Multi-frequency microwave response to periodic roughness

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Abstract— **A series of field experiments were conducted to verify the effects of roughness on passive microwave emission. From these field experiments, it was observed that surface roughness increases observed brightness temperatures (higher emissivity) at horizontal polarization while diminishing the vertically polarized brightness temperatures marginally.**

The advanced integral equation method (AIEM) and QP models were found to model the effects of surface roughness fairly reasonably. The QP model which is a parameterized version of the AIEM was found to show correspondence with the AIEM simulations and is therefore recommended for application in AMSR based data assimilation schemes.

Keywords; surface scattering; surface roughness; emission model; soil moisture)

I. INTRODUCTION

Scattering of the microwave signal as it interacts with the soil surface has been identified as one of the key factors that should be accounted for in the accurate retrieval of soil moisture. When ignored it has been found to cause under representation of soil moisture [4]. Under dry condition, volume scattering is the dominant scattering phenomenon. When the soil has considerable moisture, surface scattering dominates. Although the phenomenon of scattering in soil is well understood, it has not been reasonably explained from field experiment data at higher microwave frequencies as such data have been lacking.

Several models have been formulated to explain the surface scattering phenomenon. Among them, the Advanced Integral Equation Model (AIEM) has been shown to be best suited in describing surface scattering for a broad range of surface roughness conditions and frequencies [6],[5]. Though it is physically based, it is not easy to implement in data assimilation schemes since it requires substantial time outlay to consider surface scattering in all possible directions. A relatively new model, named the QP model [5], has been proposed targeting application in pixel based analysis such as in data assimilation schemes. This model is a parameterized version of the AIEM applicable in Advanced Microwave Scanning Radiometer (AMSR) frequencies (6-36 GHz). It is very fast in comparison to the original AIEM. However, it had not been tested rigorously on its applicability.

Our research objectives are therefore, (1) to study the response of microwave signal to surface scattering from a soil (sand) target at different frequencies (6-36 GHz) with the ultimate objective of coupling the surface scattering component with an overall radiative transfer that is applicable over land and includes atmospheric radiative transfer component, (2) generate a roughness database comprising of multi-frequency microwave observations at varying roughness and moisture conditions and (3) validate the new QP model for modeling surface scattering.

II. ROUGHNESS AND SCATTERING THEORY

A. Surface roughness

Surface roughness information is very valuable in a variety of fields, especially in agronomy, geology, microwave remote sensing and meteorology. Surface roughness is acknowledged as having a dominant effect on the observed brightness temperatures in both passive and microwave remote sensing [3], [4]. The dynamic range of the backscattering coefficient associated with surface roughness has been found to be comparable to, or larger than that associated with soil moisture [7]. Thus, surface roughness should be estimated accurately for soil moisture retrieval with good accuracy to be realized.

Surface roughness is characterized in terms of statistical parameters that are expressed as units of wavelength. The two widely used parameters for characterizing surface roughness are the standard deviation of the height variation (rms height) and the surface correlation length. Theoretical surface scattering models make use of an auto-correlation function of the surface. The two main forms of surfaces normally used are exponential and Gaussian

For microwaves, a surface is considered smooth if $k\sigma < 0.3$, medium rough if $0.3 < k\sigma < 1$, rough for $1 < k\sigma < 3$ and very rough for $k\sigma > 3$, where k is the wave number defined as $k=2\pi/\lambda$ [2]

B. Surface emission modeling

There are two main approaches in surface emission modeling that are in common usage, namely: physical and semi-empirical approaches [5]. In physical models, the effective surface reflectivity comprises of, (1) a coherent component and, (2) a non-coherent component. The non-

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coherent component is obtained by hemispherical integration of the bistatic scattering coefficient over the upper medium

$$R^e_p = r_p \cdot \exp\left[-\left(2\cdot k\sigma\cdot\cos\theta\right)^2\right] +$$

$$\frac{1}{4\pi\cos\theta}\times\int_0^{2\pi}\int_0^{\pi/2}\left[\sigma^0_{pp}\left(\theta,\theta_j,\phi_j\right)+\sigma^0_{pq}\left(\theta,\theta_j,\phi_j\right)\right]$$

$$\times\sin\theta_j\cdot d\theta_j\cdot d\phi_j \qquad (1)$$

where R^e is the effective surface reflectivity, where q and p refer to the polarization state v or h and j the scattering direction; r is the Fresnel reflectivity, σ^0 is the bistatic scattering coefficient; k and σ have the same meaning as used earlier.

The integral Equation Model (IEM) formulated in [1] has demonstrated a much wider application range for surface roughness conditions than that from conventional models such as the Small Perturbation Model (SPM), Physical Optics Model (POM) and Geometric Optics Model (GOM), and Kirchhoff Approximation (KA).

The IEM has been further been extended to the Advanced Integral Equation Model (AIEM) [6], [5] by removal of some of the simplifying assumptions made in the derivation of the original IEM. In comparison to Monte Carlo model (MCM) simulated data, the AIEM has been reported as showing significant improvement in prediction accuracy, over the original IEM. However, its application for microwave radiometer data for retrieving geophysical parameters is difficult since it is computationally intensive. To address this limitation, [5] developed a parameterized surface emission model, which they named the QP model. The model equations are as follows.

$$R_p = Q_p r_q + (1-Q_p) r_p \qquad (2)$$

$$\log(Q_p(f)) = a(f) + b(f)\log(\frac{s}{L}) + c(f)(\frac{s}{L}) \qquad (3)$$

$$Q_p(f) = d(f) + e(f)Q_p(10.65) \qquad (4)$$

where $r_{p,q}$ is the Fresnel reflectivity, $Q_{p,q}$ the corresponding Q parameter with p,q are as described earlier, s the rms height, L the correlation length. *a-e* are frequency and polarization dependent parameters

III. FIELD EXPERIMENT

To achieve our objectives, we designed a series of well controlled field experiments during which we made roughness patterns on sand target. The periodic roughness tool comprises of a detachable component onto which a roughness pattern has been made in the form of prongs curved out at defined spacing (figure 1).

Figure 1. Roughness pattern making tool

Each tool's prongs are at a constant spacing. The patterns were made at spacing of 0.5 cm, 1.0 cm, 2.0 cm and 4.0 cm to simulate variation in correlation length. The correlation length observed ranged between ~2 – 15 mm.

In order to make the desired pattern, the desired tool pattern is attached to the rake-like structure. By varying the depth to which the prongs can sink into the sand (soil) target, rms height variation is realized. The rms height observed ranged from 0.6 – 5.2 mm.

We made the periodic roughness patterns parallel and perpendicular to the field of view of the radiometers. Each roughness condition was made first perpendicular to the field of view (FOV) of the sensors and then parallel.

Figure 2. Tool in operation

Observations were made using 6 channel and 7 channel Ground Based Microwave Radiometers (GMBR) covering the frequency ranges 6.925, 10.65, 18.7, 23.8 and 36.5 GHz at both vertical and horizontal polarizations (23.8 GHz has only vertical polarization). The sand target's moisture content was regulated at 0.8%, 8% and 20% to span very dry case, slightly wet case and wet case.

We varied the moisture condition of the sand by first oven drying the sand. We made a series of observations under this very dry condition to address the volume scattering part. Under this dry condition we also made roughness observation to enable a coupling of the volume scattering and surface scattering parts. The results of the very dry case observations are reported elsewhere in this conference. In a controlled way we then added water to the sand target (8%) and (20%), and made roughness observation.

We used both the paint method and the pin profilometer method for obtaining the statistical roughness parameters. Both methods gave reasonable correlation length values, but the paint method gives better rms height estimates. Due to the looseness of the sand surface the profilometer pins sank into the sand unevenly resulting in underestimation of rms height. By carefully sinking the thin but hard paper, we were able to make the paint impression of the profile. Another impediment we encountered concerned roughness pattern at spacing shorter than 1 cm. It was not possible to have a persistent pattern. The sand particle sizes are large (~1.18 mm) and this makes it difficult to have a satisfactory pattern at a spacing less than 1 cm. this will be addressed in the future by using fine sand.

The paint method is visually better able to capture the roughness profile since the sand is loose and with care it is possible not to disturb the surface appreciably, especially if the roughness parameters are fairly large (for pattern spacing greater than 1 cm). The paint derived roughness parameters were found to be more realistic based on the model simulation results.

IV. SIMULATION AND ANALYSIS

A. Field data

Figure 3 show the apparent emissivity observed by the radiometers for 4cm roughness pattern under varying moisture conditions. The background in these observations was metal plate. The depth of the sand target was set as 3.5 cm. It can be noted that for dry case, the effect of the metal plate can be detected for frequencies below 18.7 GHz. This is in agreement with the expectation since the penetration depth decreases as the dielectric constant and frequency increases. Therefore, as moisture increases the effect of the metal plate background disappears.

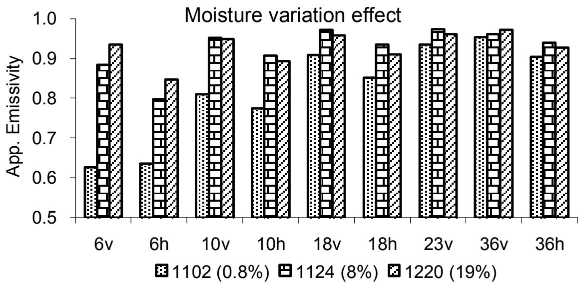

Figure 3. Moisture variation

Figure 4 shows the results of the observations made on 20th December 2005 at 20% moisture content. We first observed smooth condition and then made the roughness patterns. From the observations, roughness causes an increase in horizontal polarization but a proportionately small decrease in vertical polarization. Under wet condition, we observed that the effects of roughness are very pronounced. We note that at the lower frequencies the gap between the smooth and the rough cases is large but reduces with increase in frequency.

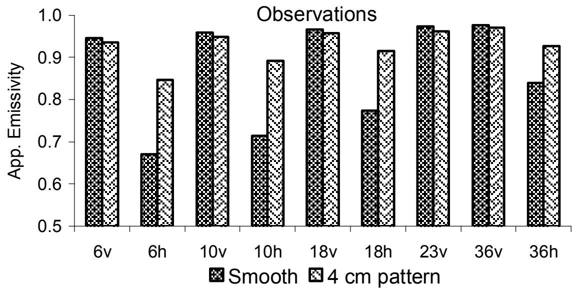

Figure 4. Observations at 20% moisture

As mentioned earlier, observations were made for both perpendicular and parallel oriented patterns. From analysis of field data we found a linear relationship, and figure 5 illustrates this relationship. From the plot it can be noted that there is an almost one to one correspondence with the perpendicular oriented pattern demonstrating a slightly higher effect. We thus adopted the perpendicular oriented patterns for our analysis

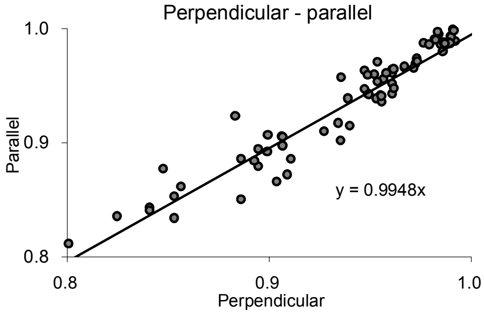

Figure 5. Roughness pattern relationship

B. Simulation

From the literature the AIEM has been reported as showing great potential for simulating the surface scattering phenomenon. Its drawback however, is the computation costs incurred in running the model. It is physically based and is therefore suited for validating other empirical and semi-empirical models if it can simulate the surface scattering of a field target.

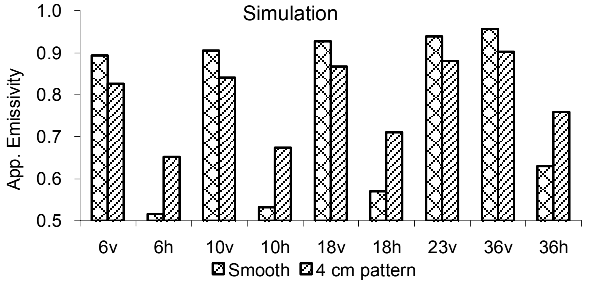

Figure 6. Simulated observations (surface emission only)

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Thus the AIEM model was used to simulate the observations as part of a validation strategy.

Figure 6 shows simulation of the observations reported earlier on (figure 4). It can be seen that although the absolute values of the emissivity results from the simulation and the observation are different, the model simulations and the observations show similar response to roughness pattern.

C. AIEM-QP relationship

Comparing simulated emissivities by AIEM and QP we observed that the QP model has a 1:1 linear relationship with the AIEM within a standard deviation of between 0.001-0.007 at the different frequencies for vertical polarization. The standard deviation for horizontal polarization lies between 0.003 and 0.019. From this comparison, it is reasonable to use the QP model to simulate surface scattering for the AMSR frequencies.

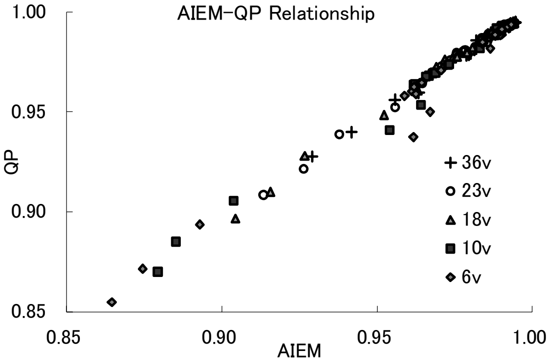

Figure 7. AIEM-QP Relationship

Figure 7 shows the relationship between the AIEM and QP models in the vertically polarized cases. Horizontally polarized cases showed a similar 1:1 relationship and are thus not shown. This relationship is reasonable since the QP model is a *'parameterized AIEM'* for the Advanced Microwave Scanning Radiometer (AMSR) frequencies.

V. SUMMARY

From analysis of the field data, we confirmed that the effects of roughness are more pronounced under wetter conditions. This justifies the generally recommended approach of using wet day's data to retrieve surface roughness conditions applicable for a land target. An increase in rms height was found to cause an increase in apparent emissivity of the target for horizontal polarization and a small reduction for vertical polarization, while an increase in correlation length had the opposite effect.

From the field observations, the effects of roughness pattern were noted as increasing emissivity for horizontal polarization and a proportionately small reduction in emissivity for vertical polarization

The field experiments helped improve our understanding of the response of multi-frequency microwave signal to periodic roughness. A database of multi-frequency microwave observation data for varying roughness and moisture conditions was generated.

A dependence of roughness pattern's orientation was found during observations. There is linear tendency and for future roughness experiments it is recommended to use the perpendicularly oriented patterns since observations showed a slightly higher sensitivity to roughness pattern oriented perpendicular to FOV of radiometer.

From model simulations, the AIEM model is reasonable for modeling surface scattering in soil. From comparison of simulation between AIEM and QP models, the QP model was found to reasonably represent AIEM for frequencies under consideration. Simulation additionally verified that the QP model can be used in place of AIEM for simulating surface scattering effect for AMSR frequencies. This is a significant step since it can be applied in emissivity transfer scheme that would allow transferring emissivity from one frequency to other frequencies given the state of the target. It can also be applied in pixel based image analysis and in Data Assimilation schemes.

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