Measurements of Microwave Polarimetric Backscattering from a Wet Soil Surface and Comparison with a Semi-empirical Scattering Model

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Abstract

Microwave polarimetric backscattering from a wet soil surface had been measured using a Ku-band polarimetric scatterometer at the incidence angles ranging from 10^0 to 70^0. Since the accurate target parameters as well as the radar parameters are necessary for radar scattering modeling, a complete and accurate set of ground truth data were also collected, from which accurate measurements were made of the rms height, correlation length, and dielectric constant. The measured polarimetric backscattering coefficients (vv-, hh-, vh-, hv-polarizations) were compared with theoretical models and empirical models. A new semi-empirical model for microwave polarimetric radar backscattering from bare soil surfaces was developed using polarimetric radar measurements and the knowledge based on the theoretical and numerical solutions. The model was found to yield very good agreement with the backscattering measurements of this study.

1. Introduction

The problem of electromagnetic wave scattering from random surfaces has long been studied and because of its complexity theoretical solution exists only for limiting cases. When deviation of the surface profile is slightly different from that of a smooth surface, perturbation solutions can be used. In the classic treatment of small perturbation method (SPM) it is required that the rms height be much smaller than the wavelength and the rms slope be same order of magnitude as the wavenumber times the rms height.

The other limiting case is when surface irregularities are large compared to the wavelength, namely the radius of curvature at each point on the surface is large. In this limit the solution is known as Physical Optics (PO) and geometrical optics (GO) models [Ulaby et al., 1986].

At microwave frequencies most of natural surfaces do not fall into the validity regions of the theoretical models. Moreover the theoretical models, especially PO and GO models, are not accurate even though in their validity regions (Fig. 1). A semi-empirical model is formulated based on an empirical model [Oh et al., 1992], a semi-empirical model [Oh et al., 1995] and measured data sets. Excellent qualitative and reasonable quantitative agreement is obtained.

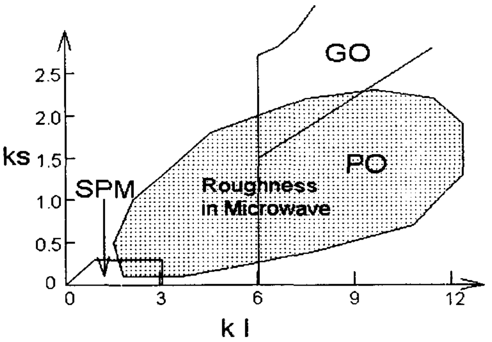


Fig. 1. Validity regions of theretical models

2. Experimental Procedure

The scatterometer system consists of an automatic vector network analyzer for receiving and processing measurement data, a pair of horn antennas for polarimetric data acquisition, an automatic turntable with a controller for obtaining independent radar data samples as shown in Fig. 2.

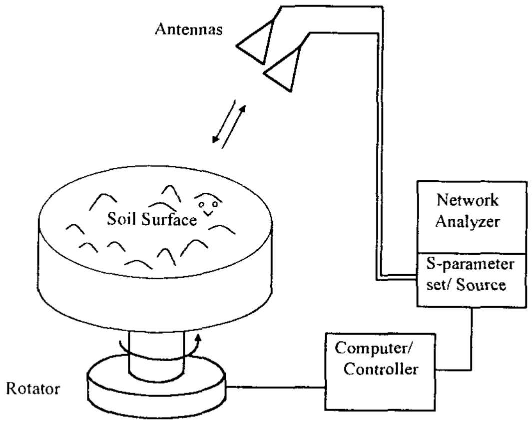


Fig. 2. Ku-band polarimetric scatterometer system

In radar measurements, the quantities of interest are the statistical properties of the scattered field per unit area. One such quantity is the scattering coefficient σ °, which is defined in terms of the second moment of the scattered fields.

Suppose the distributed target is statistically homogeneous and the antenna beam is narrow enough so that the backscattering statistics of the target can be assumed constant over the illuminated area. If the radar system and its antenna are ideal, the radar equation for a point target,

$$\frac{P_r}{P_t}=\frac{G^2\lambda^2}{(4\pi)^3R^4}\sigma, \tag{1}$$

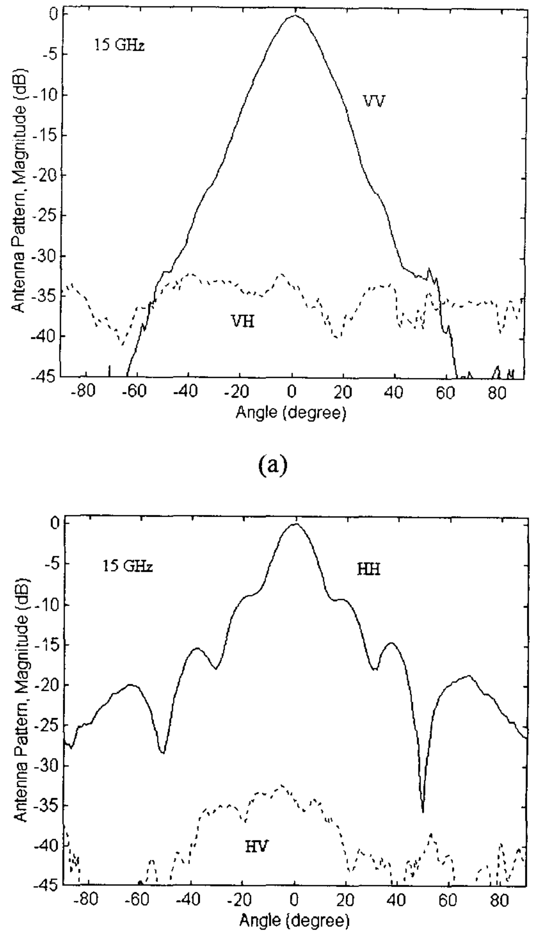
can be transformed for a distributed target as follows;

$$\frac{P_r}{P_t}=\left(\frac{G_0^2\lambda^2}{(4\pi)^3}\right)\sigma^0 A_{ill} \tag{2}$$

where the illumination integral is given as

$$A_{ill}=\int_S \frac{g^2(\theta,\phi)}{R^4(\theta,\phi)}dS. \tag{3}$$

Because the power ratio at the left-hand side of (2) and (3) was measured, the scattering coefficient σ^0 can be obtained when the constant term and the illumination integral at the right-hand side of (3). The constant term in bracket of (3) includes system loss and crosstalks for practical radar system, which are calibrated with specific calibration techniques. The illumination integral can be computed with antenna gain, antenna position and incidence angle. Three-dimensional antenna gain can usually be obtained from the polarimetric antenna patterns at E-plane and H-plane (Fig. 3).



(a)

(b)

Fig. 3. Polarimetric antenna patterns; (a) E-plane and (b) H-plane

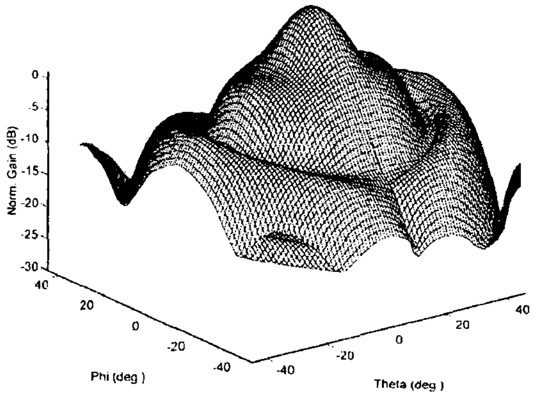


Fig. 4. Three-dimensional antenna pattern

Fig. 4 was obtained by interpolating the measured antenna pattern in Figs. 3. The illumination integral for every incidence angle was computed using the three-dimensional antenna gain and geometry. The system calibration was performed using calibration targets (a conducting sphere and a trihedral).

The measured backscattering coefficients after calibration are shown as follows;

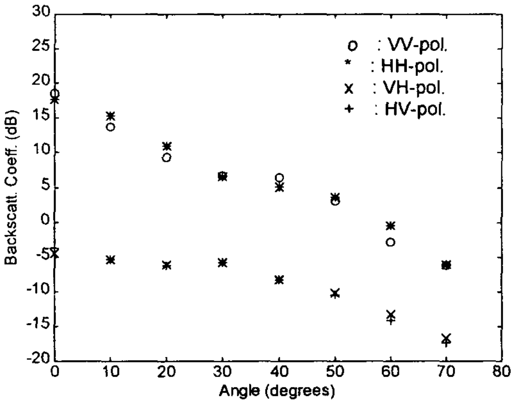


Fig. 5. Measured backscattering coefficients.

Ground truth data such as the surface height distribution functions and the soil moistures were also measured. The rms height and the correlation length of the surface were 0.45 cm and 5.59 cm, respectively. The measured autocorrelation function was quite similar with exponential function as shown in Fig. 6.

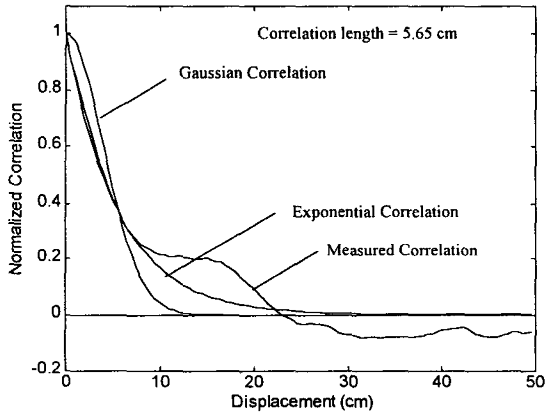


Fig. 6. Measured correlation function compared with theoretical functions.

3. Comparison with Scattering Models

Measured roughness parameters (ks=1.4, kl=17.56 where s is the rms height, l is the correlation length and k is the wavenumber) are in the validity region of PO model as shown in Fig. 1. However, the PO model does not agree with the measurements.

The failure of existing models to cover roughness conditions that occur more often in nature prompts development of semi-empirical backscattering models for random surfaces. Another reason for developing the semi-empirical model is to generate an inversion algorithm to retrieve soil moisture and surface roughness from the measured radar backscatter.

A semi-empirical model (SEM) of backscattering coefficients, σ_{vv}^0 , σ_{hh}^0 and σ_{vh}^0 was developed based on the radar backscattering coefficients measured at various roughness parameters and various soil moisture at 1.25 GHz – 9.6 GHz [Oh et al., 1992]. This semi-empirical model (SEM) was improved for angular trend including kl effect [Oh et al., 1995].

4. Development of a Scattering Model

In this study, the radar backscattering coefficients of bare soil surface was measured at 15 GHz. It was found that the measured scattering coefficients was higher than the prediction of the SEM, and the cross-polarized scattering coefficient of the SEM, σ_{vh}^0 , was not fitting well to the measured data at lower incidence angle. Moreover, the roughness spectrum (kl function) in the SEM should be revised for the correct representation of surface roughness [Oh and Kay, 1998].

Therefore, a new semi-empirical model was developed in this study based on the old SEM and the measured data. At first, the level of the cross-polarized scattering coefficient, σ_{vh}^0 , was modeled as follows;

$$\sigma^0_{vh} = c_1 \Gamma_0^{1.5} (\cos\theta)^3 \frac{1-\exp\left[-0.3(ks)^{2.3}\right]}{P} \qquad (4)$$

where c_1 is constant to be determined by the measured data and

$$P = 1 - \left(\frac{\theta}{90^0}\right)^{\frac{1}{3\Gamma_0}} \exp[-ks]. \qquad (5)$$

Then, the vv-polarized backscattering coefficient σ^0_{vv} was modeled based on the cross-polarization ratio X as developed as follows;

$$X = c_2 \frac{\exp[-ks\cos\theta]}{\sqrt{\Gamma_0}} (ks)^2 \left(0.64(ks)^{-2.6} + 0.2\right) W_k \qquad (6)$$

where W_k is the roughness spectrum term similar to that of the exponential function and is developed as follows;

$$W_k = \frac{(kl)^2}{1+2(kl\sin\theta)^2} \qquad (7)$$

The vv - and hh-polarized backscattering coefficients, σ^0_{vv} and σ^0_{hh} are computed using (4) - (7), respectively, as follows;

$$\sigma^0_{vv} = \sigma^0_{vh} X \qquad (8)$$

$$\sigma^0_{hh} = \sigma^0_{vv} P \qquad (9)$$

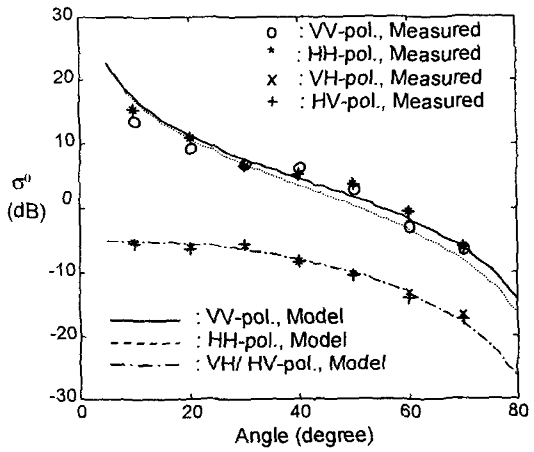


Fig. 7. Comparison between the measred data and the model.

The measured backscattering coefficients were compared with the model developed in this study as shown in Fig. 7 The model agrees very well with the measured data with $c_1 = 23.5$ and $c_2 = 27.0$.

5. Conclusions

Microwave polarimetric backscattering from a wet soil surface had been measured using a Ku-band polarimetric scatterometer at the incidence angles ranging from 10^0 to 70^0 as well as ground truth data. The measured polarimetric backscattering coefficients were compared with theoretical models and empirical models. A new semi-empirical model for microwave polarimetric radar backscattering from bare soil surfaces was developed. It was found that this model agrees very well with the backscattering measurements of this study.

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