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A SIMPLIFIED MODELLING APPROACH FOR RETRIEVING SOIL MOISTURE FROM MICROWAVE BRIGHTNESS TEMPERATURES

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ABSTRACT

A simple Soil Moisture Radiative Transfer model was developed for simulation of microwave brightness temperatures using soil moisture as the major input with four land surface parameters (surface air temperature, ground temperature, surface water vapour density and cloud liquid content). The model employed a semi-empirical sub-model for soil dielectric constant that was developed for low frequencies in the range of 1 – 20 GHz. Soil moisture retrieval was tested by conducting a simulated retrieval exercise in the high frequency ranges of the Special Sensor Microwave Imager (SSM/I) (19, 22, 37 and 85 GHz). It was observed that the five-channel SSM/I information of up to 37 GHz could adequately retrieve the five land surface parameters with an error of less than 0.05%.

1. INTRODUCTION

The upper few centimeters of soil are extremely important to the environment because they form the interface between soil science and land surface research. Soil moisture is the critical parameter in this region that determines the partitioning of heat and moisture atmospheric forcing at the land surface boundary. In rainfall-runoff models, partitioning of incoming precipitation into infiltration storage and runoff loss are determined on the basis of soil moisture condition. In order for a soil moisture information to be useful, it must be available regionally and at regular and frequent intervals. The difficulties of field soil moisture mapping lie in the extreme spatial variability of point measurements and the impracticality of obtaining a sufficient dense network of points to provide reliable regional information. Microwave remote sensing from satellites therefore provides a unique capability for direct observation of soil moisture with the possibility of frequent and global sampling over large areas. A particular advantage of passive microwave sensors is that in the absence of significant vegetation cover, soil moisture is the dominant effect on received signal. Furthermore, microwave measurements have the benefit of being largely unaffected by cloud cover and variable surface solar illumination.

Although regional and continental observations of surface soil moisture have the potential in large-scale hydrology, the most useful frequency ranges for estimation should be limited to 1- 5 GHz. This is unavailable at the presently polar orbiting radiometers in space. It is already well known that radiometers operating at low frequencies (i.e., <1.4 GHz) can provide adequate information of soil moisture with acceptable accuracy for a wide range of land cover conditions. Faced with this reality that there are currently few such satellite instruments, it seems appropriate to develop a simplified modeling approach

suitable for the currently available microwave sensors which usually operate in the high frequency channels of 20 – 85 GHz range. Of particular note is the SSM/I package on the Defense Meteorological Satellites [1] These satellites have been in operation continuously since 1987 and provide the following combination of frequencies and polarizations: 19.35 GHz H and V, 22.235 GHz V, 37.0 GHz H and V, 85.5 GHz H and V. Due to the high frequency ranges of the SSM/I, two aspects of data are affected: the contributing depth of the soil and the attenuation of the signal resulting from vegetation. However, other features of the data are well suited to large-scale soil moisture mapping and the frequency of sampling is also excellent. In the past, there have been a number of studies conducted that have attempted to relate SSM/I brightness temperature data to soil moisture [2,3]. With only a few exceptions, these investigations have mostly relied upon surrogate variables for validation of the models [4]. These models also required site-specific calibration.

In this study, a simplified modeling approach for retrieving soil moisture from a sensor's microwave brightness temperatures is therefore presented in the following manner : (1) First, a Soil Moisture Radiative Transfer (SMRT) model was developed from existing theory that was simple and required minimum calibration. This model simulated brightness temperatures at the SSM/I channels using soil moisture as the dominant input. Other media variables required were the Ground Temperature (T_g), Surface Air Temperature (T_{as}), the Surface Water Vapour density (ρ_s) and the Cloud Liquid content (m_v). (2) The dependencies of various model parameters on some electromagnetic variables were simulated to check that the simulations were consistent with theory. (3) The model retrievals were tested using simulated (i.e., synthetic) noise-free SSM/I channel Brightness Temperatures. First, using the SMRT model (in the forward direction) brightness temperatures were generated from the five randomly generated media variables. As the current sensor noise level of the SSM/I was unavailable to the author, no noise was added to these synthetic data. Then, using the inverse method and a simple iterative search technique the five media variables were retrieved from the simulated brightness temperatures. Accuracy in retrievals would reveal that the model had inverse mapping consistency with respect to the search technique used.

2. METHODOLOGY

2.1. The Special Sensor Microwave Imager (SSM/I)

The Special Sensor Microwave Imager (SSM/I) instrument package is a conical scanning total power radiometer operating with a look angle of 53.1°. The basic features of the SSM/I radiometer are summarized in Table 1. The nominal swath width is 1400 km with data collected at 128 locations across track on every scan at 85.5 GHz. Only 64 observations are made across track on every other scan at other frequencies.

2.2. The moisture radiative transfer model (SMRT)

The theory and the assumptions behind the soil moisture radiative transfer model (SMRT) are summarizes as shown in Figure-1. Five media variables are required as input. These are (1) Cloud Liquid water Content (m_v, gm m^{-3}) , (2) Surface Air Temperature (T_{as}, K), (3) Surface water vapour density (ρ_s, gm m^{-3}), (4) Surface ground temperature (T_g, K) and (5) Volumetric soil moisture (sm, gm cm^{-3}). The soil characteristics of Sand/Clay (S and C) fractions and soil bulk density are required for the soil dielectric constant sub model.

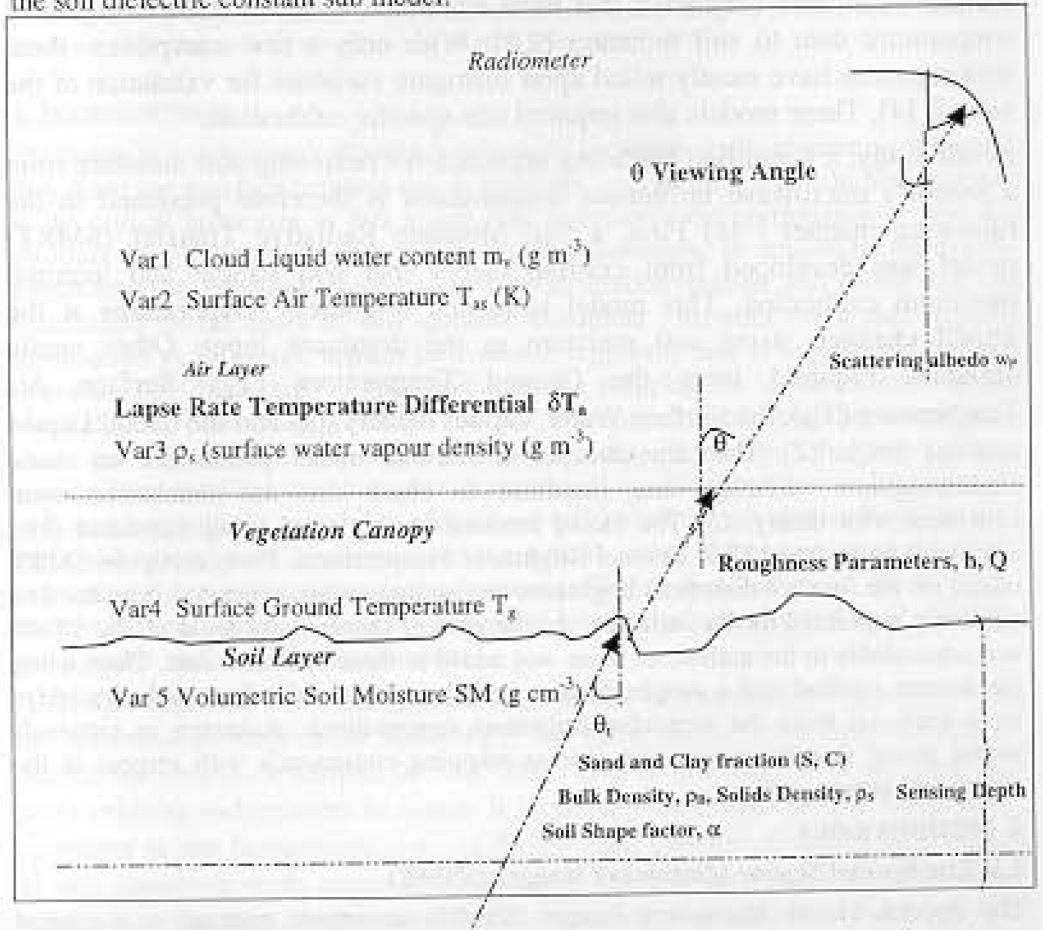

Fig. 1. Schematic diagram showing the passive microwave emission from soil to estimate the moisture content.

Table 1. SSM/I Instrument Parameters.

Parameters	Characteristic Value			
Frequencies (GHz)	19.35 H V	22.235 V	37.0 H V	85.5 H V
Altitude (km)	860.0			
Look Angle (°)	53.1			
Swath Width	1400.0			
Antenna Size (m)	0.6			
Foot Print Size (km X km)	69 X 43	60 X 40	37 X 28	15 X 13
Launch Date	First one launched in July 1987			

The SMRT theory is based on Ulaby et al. [5]. Following are the major assumptions for the simplification of modeling are provided along with the most pertinent equations: (1) Propagation Angle θ_2 within the soil is constant, (2) θ_1=Viewing Angle (θ) i.e., negligible refraction takes place in the vegetative canopy, (3) Frequency effect of salinity in free water (bound in soil pores) is negligible, (4) Shape factor, α, of Soil particles optimum for the 1.4 –18 GHz range is 0.65; (for higher frequencies, calibration may be performed to determine the optimal shape factor α), (5) The effect of Soil Moisture (SM) on the extinction coefficient K_e of soil is minimal, (6) Upwelling (T_U) and Downwelling (T_D) radiation are equal and can be approximated using the Effective Radiating Temperature (T_{ae}), (7) Beyond the Sensing Depth Passive Emission is undetectable by the radiometer. Sensing Depth is usually assumed to be 0.1 times the wavelength [6] (8) Vegetation Canopy Temperature and the Ground Temperature are assumed the same, (9) The vegetation opacity has negligible dependence on polarization and (10) The scattering albedo has negligible dependence on frequency for the ranges considered.

The dielectric constant of soil is expressed by the following equation [5] :

$$\varepsilon_{soil}{}^{\alpha} = 1 + \frac{\rho_b}{\rho_s}(\varepsilon_{ss}{}^{\alpha} - 1) + SM^{\beta}(\varepsilon_{fw}{}^{\alpha} - 1) \qquad (1)$$

where, SM = Soil Moisture (g cm^{-3}), ρ_b = Bulk Soil Density (g cm^{-3}), ρ_s = Soil Solids Density = 2.65 g cm^{-3}, ε_{ss}= Complex Dielectric Constant for soil solids = 4.7 – j0 [5] Complex Dielectric Constant of free water at the ground T_g temperature.

The Fresnel Relfectivities are given by,

$$r_{ov} = \left| \frac{\varepsilon_s \cos\theta - \sqrt{\varepsilon_s - \sin^2\theta}}{\varepsilon_s \cos\theta + \sqrt{\varepsilon_s - \sin^2\theta}} \right|^2 \qquad (2)$$

$$r_{OH}=\left|\frac{\cos\theta-\sqrt{\varepsilon_s-\sin^2\theta}}{\cos\theta+\sqrt{\varepsilon_s-\sin^2\theta}}\right|^2 \qquad (3)$$

where, θ is viewing angle of the radiometer, (neglecting refraction in the intermediate medium: air and vegetation canopy), ε stands for Complex Dielectric constant of soil which is a function of mainly Soil Moisture (SM) and is written as $\varepsilon' + j\,\varepsilon''$

With the reflectivity computed for a given polarization, the Brightness Temperature $T_{Bo\,p}$ is given by

$$T_{BOP^*} = (1 - r_{OP})\,T_g\,. \qquad (4)$$

Here p* stands for the type of polarization, T_g is Ground Temperature at the soil surface (K).

3. Applicability and accuracy of the Model

3.1. Model Theoretical Consistency Check

First, the brightness temperature sensitivity was analyzed for an assumed sinusoidal variation of volumetric soil moisture as shown in Figure 2.

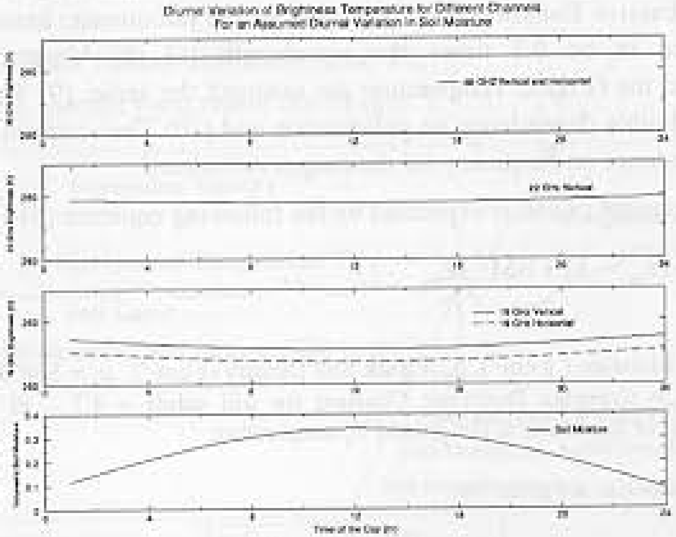

Fig. 2. An assumed soil moisture variation during the passage of a day and the corresponding simulated SSM/I brightness temperatures.

As expected, the lowest SSM/I frequency of 19 GHz showed to be most sensitive while the 85.5 GHz channel was almost insensitive for the ranges of soil moistures considered. Also, with increasing moisture the brightness temperature decreases due to the decrease in soil emissivity. Figure 3 shows the dependence of emissivity on soil moisture. Both the model simulations made perfect theoretical sense [7].

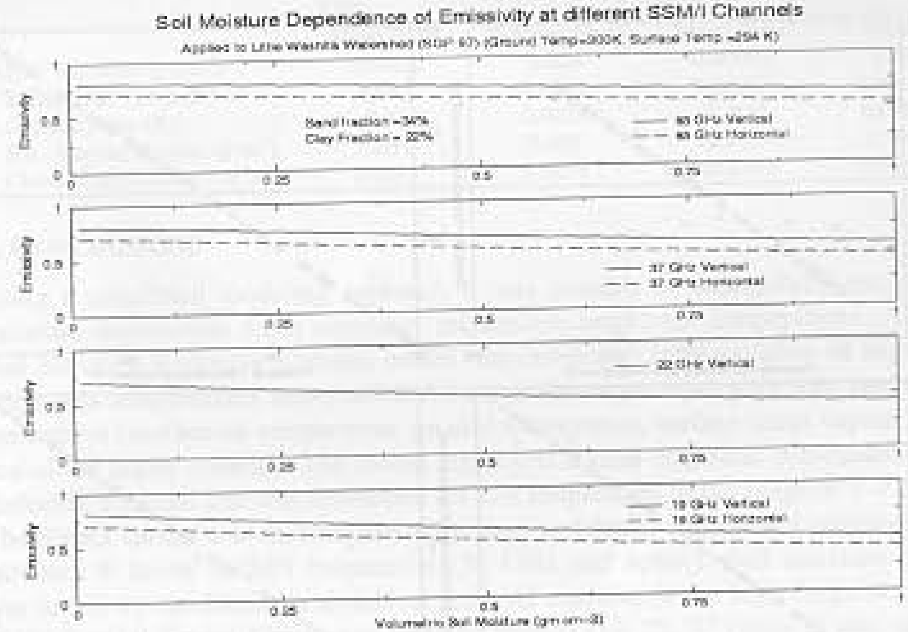

Fig. 3. Simulated Soil Moisture dependence on soil emissivity.

3.2. Model Retrieval Test

In order to test the SMRT model retrieval consistency, a simulated retrieval exercise was carried out in the following step-by-step procedure: (1) Generate random sets of the 5 media variables x, where x= $\{sm, T_{as}, T_g, m_v, \rho_s\}$. 100 sets were randomly generated in this case. (2) For each randomly generated set x, simulate the SMRT Brightness Temperatures ϕ(x) (where φ(x) is the SMRT model) at the SSM/I channels. (3) For each set of SMRT Brightness Temperatures, use the inverse method to retrieve the 5 media variables through an appropriate iterative search technique. For the iterative search algorithm, define a cost function as,

$$\text{Cost}=\sum_{i=1}^{7}(\Phi(x)_i - T_{Bi}^{obs})^2 \qquad (5)$$

Here, in Eqn. 5, the subscript *i* referred to a given frequency channel and the $T_B^{obs}i$ was the observed (but simulated) Brightness Temperature for a set of media variables 'retrieved' in the backward method.

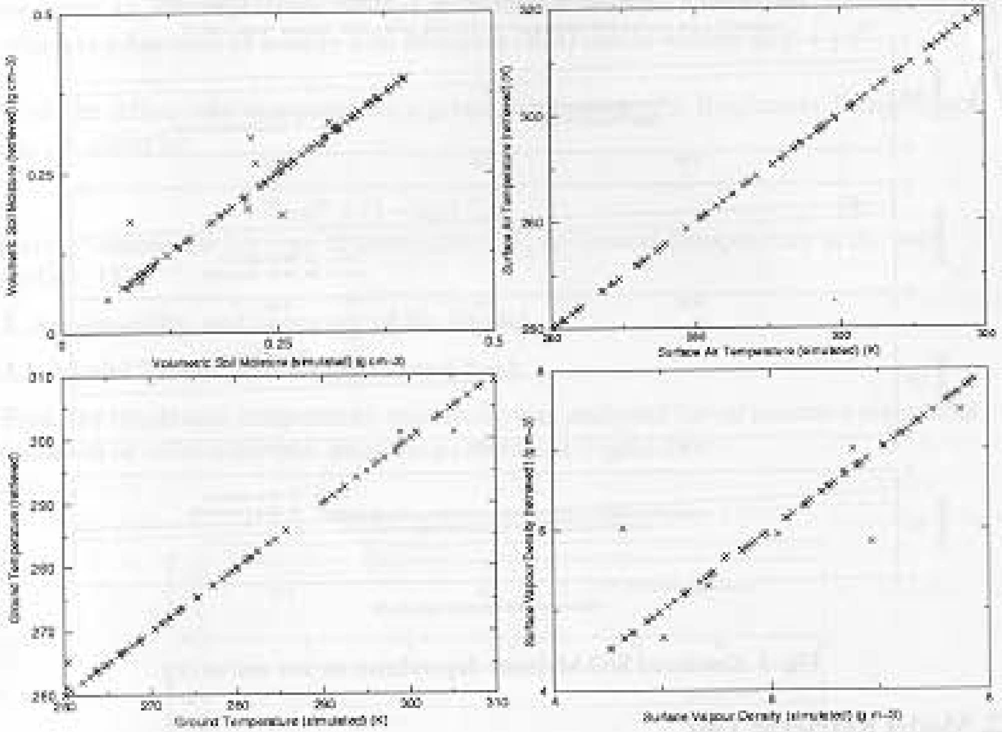

Fig. 4. Scatter plots of simulated 'retrieved' versus 'true' (or simulated) media variables (a set of 100 retrievals).

For the iterative search technique, the probabilistic Shuffled Complex Evolutionary (SCE) Algorithm by Duan et al. [8] was used primarily for the ease with which it could be coupled with a forward model. Because the 85 GHz channel was found to be very insensitive to soil moisture variations retrievals were carried out using a cost function including brightness temperature up to 37 GHz (as shown in Figure 4) for four variables. Soil moisture could be retrieved with a 0.026% mean error. There was 0.0001% mean error for surface air temperature, 0.0008% for ground temperature, 0.008% for surface vapour density and 0.0023% for cloud liquid content (Table 2).

Table 2. Retrieval test results for two different sets of synthetic SSM/I data.

	19, 22 and 37 GHz		19, 22, 37 and 85 GHz	
	Mean Error	% Mean Error	Mean Error	% Mean Error
Soil Moisture (g cm-^{3})	0.0038	0.026	0.00009	0.0004
Surface Air Temp (K)	0.032	0.0001	0.00013	0.0000004
Ground Temp (K)	0.23	0.0008	0.0049	0.000015
Sur. Vapour Density (g m^{-3})	0.051	0.008	0.0019	0.00029
Cloud Liquid Content (g m^{-3})	0.0019	0.0023	0.000046	0.000065

4. CONCLUSIONS

Using a simplified modeling approach it was possible to successfully retrieve soil moisture information from simulated microwave brightness temperatures. A simple Soil Moisture Radiative Transfer model was developed for simulation of microwave brightness temperatures using soil moisture as the major input with four land surface parameters (surface air temperature, ground temperature, surface water vapour density and cloud liquid content). The model employed a semi-empirical sub-model for soil dielectric constant that was developed for low frequencies in the range of 1 – 20 GHz. The SMRT model was theoretically consistent and found sufficiently sensitive to soil moisture at lower SMM/I frequencies (37 GHz and below). Soil moisture retrieval was tested by conducting a simulated retrieval exercise in the high frequency ranges of the Special Sensor Microwave Imager (SSM/I) (19, 22, 37 GHz). It was observed that the five channel SSM/I information of up to 37 GHz could adequately retrieve the five land surface parameters (including soil moisture) with an error of less than 0.05%. Such kind of a simplified modeling approach for retrieval of soil moisture from microwave brightness temperatures therefore hold promise in the management of water resources where soil moisture is of critical importance to the environment.

REFERENCES

[1] Hollinger, J. P., Peirce, J.L., and. Poe, G.A., 1990. SSM/I Instrument Evaluation. *IEEE Trans Geoscience Remote Sens*, **28**, pp. 781 – 790.

[2] Owe, M., A. Chang, A., and Golus, R.E., 1988. Estimating Surface Soil Moisture from Satellite Microwave Measurements and a Satellite Derived vegetation Index. *Remote Sens Environ.*, **24**, pp. 331-345.

[3] Wang, J. R., 1985. Effect of Vegetation on Soil Moisture Sensing from an Orbiting radiometer. *Remote Sens Environ.*,**17**, pp. 141 – 151.

[4] Jackson, T. J., 1993. Measuring Surface Soil Moisture using Passive Microwave Remote Sensing, *Hydrol. Processes*, 7, pp. 139 – 152.

[5] Ulaby, F. T., Moore, R.K., and Fung, A.K., 1986. Microwave Remote Sensing: Active and Passive, Volume III (From Theory to Applications). Artech House: Norwood, MA., USA.

[6] Njoku, E. G. and Li, L., 1999. Retrieval of Land Surface Parameters Using Passive Microwave Measurements at 6-18 GHz. *IEEE Trans. Geoscience and Remote Sensing*, 37(1), pp. 79 –93.

[7] Njoku, E. G. and Entekhabi, D., 1996. Passive Microwave Remote Sensing of Soil Moisture. *J Hydrol.* **184**, pp. 101 – 129.

[8] Duan, Q. Y., Gupta, V.K., and Sorooshian, S., 1993. Shuffled Complex Evolution Approach for Effective and Efficient Global Minimization. *J Optim Theory Appl.* **76**(3), pp. 501 –521.