A Parameterized Surface Reflectivity Model and Estimation of Bare-Surface Soil Moisture With L-Band Radiometer

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***Abstract*—Soil moisture is an important parameter for hydrological and climatic investigations. Future satellite missions with L-band passive microwave radiometers will significantly increase the capability of monitoring earth's soil moisture globally. Understanding the effects of surface roughness on microwave emission and developing quantitative bare-surface soil moisture retrieval algorithms is one of the essential components in many applications of geophysical properties in the complex earth terrain by microwave remote sensing. In this study, we explore the use of the integral equation model (IEM) for modeling microwave emission. This model was validated using a three-dimensional Monte Carlo model. The results indicate that the IEM model can be used to simulate the surface emission quite well for a wide range of surface roughness conditions with high confidence. Several important characteristics of the effects of surface roughness on radiometer emission signals at L-band 1.4 GHz that have not been adequately addressed in the current semiempirical surface effective reflectivity models are demonstrated by using IEM-simulated data. Using an IEM-simulated database for a wide range of surface soil moisture and roughness properties, we developed a parameterized surface effective reflectivity model with three typically used correlation functions and an inversion model that puts different weights on the polarization measurements to minimize surface roughness effects and to estimate the surface dielectric properties directly from dual-polarization measurements. The inversion technique was validated with four years (1979–1982) of ground microwave radiometer experiment data over several bare-surface test sites at Beltsville, MD. The accuracies in random-mean-square error are within or about 3% for incidence angles from 20° to 50°.**

***Index Terms*—L-band radiometer, soil moisture, surface emission.**

I. Introduction

SOIL MOISTURE is a key parameter in numerous environmental studies, including hydrology, meteorology, and agriculture. Previous investigations have established the fundamentals of passive microwave remote sensing as an important tool in determining the physical properties of soils [1]–[8]. The ability to estimate soil moisture in the surface layer to an approximately 5-cm depth by microwave remote sensing at 1.4 GHz has been demonstrated under a variety of topographic and land cover conditions. Application of microwave retrieval of soil moisture to hydrological and meteorological sciences has been influenced by the natural variability and complexity of the vegetation canopy and surface roughness that significantly affect the sensitivity of emission measurements to soil moisture. At high frequencies (C-band or higher), it is well understood that the instrument's ability to monitor soil moisture is limited by vegetation cover. At lower frequencies, this problem can be greatly reduced. Two possible future spaceborne L-band multipolarization passive microwave techniques—two-dimensional synthetic aperture interferometry [5], [8] and filled-aperture mesh deployable reflectors [9]—will significantly increase the capability of monitoring earth's soil moisture globally. In addition to operating at long wavelengths, these multipolarization instruments provide an opportunity to utilize multiple polarization data in the estimation of soil moisture. The full utilization of these data will require a further understanding of surface roughness effects on the emission signals, especially on the relationships of the emission signals at different polarizations, in order to develop a quantitative algorithm for global soil moisture mapping.

The surface reflectivity model is one of the essential components in many applications of microwave remote sensing of geophysical properties in complex earth terrain. It is a direct component in monitoring soil moisture in bare or vegetated surfaces and serves as the boundary condition in studying snow, vegetation, and atmospheric properties. Currently, there are two types of approaches used to model surface reflectivity:

1) *semiempirical approach:* this type of model is generally found to be easy to use without significant computing efforts and is generally easy to implement as an inversion model;
2) *physical modeling approach:* the surface reflectivity can be obtained by integrating the bistatic scattering coefficient over the upper hemisphere [10].

The most commonly used semiempirical model that describes the bare-surface emission as a function of the surface roughness and dielectric properties is the so-called Q/H model [11], [12]. The parameter Q describes the energy emitted in orthogonal polarizations due to surface roughness effects. H is a measure of the effect of surface roughness to increase surface emissivity. However, it has been recognized that there can be a great difference between the direct physical measurements of surface roughness in the field and those derived by fitting the Q/H model with observed soil moisture or dielectric constant measurements [13], [14]. Commonly, the surface roughness parameter in the Q/H model has to be determined empirically from the experiment data and often is called "effective roughness." This is an inconvenient technique to apply in either the forward calculation to relate the soil moisture with microwave radiometer measurements or the inverse calculation, since there are no quantitative relationships between the empirical roughness parameter and the commonly used measurable surface roughness characteristics such as the root-mean-square (rms) height s, the autocorrelation length l, and the autocorrelation function.

Attempts to improve understanding of the effects of surface roughness and how traditional surface roughness parameters can be directly related to emission signals have resulted in the development of several surface reflectivity models. In comparison with the Q/H model, all of these models determined that the Q parameter is not very important [14]–[17]. Depending on the empirical data sources and the techniques used to develop the reflectivity models, the H parameter can have a variety of different forms.

- Mo and Schmugge [15] simulated the effects of surface roughness on the effective surface reflectivity using the Kirchhoff model and compared L- and C-band measurements from three field sites with different roughness conditions. They found that the H parameter depends on soil moisture and the ratio of s/l and that it varies with the incidence angle and polarization.
- Saatchi *et al.* [16] used the traditional surface scattering models—small perturbation model, physical optical model, and geometric optical model—to simulate the effect of surface roughness for horizontal (H) polarization and compared the results with experimental data over a frequency range of 1–12 GHz. A parameterized reflectivity model was developed with two (coherent and noncoherent) components. Unfortunately, vertical (V) polarization was not studied.
- Wegmüller and Mätzler [14] developed an empirical rough-surface reflectivity model using ground radiometer measurements with frequencies ranging from 1–100 GHz and with incidence angles of 20° to 70°. The reported accuracies of the surface reflectivity in terms of the random-mean-square errors (rmse) were 0.095 and 0.061 for H and V polarizations, respectively. This level of accuracy is about 20% of the dynamic range of the surface emission response to soil moisture.
- Wigneron *et al.* [17] also developed an empirical rough-surface reflectivity model using experimental measurements over seven different roughness conditions at L-band 1.4 GHz and incidence angles $\leq$ 40°. The reported accuracy for the surface reflectivity was 0.031 (rmse). This study concluded that the H parameter is independent of both incidence angle and polarization.

VII. Conclusion

Understanding the effects of surface roughness on microwave emission and developing quantitative bare-surface soil moisture retrieval algorithms are essential to many applications of geophysical properties in complex earth terrain by microwave remote sensing. In this study, we first validated the IEM model with a highly accurate but complex 3-D Monte Carlo model. A comparison showed that the IEM model slightly overestimates the emissivity for V polarization with rmses of 0.008 and 0.013 at 40° and 50° incidence angles, respectively. For H polarization, the errors were more random with rmses of 0.01 and 0.017 at 40° and 50°. The results indicate that the IEM model can be used to simulate the surface emission quite well for a wide range of surface roughness and conditions.

Then, we used an IEM model to simulate a database with a wide range of surface roughness and dielectric conditions. Using the IEM-simulated data, we demonstrated several important characteristics of surface roughness effects on microwave emission signals that were not incorporated in currently used surface effective reflectivity models. It was found that the effects of surface roughness on microwave emission signals at V and H polarization might be different in both magnitude and direction, depending on the incidence angle, surface roughness, and dielectric properties. The overall effect of surface roughness can be explained by the combined effects from two components: the coherent component that decreases as the surface roughness increases and the noncoherent component that increases as the roughness changes. As a result, the total reflected energy may have two outcomes when comparing rough and flat surfaces. If the amount of reduction in the coherent component of the reflected energy is greater than the increase in noncoherent scattering, surface roughness reduces the effective reflectivity. This represents all cases for H polarization at all incidence angles. However, when the amount of the reduction in the coherent component of the reflected energy is less than the increase in the noncoherent scattering, surface roughness actually increases the effective reflectivity. This only occurs in V polarization. As a result, the surface effective reflectivity in V polarization could be greater than its corresponding Fresnel reflectivity depending on the incidence angle, surface roughness, and dielectric properties. This also impacts roughness effects on the polarization ratio V/H measurements. These two important characteristics have been not incorporated in the currently available semiempirical surface effective reflectivity models.

We developed a surface effective reflectivity model for L-band (1.4 GHz) utilizing both V and H polarizations and three typical correlation functions (gaussian, 1.5-power, and exponential) by parameterizing the IEM model simulated data for a wide range of surface soil moisture and roughness properties. When compared to the IEM model simulated data, the parameterized model in (4) has the accuracy (rmse) better than 0.01 for V polarization at all incidence angles with the best accuracy (0.0035) at 40°. For H polarization, the accuracy increases as the incidence angle increases with the worst accuracy (0.011) at 20° and the best accuracy (0.0028) at 60°. These results indicate that the parameterized model can reproduce the IEM model predictions over a wide range of surface roughness conditions.

Using the IEM model simulated database for a wide range of surface soil moisture and roughness properties, we developed an inversion model that uses dual polarization measurements to minimize surface roughness effects and to estimate surface dielectric properties directly. For the IEM model simulated data, the algorithm in (8) has an accuracy of 1.68% at 20°. The accuracy increases as the incidence angle increases. The best accuracy can be seen at 45° with 0.55%. Validation of this inversion technique with ground microwave radiometer experiment data indicated that there was an overall trend for soil moisture underestimation in the algorithm performance. However, all rmses are within or about 3% for incidence angle between 20° and 50°.