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State Key Laboratory of Remote Sensing Science

Optical and Microwave Modeling of Snow

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2019 International Workshop on Radiative Transfer Models for Satellite Data Assimilation

29 April – 2 May, 2019, Tianjin, China

Outline

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1. Introduction a forward Remote Sensing Model Platform
2. Progresses in Modeling Snow Properties from Optical to Microwave

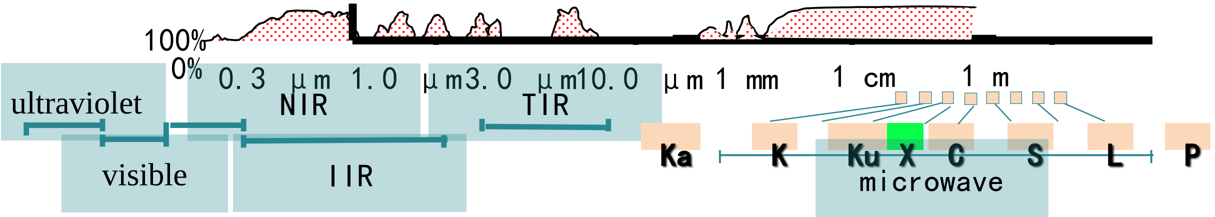
Need for a Full Wavelength RS Modeling System

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

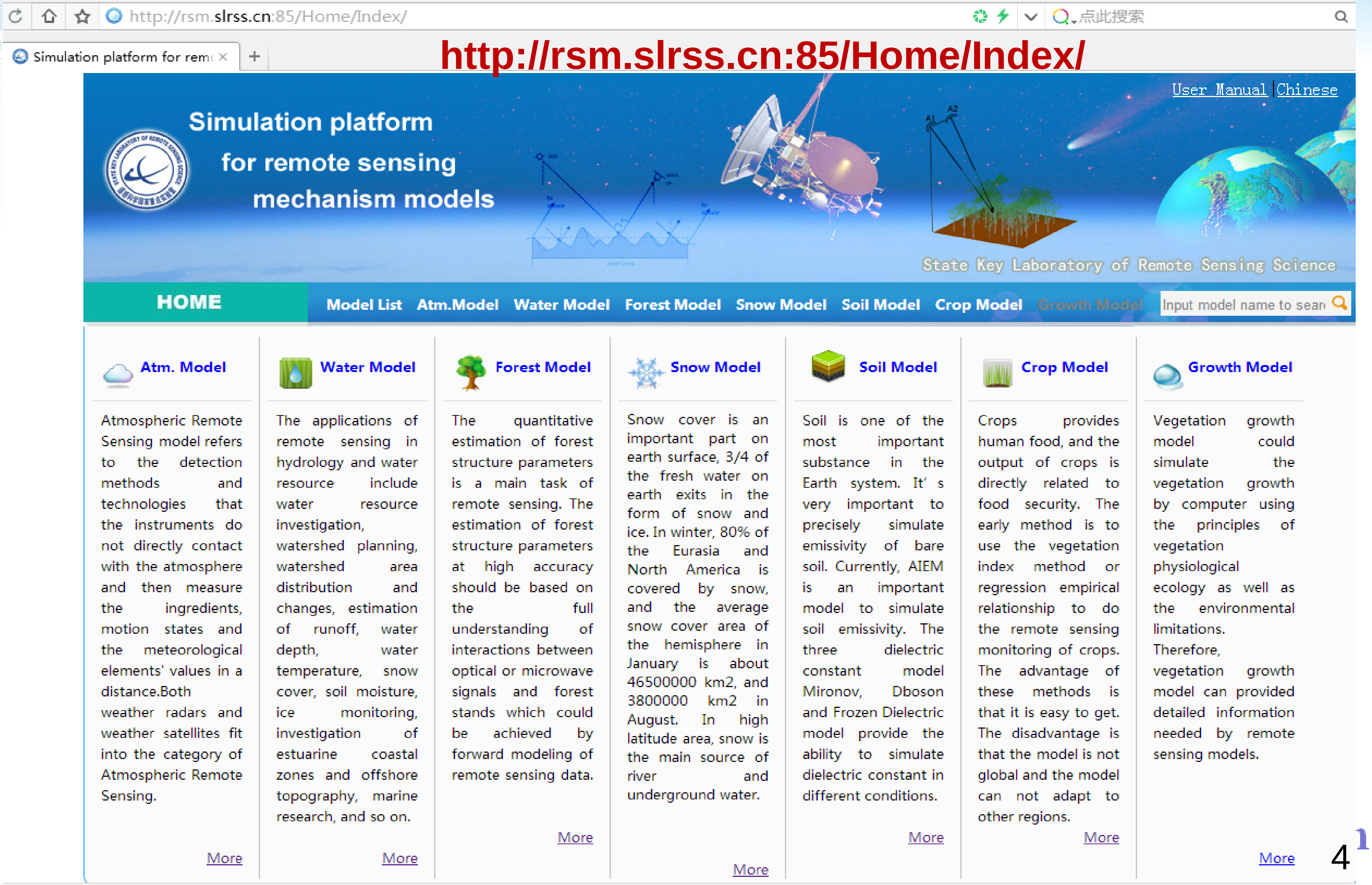
A full wavelength RS modeling system



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

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

An Open & Web based RS model platform



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

Atm. Model

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.

More

Water Model

The applications of remote sensing in hydrology and water resource include water resource investigation, watershed planning, watershed area distribution and changes, estimation of runoff, water depth, water temperature, snow cover, soil moisture, ice monitoring, investigation of estuarine coastal zones and offshore topography, marine research, and so on.

More

Forest Model

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.

More

Snow Model

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.

More

Soil Model

Soil is one of the most important substance in the Earth system. It' s very important to precisely simulate emissivity of bare soil. Currently, AIEM 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.

More

Crop Model

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.

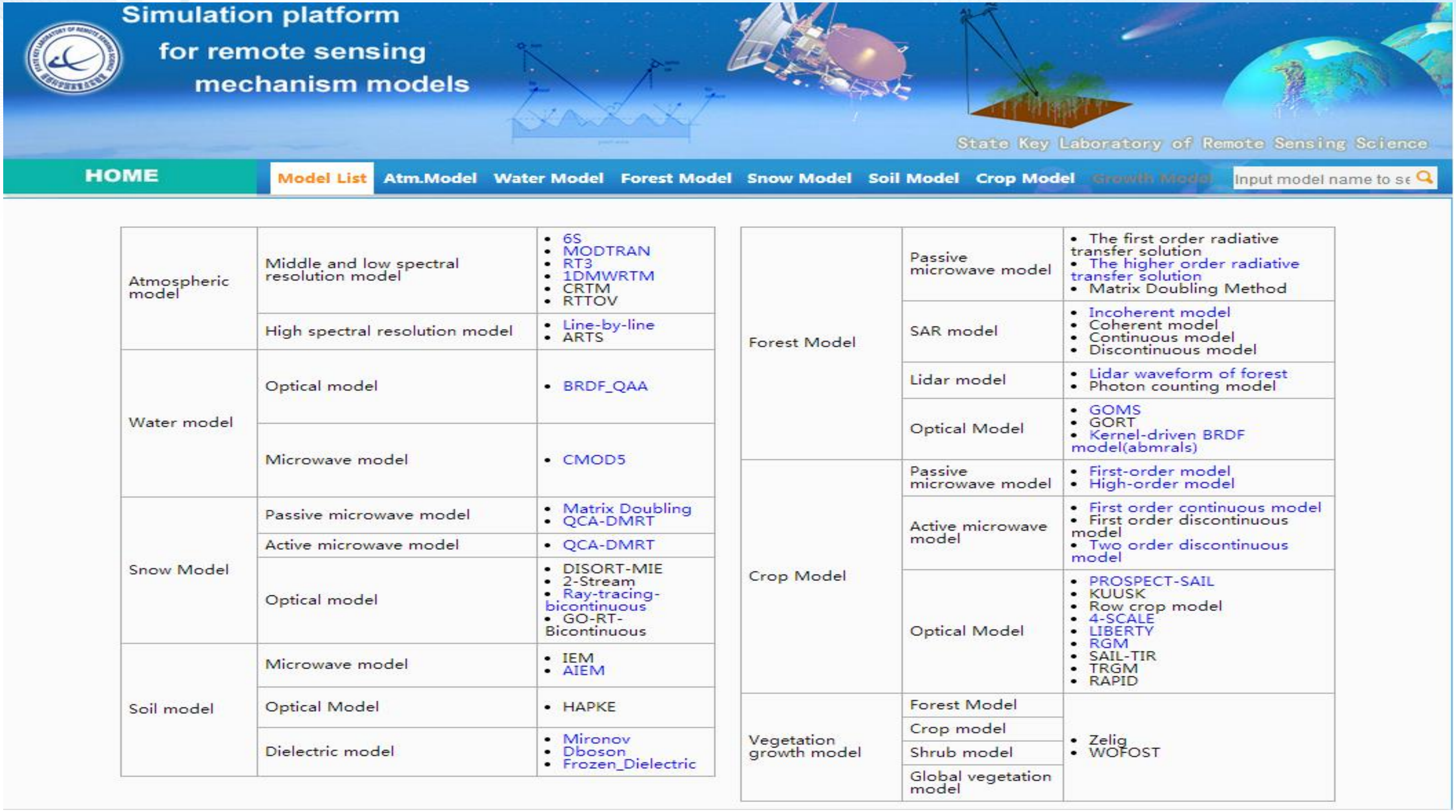
More

Growth Model

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.

More

Model List



Atmospheric model	Middle and low spectral resolution model	• 6S • MODTRAN • RT3 • 1DMWRTM • CRTM • RTTOV
	High spectral resolution model	• Line-by-line • ARTS
Water model	Optical model	• BRDF_QAA
	Microwave model	• CMOD5
Snow Model	Passive microwave model	• Matrix Doubling • QCA-DMRT
	Active microwave model	• QCA-DMRT
	Optical model	• DISORT-MIE • 2-Stream • Ray-tracing-bicontinuous • GO-RT-Bicontinuous
Soil model	Microwave model	• IEM • AIEM
	Optical Model	• HAPKE
	Dielectric model	• Mironov • Dboson • Frozen_Dielectric

Forest Model	Passive microwave model	• The first order radiative transfer solution • The higher order radiative transfer solution • Matrix Doubling Method
	SAR model	• Incoherent model • Coherent model • Continuous model • Discontinuous model
	Lidar model	• Lidar waveform of forest • Photon counting model
	Optical Model	• GOMS • GORT • Kernel-driven BRDF model(abmrals)
Crop Model	Passive microwave model	• First-order model • High-order model
	Active microwave model	• First order continuous model • First order discontinuous model • Two order discontinuous model
	Optical Model	• PROSPECT-SAIL • KUUSK • Row crop model • 4-SCALE • LIBERTY • RGM • SAIL-TIR • TRGM • RAPID
Vegetation growth model	Forest Model	• Zelig • WOFOST
	Crop model	
	Shrub model	
	Global vegetation model	

Have collected more than 50 models for different land covers from optical to microwave, 28 models (blue-colored) have already been service.

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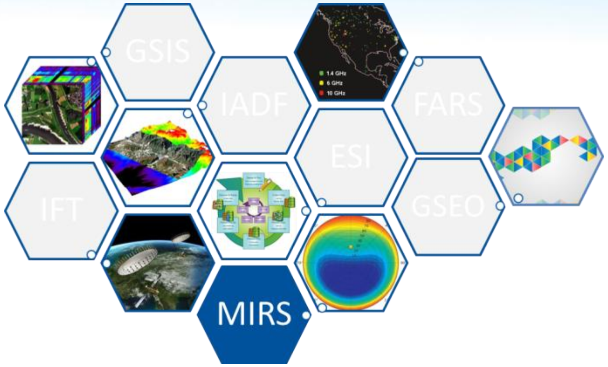
IEEE/GRSS *Modeling in Remote Sensing* Technical Committee

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.

An proposed solution for the open-web-based simulation platform

- ➢ 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

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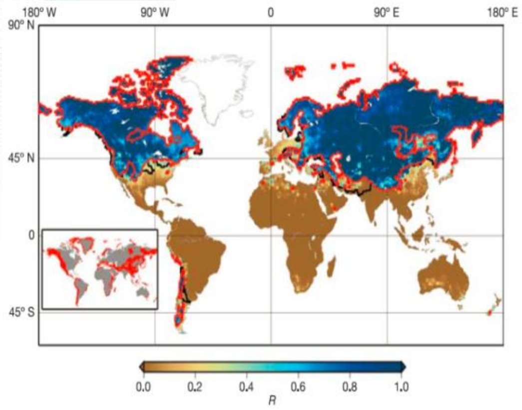
Importance of snow



Global snow melting runoff dominating area

Energy and mass balance computations

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

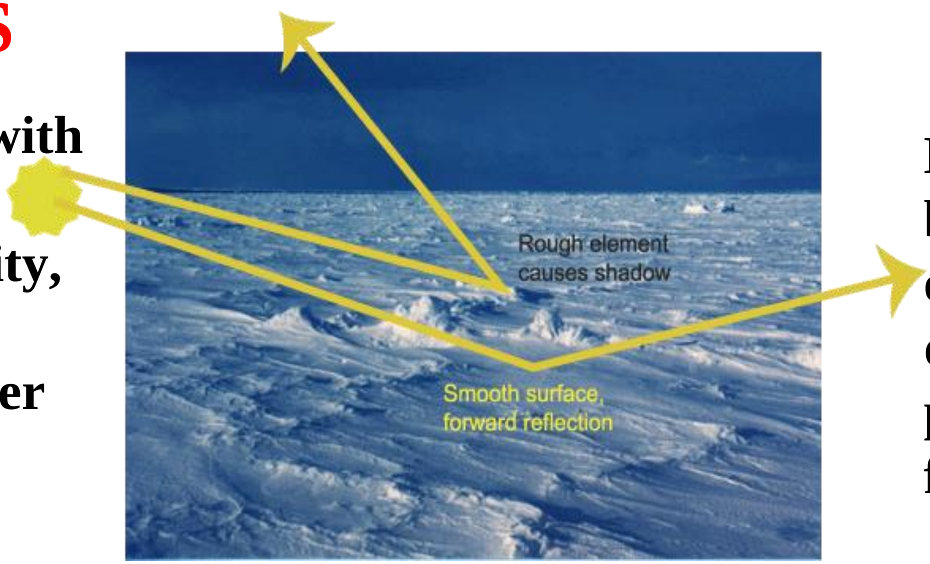
$$\cos\theta \frac{d\bar{I}(\theta,\varphi,z)}{dz} = -\kappa_e \cdot \bar{I}(\theta,\varphi,z) + \int_{-\pi/2}^{\pi/2} d\theta' \sin\theta' \int_0^{2\pi} d\varphi' \,\bar{\bar{P}}(\theta,\varphi;\theta',\varphi') \times \bar{I}(\theta',\varphi',z)$$

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

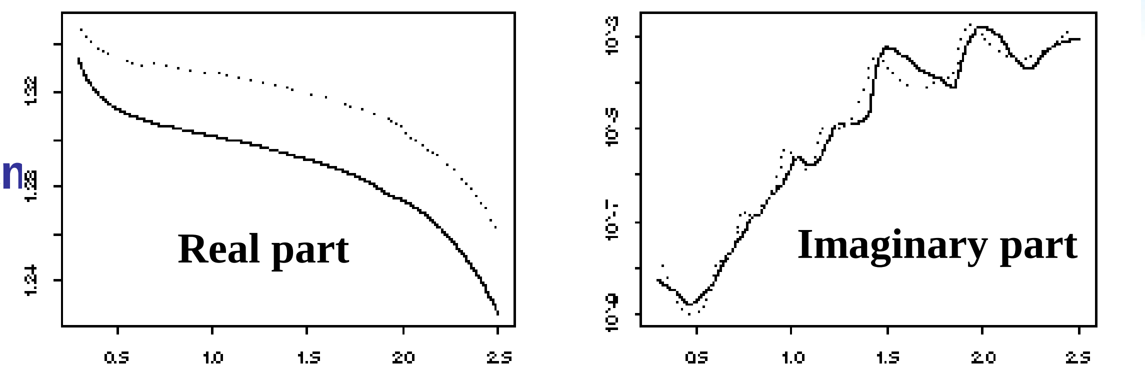


Microwave RS

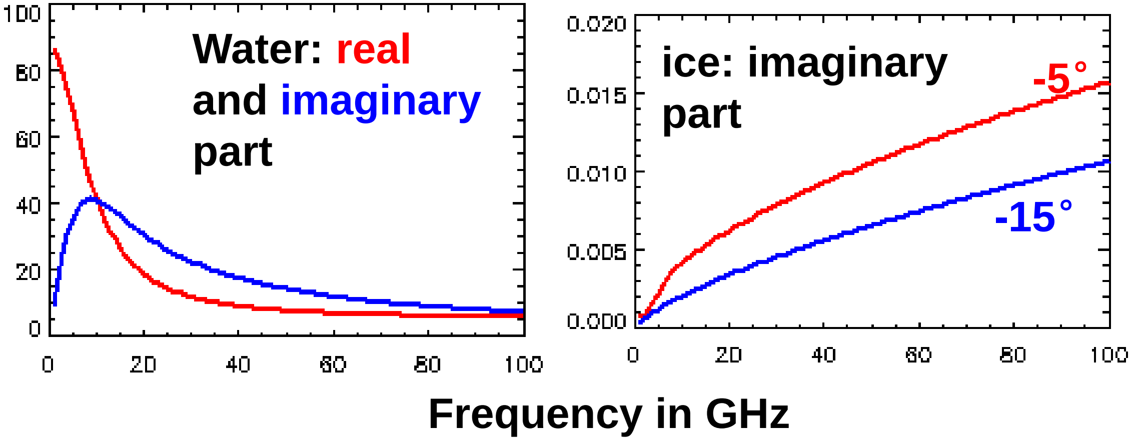
Modeling of the backscattering and emissivity with different snow parameters and near-field consideration

Dielectric feature of water and ice

optical 0.3-2.5 μm



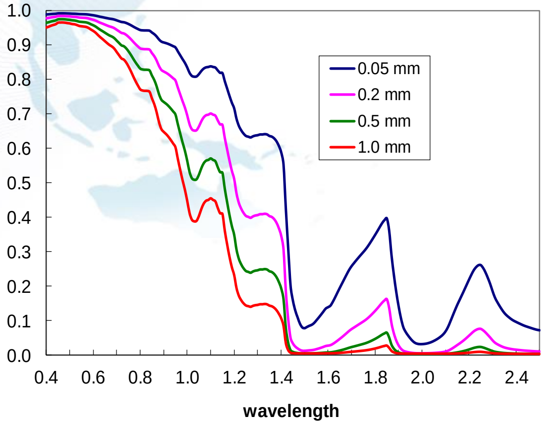
microwave

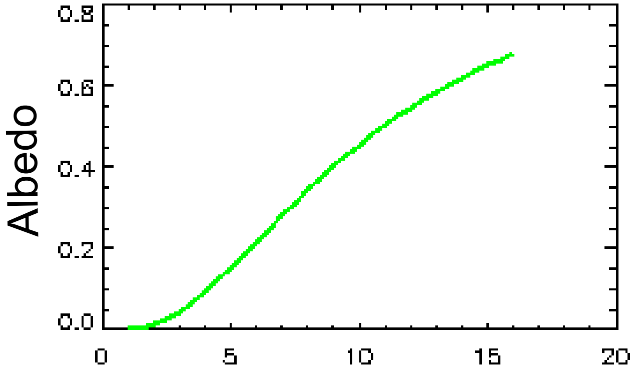


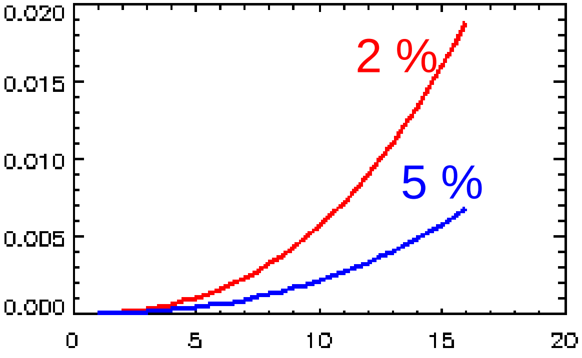
Dielectric constant of water and ice：

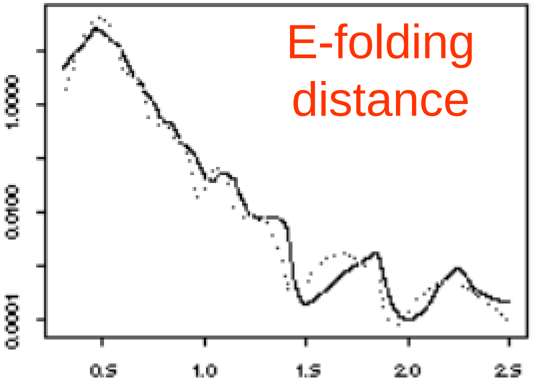
- ✓ **optical：** very close, very limited effect
- ✓ **microwave：** real part of ice **=3.18**. Very sensitive to water, significant effect on microwave signal and its penetration capability

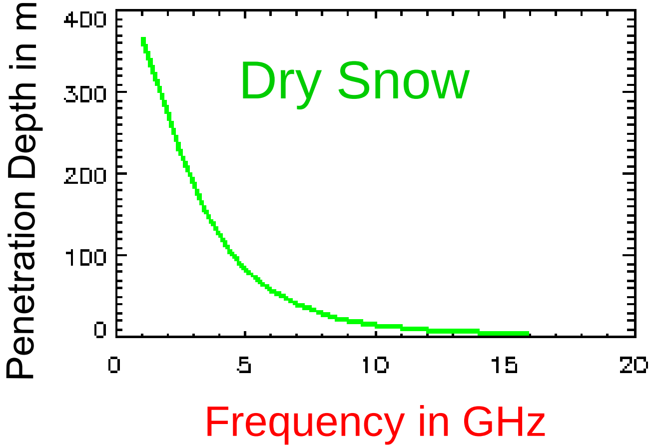
Snow: extinction feature

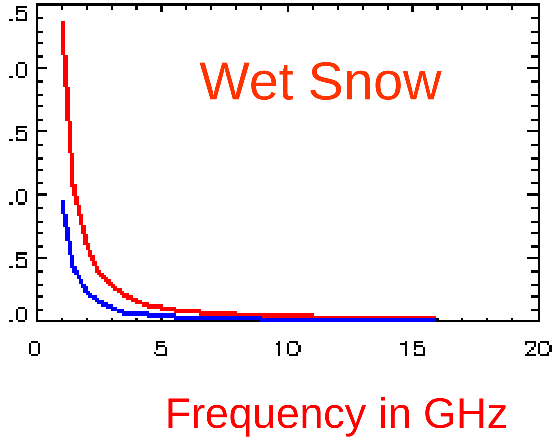










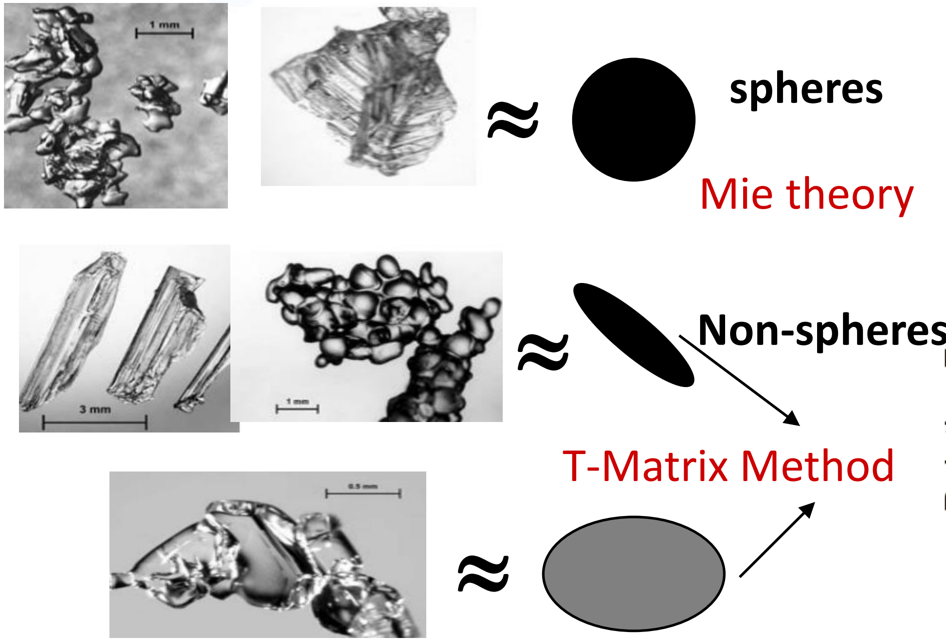


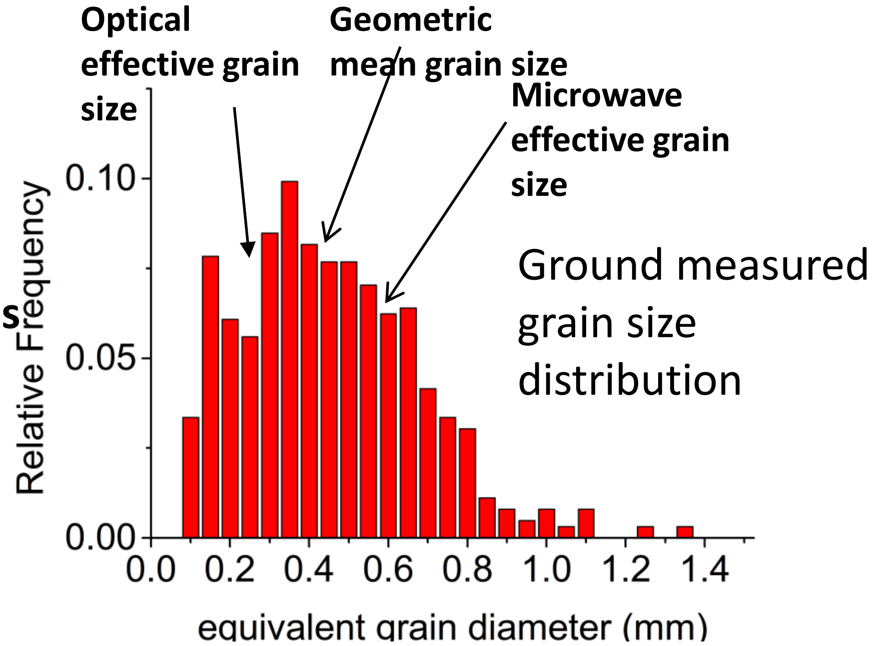
Effect of snow parameters:

- ✓ **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

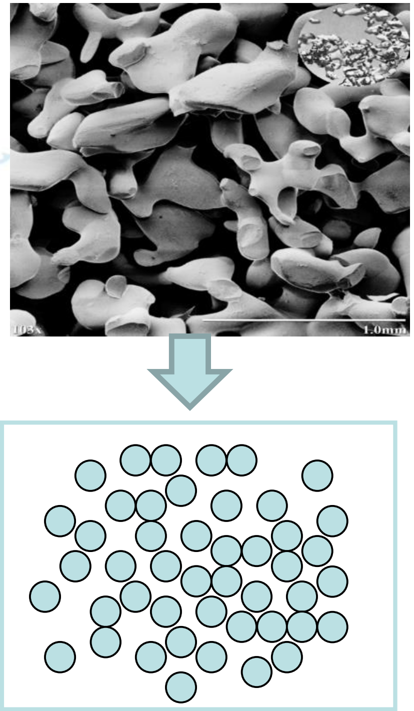




Chalenges：1) What shape？ 2) What is the relation of the effective grain sizes at optical and microwave?

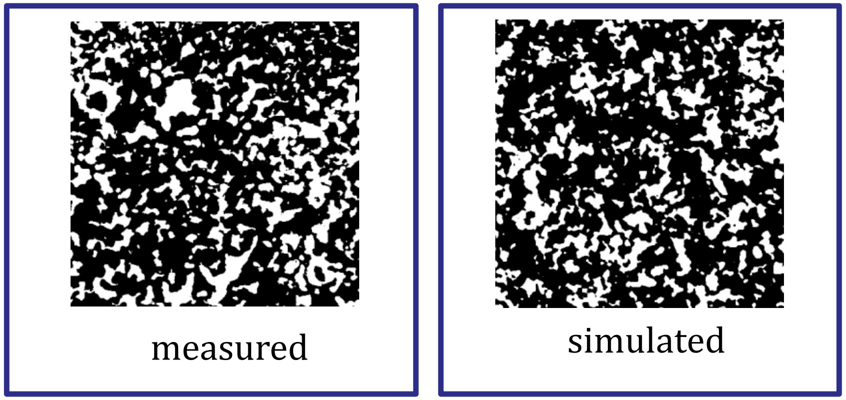
Snow bi-continuous medium model

Spheres?



Bi-continuous medium ?

$$Bicontinuous\_Structure = f\left(\langle\zeta\rangle, b, f_v\right)$$



measured

simulated

- mean grain size
- grain size distribution
- snow density

↔

$\langle\zeta\rangle$

b

f_v

Stereology method for snow sections

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

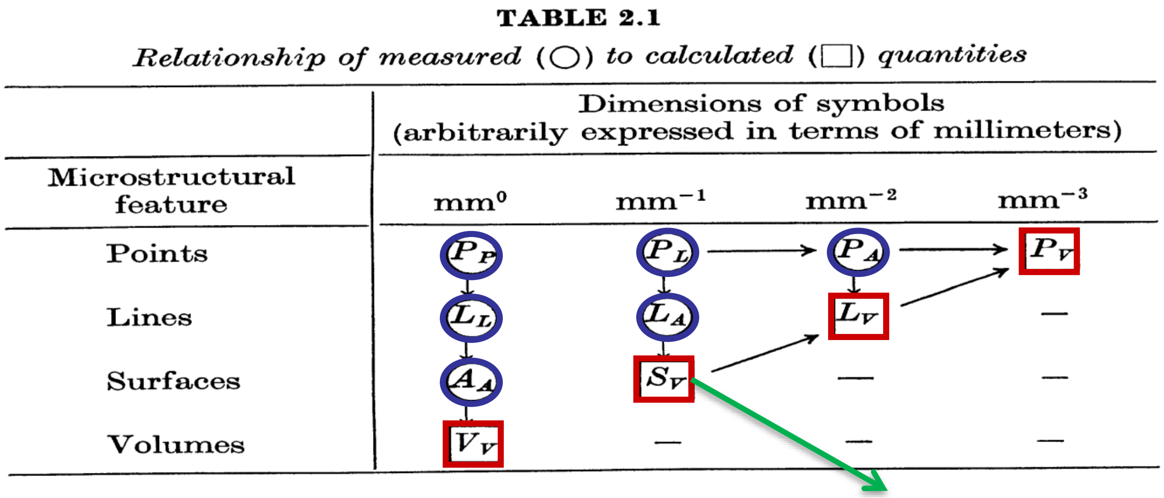


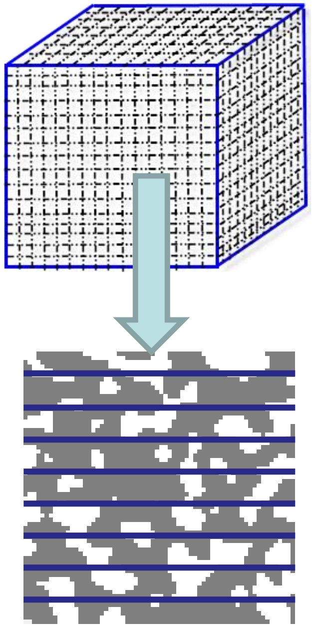
TABLE 2.1

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

Microstructural feature	Dimensions of symbols (arbitrarily expressed in terms of millimeters) mm⁰	 mm⁻¹	 mm⁻²	 mm⁻³
Points	P_P	P_L	P_A	$\boxed{P_V}$
Lines	L_L	L_A	$\boxed{L_V}$	—
Surfaces	A_A	$\boxed{S_V}$	—	—
Volumes	$\boxed{V_V}$	—	—	—

Underwood (1970)

Surface area per unit volume



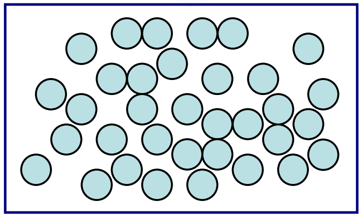
1. Directly measure density, correlation lengths, and specific surface area;
2. D_g and σ_g are geometric mean and standard deviation of grain size. They can be measured from snow section images.

$$D_g = \frac{\left(\overline{L^2}\right)^4}{\overline{L^2} \bullet \overline{L^3} \bullet \sqrt{\overline{L} \bullet \overline{L^3}}}$$

$$\log^2 \sigma_g = \log\left(\frac{\overline{L} \bullet \overline{L^3}}{\left(\overline{L^2}\right)^2}\right)$$

Analytical optical grain size

- **SSA and optical grain size**



$$\frac{\text{specific surface area}}{\text{volume of ice}}=\frac{SSA}{V}=\frac{4\pi\left(\frac{D_e}{2}\right)^2}{\frac{4}{3}\pi\left(\frac{D_e}{2}\right)^3}\Rightarrow \text{Equivalent Sphere Diemeter: } D_e=\frac{6f_v}{SSA}$$

SSA - Specific Surface Area

- **SSA calculation from correlation length**

$$\text{correlation function: } A(x)=\frac{\langle\Theta(r_1)\Theta(r_2)\rangle-f_v^{\;2}}{f_v(1-f_v)}\quad \text{correlation length: } L_c=-\left(\frac{dA(x)}{x}\right)^{-1}\Big|x=0$$

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

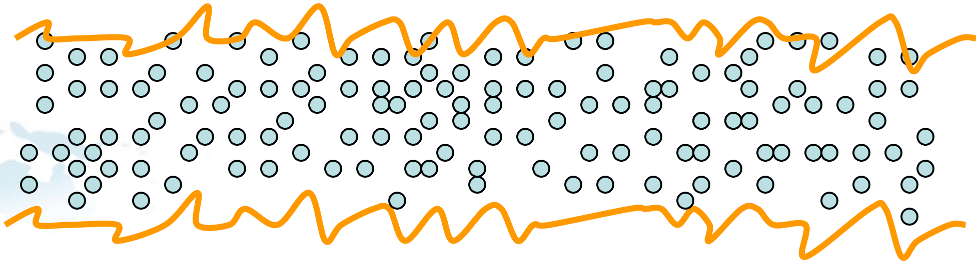
- **Correlation length of bi-continuous medium**

$$\text{correlation length: } L_c=\frac{f_v(1-f_v)2\pi\sqrt{3}}{\langle\zeta\rangle\sqrt{\frac{b+2}{b+1}}e^{-2\left(erf^{-1}(1-2f_v)\right)^2}}$$

Geometric Optical effective grain size

$$D_e=\frac{f_v3\pi\sqrt{3}}{\langle\zeta\rangle\sqrt{\frac{b+2}{b+1}}e^{-2\left(erf^{-1}(1-2f_v)\right)^2}}$$

Full wavelength bi-continuous snow model



snow medium modeling

optical： ray-tracing

Microwave: Discrete dipole approximation (DDA)

Scattering properties

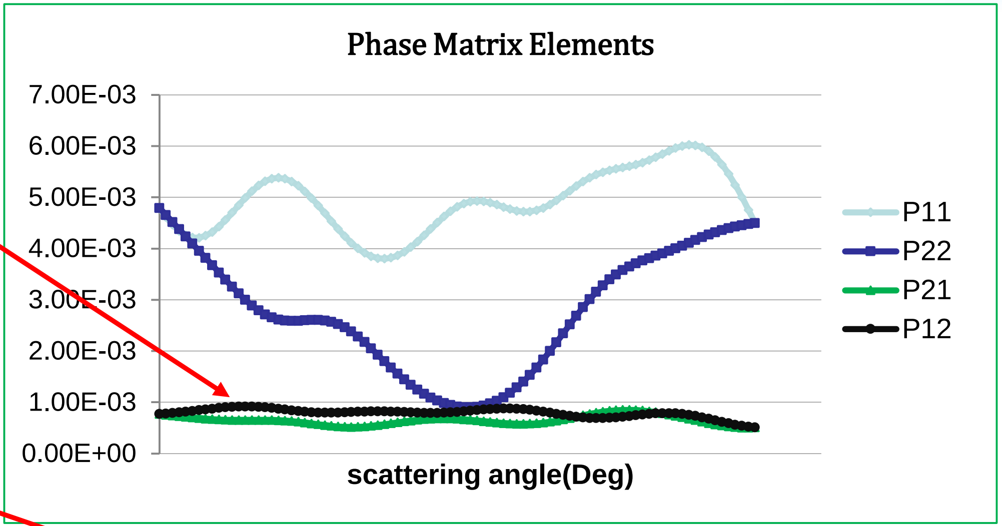
Vector radiative transfer model

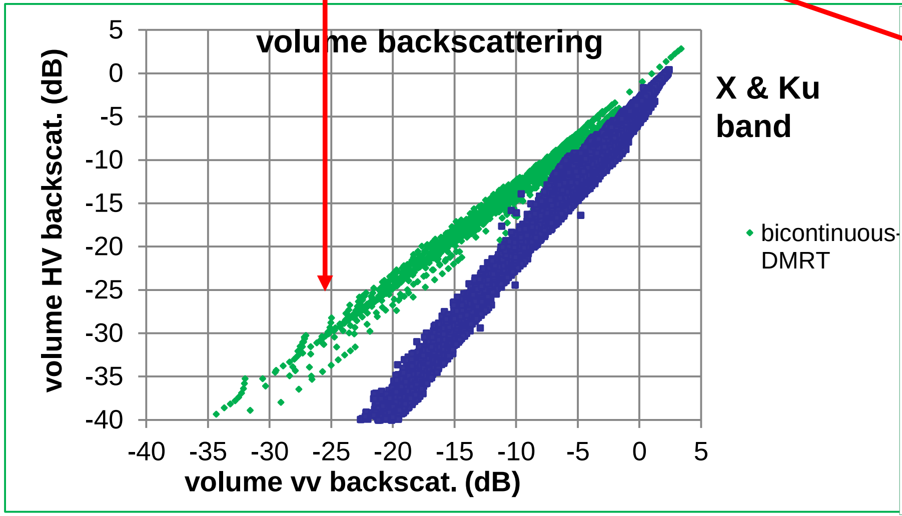
Solve VRT by Eigen-value method , multiple scattering included (Tsang et al. 2007)

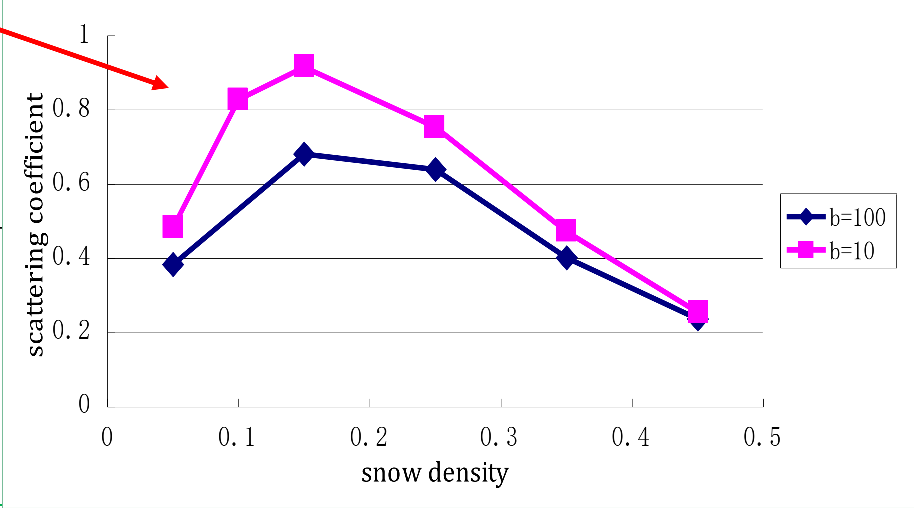
Snow-Air and Snow-Soil interface scattering : AIEM model (*Chen et al. (2003)*)

Comparison: sphere and bi-continuous

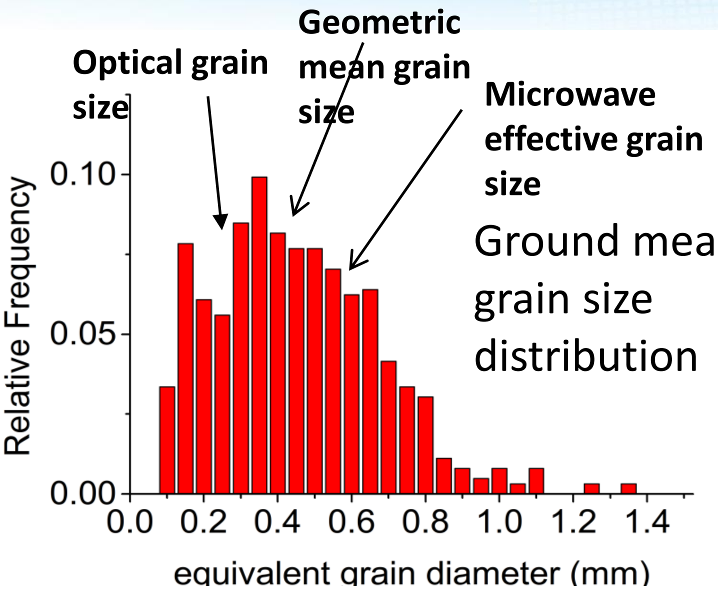
- QCA & bi-continuous phase matrix
  - QCA: cross-pol elements of phase matrix: 0
  - Bi-continuous: Nonzero
- Much stronger Co-pol and Cross-Pol relation and differs with frequency
- Much weaker near-field effect







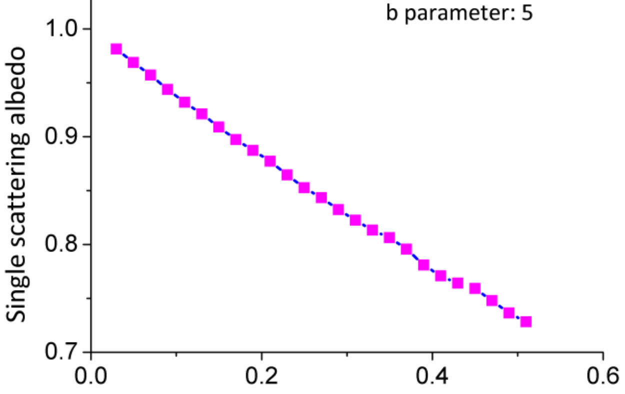
Scattering Albedo vs. Effective Grain Size

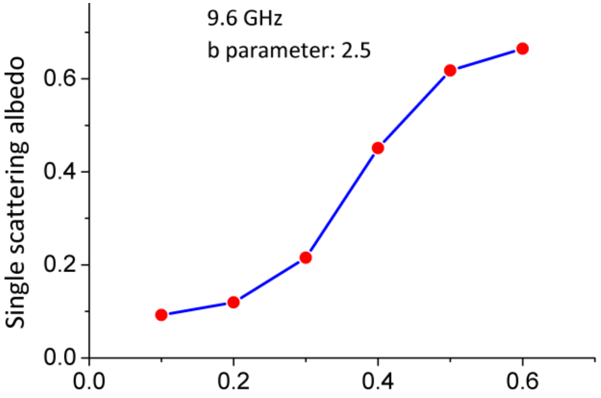


Ground measured grain size distribution

Optical： larger grain size, smaller single scattering albedo

Microwave: larger grain size, larger single scattering albedo





Geometric Effective grain size (mm)

The relationship between optical and microwave effective grain size can be derived from the full wavelength model simulations

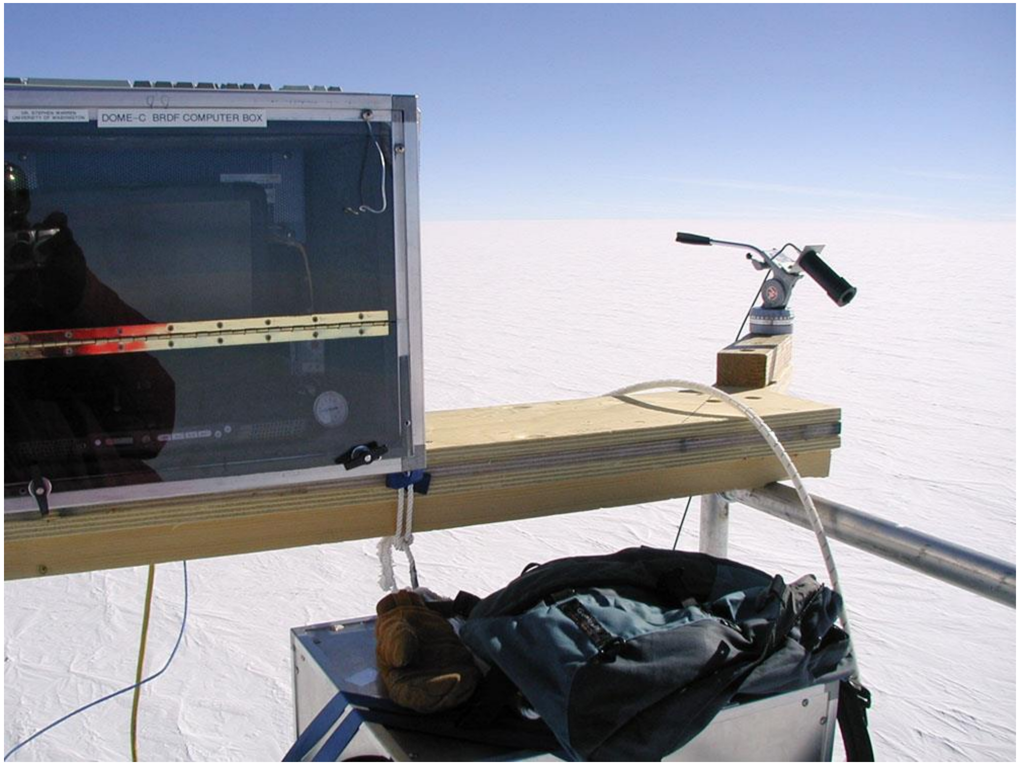
Validation (1) – Optical BRDF

New model

The BRDF measurement at Dome C Antarctic

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

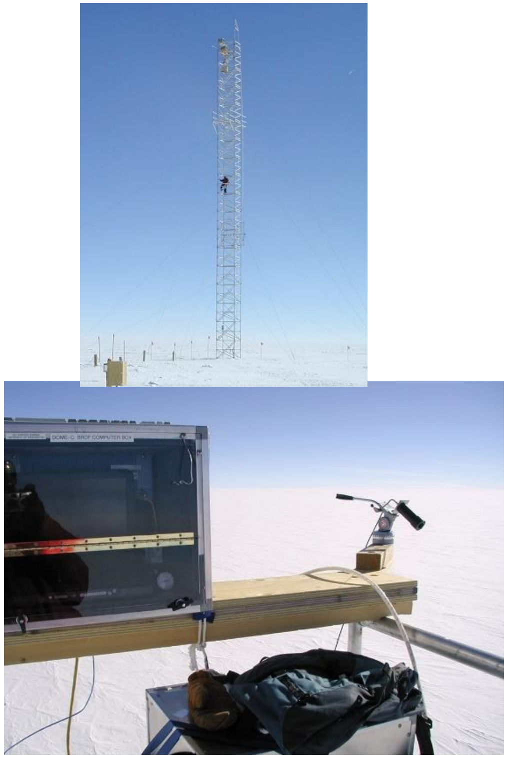
Hudson et al., 2006



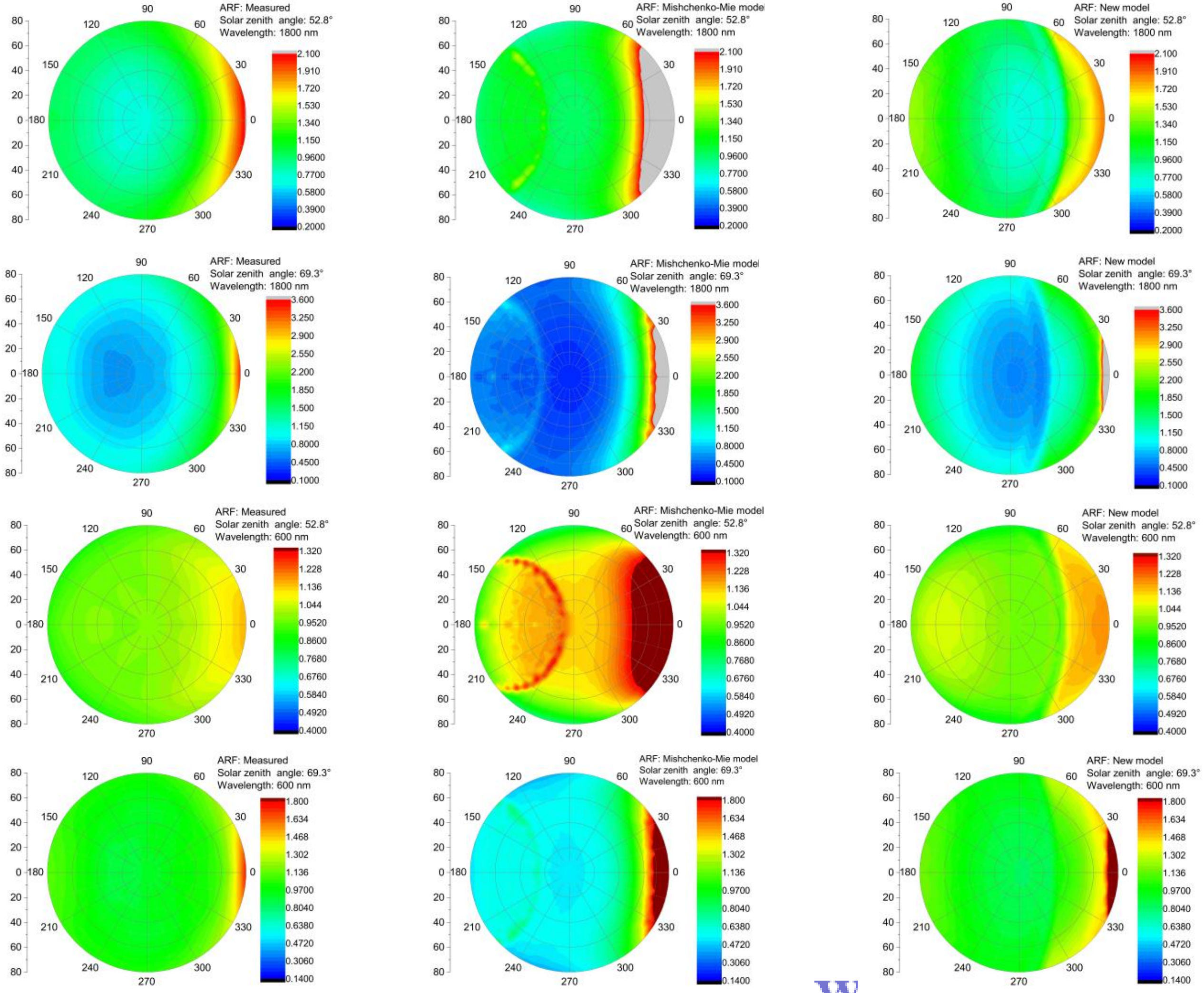
BRDF Validations (Optical)

The BRDF measurement at Dome C Antarctic

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



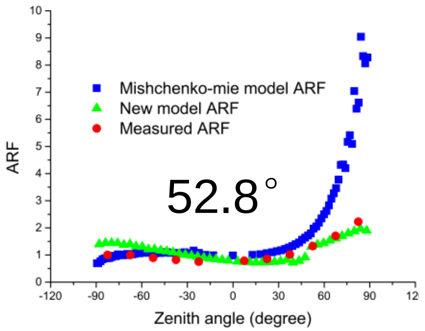
Measured BRDF **Spherical model** **New model**

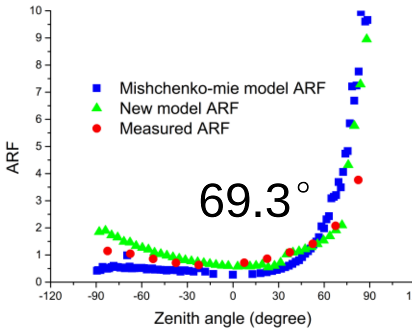


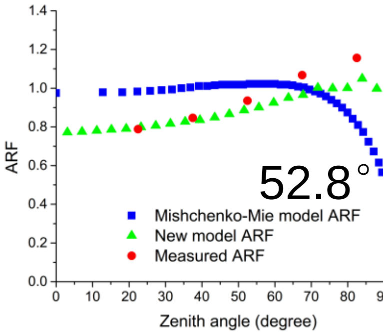
BRDF Validations (Optical)

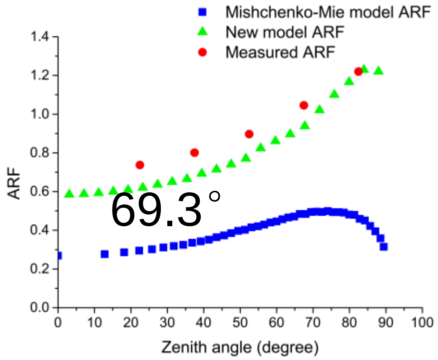
Comparison of BRDF in principle plane and plane perpendicular to the principle plane

1800 nm

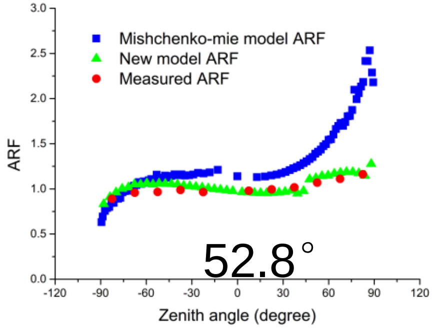


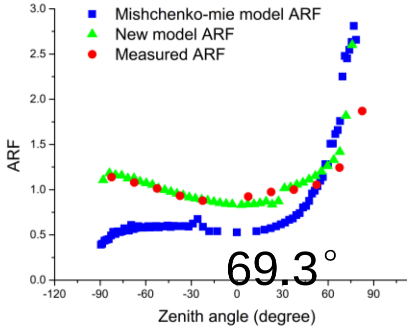


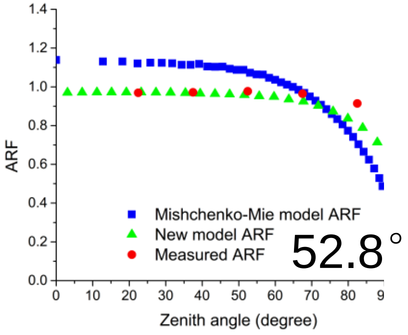


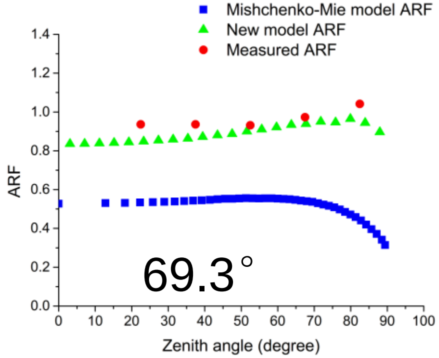


600 nm

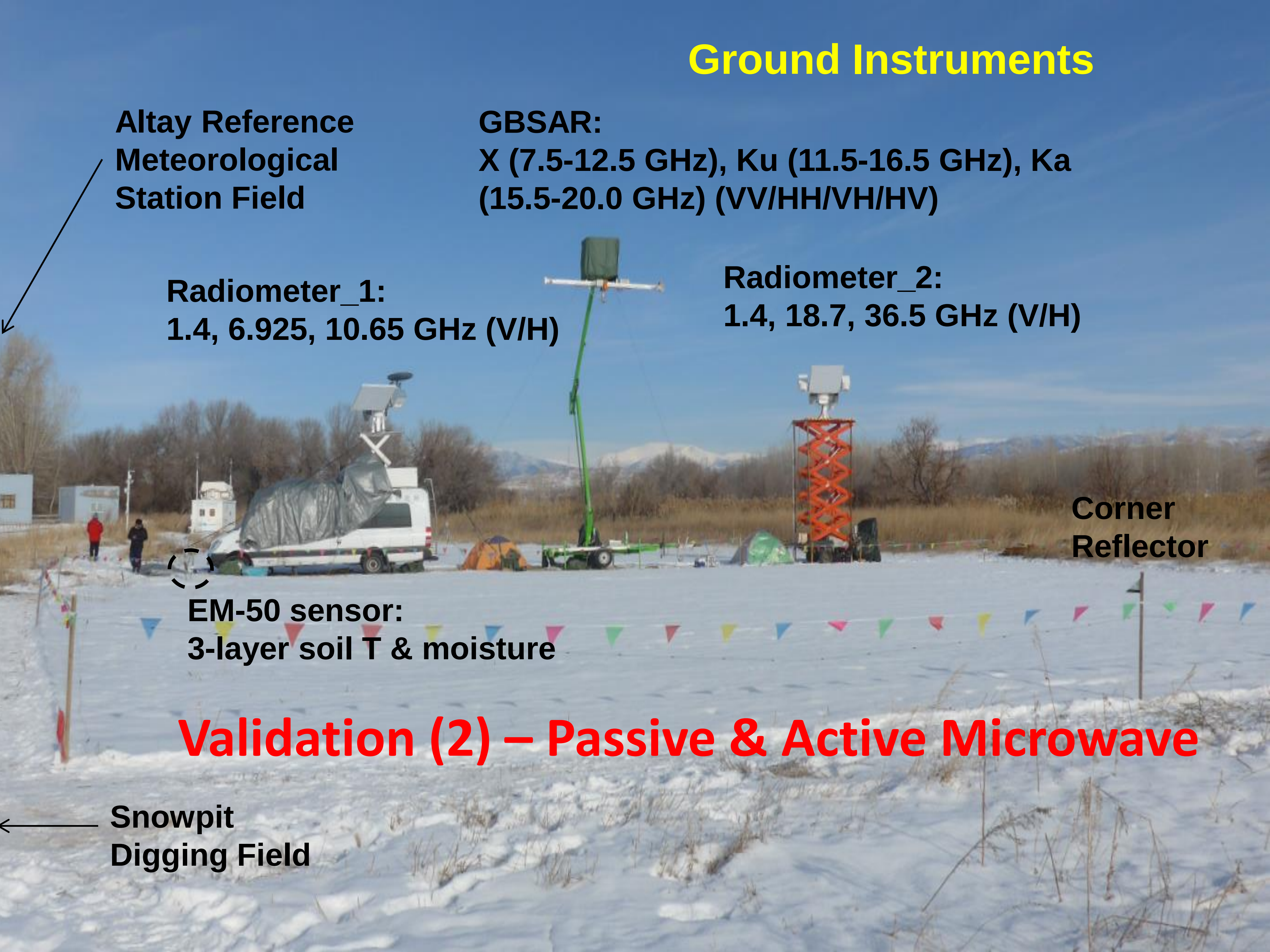








Ground Instruments



Altay Reference Meteorological Station Field

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

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

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

Corner Reflector

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

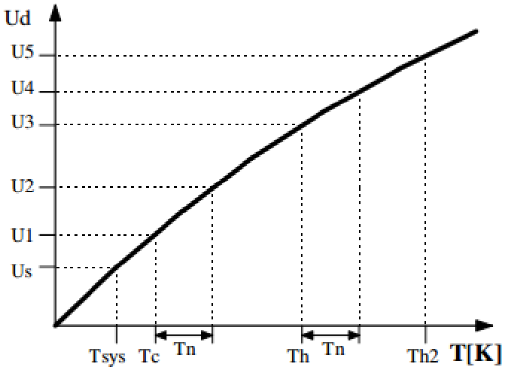
Validation (2) – Passive & Active Microwave

Snowpit Digging Field

Radiometer Calibration

- For C - Ku band

using a set of scan angles for sky tipping



$$U = GP^{\alpha} \quad 0.9 \leq \alpha < 1$$

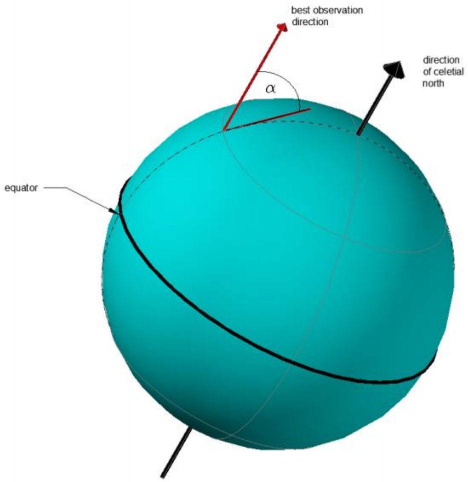
$$P(T_R) \cong \frac{1}{e^{\frac{h\nu}{k_B T_R}} - 1}$$

$$\begin{cases} U1 = G\left(P\left(T_{sys}\right) + P(T_C)\right)^{\alpha} \\ U2 = G\left(P\left(T_{sys}\right) + P(T_C) + P(T_n)\right)^{\alpha} \\ U3 = G\left(P\left(T_{sys}\right) + P(T_h)\right)^{\alpha} \\ U4 = G\left(P\left(T_{sys}\right) + P(T_h) + P(T_n)\right)^{\alpha} \end{cases}$$

Four unknown parameters: G, α, Tsys, Tn

- For L band

using a single scanning point



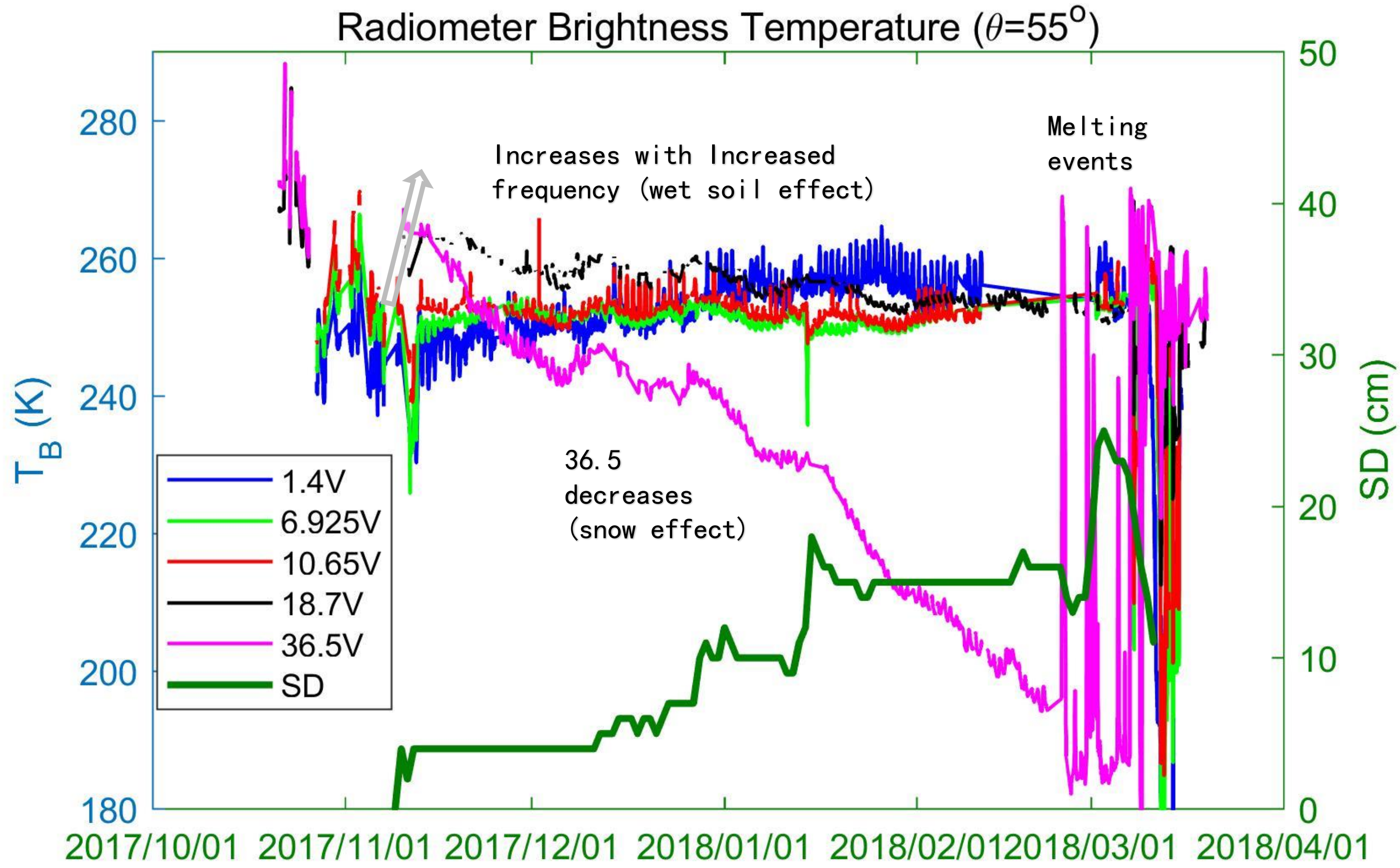
GBSAR Calibration

- Ground based SAR polarimetric calibration procedure from:

  K. Sarabandi, F. T. Ulaby and M. A. Tassoudji, "Calibration of polarimetric radar systems with good polarization isolation," in *IEEE Transactions on Geoscience and Remote Sensing*, vol. 28, no. 1, pp. 70-75, Jan 1990.

- 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.



Increases with Increased frequency (wet soil effect)

Melting events

36.5 decreases (snow effect)

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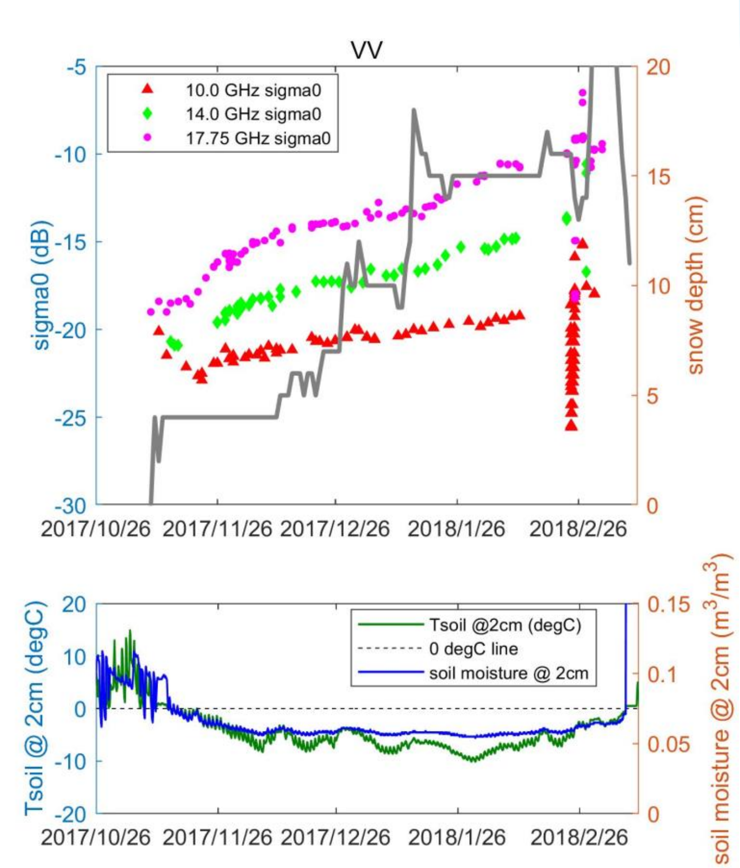
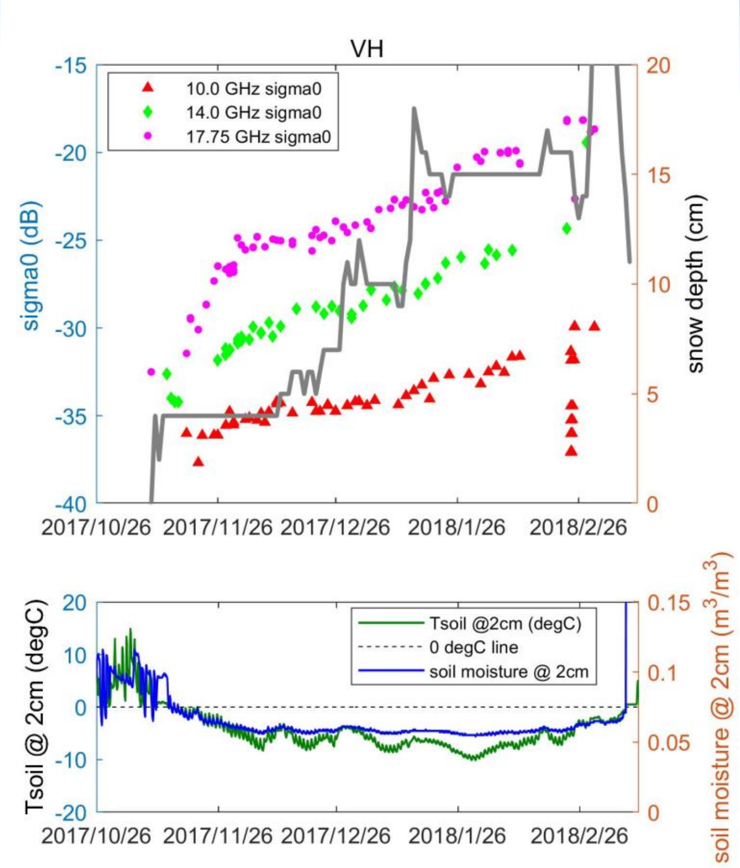
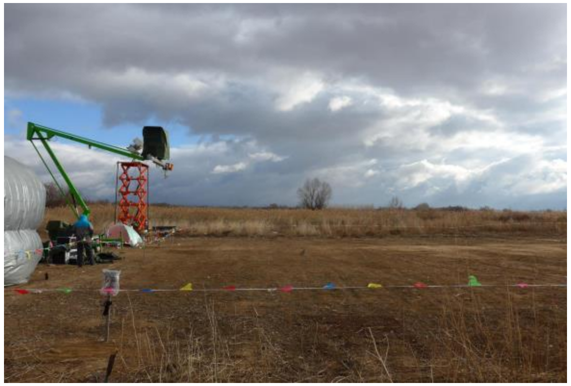
Time-series Measured Sigma0 at 40°





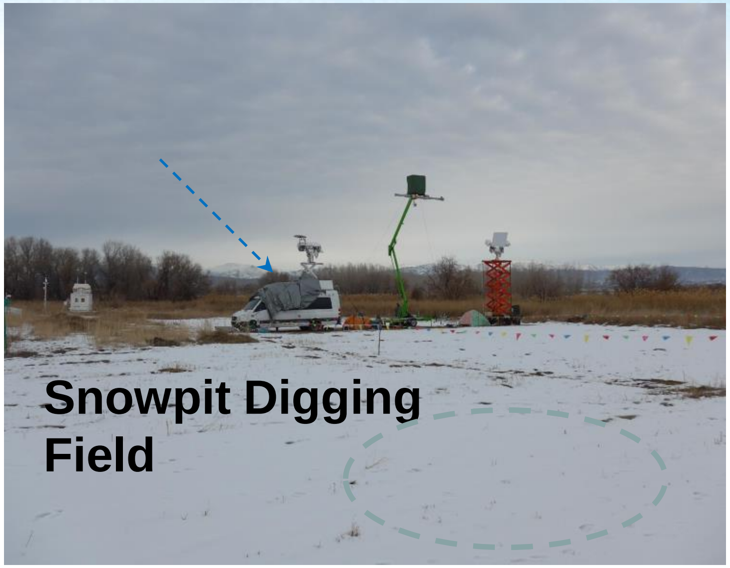
- Sensitivities of frequency dependence of snow volume backscattering to grain size and mass;
- Is the X-band backscattering time-series resulted from soil frozen process? Why there is no indication from passive measurements?
- Other possibilities?

Field Measurements



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

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

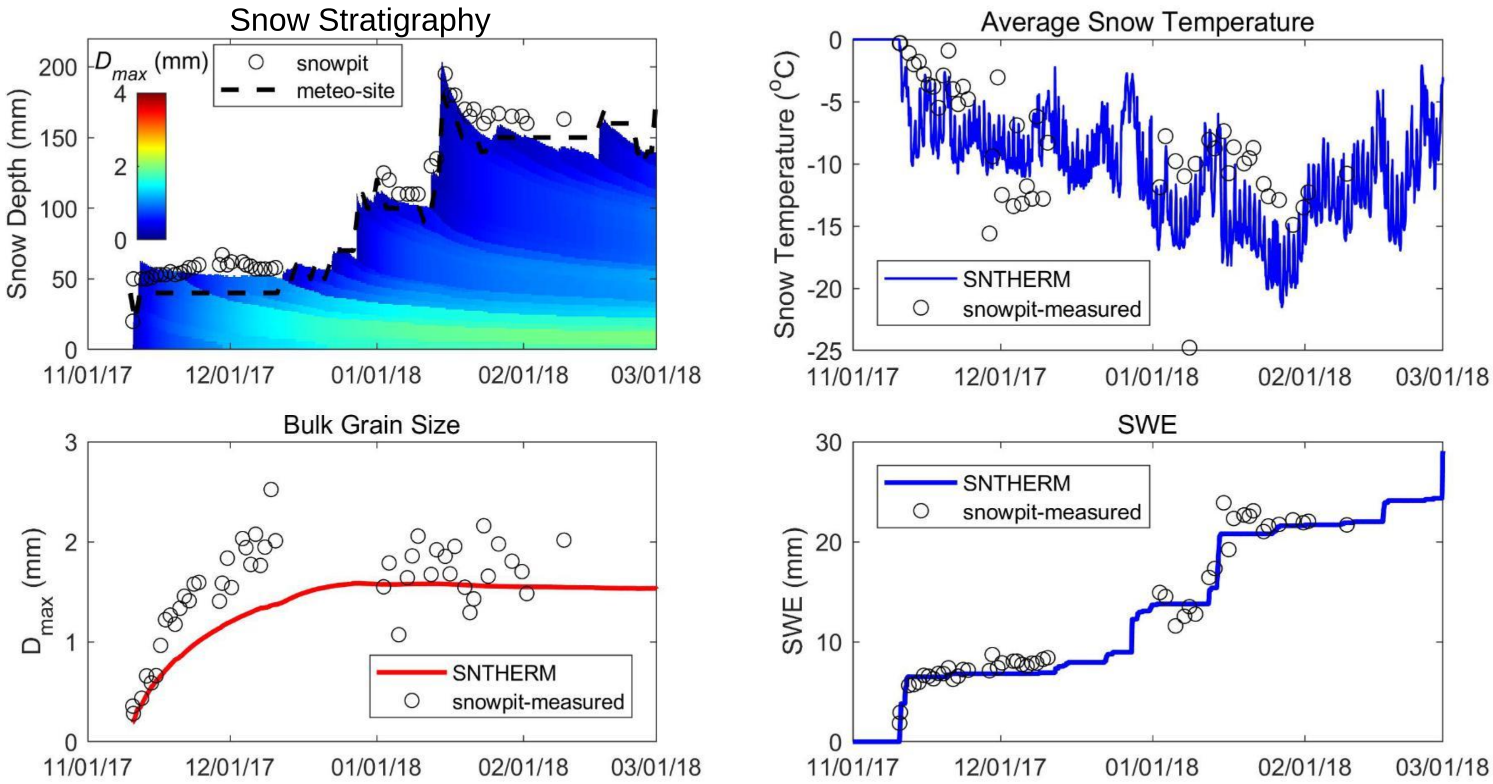


Snowpit Measurements:

- Snow Stratigraphy
- Snow Depth, SWE
- Snow Density & Snow Temp. per 5 cm
- Snow Grain size (D_{max})

SNTHERM-simulations

- **Model inputs**: T_{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

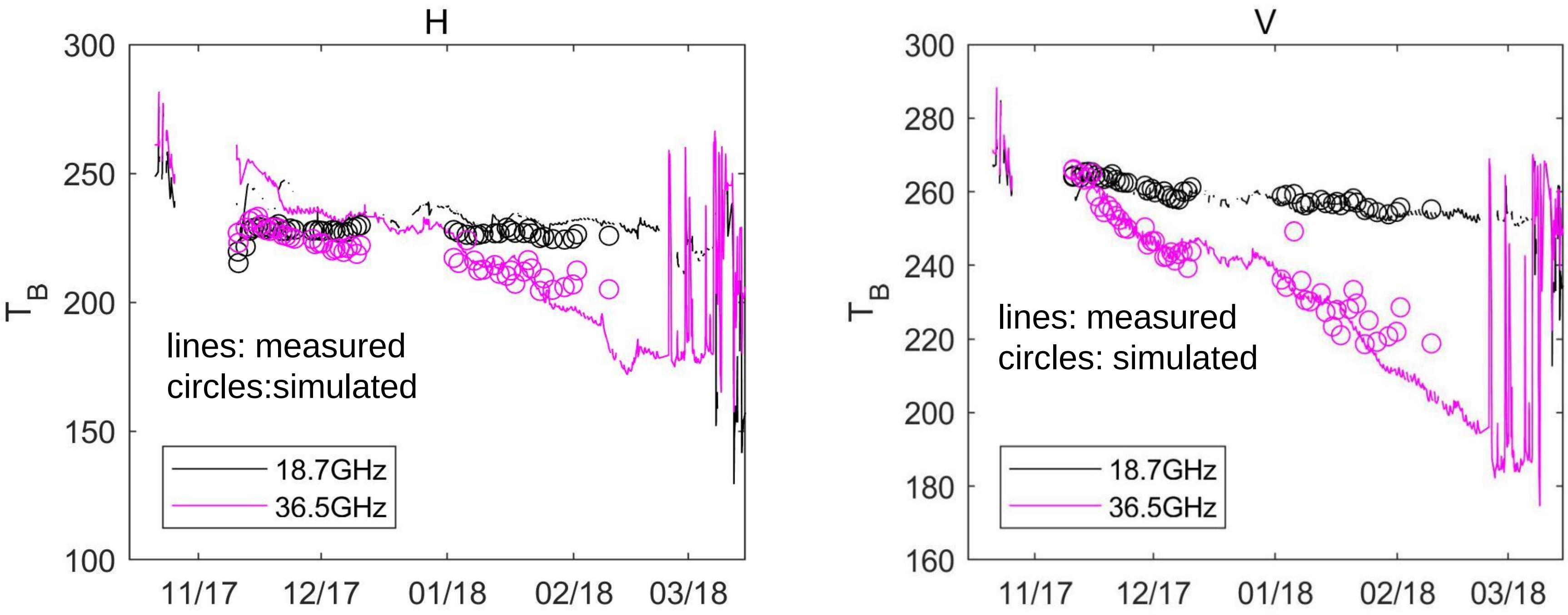
(1) Model Comparisons – MEMLS

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})]



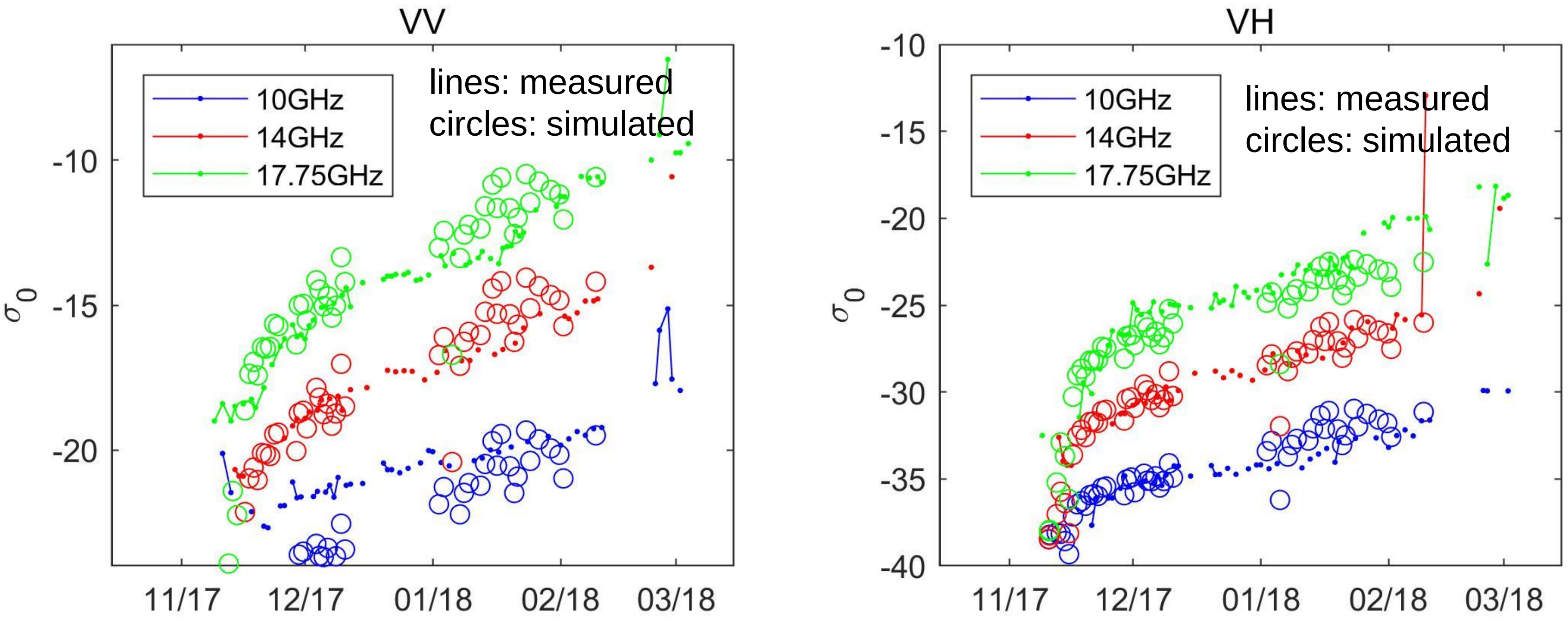
(1) Model Comparisons – MEMLS

Radar Backscattering Coefficients

pex_active=pex_passive*1.4 (compensate for the **backscattering enhancement**)

m=0.1; q=0.05;

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



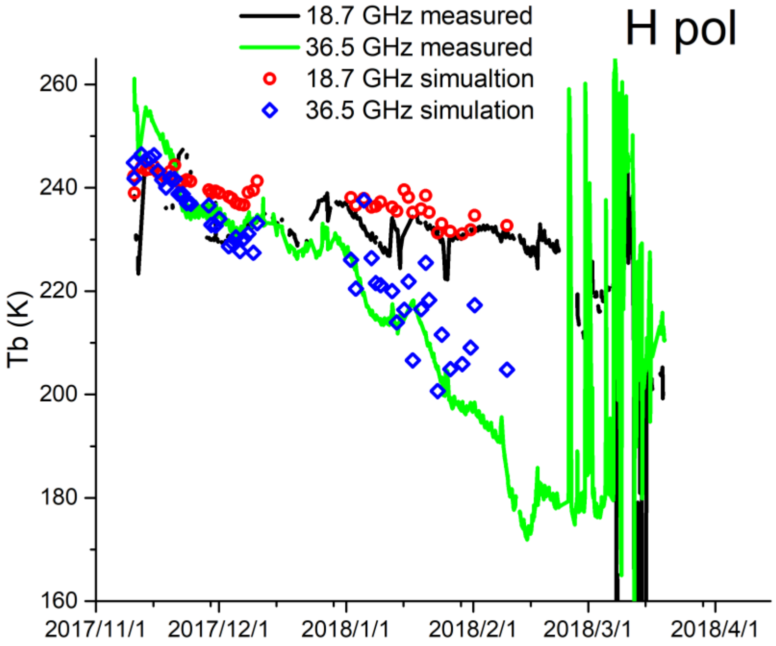
A adjustable parameter of "q" is used to parameterize the relationship between VH and VV

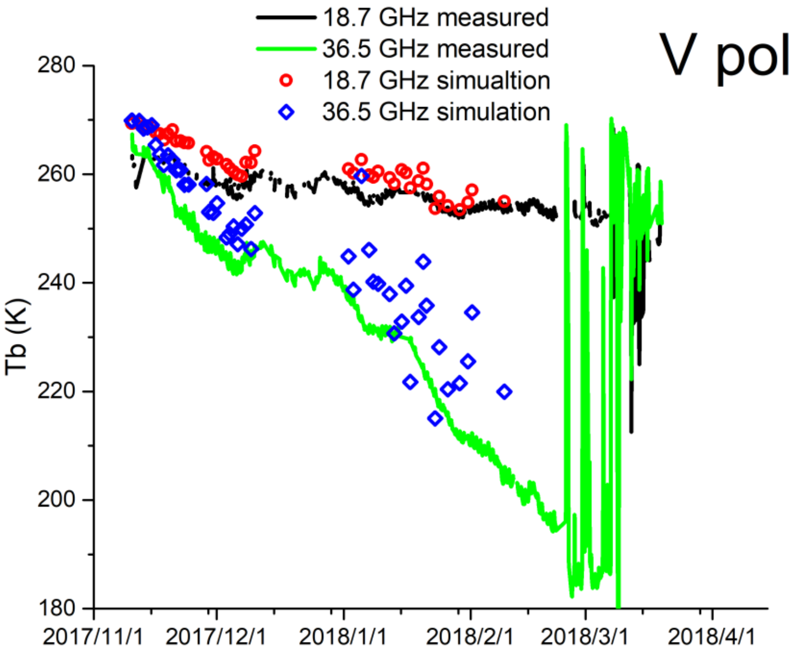
(2) Model Comparisons – DMRT

Passive Brightness Temperatures

Multi-layer DMRT-QCA

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



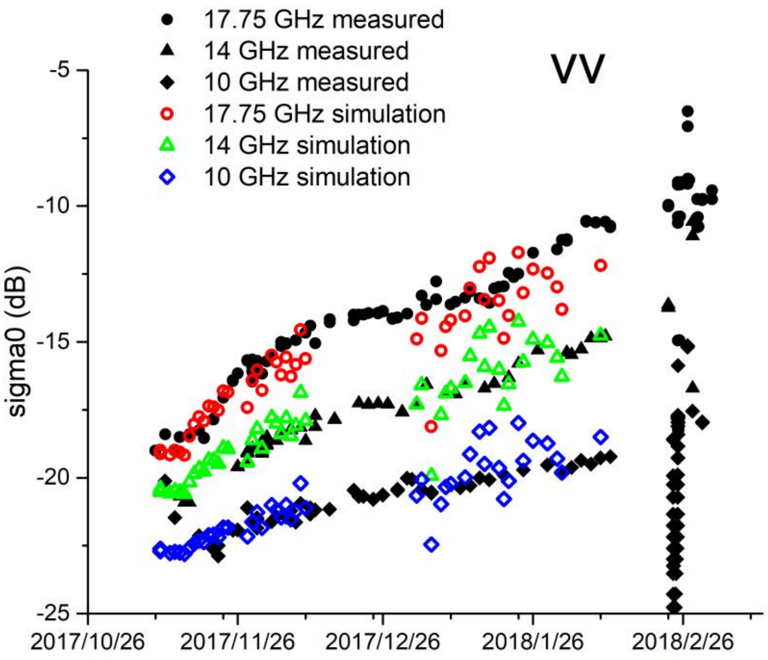


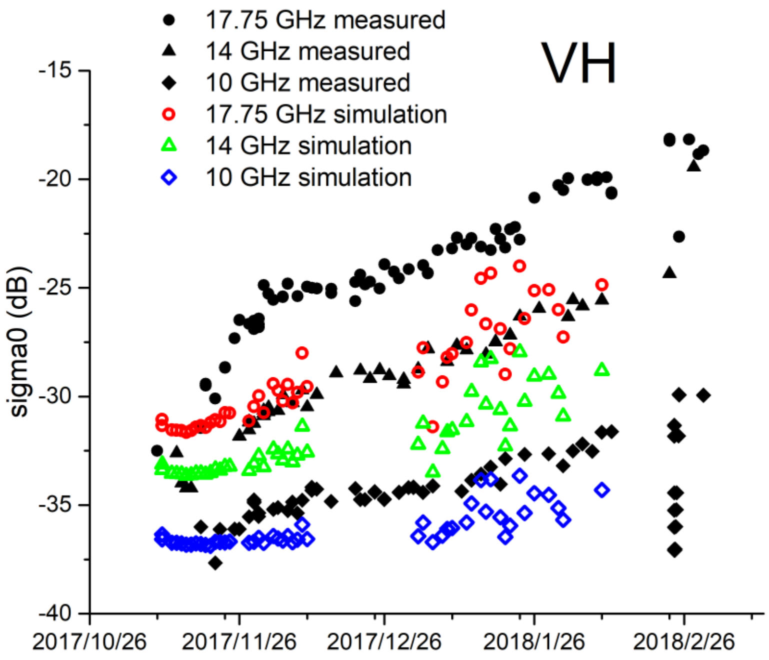
(2) Model Comparisons – DMRT

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

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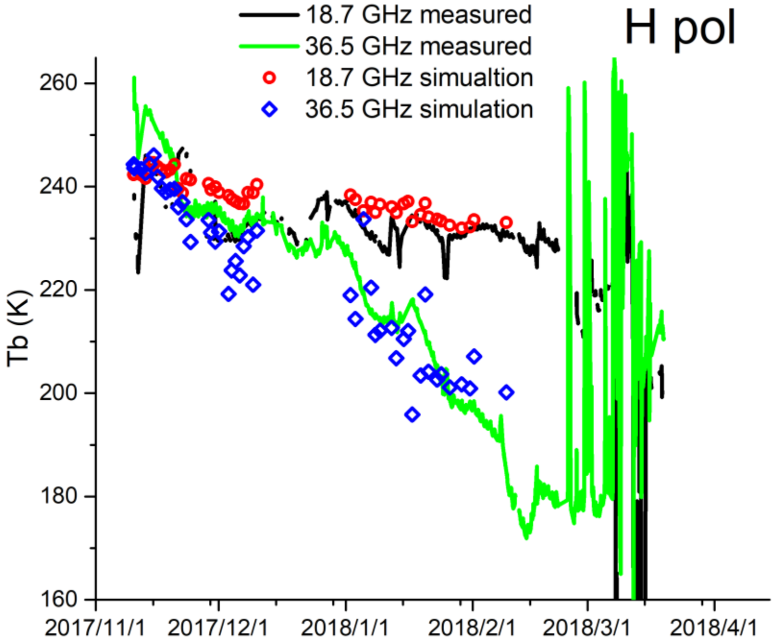
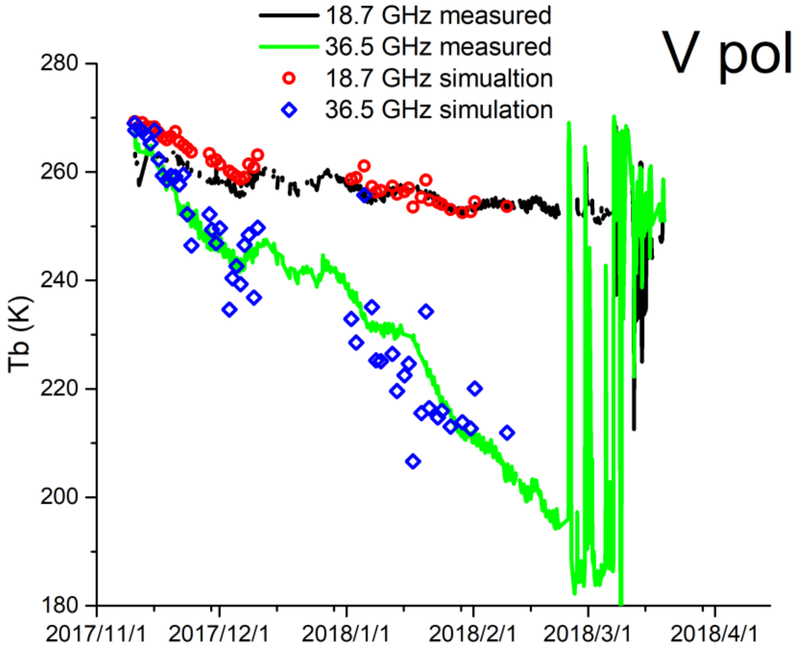
(3) Model Comparisons – VRT-Bic

Passive Brightness Temperatures

Multi-layer DMRT-Bic

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





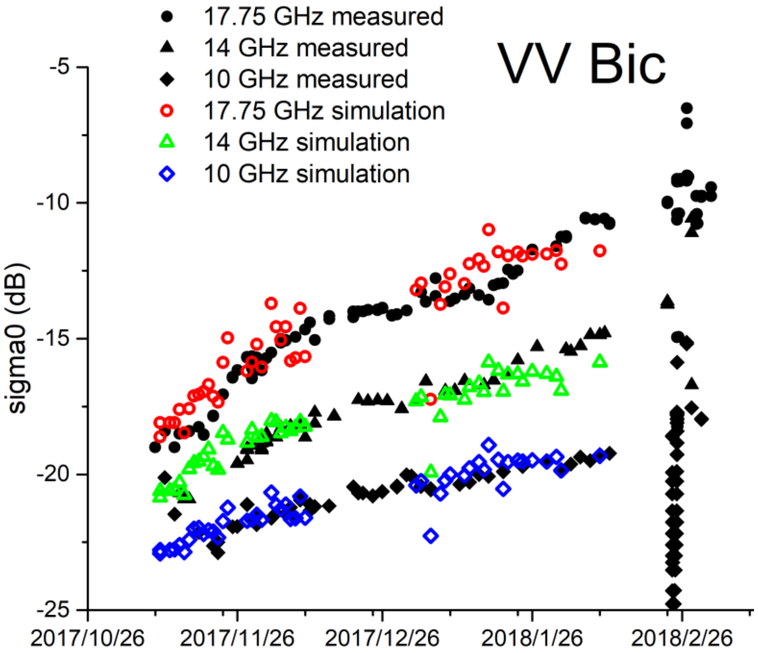
Match passive signals for different pols and frequencies **simultaneously !**

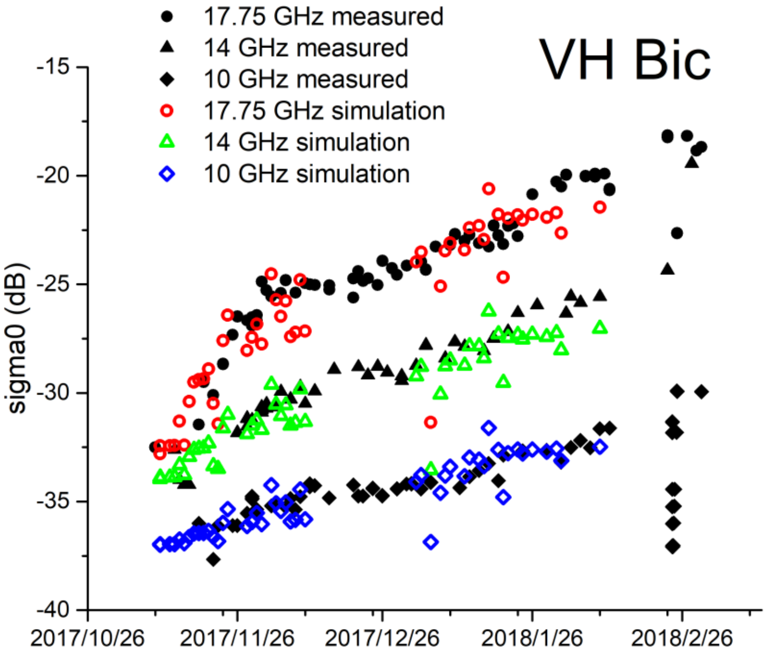
(3) Model Comparisons – VRT-Bic

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

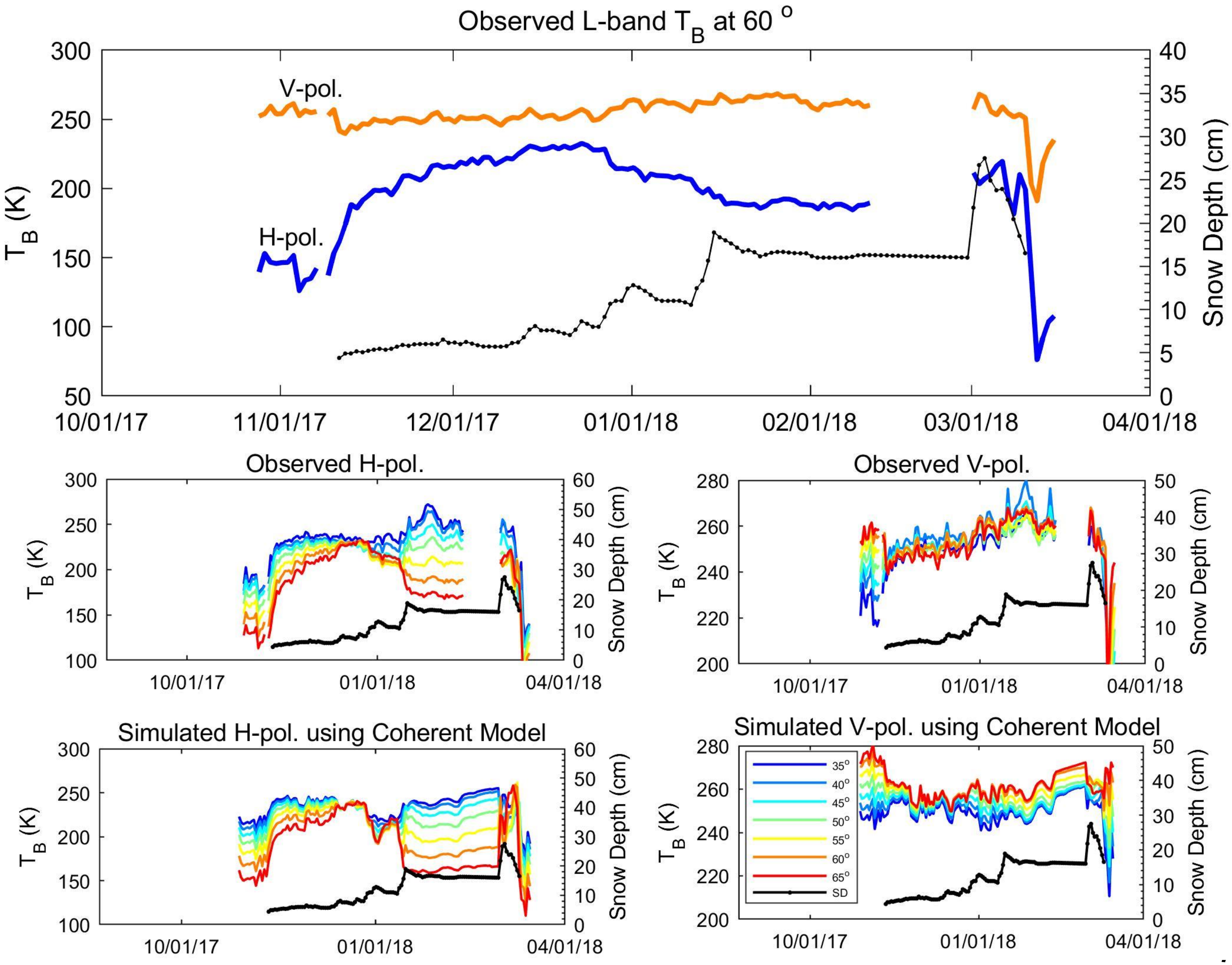




Bicontinuous model could generate much stronger VH backscattering

Match passive and active VV and VH signal **simultaneously !**

Need Coherent Model?


Observed L-band T_B at 60 ^{o}

Observed H-pol.

Observed V-pol.

Simulated H-pol. using Coherent Model

Simulated V-pol. using Coherent Model

Summary

- 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).