A Radiative Transfer Model for Soil Media with Considering the Volume Effects of Soil Particles: Field Observation and Numerical Simulation

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Abstract—**This paper presents the development of an improved soil radiative transfer model (RTM) which considering the volume scattering effect of soil particles, an unexplored part of traditional RTMs, through field experiments and numerical simulations. The field observations were conducted by using the Ground Based Passive Microwave Radiometer (GBMR) to measure the brightness temperature of dry sand layer over background materials, metal plates or absorbers. The existence of volume scattering effects in the dry sand was demonstrated through field experiments. Then, the observed data were simulated by the dense media radiative transfer (DMRT) model. The simulation results show that the DMRT model which includes the volume scattering effects performers better than the generally used surface emission model which does not include volume scattering effects.**

Keywords- soil radiative transfe model; volume scattering; field observation; GBMR; DMRT

I. INTRODUCTION

Passive microwave remote sensing provides useful information on soil moisture distribution for hydrological, climatological and meteorological applications. Retrieving surface soil moisture from spaceborne passive microwave remote sensing data has been studied by a number of researchers for many years [1], [2]. However, as mentioned in the previous paper of author [3], both the accuracy and applicable region of current soil moisture retrieval algorithms are far from satisfactory. For example, the current algorithms generally make overestimation in arid and semi-arid region. One of the key reasons of this low accuracy is that the generally used algorithms do not involve the volume scattering effects of soil particles, which becomes bigger in a dryer case.

For accurate estimation of soil moisture from space borne remote sensing data, the forward model, viz., the radiative transfer model, which builds a relationship between the soil status (texture, moisture content and so on) and the emitted microwave signatures, should be described adequately. In order to advance the understanding of the radiative transfer process that taken place in soil media, field experiments were designed to provide a chance to validate the proposed DMRT model. Therefore, in this paper, firstly, the experiment set-up and the observations are introduced. Then an analysis of the field experiment results will be provided. Afterwards the DMRT simulation results are presented and compared with the field observation. The paper concludes with some final remarks.

II. FIELD OBSERVATION

The main goal of the field experiments was to create a data set, which can be used to evaluate and improve current radiative transfer models, by observing the brightness temperature of dry sand and its physical temperature and water content simultaneously.

A. *The Test Site*

The field observations took place at the Field Production Science Center in Graduate School of Agricultural and Life Sciences in the University of Tokyo (UTFPSC), Nishi-Tokyo, Tokyo, Japan (139°32’29’’E, 35°43’21’’ N, 60 m Alt.).

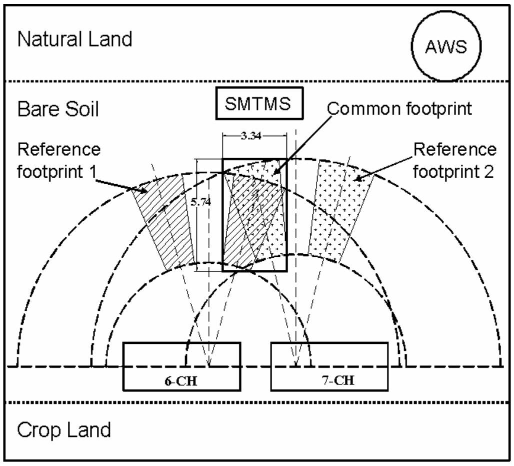

Figure 1. Sketch of experiment field

Figure 1. gives an overview of the experiment field set up. Two GBMRs, GBMR-6ch and GBMR-7ch, were installed at

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the edge of experiment field. The location for soil moisture and temperature measurement system (SMTMS) and the automatic weather station (AWS) have been selected, so that they are close to the radiometer footprints.

The common footprint of two GBMRs was decided by minimizing an area in which footprints of both GBMR-6ch and GBMR-7ch can be safely located with some redundancy. Besides the common footprint, there were two reference footprints, reference footprint 1 for GBMR-6ch and reference footprint 2 for GBMR-7ch. During observation, the common footprint was covered by background material, while the reference footprints just were bare soil.

B. The Used Facilities

The brightness temperature was measured by using GBMR-6ch (operating at frequencies of 6.9, 10.65 and 18.7GHz, both horizontal and vertical polarization) and GBMR-7ch (operating at frequencies of 18.7, 23.8, 36.5 and 89GHz, both horizontal and vertical polarization except 23.8GHz only vertical polarization), while the equipped frequencies are similar to those of the Advanced Microwave Scanning Radiometers for EOS (AMSR-E) on Aqua and AMSR on ADEOS-II [4], [5].

During the observation, the soil moisture and temperature profile was measured simultaneously by using the SMTMS, which consists of the six Time Domain Reflectormeters (TDR) and the 10 Platinum soil temperature sensors (Pts). The surface temperature of common footprint also was measured with infrared thermometers. Sand samples were taken after every measurement to obtain the sand density and water content.

In the experiments, both metal plates and flat absorbers were used as the background to provide a clear boundary condition. The metal plates were serving as a high reflectivity background while the absorbers were serving as a high emissivity background. The flat absorbers were composed of 61-*61- cm slabs of 1.9-cm thick flat absorber provided by *Emersom and Cuming Microwave Products.*

C. The Procedure

In general, all experiments were conducted as following process:

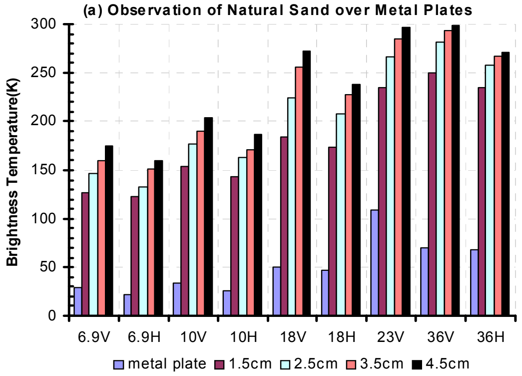
(1) Drying the sand inside an oven at 80 °C to make the sand very dry.
(2) Covering the common footprint with background materials and leveling the reference footprints 1 and 2.
(3) Measuring the brightness temperature of all footprints by using GBMR-6ch and GBMR-7ch at a fixed incident angle of 55°, which is similar to that of the AMSR and AMSR-E sensors.
(4) Measuring the sky radiation at the incident angle 55°.
(5) Increasing the sand depth with introducing one centimeter depth dry sand above the background material and making a smooth surface.
(6) Repeat step 3-5 till using up the dry sand or accessing the brightness temperature saturation.

At the beginning of every experiment, we measured the brightness temperature *TB* of background material and the brightness temperature T_{sky} of sky, and then we could calculate the effective reflectivity Γ_e of background as:

$$\Gamma_e = (T_{phy} - TB)/(T_{phy} - T_{sky}) \qquad (1)$$

where T_{phy} is the physical temperature of the background materials in Kelvin.

(a) Observation of Natural Sand over Metal Plates



(b) Observation of Dry Natural Sand over Absorbers

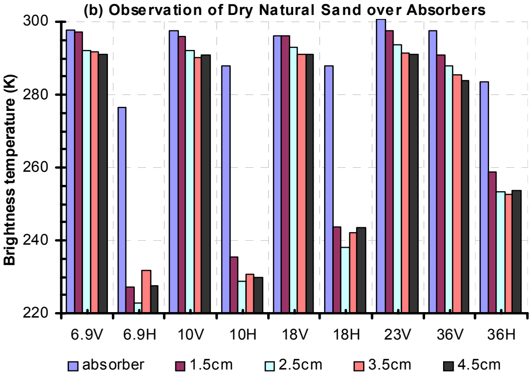


Figure 2. Brightness temperature observation results

D. The Observed Results

Figure 2 shows the observed brightness temperature for: (a) experiment using metal plates as background material, (b) experiment using absorbers as background material. The low frequencies (6.9 and 10 GHz) results were from the observation of GBMR-6ch, and other frequencies results were from that of GMBR-7ch.

From **figure 2(a)**, it is obviously that the observed brightness temperature increases as the sand depth increases. This brightness temperature increment is mainly due to the emission effects of dry sand layer. And when we added dry sand continually on the common footprint, the increment of brightness temperature due to the newly addressed one centimeter dry sand was getting smaller. This phenomenon is due to the volume scattering extinction effect of the dry sand particles [6]. The scattering effect increases as the number of scatterers and their size increases. Furthermore the smaller increment of the brightness temperature is clearer at the higher frequency in **figure 2(a)**.

The contrary phenomenon can be found from **figure 2(b)**; it is that the observed brightness temperature at vertical polarization decreases as the sand depth increases, while the higher frequency the larger value decreases. This can be explained as the high emissivity of absorbers is attenuated by the volume scattering effects of sand particles. And the darkening effects caused by volume scattering are more severe at higher frequencies because the heterogeneities are larger for shorter wavelength. Moreover, for the case using absorbers as background, there was negative spectral gradient (a higher frequency's brightness temperature minus a lower frequency's brightness temperature), which is a proof of the existence of volume scattering [7], [8]. The variation of horizontal polarization brightness temperature is not clear for all frequencies. It is partly due to the roughness effects, but more detail study should be addressed in future.

III. NUMERICAL SIMULATION

In order to improve the understanding of the radiative transfer process in dry soil media, two radiative transfer models: generally used surface emission model which does not consider volume scattering effects, and the dense media radiative transfer (DMRT) model which includes the volume scattering effects, are applied to the observed data.

A. Surface Emission Model

In this model, the sand is treated as an isothermal semi-infinite media with a specular surface. It is widely used in many algorithms and the microwave brightness temperature is calculated by the model as follows:

$$TB = eT_{phy} + (1-e)T_{sky} \tag{2}$$

where e is the emissivity of the media, and the meaning of other symbols is the same as in equation (1).

Emissivity is related to reflectivity Γ by $e=1-\Gamma$, while the reflectivity is calculated from Fresnel equations by assuming a specular surface [9] and the dielectric constant of soil is calculated by using the Dobson model [10].

B. DMRT

In DMRT, the sand in the experiments is treated as a slab containing many densely packed spherical particles overlaying a boundary with a reflectivity of Γ_e calculated from equation (1). In order to involve the volume scattering effects of sand particles into the emitted signature, the radiative transfer process inside the sand is simulated as [11] by treating the sand slab as a homogeneous and isothermal multi-layer structure. And the radiative transfer equation (RTE) was solved by the discrete ordinate method (4 streams) and the Henyey-Greenstein phase function, in order to save computing time while maintaining accuracy. Detail of the RTE and solution can be found at the former study [3].

In solving the RTE, the extinction coefficient K_e and albedo ω of soil media were calculated by the so-called DMRT under the Quasi Crystalline Approximation with Coherent Potential (QCA-CP) [12], [13]. Dense Media radiative transfer theory was derived from Dyson's equation under the QCA-CP and the Bethe-Salpeter equation under the ladder approximation of correlated scatterers. The numerical solutions of the dense radiative transfer equation are similar to those of the conventional radiative transfer method, provided that the extinction coefficient K_e and the single scattering albedo ω are introduced.

C. Results and Discussion

In order to run the DMRT, simultaneously observed sand properties (temperature, water content, depth, density and texture) were used as input parameters, with the only exception of the particle size, which was decided through a best fitting way.

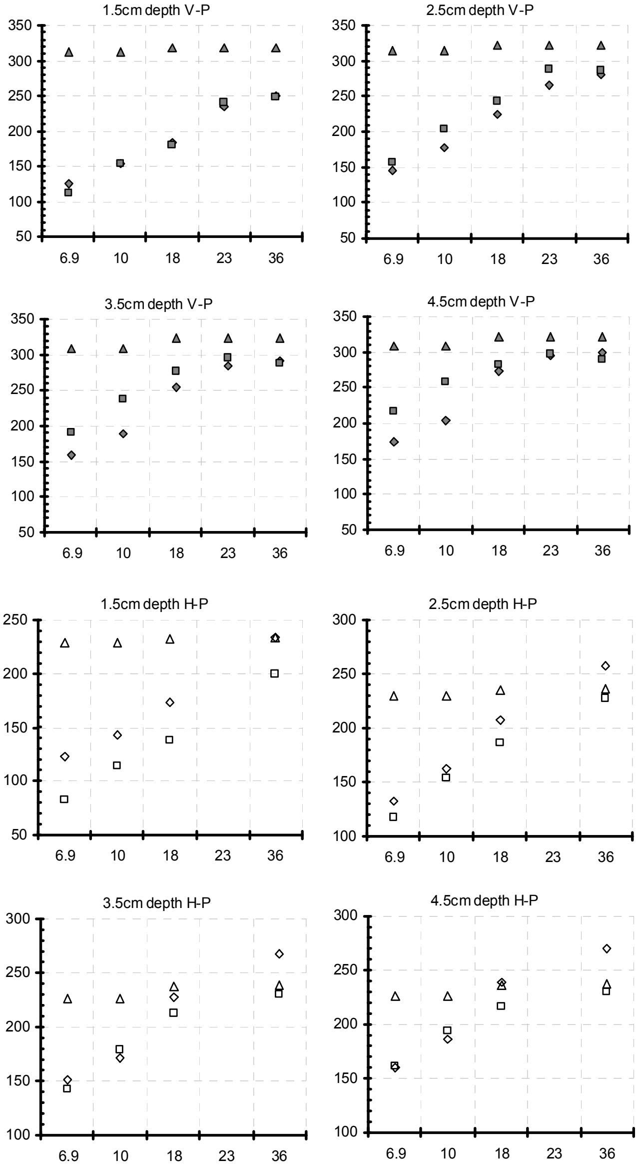


Figure 3. Observation and simulation of dry sand over metal plates

Figure 3 shows the simulation results of DMRT model and surface emission model for dry sand observation over metal plates, while the sand surface was controlled to be as smooth as we can. The x-axis is the frequency in GHz while the y-axis is the brightness temperature in Kelvin. The diamonds represent the observed brightness temperature; the rectangles represent the simulated result of DMRT; and the triangles represent the simulated result of surface emission model. The solid symbols are for vertical polarization cases, while the open symbols are for horizontal polarization cases.

From **figure 3**, we can say that the dense media model is able to reproduce experimental data well for all the cases, while the surface emission model gives a much larger value than observed one. It is due to the volume scattering effects, which increase the extinction coefficient of sand then make the actual emissivity smaller than the surface emission model predicted. For the metal plate background, it is obvious that the DMRT gives better result than the surface emission model.

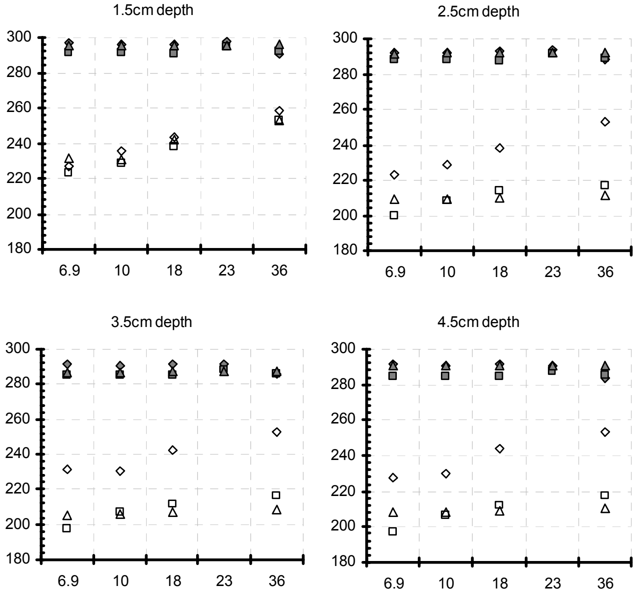


Figure 4. Observation and simulation of dry sand over absorber

Figure 4 shows the observation and simulation results for the cases of dry sand over absorber. Due to the high emissivity of absorber, the observed brightness temperature of common footprint was high and the difference between two models is not so clear. And generally, both DMRT and surface emission model make reasonable predictions for vertical polarization cases, while underestimation for horizontal polarization cases, especially at high frequency and large sand depth cases. Such errors partly come from the surface roughness effect dictated by sand particle, which becomes more important for high frequencies and horizontal polarization cases. Another reason is the depth uncertainty which is larger for the deeper case.

IV. CONCLUSION

Spatial distributed soil moisture information is an essential parameter for hydrological, meteorological and ecological studies. This paper presents a radiative transfer model of soil with considering the volume scattering effects of soil particles. Field experiments under well-controlled circumstance were conducted to provide a data set to validate the proposed radiative transfer model.

The experiment results show that the volume scattering extinction effects of soil particles should be taken into account in analyzing microwave radiative transfer process of dry soil media. Moreover, the simulation results of DMRT model demonstrate its reasonable applicability to the dry soil, for both the metal plate background which represents as a cold bottom boundary condition and the absorber background which represents as a hot bottom boundary condition; while for surface emission model, the simulated brightness temperature is larger than observed one for metal plates background cases. As future work, the experiments by changing the particle size of target material are under study and they will improve our understanding of radiative transfer processed in soil medium.

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