Optical and Microwave Modeling of Snow

Jiancheng Shi

2019 International Workshop on Radiative Transfer Models for Satellite Data Assimilation
29 April – 2 May, 2019, Tianjin, China
Outline

1. Introduction a forward Remote Sensing Model Platform

2. Progresses in Modeling Snow Properties from Optical to Microwave
Need for a Full Wavelength RS Modeling System

Trend in remote sensing

Scientific requirements: high accuracy and systematic spatial-temporal distribution of earth system variables ↔ full wavelength multi-source satellites jointly observations

To abandon the way of Separate research of optical, infrared and microwave RS

Lack of the understanding of multi-source jointly remote sensing

Full wavelength modeling capability

A full wavelength RS modeling system

Model capabilities: Visible, TIR, microwave; active and passive; polarization and interferometry ...

Various natural targets: soil, vegetation, snow, atmosphere and water body, ...

www.slrss.cn
An Open & Web based RS model platform

http://rsm.slrss.cn:85/Home/Index/

Simulation platform for remote sensing mechanism models

Atmospheric Remote Sensing model refers to the detection methods and technologies that the instruments do not directly contact with the atmosphere and then measure the ingredients, motion states and the meteorological elements' values in a distance. Both weather radars and weather satellites fit into the category of Atmospheric Remote Sensing.

The quantitative estimation of forest structure parameters is a main task of remote sensing. The estimation of forest structure parameters at high accuracy should be based on the full understanding of interactions between optical or microwave signals and forest stands which could be achieved by forward modeling of remote sensing data.

Snow cover is an important part on earth surface, 3/4 of the fresh water on earth exits in the form of snow and ice. In winter, 80% of the Eurasia and North America is covered by snow, and the average snow cover area of the hemisphere in January is about 46500000 km² and 3800000 km² in August. In high latitude area, snow is the main source of river and underground water.

Soil is one of the most important substance in the Earth system. It’s very important to precisely simulate emissivity of bare soil. Currently, ALEM is an important model to simulate soil emissivity. The three dielectric constant model Mironov, Dboson and Frozen Dielectric model provide the ability to simulate dielectric constant in different conditions.

Crops provides human food and the output of crops is directly related to food security. The early method is to use the vegetation index method or regression empirical relationship to do the remote sensing monitoring of crops. The advantage of these methods is that it is easy to get. The disadvantage is that the model is not global and the model can not adapt to other regions.

Vegetation growth model could simulate the vegetation growth by computer using the principles of vegetation physiological ecology as well as the environmental limitations. Therefore, vegetation growth model can provided detailed information needed by remote sensing models.
Have collected more than 50 models for different land covers from optical to microwave, 28 models (blue-colored) have already been service.
IEEE/GRSS *Modeling in Remote Sensing* Technical Committee

**TC Chairs:**
- Jiancheng Shi (RADI)
- John Kerekes (RIT)
- Joel T Johnson (OSU)

Currently: 98 Members

Contact: mirs_chairs@grss-ieee.org

- Addresses the technical space between basic electromagnetic theory and data collected by remote sensing instruments;
- Focuses on models and techniques used to take geometric, volumetric and material composition descriptions of a scene along with their EM (e.g., scattering, absorption, emission, optical BRDF, dielectric properties, etc.) attribute;
- Predict the resulting observation for a given remote sensing instrument.
MIRS TC proposes the joint support by IEEE/GRSS and the local Institutions to extend an existing model platform to form a "mirror" like platform, starting in 2020.

Existing Models Linked from Website

1. **PolSARPro**: The Polarimetric SAR Data Processing and Educational Tool aims to facilitate the accessibility and exploitation of multi-polarized SAR datasets.

2. **PROSAIL**: The combined PROSPECT leaf optical properties model and SAIL canopy bidirectional reflectance model.

3. The Open Web based Models from optical to Microwave for 7 different Earth categories
Outline

1. Introduction a forward Remote Sensing Model Platform

2. Progresses in Modeling Snow Properties from Optical to Microwave
Importance of snow

**Importance**

1）**Snow water equivalence:** great importance to snowmelt runoff forecast, water resources management and flood prediction. Snowmelt is an important factor of water cycle and the main source of freshwater in many areas.

2）**Snow cover area and SWE** are important elements of hydrology, meteorology and climate monitoring, and the key variables for energy and mass balance in water cycle model.

**Terrestrial Snow: Spatial-temporal distribution characteristics and its change characteristics**

**Key Science Questions**

1）What is the impact of snow on global and regional energy and mass balance and its response ?

2）In the background of global changing, what is the spatial-temporal distribution characteristics and its change characteristics of snowfall ?

3）what is the impact on global and regional water resources ?
Basic characteristics of RT

RT model

$$\cos \theta \frac{d \bar{I}(\theta, \varphi, z)}{dz} = -\kappa_e \cdot \bar{I}(\theta, \varphi, z) + \int_{-\pi/2}^{\pi/2} d\theta' \sin \theta' \int_0^{2\pi} d\varphi' \bar{P}(\theta, \varphi; \theta', \varphi') \times \bar{I}(\theta', \varphi', z)$$

**Scalar:** no polarization effect, **Vector:** polarization effect considered

1) scattering phase matrix, 2) scattering properties, 3) absorption properties

Optical RS

Modeling BRDF with different snow parameters (density, depth, grain size, temperature) under independent scattering

Microwave RS

Modeling of the backscattering and emissivity with different snow parameters and near-field consideration
Dielectric feature of water and ice

Optical: 0.3-2.5 μm

Real part

Imaginary part

Microwave

Water: real and imaginary part

Ice: imaginary part

Frequency in GHz

Dielectric constant of water and ice:

✓ optical: very close, very limited effect
✓ microwave: real part of ice = 3.18. Very sensitive to water, significant effect on microwave signal and its penetration capability
Effect of snow parameters:

- **optical**: independent scattering, single scattering albedo inversely related to grain size;
- **microwave**: Collective scattering (dense media effect), single scattering albedo positively related to grain size
Known problems

What is snow particle? An important parameter, but the microstructure of snow is complex, and the shape is irregular and grain size has a wide distribution.

Challenges: 1) What shape? 2) What is the relation of the effective grain sizes at optical and microwave?
Snow bi-continuous medium model

Spheres?

Bi-continuous medium?

\[ \text{Bicontinuous Structure} = f (\langle \zeta \rangle, b, f_v) \]

- mean grain size
- grain size distribution
- snow density

measured

simulated

www.slrss.cn 14
Stereology method for snow sections

- stereology: unbiased 3D information from 2d section images
- measured vs. derived variables

**TABLE 2.1**

*Relationship of measured (○) to calculated (□) quantities*

<table>
<thead>
<tr>
<th>Microstructural feature</th>
<th>Dimensions of symbols (arbitrarily expressed in terms of millimeters)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>mm(^0)</td>
</tr>
<tr>
<td>Points</td>
<td>(P_P)</td>
</tr>
<tr>
<td>Lines</td>
<td>(L_L)</td>
</tr>
<tr>
<td>Surfaces</td>
<td>(A_A)</td>
</tr>
<tr>
<td>Volumes</td>
<td>(V_V)</td>
</tr>
</tbody>
</table>

Underwood (1970)

1. Directly measure density, correlation lengths, and specific surface area;
2. \(D_g\) and \(\sigma_g\) are geometric mean and standard deviation of grain size. They can be measured from snow section images.

\[
D_g = \frac{\left(\frac{\bar{L}^2}{\bar{L}}\right)^4}{\bar{L}^2 \cdot \bar{L}^3 \cdot \sqrt{L} \cdot \bar{L}^3}
\]

\[
\log^2 \sigma_g = \log \left( \frac{\bar{L} \cdot \bar{L}^3}{\left(\bar{L}^2\right)^2} \right)
\]
Analytical optical grain size

**SSA and optical grain size**

\[
\text{specific surface area} = \frac{\text{SSA}}{V} = \frac{4\pi \left( \frac{D_e}{2} \right)^2}{\frac{4}{3} \pi \left( \frac{D_e}{2} \right)^3} \Rightarrow \text{Equivalent Sphere Diameter: } D_e = \frac{6f_v}{\text{SSA}}
\]

SSA - Specific Surface Area

**SSA calculation from correlation length**

Correlation function: \(A(x) = \frac{\langle \Theta(r_x) \Theta(r_z) \rangle - f_v^2}{f_v (1-f_v)}\)

Correlation length: \(L_e = \left( \frac{dA(x)}{dx} \right)_x = 0\)

Debye et al. (1957): \(\text{SSA} = \frac{4f_v (1-f_v)}{L_e}\)

**Correlation length of bi-continuous medium**

Correlation length: \(L_e = \frac{f_v (1-f_v) 2\pi \sqrt{3}}{\langle \zeta \rangle \sqrt{\frac{b+2}{b+1} e^{-2(\text{erf}^{-1}(1-2f_v))^2}}}\)

www.slrss.cn
Full wavelength bi-continuous snow model

- **Snow medium modeling**
- **Scattering properties**
  - Optical: ray-tracing
  - Microwave: Discrete dipole approximation (DDA)

**Vector radiative transfer model**

- Solve VRT by Eigen-value method, multiple scattering included (Tsang et al. 2007)
- Snow-Air and Snow-Soil interface scattering: AIEM model (Chen et al. 2003)
Comparison: sphere and bi-continuous

- QCA & bi-continuous phase matrix
  - QCA: cross-pol elements of phase matrix: 0
  - Bi-continuous: Nonzero
- Much stronger Co-pol and Cross-Pol relation and differs with frequency
- Much weaker near-field effect
Scattering Albedo vs. Effective Grain Size

Optical: larger grain size, smaller single scattering albedo
Microwave: larger grain size, larger single scattering albedo

The relationship between optical and microwave effective grain size can be derived from the full wavelength model simulations.
Validation (1) – Optical BRDF

New model

The BRDF measurement at Dome C Antarctic

FieldSpec spectrometer 350 to 2500 nm with 3- to 30-nm resolution

Hudson et al., 2006
The BRDF measurement at Dome C Antarctic FieldSpec spectrometer 350 to 2500 nm with 3- to 30-nm resolution

<table>
<thead>
<tr>
<th>Measured BRDF</th>
<th>Spherical model</th>
<th>New model</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image1.png" alt="Measured BRDF" /></td>
<td><img src="image2.png" alt="Spherical model" /></td>
<td><img src="image3.png" alt="New model" /></td>
</tr>
<tr>
<td><img src="image4.png" alt="Measured BRDF" /></td>
<td><img src="image5.png" alt="Spherical model" /></td>
<td><img src="image6.png" alt="New model" /></td>
</tr>
<tr>
<td><img src="image7.png" alt="Measured BRDF" /></td>
<td><img src="image8.png" alt="Spherical model" /></td>
<td><img src="image9.png" alt="New model" /></td>
</tr>
<tr>
<td><img src="image10.png" alt="Measured BRDF" /></td>
<td><img src="image11.png" alt="Spherical model" /></td>
<td><img src="image12.png" alt="New model" /></td>
</tr>
<tr>
<td><img src="image13.png" alt="Measured BRDF" /></td>
<td><img src="image14.png" alt="Spherical model" /></td>
<td><img src="image15.png" alt="New model" /></td>
</tr>
<tr>
<td><img src="image16.png" alt="Measured BRDF" /></td>
<td><img src="image17.png" alt="Spherical model" /></td>
<td><img src="image18.png" alt="New model" /></td>
</tr>
</tbody>
</table>

ARF: Measured Solar zenith angle: 52.6° Wavelength: 1500 nm
BRDF Validations (Optical)

Comparison of BRDF in principle plane and plane perpendicular to the principle plane

1800 nm

600 nm
Radiometer_1: 1.4, 6.925, 10.65 GHz (V/H)

Radiometer_2: 1.4, 18.7, 36.5 GHz (V/H)

GBSAR: X (7.5-12.5 GHz), Ku (11.5-16.5 GHz), Ka (15.5-20.0 GHz) (VV/HH/VH/HV)

EM-50 sensor: 3-layer soil T & moisture

Altay Reference Meteorological Station Field

Ground Instruments

Corner Reflecter

Validation (2) – Passive & Active Microwave

Snowpit Digging Field
Radiometer Calibration

• For C - Ku band

using a set of scan angles for sky tipping

\[ U = GP^\alpha \quad 0.9 \leq \alpha < 1 \]

\[ P(T_R) \equiv \frac{1}{\frac{hv}{e^{k_B T_R}} - 1} \]

\[
\begin{align*}
U1 &= G \left( P(T_{sys}) + P(T_C) \right)^\alpha \\
U2 &= G \left( P(T_{sys}) + P(T_C) + P(T_n) \right)^\alpha \\
U3 &= G \left( P(T_{sys}) + P(T_h) \right)^\alpha \\
U4 &= G \left( P(T_{sys}) + P(T_h) + P(T_n) \right)^\alpha
\end{align*}
\]

Four unknown parameters: G, \( \alpha \), Tsys, Tn

• For L band

using a single scanning point
GBSAR Calibration

- Ground based SAR polarimetric calibration procedure from:


  - two trihedral + one dihedral, carefully leveled and centered to antenna. Antennas are pointing vertically down.
  - Trihedral radar responses were measured at anechoic chamber.
  - Using time (range) gating to find the radar response of trihedral or dihedral.
  - Background scattering is subtracted using background measurement.
TB measurements at V-pol.

Radiometer Brightness Temperature ($\theta=55^0$)

- Increases with increased frequency (wet soil effect)
- Melting events
- 36.5 decreases (snow effect)
• Sensitivities of frequency dependence of snow volume backscattering to grain size and mass;
• Is the X-band backscattering time-series resulted from soil frozen process? Why there is no indication from passive measurements?
• Other possibilities?
Field Measurements

Before the snowfalls, cut dry grass and installed soil measurement instrument.

Snowpit Measurements:
- Snow Stratigraphy
- Snow Depth, SWE
- Snow Density & Snow Temp. per 5 cm
- Snow Grain size ($D_{\text{max}}$)

EM-50 Measurements:
- Soil Moisture & Temperature at -2, -5, -10 cm

Snowpit Digging Field

Installing EM50
**Model inputs:** $T_{\text{air}}$, Prep, Downward long & shortwave radiation, RH, Wind speed from Altay meteorological station
Comparison of Different Models

- Snow properties with the ground measurements are used;
- Three physical based microwave snow models are compared with both Active/Passive measurements:
  1. MEMLS;
  2. DMRT/QCA – Dense Media Vector Radiative Transfer Model
  3. VRT-Bic – Bicontinue Vector Radiative Transfer Model
Passive Brightness Temperatures

Model (1): MEMLS3&a with Improved Born Approximation

(Matzler&Wiesmann,1999; Proksch et al., 2005)

setting: grain diameter = 1.2 * [0.18 + 0.09*\log(D_{max})]
(1) Model Comparisons – MEMLS

Radar Backscattering Coefficients

\[
p_{\text{active}} = p_{\text{passive}} \times 1.4 \quad \text{(compensate for the backscattering enhancement)}
\]

\[
m = 0.1; \quad q = 0.05;
\]

smooth soil surface; 95% coherent component (compensate for empirical soil model error)

A adjustable parameter of “q” is used to parameterize the relationship between VH and VV.
(2) Model Comparisons – DMRT

Passive Brightness Temperatures

Multi-layer DMRT-QCA

Inputs: snow parameters from snowpits; grain diameter = 0.25*Dmax; stickiness = 0.1
Radar Backscattering Coefficients

Multi-layer DMRT-QCA, Oh rough surface scattering model

**Inputs:** snow parameters from snowpits; grain diameter = 0.25*Dmax; stickiness = 0.1

DMRT-QCA model significantly underestimated the VH backscattering
(3) Model Comparisons – VRT-Bic

Passive Brightness Temperatures

Multi-layer DMRT-Bic

Inputs: snow parameters from snowpits; Optical grain radius = Dmax/7; b = 1.2

Match passive signals for different pols and frequencies simultaneously!
(3) Model Comparisons – VRT-Bic

Radar Backscattering Coefficients

Models: multiple layer VRT-Bic, Oh rough surface scattering model
Inputs: snow parameters from snowpits; Optical grain radius = Dmax/7; b = 1.2

Bicontinuous model could generate much stronger VH backscattering
Match passive and active VV and VH signal *simultaneously*!
Need Coherent Model?
The geometrical equivalent grain size can be used as the bridge to describe the relation between the optical effective grains at the optical and microwave spectrum;

Evaluation of 3 most currently used microwave models (MEMLS, DMRT–QCA, and VRT–Bic), VRT–Bic has been confirmed as the best model. It can match all multi-frequency-pols measurements using one set of snow properties.

The coherent model is needed for low frequency (L-band).