Simulations and Observations of Surface Properties for Supporting Satellite Data Assimilation

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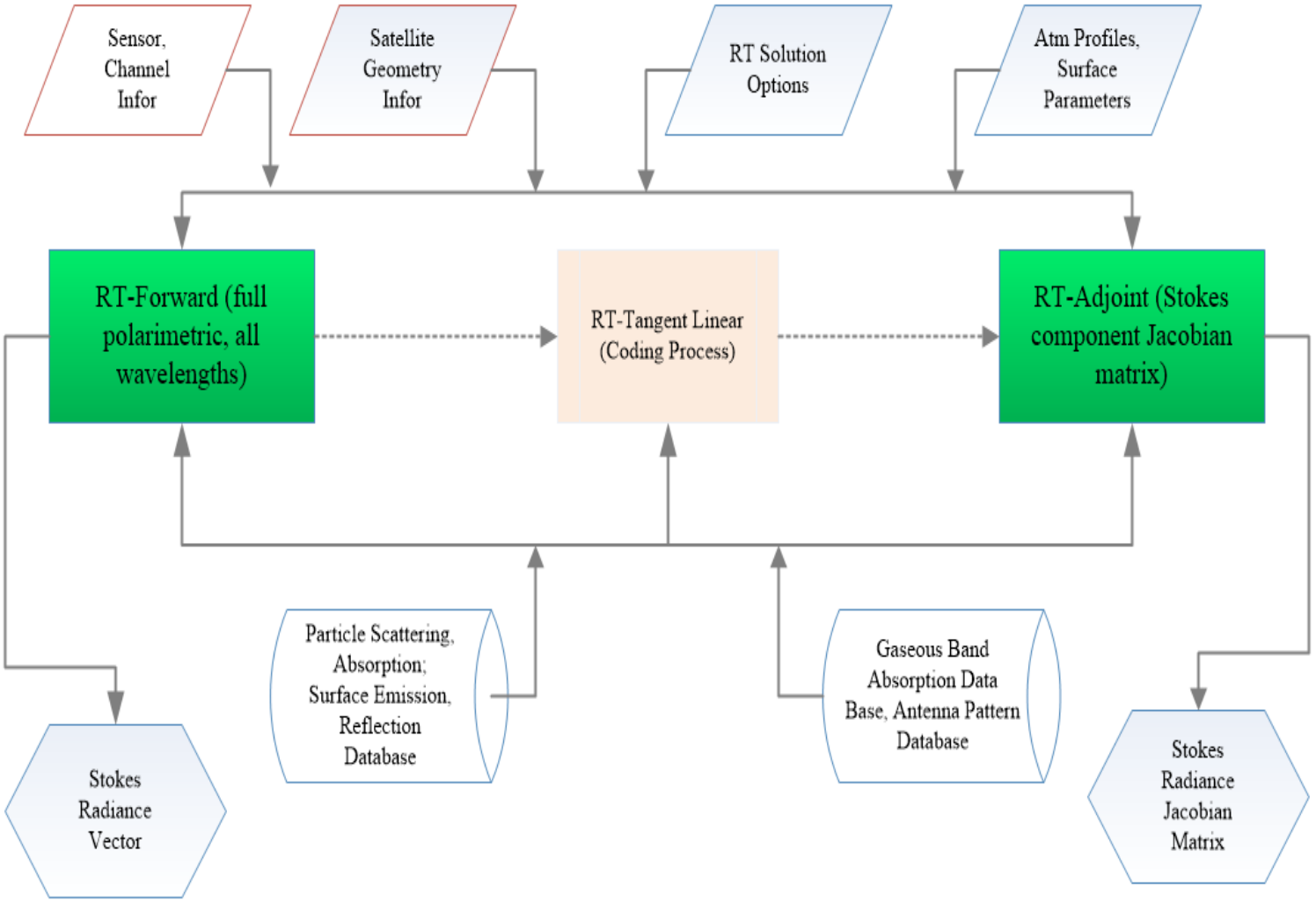
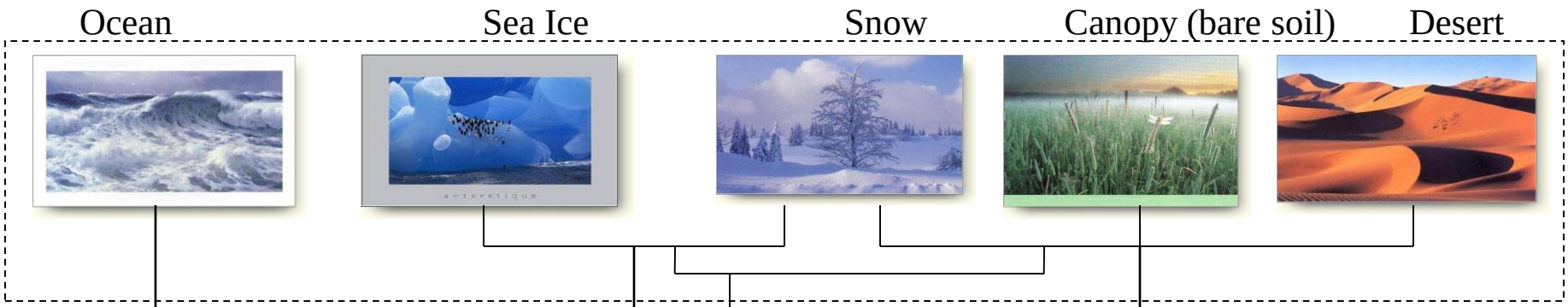
Advanced Radiative Transfer Modeling System (ARMS）



ARMS Uniqueness

- Improve the performance of simulated radiance under aerosols, cloudy and precipitation conditions through better scattering tables
- Improve the accuracy in simulating TOA radiances through vector radiative transfer models
- Adapt the analytic adjoint models developed earlier for vector matrix operator, DISORT and VDISORT
- Increase the computational speeds in scattering conditions through GPU and better software engineering
- Prepare NWP community full readiness for using a variety of Chinese instruments (e.g. FY, HY and GF)
- Improve surface emissivity modeling over Chinese western parts (e.g. Plateau) and polar regions, aka three poles

Surface Emissivity Models



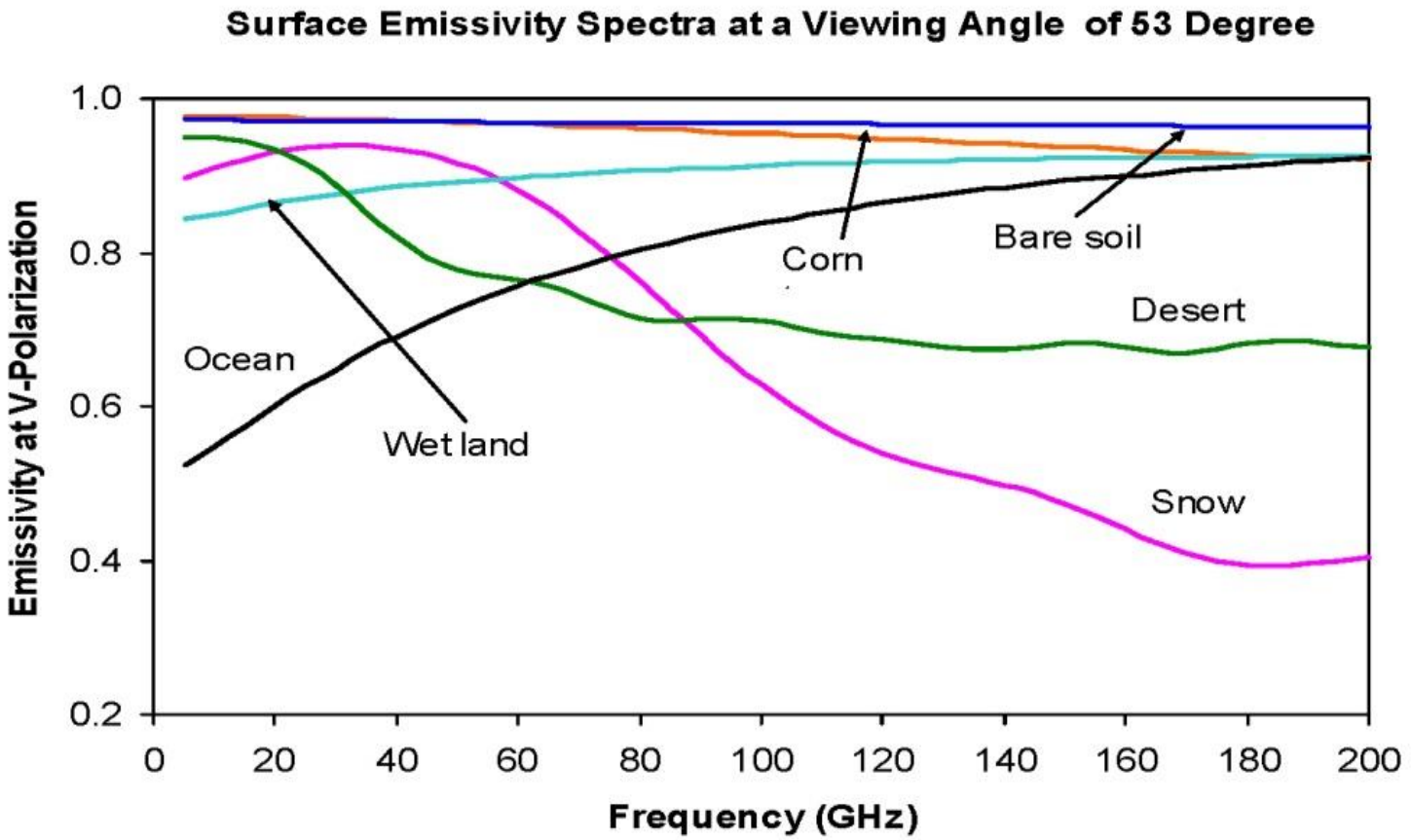
Microwave land emissivity model (NESDIS model)
(Weng et al, Yan, Grody, 2001), desert microwave emissivity library (Yan and Weng, 2011) TELSEM, and CNRM databases (Prigent, 200x)
Vegetation (Chen and Weng, 2014)
Surface roughness (Chen and Weng, 2015)

NPOESS Infrared emissivity database
IASI Land Infrared emissivity database
UWIREMIS database

Empirical snow and sea ice microwave emissivity algorithm (Yan and Weng, 2003; 2008)

FASTEM microwave emissivity model (Liu et al., 2010, English , 199x)
IR emissivity model (Wu and Smith, 1991; van Delst et al., 2001; Nalli et al., 2008)

Microwave Emissivity Spectra over Various Surface Conditions



Refractivity or Emissivity for a Flat Surface

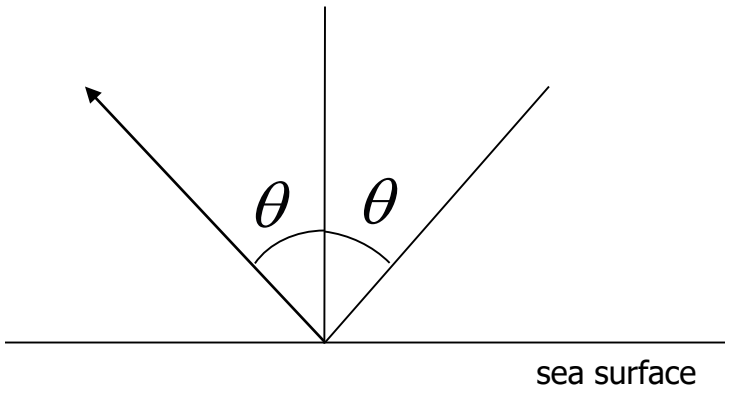
$$\varepsilon_p(\nu,\theta) = 1 - \Gamma_p(\nu,\theta) \quad (p = \text{h or v})$$

$\Gamma_p(\nu,\theta)$ Total Reflectivity ν Frequency θ Zenith angle

For a specular surface, reflectivity can be calculated by Fresnel law:

$$\Gamma_v = \frac{\varepsilon_v(\nu,\theta)\cos\theta - \sqrt{\varepsilon_v(\nu,\theta) - \sin^2\theta}}{\varepsilon_v(\nu,\theta)\cos\theta + \sqrt{\varepsilon_v(\nu,\theta) - \sin^2\theta}}$$

$$\Gamma_h = \frac{\cos\theta - \sqrt{\varepsilon_h(\nu,\theta) - \sin^2\theta}}{\cos\theta + \sqrt{\varepsilon_h(\nu,\theta) - \sin^2\theta}}$$



Foam Coverage Formula

Foam is a mixture of air and water and has a higher emissivity than flat water

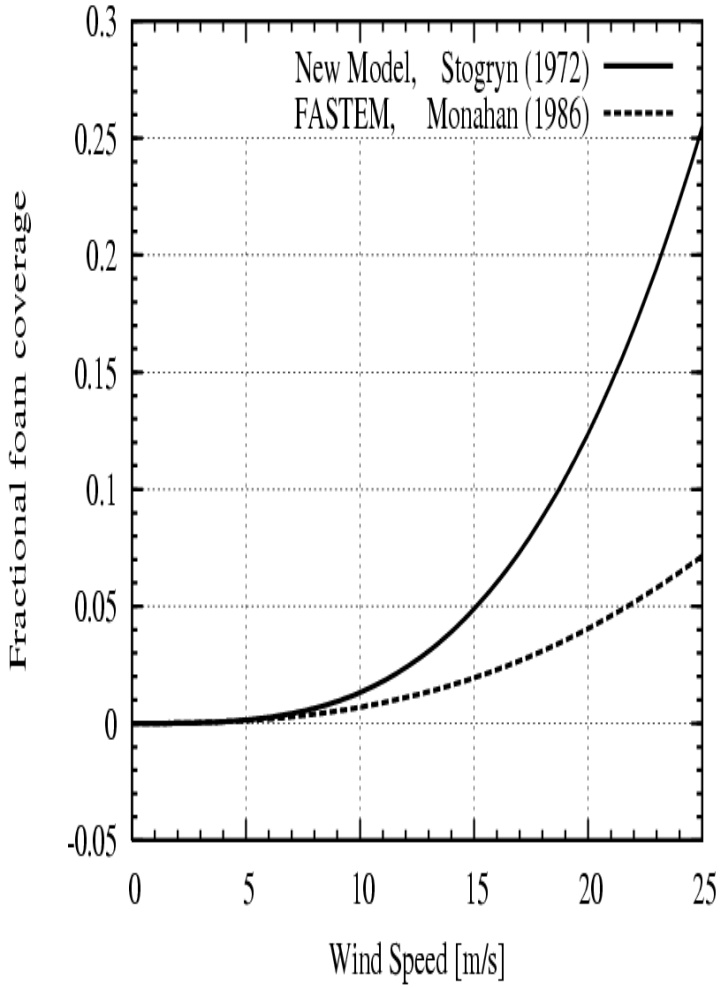
Foam coverage:

Stogryn, 1972

$$f_c = 7.75\times10^{-6}\left(\frac{V}{V_0}\right)^{3.231}$$

Monahan, 1986

$$f = 1.95\times10^{-5}u^{2.55}$$



Foam Emissivity vs. Angle

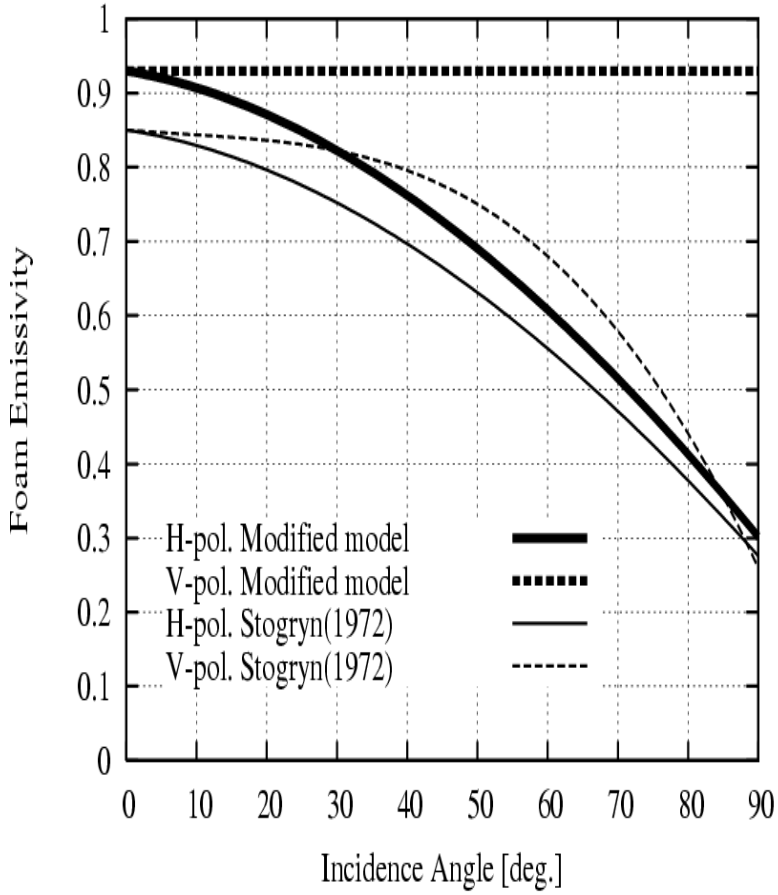
Foam emissivity (angular dependent and frequency dependent):

H-Pol

rfoam = 1.0-(208.0+1.29e-9*f)/t*g

V-Pol

rfoam = 1.0-(208.0+1.29e-9*f)/t*g



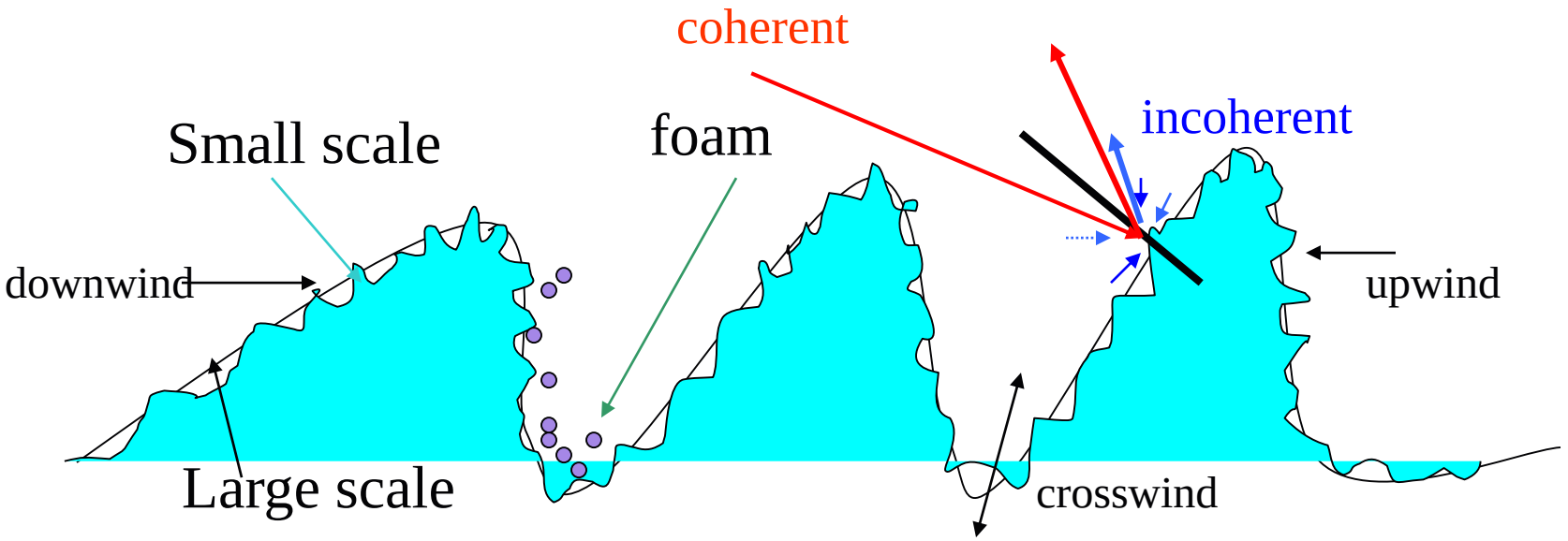
Total Reflectivity (1 - Emissivity)

$$\Gamma_p(\nu,\theta,T_s,W,S) = f(\nu,\theta,W)\left|R_{p,\text{Foam}-\text{covered}}(\nu,\theta,T_s,W)\right|^2 + \left(1-f(\nu,\theta,W)\right)\left|R_{p,\text{Foam}-\text{free}}(\nu,\theta,T_s,W,S)\right|^2$$

where

W: Wind speed
θ: local zenith angle
S: Salinity
Ts: sea surface temperature

Ocean Roughness and Emissivity Model



The large-scale roughness is dependent on the gravity waves and whereas the small irregularities is affected by capillary waves. There are coherent reflection and incoherent scattering associated with the waves in both scales

Stokes Vector Reflectivity or Emissivity

$$\mathbf{A} = \mathbf{A}_{co} + \mathbf{A}_{in}$$

Coherent term is related to the reflection of large scale roughness):

$$\mathbf{A}_{co} = \frac{4\pi\delta(\mu-\mu')\delta(2\pi+\phi-\phi')}{(1-\mu^2)^{\frac{1}{2}}} \times \begin{pmatrix} |R_{ll}|^2 & |R_{lr}|^2 & Re(R_{rr}R_{rl}^*) & -Im(R_{rr}R_{rl}^*) \\ |R_{rl}|^2 & |R_{rr}|^2 & Re(R_{lr}R_{ll}^*) & -Im(R_{lr}R_{ll}^*) \\ 2Re(R_{rl}R_{ll}^*) & 2Re(R_{rr}R_{lr}^*) & Re(R_{rr}R_{ll}^* + R_{rl}R_{lr}^*) & -Im(R_{rr}R_{ll}^* - R_{rl}R_{lr}^*) \\ 2Im(R_{rl}R_{ll}^*) & 2Im(R_{rr}R_{lr}^*) & Im(R_{rr}R_{ll}^* + R_{rl}R_{lr}^*) & Re(R_{rr}R_{ll}^* - R_{rl}R_{lr}^*) \end{pmatrix}.$$

$$\mathbf{R} = \begin{pmatrix} R_{ll}^{(0)} + R_{ll}^{(2)} & R_{lr}^{(2)} \\ R_{rl}^{(2)} & R_{rr}^{(0)} + R_{rr}^{(2)} \end{pmatrix},$$

$$R_{\alpha\beta}^{(2)}(\theta,\phi) = \int_0^{2\pi}\int_0^{\infty} k_0^2 W_s(k_{\rho i}cos\phi - k_\rho cos\phi', k_{\rho i}sin\phi - k_\rho sin\phi') g_{\alpha\beta}^{(2)} k_\rho d\phi',$$

Stokes Vector Reflectivity or Emissivity

Incoherent term is related to the reflection of small scale roughness:

$$\mathbf{A}_{in} = \begin{pmatrix} \gamma_{llll} & \gamma_{lrlr} & Re(\gamma_{rrrl}) & Im(\gamma_{rrrl}) \\ \gamma_{rlrl} & \gamma_{rrrr} & Re(\gamma_{lrll}) & Im(\gamma_{lrll}) \\ 2Re(\gamma_{rlll}) & 2Re(\gamma_{rrlr}) & Re(\gamma_{rrll}+\gamma_{rllr}) & -Im(\gamma_{rrll}-\gamma_{rllr}) \\ 2Im(\gamma_{rlll} & 2Im(\gamma_{rrlr}) & Im(\gamma_{rrll}+\gamma_{rllr}) & Re(\gamma_{rrll}-\gamma_{rllr}) \end{pmatrix},$$

$$\gamma_{pq\alpha\beta}(\theta,\phi,\theta',\phi') = 4\pi k_0^4 cos\theta' F_{pq\alpha\beta}(\theta,\phi,\theta',\phi')$$

Stokes Vector Emissivity
Wave Spectrum Function (W_s)

$$W(K,\varphi) = \frac{1}{2\pi K} S(K)\Phi(K,\varphi)$$

$S(K)$ is an omni-directional spectrum

$\Phi(K,\varphi)$ is the angular portion of the spectrum

φ is the wave direction relative to wind

$$\Phi(K,\varphi) = 1 + d[1 - \exp(-sK^2)]\cos 2\varphi$$

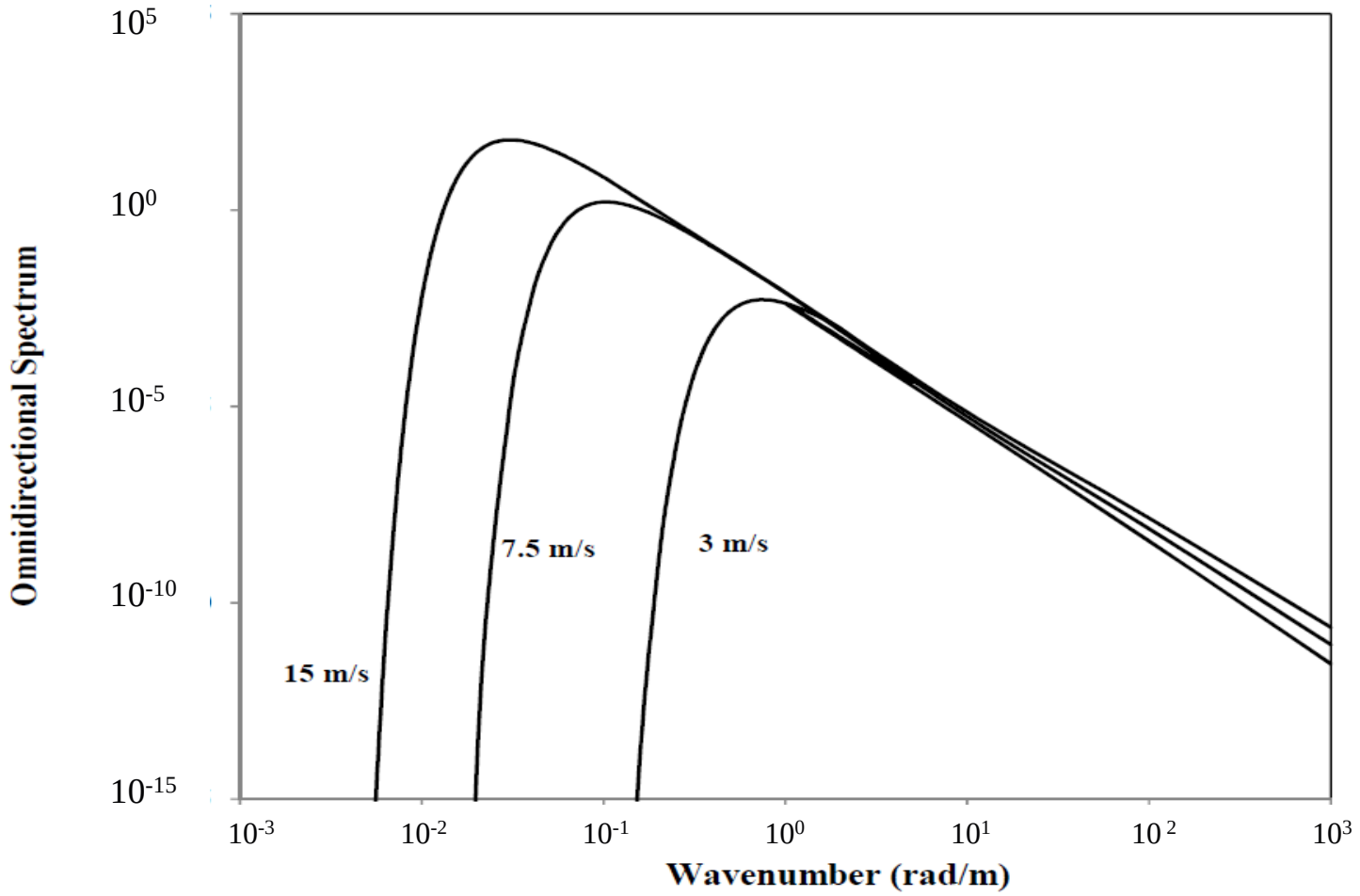
when $K < K_j$

$$S(k) = \frac{a}{2\pi} K^{-3} \exp[-0.74(K_0 / K)^2]$$

When $K \geq K_j$

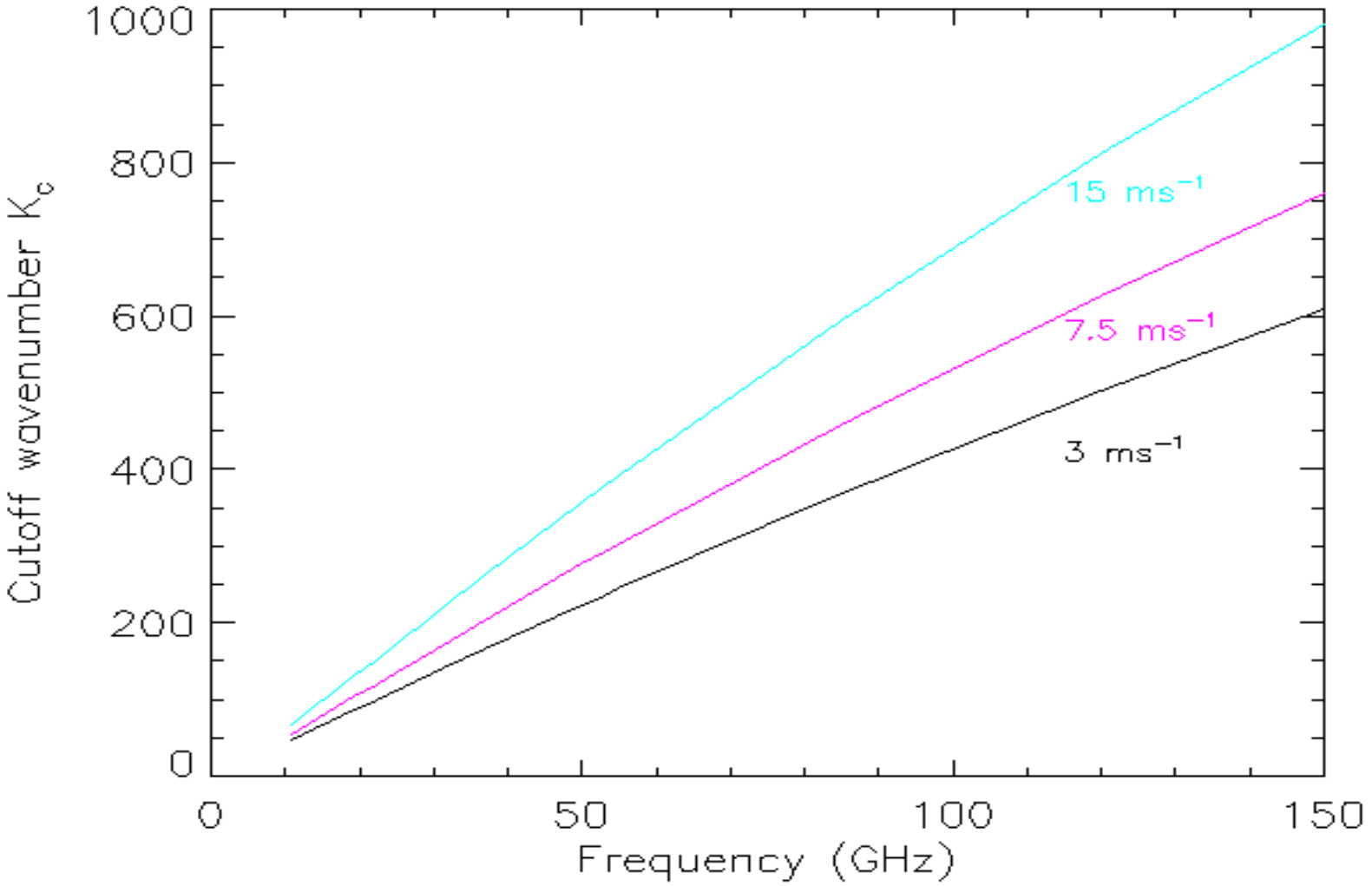
$$S(K) = \frac{a}{2\pi} K^{-3} \left(\frac{bKu_*^2}{g + \gamma K^2}\right)^{c \log_{10}(K/K_j)} \exp[-0.74(K_0 / K_j)^2]$$

Bjerkaas/Riedel (BR) Ocean Roughness Spectrum



(Elfouhaily et al., 1997).

Cutoff Wavenumber



Water Permittivity Models

- Permittivity models are either single or double Debye's formula, taking into account polarization.
  - Single Debye's model: Stogryn, 1971; Klein and Swift, 1977; Ellison et al., 1998; Guillou et al., 1998.
  - Double Debye's model: Ellison et al., 2003; Meissner and Wentz, 2004; Romaraju and Trumpf, 2006.
- For a low frequency (< 20 GHz), permittivity depends on salinity
- Permittivity model of Ellison et al. (2003) is used in the FASTEM emissivity model

Ocean Permitivity Model (1/2)

Debye (1929) model for pure water, the permitivity

$$\varepsilon = \varepsilon_\infty + \frac{\varepsilon_s - \varepsilon_\infty}{1 + j2\pi f\tau}$$

Dissolved salt in water will be a good conductor and contributes to imaginary part

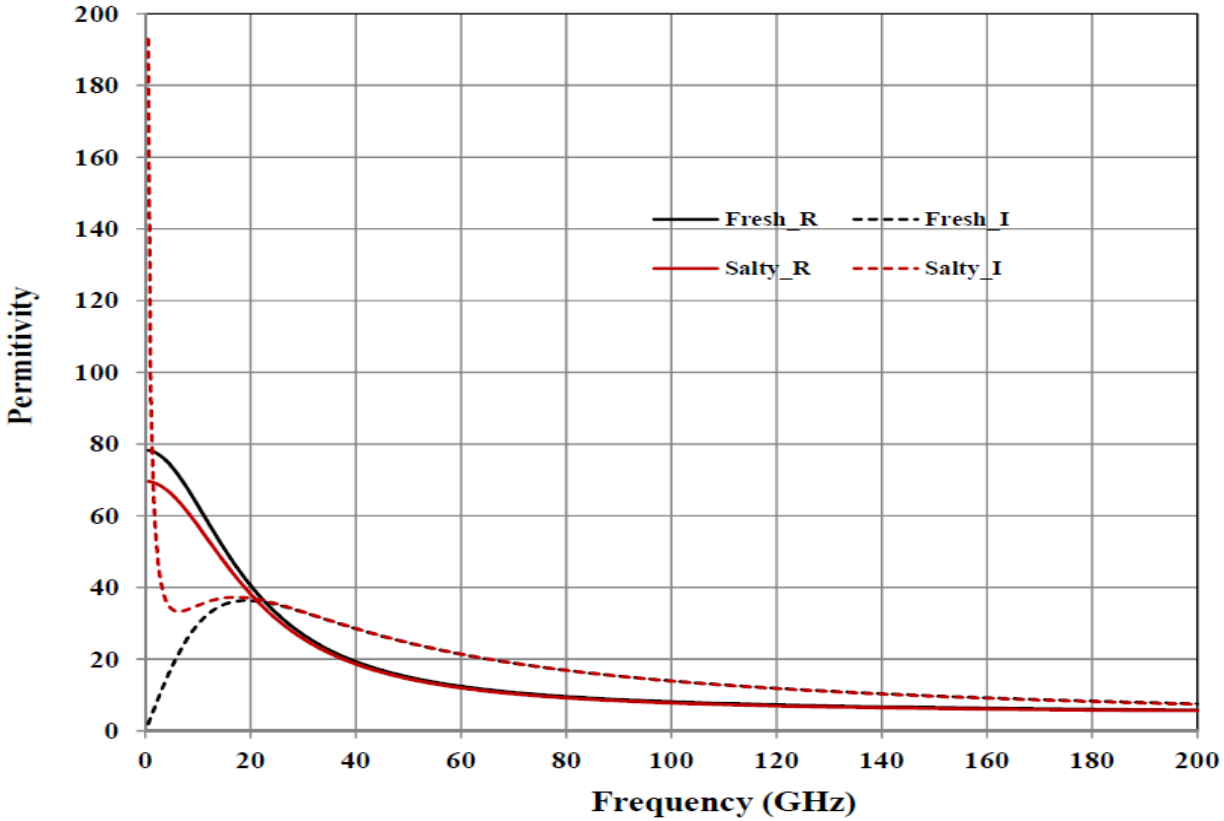
$$\varepsilon = \varepsilon_\infty + \frac{\varepsilon_s - \varepsilon_\infty}{1 + j2\pi f\tau} + j\frac{\alpha}{2\pi f\varepsilon_0}$$

For a better performance at higher frequency, it is found that double Debye is needed with

$$\varepsilon = \varepsilon_\infty + \frac{\varepsilon_s - \varepsilon_1}{1 + j2\pi f\tau_1} + \frac{\varepsilon_1 - \varepsilon_\infty}{1 + j2\pi f\tau_2} + j\frac{\alpha}{2\pi f\varepsilon_0}$$

ε_1 **is the permittivity at an intermediate frequency**

Water Permittivity vs. Frequency

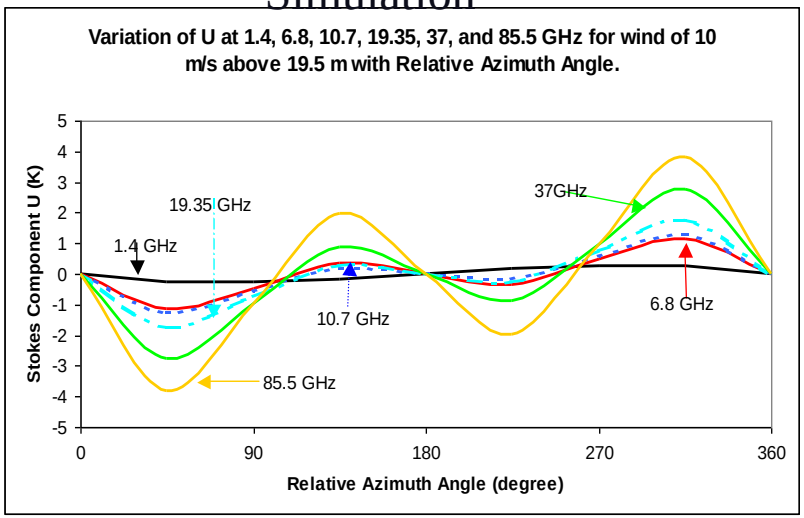


The permittivity model of Ellison (2003) is for a fixed salinity of 35‰. The permittivity model of Somaraju and Trumpf (2006) has a simple expression, but its empirical coefficients were not derived from measurements. The model of Meissner and Wentz (2004) can be used for frequencies up to 500 GHz. The model fits measurements well. But its permittivity at an infinitive frequency depends on salinity, conflict with physics. Our model removes the salinity dependency and revises fitting coefficients

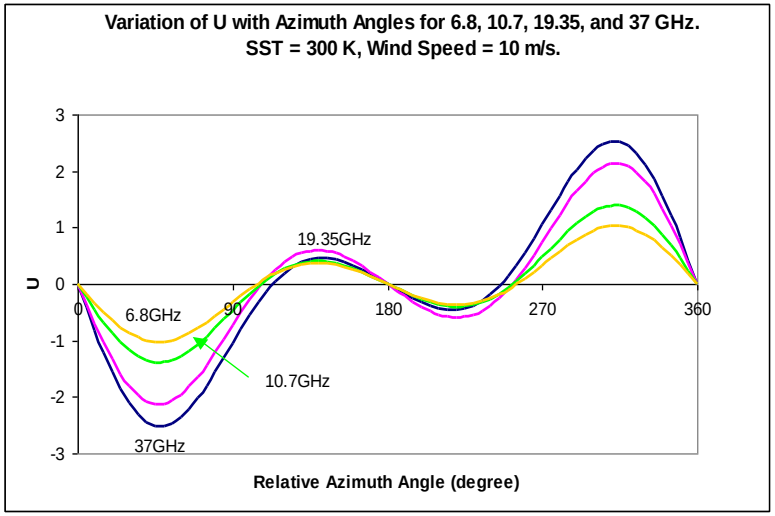
Black line for fresh water and red line for sea water. The symbol squares are measurements for fresh water (black) and sea water (red).

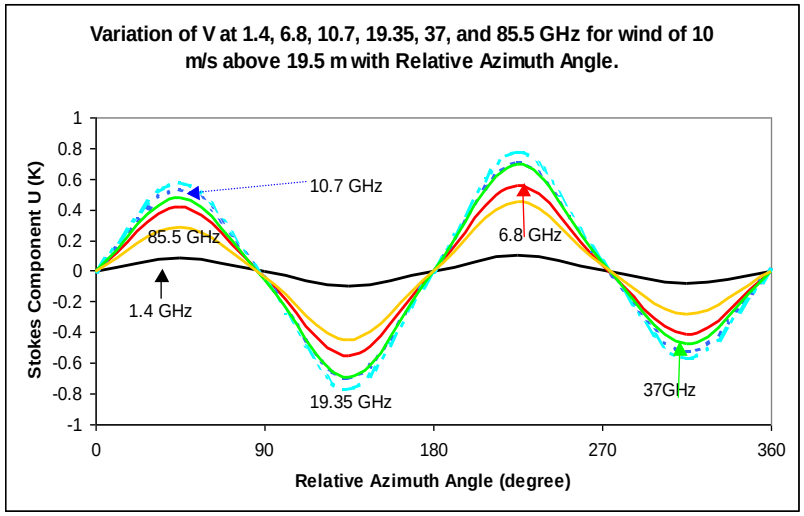
Oceanic Emission Model vs. Observations

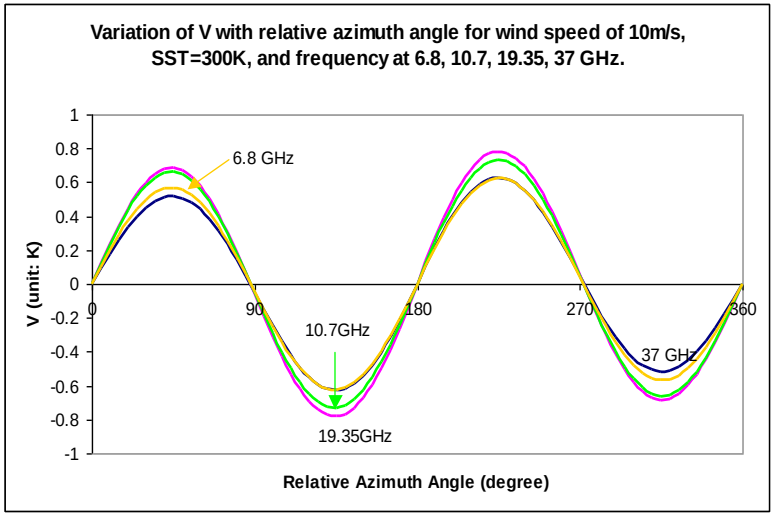
Simulation



Measurement

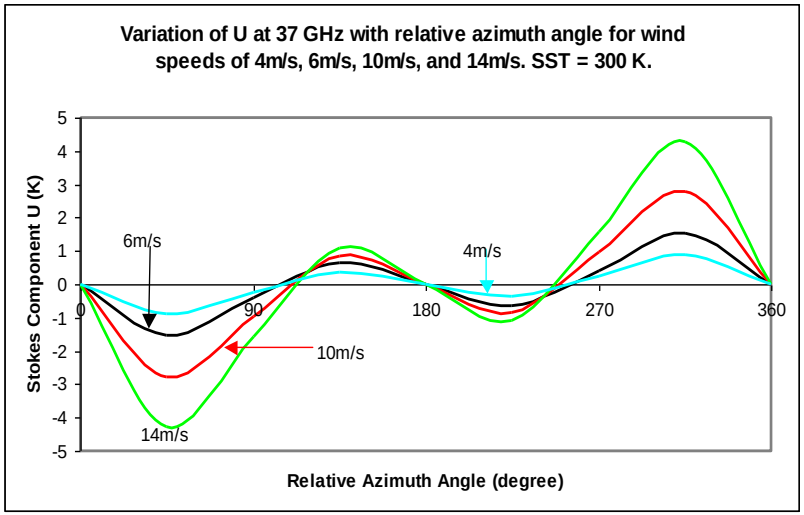


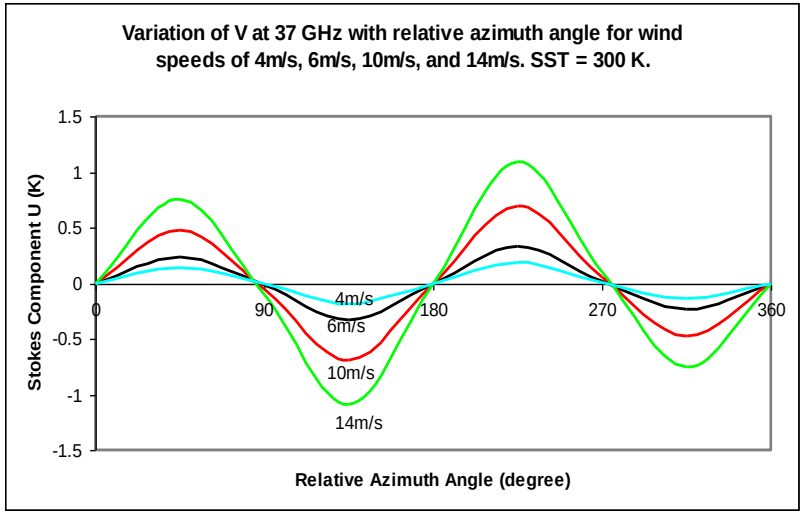




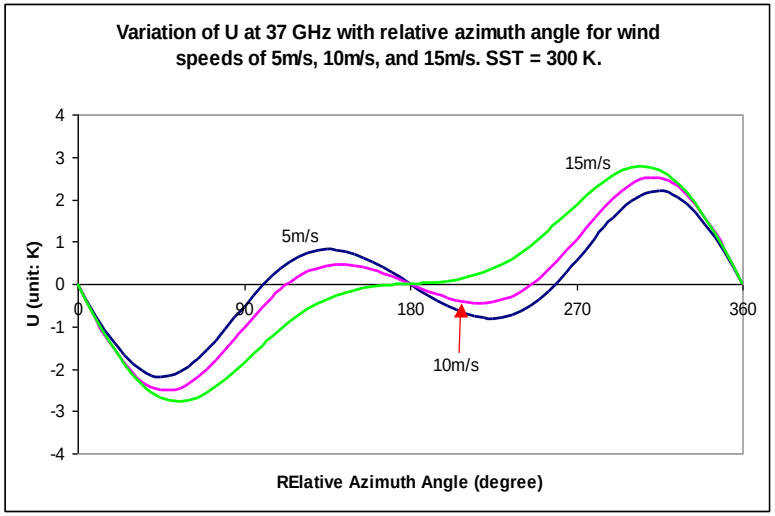
Oceanic Emission Model vs. Observations

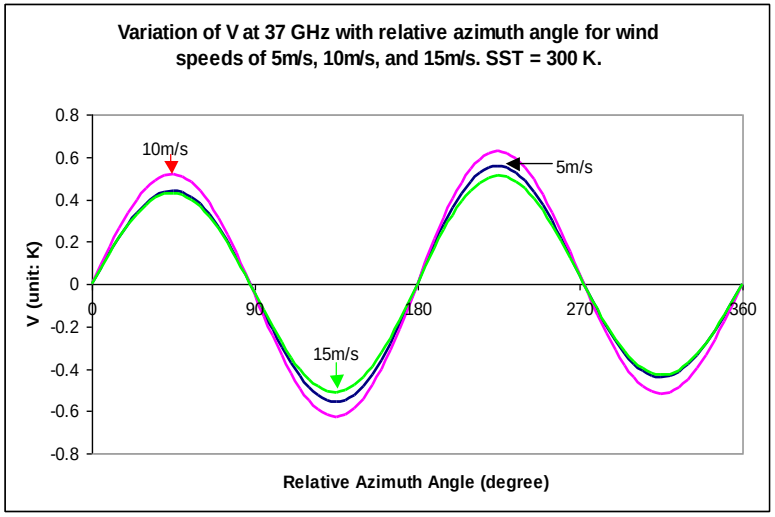
Simulation





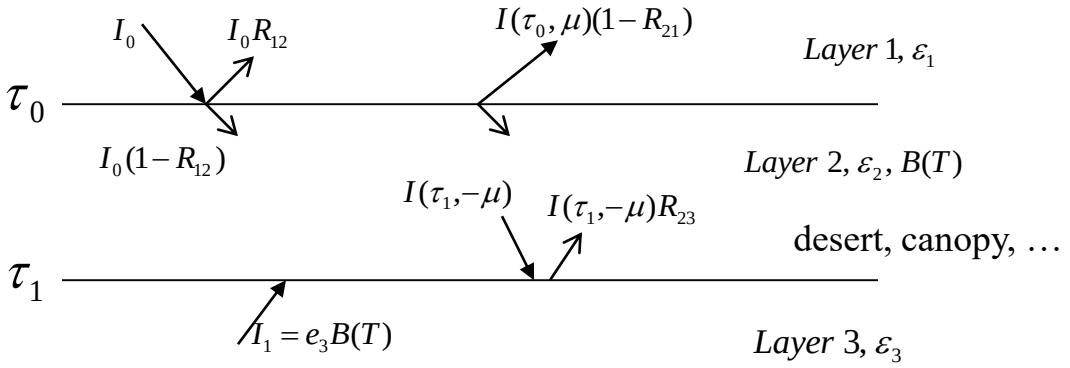
Measurement





Microwave Land Emissivity Model (LandEM)

(1) Three layer medium:



(2) Emissivity derived from a two-stream radiative transfer solution and modified Fresnel equations for reflection and transmission at layer interfaces:

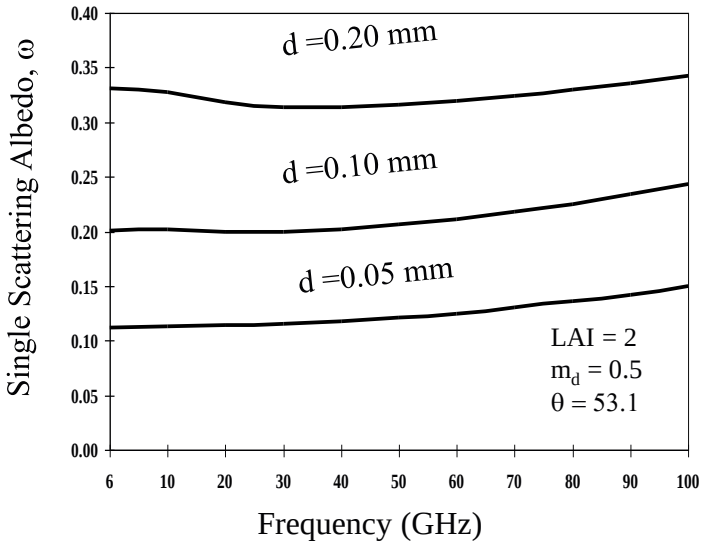
$$e = \alpha R_{12} + (1-R_{21})\frac{(1-\beta)[1+\gamma e^{-2k(\tau_1-\tau_0)}]+\alpha(1-R_{12})[\beta-\gamma e^{-2k(\tau_1-\tau_0)}]}{(1-\beta R_{21})-(\beta-R_{21})\gamma e^{-2k(\tau_1-\tau_0)}}$$

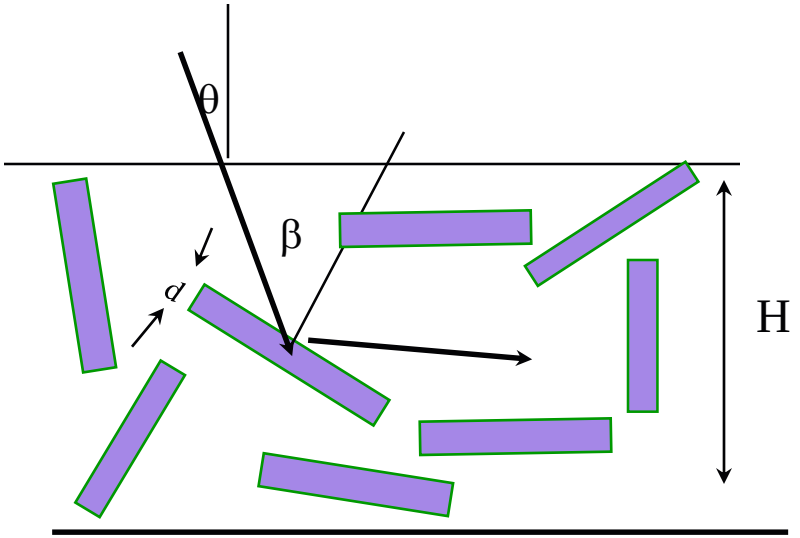
Weng, et al, 2001

Optical Properties for Vegetation Canopy

Geometric optics is applied because the leaf size is typically larger than wavelength

- Wegmuller et al.'s derivation
- Canopy leaves are oriented
- Matzler's dielectric constant





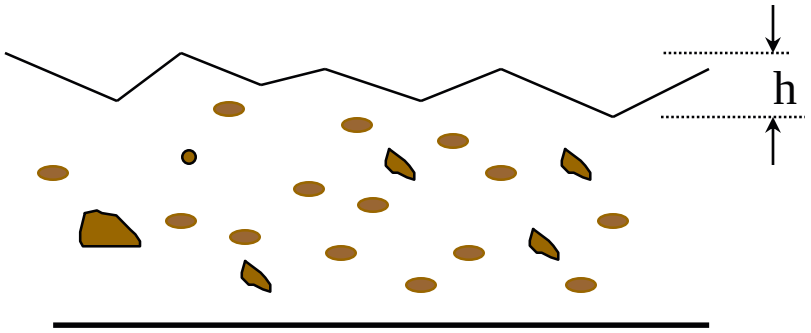
d - leaf thickness
H - canopy height
LAI - leaf area index
m_d – dry matter content

$m_{deg} = 0.52 m_d^2 + 0.84 m_d + 0.51$

β – leaf orientation angle
θ – incident angle of EM wave

Land Surface Roughness Model

$$R_p = [(1-Q)r_p + Qr_q]P$$



Wang's model ($h = 4k^2\sigma^2$): L-band

$$P(k,\sigma,\vartheta) = \exp\left(-4k^2\sigma^2 G(\vartheta)\right)$$

$G = \cos^2\theta$

Coppo's model: 1.4 to 36.6 GHz, an angle range of 10~60 degree.

$$P(\lambda,\sigma;A) = \exp\left(-A\sqrt{\frac{\sigma}{\lambda}}\right)$$

Wegmüller model: 1 to 100 GHz, the incidence angles from 20 – 70 *degree*

$$P = \exp\left(-(k\sigma)^{\sqrt{0.1\cos\vartheta}}\right)$$

m_v - volumatric moisture

ε - dielectric constant of soil solids

ρ_b - density of soil

ρ_s - density of solids

S - sand fraction

C - clay fraction

h - roughness height

q- cross-polarization factor

Improved Surface Roughness Model

Attenuation Function:

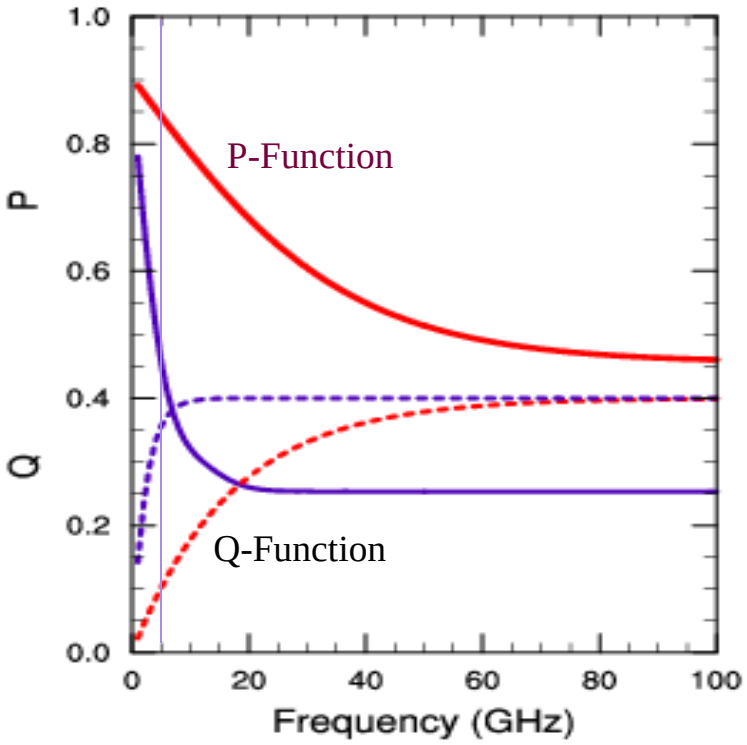
$$P(k,\theta,\sigma) = \frac{1}{2}\left[A + B\tanh\left(\frac{x - x_0}{w_0}\right) + c\tanh\left(\frac{x - x_0}{w_1}\right)\right]$$

$$x(k,\theta,\sigma) = 2k\sigma\cos(\theta) \quad k = 2\pi f \,/\, 30$$

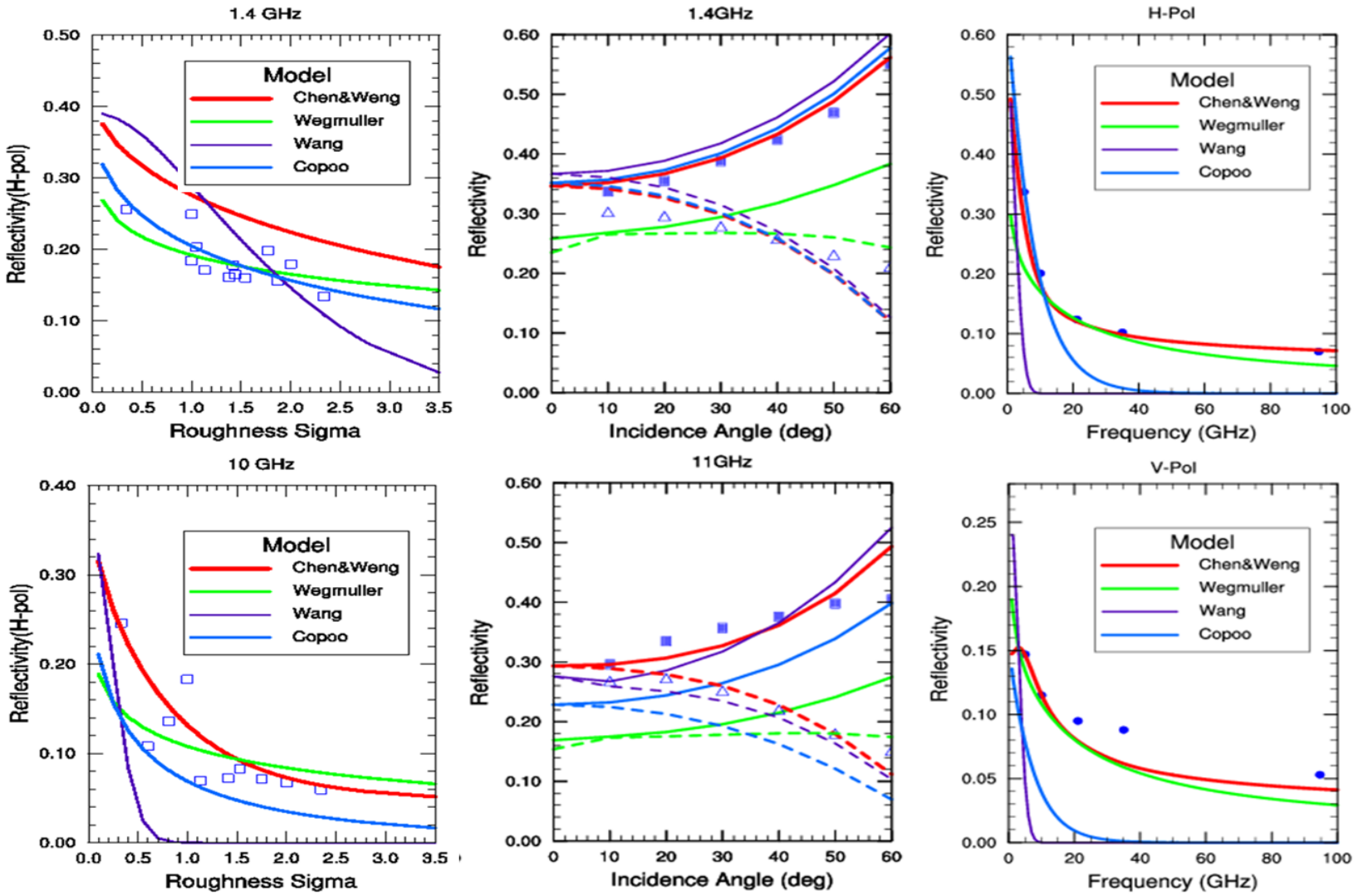
Cross-Polarization Function:

$$Q(\kappa,\sigma,\theta) = B_1(1 - e^{-B_2\kappa\sigma\cos^2\theta})$$

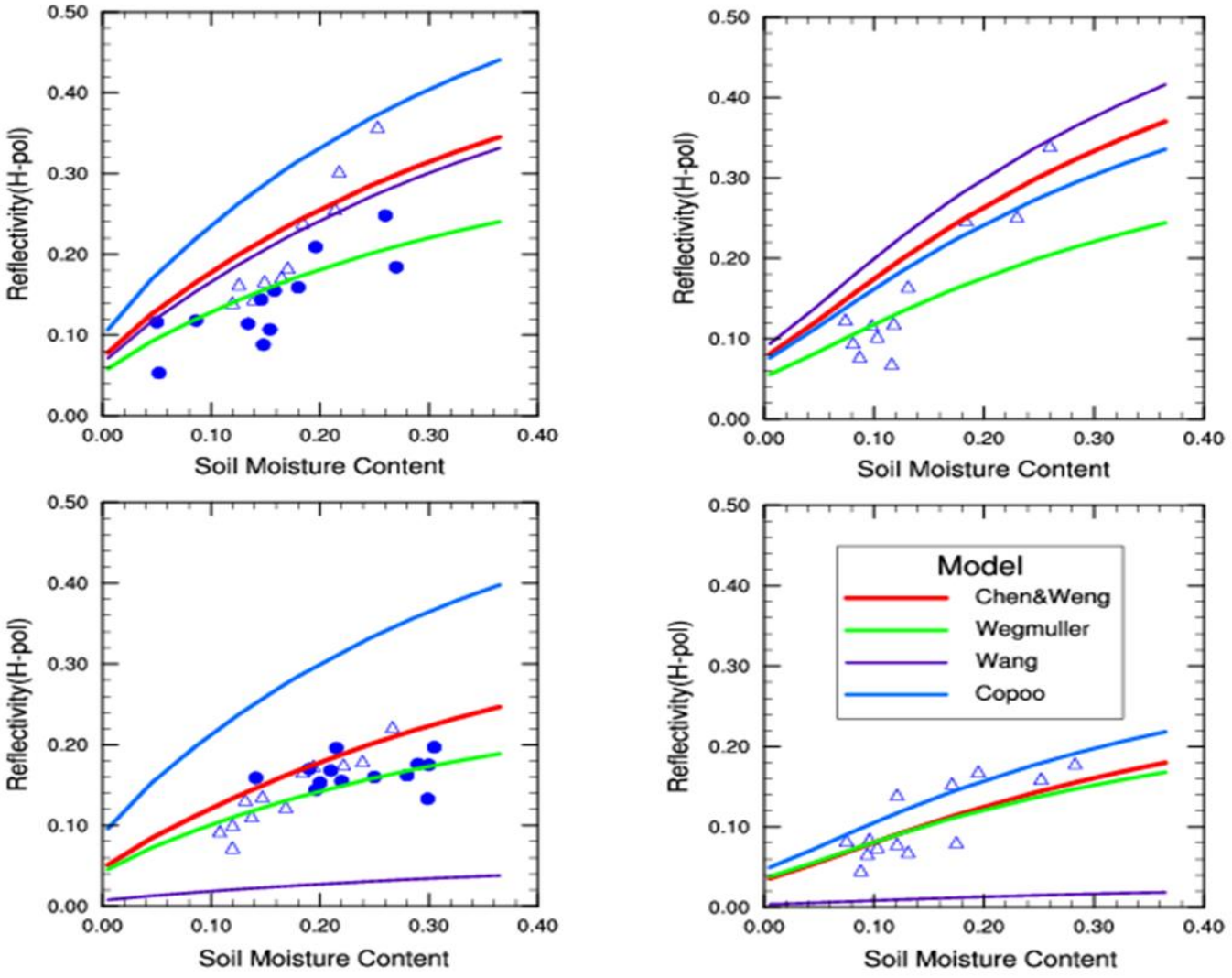
Soil Roughness Correction



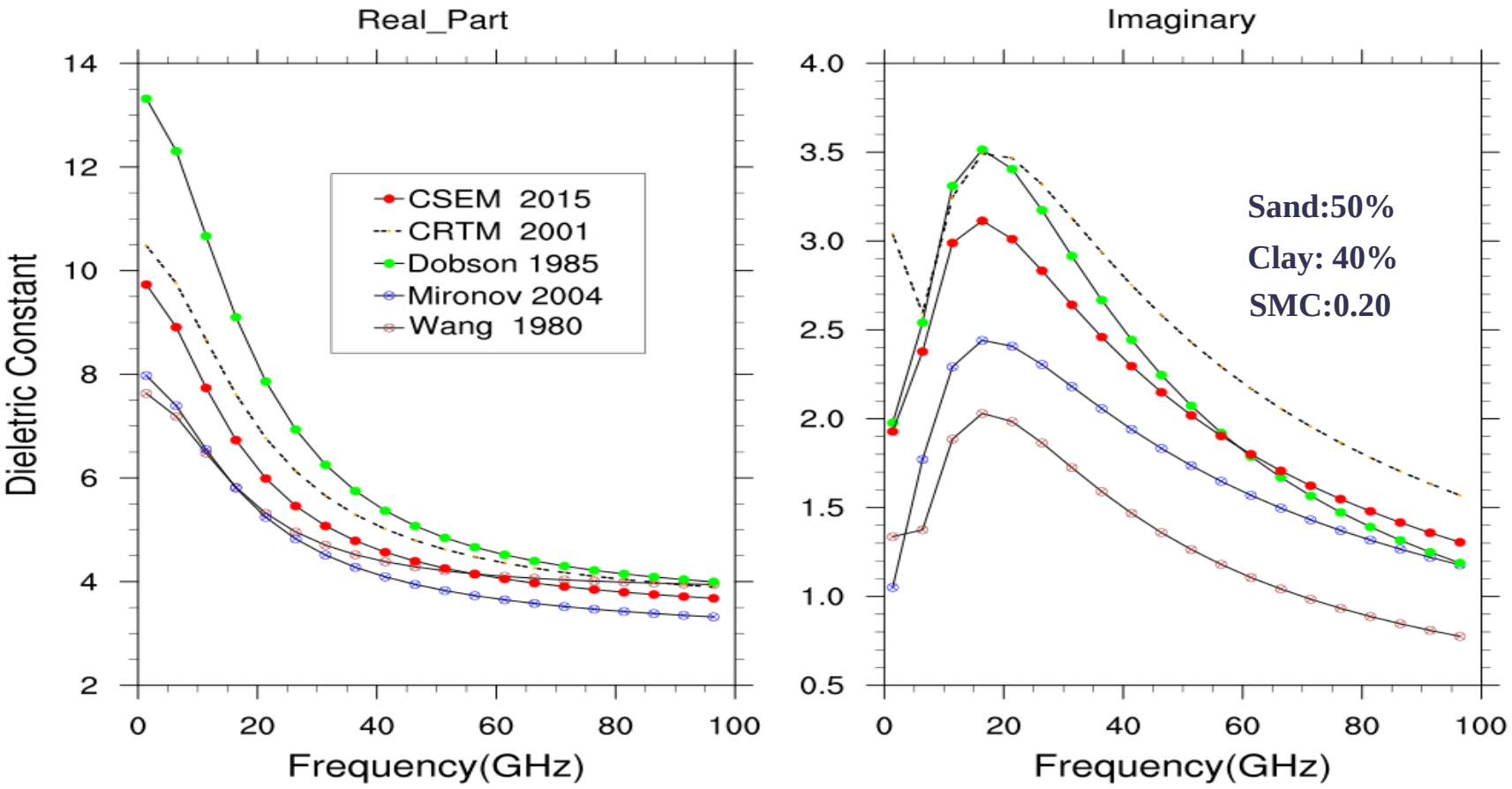
Verification of MW Soil Emission Model with Ground Measurements (1)



Verification of MW Soil Emission Model with Ground Measurements (2)



Optimization of MW Soil Dielectric Model



There also exists large uncertainty in the calculation of the MW soil permittivity. Several soil MW permittivity models (Weng et al 2001; Wang et al, 1980; Mironov et al, 2004; Dobson et al., 1985) are implemented in CSEM for research purpose and model optimization purpose.

Optical Properties of Dense Medium

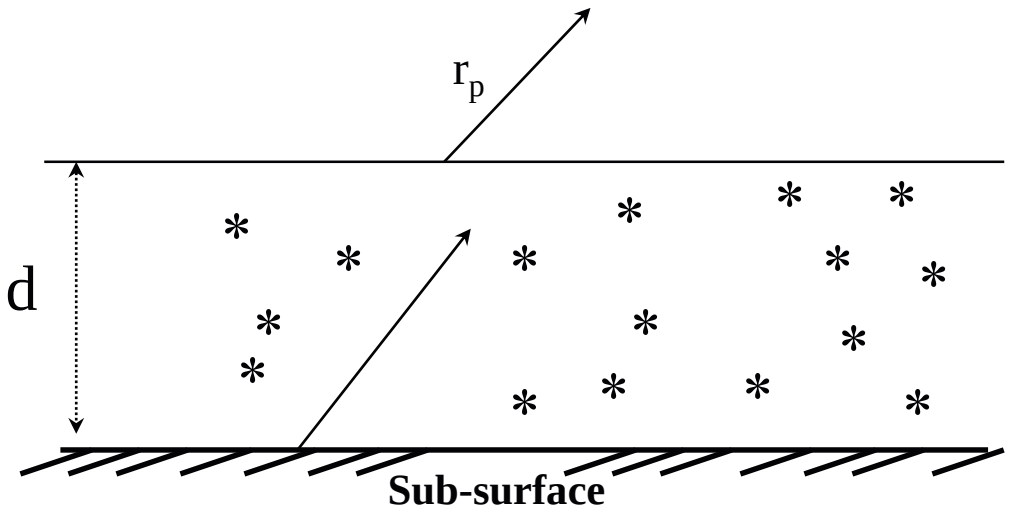
Small perturbation method
(Tsang at al., 1985)

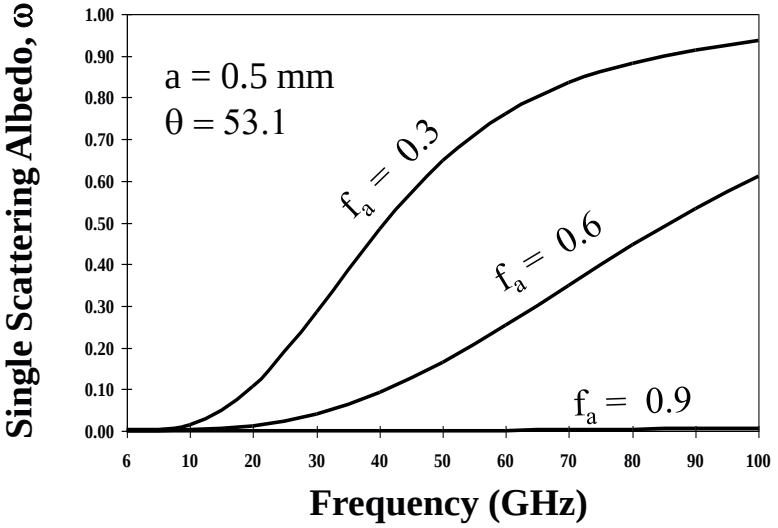
$$\varepsilon_{eff} = \frac{1+2f_a y}{1-f_a y} + i\frac{2f_a y^2(\kappa a)^3(1-f_a)^4}{(1-f_a y)^2(1+2f_a)^2}$$

$$\kappa = \sqrt{3(1-\omega)(1-\omega g)}$$

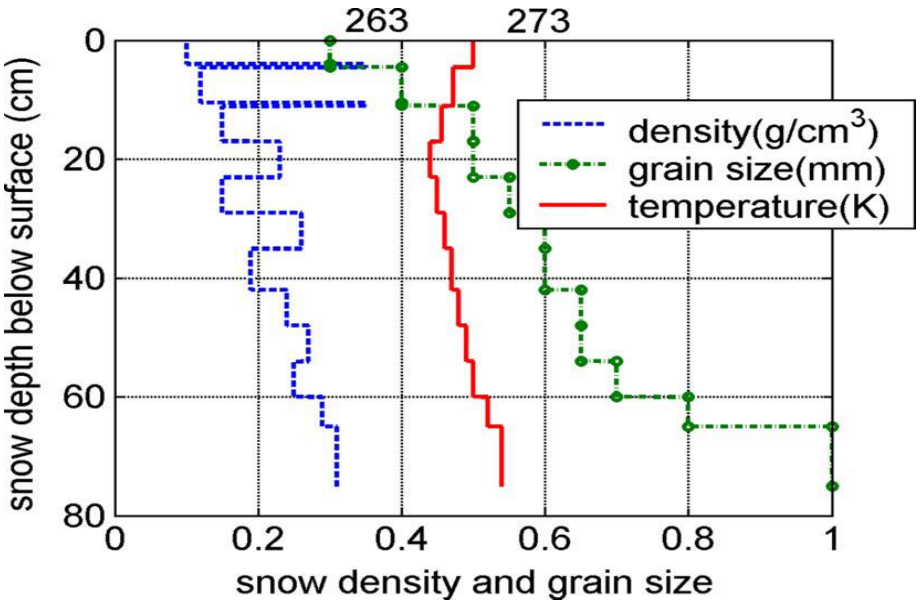
$$y = \frac{\varepsilon_s - \varepsilon}{\varepsilon_s + 2\varepsilon}$$

f_a - ice-volume fraction
d - snow depth
a - snow particle size





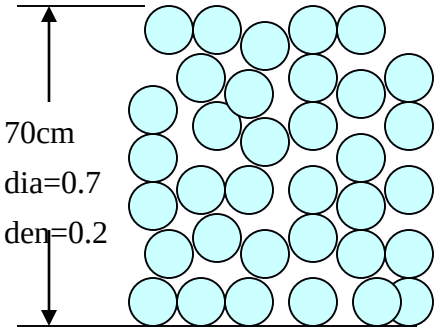
Multilayer Snow Emissivity Modeling



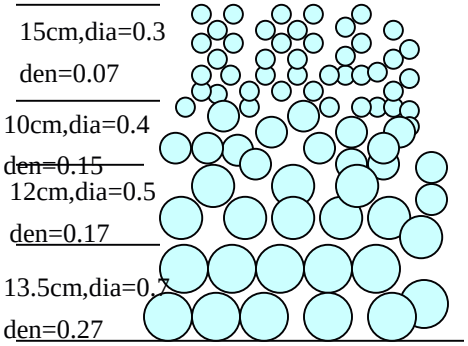
Input snow parameters: **grain size profile, density profile, temperature profile**

Conceptual Model for Vertical Stratification

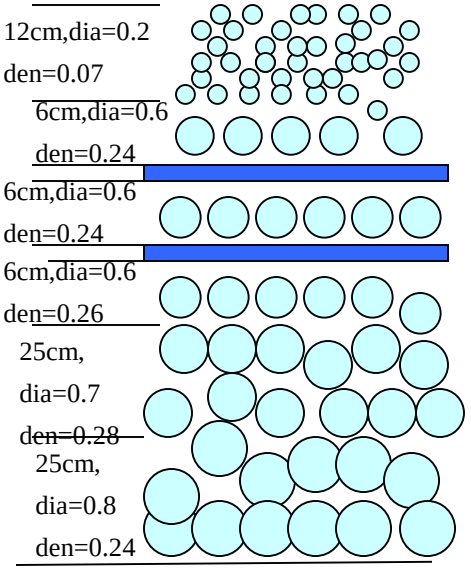
1. New snow pack vertically homogeneous layer



2. New snow with small grain size accumulated on thick snow pack



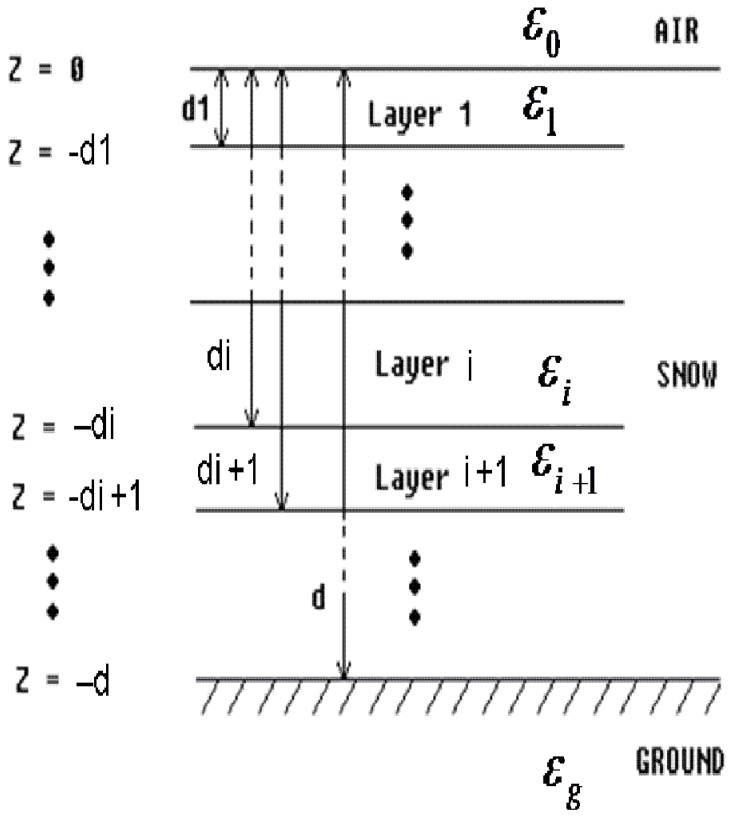
3. New snow with small grain size accumulated on thick snow pack with ice crusts



Dense Media Radiative Transfer Equation

Dense media radiative transfer (DMRT) equations in layer i (Liang and Tsang, 2009) **:**

$$\cos\theta \frac{d\bar{I}_i(\theta,z)}{dz} = -\kappa_{ei}\cdot\bar{I}_i(\theta,z) + \kappa_{ai}T^i + \int_0^\pi d\theta' \sin\theta' \bar{\bar{P}}_i(\theta;\theta')\bar{I}_i(\theta',z)$$



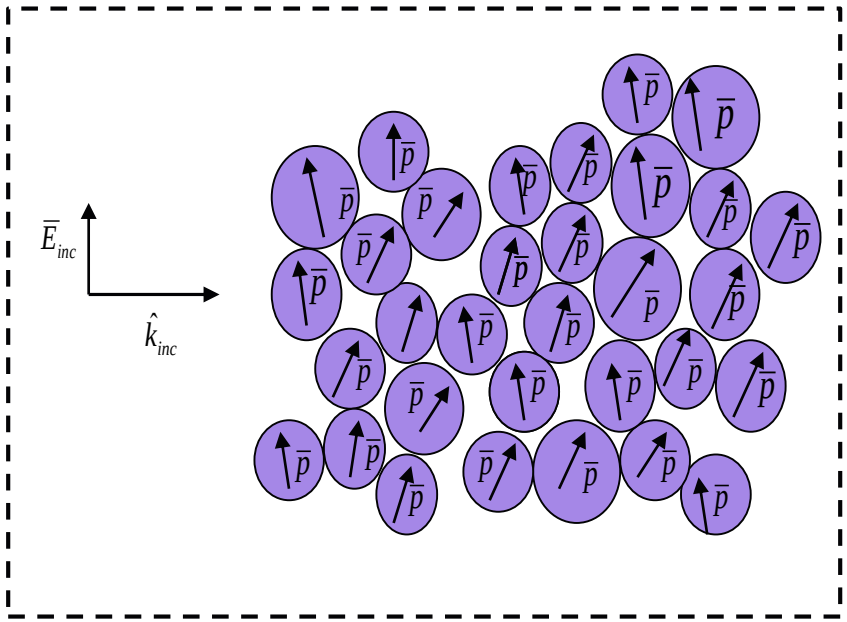
where phase matrix and extinction coefficients are computed using QCA

Dense Media Including Collective Scattering Effects

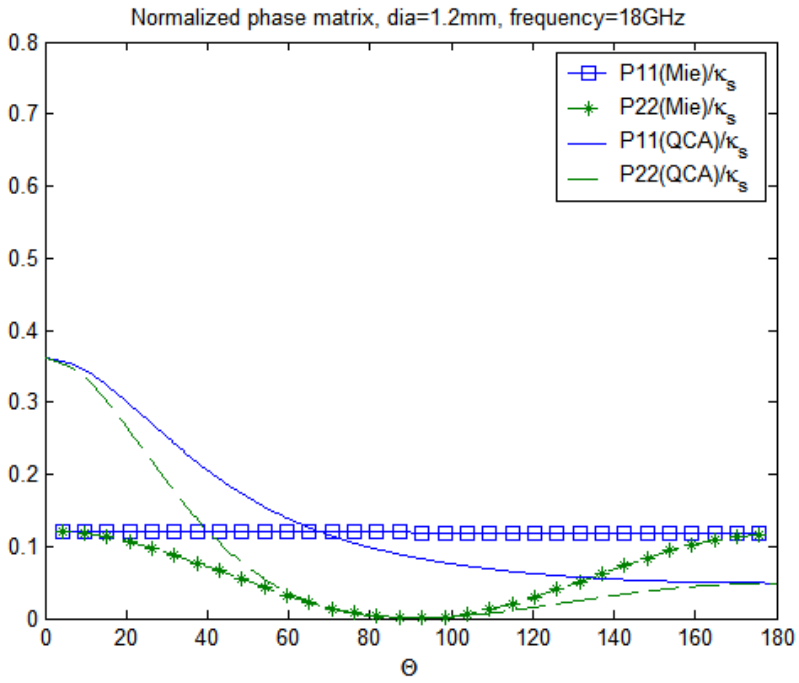
•Snow , dense media ; Particles lie in close proximity much closer than a wavelength; many particles in one wavelength tube

• Induced dipoles in the particles affect each other, near field coherent interactions

• Mutual coherent wave interaction depends on particles' relative positions, i.e. pair distribution functions



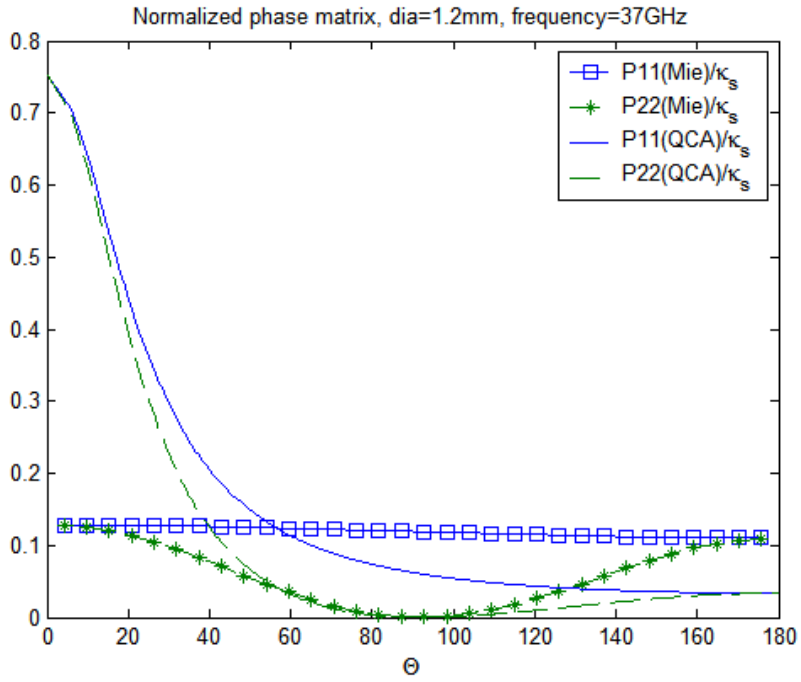
Phase Matrix: QCA compared with Mie Theory



a = 0.06cm

$f = 0.2$

frequency =18GHz,



a = 0.06cm

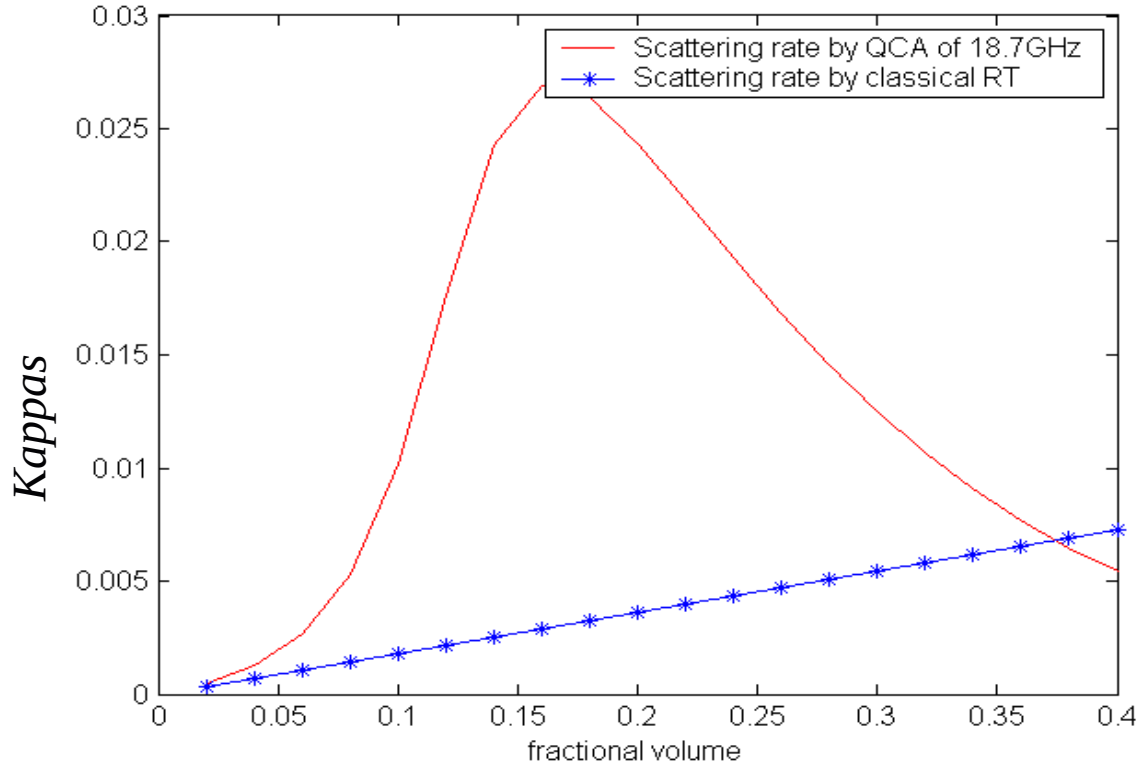
$f = 0.2$

frequency = 37GHz,

Sticky particles (QCA) have larger forward scattering

Sticky particles (QCA) tends to form cluster to have larger effective size

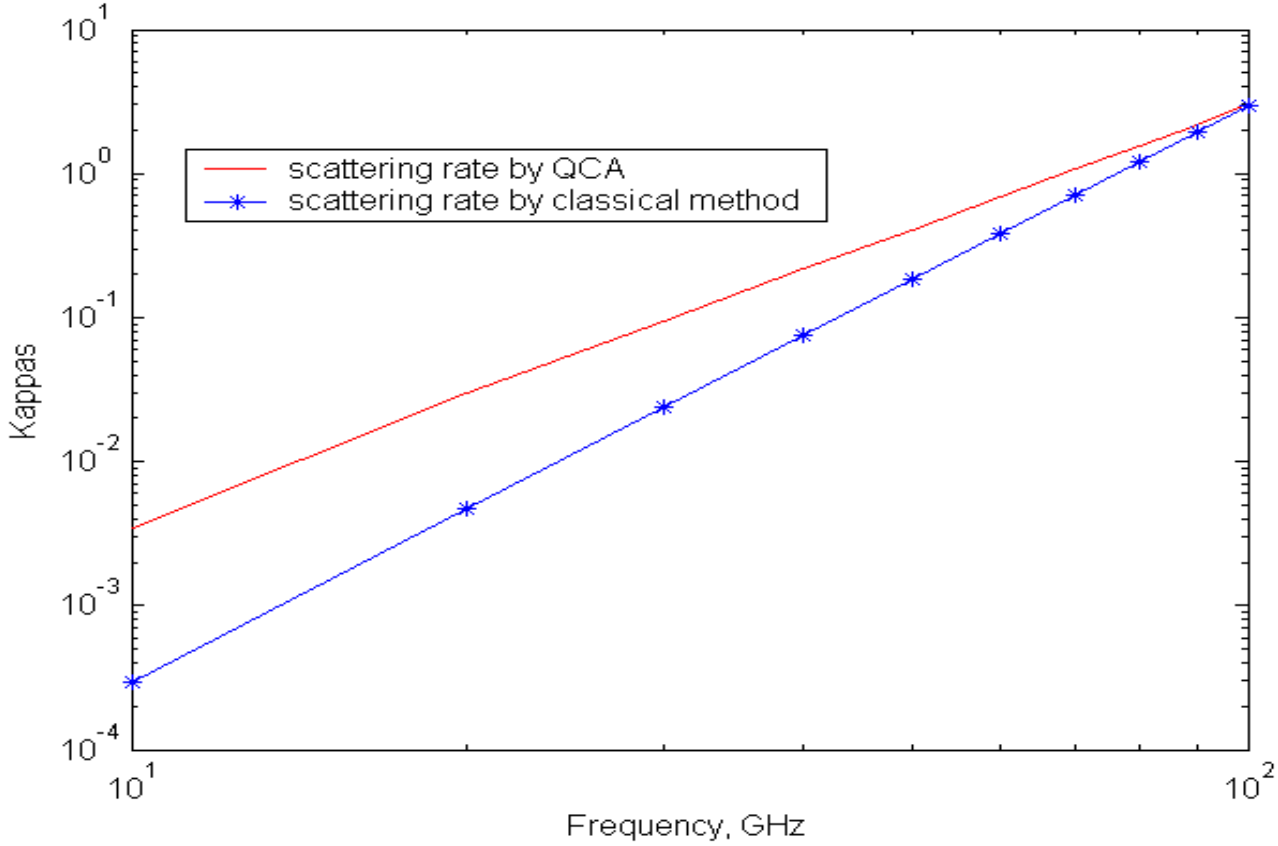
Scattering Efficiency vs Fractional Volume



a=0.06cm,
frequency=18.7GHz

Kappas of QCA is nonlinear of fractional volume in dense media scattering

Scattering Rate: QCA Compared with Mie Theory

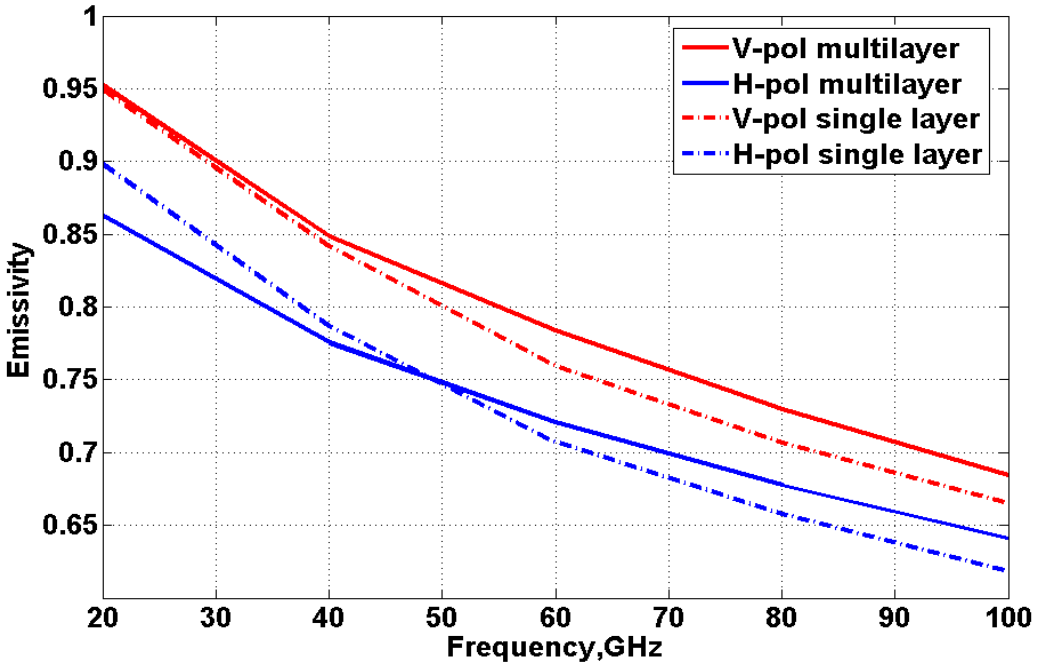


Diameter: 2a = 0.12cm

fractional volume: f=0.2

QCA has weaker frequency dependence

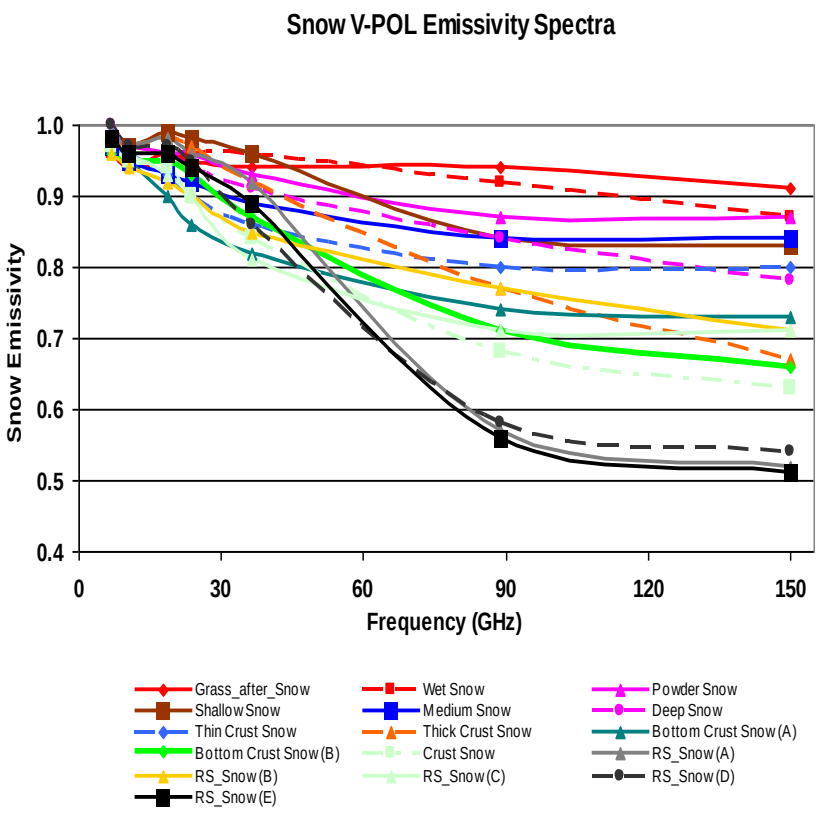
Multilayer vs Single Layer Model Results

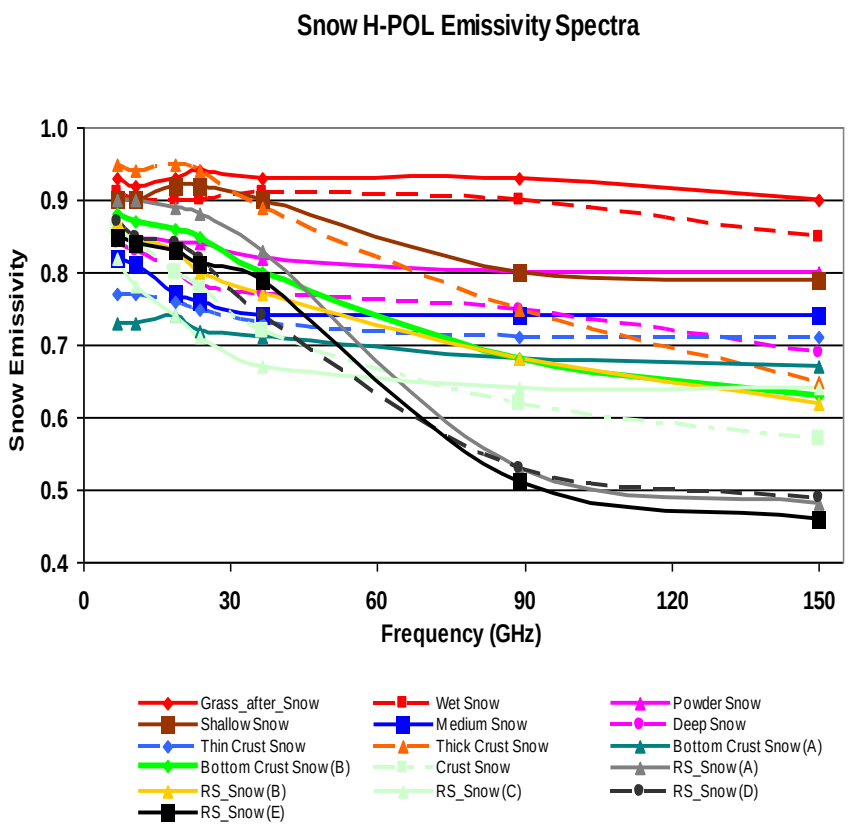


Multi-layer model predicts larger polarization difference and lower frequency difference than a single-layer snow model

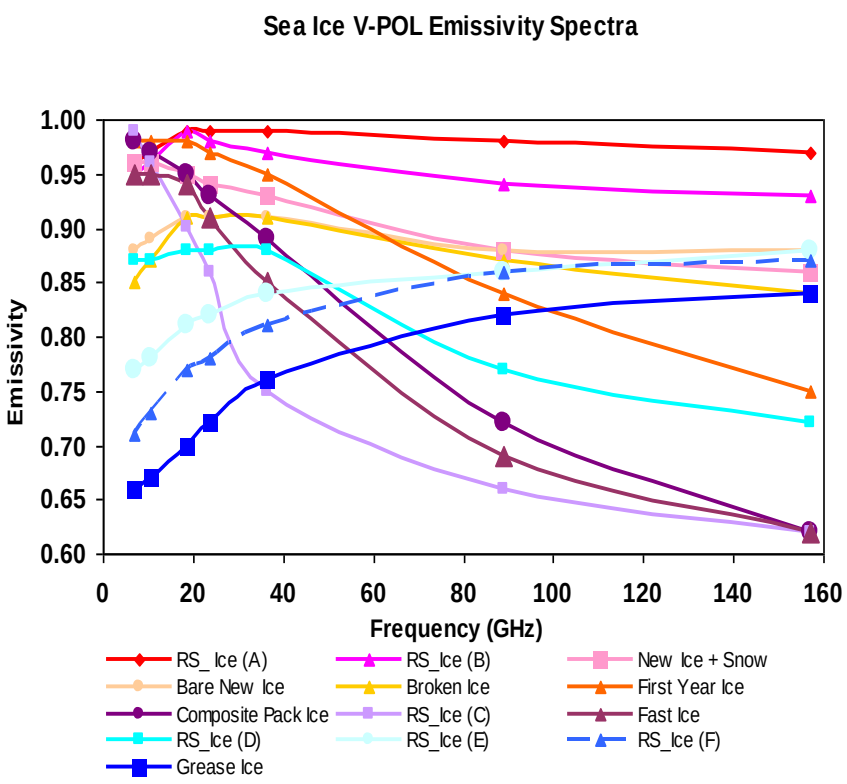
Multi-layer model predicts higher emissivity than a single-layer snow model at high frequency

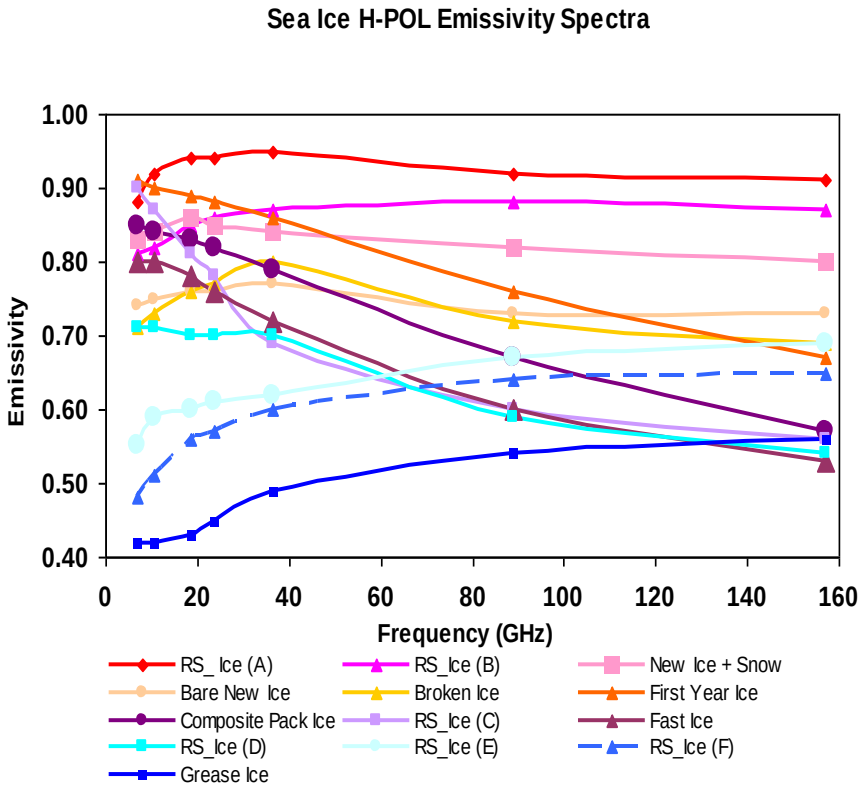
Snow Microwave Emissivity Spectra





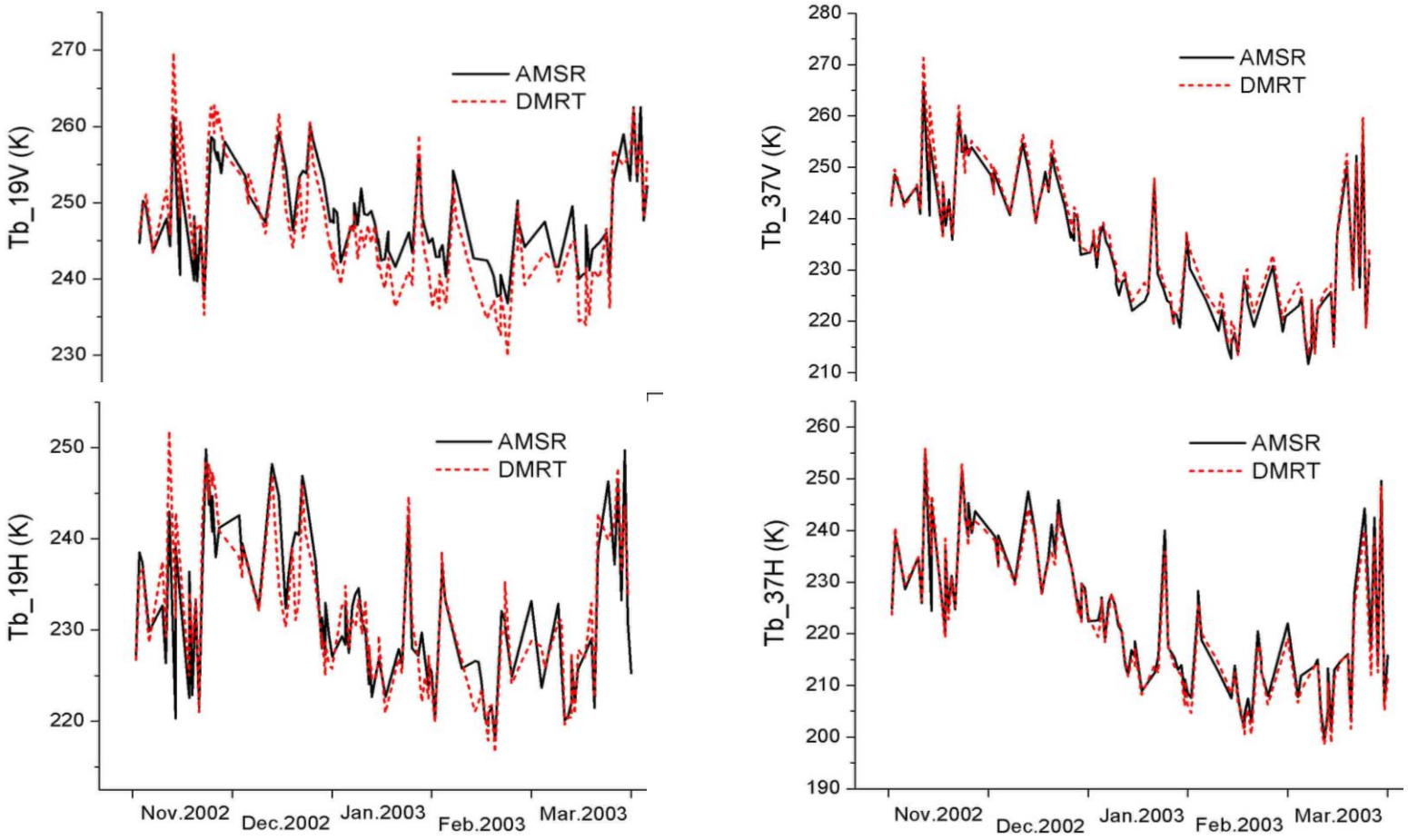
Sea Ice Microwave Emissivity Spectra



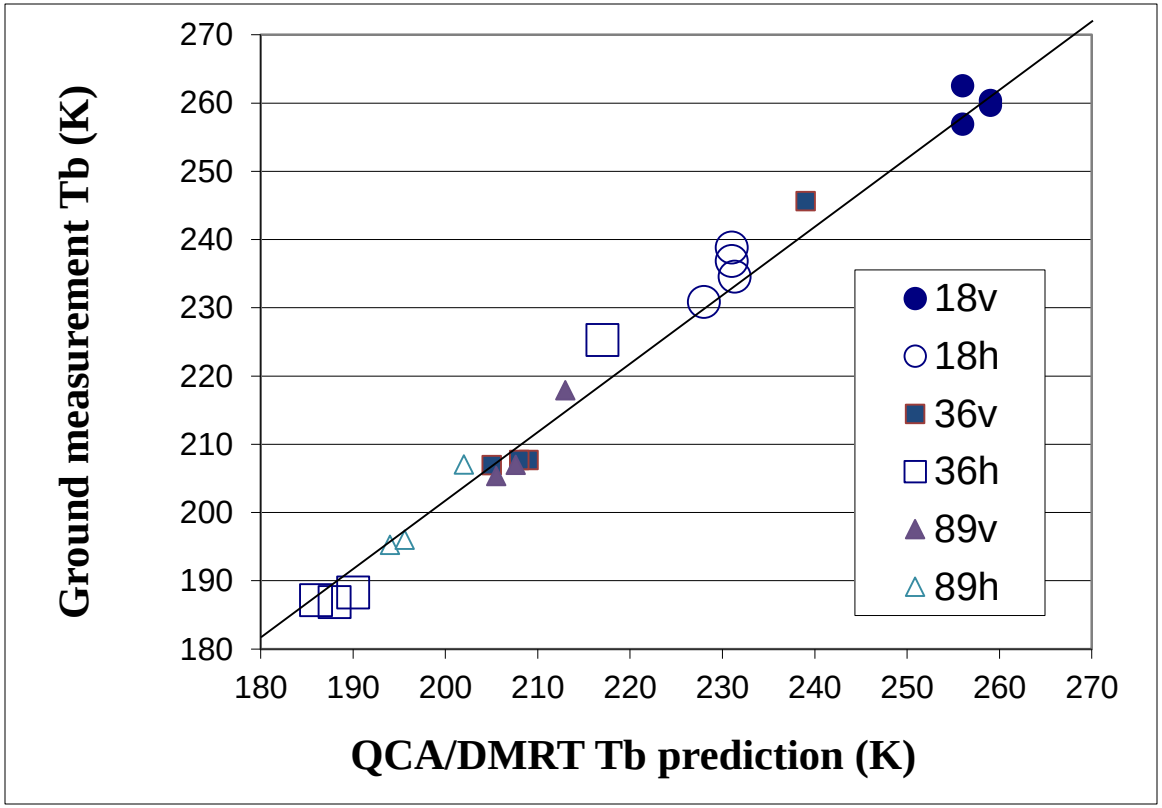


Comparison of DMRT with AMSR Measurements

WMO 71825,52N,66W, 2002,11,1~2003,3,31



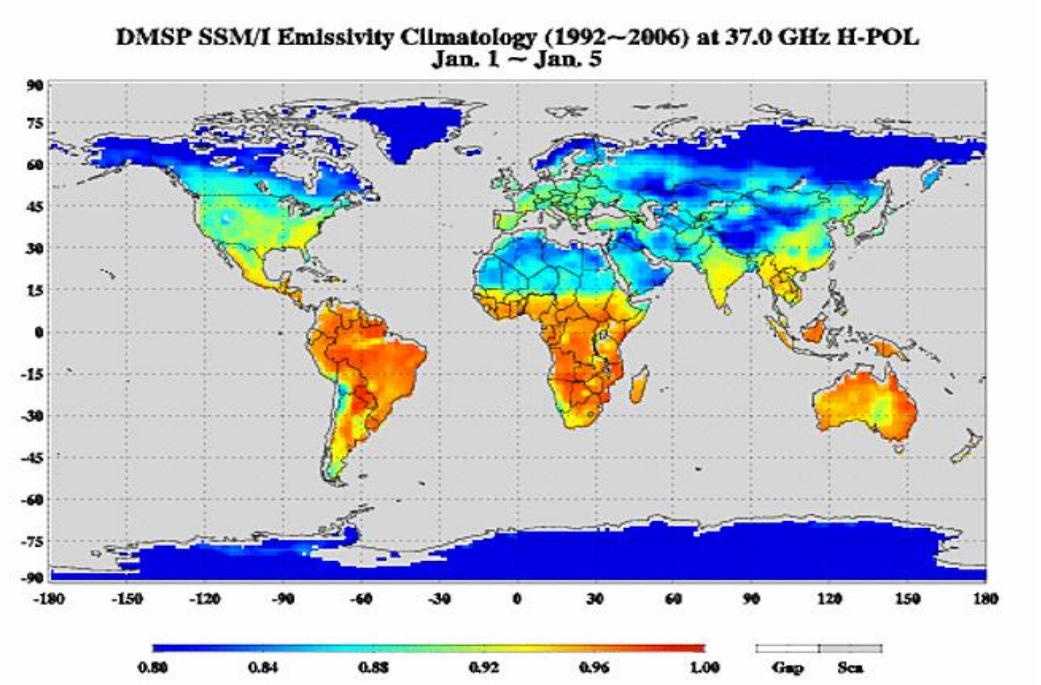
Validation of QCA/DMRT Brightness Temperatures with GBMR Observations



The model Tb prediction shows close agreement with the ground Tb observation

Global Land Emissivity Characterization SSM/I Fifteen Year Time Series

- Large season change at higher frequencies
- Large polarization difference for several surfaces (e.g. desert, snow, flooding)
- Deserts appear as a scattering medium



Click following hyperlinks for other channel emissivity pentad looping images

19V 19H 37V 37H 85V 85H

SSM/I surface emissivity climatological data set is developed at various time scales (e.g. pentad, weekly and monthly, anomaly). SSM/I sensors from F10 to 15 satellites are intercalibrated to a reference satellite (F13)

Summary and Conclusions

- Developed physical modules for surface optical properties
- Improved the surface roughness models (e.g. two-scale model of oceans and Rayleigh approximation of land roughness height)
- Radiative transfer solvers for surface media could be very complex and require considerations of coherent scattering when the particles are close to each other (e.g. surface snow)
- Full polarimetric Stokes components should be included when two media forms a clear interface (e.g. air/snow, air/water)
- Surface scattering related to snow grain, leaf and quartz must be derived through generalized scattering theory (e.g. discrete dipole approximation)
- The permittivity for some soil types at certain wavelength is largely unknown and can be inferred if the spectral properties in other regions are measured
- Remote sensing of surface emissivity is also an active topic and requires removal of atmospheric contributions to the satellite radiances and also a good quality control for removing cloud effects