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Modeling and Analysis of Microwave Emission from Multiscale Soil Surface

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Abstract

This paper analyzes the microwave emission from the multiscale soil surface, characterized by a modulated correlation function. The modulation ratio, defined as the ratio of baseband correlation length and modulated length, determines the degree of multiscale roughness. We examine the frequency and look angle response of emission to the multiscale roughness. The results indicate that, as the modulation ratio increases, the H polarized emissivity increases more obviously. By comparison, the V polarized emissivity is less sensitive to the multiscale effect. Besides, both the H and V polarized emissivities, given rise from the modulation effect, are significantly enhanced at small and moderate look angles. Results suggest that the multiscale effect may be negligible when the look angles are around 45°~50° at V polarization. The results in this study may provide a promising clue to decouple the multiscale effects, thus leading to more reliable emission observations.

1. Introduction

Many parameters control the roughness variation in the formation process of the soil surface, resulting in multi-scale in nature, ranging from topographic to microstructure scales. In terms of autocovariance function, there exist spatial short-range and long-range correlations. The soil surface's scale-dependent roughness variations were documented in [1,2]. Good attempts were made to model the sources of spatial variations by fractals and non-fractals approaches. Mattia et. al [3] applied the random fractals to describe the multiscale roughness of a soil surface. More on the multifractals to model the soil surface for radar backscattering with satisfactory results were reported in [4-6]. Chen et al. [7] applied the frequency modulation concept to model the multiscale roughness. It is generally acceptable that the two-scale model [8] was able to recover, to a reasonable extent, the measured scattering data. Plant [9] considered a three-scale to model the radar backscatter from the sea in which waves were divided into small-, intermediate-, and large-scale waves, where the small and intermediate scales are tilted, advected, and modulated by larger-scale waves. However, in terms of parameters estimation from radar measurement, the cut-off boundary of the various scale from large to small scales is not set systematically but heuristically. More recently, a multiscale roughness model was proposed [10] to estimate surface roughness at different spatial scales using proxy variables, for the purpose of improving the soil moisture from radiometer observations. For the surface to be multi-scale, how the individual scale plays and interplays with another scale contribute to the scattering and emission remains explored. A recent work [11] demonstrated that modulation concept offers higher flexibility to model the radar scattering of multiscale rough surface. By extending the work of [11], this paper evolves to improve the understanding of the frequency response of microwave emission to the multiscale roughness.

2. Multiscale Rough Surface

As shown in Figure 1, the geometric components of the multiscale rough surface profile contain small-, intermediate-, and large-scale waves. In [11], the modulation concept is used to describe the correlation function of many continuous scales, in which the individual scale plays and interplays with another scale are considered in the context of microwave emission.

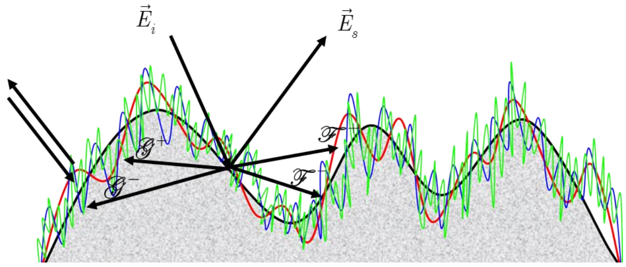


Figure 1. The geometric components of multiscale rough surface profile.

Referring to [11], a multiscale rough surface can be modeled by modulating a single scale surface with a carrier:

$$\rho_m(\mathbf{r}) = \rho(\mathbf{r}) J_0\left(\frac{2\pi}{\lambda_m}|\mathbf{r}|\right) \tag{1}$$

where the carrier $J_0(\cdot)$ is the zeroth-order Bessel function, λ_m is the modulation length, $\mathbf{r}$ is the lag distance, $\rho(\mathbf{r})$ is the correlation function of baseband.

The RMS slope s is given by the second deritive of the correlation function:

$$s=\sqrt{-\sigma^2\rho''(0)} \tag{2}$$

As an example, for a Gaussian modulated sueface, we have

$$s=\frac{\sigma}{l}\sqrt{2\left(1+\pi^2 r_m{}^2\right)} \tag{3}$$

For a multiscale surface, this is the local RMS slope, which is determined by the basedband correlation length and modulation length. When $r_m=0$, $s=\sqrt{2}\sigma/l$, which is the slope of baseband Gaussian correlated surface.

3. Emission from Multiscale Rough Surface

As shown in Figure 2, we plot the emissivity as a function of frequency. The exponential modulated multiscale surface was selected with the modulation ratio varying from 0 to 1. For numerical illustrations, we selected the look angle of 40° and the RMS height of 0.5 cm. The permittivity was set as 12-*j*1.8. For unmodulated rough surface ($r_m=0$), the baseband correlation length was fixed to 5cm. For exponential modulated surfaces, we calculate the emissivity with two effective correlation lengths: $l_{eff}=1.92cm\left(r_m=0.6\right)$ and $l_{eff}=1.25cm\left(r_m=1.0\right)$. By comparison, the V polarized emissivity is less sensitive to the multiscale effect. As the modulation ratio increases, the H polarized emissivity increases. The difference of H and V polarized emissivities decreases with frequency. Besides, a larger r_m shrinks the polarization difference, especially at higher frequency region (>9.6GHz). As the frequency increases, the polarization diversity of the emissivity drops when more fine scales of roughness are present.

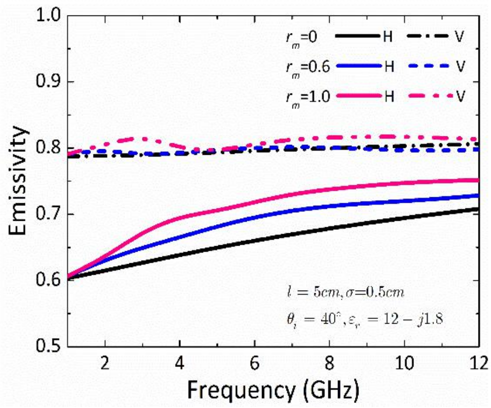


Figure 2. Emissivity as function of frequency for exponential modulated multiscale rough surfaces $\sigma=0.5cm, \varepsilon_r=12-j1.8,\ l=5cm\left(r_m=0\right),\ l_{eff}=1.92cm\left(r_m=0.6\right)$ $l_{eff}=1.25cm\left(r_m=1.0\right)$, $\theta_i=40°$.

In what follows, we examine the emissivity as a function of look angle (0~80°) for unmodulated ($r_m=0$) and modulated ($r_m=0.6\ \&\ 1.0$) rough surfaces in Figure 3. We set the frequency of 5.5 GHz, the RMS height of 0.5 cm, and the permittivity of 12-*j*1.8. From Figure 3, we see that both the H and V polarized emissivities, due to modulation effect, are significantly enhanced at small and moderate look angles. This deviation may be attributed to the change of effective roughness at a small look angle. If the multiscale effect is ignored, the emissivities are underestimated, especially at small and moderate look angles. Besides, as the modulation ratio increases, the V-polarized emissivity decreases slightly at large look angles.

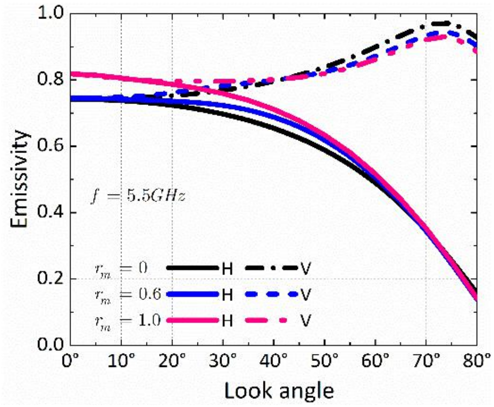
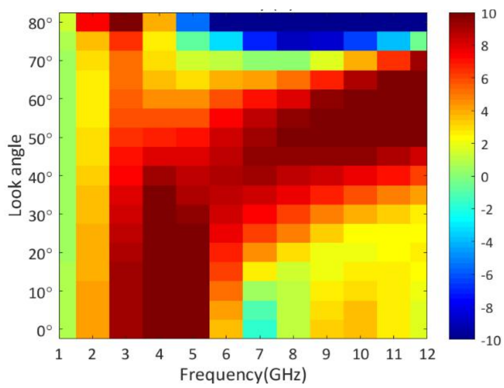
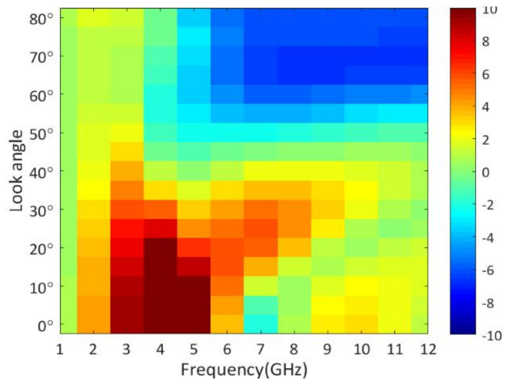


Figure 3. Emissivity as function of look angle from exponential modulated multiscale rough surfaces, $\sigma=0.5cm, \varepsilon_r=12-j1.8,$ $l=5cm\left(r_m=0\right),$ $l_{eff}=1.92cm\left(r_m=0.6\right)$ $l_{eff}=1.25cm\left(r_m=1.0\right)$, $f=5.5GHz$.

To examine the coupling effects of frequency and look angle, we present the emissivity pattern varying with these two parameters simultaneously in Figure 4. For the convenience of simulation, we choose $l=5cm\left(r_m=0\right)$ as the carrier correlation length. The emissivities of multiscale surface are evaluated with modulation ratio of 1.0. The RMS height is set as 0.5 cm, and the relative permittivity is 12-*j*1.8. From Figure 4, we clearly see that the dynamic range of the difference of emissivity is -10%~10%. For V polarization, the difference of emissivity is close to zero at 45°~50° of look angle. The Results confirm that the multiscale effect is negligible when measure V-polarized emissivity at 45°~50° of look angle at C band.



(a)



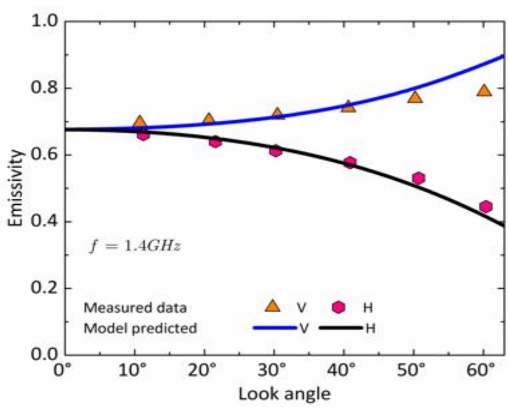
(b)

Figure 4. The difference of emissivity ($\left(e_{p,mo}-e_{p,unmo}\right)/e_{p,unmo}$) as function of frequency and look angle. σ=0.5cm,$\varepsilon_r = 12 - j1.8$, $l = 5cm\left(r_m = 0\right)$, $l_{eff} = 1.25cm\left(r_m = 1.0\right)$. (a) H polarization ; (b) V polarization.

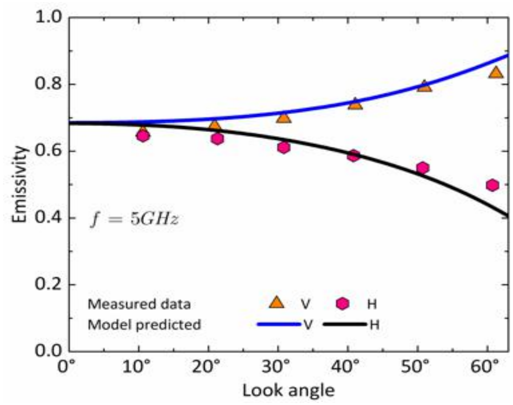
4. Applying in Nature Surface

4.1 Bare Fields

As shown in Figure 5, we compare the emissivity between the model predictions and measurements. The measurements were collected over bare fields with microwave radiometers at 1.4GHz, 5GHz, and 10.7GHz [12]. According to [12], in this test site, the soil type was Mattapex silty loam, consisting of 32% sand, 43% silt, and 25% clay. The soil physical temperature was measured to be ~ 20°C. The volumetric soil moisture content was ~ 0.26. The measured brightness temperatures over the incident angle of 10°-60° were reported in [12]. For model simulations, we adopted the roughness parameters of RMS height ($\sigma = 0.73\text{cm}$). There was no description of the correlation length for this test site. After several trials, we found that by setting the effective correlation length to $l_{eff} = 8.85cm$ and modulation ratio to $r_m = 0.12$, the model predictions at both H and V polarized emissivities match the measured data well at L、C and X bands. The results highlight the influence of multiscale roughness on the emissivity from the bare soil surfaces.



(a)



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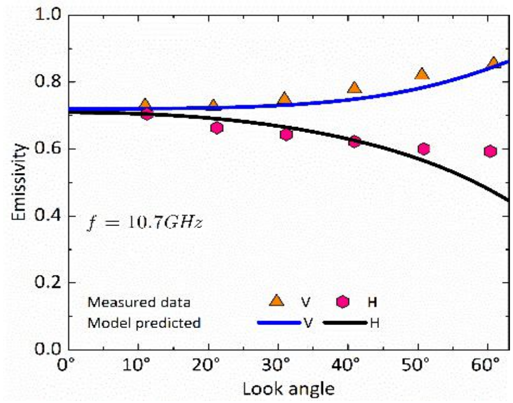
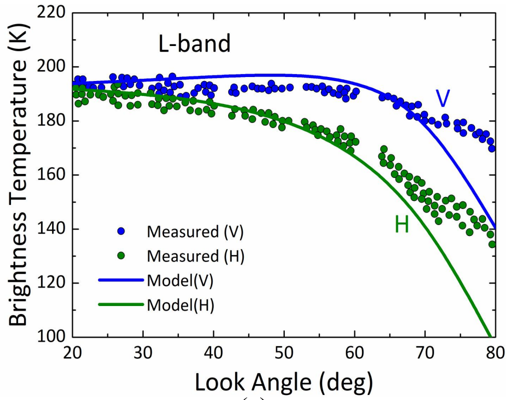


(c)

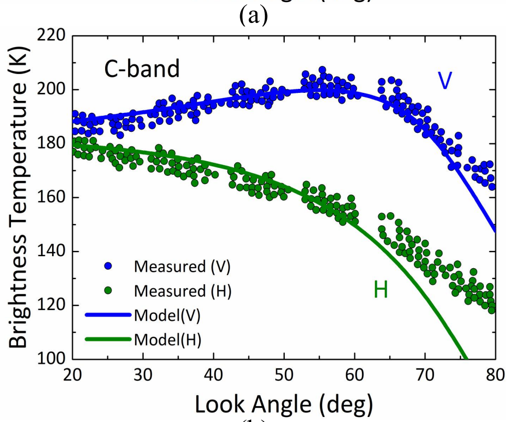
Figure 5. Comparison of the emissivity between model predictions and measurements [12]: $\sigma = 0.73\text{cm}, m_v = 0.26,\ \ l = 10cm, l_{eff} = 8.85cm\left(r_m = 0.12\right)$. (a) $f = 1.4GHz$; (b) $f = 5GHz$; (c) $f = 10.7GHz$.

4.2 Snow Surface

The brightness temperature measurements were collected from snow surface at L- & C- band in V & H polarization [13], carried out in 2004/2005 Austral summer at Dome-C, called "DOMEX" within the SMOS program. As reported in [13], the snowpack was composed of a succession of soft layers of kinetic growth grains, alternating with harder layers of rounded grains. The real part of the dielectric constant was 1.4~1.85, and the infrared surface temperature of snow was around −25°C. The surface roughness was slightly rough. The measurements over the incident angle of 20°~80° were reported. From Figure 6, we note that by setting the modulation ratio to $r_m = 0.12$, the model predections at both V and H polarization match the measurements well in the angular trends up to 70^{o} of look angle. The reasons attributed to the deviation of model and measurements are unknown yet. One possibility, perhaps, is due to the strong multiple scattering that is ignored in the model calculations. Nevertheless, the preliminary results demonstrate the multiscale is in effect and is not negligible to model the emission of the rough surface.



(a)



(b)

Figure 6. Brightness temperature as function of look angle in H and V polarization [13]. $\sigma = 0.05\mathrm{cm}$ $l = 20cm, l_{effect} = 17.71cm\left(r_m = 0.12\right)$:(a) L band ($f = 1.413GHz$), (b) C band ($f = 6.8GHz$).

5. Conclusion

This study examines the microwave emission from a multiscale soil surface. We used the modulation concept to describe the correlation function of continuous scales, in which the individual scale plays and interplays with another scale are considered. We investigate the frequency and look angle response of emission to different multiscale roughness. Numerical results indicate that the H polarized emissivity increases faster than V polarized one with the modulation ratio increasing. The H polarized emissivity is more sensitive to the multiscale effect, particularly at larger look angles. In addition, a larger modulation ratio enhances the emissivity at small and moderate look angles. The V-polarized emissivity decreases slightly at large look angles. In general, during the measurement of emissivity, when the look angle is 45°~50° in V polarization at the C band, the multiscale effect is negligible.

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