Modeling Radar Scatter from Icy and Young Rough Lunar Craters

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Abstract

• For lunar orbital synthetic aperture radars, such as the Chandrayaan Mini-RF operating at S-band (13-cm) wavelength and the Lunar Reconnaissance Orbiter Mini-RF operating at S-band and X-band (3-cm) wavelengths, it is important to understand the radar backscattering characteristics of the icy and young, rough craters. Assuming a mixing model consisting of diffuse and quasi-specular scattering components, we have modeled the opposite-sense circular (OC) and same-sense circular (SC) backscattering characteristics. The specular component, consisting of only OC echoes, represents the echoes from the surface and subsurface layers that are oriented perpendicular to the radar’s line-of-sight. The diffuse component, consisting of both SC and OC echoes, represents the echoes associated with either rocks or ice. Also, diffuse echoes have backscatter that is proportional to the cosine of the incidence angle. We modeled how these two (specular and diffuse) radar scattering components could be modulated by factors such as surface roughness associated with young craters. We also modeled how ice radar scattering components could be modulated by a thin regolith covering, and/or by the situation where ice occupies small patches within a larger radar pixel.

• We tested this modeling by examining 4 nonpolar craters and 12 polar craters using LRO Mini-RF data. Results indicate that icy and young rough craters can be distinguished based upon their SC enhancements (Alpha) and OC enhancements (Gamma). In addition, we also examined the craters that have unusual circular polarization ratios (CPRs) that likely result from a double bounce mode of scattering. Blocky fresh craters, icy craters, and craters exhibiting double bounce scattering can be separated based on the values of Alpha, Gamma, the ratio of Alpha/Gamma and the weighted sum of Alpha and Gamma.
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• Rationale for Modeling and Mini-RF Overview
• Lunar Radar Scattering Mechanisms - Quasi-Specular and Diffuse Components
• Modeling Lunar Radar Backscatter Cross-sections Assuming Differences in Quasi-Specular and Diffuse Scattering Components
• Preliminary Comparison of Model with LRO Mini-RF Polar Data

References
• Modeling Radar Scattering from Icy Lunar Regoliths at 13-cm and 4-cm Wavelengths, Thompson, Ustinov, and Essam Heggy. JGR, Jan, 2011
• Initial Results for The North Pole of the Moon from Mini-SAR, Chandrayaan-1 Mission, Spudis et al. GRL, Vol. 37, 2010
Rationale for Modeling and Mini-RF Overview
If there is ice on the Moon like that at the poles of Mercury and Mars or like the Galilean satellites, then it would have echo enhancement of 10 or more and a Circular Polarization Ration (CPR) greater than unity.

This is not yet observed on the Moon.

Thus, can we generate models that predict how these otherwise strong signals are muted/masked by regolith?

From Ostro, 2002
Chandrayaan-1 and LRO were in polar orbits thus enabling the Mini-RF observations of polar regions.
Chandrayaan Mini-RF Overview

Mini-RF Objectives
- Discover and map near-polar putative water-ice deposits
- Characterize lunar surface, especially permanently shadowed areas

Radar parameters:
- S-band 13 cm wavelength / Angle of incidence (at the surface) = 39° ± 10°
- Resolution = 150 m / Looks = 16 (about the same as Magellan)

Radar Implementation
- Transmit right-circular polarization (RCP)
- Receive opposite (H and V) Linears and generate Circular Polarization Ratio (CPR = RCP/LCP) via Stokes Parameters (CPR = (S1 – S4) / (S1 + S4)),
- Expected Ice signature = High reflectivity, large CPR, and Stokes parameters

Imaging Strategies
- Strip maps on sequential orbits for 28 days converted to mosaics
- Swath width 18 km or more / Repeat left and right at both North and South Poles

Expected Results:
- Total reflectivity and CPR of both poles with imagery and/or scatterometry

Modeling Radar Scatter from Icy and Young Rough Lunar Craters
# Chandrayaan-1 and LRO Mini-RF Radar Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Chandrayaan-1</th>
<th>LRO S-Band</th>
<th>LRO X-Band</th>
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<td>2380 MHz</td>
<td>7140 MHz</td>
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<td>Wavelength</td>
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<td>12.6 cm</td>
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<td>7.5 and 75 m</td>
<td>7.5 and 75 m</td>
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<tr>
<td>Number of Looks</td>
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<td>8 and 16</td>
<td>8 and 16</td>
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<tr>
<td>Swath Width</td>
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<td>4 and 6 km</td>
<td>4 km</td>
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<tr>
<td>Angle of Incidence (Center-Beam)</td>
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<td>49°</td>
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<tr>
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<td>Antenna Beam-Width (Range)</td>
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**Chandrayaan-1** Mini-RF Operations – October’08 – August’09

**LRO** Mini-RF Operations July’09 – December’10

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Lunar Radar Scattering Mechanisms
Quasi-Specular and Diffuse Components

References


Lunar Radar Images at 70 cm

- Echoes are modulated by slope and roughness
- Mare-Terra differences are 2-to-4:1
- Strongest roughness deltas about 10:1
Lunar surface and regolith is a matrix of sand-like soil and rocks.
Schematic of Lunar Subsurface (Apollo 17 Preliminary Science Report)

Figure 7-28. – Block diagram depicting the reconstruction of regolith history in the vicinity of deep drill string (LM area). The front face is a radial section through Camelot Crater, the drill-stem site, and the LM site; the other faces parallel the standard lunar surface grid. (Vertical exaggeration is 200x.)

Subsurface crater ejecta layers provide specular scattering

Modeling Radar Scatter from Icy and Young Rough Lunar Craters
Lunar regolith is a layered mixture of sand-like soil and rocks.
Lunar regolith is a mixture of sand-like soil and rocks. Density differences will generate radar backscatter.
Average Lunar Radar Behavior

**OBSERVATIONS**

POLARIZED (OC) + DEPOLARIZED (SC)

**INFERRED SCATTERING MECHANISMS**

SPECULAR + DIFFUSE

- FROM SURFACE
- FROM SURFACE/ SUBSURFACE ROCKS
- FROM BURIED CRATER EJECTA LAYERS

- FROM SURFACE
- FROM SURFACE/ SUBSURFACE ROCKS

Modeling Radar Scatter from Icy and Young Rough Lunar Craters
Modeling Lunar Radar Backscatter Assuming Differences in Quasi-Specular and Diffuse Scattering Components

Reference
Modeling Radar Scattering from Icy Lunar Regoliths at 13-cm and 4-cm Wavelengths, Thompson, Ustinov, and Essam Heggy, JGR, Jan, 2011
### Modelling Lunar Radar Scattering
**Diffuse and Specular Components**

#### OBSERVATIONS

<table>
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<tr>
<th>OPPOSITE-SENSE</th>
<th>SAME-SENSE</th>
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#### INFERRED SCATTERING MECHANISMS

<table>
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<tr>
<th>SPECULAR</th>
<th>DIFFUSE (ROCKS)</th>
<th>OR</th>
<th>DIFFUSE (ICE)</th>
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<tr>
<td>FROM</td>
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<tr>
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<td></td>
<td>ICE</td>
</tr>
</tbody>
</table>

#### Note – Only Diffuse scattering contribute to SC (Same-Sense Circular) echoes

**Modeling Radar Scatter from Icy and Young Rough Lunar Craters**
Assumed Lunar Ice Conditions

Thick (>100\(\lambda\)) ice lens covered with thin regolith

Ice patches inside a radar pixel
North Pole Radar CPR Mosaic – Chandrayaan-1

From Spudis et al., Initial results for the north pole of the Moon from Mini-SAR, Chandrayaan-1 mission, *GRL*, 2010.
Examples of Blocky and Icy Craters

Fresh crater
Main L, 14 km diameter, 81.4° N, 22° E

From Spudis et al., Initial results for the north pole of the Moon from Mini-SAR, Chandrayaan-1 mission, *GRL*, 2010.

Modeling Radar Scatter from Icy and Young Rough Lunar Craters
Preliminary Comparison of Model with LRO Mini-RF Polar Data
Modeling Results – Icy Crater

Hermite-A - Icy Crater

- CPR Obs
- CPR Rough
- CPR Patches
- CPR Thin Regolith
Double Bounce – Anomalous Crater

Floor-wall image characteristic

Direct path (rim image)

Image location of floor-wall double-bounce backscatter

Floor-far-wall double bounce

~Extra range

Rim

Far-side exterior

Floor

Courtesy of Keith Raney, APL, 2011

Modeling Radar Scatter from Icy and Young Rough Lunar Craters
Modeling Results – Anomalous, Double Bounce Crater

![Graph showing modeling results for Shackleton Anomalous, Double Bounce](image)

Modeling Radar Scatter from Icy and Young Rough Lunar Craters
# Modeling Results – 16 Craters

## Fresh Non-Polar
- Giordano Bruno: $\alpha = 4.20$, $\gamma = 2.02$, $\text{Ratio} = 2.1$, $\text{Sum} = 2.27$ - Rough Surface
- Byrgius A: $\alpha = 2.36$, $\gamma = 1.97$, $\text{Ratio} = 1.2$, $\text{Sum} = 2.02$ - Rough Surface
- Euclides - New: $\alpha = 1.90$, $\gamma = 0.93$, $\text{Ratio} = 2.0$, $\text{Sum} = 1.04$ - Rough - Patches

## Fresh Polar
- Main L: $\alpha = 2.69$, $\gamma = 1.26$, $\text{Ratio} = 2.1$, $\text{Sum} = 1.43$ - Rough Surface
- Other Rozhdestvensky: $\alpha = 1.47$, $\gamma = 1.12$, $\text{Ratio} = 1.3$, $\text{Sum} = 1.16$ - Rough Surface

## Icy
- Floor of Peary 1: $\alpha = 1.10$, $\gamma = 0.65$, $\text{Ratio} = 1.7$, $\text{Sum} = 0.70$ - Thin Regolith
- Floor of Peary 2: $\alpha = 1.81$, $\gamma = 0.80$, $\text{Ratio} = 2.3$, $\text{Sum} = 0.92$ - Ice Patches
- Rozhdestvensky N: $\alpha = 1.31$, $\gamma = 0.79$, $\text{Ratio} = 1.7$, $\text{Sum} = 0.85$ - Ice Patches
- Floor of Hermite Cut 1: $\alpha = 1.30$, $\gamma = 0.60$, $\text{Ratio} = 2.2$, $\text{Sum} = 0.68$ - Thin Regolith
- Floor of Hermite Cut 2: $\alpha = 1.77$, $\gamma = 0.70$, $\text{Ratio} = 2.5$, $\text{Sum} = 0.82$ - Ice
- Hermite A: $\alpha = 1.75$, $\gamma = 0.49$, $\text{Ratio} = 3.6$, $\text{Sum} = 0.64$ - Thin Regolith
- Erlanger: $\alpha = 1.33$, $\gamma = 0.36$, $\text{Ratio} = 3.7$, $\text{Sum} = 0.47$ - Thin Regolith

## Anomalous / ? Double-Bounce?
- **Anomalous** $\alpha = 0.84$, $\gamma = 0.30$, $\text{Ratio} = 2.8$, $\text{Sum} = 0.36$ - YES >> All 3
- Rozhdestvensky - Floor: $\alpha = 0.65$, $\gamma = 0.39$, $\text{Ratio} = 1.7$, $\text{Sum} = 0.42$ - LIKELY >> All 3
- Other Rozhdestvensky - Floor: $\alpha = 0.88$, $\gamma = 0.42$, $\text{Ratio} = 2.1$, $\text{Sum} = 0.47$ - LIKELY >> All 3
- Shackleton: $\alpha = 0.78$, $\gamma = 0.50$, $\text{Ratio} = 1.6$, $\text{Sum} = 0.53$ - LIKELY >> All 3

### Anomalous Models
- No Specular - Diffuse = Ave Diffuse: $\alpha = 1.00$, $\gamma = 0.26$, $\text{Ratio} = 3.8$, $\text{Sum} = 0.35$
- SC Diffuse = 0.8 / OC Diffuse = 1.25: $\alpha = 0.80$, $\gamma = 0.33$, $\text{Ratio} = 2.4$, $\text{Sum} = 0.38$
- SC Diffuse = 0.8 / OC Diffuse = 1.5: $\alpha = 0.80$, $\gamma = 0.39$, $\text{Ratio} = 2.0$, $\text{Sum} = 0.44$
Modeling Results: Alpha vs. Gamma

Modeling Radar Scatter from Icy and Young Rough Lunar Craters
Modeling Results: Weighted Sum vs. Ratio

\[ \alpha = \text{SC Enhancement} \quad / \quad \gamma = \text{OC Enhancement} \]

Diagram showing the weighted sum \((0.12\alpha + 0.88\gamma)\) vs. the ratio \(\alpha/\gamma\) as a proxy for CPR.

Legend:
- Diamonds: Rough
- Red Squares: Icy
- Green Triangles: Anomalous
Rules of Engagement / Next Step

For Blocky Craters:
Alpha > 1.5; Gamma > 1.0 or 1.25
Ratio (Alpha/Gamma) > 1.25 or 1.5
Weighted Sum > 1.0 or 1.25

For Icy Craters:
Alpha > 1.0 or 1.25; 0.5 < Gamma < 1.0 or 1.25
Ratio (Alpha/Gamma) > 1.5
0.5 < Weighted Sum < 1.0

For Anomalous, Double Bounce Craters:
Alpha < 1.0; Gamma < 0.5
Ratio (Alpha/Gamma) > 1.5
Weighted Sum < 0.5

• Next Step: Produce North and South Polar mosaics using automated identification of Icy, Rough Fresh and Double Bounce classes of craters
Concluding Remarks

• We tested our model assuming diffuse and specular scattering components by examining 12 polar and 4 non-polar craters using LRO Mini-RF data for the Lunar North Polar Region

• Results indicate that there are separable classes of craters (Icy, Rough, and Double Bounce) based upon their SC enhancements ($\alpha$) and OC enhancements ($\gamma$), their ratio ($\alpha/\gamma$), and weighted sum. Use of these four variables together is a better discriminator than using CPR alone

• Next Step: Produce North and South Polar mosaics using automated identification of Icy, Rough Fresh and Double Bounce classes of craters
BACK-UP
CPR Roughness + Ice, SC Enhancement = 2
(Weak Enhancement)

Separates for Thin Regolith over Ice from Rough Surface

No Separation for Ice Patches from Rough Surfaces

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