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Error and Domain of Applicability Studies for the Schmugge’s Dielectric Model of Moist Soils

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Abstract — In this paper, there was studied correlation of dielectric predictions for moist soils with the measured values, regarding the well known empirical dielectric model proposed by J. R. Wang and T. J. Schmugge. The analysis is based on the measured dielectric data borrowed from the Technical Report EL-95-34, by J. O. Curtis et al., in which the assemblage of soils measured included all of grain-size distributions that are observed in nature, with measurements being performed over the frequency range from 45 MHz to 26.5 GHz at the moistures spanning from the nearly dry samples to the ones saturated close to the field capacity values. As far as it concerns the dielectric constant, the Schmugge model was shown to be applicable in the frequency range from 0.3 to 14 GHz to the soils beyond the ensemble of soils with dielectric data of which it was developed. In the case of loss factor, this model was found to provide for accurate dielectric predictions only over the frequency range from 5.0 GHz to 14 GHz, concerning the ensemble of dielectric data independently measured.

1. INTRODUCTION

An adequate dielectric model is an essential element of all the data processing algorithms used in the radar and radio thermal remote sensing of the land. The well known Schmugge dielectric model for moist soils [1] is used in the algorithms of radio brightness data processing [2]. This model is based on the dielectric data measured only at three frequencies 1.4, 1.412 and 5.0 GHz, moistures varying from 0 to the field capacity values, and soil clay contents from 0 to 62 percent. Regarding the soil mineralogy properties, the Schmugge dielectric model uses the clay and sand gravimetric percentages as the only input parameters. The dielectric predictions by this model are accurate with regard to all the dielectric data used for its development in [1]. The main cause for good accuracy achieved is that it takes into account the property of the initially adsorbed molecules of the bound water in soil. At the same time, a domain of applicability and error of the Schmugge model have not been studied yet, regarding other frequencies and soils. This problem is analyzed by the authors on the bases of the comprehensive dielectric data set available in [3]. The data base taken from [3] covers the frequency range from 0.045 to 26.5 GHz, clay contents from 0 to 76 percent and the moistures up to field capacity values.

2. THE EMPIRICAL MODEL CONCEPT

The empirical approach of the Schmugge model [1] deals with the direct mixing of the dielectric constants of moist soil constituents. It bases on the straightforward combination of the dielectric constants of ice, bound and free water, air, and rock. The expressions for the complex dielectric constant, $\varepsilon$, of a soil-water mixture are given by

$$\varepsilon = W\varepsilon_b + (P - W)\varepsilon_a + (1 - P)\varepsilon_r, \quad W \leq W_t$$ (1)

with

$$\varepsilon_b = \varepsilon_i + \left(\varepsilon_w - \varepsilon_i\right) \frac{W}{W_t}\gamma$$ (2)

and

$$\varepsilon = W\varepsilon_b + (W - W_t)\varepsilon_w + (P - W)\varepsilon_a + (1 - P)\varepsilon_r, \quad W > W_t$$ (3)

with

$$\varepsilon_b = \varepsilon_i + (\varepsilon_w - \varepsilon_i)\gamma.$$. (4)

Here $P$ is the porosity of the dry soil. $\varepsilon_a$, $\varepsilon_w$, $\varepsilon_r$, and $\varepsilon_i$, are the dielectric constants of air, water, rock, and ice, respectively. $\varepsilon_b$ stands for the dielectric constant of the initially absorbed water (bound water). With $W$ is designated the volumetric water content in the soil, $W_t$ is the transition moisture. $\gamma$ is a parameter which can be chosen to best fit (1)–(4) to the experimental data. The complex dielectric constant has the real and imaginary parts further referred to as the dielectric constant (DC), $\varepsilon'$, and the loss factor (LF), $\varepsilon''$. 
For the LF at low frequencies it is necessary to add ohmic conductivity losses. Therefore, the total LF, \( \varepsilon''_w \), has to be written in the form
\[
\varepsilon''_w = \varepsilon'' + \alpha W^2
\]
where \( \varepsilon'' \) is given by (1)–(4) and \( \alpha \) is the parameter chosen to best fit Formula (5) to the measured \( \varepsilon''_w \) at low frequencies. Applying regression analysis, over the dielectric data set available in [1] at frequencies 1.4 and 5.0 GHz the authors of [1] determined the parameters \( \gamma, W_t \), as a function of wilting point \( WP \) as follows:
\[
\gamma = -0.57 WP + 0.481, \quad W_t = 0.49 WP + 0.165,
\]
with correlation coefficients being of 0.79 and 0.91 for \( \gamma \) and \( W_t \), respectively. The wilting point \( (WP) \) of soils in percent of dry weight was previously obtained by Schmugge et al. [4] from a multiple regression analysis of over 100 data sets of soil moistures characteristics. The expression for \( WP \) in terms of volumetric water content \( (\text{cm}^3/\text{cm}^3) \) was redetermined by the same procedure and the result is expressed in the form
\[
WP = 0.06774 - 0.00064 S + 0.00478 C
\]
while fitting in [1] the complex dielectric constants calculated with the use of (1)–(5) to the measured ones, the liquid water complex dielectric constant, \( \varepsilon'_w \) at the frequency of 1.4 GHz was assigned with the following values of DC, \( \varepsilon'_{w,1} = 79.5 \), and LF, \( \varepsilon''_{w,1} = 6.63 \). At the frequency of 5.0 GHz, the authors of [1] suggested to calculate the water complex dielectric constant with the use of the Debye formula,
\[
\varepsilon''(f) = \frac{\varepsilon_0 - \varepsilon_\infty}{1 + (2\pi f \tau_w)^2}, \quad \varepsilon''(f) = \frac{\varepsilon_0 - \varepsilon_\infty}{1 + (2\pi f \tau_w)^2} 2\pi f \tau_w + \frac{\sigma_w}{2\pi \varepsilon_r f}.
\]
In Formulas (9), the value \( f \) designates wave frequency, while the values \( \varepsilon_0 \), and \( \varepsilon_\infty = 4.9 \), \( \tau_w \), and \( \sigma_w \), are the low and high frequency limits DC, relaxation time, and ohmic conductivity, respectively. While \( \varepsilon_r \) is the DC of the vacuum. In order to use Formula (9) the respective spectroscopic parameters have to be known. To derive the spectroscopic parameters, \( \varepsilon_0, \tau_w, \) and \( \sigma_w \), we fitted Formula (9) at the frequency of 1.4 GHz to the values of \( \varepsilon''_{w,1}(1.4 \text{ GHz}) = 79.5 \) and \( \varepsilon''_{w,1}(1.4 \text{ GHz}) = 6.63 \) given by Schmugge et al. in [1] thus obtaining the following spectroscopic parameters:
\[
\varepsilon_0 = 80, \quad \tau_w = 9.28 \times 10^{-12}, \quad \text{s and } \sigma_w = 0.04232, \quad \text{Sm/m}.
\]
As a result, the values of \( \varepsilon'_{w,1} = \varepsilon'_{w,1}(f) \) \( \varepsilon'_w = \varepsilon'_w(f) \) can be calculated with the use of (9) and (10) at any frequency assigned. At the frequency of 5.0 GHz, we obtained the numerical values for DC, \( \varepsilon'_{w,1} = 74.1 \) and LF, \( \varepsilon''_{w,1} = 20.4 \) of the water dielectric constant, which should be used in Formulas (1)–(4). With the Equations (9) and (10) being available, the set of Formulas (1)–(8) are sufficient to make predictions of the DCs and LFs as a function of volumetric moisture, and clay content not only at the frequencies of 1.4 and 5.0 GHz, but at any frequency assigned, thus allowing to validate the Schmugge model dielectric predictions for the values measured in [3] in a large frequency range from 0.045 to 26.5 GHz. In the following section, the error and frequency domain of the Schmugge model applicability is analyzed.

3. ERROR AND FREQUENCY DOMAIN OF APPLICATION

To consider the frequency domain of application and error for the Schmugge model, the DCs and LFs predictions provided with this model were correlated with the measured ones available in [3]. The DCs and LFs measured in [3] belong to a broad variety of 11 soils, clay gravimetric contents varying from 0 to 76%. The values of DC and LF were measured in an extended frequency range from 0.045 to 26.5 GHz at the moistures spanning from air dry soils to those saturated at field
capacity. First of all, we validated the predictions obtained with the Schmugge model at 1.4 and 5.0 GHz. In this case, all the input parameters in Formulas (1)–(8) are directly available from [3].

Figure 1 shows the DC, \( \varepsilon'_m \), and LF, \( \varepsilon''_m \), measured as a function of the DC and LF predictions calculated with the Formulas (1)–(10).

As seen from Fig. 1, in the case of DC there is a good correlation between the measured and predicted values, with the correlation coefficients and standard deviations being on the same order at both frequencies. While the predicted LFs at the lower frequency of 1.4 GHz appeared to be noticeably less correlated with the measured ones. For this frequency, not only the values of correlation coefficient and standard deviation are found to be lower and greater, respectively, then the ones relating to the frequency of 5.0 GHz, but also a substantial squint of the linear fits relative to the bisectors are clearly observed. At the same time, the Schmugge model predictions for the LFs calculated at the frequency of 1.4 GHz showed a lot better correlation to the ones measured for the variety of soils used for its developing [1].

With this in mind, we correlated the DCs and LFs calculated with the Formulas (1)–(10) to the ones measured for two groups of frequencies: \( f = 0.3; 0.5; 1.4; 5; 14 \) GHz and \( f = 5; 10; 14 \) GHz. The result of that analysis presented in Fig. 2 proves the Schmugge model to give good DC predictions for the soil types and frequencies other than those used for its development. On the other hand, in the case of the LF, the Schmugge model was found to provide for predictions with acceptable error only at the frequency of 5.0 GHz (see Fig. 1). We extended this frequency range to the higher frequencies, with the value of parameter \( \alpha \) in (2) being equal to zero as calculated in [1], and found good correlation between the predicted values with the LFs measured in [3] for other soils in the extended frequency range, from 5.0 to 14 GHz, as seen from Fig. 2.
4. CONCLUSION

As far as it concerns the DC, the Schmugge model provides for the predictions on the same order of error with regard to all frequencies, soils and moistures independently measured in [3] as it does for the soils, frequencies and moistures measured in [1], to develop this model. As a result the Schmugge model was shown to be applicable to the soils beyond the ensemble of soils with dielectric data of which it was developed and not only for the frequencies of 1.4, 1.412 and 5.0 GHz, but in the whole range from 0.3 to 14 GHz. At the same time in the case of LF, the Schmugge model was found to provide for accurate dielectric predictions only over the frequency range from 5 to 14 GHz, concerning the ensemble of soils independently measured in [3].

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