Physical Model based SWE Retrieval Algorithm Using X- and Ku- band Radar Backscatter

Jiyue Zhu, Shurun Tan, and Leung Tsang
Joshua King, and Chris Derksen
Juha Lemmetyinen

1 Radiation Laboratory, Department of Electrical Engineering and Computer Science, The University of Michigan, Ann Arbor, 48109-2122 MI USA
2 Climate Research Division, Environment and Climate Change Canada, Toronto, ON M3H 5T4, Canada
3 Arctic Research Centre, Finnish Meteorological Institute P.O.Box 503, Fin-00101 Helsinki Finland
Outlines

A. Background scattering subtraction

B. Forward model:
   i. Bicontinuous / DMRT model and regression training
   ii. Parameterized model: only 2 parameters $\omega_X$ and $\tau_X$

C. Physical model based SWE retrieval algorithm
   i. Radar retrieval algorithm
   ii. Classify backscatter w.r.t. $\omega_X$
   iii. SWE retrieval performance Using SnowSAR backscatter $\sigma_{VV}$ (9.6 GHz and 17.2GHz)
Radar backscattering: volume and surface scattering

\[ \sigma_{pq}^{\text{total}} = \sigma_{pq}^{\text{volume}} + \sigma_{pq}^{\text{surface}} \exp \left( -\frac{2\tau}{\cos \theta_t} \right) \]

- \( \sigma_{pq}^{\text{volume}} \): volume scattering from snowpack
- \( \sigma_{pq}^{\text{surface}} \): surface scattering from ground

Poster 20
Shurun Tan et al., “Assessment of Background Scattering at X- and Ku-band in Snow Remote Sensing”.
Background scattering subtraction in the SWE retrieval algorithm

\[
F = \min_{\omega_x, \tau_x} \left\{ w_1 \left( \sigma_{X, \text{obs}}^{X, \text{mod}} - \sigma_{X}^{X, \text{mod}} \left( \omega_x, \tau_x \right) \right)^2 + w_2 \left( \sigma_{Ku, \text{obs}}^{Ku, \text{mod}} - \sigma_{Ku}^{Ku, \text{mod}} \left( \omega_x, \tau_x \right) \right)^2 + w_3 \left( \omega_x - \bar{\omega}_x \right)^2 \right\}
\]

Forward model

Parameterized Bic/DMRT model

\[
\sigma_{X}^{X, \text{mod}} \left( \omega_x, \tau_x \right) = \ldots
\]

Radar observations

Snow on measurements

Snow free measurements / Surface scattering model

Extract volume scattering

Extract volume scattering

A priori information

- \( \bar{\omega}_x \)
SnowSAR (Canada TVC 2013) X- and Ku-band backscatter: raw data

- $\sigma_{VV}^X$: ranged from -18dB to -11dB
- $\sigma_{VV}^{Ku}$: ranged from -11dB to -6dB
Bic/DMRT LUT compare with Canada SnowSAR

- Model: volume scattering
- SnowSAR data: volume scattering + background scattering
Background scattering subtracted from raw data

- Volume scattering of SnowSAR within model predictions
- Shift data more in X band than Ku band
- Larger dynamic range in volume scattering
SWE retrieval algorithm flow chart

Forward model

Parameterized Bic/DMRT model

\[ \sigma_{VV}^{X,\text{mod}el}(\omega_X, \tau_X) \quad \sigma_{VV}^{Ku,\text{mod}el}(\omega_X, \tau_X) \]

Radar observations

Snow on measurements

Snow free measurements / Surface scattering model

Extract volume scattering

\[ \sigma_{VV}^{X,\text{obs}} \quad \sigma_{VV}^{Ku,\text{obs}} \]

\[ \sigma_{VV}^{X,\text{ground}} \quad \sigma_{VV}^{Ku,\text{ground}} \]

Retrieval algorithm

\[ F = \text{MIN}_{\omega_X, \tau_X} \left\{ w_1 \left( \sigma_{VV,\text{vol}}^{X,\text{obs}} - \sigma_{VV}^{X,\text{mod}el}(\omega_X, \tau_X) \right)^2 + w_2 \left( \sigma_{VV,\text{vol}}^{Ku,\text{obs}} - \sigma_{VV}^{Ku,\text{mod}el}(\omega_X, \tau_X) \right)^2 + w_3 \left( \omega_X - \bar{\omega}_X \right)^2 \right\} \]

A priori information

\[ \bar{\omega}_X \]

Estimated Variables

SWE

\[ \omega_X \]

Retrieved

\[ \omega_X, \tau_X \]
Computer Generated Snow: Bicontinuous Medium


Real snow cross section image

Computer-generated

Comparison through correlation function

Poster 7
Weihui Gu et al., “DMRT Models for Active and Passive Microwave Remote Sensing”
Snow homogeneous: Bicontinuous Dense Media Radiative Transfer (Bic/DMRT)

**coherent**

Solve Maxwell’s Eq. over a block of computer snow \((3\lambda - 5\lambda)\) with DDA:
get effective \(P, \kappa_e, \varepsilon_{\text{eff}}\)

**incoherent**

Substitute the effective parameters into & Solve RTE:
Backscatter: \(\sigma\)

Discrete Dipole Approximation (DDA)

\[
\overline{E}(\overline{r}_i) = \overline{E}_{\text{inc}}(\overline{r}_i) + \frac{k^2}{\varepsilon} \sum_{j=1}^{N} \overline{G}(\overline{r}_i, \overline{r}_j) \cdot \Delta V_j (\varepsilon_r(\overline{r}_j) - 1) \overline{E}(\overline{r}_j)
\]

Radiative Transfer Equation

\[
\frac{dI(\hat{s})}{ds} = -\kappa_e I(\hat{s}) + \int d\hat{s}' P(\hat{s}, \hat{s}') I(\hat{s}')
\]

\(P(\hat{s}, \hat{s}')\): phase matrix
\(\kappa_e\): extinction coefficient
\(I(\hat{s})\): Intensity in direction \(\hat{s}\)
Look-up table (LUT) of Bic/DMRT

### Parameters

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Minimum</th>
<th>Maximum</th>
<th>Interval</th>
</tr>
</thead>
<tbody>
<tr>
<td>Volume fraction $f_v$</td>
<td>10%</td>
<td>45%</td>
<td>5%</td>
</tr>
<tr>
<td>$b$ parameter</td>
<td>0.6</td>
<td>1.6</td>
<td>0.2</td>
</tr>
<tr>
<td>$\langle \zeta \rangle$ parameter (m$^{-1}$)</td>
<td>5000</td>
<td>15000</td>
<td>2000</td>
</tr>
<tr>
<td>Snow depth $d$ (m)</td>
<td>0.1</td>
<td>1.2</td>
<td>0.1</td>
</tr>
</tbody>
</table>

### LUTs

<table>
<thead>
<tr>
<th>SWE</th>
<th>$(\langle \zeta \rangle, b, \rho_{\text{snow}}, d)$</th>
<th>$(\sigma_{VV}^X, \sigma_{VV}^{KU})$ dB</th>
<th>$\omega_X$</th>
<th>$\tau_X$</th>
<th>...</th>
</tr>
</thead>
<tbody>
<tr>
<td>55.02</td>
<td>(9000, 1.2, 10%, 0.6)</td>
<td>(-15.3, -10.6)</td>
<td>0.6805</td>
<td>0.0166</td>
<td>...</td>
</tr>
<tr>
<td>64.19</td>
<td>(9000, 1.2, 10%, 0.7)</td>
<td>(-14.9, -10.1)</td>
<td>0.6805</td>
<td>0.0194</td>
<td>...</td>
</tr>
<tr>
<td>73.36</td>
<td>(9000, 1.2, 10%, 0.8)</td>
<td>(-14.6, -9.7)</td>
<td>0.6805</td>
<td>0.0221</td>
<td>...</td>
</tr>
<tr>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
</tbody>
</table>
Parameterization: scattering albedo \( \omega \) and optical thickness \( \tau \), retrieve \( \tau_a \)

\[ \kappa_s \text{: scattering coefficients} \]
\[ \kappa_a \text{: absorption coefficients} \]
\[ \kappa_e \text{: extinction coefficients} \]

\[ \kappa_e = \kappa_a + \kappa_s \]

\( \square \) Scattering albedo:

\[ \omega = \frac{K_s}{K_s + K_a} = \frac{K_s}{K_e} \]

\( \square \) Optical thickness:

\[ \tau = \kappa_e d \]

\( \square \) Absorption loss is proportional to SWE

\[ \tau_a = (1 - \omega) \tau = \kappa_a d \propto \text{SWE} \]

\( \square \) Two frequencies, four parameters: \( \omega_X, \tau_X; \omega_{\text{Ku}}, \tau_{\text{Ku}} \)
Parameterize Model
Regression Training
Look up table of Bic/DMRT outputs
Snow Parameter
       : snow density       : ...
Two unknowns and two equations:
\( \sigma_X, \sigma_X \) vs. \( \omega_X, \omega_X \)
\( \sigma_X, \sigma_X \) vs. \( \omega_X, \omega_X \)

Bicontinuous DMRT (Multiple scattering)

\( \nu \), related to the tail of correlation function
\( d \), related to snow grain size

\( \rho \), related to snow density

Two parameters

Two observations

Two parameters

Two observations

Regression training: reduce \( \omega_X, \omega_X, T_Ku, T_X \) to \( \omega_X, T_X \)
Regressions between $\tau_{Ku}$ and $\tau_X$, $\varpi_{Ku}$ and $\varpi_X$: based on LUT

**Curve fitting of $\tau$**

- $R^2 = 0.990$
- RMSE = 0.03
- Bias = 0.02

**Curve fitting of $\omega$**

- $R^2 = 0.987$
- RMSE = 0.02
- Bias = 0.01

Correlation between $(\tau_X, \tau_{Ku})$

Correlation between $(\omega_X, \omega_{Ku})$
Regression between single and multiple scattering

Backscatter for X band $\sigma_X \left( \sigma_X^{(1)}(\omega_X, \tau_X) \right)$

Backscatter for Ku band $\sigma_{Ku} \left( \sigma_{Ku}^{(1)}(\omega_{Ku}, \tau_{Ku}) \right)$

Curve fitting of X-band

- $R^2 = 0.963$
- RMSE = 1.05 dB
- Bias = 0.83 dB

Curve fitting of Ku-band

- $R^2 = 0.970$
- RMSE = 0.90 dB
- Bias = 0.72 dB
Validation of parameterized Bic/DMRT model: Canada SnowSAR

- **X band**
  - $R^2 = 0.954$
  - RMSE = 0.28 dB
  - Bias = -0.02 dB

- **Ku band**
  - $R^2 = 0.943$
  - RMSE = 0.24 dB
  - Bias = 0.04 dB

- Good agreement: achieve RSME < 0.28 dB
SWE retrieval algorithm flow chart

Forward model

Parameterized Bic/DMRT model

\[ \sigma_{VV}^{X,\text{mod}}(\omega_X, \tau_X) \quad \sigma_{VV}^{Ku,\text{mod}}(\omega_X, \tau_X) \]

Retrieval algorithm

\[ F = \min_{\omega_X, \tau_X} \left\{ \begin{align*} &w_1 \left( \sigma_{VV,\text{vol}}^{X,\text{obs}} - \sigma_{VV,\text{mod}}^{X,\text{model}}(\omega_X, \tau_X) \right)^2 \\ &+ w_2 \left( \sigma_{VV,\text{vol}}^{Ku,\text{obs}} - \sigma_{VV,\text{mod}}^{Ku,\text{model}}(\omega_X, \tau_X) \right)^2 \\ &+ w_3 \left( \omega_X - \bar{\omega}_X \right)^2 \end{align*} \right\} \]

A priori information

\[ \bar{\omega}_X \]
Radiation Laboratory

Classification: two classes of backscatter, Canada SnowSAR

- Background scattering subtraction & backscatter classification w.r.t. $\omega_X$
  enhances sensitivity of backscatter to SWE
- SWE doubles, Backscatter increases about 2-3dB

\[ \omega_X < 0.49 \]
\[ \omega_X > 0.49 \]
Radar datasets used

<table>
<thead>
<tr>
<th>Dataset</th>
<th>Location</th>
<th>Date</th>
<th>Frequency</th>
<th>Polarization</th>
</tr>
</thead>
<tbody>
<tr>
<td>Finland SnowSAR1</td>
<td>Sodankylä, Finland</td>
<td>Mar. 17th, 2011</td>
<td>X and Ku band</td>
<td>VV&amp;HV</td>
</tr>
<tr>
<td>Finland SnowSAR2</td>
<td>Sodankylä, Finland</td>
<td>December 19th, 2011 to March 24th, 2012</td>
<td>X and Ku band</td>
<td>VV&amp;HV</td>
</tr>
<tr>
<td>Canada SnowSAR</td>
<td>Trail Valley Creek (TVC), the Northwest Territories, Canada</td>
<td>winter 2012~2013</td>
<td>X and Ku band</td>
<td>VV&amp;HV</td>
</tr>
</tbody>
</table>
Performance of SWE retrieval algorithm: Canada SnowSAR

- Achieves RMSE = 26.98 mm, and $r = 0.7$
- For SWE < 200 mm, RMSE = 24.31 mm

SCLP requirement: RMSE < 20 mm for SWE < 200 mm and RMSE < 10% of total SWE for SWE > 200 mm
Performance of SWE retrieval algorithm: Finland SnowSAR1 and SnowSAR2

- Achieves RMSE = ~18 mm
- Achieves RMSE = ~24 mm

SnowSAR1
- SWE Retrieval Algorithm

SnowSAR2
- SWE Retrieval Algorithm

Correlation coefficients:
- r = 0.728
- RMSE = 17.62 mm
- Bias = 1.22 mm

r = 0.659
- RMSE = 24.23 mm
- Bias = -7.09 mm
Methods to improve the algorithm

Better background scattering subtraction

- Radar observation $\sigma_{obs}$ from snow free conditions
- Polarimetry: volume / surface scattering decomposition
- Combine active and passive measurements to retrieve both soil and snowpack parameters

Better a priori estimate of $\omega_X$ (or effective grain size)

- Solution 1: snow thermodynamics model with ancillary meteorological data
- Solution 2: combine active and passive microwave measurements
Summary

A. Background scattering subtraction:
   i. Affects more in X band than Ku band
   ii. Volume backscatter sensitive to SWE

B. Forward model: parameterized Bic/DMRT
   i. Regression training: 2 observations vs. 2 unknowns \((\omega_X \text{ and } \tau_X)\)
   ii. Validated against SnowSAR data

C. Retrieval algorithm: SWE \(\propto \tau_{a,X} = (1 - \omega_X)\tau_X\)
   i. A priori \(\omega_X\)
   ii. Classify backscatter w.r.t. \(\omega_X\) restores its high sensitivity to SWE
   iii. Performance: RMSE <30mm for SWE up to 300mm
Thanks for your attention!
Any question?