave is found to be attenuated at a faster rate. In such cases, the backscatter profile is majorly dominated by the top surface contribution, with substantial decrease in the diffuse scattering powers at reduced ^{3}He abundances, for the entire range of incidence angles. Thus, it would be difficult to discriminate the polarimetric signatures of the regolith having low and high amounts of ^{3}He respectively. Higher penetration depth of L-band further facilitates a criterion to characterize the variations in loss tangent as a function of $FeO+TiO_2$ content that might prove essential for quantifying the buried volatile detection.

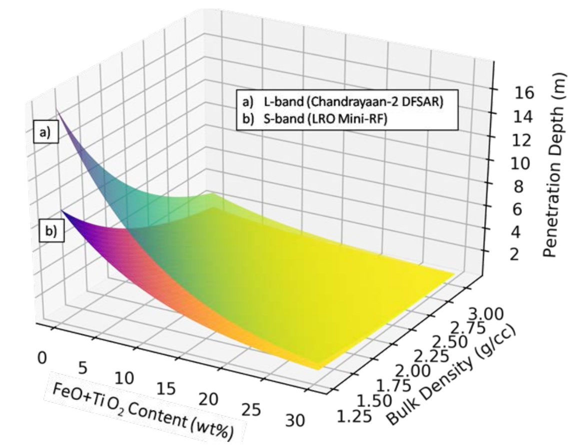

Figure 1. Variations in penetration depth for S- and L-band.

The regolith thickness and surface roughness also remain important proxies for revealing the subsurface environment of buried volatiles. In the case of lunar mare, the regolith can be described as smooth and thin, wherein the polarized radar intensity is expected to be low with greater subsurface penetration and hence, more prone to reaching the buried inclusions.

Dielectric Inversion. The training and testing R-squared are found to be 0.9521 with a mean squared error of 0.27. Since the validation dataset is never exposed to the model while training, the inversion results are significant and reliable. The performance also suggests that the model is not overfitted and the results are in close agreement with the Apollo science data for making inference to the up-scaled global and polar products. One of the interesting findings addresses the potential of our inversion model to capture the minute details about the contribution of buried inclusions and subsurface while estimating the dielectric constant.

Implications from Mini-RF and DFSAR. In order to explore the differences in the expected polarimetric response of buried volatiles, we hypothesize four parametric models of regolith layer with a) buried rocks, b) buried ice inclusions, c) buried ^{3}He, and d) buried rocks overlaid on a pure homogenous icy bedrock. Our forward model proposes that it will be difficult to discriminate the radar response of the regolith with buried rocks from icy bedrock due to the similar dielectric nature and reduced subsurface scattering contributions at both S- and L-band. Given the higher dielectric contrast between silicate rocks and ice/^{3}He, it is possible yet challenging to identify the volatiles for incidence angles > 30˚. Particularly, the characterization of high abundant ^{3}He deposits could be more feasible than ice. Moreover, as wavelength scale roughness increases, the possibility of detecting both ice and ^{3}He drastically reduces. The use of Mini-RF S-band seems optimal because of its larger incidence angle. However, as the size of buried particles increases, there is a better possibility to discriminate the radar response from L-band. In this regard, DFSAR L-band proves significant due to the additional penetration depth that has not been explored yet. For homogenous media containing pure ice, we even observe better capability of DFSAR L-band to penetrate, by a factor of two, compared to Mini-RF S-band. Also, the magnitude of CBOE, affected by incidence angle (i.e. lower angle translates to stronger response), is expected to be prominently captured by DFSAR. This can further reveal useful and complementary information about the physical nature of volatiles observed over a much larger range of incidence angles when augmented with Mini-RF data products.

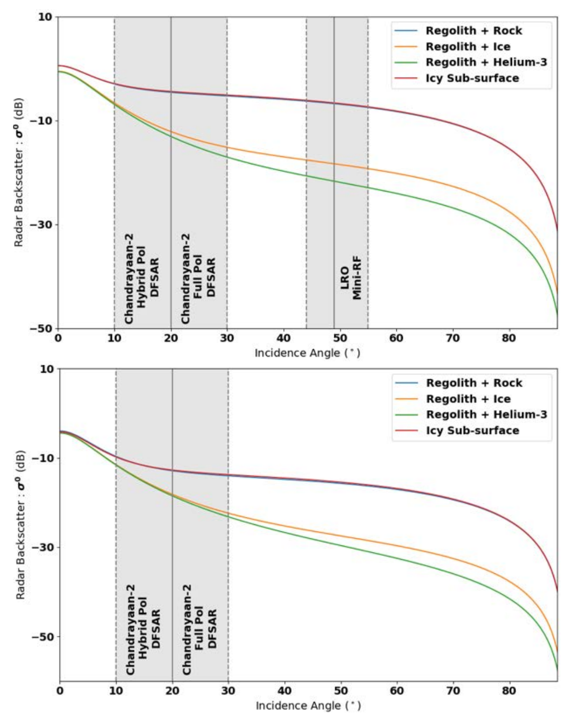

Figure 2. Variations in radar backscatter for different regolith models at (top) S-band and (bottom) L-band. The plots show similar trends as reported in [4].

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