**QUANTITATIVE CONSTRAINTS OF NEAR SURFACE ROUGHNESS ON LUNAR WATER ICE UNDER BISTATIC RADAR CONFIGURATION.**

S. Shukla[1], G. W. Patterson[2], N. T. Dutton[2], T. P. Himani[3], A. Maiti[4]. [1]Technische Universiteit Delft, The Netherlands (s.shukla@tudelft.nl), [3]Johns Hopkins University Applied Physics Laboratory, Laurel, MD, [3]Dept. of Earth and Planetary Science, Johns Hopkins University, Baltimore, MD, [4]Faculty ITC, University of Twente, Enschede, The Netherlands.

**Introduction:** Understanding the abundance and physical form of lunar water is significant in developing new human exploration strategies on the Moon. Monostatic and bistatic radar observations provide the potential for detection of water ice at the lunar poles [1]. This can be examined by the use of radar data which contains information on the structure and dielectric properties of surface and buried inclusions (like rocks and/or water ice) within the penetration depth of ~1 m [2] ('near surface' from hereafter). Laboratory data and analog experiments also suggest there is sensitivity of lunar scattering processes to variations in bistatic angle [3-4].

The presence of water ice near the surface can exhibit a strong response due to the Coherent Backscatter Opposition Effect (CBOE) at radar wavelengths. Such a response can be identified by the circular polarization ratio (CPR) of returned radar data. However, there is no evidence of this effect from ground-based bistatic observations of south polar craters [5], which is later supported by LRO Mini-RF and Chandrayaan-2 Mini-SAR monostatic observations of Cabeus [6]. In contrast, a clear opposition effect is observed in the floor materials of Cabeus by Mini-RF bistatic observations [1].

For icy materials, observed CPR typically exceeds unity [7]. However, near surface roughness can also contribute to CPR and thus, can reduce the diffuse radar scattering processes from a regolith mixed with water ice. In such scenarios, rough surface scattering dominates the observed backscatter which can further influence the detectability of water ice from radar. The impact of near surface roughness on bistatic radar signatures of lunar water ice is also poorly understood and not quantified in previous studies. It is further difficult to understand rough surface scattering processes solely based on radar observations. Radiative transfer (RT) models can help to quantify the scattering power from the near surface of varying scales of roughness.

In this regard, our present work aims to address the following questions: a) How can we quantify the influence of near surface roughness on radar scattering at varying bistatic angles? and b) What are the constraints of roughness on the abundance and physical form of water ice at the lunar poles?

**Model Description:** We consider the lunar near surface as a homogenous fine-grained layer with buried inclusions of rocks/water ice defined by roughness and dielectric constant. Near surface roughness can be quantified into horizontal scale, i.e. autocorrelation length, and vertical scale, i.e. RMS height. In order to simulate the bistatic scattering response of the lunar near surface described by roughness, we use an advanced integral equation model (AIEM). The AIEM is a two-dimensional, point-scale model and is valid over a broader range of roughness values than other equivalent rough surface scattering models [8]. The validity range is described up to 1 m autocorrelation length and 10 cm RMS height.

In our simulations, the autocorrelation length, equivalent to the wavelength of incident radar wave (i.e. 12.6 cm), is used along with an exponential correlation function. This is because of the lack of roughness information comparable to Mini-RF spatial resolution. The variation in roughness is then defined by RMS height, i.e. 0.5 cm for a smooth near surface and 2 cm for a rough near surface. The effective dielectric constant is estimated using three component Polder van Santen dielectric mixing formula [9]. Here, we consider two cases: a) 50:50 mixture of vacuum and silicate grains to represent a pure regolith, b) 50:25:25 mixture of vacuum, silicate grains, and rocks (or water ice) to represent a regolith with buried rocks (or a regolith with buried water ice). For these cases, we use the dielectric constant of 8 + j0.07 for silicate grains (equivalent to a solid rock with 3.2 g/cm$^3$ density and 5 wt% $FeO+TiO_2$), 3.15 + j0.001 for water ice, and 6 + j0.01 for rocks [10]. As part of radar configuration parameters, we replicate the Mini-RF geometry for Cabeus, i.e. incidence and emission angle of 84$^o$ and bistatic angle from 0$^o$ to 10$^o$.

Ultimately, we parameterize the AIEM for all the above cases to simulate the co-pol horizontal (HH) and vertical (VV) channels. Note that the conversion of quad-pol scattering matrix into the Stokes parameters for circular transmit and dual linear receive mode results in the identical derivation of hybrid-pol Stokes parameters [11]. Due to varying penetration depths of horizontal and vertical channels, we use a co-pol ratio (HH/VV) as a diagnostic indicator of scattering processes from near surface. We also vary this ratio over a range of bistatic angles to identify the variations in the scattering behavior because of water ice. We calculate the percent change in the co-pol ratio of regolith and buried water ice (or rocks) with respect to the co-pol ratio of pure regolith for different roughness conditions (smooth or rough). If there is an addition of buried water ice (or rocks), positive change indicates that the ratio has increased and negative change is the decrease in the ratio.

**Results:** We see a significant variation in the co-pol ratio as a function of bistatic angle from smooth to rough regolith containing either buried water ice or buried rocks (Figure 1). The ratio tends to decrease with bistatic angle, indicating that the ratio in monostatic configuration (i.e. 0º bistatic angle) is predicted to be higher. As the near surface roughness increases, there is an enhancement in the ratio which is more easily detected and recognizable from the smooth case at higher bistatic angles. However, for smaller bistatic angles (i.e. < 2º), the difference is minimally separated. This suggests that the co-pol ratio suppresses the roughness information at lower bistatic angle.

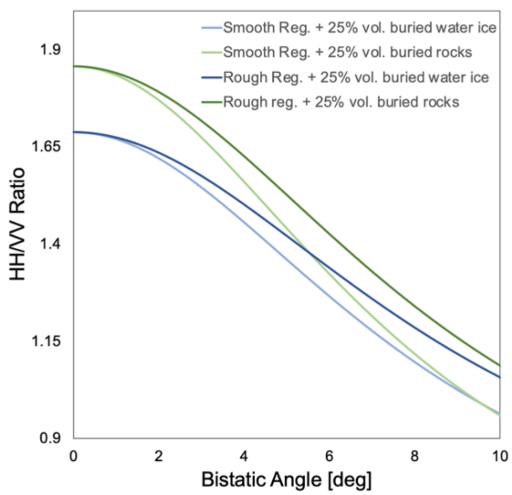


**Figure 1.** Variations in co-pol ratio with bistatic angle for a regolith with buried water ice (or rocks) of varying roughness conditions (smooth or rough)

When a regolith layer is mixed with water ice, then the ratio is observed to be lower when compared to that of buried rocks. This could be linked with the changes in dielectric contrast of regolith, i.e. 25% vol. water ice (or rocks) corresponds to ~26% (or ~9%) decrease in effective dielectric constant. Moreover, the percent change in co-pol ratio increases with bistatic angle upon the addition of buried rocks (or water ice) but with different rates (Figure 2). The rate of increase in the case of water ice is sharper when compared to rocks. We also see that the percent change in ratio for rocks ranges between -5% and 0%, which makes it very difficult to distinguish a pure regolith from buried rocks.

The presence of water ice in the regolith reduces the co-pol ratio by ~13% compared to pure regolith for monostatic case. At higher bistatic angle (i.e. 10º), the surficial water ice is undetectable from pure regolith for smooth surface. There exists a clear surge in the percent change after 2º bistatic angle. Additionally, the differences in the percent change between rough near surface and smooth near surface tend to increase with bistatic angle. This attributes to better identification of near surface reservoirs of 25% vol. water ice at lower bistatic angles, about < 2º, where the effect of roughness on co-pol ratio is negligible. We can further delineate the proportion of buried rocks from water ice deposits owing to a ~9% difference in percent change at bistatic angle less than 2º.

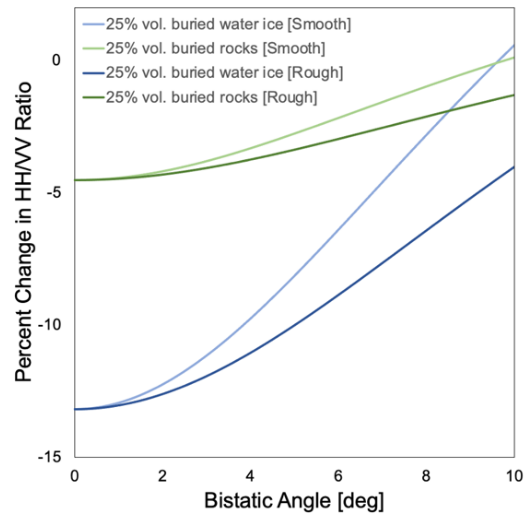


**Figure 2.** Percent change in co-pol ratio as a function of bistatic angle for 25% vol. of water ice and rocks buried in a smooth (or rough) regolith layer

**Take Away Message:** In the present work, we underline the importance of roughness on bistatic co-pol ratio of near surface regolith with water ice (or rocks). For both the cases, the ratio decreases with bistatic angle with the effect of roughness more pronounced from bistatic angle > 4º. However, note that we do not currently account for the diffuse scattering component, which makes the smooth case slightly underestimated. The rate of percent change in co-pol ratio of near surface regolith is controlled by the proportion and nature of buried material, i.e. 25% vol. water ice yields sharper curve compared to 25% vol. rocks. Our initial findings provide an opportunity to separate and quantify the scattering behavior of lunar water ice deposits from pure regolith and regolith with buried rocks at bistatic angles < 2º, similar to [2]. In the future, we plan to compare the bistatic co-pol ratio with Mini-RF CPR observations for reliable inference of water ice at the lunar poles.

**References:** [1] Patterson et al. (2017), *Icarus 283*, 2-19. [2] Patterson et al. (2022), *Europlan. Sci. Cong.*, #1095. [3] Piatek et al. (2004), *Icarus 171*, 531-545. [4] Hapke et al. (1998), *Icarus 133*, 89-97. [5] Campbell D. B. et al. (2006), *Nature 443*, 835–837. [6] Neish C. D. et al. (2011), *JGR 116*, E01005. [7] Harmon J. K. et al., (1994), *Nature 369*, 213–215. [8] Wu et al. (2008), *IEEE TGRS 46(9)*, 2584-2598. [9] Sihvola (1999), *IET*, 0852967721. [10] Fa et al. (2011), *JGR 116,* E03005. [11] Raney et al. (2012), *JGR 117,* E00H21.