Recognition of Volumetric Scattering of Lunar Regolith Media in the PSR via Fully Polarimetric SAR Data

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Abstract—Data of fully polarimetric synthetic aperture radar onboard Chandrayaan-2 make it feasible to analyze the geometric and physical properties of the lunar soil layer. A specific mission of Chandrayaan-2 is to investigate if there is water–ice in the regolith of the permanently shadowed region (PSR). Volatile substances are likely to accumulate in the ancient regolith media. Volumetric scattering of the regolith media might indicate specific characteristics of the regolith. Scattering from surface, rocks should be excluded. Such flat regions are difficult to identify in the digital elevation model. In this article, Chandrayaan-2 full-pol data at L-band are used for this purpose. The co-pol and cross-pol scattering coefficients and decomposition parameters, such as $H$, $\alpha$, degree of polarization, and circular polarization ratio of lunar surface, are studied. High-order scattering from rough surface is numerically simulated and analyzed by the bidirectional analytical ray-tracing code. It is found that rocky rough surface causes high co-pol scatterings. High-order scatterings of the rough surface and volumetric scatterers can enhance cross-pol scattering. Criteria are proposed to select volume scatterings at flat regions at Mare Serenitatis and a PSR crater. Regions with weak co-pol backscattering in a PSR crater at $85.9^\circ$N, $111.7^\circ$E are classified as flat surface. It is found that a flat region with weak co-pol and high cross-pol terms appears different from surrounding regions. The enhanced cross-pol is likely to be caused by volumetric inhomogeneity in the regolith. This unusual region shows its inhomogeneous soil layer and deserves further study.

Index Terms—Fully polarimetric (full-pol) synthetic aperture radar, permanently shadowed region (PSR), regolith media, surface and volume scattering.

I. INTRODUCTION

DUAL-FREQUENCY fully polarimetric (full-pol) SAR onboard Chandrayaan-2 makes it feasible to analyze the co-polarized (co-pol) and cross-pol scatterings from lunar surface [1], [2], [3].

A main purpose of this mission is to explore if there is water–ice in lunar permanently shadowed regions (PSRs). It is uncertain that which kind of scattering signals can be taken as the indicator of water–ice [4]. PSRs usually locate in the craters near lunar poles where direct solar illuminations are unavailable. The inner parts of fresh craters are rough. Bombardments of cosmic rays and solar wind, meteorite impacts, and huge temperature variations make large rocks breakdown. The inner parts of degraded craters become smooth. Flat surfaces without rocks distribute sporadically between small craters. In PSR, flat regions ensure the accumulation of volatile substances implanted by the solar wind proton flux or degassing from the lunar interior and avoid the dilution by impact gardening [5], [6].

It is difficult to identify volume scatterings from flat regions and exclude the rocks with the digital elevation model (DEM), which was homogenized to reduce the orbital error [7]. High-resolution SAR image is capable of detecting scattering mechanism [8]. The measured backscattering coefficients are contributed by rough lunar surface, rocks, and underlying soil media.

In this article, a method is proposed to identify volume scatterings from lunar soil in PSR. The backscattering coefficients and decomposition parameters from Chandrayaan-2 pol-SAR data, such as entropy $H$, $\alpha$ angle, degree of polarization (i.e., $m$), and circular polarization ratio (CPR) are analyzed to study the scattering of lunar surfaces [9], [10]. Based on the rough surface model, high-order scattering is simulated by the bidirectional analytical ray-tracing (BART) code [11]. It shows the functional dependence of co-pol and cross-pol upon the incident angle and surface roughness.

As an example, a flat region in Mare Serenitatis and a PSR in the crater ($85.9^\circ$N, $111.7^\circ$E) are classified. The optical image and radar image of the region in Mare Serenitatis are presented for comparison. The flat areas are classified with low-co-pol backscattering, where the local incidence angles are around $26^\circ$. It is found that a flat region with low co-pol and high cross-pol appears different from surrounding regions. This enhanced cross-pol is most likely to be contributed by inhomogeneous volumetric scatterers in the regolith layer. This unusual region shows its inhomogeneous soil layer and is special for further study.

The rest of this article is organized as follows. Section II introduces the pol-SAR datasets. Section III analyzes the SAR images of lunar rough surfaces. Section IV gives numerical simulation of...
the BART in comparison with the SAR data. Section V presents the recognition of flat areas that display clustered volumetric scattering, which are different from surrounding areas and might deserve further study. Finally, Section VI concludes this article.

II. CHANDRAYAAN-2 SAR PRODUCTS

A. Chandrayaan-2 Full-Pol Dataset

The full-pol SAR onboard Chandrayaan-2 operates at L-band (1.25 GHz) and S-band (2.5 GHz) [1]. The radiometric calibration is performed using lab-characterized system parameters. In this article, full-pol data at L-band are used. The incidence angle of the radar wave is about 26°. The spatial resolution of the calibrated single-look complex (SLC) data is about 0.5 m/pixel in the azimuth and 9.6 m/pixel in the slant range. After performing multilook process (in the azimuth direction) in which the number of look is 20, the resolution becomes 10 m/pixel in the azimuth.

The average radar cross-sections per unit area, which is written as \( \sigma^0 \), of each polarization channel can be derived with Chandrayaan-2 SLC data. \( \sigma^0 \) is also referred to as the backscattering coefficient or radar reflectivity [12].

Cross-pol is mainly caused by high-order scattering. The ratio of cross-pol to co-pol backscattering coefficients is defined as

\[
R = \frac{2\sigma^0_{HV}}{\sigma^0_{HH} + \sigma^0_{VV}}
\]

where the subscript \( HV \), for instance, denotes the transmitting vertical-pol and receiving horizontal-pol.

In polarization decomposition, the parameters \( H \) and \( \alpha \) can indicate the scattering mechanism [10]. A large entropy \( H \) indicates more randomness from the media. The average scattering angle \( \alpha \) is helpful in identifying the scattering mechanism. Similar with \( H \), the degree of polarization (i.e., \( m \)) can indicate the randomness as well [9].

\( \text{CPR} \) can be derived with full-pol SAR. With the symmetry assumption of \( S_{HV} = S_{VH} \), \( \text{CPR} \) in full-pol can be rewritten as [8]

\[
\text{CPR} = \frac{4 |S_{HH} - S_{VV}|^2}{|S_{HH} + S_{VV}|^2} + \frac{4 \text{Im}(S_{HH} - S_{VV})S^*_{HV}}{|S_{HV} + S_{VV}|^2}
\]

where \( S_{pq} (p, q = H, V) \) represents the scattering component of the scattering matrix [13].

The scattering coefficients \( \sigma^0 \) can be derived with \( S \) as [12]

\[
\sigma^0_{pq} = 4\pi|S_{pq}|^2/A, p, q = H, V
\]

where \( A \) is the illuminated area of the radar wave.

B. Slope Correction

Due to the surface slope [14], the actual illuminated area of each pixel is different. The backscattering coefficients need to be corrected as [15]

\[
\sigma^0_{pq} = \sigma^m_{pq} \frac{\cos \theta_e}{\sin \theta_0}
\]

where \( \sigma^m_{pq} \) is the measured value, \( \theta_0 \) is the incidence angle on flat surface without slopes, \( \theta_0 \) is 26° in this case, and \( \theta_e \) is the angle between the tilted surface and the plane composed by slant and azimuth ranges.

III. POLARIZATION FEATURES OF LUNAR SURFACE

A. Full-Pol SAR Image of Flat Surface

Fig. 1(a) shows the optical image of a relatively flat surface near 85.40°N, 114.21°E in non-PSR. This region is called flat, because few rocks are visible in the optical image. The diameters of small craters at this region are less than 100 m.

Fig. 1(b) and (c) show \( \sigma^0_{HH} \) and \( \sigma^0_{HV} \) from the Chandrayaan-2 observation, respectively. The length of this region is 400 m and the width is about 550 m. Fig. 1(d) shows the local incidence angles on each pixel, ranging from 24° to 28°. The local incidence angles are derived from the DEM data. The resolution of DEM data is 40 m/pixel [16]. Linear interpolation is used to produce the local incidence angle corresponding to the radar data. Fig. 1(e) shows the co-pol and cross-pol terms at different local incidence angles. The average \( \sigma^0_{HH} \) and \( \sigma^0_{HV} \) are about −18 and −26 dB, respectively.

Fig. 2(a)–(c) show the \( \text{CPR} \) decomposition. It shows that the flat surface with few rocks has low and medium \( H \). Meanwhile, \( \alpha \) angle is less than 40°.

Fig. 3(a) shows the co-pol ratio \( \sigma^0_{HH}/\sigma^0_{VV} \), and 72% of pixels are with \( \sigma^0_{HH}/\sigma^0_{VV} \) between 0.8 and 1.2. The average
Fig. 2. $H$–$\alpha$ decomposition of a flat region. (a) $H$. (b) $\alpha$. (c) $\alpha$ versus $H$.

Fig. 3. Polarized parameters of a flat region at 85.40°N, 114.21°E. (a) $\sigma_{HH}^0/\sigma_{VV}^0$. (b) Relative phase angles between $HH$ and $VV$ terms. (c) $R$.

$\sigma_{HH}^0/\sigma_{VV}^0$ is 0.99. This means that $\sigma_{HH}^0 \approx \sigma_{VV}^0$. The relative phase between $HH$ and $VV$ components is about 0° in Fig. 3(b), which can be explained by the geometric optics (GO) model.

Fig. 3(c) shows the ratio $R$, and 98% pixels are with $R < 1/3$. The cross-pol term of the flat surface is much lower than co-pol terms. $R$-values will be influenced by the resolution and the number of look as well. For comparison, the data in this article keep the same resolution and the number of look.

B. Rocky Surface in Radar Image

Fig. 4(a) shows the optical image of a rocky surface at 85.64°N, 115.26°E, where rocks are distributed in strip. Fig. 4(b) is the enlarged image of the circled region in Fig. 4(a), and (c) gives the local incidence angles. Since the size of these rocks is only about several meters, they cannot be identified in DEM images.

Discrete rocks on the surface enhance both co-pol and cross-pol scatterings, as shown in Fig. 4(d) and (e). It can be seen that most of co-pol $\sigma_{HH}^0$ is larger than $-18$dB. However, due to low proportion of high-order scattering, its $R$-values are less than 1/3, as shown in Fig. 4(f).

In addition, Fig. 4(g) and (h) show the $H$ and $\alpha$ images, respectively. In the circled region, $H$ is less than 0.6 and $\alpha$ is less than 40°.

The co-pol ratio $\sigma_{HH}^0/\sigma_{VV}^0$ of more than 50% pixels of this region in Fig. 4(i) is in the range of 0.8–1.2 with a mean value of 0.9. $\sigma_{HH}^0$ and $\sigma_{VV}^0$ are almost equal. Fig. 4(j) shows the relative phases between $HH$ and $VV$ are around 0°.

C. SAR Images of PSR Crater

Fig. 5(a) shows an optical image of the crater (85.9°N, 111.7°E), whose inner part is PSR [17]. The diameter is about 4 km. There is no instant solar illumination in the dark region in Fig. 5(a). The radar wave comes from the left-hand side to the right-hand side, as shown by a white arrow in Fig. 5(b).

Fig. 5(b)–(e) show $\sigma_{HH}^0$, $\sigma_{HV}^0$, $H$, and $\alpha$ of this crater, respectively. The local incidence angles vary with the local surface slopes, as shown in Fig. 5(f). They are reprojected according to the distance between each pixel and the satellite, corresponding to the parallax in radar images.

Some typical regions, indicated by A–E in Fig. 5(b), are especially selected for analysis of $\sigma_{HH}^0$, $\sigma_{HV}^0$, and $R$ against local incidence angles, as shown in Fig. 6(a)–(c).

The local incidence angles in the square A, which locates on the crater wall facing the radar, are less than 20°. The $\sigma_{HH}^0$ data in square A are the largest in Fig. 6(a). The entropy $H$ is smaller than 0.5 and the $\alpha$ angle is less than 40°. Single-order scattering
is dominant at small incidence angle, which results in small $R$ in Fig. 6(c).

In the square B at the flat bottom of the crater, the local incidence angles are around the principal 26°, $\sigma_{HH}^0$, $\sigma_{HV}^0$, and $R$ of the square B are small due to smooth surface. Both squares C and E locate on the rocky crater walls. $\sigma_{HH}^0$ and $\sigma_{HV}^0$ of squares C and E keep large. Square C is on the crater wall backwards to the incidence and the local incidence angles become large. This may make the $\sigma_{HH}^0$ and $\sigma_{HV}^0$ in square C lower than that in square E. The ratio $R$ is large in squares C and E. The large entropy $H$ values in Fig. 5(d) indicate high randomness in square C, which may be caused by roughness and large incidence angle.

In contrast, $\sigma_{HH}^0$ and $\sigma_{HV}^0$ in square D are smaller than that at region C in Fig. 6 even with small incidence angles. The ratio $R$ is small as well, implying a smooth surface at region D.

The entropy $H$, $\alpha$ angles, CPR, and $m$ in Fig. 5(d), (e), (i), and (j), respectively, vary correspondingly to $R$ in Fig. 5(g). The entropy $H$ is smaller than 0.5 and the $\alpha$ angle is less than 40° in square A. While in square C, $H$ is larger than 0.5 and $\alpha$ angles are in the range of 30°–60°.

The co-pol ratio of $\sigma_{HH}^0/\sigma_{VV}^0$ decreases at large angles of incidence in square C shown in Fig. 5(k). $\sigma_{HH}^0/\sigma_{VV}^0$ of the small perturbation model decreases with incidence angles as well [18], but the topography of lunar surface is more complex. The relative phase between $HH$ and $VV$ is about 0° out of the crater and in square A in Fig. 5(h). The amplitudes of relative phase become large at large incidence angles in square C.

IV. SIMULATED SCATTERING FROM ROUGH SURFACE

Fig. 7 shows the $\sigma_{HH}^0$, $\sigma_{VV}^0$, $\sigma_{HV}^0$, and the local incidence angle of a complete crater located at 85.51°N, 115.32°E. The depth of the crater is 175 m and the diameter is 1.6 km. Slopes in the crater are in the range of 0°–30°. Given that a slope is 20° in slope correction, the corrected backscattering coefficients decrease by 6 dB, if the slope faces the radar, and the backscattering coefficients will increase by 2 dB, if the slope faces away from the radar. $\sigma_{HH}^0$ is similar with $\sigma_{VV}^0$, except at the crater wall facing away from the radar with large angles of incidence.

Both co-pol and cross-pol scatterings are contributed by rough surface and inhomogeneous regolith scatterers in penetration depth. It is difficult to recognize which one, lunar surface or buried scatterers in regolith, plays the dominate role in scattering. Scatterings from lunar soil can be simulated with the vector radiative transfer (VRT) theory [19], [20], but VRT ignores the coherence of scattered waves. As a result, the effects of volume
scatterings from soil on relative phase, which is critical for some polarized parameters, are not considered.

To evaluate high-order co-pol and cross-pol scatterings of a parameterized surface model, the BART code [11] is applied to calculating single-, double-, and triple-bounce scatterings from rough surface. BART can calculate high-order scattering from electric-large object. Computational complexity is dependent on the number of facets. The frequency is set at 1.25 GHz, which is the same as Chandrayaan-2 data. Changes in relative phases by multiple scattering can be considered in BART, but the attenuation caused by the lunar soil layer and volume scatterings are not considered.

A Gaussian rough surface with root mean square height \( h = 1 \text{ m} \) and correlation length \( L = 2 \text{ m} \) is generated [21], and then divided into a number of small triangle meshes with the length of 0.5 m when projected on the horizontal plane, as shown in Fig. 8(a). The area of the Gaussian rough surface is 2500 m\(^2\) with a length of 50 m. A small perturbation of \( kh_1 = 0.3 \) and \( kL_1 = 3 \text{ m} \) is added on all meshes, where \( k \) is the wavenumber in vacuum.

Multiple scatterings between the meshes are counted with the ray-tracing method. Single-bounce scattering from each mesh is described with the physical optics (PO) approach. The multiple scattering includes one PO and several GO scatterings in the ray paths. Small-scale roughness is used in the PO approach [11]. The scattered fields from each ray are summed coherently. Backscattering coefficients are simulated where the azimuth angle is set at 90°, 89.9°, and 89.8°. Average backscattering coefficients under multilook are calculated.

It is found that the cross-pol is governed by high-order scatterings resulting from large-scale roughness \( h/L \). The roughness parameters in the simulation are selected to fit the data.

Fig. 8(b) and (c) show the simulated \( \sigma_{HH}^0 \) and \( \sigma_{HV}^0 \) at different incidence angles, in comparison with the Chandrayaan-2 data from Fig. 7. In simulation, the dielectric constant of the meshed surface is set at 4.5, which is higher than the dielectric constants of lunar soil and is lower than that of rocks [22].

In Fig. 8(b), the average \( \sigma_{HH}^0 \) data drops rapidly from 0.8 dB at 10° to −11.8 dB at 20°, and then slowly decreases to −14.7 dB at 47°. It also shows the simulated \( \sigma_{HH}^0 \) from single- and double-bounce scattering. Single-order scattering is dominant at small incidence angle. When the incidence angle increases, the importance of double-bounce scattering also increases.

Fig. 8(c) shows the cross-pol \( \sigma_{HV}^0 \). It can be seen that the average \( \sigma_{HV}^0 \) data drops from −16.8 dB at 10° to −22.2 dB at 26°, and then raises to −18.1 dB at 47°. Low \( \sigma_{HV}^0 \) data mainly locate at the flat bottom of the crater where the local incidence angles are about 26°. Data of high \( \sigma_{HV}^0 \) at large incidence angle are from the rocky areas, which are caused by high-order scatterings.

Fig. 8(d) shows the \( R \). The average \( R \) data increase with the incidence angles from about 0.04 at 10° to 0.40 at 47°. When the single-bounce surface scattering dominate, \( R \)-values are small. \( R < 1/3 \) will be taken as the typical value of the smooth surface scattering. The simulated \( R \) is different from the data, because the real situation of multiscale roughness is more complicated than the constructed Gaussian surface. Multiple scatterings from rocky surfaces and lunar soil may enhance \( R \).

V. VOLUME SCATTERING IN SPECIAL AREA OF PSR

As aforementioned discussion on data and simulation, we have found that the following conditions hold.

1) Since the principal incidence angle of SAR is 26°, if the local incidence angles of an area are limited around 26° (e.g., less than 36°), this area is seen as flat.

2) If there are few rocks in this flat area, its co-pol \( \sigma_{HH}^0 \) and \( \sigma_{HV}^0 \) are less than −18 dB.

3) If single-bounce surface scattering dominates, cross-pol is so weak that the ratio \( R \) is less than 1/3.

In other words, if the surface satisfies (1) and (2), but \( R > 1/3 \), it means that the enhanced cross-pol \( \sigma_{HV}^0 \) with weak co-pol terms is mainly contributed by high-order volumetric scattering from the regolith media. Total scattering is contributed by both the
rough surface and underlying regolith media. But, the enhanced $R$ indicates the volumetric scattering and the physical properties of the regolith might be different from the surrounding areas.

Fig. 9(a)–(c) show the optical image, $\sigma_{HH}^0$, and $R$ of a flat region at Mare Serenitatis at 23.704°N, 13.376°E. Small craters randomly distribute in this region. White pixels in Fig. 9(d) are with small co-pol $\sigma_{HH}^0, \sigma_{VV}^0 \leq -18$ dB and $R>1/3$. Some small craters are included in white circles shown in Fig. 9(a)–(c). Resolution of DEM data at low latitude is about 60 m/pixel, which is larger than the diameter of small craters shown in Fig. 9(a). There is almost no tilt for the surface shown in Fig. 9(a). The measured data are taken as the $\sigma^0$ without slope correction. Small craters change the local incidence angle. Radar echoes are strong at these small craters in Fig. 9(b), while $R$-values are small in Fig. 9(c). Some white pixels are included in red circles shown in Fig. 9(d), corresponding to flat regions with few craters in Fig. 9(a). Volume scatterings at these pixels are mainly from the lunar soil layer.

Then, this method is applied to PSR. From the data shown in Fig. 5, Fig. 10 classified such flat areas with small co-pol $\sigma_{HH}^0, \sigma_{VV}^0 \leq -18$ dB and $R>1/3$, where the local angles of incidence are within $26^\circ \pm 10^\circ$, as shown by the white pixels. The white pixels in the red box all locate at the bottom of the crater in PSR.

Fig. 11(a) shows the enlarged image of the red box in Fig. 10. Fig. 11(b) and (c) show the local incidence angle and $R$ in this area. It can be seen that about 90% of $R$-values are smaller than 1/3.

Fig. 12(a) shows the $R$ versus the local incidence angle of these white pixels. The incidence angles are around $26^\circ$. The $R$-values of two pixels shown in Fig. 12(a) reach 0.74 and 0.99, while other $R$-values are smaller than 0.6.

Fig. 12(b) shows the decomposition parameters $H$ and $\alpha$ of these white pixels. There is $H > 0.5$ and most of $\alpha$ angles are in the range of $35^\circ$–$50^\circ$, indicating scattering with high randomness. The volumetric scatterings from the regolith media within penetration depth may play a role. The large $R$-values imply that the regolith in this area is special in physical properties, which is different from the surrounding media.

Certainly, $\sigma_{HH}^0$ and $\sigma_{VV}^0$ are affected by the dielectric constant of the regolith and the distribution of small craters. The loss tangents of lunar surface are influenced by the ilmenite content [23]. The threshold of $\sigma_{HH}^0$ and $\sigma_{VV}^0$ at different geological units may need to be re-evaluated.
VI. CONCLUSION

Full-polarimetric SAR onboard Chandrayaan-2 acquired radar images from lunar PSRs and non-PSRS. The co-polar and cross-polar backscattering coefficients, decomposition parameters, e.g., $H$, $\alpha$, $m$, and CPR, and their functional dependences upon local incidence angle, rocks' distribution, multiscale roughness, etc., were studied to classify the lunar surface.

A numerical BART model was employed to calculate high-order co-polar and cross-polar scatterings from parameterized rough surface.

Full-polarimetric scatterings were contributed by both rough surface and underlying soil media. To detect the volume scatterings from lunar soil layer, full-polarimetric SAR data of lunar surface were analyzed.

It is found that if the lunar surface is flat and smooth without large rocks over surface, its co-polar $\sigma_{HH}^0$, $\sigma_{VV}^0$ is less than $-18$ dB. When surface scattering is dominant, its cross-polar $\sigma_{HV}^0$ is even much lower. It leads to $R < 1/3$.

However, if there is clustered flat areas with $R > 1/3$, the large $R$-values are most likely caused by volumetric scatterings from underlying regolith media, instead of the surface. Recognition of volumetric scatterings from the flat region can be of help in classifying the regions with different physical properties in PSR, which deserves further study to determine if there is water–ice.

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