Electromagnetic Models of Co-Polarization and Cross-Polarization in Radar Remote Sensing of Terrestrial Snow at X- and Ku-band for CoReH2O and SCLP applications

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Outline

• Background
• Active Forward Model for Dry Snow
  – Volume scattering: DMRT
    • Sticky Hard sphere and bi-continuous medium
    • NNM3D to calculate Phase Matrices in DMRT
  – Surface scattering
    • NMM3D
  – Sensitivity studies
• Comparisons with CLPX II data
• Summary
Background

- Two new satellite radar missions:
  - **CoReH2O**
    - Frequency: 9.6GHz/17GHz
    - Polarization: Co-/Cross-pol
  - **SCLP**
    - Frequency: To be decided
      - From 9.6GHz, 13GHz, 17GHz,
    - Polarization: Co-/Cross-pol

- Physical Model
  - to analyze the snow signature in the microwave frequency
Random Media - snow

Snow is a random media, a mixture of ice grains and air.

(A) Sticky Hard Sphere Model:
- Ice grains is modeled as spheres
- The spheres bond with each other to form snow structure ($\tau$)
  e.g. Fresh snow, depth hoar

(B) Bi-continuous Media:
Different structure setup by Bi-continuous model

The random morphology of bi-continuous structure can be modeled by superimposing

\[ N \] number of stochastic scattering wave

\[ A_n, \bar{k}_n, \delta_n \] are the random variables

\[ S(\vec{r}) = \frac{1}{\sqrt{N \langle A^2 \rangle}} \sum_{n=1}^{N} A_n \cos(\bar{k}_n \cdot \vec{r} + \delta_n) \]

\[ \Theta_{\alpha\beta}(S(\vec{r})) = \begin{cases} 1 & \text{for } \alpha < S(\vec{r}) < \beta \\ 0 & \text{otherwise} \end{cases} \]

\[ A_n = 1 \text{ normalized amplitude, } \delta_n \in [0, 2\pi] \text{ uniformly distributed} \]

\[ \bar{k}_n \text{ is a vector described by } (k, \theta, \phi) \]

\[ \theta, \phi \text{ are uniformly distributed in } [0, \pi] \& [0, 2\pi] \text{ media is statistically isotropic} \]

\[ k \text{ obeys the gamma distribution with shape and scale parameter } zp, kc \]

Case 1

\[ kc = 3000m^{-1} \]
\[ zp = 100 \]

Case 2

\[ kc = 1500m^{-1} \]
\[ zp = 10 \]

\[ fv = \left\langle \Theta_{\alpha\beta}(S(\vec{r})) \right\rangle = 30\%, \ \beta = \infty, \alpha = 0.371 \]
Hard-Sphere v.s. Bi-continuous model

• Hard Sphere Model:
  – Grain size is clearly defined.
  – The aggregation is formed through bonding

• Bi-continuous Model
  – More flexibility to model complex structure
  – The aggregation depends on the distribution function
Electromagnetic scattering model

Sticky Hard Sphere Model
- Analytical method: Quasi-crystalline Approximation
- Numerical Maxwell Method of 3D: Foldy-Lax Equations

Bi-continuous Media Model
- Numerical Maxwell Method of 3D: Discrete Dipole Approximation
Volume Scattering: 
Backscattering calculation through DMRT

\[ \theta = 35^\circ \]

Dense Media Radiative Transfer Equations

\[
\cos \theta \frac{d\bar{I}(z, \theta, \phi)}{dz} = -\kappa_e \cdot \bar{I}(z, \theta, \phi) + \kappa_d CT + \int_0^{2\pi} \int_0^{\pi} d\theta' d\phi' \sin \theta' \bar{P}(\theta, \phi; \theta', \phi') \bar{I}(z, \theta', \phi')
\]

Boundary Conditions

\[ z = 0 \]
\[ \bar{I}(\pi - \theta, \phi, z = 0) = r(\theta)\bar{I}(\theta, \phi, z = 0) + t(\theta_0)\bar{I}(\theta_0 \delta(\cos \theta_0 - \cos \theta_{inc}) \delta(\phi - \phi_{inc}) \]

\[ z = -d \]
\[ \bar{I}(\theta, \phi, z = -d) = r(\theta)\bar{I}(\pi - \theta, \phi, z = -d) \]
Phase Matrix Comparison between QCA and Bi-continuous Model

- **Discrete spheres: QCA**
  
  \( \text{dia} = 0.44 \text{mm} \)  
  \( \text{fv} = 20\% \)
  
  Computed extinction = 0.26 m\(^{-1}\)

- **Bicontinuous**
  
  \( \text{kc} = 3000 \text{m}\(^{-1}\) \)  
  \( \text{zp} = 100 \)
  
  \( \text{fv} = 20\% \)
  
  Computed extinction = 0.25 m\(^{-1}\)

With the similar co-pol phase matrix, the Bi-continuous model gives Non-zero cross-pol
Features of Bi-continuous Model

- Frequency dependence vary from 1.7~3.8
- Case 1/2 as boundary
- $\Delta$ is snow sample measurement from Hallikainen1987
- Co-Pol to Cross Pol Ratio vary from 8 To 20
Bicontinuous/DMRT: 1st order solution simulation

Due to the microstructure of the Bicontinuous media, the 1st order solution will give large cross-pol backscattering.
Cross-pol backscattering comparison between Hard-Sphere model and Bi-continuous model

grain size = 1mm, fractional volume = 30%, snow depth = 30cm.

With the similar setup, the Bicontinuous model give larger cross-pol backscattering due to the fine structure.

Case 1, fractional volume = 30%, snow depth = 30cm.
Without surface scattering, the snow depth sensitivities are around same in both frequencies.
Surface Scattering - Ground Roughness

• rough surface – Numerical Method (NMM3D)
  – Generate profiles of 3D random rough surface Use exponential correlation functions
  – Solve Maxwell Equations
    • Based on Method of Moment (MoM) solution of Maxwell Equations
    • Lookup table is used to corporate with volume scattering part
Total Backscattering

- Two contributions from rough ground surface
  - Direct surface scattering
  - Coherent reflectivities

\[ \sigma_t = DMRT(dia, swe, \rho, r_p) + \sigma_{\text{surface}} \exp(-\tau) \]
Snow depth sensitivities (X-band) with/without rough surface effect

With rough surface effect

Without rough surface effect

rms = 0.3cm, cl = 1.2cm, frozen ground with permittivity = 5

The rough surface scattering decrease the backscattering sensitivity to the snow depth
Snow depth sensitivities (Ku-band) with rough surface effect

With rough surface effect

Without rough surface effect

$rms = 0.3\text{cm}$, $cl = 1.2\text{cm}$, frozen ground with permittivity = 5

The rough surface scattering has less effect in Ku-band
At Snow Depth = 30cm

<table>
<thead>
<tr>
<th></th>
<th>Volume scattering</th>
<th>Surface scattering</th>
<th>Total scattering</th>
</tr>
</thead>
<tbody>
<tr>
<td>X band: vv</td>
<td>-16.9</td>
<td>-15.4</td>
<td>-13.1</td>
</tr>
<tr>
<td>X band: hh</td>
<td>-16.6</td>
<td>-17.0</td>
<td>-13.8</td>
</tr>
<tr>
<td>X band: hv</td>
<td>-27.7</td>
<td>-25.7</td>
<td>-23.6</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ku band: vv</td>
<td>-11.4</td>
<td>-13.8</td>
<td>-9.5</td>
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<tr>
<td>Ku band: hh</td>
<td>-11.2</td>
<td>-15.3</td>
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</tr>
<tr>
<td>Ku band: hv</td>
<td>-21.4</td>
<td>-22.4</td>
<td>-18.9</td>
</tr>
</tbody>
</table>

Case 1 snow sample, fv = 0.3 (snow density 276g/cm3)
rms = 0.3cm, cl = 1.2cm, frozen ground with permittivity = 5
CLPX II field campaigns on Feb 2008 at Kuparuk, AK

- Ku-band (13.95GHz): POLSCAT 100 m footprint
- X-band (9.6GHz): Terra-SAR 10 m resolution
- Ground measurement
Total 28 sites included
Measurement Dataset CLPXII

Discrete Data: Raw data directly from the sensor
Line: Liner smooth out

Key point:
1. Large cross-polarization is observed in both frequency
2. Low frequency dependence
3. Co-pol has larger sensitivity of snow depth than cross-pol
4. X-band has larger cross-pol than Ku-band
Comparisons with the simulation Bi-continuous/DMRT with rough surface

Ku-band: both co-pol and cross-pol could match the measurement data very well
X-band: Co-pol could match well. The cross-pol is underestimated
Surface scattering reduce the overall frequency dependence
Summary

• Comparisons: Sticky Hard sphere and Bi-continuous medium
• Bi-continuous model incorporated in DMRT to calculate backscattering
• Rough surface effect: Calculated by NMM3D; Roughness effect has larger impact in lower frequency.
• Comparison with the CLPX II datasets: using Bi-continuous/DMRT and Rough Surface NMM3D
Thank you!

Q & A