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Study on the relationship between soil moisture and its dielectric constant obtained by space-borne microwave radiometers and scatterometers

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Abstract. For obtaining spatial-temporal soil moisture information in large range, a study on the relationship of soil moisture and dielectric constant obtained by space-borne microwave radiometers and scatterometers data was performed. Microwave signal is much related to dielectric constant of object observed, and soil dielectric constant is decided by soil moisture, this is the basis of using microwave remote sensing technology for soil moisture monitoring. This study focuses on the transformation of soil moisture and soil dielectric constant. The Dobson semi-empirical model was used to build a simulated database, then, the coefficients calibrated of Hallikainen formula by the least square regression method at radiometer SMOS(1.4GHz), AMSR-E(6.9GHz), and scatterometer ERS-WCS and METOP-ASCAT (both at 5.3GHz) frequency-points were performed to set up the simplified models to related the real part of the dielectric constant and the soil volumetric moisture content. The validations are performed using both simulated data of the Dobson model and in-situ observations, the results show that the simplified models have good accuracy and practicality.

1. Introduction

Although soil moisture constitutes only about 0.005% of the global water resources, it's important as a boundary condition for hydrologic and climate models. Soil moisture directly affects the energy and hydrology exchange between earth surface and atmosphere cycle. Moreover, soil moisture is also an important parameter in draught monitoring and crop yield estimation. Thus, it is important to obtain soil moisture information on a large scale both in time and space. The space-borne microwave radiometer and scatterometer can provide earth observation data with a resolution of dozens of kilometers, so they are very suitable for soil moisture monitoring on a large scale, and also the most important basis data source for agricultural research and draught monitoring [1,2].

The soil dielectric constant, especially the change of the real part of the dielectric constant was the main factor of the radar backscatter coefficient and the brightness temperature observed by active and passive microwave remote sensing, respectively, and was also the basis of microwave remote sensing techniques for soil moisture monitoring [3].

Traditionally, in the society of soil moisture estimation using microwave technique, scientists usually focus on establishing the relation model of microwave signal (active: backscattering

coefficient; passive: brightness temperature) and soil moisture, such as in the work of Grippa et al. to monitor soil moisture using microwave scatterometer, soil moisture is represented as Fresnel reflectivity at normal incidence angle directly [4]. Shi et al. used polarization amplitude on behalf of soil moisture when they used SAR to estimate soil moisture [5]. In passive microwave remote sensing, reflectivity or dielectric constant is a representative of soil moisture more often [6,7]. By contrast, quantitative conversion relationship between the dielectric constant and soil moisture are often not much concerned. Typically, Hallikainen et al. set up a quadratic polynomial fitting model in 1985, according to different soil type experimental results [8]. But, the model coefficients only fitted in a few fixed frequency points, which also not normal frequency points of microwave remote sensing, what's more, the numbers for calibrated coefficient sample are too little(samples number N<100).In addition, Dobson et al. raised a semi-empirical model, by measurements from five kinds of soil using Wave-Guide Dielectric Constant Measurement System and Free Space Spread Technology, and established the relationship of soil dielectric constant and volumetric soil moisture [9]. The Dobson model has much higher accuracy and can be used at wider bands, also its independent of the category of soil, made the model has been widely used for conversion between soil moisture and soil dielectric constant. However, soil bulk density, temperature, sand and clay content are four inputs in advance, which limits the usefulness of the model.

2. Model and Method
For the conversion of soil dielectric constant and soil volumetric moisture content, the most commonly used models are Hallikainen empirical model and Dobson semi-empirical model.

2.1. Hallikainen empirical model
Hallikainen empirical model can be expressed as [8]

$$\varepsilon^{'} = (a_0 + a_1 S + a_2 C) + (b_0 + b_1 S + b_2 C)m_v + (c_0 + c_1 S + c_2 C)m_v^2 \tag{1}$$

Where S and C is percentage of soil sand and clay, respectively. a_0, a_1, a_2, b_0, b_1, b_2, c_0, c_1, c_2 are all constant factors, which already calibrated at some frequencies (namely 1.4，4，6，8，10，12，14，16 and 18GHz) using soil dielectric measurements. So, only S and C parameters necessary when soil dielectric constant transfer to soil moisture at above frequency points. Unfortunately, the above frequency points are not commonly used in microwave remote sensing society.

2.2. Dobson semi-empirical model
The classical Dobson model which is the most widely used in changing soil dielectric constant to soil moisture can be expressed as [9]

$$\varepsilon^{'} = [1 + \frac{\rho_b}{\rho_s}(\varepsilon_s^{\alpha} - 1) + m_v^{\beta^{'}} \varepsilon_{fw}^{'\alpha} - m_v]^{\frac{1}{\alpha}} \tag{2}$$

Where ρ_b is bulk density of soil (g/cm3), ρ_s is the density of soil solids, because there is no big difference between difference type soil, ρ_s usually takes the constant 2.66 g/cm3, ε_s is dielectric constant of soil solids, can be obtained using ρ_s and soil temperature (℃), α is also a constant factor 0.65, $\beta^{'}$ is relative to percentage of soil sand and clay, $\varepsilon_{fw}^{'}$ is the real part of the dielectric constant of water, which can be obtained when water temperature and frequency available. So, four parameters necessary when soil dielectric constant transfer to soil moisture, they are percentage of soil sand and clay, bulk density and soil temperature (assuming the same as water temperature).

The original Dobson model can only be used at frequency range 1.4-18Ghz. Neil R.Peplinski et al. made the model expanded in 0.3~1.3Ghz frequency range, allowing the model can be used 0.3~18Ghz frequency range.[10,11]

The Dobson model is a semi-empirical model, the advantage is its much higher accuracy, but theory complex, simplicity is far less than Hallikainen empirical model.

2.3. Method

The Dobson semi-empirical model was used to build a simulated database, then, the coefficients calibrated of Hallikainen formula by the least square regression method at radiometer SMOS(1.4GHz), AMSR-E(6.9GHz), and scatterometer ERS-WCS and METOP-ASCAT (both at 5.3GHz) frequency-points were performed to set up the Simplified models to related the real part of the dielectric constant and the soil volumetric moisture content.

2.3.1. Establishment of simulation database.

Base on the Dobson semi-empirical model, a simulation database is set up. The changing parameters includes percentage of soil sand and clay, bulk density and soil temperature. When the frequency is set at 1.4、6.9 and 5.3GHz, respectively, simulation of the input parameters range as shown in table 1. Taking into account the actual surface conditions, the simulation data is persisted in the database when $(S+C) \leq 1$.

Table 1. The range of the parameters used to simulate the database by Dobson model

Soil parameters	Vol. moisture m_v /(%)	Bulk density ρ_b /(g/cm^3)	Temperature T /(℃)	Sand percentage S/(%)	Clay percentage C/(%)
Max.	2	0.9	5	5	5
Min.	60	1.7	40	95	95
Step	4	0.1	1	5	5

2.3.2. Least- squares regression calibration coefficients.

The Hallikainen formula can be expressed as follow

$$\varepsilon^{'} = a_0 + a_1 S + a_2 C + b_0 m_v + b_1 S \times m_v + b_2 C \times m_v + c_0 m_v^2 + c_1 S \times m_v^2 + c_2 C \times m_v^2 \qquad (3)$$

We take the eight parameters S, C, m_v, $S \times m_v$, $C \times m_v$, m_v^2, $S \times m_v^2$, $C \times m_v^2$ as independent variables, and a_0, a_1, a_2, b_0, b_1, b_2, c_0, c_1, c_2 as calibration coefficients, so we change the original nonlinear problem to a linear problem. Using the above simulation database, the 9 pending calibration parameters can be obtained. By least-squares regression analysis, the result of a case study of frequency 1.4GHz is

$$\varepsilon^{'} = [2.378 + 0.326S - 0.046C] + [10.750 + 59.894S + 15.703C]m_v + [73.555 - 58.372S - 14.154C]m_v^2 \qquad (4)$$

Similarly we get the calibration parameters at the frequency of 5.3 and 6.9GHz, as shown in table 2.

Table 2. The look-up table of the Simplified model at the three frequency points

Fre./ (GHz)	$\varepsilon^{'} = (a_0 + a_1 S + a_2 C) + (b_0 + b_1 S + b_2 C)m_v + (c_0 + c_1 S + c_2 C)m_v^2$								
	a_0	a_1	a_2	b_0	b_1	b_2	c_0	c_1	c_2
1.4	2.378	0.326	-0.046	10.750	59.894	15.703	73.555	-58.372	-14.154
5.3	2.388	0.348	-0.033	10.418	56.211	14.750	68.507	-54.968	-13.351
6.9	2.395	0.361	-0.025	10.188	53.775	14.119	65.180	-52.714	-12.819

2.3.3. The comparison of Simplified model and Dobson model.

The above simplified model are compared with Dobson model under the same conditions. For the comprehensiveness of the comparison, fixed the two parameters of S,C and m_v respectively, and changing the last one. The results are shown as Figure 1.(Taking 1.4GHz as an example)
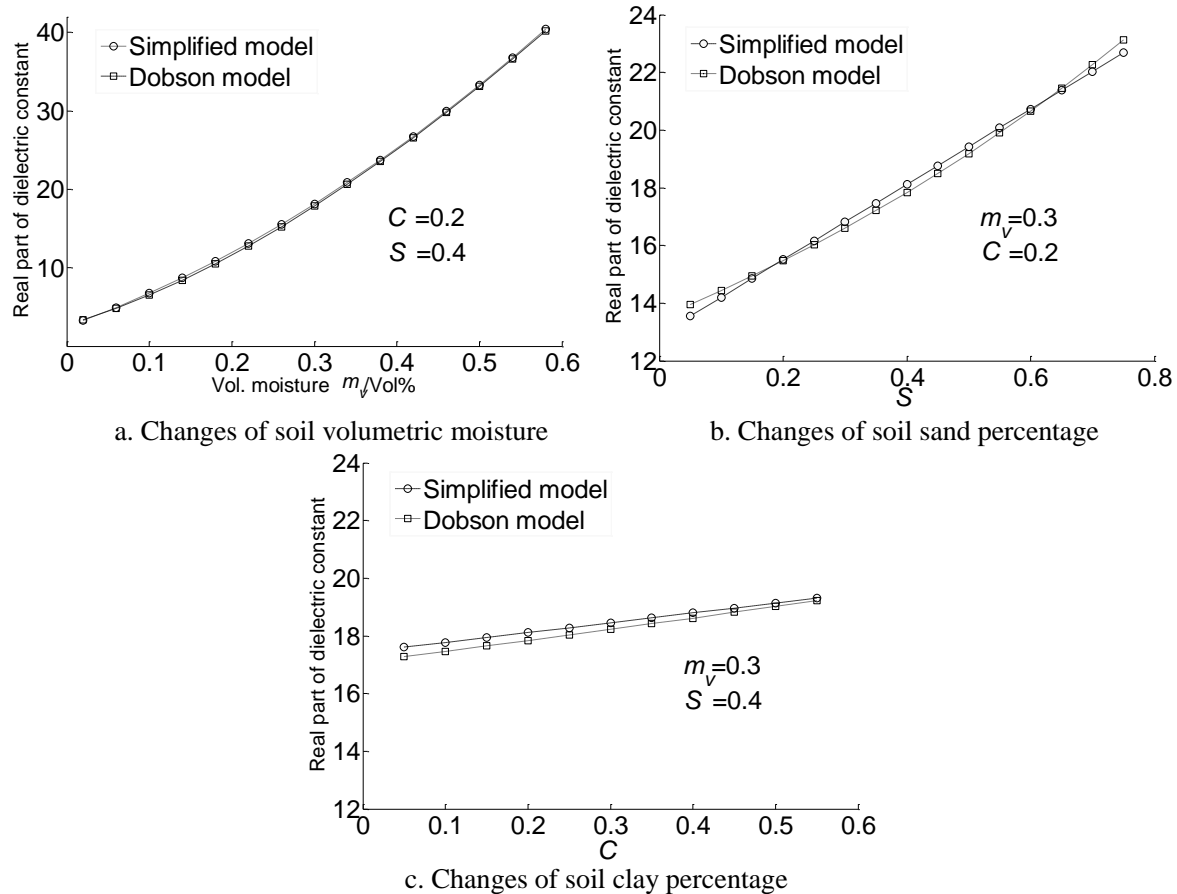

a. Changes of soil volumetric moisture   b. Changes of soil sand percentage

c. Changes of soil clay percentage

Figure 1. The comparison of the simplified model with the Dobson model (L Band 1.4GHz) for the real part of dielectric constant

As shown in Figure 1, the simulation results of Simplified model have quite good consistency with Dobson model under the same conditions. The difference of two models is due to ignorance of bulk density and soil temperature in Simplified model. Least-squares regression method made the effect of the two parameters contained by 9 coefficients of Simplified model.

3. Validation

In 2.3.3, the Simplified model is compared with Dobson model using simulated data, which proved that, ignoring bulk density and soil temperatures, but the simplified model can still keep up with Dobson model of high consistency. In this part, the model is validated using measurements from different kinds of soil. 30 measurement of soil samples collected in Beijing, and in Dengfeng City of Henan, Xingan County of Jiangxi and Liaocheng city of Shandong take 4 samples, respectively, which constitutes 42 test samples. The real part of dielectric constant of the samples are measured using Microwave Vector Network Analyzer E8362B. Due to constraints we can not access to the fine-scale *S* and *C* resource, large-scale percentage of sand and clay provided by National Geophysical Data Center(NGDC) are used in experiment, whose resolution is 0.0833° (approximate 10Km, which is the same scale of resolution of space-borne microwave radiometers and scatterometers)[12]. Taking the measurements of real part of dielectric constant and large-scale *S* and *C* from NGDC into Simplified

model, the volumetric soil moisture can be calculated, then compared with the measurements soil moisture by drying oven directly, the results are shown in Figure 2.
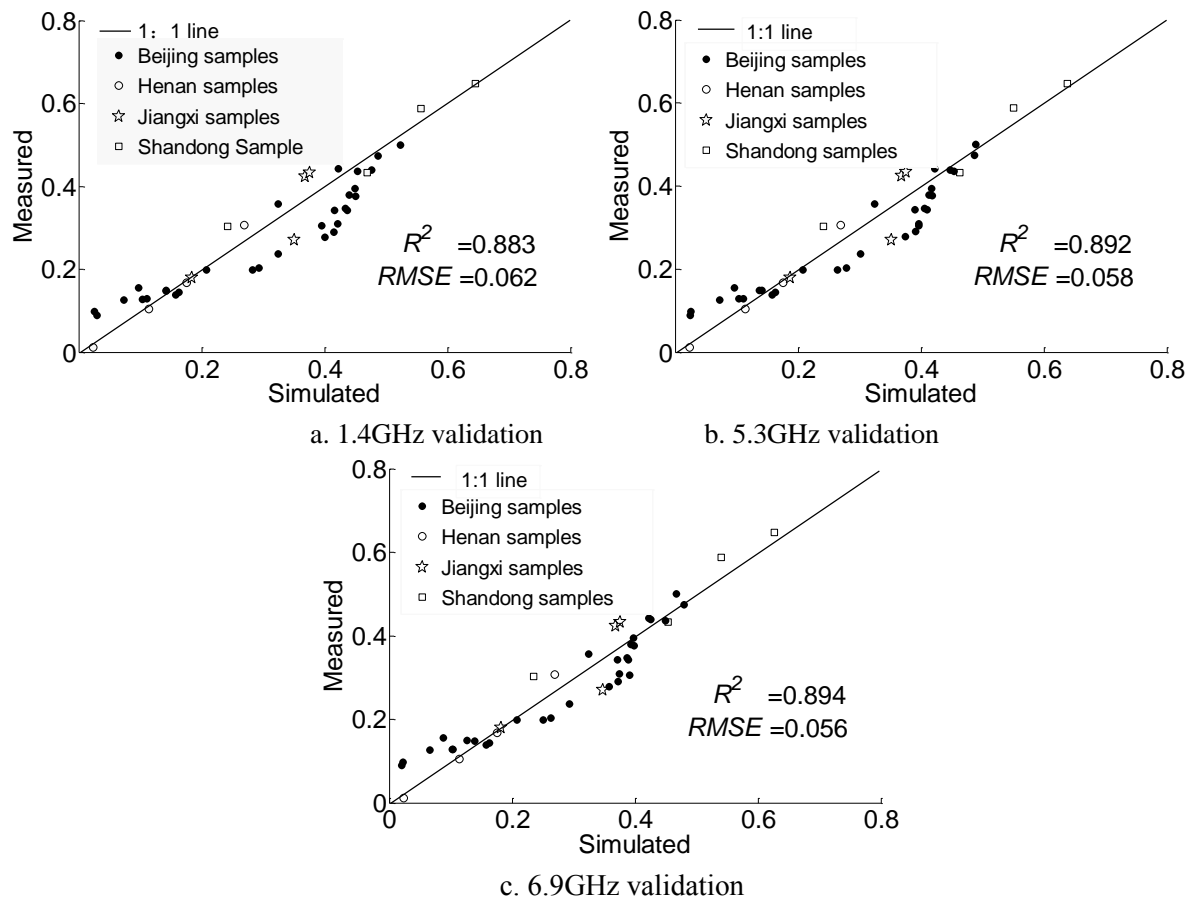

a. 1.4GHz validation   b. 5.3GHz validation

c. 6.9GHz validation

Figure 2. The comparison of the Simplified model with the measured real part of dielectric constant

As shown in Figure 3, in all three frequencies, the correlation coefficients are all close to 0.9 and RMSE not more than 0.07, which show good correlation between the measured data and Simplified model. Analysis of error source, some part is due to the accuracy of Dobson model itself, because Dobson model is the basis of this study, another part is because the ignorance of bulk density and temperature in Simplify model, the last error source is due to lack of fine-scale S and C.

4. Conclusion

For the purpose of solving the problem of the conversion between soil moisture and soil dielectric constant, the Dobson semi-empirical model was used to build a simulated database, then the coefficients of the Hallikainen formula were calibrated by the least-squares regression method at the frequency points of radiometer SMOS(1.4GHz), AMSR-E(6.9GHz), and scatterometer ERS-WCS, METOP-ASCAT (both at 5.3GHz) by using the simulated database. Finally, The Simplified models to transform the real part of dielectric constant to soil volumetric moisture content was built. In order to verify the accuracy and practicality of the model, validations were performed by using both simulated data of the Dobson semi-empirical model and measured data which were collected from the city of Beijing, Dengfeng(in Henan province), Xingan(in Jiangxi province) and Liaocheng(in Shandong province), respectively. The results showed that at 1.4GHz frequency-point, the determination coefficient(R^2) and root mean square error(RMSE) were 0.883 and 0.062, and at 5.3GHz frequency-point, the corresponding values were 0.892 and 0.058; and at 6.9GHz frequency-point, the corresponding values were 0.894 and 0.056. The results show that the Simplified models have good accuracy and practicality.

5. Acknowledgements

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