Observations and Simulations of Microwave Land Emissivity

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ABSTRACT

Sensitivity of brightness temperatures at several AMSU-A and MHS is calculated and classified according to different atmospheric and surface conditions. A typical atmospheric sounding channel can become very sensitive to surface emissivity as atmosphere is relatively dry and surface elevation is higher. A methodology for deriving the microwave land emissivity from satellite observations is discussed. It is found that surface emissivity spectra for snow and desert are mostly complex and need to be further classified into subtype. For simulating the surface emissivity over snow conditions, the dense medium radiative transfer (DMRT) model is developed and the quasi-crystalline approximation (QCA) is used to compute the snow scattering and phase matrix. Comparing to the Mie theory, QCA produces much larger scattering coefficients. Also, the DMRT multilayer model simulates a relatively larger emissivity at higher frequencies.

1. Introduction

The knowledge of microwave and infrared surface emissivity is important for improving the accuracy of atmospheric and surface parameter retrievals (Weng et al., 2001), and the utilization of satellite data in numerical weather prediction models. Variability of land surface emissivity and its spectra are not known well over different surfaces types. The uncertainty in simulating microwave land emissivity is still a major obstacle that affects uses of satellite data over land in NWP systems. In the past, various techniques were developed to retrieve the microwave emissivity over land using the Special Sensor Microwave Imager (SSM/I) together with auxiliary data (Prigent et al., 2006, 2008) and the advanced microwave sounding unit (AMSU) (Karbou et al., 2005; Boukabara and Weng, 2007 and Ruston et al., 2008; and yan et al., 2008). The retrievals of land emissivity spectrum were best performed using the lower frequency channels at 19 and 37 GHz where the need for correcting atmospheric emission is minimal. However, the emissivity spectra can only be derived at the SSM/I viewing angle of 53.1 degree. Also, since the satellite field of view varies with frequency, it is difficult to interpret the SSM/I emissivity spectra over complex terrain, near coast lines, lakes and rivers without reducing all the measurements to the largest satellite field of view.

The models were also developed to simulate microwave emissivity over a variety of land surface conditions. For a land covered by vegetation, the emissivity is simulated for the vegetation canopy that has a distinct orientation of leaves and is characterized with a permittivity value which is a function of canopy water and dry matter content. Snow grains lie in close proximity much closer than a wavelength with many particles in one wavelength tube. As a result, a single dipole scattering from particles affect each other through near-field coherent interactions. Mutual coherent wave interaction depends on the particle relative positions or pair distribution functions. These effects can be simulated through a quasi-crystalline approximation (QCA) (Liang et al., 2008). Also, the Dense-Medium Radiative Transfer (DMRT) model was developed to simulate the snow emissivity for stratified snow (Tsang et al, 1985).

This report will first present a methodology to retrieve the land surface emissivity and highlight the critical aspects that need to be addressed in the emissivity modeling.

2. Satellite Radiance Sensitivity to Surface Emissivity

To illustrate the importance of surface emissivity in radiative transfer, we first use an approximated radiative transfer equation. The radiation emanating from a scattering-free atmosphere is related to surface emissivity, ε, and surface temperature, Ts, through

$$T_B = \varepsilon T_s \Gamma + T_u + (1-\varepsilon) T_d \Gamma \quad (1)$$

where T_u and T_d are the brightness temperatures associated with upwelling and downwelling radiation components, respectively, and Γ is the atmospheric transmittance. In the satellite data assimilation scheme, we need to calculate the brightness temperatures at various frequencies with surface emissivity information. An error in surface emissivity Δε can result in an error in brightness temperature, viz.

$$\Delta T_B = \Gamma (T_s - T_d) \Delta\varepsilon \quad (2)$$

Assume Δε of 0.04 which is the error of surface emissivity, Table 1 lists the errors of brightness temperatures at the top of atmosphere. Apparently, at a window channel where Γ is relatively large (or atmosphere is relatively transparent) and T_d is also small, the emissivity uncertainty can have some significant effects on brightness temperatures. For example, at 150 GHz, ΔT_B is about 8.8 K when total precipitable water, *TPW* is 0.5 mm, T_s is 230 K and surface pressure, P_s is 600 hPa. At the microwave sounding channels near the 50 - 60 GHz oxygen absorption band, ΔT_B decreases as the frequency approaches to the center of the absorption band. However, the effect of surface emissivity

Table 1. Biases (ΔT_B) in brightness temperatures at several microwave window and low sounding channels due to a bias of 0.04 in emissivity.

Frequency (GHz)	Ts = 230 K and TPW = 0.5 mm					
	Ps = 600 (mb)			Ps = 1000 (mb)		
	Td(K)	τ	ΔT_B(K)	Td(K)	τ	ΔT_B(K)
6.925	1.50	0.99	9.08	4.00	0.98	8.87
10.65	1.60	0.99	9.07	4.40	0.98	8.84
18.7	2.30	0.99	9.02	6.20	0.97	8.70
23.8	3.30	0.98	8.93	8.50	0.96	8.51
36.5	7.10	0.97	8.63	19.10	0.91	7.69
50.3	49.30	0.77	5.59	112.50	0.49	2.29
52.8	111.20	0.49	2.34	188.60	0.15	0.25
89	8.20	0.96	8.54	22.30	0.90	7.46
150	4.40	0.98	8.84	12.50	0.94	8.21
183.3±7	16.60	0.93	7.89	43.50	0.81	6.02
183.3±3	55.30	0.75	5.24	104.10	0.54	2.71
183.3±1	134.60	0.39	1.50	160.10	0.29	0.81

on brightness temperature at 52.8 GHz can be still significant at the high elevation area. For example, ΔT_B increases from 0.2 K to 2.3 K as P_s decreases from 1000 to 600 hPa. At the water vapor sounding channels near 183.3 GHz water vapor absorption band, ΔT_B strongly varies with *TPW*, P_s, and frequency. At 183.3 ± 7 GHz which is the furthest from the center of water vapor absorption band, ΔT_B increases from 1.8 K to 6.0 K as *TPW* decreases from 2.0 to 0.5 mm for P_s of 1000 hPa. For P_s of 600 hPa, ΔT_B is up to 7.9 K. At 183.3±1 GHz, the impact of surface emissivity on brightness temperature is the smallest (~ 0.01 K) for a *TPW* of 2.0 mm. However, for a drier atmosphere, the impact is significantly higher, especially over a region where the surface pressure is lower. For example, ΔT_B at 183.3±1 GHz increases from 0.8 K to 1.5 K as P_s decreases from 1000 to 600 hPa for *TPW* of 0.5 mm. Therefore, the lower sounding channels (e.g. 183.3 GHz) can be highly affected by surface under a dry atmospheric condition.

3. Microwave Land Emissivity Spectra

From Eq. (1), microwave emissivity can also be derived analytically, assuming other parameters such as atmospheric transmittance, upwelling and downwelling radiation components can be determined accurately from other data sources, i.e.,

$$\varepsilon = \frac{T_B - T_u - T_d \Gamma}{\Gamma\left(T_s - T_d\right)} \tag{3}$$

where T_B is the observed satellite brightness temperature at the required frequency. In our studies, the transmittance, upwelling and downwelling radiation components are computed using the temperature and water vapor profiles from NWP model analysis fields. Some of these parameters such as downwelling radiation can also be observed from ground-based up-looking radiometers.

The accuracy of emissivity retrieved from Eq. (3) is affected by the quality of atmospheric profiles. A good quality control of satellite data is also important. If the brightness temperatures are observed under a cloudy condition and are used in the emissivity calculation, the errors will likely to be significantly higher since the analysis fields from NWP models do not normally include the reliable cloud parameters for radiative transfer calculations. The errors in brightness temperature calibration can also cause some errors in emissivity. In the past, the satellite measurements in various formats have been used in many of emissivity studies but some of the data sets used in the studies in literature were the antenna brightness temperatures which include the spill-over contributions from the antenna sidelobe and the leakage from cross-polarization. It should be made clear that in our studies satellite measurements in the format of sensor data record (SDR) are used for retrievals. For microwave data archived at NOAA, satellite data in Level 1B radiances can be also used in the studies. However, the corrections for the antenna sidelobe effect, though the magnitudes are small, were not included in Level 1B data. Users should request a separate algorithm for each NOAA microwave instrument in order to do the antenna temperature correction.

Using SSMIS, AMSR-E SDR and some ground-based radiometer measurements at lower frequencies, we can now derive the emissivity spectra for various surface conditions. For example, the emissivity spectra associated with snow types are derived and shown in Figure 1. For shallow, power and deep snow, their emissivity slowly decreases as frequency increases. When the snow metamorphoses to form a crust layer in the bottom, the emissivity decreases rapidly with frequency. For wet snow, the emissivity does not exhibit a significant spectral change.

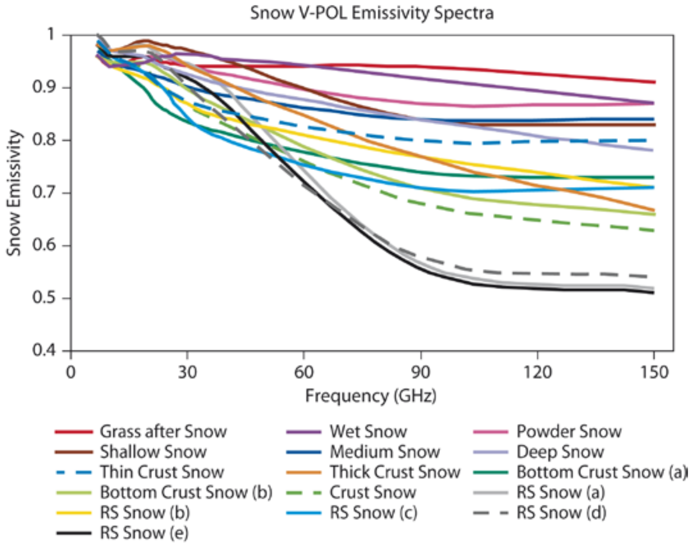

Figure 1. Snow microwave emissivity spectra between 4.9 and 150 GHz

Using AMSR-E, we derive emissivity spectra over desert conditions at both polarization states as shown in Fig. 2. A largest polarization difference occurs at the lowest frequency (6 GHz). For a soil with more organic materials, the emissivity at the horizontal polarization is the lowest at 6 GHz and increases rapidly with frequency (pink). For sandy/loam sand, the emissivity is much higher for vertical polarization (red and blue on right panel).

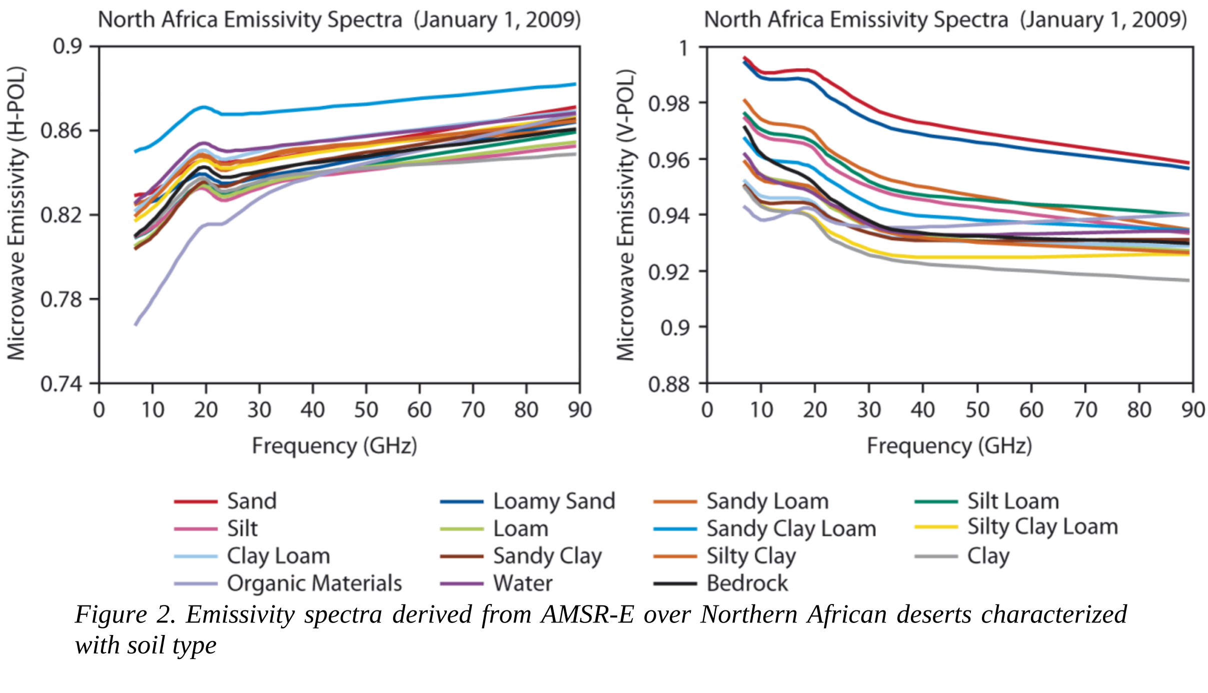

Figure 2. Emissivity spectra derived from AMSR-E over Northern African deserts characterized with soil type

It should be pointed that relative lower emissivity values at the horizontal polarization at 23 GHz (left panel above figure) may be associated with the errors in calculating the various terms in Eq. (3) from uses of NWP analysis fields and/or the errors of the water vapor absorption coefficient in the forward model.

4. Microwave Land Emissivity Modeling

The MW land emissivity model computes land surface emissivity for various surface types, including snow, deserts and vegetation using the two-stream radiative approximation (Weng et al, 2001). The reflection and emission occurring at the interfaces above and below the scattering layer are taken into account and the cross polarization and attenuation due to surface roughness are parameterized as a function of roughness height and frequency. For the vegetation canopy the optical parameters are derived using geometric optics. For a medium with a higher fractional volume of particles such as snow and deserts, the scattering and absorption coefficients are approximated using the dense medium theory. The model takes satellite zenith angle, MW frequency, soil moisture content, vegetation fraction, soil temperature, land surface temperature and snow depth as inputs and computes surface emissivity at V and horizontal H polarizations.

Overall, the emissivity model correctly simulates the spectra, comparing to the observations. For a newly formed snow, the emissivity spectrum is similar to those new and powder snow in Figure 1. The emissivity for corn fields, the emissivity slightly varies with frequency. For a comparison, the emissivity spectra for oceanic surfaces are also plotted.

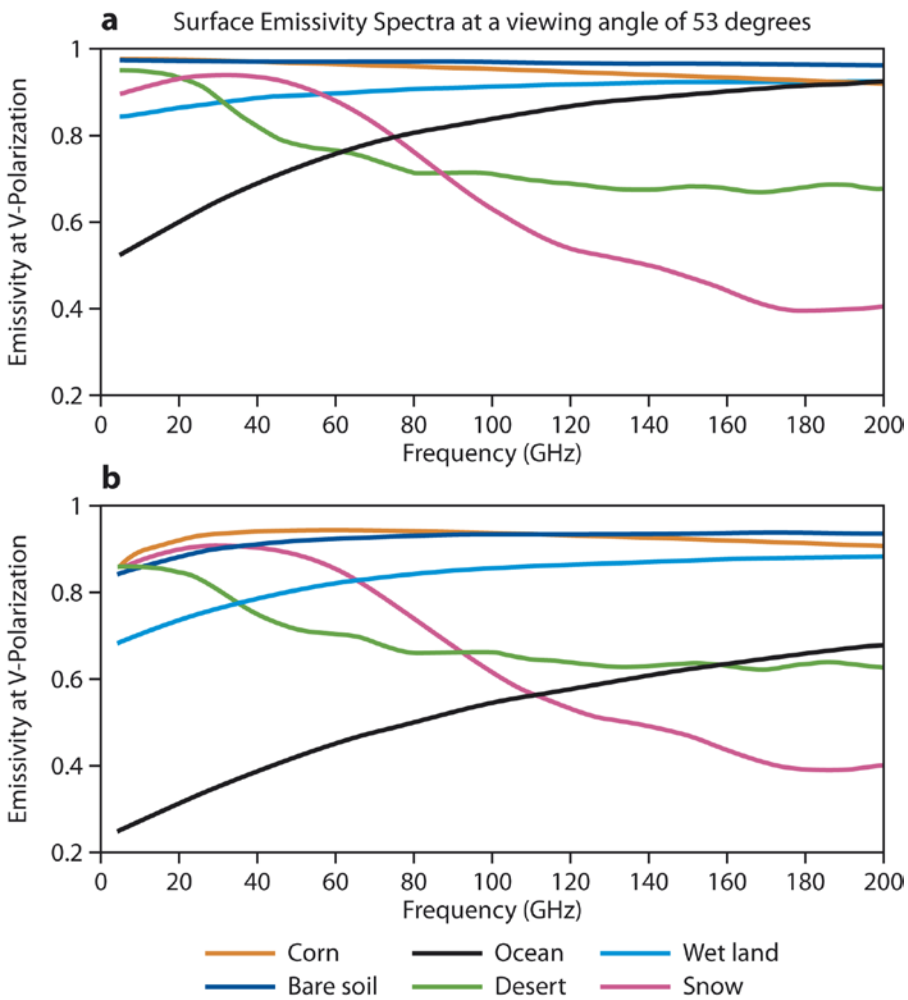

Figure 3. The emissivity simulated using the surface radiative transfer model (Weng et al., 2001).

After snow experiences a metamorphosis process, it forms stratification and snow grains become sticky and clustering. The aged snow requires a dense media radiative transfer (DMRT) theory with the quasi-crystalline approximation (QCA) which provides more accurate results when compared to emissions determined by a homogeneous snowpack and other scattering models (Liang et al., 2008).

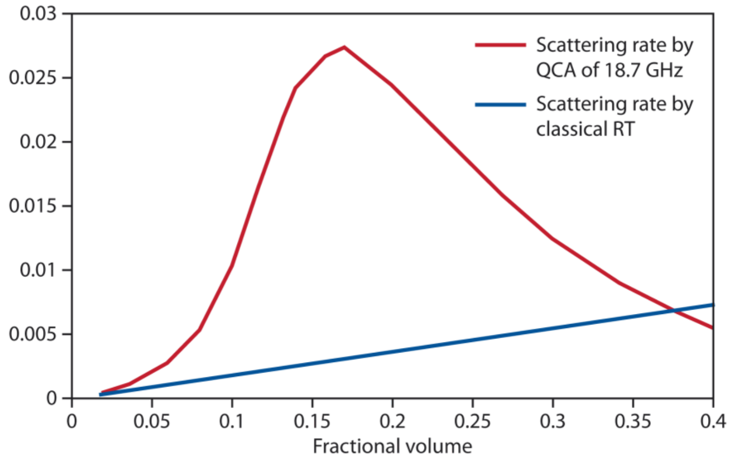

Figure 4. Scattering coefficients for a particle of 0.6 mm in diameter, derived from QCA (red line) compared with Mie scattering, as a function of particle fraction volume.

In general, the QCA derives a much larger scattering as the fractional volume of particles is a range of 0.1- 0.25. As the fractional volume increases to 0.4, the scattering coefficient is smaller than from Mie. A directional scattering from QCA in term of phase matrix elements is also significantly different from Mie phase matrix and is more dominant in forward direction (Liang et al., 2008).

The DMRT can account for adhesive aggregate effects, which leads to dense media Mie scattering by using a sticky particle model. With the multilayer model, both the frequency and polarization dependence of the brightness temperatures from representative snowpacks are derived and compared to the results from a single-layer model. It is found that the multilayer model predicts higher polarization differences, twice as much, and weaker frequency dependence (Liang and Weng, 2010). However, the emissivity decreases as more rapidly with frequency compared those from observations. This needs to be further investigated.

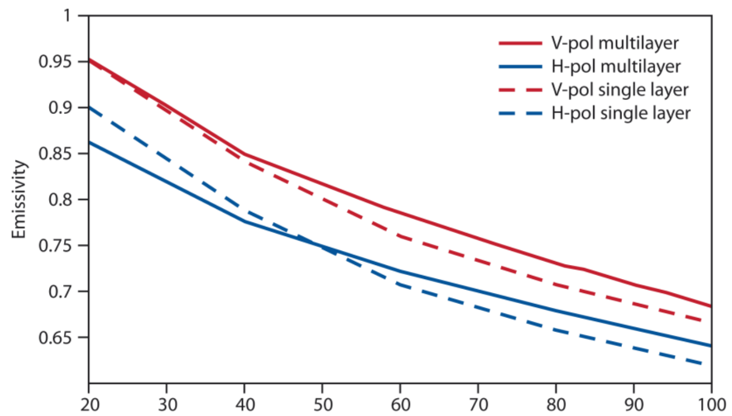

Figure 5. Snow surface emissivity derived from a multilayer vs. single layer DMRT model.

5. Concluding Remark

Currently, microwave land emissivity can be derived through several approaches such as 1DVAR and an analytic approach. In 1DVAR system, the emissivity can be treated as a state vector with the error covariance generated from the emissivity model. The study is more suitable for the satellite measurements with both sounding and imaging channels together such as SSMIS and AMSU-A/MHS (Boukabara and Weng, 2007; Ruston et al., 2008).

Various groups are now using an analytic approach as discussed in this paper to derive the land surface emissivity. However, the quality of the emissivity retrievals is more affected by the input profiles that are used to compute atmospheric contributions to satellite brightness temperatures. Some other factors such as calibration, atmospheric spectroscopy and approximation of surface reflection can all have some additional influences on the results.

An evaluation of the emissivity spectra over various surface conditions is important. It is believed that at microwave frequencies the surface emissivity has no specific resonance feature at any frequency. Thus, the emissivity should display a smooth transition throughout wavelength. The emissivity spectra could be manifested as some strange features at some channels if atmospheric contributions are not computed correctly and satellite observations include some calibration errors.

Modeling of microwave land emissivity remains qualitative in nature. At this stage, most of the emissivity model inputs are not available by any means. Thus, it is difficult to rule out if the model likely has a problem or the inputs are not adequate for the modeling requirements. In general, inputs such as canopy water content and gravimetric soil moisture, and snow grain profiles must be parameterized in NWP land surface model outputs. However, the emissivity models do offer some unique tests of physical retrievals of surface parameters from satellite microwave technology.

6. References

Boukabara, S., and F. Weng, 2007: Microwave emissivity over ocean in all-weather conditions. validation using WINDSAT and airborne GPS-Dropsondes, *IEEE Trans Geosci., Remote Sens.*, **46**, 376-384

Karbou, F., C. Prigent, L. Eymard, and J. R. Pardo, 2005: Microwave land emissivity calculations using AMSU measurements, *IEEE Transactions on Geoscience and Remote Sensing*, **43**, 948-958.

Liang, D., X. Xu, L. Tsang, K. M. Andreadis, and E. G. Josberger, 2008: The effects of layers in dry snow on its passive microwave emissions using dense media radiative transfer theory based on the Quasi-Crystalline Approximation (QCA/DMRT), *IEEE Trans. Geosci. Remote Sens.*, **46**, 3663-3671.

Tsang, L., J. A. Kong and R. T. Shin, 1984: Radiative transfer theory for active remote sensing ellipsoidal scatterers, *Radio Science*, **19**, 629-642.

Prigent, C., F. Aires, and W. B. Rossow, 2006: Land surface microwave emissivities over the globe for a decade, *Bull. Amer. Meteorol. Soc.*, **87**, 1573 - 1584.

Prigent, C., W. B. Rossow and E. Matthews, 1997: Microwave land surface emissvities estimated from SSM/I observations, *J. Geophys. Res.*, **102**, 21, 867-21,890.

Ruston, B., F.Weng, B. Yan, 2008: Uses of 1D var retrieval to diagnose estimates of infrared and microwave surface emissivity over land for the ATOVS sounding instruments, *IEEE Trans. Geosci. Remote Sens*., **46**, 393-402

Tsang, L., J. A. Kong, and R. T. Shin, 1985: *Theory of microwave remote sensing*, A Wiley-Interscience Publication, John Wiley & Sons, 613.

Weng, F., B. Yan, and N. Grody, 2001: A microwave land emissivity model, *J. Geophys. Res*., **106**, 20,115 - 20,123.

Yan, B., F. Weng, and H. Meng, 2008: Retrieval of Snow Surface Microwave Emissivity from Advanced Microwave Sounding Unit (AMSU), *J. Geophys. Res*., **113**, D19206, doi:10.1029/2007JD009559.