Scattering mechanism-based algorithm for improved mapping of water-ice deposits in the lunar polar regions

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Due to the smaller axial tilt of the Moon, interiors of some of the polar craters on the lunar surface never get sunlight and are considered to be permanently shadowed regions. Several of such regions are known to contain water-ice deposits. These regions are expected to show elevated values of circular polarization ratio (CPR). Hence, the interiors of craters containing water-ice deposits are characterized by elevated CPR values as observed by the S-band synthetic aperture radar (Mini-SAR) on-board Chandrayaan-1 mission of ISRO. However, elevated CPR values were also observed from the interiors of some non-polar craters and also from young, fresh polar craters. Thus, elevated CPR values are not a unique signature of water-ice deposits. Therefore, additional information related to geological setting and roughness patterns should also be considered while identifying the regions containing water-ice deposits. For identifying a unique signature of water-ice deposits, analysis of radar scattering mechanism in elevated CPR regions was carried out. Areas of elevated CPR due to double-bounce and surface scattering conditions were segmented and polarimetric, backscattering properties of diffuse scatterers were analysed. Based on the signatures of diffuse scatterers and radar backscattering coefficient, a scattering mechanism-based algorithm was developed, which has the advantage in classifying regions showing elevated CPR due to surface and double-bounce scattering effects. The algorithm was then tested using Mini-SAR data and it was also found to be useful in eliminating regions of elevated CPR in fresh craters observed due to the double-bounce effect.

Keywords: Circular polarization ratio, craters, lunar surface, water-ice deposits.

Recent investigations of lunar polar regions using remote sensing data suggested the existence of water-ice in permanently dark regions of polar craters1–4. Because of the small tilt of the Moon’s axis with respect to the Sun, craters and other depressions near the poles never receive sunlight and remain in permanently shadowed zones. This condition creates cold trap zones with temperatures as low as 50–70°C, in which water-ice may have existed for at least two billion years5. Cometary debris and meteorites containing water-bearing minerals bombard the Moon’s surface and the water is mostly lost in space. It is believed that the water molecules which are trapped in such cold traps, can never find a way to come out and significant quantities of water-ice would accumulate in geological timescale.

Radar is an optimal instrument for detecting metre-thick deposits of water-ice due to its distinctive polarization signature compared to the surrounding silicate regolith6. One of the methods to detect such ice deposits is the use of radar polarimetry which has the potential to provide additional information about the surface and subsurface physical properties, and it has been often demonstrated in remote sensing studies of our solar system6. The key radar parameter for detection of water-ice is the circular polarization ratio (CPR), which is the ratio of the same-sense circular (SC) echoes to the opposite-sense-circular (OC) echoes. In case of circular transmit polarization and linear received polarization system, it is the ratio of left circular polarized to opposite polarized signal, that is right circular polarization. Specular echoes from surfaces that are smooth at wavelength scales will lead to low ratios and hence low CPR values, while diffuse scattering from rough surface generates CPR values approaching one or even greater than one for extremely rough terrain (caused by multiple double-bounce reflections). Also, low temperature water-ice when it is present as ice is transparent to RF energy and radar is multiple scattered by imperfections and inclusions in the ice1. Further, as observed from some planetary bodies, the ice inhomogeneities exhibit a phenomenon known as coherent backscatter opposition effect7 (CBOE), which causes an increase in the radar echo reflectivity and enhancement of CPR along the backscatter direction.

The Clementine bi-static radar experiment detected elevated CPR values in the south pole of the Moon, suggesting the presence of patchy ice deposits in the permanently shadowed areas of Shackleton crater8,9. This was later questioned by further studies using ground-based Arecibo observatory and Green Bank Telescope (GBT) at a bi-static angle of 0.37°, by suggesting that high CPR
values observed near the south pole are caused by surface roughness of the rugged inner walls of Shackleton crater and proximal ejecta of impact craters\textsuperscript{10}. However, with the availability of data from the first orbital Synthetic Aperture Radar (SAR) around the Moon, the Mini-SAR on-board Chandrayaan-1, Spudis \textit{et al.}\textsuperscript{1} showed the anomalous behaviour of craters which are under permanent Sun shadow, i.e. elevated CPR values in their interiors, but not exterior to their rims. Spudis \textit{et al.}\textsuperscript{1} analysed CPR distributions at both the interior and exterior of a small polar anomalous crater, a polar fresh impact crater and another small non-polar anomalous crater. It was found that the CPR distributions of non-polar anomalous crater, which is exposed to full sunlight over the course of a lunar day, and the fresh impact crater are similar, but not the polar anomalous crater. Statistical analysis predicted deposits of water-ice inside the polar anomalous crater, which correlate with the proposed locations of predicted deposits of water-ice inside the polar anomalous crater, a polar fresh impact crater and another small non-polar anomalous crater. It was found that the CPR distributions of non-polar anomalous crater, which is exposed to full sunlight over the course of a lunar day, and the fresh impact crater are similar, but not the polar anomalous crater. Statistical analysis predicted deposits of water-ice inside the polar anomalous crater, which correlate with the proposed locations of water-ice modelled on the basis of Lunar Prospector epithermal neutron data\textsuperscript{11}. Thomson \textit{et al.}\textsuperscript{1} suggested an upper limit of ~5–10 wt% H\textsubscript{2}O ice (up to 30 vol%) present in the uppermost metre of regolith within the Shackleton crater floor at the lunar south pole. Modelling of radar scattering at two different wavelengths by Thompson \textit{et al.}\textsuperscript{12} indicated that scattering from near-surface ice covered by a thin regolith layer can be separated from rocks if the SC enhancement is twice the average or more. It was also observed that if the lunar ice is dispersed throughout the regolith as ice-filling pores, then scattering differences might be too small to detect\textsuperscript{12}.

The high CPR values, thought to be due to scattering from water-ice, were also found to be within fresh, young craters due to roughness/double-bounce effect associated with them. The anomalous scattering properties were also observed at many non-polar craters on the Moon. Thus, CPR values greater than one alone could not be attributed to ice deposits. Hence for the unambiguous detection of water-ice, it is required to separate the high CPR areas caused by double-bounce effect, and the exact locations within the interior of the polar anomalous craters which contribute to volume/diffuse scattering must be identified and mapped. In order to eliminate regions of high CPR due to double-bounce, an algorithm was proposed, which removes the contribution of multiple double-bounce reflections from the total signal received from areas having CPR values greater than one. In this case, since the SC signals are more enhanced than the OC signals received, surface scattering (Bragg scattering) contribution is negligible. This algorithm was tested using Chandrayaan-1 Mini-SAR data.

Mini-SAR data and derived polarimetric parameters

Mini-SAR imaging radar on-board Chandrayaan-1 of ISRO was the first lunar orbiting mono-static SAR with a unique hybrid polarity architecture\textsuperscript{13}, flown in October 2008 with a primary scientific objective to detect water-ice in the permanently shadowed regions on the lunar poles up to a depth of a few metres. Mini-SAR operated at the S-band (2.38 GHz) frequency with left circular polarization (LCP) transmission and reception in linear horizontal (H) and vertical (V) polarizations. During its operational period, Mini-SAR mapped over 95% of the lunar poles (lat. > 80°) at 35° incidence angle with a ground resolution of 150 m. This radar used Stokes’ parameters and derived daughter products such as CPR, degree of linear polarization and relative phase to describe the backscattered field, in order to distinguish volume scattering from other scattering mechanisms\textsuperscript{14} (e.g. sub wavelength-scale surface roughness).

A typical Mini-SAR image strip contains 16 bytes of data in four channels of four bytes per pixel, given by $|LH|^{2}$, $|LV|^{2}$, Real ($LH \cdot LV$) and imaginary ($LH \cdot LV$). The first two channels represent the intensity images for horizontal and vertical receive and the last two represent real and imaginary components of the complex cross-power intensity between the horizontal and vertical receive, respectively. From these data, Stokes’ vector can be generated\textsuperscript{15} to completely describe the polarization state of the received wave as:

$$S = \begin{bmatrix} S_{0} = \langle LH \cdot LH \rangle + \langle LV \cdot LV \rangle \\ S_{1} = \langle LH \cdot LH \rangle - \langle LV \cdot LV \rangle \\ S_{2} = 2Re(LH \cdot LV) \\ S_{3} = -2Im(LH \cdot LV) \end{bmatrix},$$

where the terms $LH$ and $LV$ are complex numbers denoting magnitudes of electric fields corresponding to LCP transmission and $H$ and $V$ receive respectively; $\langle \rangle$ represents ensemble averaging in time or spatial domain, $*$ represents the conjugate and $Re$ and $Im$ are the real and imaginary parts, respectively, of the complex number. The sign on $S_{0}$ is negative, which is consistent with the backscattering alignment (BSA) convention. The Mini-SAR data were found to have a $LH-LV$ relative phase ($\delta$) shift of 45° based on the analysis of different portions of the lunar surface\textsuperscript{15}. In order to overcome this systematic error, a phase calibration was done and phase offset of 45° was applied to the Mini-SAR data before further processing, as explained in recent studies\textsuperscript{15,16}.

Several useful quantitative measures follow from Stokes vector\textsuperscript{15}; some of the important derived measures have been explained in Mohan \textit{et al.}\textsuperscript{15}. The decomposition of $m$-delta ($m$ – degree of polarization, delta – relative phase) feature space offers a novel way of determining the odd, even bounce and volume scattering contributions corresponding to a target or within a radar resolution cell\textsuperscript{13}. The degree of polarization has long been recognized as the single most important parameter characteristic of a partially polarized EM field, which
### Table 1. Average values of total backscattered power, circular polarization ratio (CPR), relative LH and LV phase (delta) and Degree of polarization (DoP) at interior (int) and exterior (ext) regions of various craters studied here. The CPR values indicate mean ± (–) standard deviation.

<table>
<thead>
<tr>
<th>Crater diameter (km)</th>
<th>Total backscattered power (dB)</th>
<th>CPR</th>
<th>Delta (degree)</th>
<th>DoP (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Int</td>
<td>Ext</td>
<td>Int</td>
<td>Ext</td>
</tr>
<tr>
<td></td>
<td>Int</td>
<td>Ext</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Polar anomalous craters</td>
<td>16</td>
<td>–13.32</td>
<td>–13.42</td>
<td>0.7 ± 0.27</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>–11.36</td>
<td>–10.86</td>
<td>0.77 ± 0.28</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>–12.7</td>
<td>–13.48</td>
<td>0.85 ± 0.32</td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>–14</td>
<td>–10.35</td>
<td>0.7 ± 0.26</td>
</tr>
<tr>
<td></td>
<td>11</td>
<td>–14</td>
<td>–13.44</td>
<td>0.57 ± 0.21</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>–13.53</td>
<td>–12.9</td>
<td>0.68 ± 0.25</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>–13</td>
<td>–12.82</td>
<td>0.68 ± 0.27</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>–9</td>
<td>–12.37</td>
<td>0.74 ± 0.31</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>–13</td>
<td>–14</td>
<td>0.74 ± 0.31</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>–10.86</td>
<td>–9.1</td>
<td>0.63 ± 0.23</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>–15</td>
<td>–12.74</td>
<td>0.55 ± 0.19</td>
</tr>
<tr>
<td></td>
<td>14</td>
<td>–11.8</td>
<td>–9.45</td>
<td>0.66 ± 0.25</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>–13.33</td>
<td>–14.3</td>
<td>0.84 ± 0.31</td>
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<tr>
<td>Polar fresh craters</td>
<td>20</td>
<td>–12.33</td>
<td>–9.26</td>
<td>0.77 ± 0.27</td>
</tr>
<tr>
<td></td>
<td>14</td>
<td>–9.6</td>
<td>–5.34</td>
<td>0.81 ± 0.29</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>–13</td>
<td>–3.65</td>
<td>0.75 ± 0.24</td>
</tr>
<tr>
<td>Non-polar anomalous craters</td>
<td>5</td>
<td>–10.31</td>
<td>–9.32</td>
<td>1.11 ± 0.35</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>–9.16</td>
<td>–11</td>
<td>1.08 ± 0.39</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>–11.13</td>
<td>–11.32</td>
<td>0.68 ± 0.21</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>–9.95</td>
<td>–9.04</td>
<td>0.85 ± 0.29</td>
</tr>
</tbody>
</table>

**Figure 1.** North polar anomalous craters: Total backscattered power (S0) and circular polarization ratio (CPR) images for each crater are represented by (i) and (ii) respectively. (a) Mouchez M crater, (b) Hermite A crater (c) Small crater on the floor of the bigger crater Hermite, (d) Whipple crater to the north of Peary crater, indicated by an arrow. Scale bar at the bottom indicates the range of CPR values.
represents the fully polarized case \( (m = 1) \) and the fully depolarized case \( (m = 0) \), and is not affected by polarimetric basis transformations\(^{13} \). The \( \text{LH} - \text{LV} \) relative phase \( (\delta) \) is highly sensitive to polarimetric variations in the backscattered field, and under the condition of circularly polarized illumination, it is the prime indicator of double-bounce scattering. A decomposition technique based on the parameters \( m \) and \( \delta \) derived from the hybrid polarimetric SAR data was found to be effective in identifying dominant scattering mechanisms associated with a radar resolution cell\(^{13} \). The \( m-\delta \) scatter plot gives overall information of the scattering contributions within the area under consideration; so a decomposition colour code\(^{17} \) was introduced given by

\[
\begin{align*}
R &= \sqrt{S_0 \times m \times (1 + \sin \delta)/2} \\
&\text{indicates double-bounce backscatter}
\text{(dihedral reflectors),}
\end{align*}
\]

\[
G = \sqrt{S_0 \times (1 - m)} \quad \text{indicates volume scattering} \\
\text{(randomly polarized targets),}
\]

\[
B = \sqrt{S_0 \times m \times (1 - \sin \delta)/2} \\
\text{indicates single bounce backscatter}
\text{(specular reflection),}
\]

where the total backscattered power \( S_0 = R^2 + B^2 + G^2 \).

A circular wave backscattered by a surface rotates the incident wave in the opposite direction. Consequently, for the case of left circularly polarized transmission, a dominant surface scattering mechanism will return a right circular polarized wave (\( \delta = -90^\circ \)). So in terms of \( m \)-\( \delta \) representation, the surface scattering term consists of \((1 - \sin \delta)\) term. This colour code was applied for the study regions to identify the scattering mechanism.

**Study area and methodology**

In this study, scattering properties of 20 craters were analysed; 16 of them are at the north pole and the remaining craters belong to non-polar regions of the Moon. Out of the 16 north polar craters, 13 have permanently shadowed regions\(^1 \) (which makes up to one-third of the total north pole anomalous craters), while the remaining three are fresh impact craters with their ejecta fields distinctly visible in the Mini-SAR images. An inventory of craters analysed in this study is summarized in Table 1. The total backscattered power and CPR images of four polar anomalous craters are shown in Figure 1. To begin with, the CPR distributions over the interior and exterior portions of the north polar craters (both fresh and anomalous) were analysed and found to be in good correlation with earlier results\(^1 \).
A few non-polar craters were identified that exhibit anomalous scattering properties, as observed by Spudis et al., like the crater to the north of Byrgius (24°S, 65.3°W; 5 km diameter). The backscatter properties of this crater along with three other non-polar anomalous craters with elevated CPRs in their interiors (Figure 2) were analysed. These craters are in the sunlit region where water-ice cannot exist and are listed from Table 1. The Mini-SAR data were analysed in terms of backscatter and derived Stokes parameters. Radar backscatter was analysed for the effect of surface roughness, whereas polarimetric parameters were used for identifying the scattering mechanism.

**Analysis of scattering mechanism in high CPR regions**

The high CPR values can be associated with areas of water-ice deposits, or due to very rough surfaces such as a rough, blocky lava flow, which has angles that form many small corner reflectors. In this case, the radar signal could hit a rock face (changing LCP into RCP) and then bounce over to another rock face (changing RCP back into LCP) and hence to the receiver, which produces a double-bounce effect that could mimic the enhanced CPR obtained from ice targets. Therefore, elevated CPR alone cannot be considered as a derived indicator of the presence of water-ice particles distributed in the regolith, and we require to understand the scattering mechanism within the elevated CPR regions as well.

**Analysis of decomposition images:** From the colour-coded decomposition images, various scattering mechanisms present in a given region could be identified. Figure 3 shows the m-delta decomposition images of three polar craters. The 8 km diameter crater on the floor of Rozhdestvensky (Figure 3a) and the Whipple crater (Figure 3c) are anomalous and the Main L crater (14 km diameter, Figure 3b) is a fresh crater. As observed from Figure 3, the dominant scattering mechanism is volume scattering in the interior of both the anomalous craters and a mixture of even and odd bounce scattering beyond their rims. A characteristic double-bounce feature, as explained by Raney et al., could be observed towards the western edge of the small anomalous crater on the floor of Rozhdestvensky (Figure 3a). In the case of fresh impact crater Main L, a mixture of double-bounce and volume scattering (Figure 3b) was observed to be dominant both inside and outside the rim of the feature. This is consistent with its high CPR values due to enhanced degree of wavelength-scale roughness caused by the abundant blocks present within the interior and at the ejecta deposits of the crater. Each of the craters along with its impact ejecta region was analysed in terms of radar backscatter and scattering mechanism to study the anomalous scattering properties. Table 1 shows the average values of various polarimetric parameters associated with the analysed craters which are $S_0$, CPR, $m$ and $\delta$. The craters are classified into anomalous and fresh (young) according to the mean CPR values observed. Since high CPR regions were to be analysed, the areas with CPR values greater than 1 at the crater interior were masked out for subsequent analysis.

**Analysis of scatter plots:** The scatter plots of scattering mechanisms derived from $m-\delta$ decomposition method.
against CPR were analysed for each class of crater as described in Table 1. The high CPR regions (CPR > 1) showed contributions from surface, volume and double-bounce scattering mechanisms for all the craters. This could be observed in the plots of scattering mechanism versus CPR (Figure 4) for the three craters shown in Figure 3. Thus, high CPR regions exclusively contributed by diffuse/volume scattering were identified using an algorithm proposed here.

**CPR-delta-backscatter algorithm for water-ice detection**

Since the relative phase delta (δ) is a sensitive indicator for odd and even bounce scattering, regions showing surface scattering (specular or mirror-like reflections) could be separated from other regions. Therefore, use of CPR in conjunction with δ could give improved understanding of scattering types in a region. For this analysis, CPR values were plotted against δ (Figure 5) and the scatter plots were studied. In CPR space, the image pixels for which CPR < 1 were found to be confined to the region of δ = −180° to δ = 0°, and the upper half of the plane (δ = 0° to
**Figure 7.** The CPR–delta algorithm for identification of water-ice in lunar polar regions.

**Figure 8.** Regions of volume scattering (in green) overlaid on $S_0$ images of the small crater on the floor of Rozhdestvensky using (a) existing method (regions of CPR > 1) and (b) the algorithm developed.


\( \delta = 180^\circ \) contained pixels with CPR > 1, which have contributions from both double-bounce and volume scattering. In this way, contribution from surface scattering was eliminated. As the Mini-SAR transmitted LCP, a dominant double-bounce scattering mechanism will return a left circular polarized wave again, which will be centred at \( \delta = +90^\circ \). So the pixels with delta values of \( 90^\circ \pm 10^\circ \) were removed to separate the regions having contribution from both double-bounce and volume scattering. A graphical representation of this segmentation using CPR and delta values is shown in Figure 6.

Also, as a threshold value of \(-15\) dB was chosen based on the observations of mean backscatter at regions of CPR > 1 at the interior of the analysed craters. This backscatter threshold was applied to mask out two regions: interior of non-polar anomalous craters which mimic the water-ice-like condition and very high backscatter observed at the crater walls which are oriented in the direction of the radar (in the order of \( +5\) dB to \(-8\) dB). Based on the above inputs, an algorithm was developed as shown in Figure 7, which can be used to represent the areas of possible locations of water-ice.

**Results and discussion**

Table 1 gives an estimate of the average scattering properties at the interior and exterior of the craters analysed in this study. It can be observed from Table 1 that the interior and exterior regions of the polar anomalous craters are characterized by volume scattering with low \( m \) values and surface scattering with relatively high \( m \) values respectively. Regions both interior and exterior to the rim of young, fresh craters were observed to have low \( m \) values. In case of non-polar anomalous craters, the values indicate the presence of mixed scattering contributions with lower \( m \) values.

The results of the existing decomposition technique and the algorithm developed are shown in Figures 8 and 9. The green pixels overlaid on \( S_0 \) images indicate the possible locations of water-ice according to the two methods. Clear differences could be observed between the two methods in depicting the possible water-ice regions within the permanently shadowed regions of the crater interior. Even though some non-polar craters also exhibit anomalous scattering properties, they are characterized by high backscatter values in their interiors (average values around \(-10\) dB) in contrast to the low values of polar anomalous craters, suggestive of diffuse scattering likely due to water-ice particles mixed with the regolith. Thus, CPR–delta method was implemented for detecting regions of water-ice along with a backscatter criterion that helps in differentiating polar anomalous craters from those of non-polar origin.

**Conclusion**

The CPR–delta approach along with backscatter analysis used in this study provides a better method to identify...
water-ice deposits by separating them from young, fresh craters with elevated CPR values. Identification of regions which exclusively contribute to volume scattering in the permanently shadowed regions is important in supporting the debate over the possible existence of water-ice in those areas, since a high degree of correlation between the occurrence of high CPR values and the transition from seasonally sunlit to permanently shadowed regions of the crater wall is certainly required. The algorithm showed promising results for identifying craters with water-ice deposits and separating them from young, fresh craters with elevated CPR values.


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