Use of uniform distribution for generating synthetic brightness temperature in passive microwave soil moisture retrieval

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ABSTRACT: Passive microwave remote sensing technique have shown great potential for monitoring regional/global surface soil moisture. Given a single measurement at dual polarization/single frequency/single view angle, a strategic approach to artificially generating multiple microwave brightness temperatures is presented. And then the statistically generated microwave brightness temperature data are applied to the inverse algorithm, which mainly relies on a physically based microwave emission model and an advanced single-criterion multi-parameter optimization technique, to simultaneously retrieve soil moisture and vegetation characteristics.. The procedure is tested with dual polarized Tropical Rainfall Measurement Mission Microwave Imager (TRMM/TMI) over two different cover sites in Oklahoma and Beltsville field experimental data. The retrieval results are analyzed and show excellent performance.

Keywords: Soil moisture, Optical depth, Passive microwave, Multi-configuration

1 INTRODUCTION

Surface soil moisture plays a major role in water and energy balance at the land surface/atmosphere interface, which has direct implications in hydrological, climate, and weather forecasting model. There is an urgent need to have access to distributed soil water fluxes over a large scale on a regular basis. The estimation of the ratio between baseflow and surface runoff is still imprecise and correct estimation of surface soil moisture in the vedose zone is an important issue for short/medium term hydrologic modeling and the monitoring of plant carbon dioxide assimilation and plant growth (Kerr et al., 2001). Passive microwave remote sensing has been a promising tool for monitoring regional/global surface soil moisture and scientists mainly rely on a physically based microwave emission model in the passive soil moisture remote sensing and various factors of surface characteristics contribute to the final surface microwave signal. The nonlinearity of the microwave emission model and the uncertainty of the parameter measurement make the retrieval process more difficult. Alternatively it is likely that many scientists have turned to the two-parameter or three-parameter method, which retrieves surface soil moisture/vegetation properties or surface soil moisture/effective temperature/vegetation properties simultaneously from the multi-configuration (frequency, polarization, and view angle) (Kerr et al., 2001) microwave observations.

The two/three-parameter method are advantageous in that there is no need to prescribe the vegetation water content and the opacity coefficient, b in the retrieval process, despite of the requirement of better understanding of the dependency of the optical depth on the system configuration parameters (frequency, polarization, and view angle). However, in practice, there are some obstacles to apply the two/three parameter approach for the microwave brightness temperature observations, which are not originally designed for multi-configuration observations, because of the small number of observations. To apply the two/three parameter retrieval approach with suitable optimization scheme, a set of multiple observations at a fixed time and space is essential.

The main goal of the study is to present a strategic statistical approach to generating a set of synthetic microwave brightness temperature from a single measurement, which is dual-polarized but single frequency/single view angle at a fixed time and space, for the simultaneous retrieval of surface soil moisture and optical depth. Then the set of data generated are used to retrieve the surface variables on the basis of a physical emission model.

2 STUDY REGION AND DATA

There are two different data sets used in this study: one is satellite-based and the other is truck-mounted field experiment. The first data set is facilitated in two distinct 36km grid areas in Oklahoma in association with biomass: middle (hereafter named NORM) and low (hereafter named KING) vegetation (Lee, 2005). The TRMM/TMI is a nine-channel passive microwave radiometer and the TRMM data used in this study is the 10.7 GHz channel of Microwave Imager (TMI) measurements. The footprints of TRMM/TMI (Kummerow et al., 1998) from successive scans overlap the previous scans, which are dual-polarization with the view angle of 52.75^{o} at 10.7 GHz. The EFOVs of TMI is ~9.1km for single sample regardless of their actual beam widths, which is the result of only one integration time period. The standard TMI brightness temperature data, which is considered as equivalent beam EFOV, can be formed by joining a number of neighboring single-sample EFOVs (Kummerow et al., 1998). Hence, the TRMM/TMI observations can be viewed as multiple measurements with a single view angle/single frequency/dual-polarization at a fixed time. Soil texture data derived from the Global Soil Data Task (2000) was used to describe the nature of soil properties. The study period consists of a continuous warm season (May-October) of the year 1998. The soil textures (Global Soil data Task, 2000) for KING (NORM) are sand and clay at 23% (23%) and 37% (37%) coverage, respectively. The latitude/longitude centers of the KING and NORM sites are 35.9N/97.9W and 35.3N/97.5W, respectively.

The second experimental data set were collected over a bare soil during a field experiment carried out in 1985 at the USDA, ARS Beltsville Agricultural Research Center, USA. The site consisted of a 10×10m controlled plot containing loamy sand soil. A dual polarized L-band (1.4GHz) and C-band (5.0 GHZ) passive microwave radiometer measured brightness temperature at view angles of 10^{o} and 20^{o}. In addition to the radiometric measurement, soil moisture and soil temperature were measured. The data from Beltsville site used in this study fall into the period of Jul-Oct (DOY 190-304). The surface roughness was assumed to be smooth.

3 GENERATION OF SYNTHETIC BRIGHTNESS TEMPERATURE

One of main issues in this study is how to generate a number of synthetic microwave brightness temperatures from a known single measurement, with minimal loss of the statistical properties. To do this, firstly, we investigated a general trend of the grid averaged microwave brightness temperatures and surface soil moisture and optical depth retrieved from multiple observations described earlier. Figure 1 shows a time course plots of the retrieved soil moisture (figure 1a) and the optical depth (figure (1b) and the grid averaged microwave brightness temperature (figure 1c) as a function of Julian day on the horizontal axis.

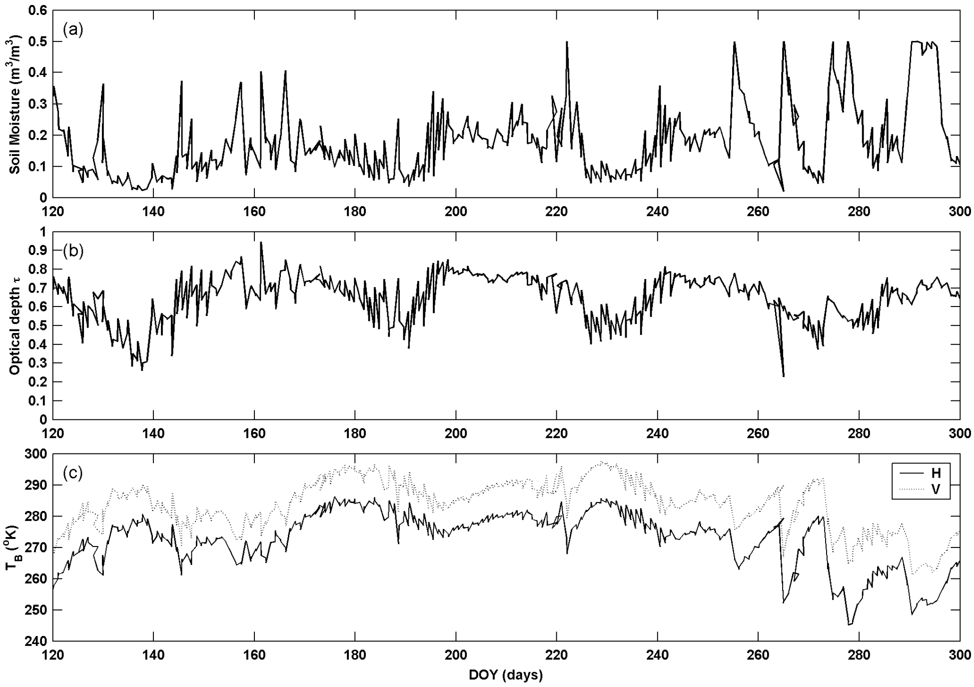

Fig.1 : Microwave brightness temperature and the corresponding retrieved soil moisture and optical depth as a function of Julian day (in days) for NORM site of the year 1999. (a) soil moisture (in m^3/m^3) (b) optical depth (c) microwave brightness temperature (^oK).

The general trend of three variables is consistent and the retrieval process reproduces the dynamics of the soil moisture and optical depth reasonably. The vertically polarized brightness temperature is systematically ~10 ^{o}K higher comparing to the horizontally polarized brightness temperature as expected. On the basis of the figure 1, it is believed that the averaged microwave brightness temperature over the grid area can be a representative for the multiple scanning of the grid. Secondly, we investigated the histogram for the dual-polarized TRMM/TMI microwave brightness temperature. Figure 2 present a histogram of the vertically polarized TRMM/TMI microwave brightness temperature at different Day of Year (DOY) for two different locations.

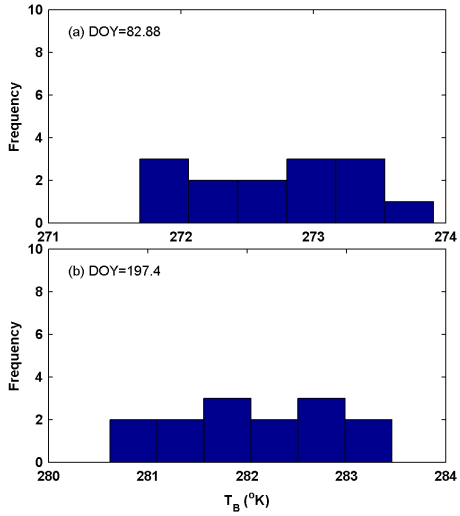

Fig. 2 : Histogram of the measured TRMM/TMI microwave brightness temperature

Random element of microwave brightness temperature can be selected from any suitable probability of distribution, as long as the elements are independent of each other, so that we can generate a set of brightness temperature data having statistical properties equal to the properties of the sample used in estimating the population parameters. To author's knowledge, the probability of distribution is mainly selected from the analysis of the field sampling data. On the basis of the figure 2, it is likely that a uniform distribution is presumably suitable for the microwave brightness temperature sampling in TRMM/TMI. Hence, we selected a uniform distribution to randomly generate synthetic microwave brightness temperature at both horizontal and vertical polarization. Then we assumed a set of the randomly generated brightness temperature observations at each visiting time correspond to those that is provided during the TRMM/TMI mission.

4 RETRIEVAL ALGORITHM

The retrieval algorithm used herein is mainly followed by two-parameter method, which has been studied by some scientists in the past (Lee, 2005; Wigneron et al. 2000; Van de Griend and Owe, 1996).

Briefly speaking, the main strategy adopted here is to deliver both soil moisture and optical depth using a microwave emission model on the basis of a linked soil/vegetation/atmosphere system. The transmissivity of the vegetation can be expressed as

$$\Gamma(\theta) = \exp(-\tau \sec\theta) \tag{1}$$

where τ is the optical depth and θ is the view-angle and Γ is the transmissivity of vegetation. It is based on the simple Fresnel model for soil emissivity. The three main contributions of the radiation signal are from 1) portion of the soil beneath the vegetation canopy, 2) portion of the vegetation volume itself, and 3) portion of the interaction between soil and vegetation. Keeping these in mind, the microwave brightness temperature measured from a vegetation covered satellite field of view area can be simulated as follows:

$$T_B(\theta, p)_{canopy} = [1 + r_s(\theta, p)\Gamma(\theta)][1 - \Gamma(\theta)](1 - \omega)T_v + [1 - r_s(\theta, p)]\Gamma(\theta)T_s \tag{2}$$

where ω is the single-scattering albedo and $r_s(\theta, p)$ is the air-soil reflectivity under the influence of overlying vegetation with a physical temperature T_v and T_s (in ${}^oK$) for vegetation and soil respectively. The single scattering albedo, ω, is a parameter affecting the transmissivity of the vegetation canopy, but not typically measured in the field. This parameter is often neglected when dealing with lower microwave frequencies (Wigneron et al., 2003), while at high frequencies (e.g. 10.7 GHz) its dynamic range is relatively large and cannot be neglected. Both soil temperature, T_s and vegetation temperature, T_v can be equal around sunrise due to thermal equilibrium (Kerr et al., 2001), but can differ during most of day. However, due to difficulties in determining the temperature profile in the soil and vegetation canopy they are often assumed to be equal such as this study. Surface roughness is given as known and set to be smooth. The effect of the atmosphere is ignored.

In the inverse algorithm, we denote **X** the set of variables to be retrieved (surface soil moisture and optical depth) at the spatial resolution of the TMI 10.7 GHz sampling area. A simple least square method is used as an objective function, F_{obj}, that evaluates the agreement between TMI observations and microwave emission model simulations as follows;

$$F_{obj} = \min\left[(T_{B.H}(\mathbf{X}) - T_{B.H.obs})^2 + (T_{B.V}(\mathbf{X}) - T_{B.V.obs})^2\right] \tag{3}$$

where the subscript "obs" indicates TMI observation, while the simulated brightness temperature, $T_{B.H}$ and $T_{B.V}$ are horizontally and vertically polarized microwave brightness temperature denoted as function of variable **X**, respectively. To minimize the objective function in equation (3) we introduced the Shuffled Complex Evolution (SCE) optimization algorithm. The SCE is a single-criterion, multi-parameter optimization technique and it is a general-purpose global optimization method designed to handle many of the cost function surface problems encountered in the calibration of nonlinear models in hydrology. 0.05 m^3/m^3 is set to be a maximum soil moisture condition.

5 RESULTS

5.1. Application to TRMM/TMI Data

The central goal of the present study is to use the statistically generated synthetic microwave brightness temperature data to retrieve surface variables using two-parameter approach, in the event that there is a single measurement at dual-polarization. The methodology described in section II was applied to TRMM/TMI data set for the period of year 1998 (March-Oct).). We assumed the averaged microwave brightness temperature over the grid area for each polarization is a single measurement at fixed time, which are 10.7 GHz and the view-angle of 52.75^o. In more details, a set of multiple brightness temperature is formed by joining a number of neighboring single-sample EFOVs of the TRMM/TMI (Kummerow et al., 1998). The soil moisture and optical depth are retrieved from the set of data and considered as a truth here. A representative value of brightness temperature for each polarization is aggregated from the set of multiple measurements of brightness temperature data. Now we assume that the representative value is a single measurement value. Then, 50 disturbed microwave brightness temperature data with uniform distribution are synthetically generated as described in section 3. The scatter plots for the retrieved soil moisture derived from microwave brightness temperature are shown in Figure 3 on the basis of the one-to-one correspondence comparisons. The truth is specified on the vertical axis and the retrievals derived from the randomly generated brightness temperature are specified on the horizontal axis. Apparently the agreement is excellent and the retrieval is very successful with errors in both soil moisture and optical depth, which implies that the uniform distribution of randomly generated brightness temperature reproduces the sampling structure reasonably. However there is some evidence that the errors increase with the increase of the random error range of the brightness temperature as see in figure 3.

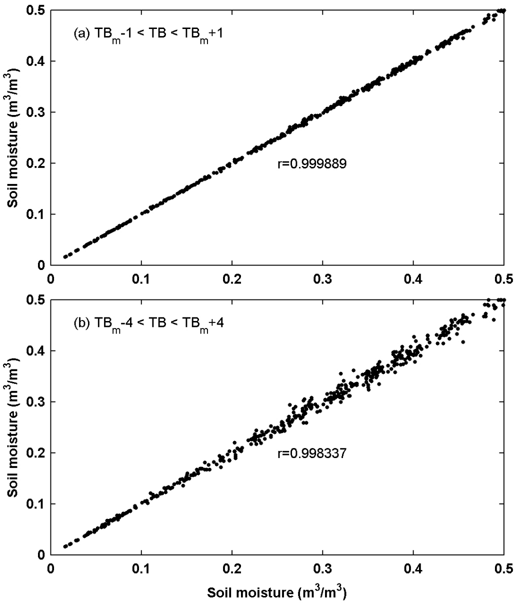

Fig. 3: scatterogram for the retrieved soil moisture versus truth for different random error ranges

Many studies have been using an optimization scheme in two/three parameter approach and they stated that the number of microwave brightness observations was important for the accuracy in optimization technique. There is no hard and fast rule, but generally there should be a number of independent data points per parameter in the optimization technique. Thus, it is interesting to see how the number of observations affects the retrieval results. To explore the impact of the number of observations on the retrieval results, we next carried out the retrieval process with a various number of brightness temperature observations which are randomly generated in the range of $T_{B.m} - 1 \leq T_B \leq T_{B.m} + 1$. Figure 4 show the retrieval results as a function of the number of the microwave brightness temperature observations. The most noticeable and significant result demonstrated by figure 4 is that, at small number of observations, the uncertainties of the retrieval are large and the retrieval is unstable but the errors in the retrieval converges at large numbers of observations as expected. There is also tendency for the errors in the retrieved values to be larger for high soil moisture.

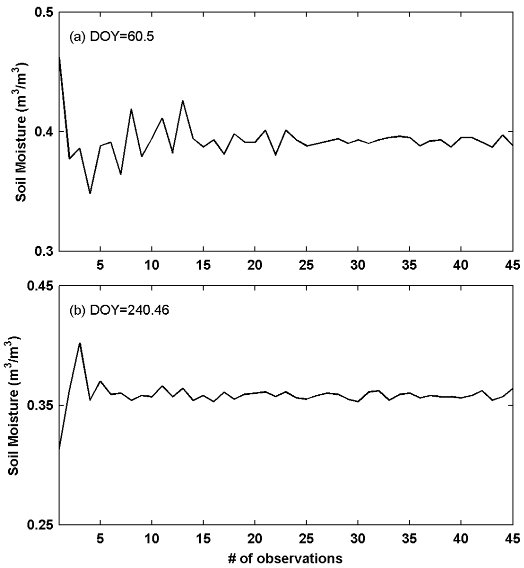

Fig. 4: Retrieved soil moisture as a function of the number of observations

5.2. Application to Beltsville data

Next the methodology was applied to the ground based microwave brightness temperature experimental measurement carried out in Beltsville, Maryland. The single measurement of dual-polarized microwave brightness temperature was selected at four different cases (L-band 10^o, L-band 20^o, C-band 10^o, C-band 20^o) and then 50 disturbed microwave brightness temperatures were generated in the range of $T_{B.m} - 1 \le T_B \le T_{B.m} + 1$ for each case. Much physical concept has not been explored for the microwave optical depth related to the vegetation dynamics and no measurement are available to date. Both soil moisture and vegetation characteristics contribute to the microwave signal and these features are interactive in the multiple parameter technique. The space-borne microwave brightness temperature is a spatial average integrated over the footprint, whereas the ground based soil moisture data are often point measurement. Thus, it is hard to evaluate the retrieval algorithm in terms of the optical depth and soil moisture in the microwave remote sensing study. In this study we selected the microwave experimental measurement over a bare soil. In practice it is advantageous that the retrieved optical depth is known as zero, which enables one-to-one correspondence comparisons in the inverse study. Also the soil moisture and soil temperature can be viewed as a point measurement and these are considered as a truth. The retrieval results are shown in Figure 5 and 6. The retrieved values are specified on the vertical axis as a function of Julian day. The retrieved soil moisture should be viewed qualitatively because the sensing depth of bare soil for L- and C- band at each frequency is approximate and then one-to-one comparison is difficult. The 5cm soil moisture measurements are used for L-band (figure 5). It is general feature that the agreement is excellent and the retrieval is very successful. Also the retrieval reproduces dry down very well.

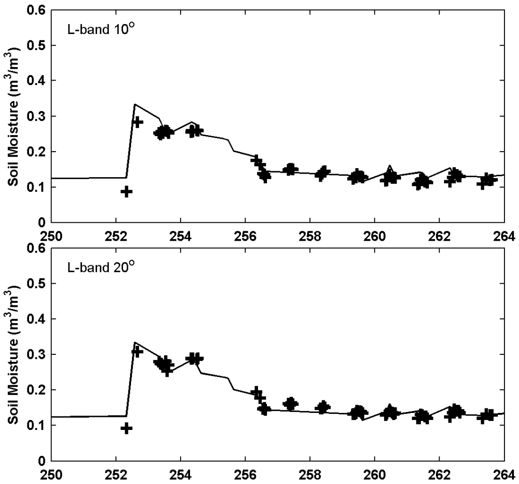

Fig. 5: Soil moisture retrieval (in m^3/m^3) as a function of Julian day for a bare soil, Beltsville, MD, USA, 1985. The 5cm soil moisture measurements were used

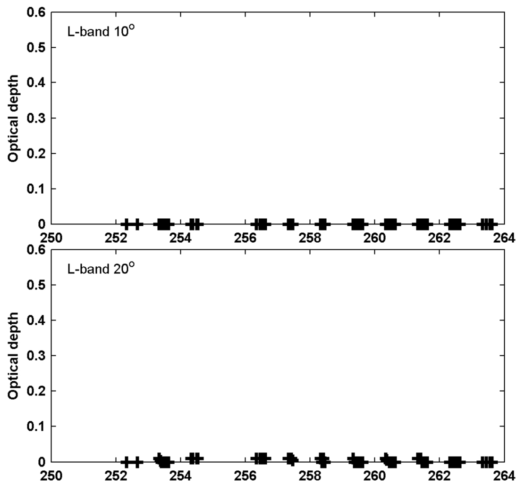

Fig. 6: same as fig. 5 but for optical depth

6 CONCLUSION

This study investigated the potential use of the statistical approach to retrieving the surface variables using two-parameter method. The method suggested here is especially useful for a dually polarized single measurement, which is mostly the case for the existing microwave brightness data. The strategy adopted was, firstly, to generate a number of observations of microwave brightness temperature with known probability distribution and mean values for two different sites. Then, the required values were found using the two-parameter method which is based on a two-source Fresnel representation of microwave emission and advanced optimization technique. The primary conclusions of the present study are as follows:

- The statistical approach suggested here provides very successful retrieval results in both soil moisture and optical depth.
- The uniform distribution reproduces the microwave brightness temperature structure reasonably.
- The errors in the retrieved values increase with the increase of the random error range of the brightness temperature. Hence small random error is likely to be appropriate in simulating the multiple observations of microwave brightness temperature.
- The uncertainties of the retrieval are large at small number of observations but errors are stable at large number of observations as expected.

On the basis of the results above it is encouraging that the statistical approach suggested here might be useful to generate the synthetic microwave brightness data set from the known single measurement in the passive microwave remote sensing but further validation is needed for general use.

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