Reanalysis of L-band Brightness Predicted by the LSP/R Model for Prairie Grassland: Incorporation of Rough Surface Scattering

Y.-A. Liou, Member, IEEE, K.-S. Chen, Senior Member, IEEE, and T.-D. Wu

Abstract—L-band brightness predicted by the land surface process/radiobrightness (LSP/R) model for prairie grassland appears to be somewhat lower than expected [1]. A crucial reason for the underestimate of the L-band brightness is that the soil surface was treated as smooth. In this paper, surface scattering of the soil determined by the IEM model is incorporated into the LSP/R model to examine its impact on the predicted L-band brightness. Eight sets of surface parameters, two correlation lengths \( L \) of 3 and 6 cm \( \times 4 \) root mean squared (RMS) heights \( \sigma \) of 0.3, 0.6, 0.8, and 1.0 cm, are utilized to characterize the emission of the soil surface. It is found that H-polarized, L-band brightness is expectedly increased by different levels for all of the eight rough surface cases compared to the smooth surface case. The increase in the average of the H-polarized, L-band brightness is by as much as 13.2 K for the case with \( L = 3 \) cm and \( \sigma = 1.0 \) cm. In addition, L-band’s sensitivity to soil moisture is found to be approximately equal with and without the scattering effects. An increase in H-polarized, L-band brightness by about 12 K at the end of a 14-day simulation by the LSP/R model is in response to a decrease in soil moisture by 7% for all of the nine cases of concern (eight rough plus one smooth soil surfaces).

Index Terms—L-band brightness temperature, polarization index, surface scattering.

I. INTRODUCTION

Surface temperature, and water in soil and vegetation that is available to the atmosphere play a key role in the land–air exchanges of energy and moisture so that they become key parameters in atmospheric models for continental weather and climate ([2]–[5]). In addition, they govern infrared and microwave emission of the land surface. This allows one to take into account coupled heat and moisture transport within prairie grassland [1]. While this prairie LSP/R model was validated with observations from a field campaign, the assumption of a smooth soil surface in its R module is simple and can be improved by taking into account the effect of rough surface scattering. In addition, the LSP/R model seems to underestimate L-band brightness (Schmugge, T. J., 1997, personal communication). Moreover, it was suggested that the requirement for the accuracy in computing bistatic scattering coefficients should be within 1% in order to obtain reliable estimates of rough surface emissivities for passive remote sensing applications [15]. However, it is almost impossible to achieve this requirement, an adoption of a surface scattering model must be carefully determined.

In this paper, the IEM surface scattering model is incorporated into the LSP/R model for prairie grassland to investigate the influence of surface scattering from the soil on the L-band radiometric signatures. L-band has been recognized as an appropriate channel for mapping surface soil moisture ([16]–[19]). Descriptions of the LSP/R model and IEM model, and their validations are given in Section II. Results of numerical simulations are presented in Section III.

II. LSP/R AND IEM MODELS

A. LSP/R Model

The LSP/R model consists of two modules, an LSP module and an R module [1]. The LSP module simulates the exchanges of energy and moisture among air, vegetation, and soil. The R module estimates the brightness of the vegetated-cover terrains by treating the soil surface as smooth. As shown in Fig. 1, the total brightness of the module is comprised of the following four components.

\[ T_{b_{soil}} \quad \text{soil brightness attenuated by one trip through the canopy;} \]

\[ T_{b_{c,d}} \quad \text{downwelling canopy brightness reflected by the soil and attenuated by one trip through the canopy;} \]
Fig. 1. Radiobrightness components of the R module.

\[ T_{b_{u}} = T_{b_{u}} + T_{b_{s}} + T_{b_{sk}} \]

- \( T_{b_{u}} \) upwelling canopy brightness
- \( T_{b_{s}} \) sky brightness reflected by the soil and attenuated by two trips through the canopy.

That is

\[
T_{b_{s}} = T_{s,e}(1 - R_{F_{s},p} / \mu) e^{-\tau_{0}/\mu} \\
T_{b_{s,2}} = T_{s,e}(1 - e^{-\tau_{0}/\mu}) R_{F_{s},p} / \mu e^{-\tau_{0}/\mu} \\
T_{b_{s,u}} = T_{s,e}(1 - e^{-\tau_{0}/\mu}) \\
T_{b_{sk}} = T_{s,sk} R_{F_{s},p} / \mu e^{-\tau_{0}/\mu}
\]

(1)

where

- \( T_{s,e} \) effective emitting temperature of the soil [13], [14], [1], K;
- \( R_{F_{s},p} \) Fresnel reflectivity of the moist soil for polarization \( \mu \);
- \( \mu \) cosine of the SSM/I incidence angle of 53°;
- \( T_{c,e} \) effective emitting temperature of the canopy, K;
- \( \tau_{0} \) optical depth of the air-grass mixture layer, nepers.

To run the LSP/R model for the purpose of validation, the model was driven by meteorological and sky radiance data from the radiobrightness energy balance experiment (REBEX-1) on prairie grassland near Sioux Falls, SD, during the fall and winter of 1992-1993 [20]. Model predictions were compared with 995 consecutive REBEX-1 observations over a 14-day period in October. The special sensor microwave/imager (SSM/I) channels (19, 22, 37, and 85 GHz), and L-band were chosen in the study so that an incidence angle of 53° was used to compute the radiobrightnesses. While the H-polarized, 19 GHz brightnesses were shown to agree with observations from REBEX-1, the 37 GHz brightnesses were found to be overestimated due to the ignorance of scatter darkening. Moreover, predictions of H-polarized, L-band brightnesses were considered to be lower than expected (Schmugge, 1997, personal communication). A crucial reason for the underestimate of the L-band brightnesses is that surface scattering from the soil was not taken into account.

To investigate the impact of soil surface scattering on the L-band radiometric signatures, the IEM model is utilized to determine the surface scattering from the soil that is subsequently incorporated into the LSP/R model in the current presentation.

B. IEM Model

Among the rough surface scattering models, the IEM rough surface scattering model is of a major one [21]. It was first developed to describe electromagnetic wave scattering for a randomly rough, perfectly conducting surface [22], and later, for a randomly rough dielectric surface [23]. The IEM surface scattering model was then extended to take into account the influence of multiple scattering from two surface points near nor far [24], [25], and applied to develop a transition model for the reflection coefficient in surface scattering [26]. The extended IEM surface scattering model was validated with measurements acquired at the University of Texas, Arlington, for a rough perfectly conducting surface, and with those acquired at the European Microwave Signature Laboratory (EMSL), Ispra, Italy, for a very rough dielectric surface.

The emissivity of the soil is expressed as

\[ e_{\theta}(\theta) = 1 - R_{p}(\theta) \]

\[ = 1 - \frac{1}{4\pi \cos \theta} \int_{0}^{\pi/2} \int_{0}^{\pi/2} \frac{\sigma_{\theta}^{0}(\theta, \theta'; \psi_{s} - \phi) + \sigma_{\psi}^{0}(\theta, \theta'; \psi_{s} - \phi)}{\sin \theta_{s}} d\theta_{s} d\phi_{s} - R_{F_{s},p}(\theta) e^{-\left(\frac{4\pi \cos \theta}{\lambda}\right)^{2}} \]

(2)

where

- \( R_{p} \) reflectivity;
- \( \sigma_{\theta}^{0} / \sigma_{\psi}^{0} \) like-/cross-polarized bistatic scattering coefficient that is estimated by the IEM model [26];
- \( \theta \) and \( \phi \) spherical coordinates;
- \( \psi_{s} \) subscript s represents the direction of the scattered power;
- \( \mu \) roughness factor to correct the specular coherent term;
- \( \lambda \) wavelength of the operating frequency.

(2) is appropriate for a half-space lossy medium with negligible power transmitted into the medium.

To validate the emissivity predicted by the IEM model, estimates of the emissivity based on (2) are compared with measurements from a moderately-rough surface reported by the EMSL Joint Research Center, European Commission (EMSL/JRC), Ispra, Italy [27]. The rough surface is a Gaussian correlated surface with an RMS height of 0.4 cm and a correlation length of 6.0 cm. Fig. 2 shows V- and H-polarized emissivities at 6.8 and 10.6 GHz estimated by the IEM model for incidence angles from 20 to 60° at an interval of 5°, and acquired by EMSL/JRC. Model predictions agree with measurements very well. Table I lists the standard deviations in H-polarized (V-polarized) emissivity between model predictions and observations. Good agreements enable us to conduct further numerical simulations by incorporating the IEM model into the prairie LSP/R model, as discussed in Section III. Emissivity measurements are not available for L-band, so we cannot show the similar comparison for L-band.

Note that an exponential correlation function (ECF) is often found to best characterize the measured surfaces of interest [28]. Hence, it is a common practice to describe a naturally rough surface with an ECF as we present in this paper. Nevertheless, the ECF is not differentiable at the origin and cannot be used to define an RMS slope for rough surfaces [21]. We are unaware of measurements from laboratory-controlled experiments for exponential correlated surfaces, so that the use of the IEM theory is validated by comparing its bistatic scattering predictions with measurements from Gaussian correlated surfaces. For the sake of comparison, predictions from the use of the IEM
theory for Gaussian correlated surfaces are also presented after the treatments of exponential correlated surfaces are detailed in Section III.

III. NUMERICAL SIMULATIONS

A. Exponential Correlated Surfaces

The LSP/R model with incorporation of the IEM model is used to determine the L-band brightnesses for eight exponential correlated surfaces, two correlation lengths of 3 and 6 cm × 4, and RMS heights of 0.3, 0.6, 0.8, and 1.0 cm. The simulations are executed for the same 14-day period used to validate the LSP/R model so that model predictions of L-band brightness can be compared. The ECF can be written as

\[ \rho(\tau) = e^{-\tau/L} \]  

where \( L \) is the correlation length [23].

Fig. 3 shows H-polarized, L-band brightnesses versus daynumber for (a) \( L = 3 \text{ cm} \) and (b) \( L = 6 \text{ cm} \), and versus soil moisture for (c) \( L = 3 \text{ cm} \) and (d) \( L = 6 \text{ cm} \). The corresponding results for the smooth soil surface case are also included. Notations used in the figure are explained in Table II.

In contrast, V-polarized, L-band brightnesses are decreased by different amounts for the eight rough surface cases compared to the smooth soil surface case. Fig. 4 shows the V-polarized, L-band brightnesses versus daynumber for (a) \( L = 3 \text{ cm} \) and
TABLE II
NOTATIONS USED TO REPRESENT THE EIGHT ROUGH SURFACE CASES, AND INCREASES IN THE AVERAGE OF H-POLARIZED, L-BAND BRIGHTNESSES ($\Delta T_{B_H}$) AND DECREASES IN V-POLARIZED, L-BAND BRIGHTNESSES ($\Delta T_{B_V}$) FOR EIGHT ROUGH SURFACE CASES COMPARED TO THE SMOOTH SOIL SURFACE CASE

<table>
<thead>
<tr>
<th>Cases</th>
<th>$L$, cm</th>
<th>$\sigma$, cm</th>
<th>$\Delta T_{B_H}$, K</th>
<th>$\Delta T_{B_V}$, K</th>
</tr>
</thead>
<tbody>
<tr>
<td>L3.03</td>
<td>3.0</td>
<td>0.3</td>
<td>1.39</td>
<td>-0.30</td>
</tr>
<tr>
<td>L3.06</td>
<td>3.0</td>
<td>0.6</td>
<td>4.89</td>
<td>-0.94</td>
</tr>
<tr>
<td>L3.08</td>
<td>3.0</td>
<td>0.8</td>
<td>8.63</td>
<td>-1.46</td>
</tr>
<tr>
<td>L3.10</td>
<td>3.0</td>
<td>1.0</td>
<td>13.20</td>
<td>-2.05</td>
</tr>
<tr>
<td>L6.03</td>
<td>6.0</td>
<td>0.3</td>
<td>1.06</td>
<td>-0.57</td>
</tr>
<tr>
<td>L6.06</td>
<td>6.0</td>
<td>0.6</td>
<td>3.68</td>
<td>-1.47</td>
</tr>
<tr>
<td>L6.08</td>
<td>6.0</td>
<td>0.8</td>
<td>6.34</td>
<td>-2.39</td>
</tr>
<tr>
<td>L6.10</td>
<td>6.0</td>
<td>1.0</td>
<td>9.68</td>
<td>-3.50</td>
</tr>
</tbody>
</table>

Fig. 4. V-polarized, L-band brightnesses versus daynumber for (a) $L = 3$ cm and (b) $L = 6$ cm, and versus soil moisture for (c) $L = 3$ cm and (d) $L = 6$ cm. The corresponding results for the smooth soil surface case are also included.

(b) $L = 6$ cm, and versus soil moisture for (c) $L = 3$ cm and (d) $L = 6$ cm. The decreases in V-polarized, L-band brightness are listed in Table II. We notice that the magnitudes of $\Delta T_{B_H}$ appear to relatively small compared to those of $\Delta T_{B_V}$. The largest decrease occurs by $-3.5$ K for the case with $L = 6$ cm and $\sigma = 1.0$ cm. This indicates that the smooth surface high emissivity is due to the Brewster angle effect and is partially reduced by surface roughness. Scattering results in depolarization of the surface emission so that L-band brightnesses are increased for the H-polarization but decreased for the V-polarization. That is, the difference in V- and H-polarized, L-band brightnesses is decreased with increasing surface roughness.

An alternative way to quantify the depolarization of the surface emission caused by the roughness is through an evaluation of the polarization index (PI) defined as

$$PI = \frac{T_{B_H} - T_{B_V}}{T_{B_H} + T_{B_V}}$$

where $T_{B_H}$ is the V-polarized brightness, and $T_{B_V}$ is the H-polarized brightness. Fig. 5 shows the L-band polarization index based on the 14-day simulations of the prairie LSP/R model with and without incorporation of the IEM rough surface scattering model. Similarly, PI is decreased with increasing surface scattering.

B. Gaussian Correlated Surfaces

To examine the impact of correlation function on L-band brightness, the LSP/R model and the IEM model are simulated for eight Gaussian correlated surfaces. The conditions of roughness for the eight Gaussian correlated surfaces are as same as those used for the exponential correlated surfaces. Fig. 6 shows the V-polarized, L-band brightnesses versus daynumber for (a) $L = 3$ cm and (b) $L = 6$ cm, and versus soil moisture for (c) $L = 3$ cm and (d) $L = 6$ cm for the Gaussian correlated surfaces. The changes in both H-polarized and V-polarized, L-band brightness are listed in Table III. H-polarized, L-band brightness are not shown because they are less influenced by the correlation function than the V-polarized, L-band brightnesses. A comparison between Figs. 4 and 6 and a comparison between Tables II and III demonstrate that the use of both correlation functions results in similar impacts on L-band brightness. As examples, the sensitivity of L-band brightness to soil moisture is about equal for all rough surfaces, and it is little correlation function-dependent, and the magnitudes of $\Delta T_{B_H}$ and $\Delta T_{B_V}$ increase with increasing RMS height for the same correlation length. The exception is that the decrease in $T_{B_V}$ is more profound for Gaussian correlated surfaces than exponential correlated surfaces. This suggests that the IEM
LIOU et al.: REANALYSIS OF L-BAND BRIGHTNESS

Fig. 6. V-polarized, L-band brightnesses versus day number for (a) \( L = 3 \) cm and (b) \( L = 6 \) cm, and versus soil moisture for (c) \( L = 3 \) cm and (d) \( L = 6 \) cm for the eight Gaussian correlated surfaces.

TABLE III
INCREASES IN THE AVERAGE OF H-POLARIZED, L-BAND BRIGHTNESSES (\( \Delta T_{B_H} \)) AND DECREASES IN V-POLARIZED, L-BAND BRIGHTNESSES (\( \Delta T_{B_V} \)) FOR THE EIGHT GAUSSIAN CORRELATED SURFACES COMPARED TO THE SMOOTH SOIL SURFACE CASE

<table>
<thead>
<tr>
<th>Cases</th>
<th>( L ), cm</th>
<th>( \sigma ), cm</th>
<th>( \Delta T_{B_H} ), K</th>
<th>( \Delta T_{B_V} ), K</th>
</tr>
</thead>
<tbody>
<tr>
<td>L3.03</td>
<td>3.0</td>
<td>0.3</td>
<td>1.44</td>
<td>-0.55</td>
</tr>
<tr>
<td>L3.06</td>
<td>3.0</td>
<td>0.6</td>
<td>3.18</td>
<td>-1.56</td>
</tr>
<tr>
<td>L3.08</td>
<td>3.0</td>
<td>0.8</td>
<td>8.94</td>
<td>-2.55</td>
</tr>
<tr>
<td>L3.10</td>
<td>3.0</td>
<td>1.0</td>
<td>13.69</td>
<td>-3.75</td>
</tr>
<tr>
<td>L6.03</td>
<td>6.0</td>
<td>0.3</td>
<td>0.91</td>
<td>-1.08</td>
</tr>
<tr>
<td>L6.06</td>
<td>6.0</td>
<td>0.6</td>
<td>3.08</td>
<td>-3.66</td>
</tr>
<tr>
<td>L6.08</td>
<td>6.0</td>
<td>0.8</td>
<td>5.28</td>
<td>-6.22</td>
</tr>
<tr>
<td>L6.10</td>
<td>6.0</td>
<td>1.0</td>
<td>8.04</td>
<td>-9.34</td>
</tr>
</tbody>
</table>

Fig. 7. L-band polarization index based on the 14-day simulations of the prairie LSP/R model with and without incorporation of the IEM model for the eight Gaussian correlated surfaces.

model predicts stronger bistatic scattering for the Gaussian correlated surfaces than the exponential correlated surfaces for V-polarization at L-band for the incident angle of our concern since the specular coherent term in (2) is correlation function independent. Consequently, depolarization of the surface emission at L-band is more profound for the Gaussian correlated surface as shown in Fig. 7. It is clearly observable that PI values are decreased most obvious for the case with \( L = 6 \) cm and \( \sigma = 1.0 \) cm than the other cases.

IV. CONCLUSIONS

L-band radiometric signatures are re-analyzed using predictions from the LSP/R model with and without incorporation of the rough surface scattering. The scattering from soil surface is estimated by the IEM model. While there are no field experiments to verify the L-band emissivities predicted by the IEM model, we do validate the model predictions of emissivities at 6.8 and 10.6 GHz. Good agreements in emissivity at the two frequencies between model predictions and measurements acquired by the EMSL/JRC are achieved for two moderately rough surfaces.

Upon validating the emissivity predictions from the IEM model, the model is incorporated into the LSP/R model to calculate surface scattering from the soil at L-band. Eight sets of surface parameters are considered. Very encouraging results are obtained because H-polarized, L-band brightnesses are increased by different amounts for all of the eight rough surface cases compared to the smooth soil surface case, whose predictions were considered to be somewhat lower than expected (Schmugge, T.J., 1997, personal communication). The increases in the average of the H-polarized, L-band brightness range from 1.1 K for \( L = 6 \) cm and \( \sigma = 0.3 \) cm to 13.2 K for \( L = 3 \) cm and \( \sigma = 1.0 \) cm. In contrast, V-polarized, L-band brightnesses are decreased since surface scattering results in depolarization of the soil surface emission. The decreases in the average of the V-polarized, L-band brightness range from 0.39 K for \( L = 3 \) cm and \( \sigma = 0.3 \) cm to -3.50 K for \( L = 6 \) cm and \( \sigma = 1.0 \) cm.

In addition, L-band’s sensitivity to soil moisture is shown to remain about the same with and without the scattering effects. An increase in H-polarized, L-band brightness by about 12 K at the end of the 14-day simulations is in response to a decrease in soil moisture by 7% for the nine cases of interest. There is almost no difference in L-band’s sensitivity to soil moisture, probably because the factors dominating surface scattering are not changed during the 14-day period of the simulations.
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REFERENCES


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