An Inversion Algorithm For Retrieving Soil Moisture And Surface Roughness From Polarimetric Radar Observation

Yisok Oh

Department of Radio Science and Engineering
Hong-Ik University, Seoul, Korea

Kamal Sarabandi and Fawwaz T. Ulaby

Radiation Laboratory
Department of Electrical Engineering and Computer Science
The University of Michigan, Ann Arbor, MI 48109-2122, USA

Abstract

A semi-empirical polarimetric scattering model for bare soil surfaces is developed. This scattering model is constructed based on the existing theoretical models in conjunction with an extensive experimental data collected with polarimetric scatterometer systems at microwave frequencies. The backscattering coefficients as well as parameters of phase difference statistics, degree of correlation (α) and polarized phase difference (ζ), are expressed in terms of both surface parameters (rms height, correlation length, and dielectric constant) and radar parameters (frequency and incidence angle). The semi-empirical model is used as a basis for an inversion algorithm to estimate the surface parameters from the polarimetric backscatter response of a surface when the radar parameters are known. By performing a sensitivity analysis, a set of optimum parameters are chosen for the inversion algorithm. It is shown that the co-polarized ratio ($\sigma^\circ_{hh}/\sigma^\circ_{vv}$), the cross-polarized ratio ($\sigma^\circ_{hv}/\sigma^\circ_{vv}$), and the degree of correlation for co-polarized phase difference are most sensitive to the surface parameters and least affected by the measurement errors.

1. Introduction

An empirical model and an inversion technique for radar backscattering from bare soil surfaces was recently developed [Oh et al., 1992]. This model is only based on the magnitudes of the measured radar backscattering coefficients. In this paper the previous model is extended to include both the magnitude and phase of the radar backscatter which would enhance the soil moisture estimation using a polarimetric radar backscatter. This scattering model is constructed based on the existing theoretical models in conjunction with extensive experimental data. The behaviors of theoretical models (the small perturbation and the Kirchhoff approximation) [Ulaby et al., 1986] were studied to relate the backscattering coefficients from homogeneous random surfaces with the surface parameters (dielectric constants, rms height, correlation length) and the radar parameters (frequency, polarization, and incidence angle).

The experimental data in this investigation were acquired by the University of Michigan truck-mounted L-, C-, and X-band Polarimetric Scatterometers over the range of the incidence angles from 20° to 70° with 10° steps. Rough surfaces under variety of soil moisture and roughness conditions were prepared and measured with the scatterometer. A laser profile meter and dielectric probes were used to measure the surface height statistics and the soil dielectric constants, respectively.

The effect of the surface auto-correlation function is also included in the enhanced semi-empirical model. By studying the auto-correlation function of naturally occuring rough surfaces, a generic functional form for the auto-correlation function is adopted, which is fully characterized by a single parameter, the correlation length.

2. Semi-empirical Model

The auto-correlation function of eleven different fields were generated from more than 300 linear traces of 1-m long surface profiles. It was found that the functional form of the auto-correlation functions are very similar each other. Figure 1 shows the averaged normalized auto-correlation function of all eleven fields and is compared with Gaussian and exponential auto-correlation functions. The measured correlation function could be modelled by a quadratic-exponential function given by

$$\rho(\xi) = \{1-\xi^2/(al)^2\} \exp[-\xi/(bl)] \quad (1)$$

where a and b are constants and l is the correlation length.

Based on the theoretical models, a functional form of the backscattering coefficients for vv-polarization were chosen, and the unknown constants of the expression were obtained using the measured data. The expression for the vv-polarized backscattering coefficient was found to be

$$\sigma^\circ_{vv} = 13.5 e^{-1.4(ks)^{0.2}} \frac{1}{\sqrt{p}} \Gamma_h (ks)^2 (\cos\theta)^{3.25-0.05kl} \cdot e^{-(2ks\cos\theta)^{0.6}} W_k \quad (2)$$

where W_k is the roughness spectrum corresponding to the quadratic-exponential correlation function in (1), and is given by

$$W_k = \frac{(kl)^2}{1+(2.6kl\sin\theta)^2}\left[1 - 0.71\frac{1-3(2.6kl\sin\theta)^2}{[1+(2.6kl\sin\theta)^2]^2}\right] \quad (3)$$

and

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$$\Gamma_h = \left| \frac{\cos\theta - \sqrt{\epsilon_r - \sin^2\theta}}{\cos\theta + \sqrt{\epsilon_r - \sin^2\theta}} \right|^2 .$$

Examination of theoretical models and experimental results reveals that the co-polarized ratio ($p=\sigma^\circ_{hh}/\sigma^\circ_{vv}$) is a strong function of rms height and independent of correlation length. It wad found that [Oh et al., 1992] this quantity can simply be obtained from

$$\sqrt{p} = 1 - \left(\frac{2\theta}{\pi}\right)^{0.314/\Gamma_0} e^{-ks}. \quad (4)$$

Since the first-order theoretical models are incapable of predicting the cross-polarized ratio ($q=\sigma^\circ_{hv}/\sigma^\circ_{vv}$), this ratio is obtained purely from the measured data and is given by

$$q = 0.25\sqrt{\Gamma_0}(0.1 + \sin^{0.9}\theta)\left[1 - e^{-(1.4-1.6\Gamma_0)ks}\right]. \quad (5)$$

Both ratios are independent of the correlation length and sensitive to rms height (vertical roughness) and dielectric constant. The soil moisture is the dominant factors in both p and q. The model for the backscattering coefficients is compared with one of the backscatter measurements and is shown in Fig. 2.

The degree of correlation, which is one parameter of the phase-difference statistics, was modelled empirically as reported in [Oh et al., 1993];

$$\alpha = \left[1 - 0.2(\sin\theta)^{A(ks,\Gamma_0)}\right](\cos\theta)^{B(ks,\Gamma_0)} \quad (6)$$

where

$$A(ks,\Gamma_0) = (16.5\Gamma_0 + 5.6)\exp[-41.6ks\Gamma_0^2] \quad (7)$$

and

$$B(ks,\Gamma_0) = 8.1\Gamma_0 ks \exp[-1.8ks]. \quad (8)$$

The model for the degree of correlarion is compared with the measurement for a soil surface and is shown in Fig. 3.

Since the polarized-phase difference is a function of the real and imaginary parts of an element in the Mueller matrix ($W_{33} = \langle S^*_{hh}S_{vv}\rangle$) [Sarabandi, 1993], the polarized-phase difference could be modelled using the magnitudes of backscattering coefficients, that is

$$\zeta = \tan^{-1} y \quad (9)$$

where y is found to be

$$y = 2.6\theta^2 ks \exp -1.6\sin\theta ks \quad (10)$$

Here θ is in radian. Expression (10) is compared with the measured ζ and is shown in Fig. 4.

3. Inversion Algorithms and Discussions

Based on the semi-empirical model derived above, several inversion algorithms can be considered. At first, the rms height and the dielectric constant of soil surface can be retrieved using only the co- and cross-polarized ratios since the ratios are most sensitive to the surface parameters. The dielectric constant can be converted to the volumic moisture content using the existing empirical formula [Hallikainen et al., 1985]. Figure 5 shows an inversion diagram using the ratios. Second, the model for degree of correlation can be used to improve the inversion results, since the degree of correlation is also sensitive to the surface parameters. Third, the correlation length can be retrieved using the model for the vv-polarized backscattering coefficients substituting the rms height and dielectric constant obtained by the inversion technique.

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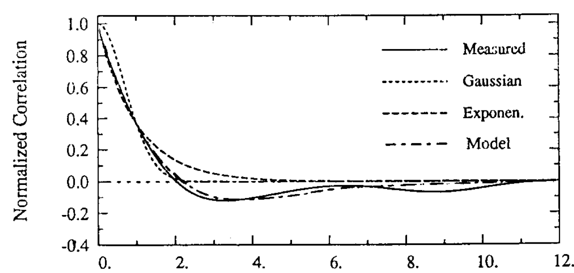
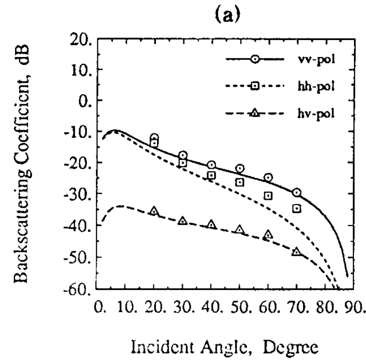


Figure 1. The measured correlation function for natural rough surfaces (comparison with a Gaussian and an exponential functions having the same correlation length).

(a)



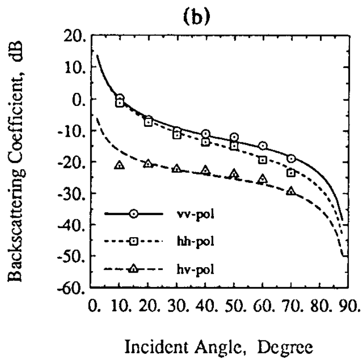


Figure 2. The semi-empirical model for backscattering coefficients compared with the measured data for a wet and smooth surface at (a) 1.5 GHz and (b) 9.5 GHz.

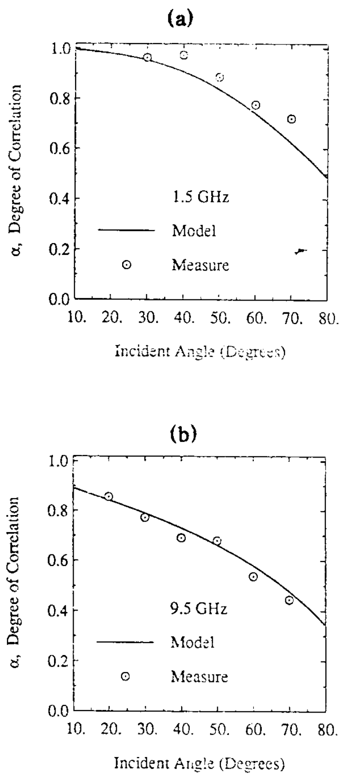


Figure 3. The empirical model for the degree of correlation compared with the measured data for a wet and smooth surface at (a) 1.5 GHz and (b) 9.5 GHz.

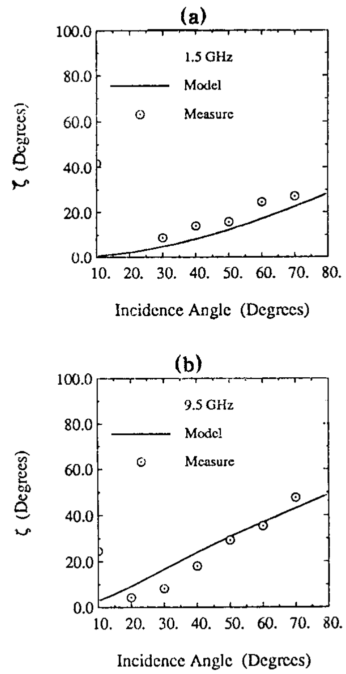


Figure 4. The empirical model for the polarized-phase diference. Comparison with the measured data for a wet and smooth surface at (a) 1.5 GHz and (b) 9.5 GHz.

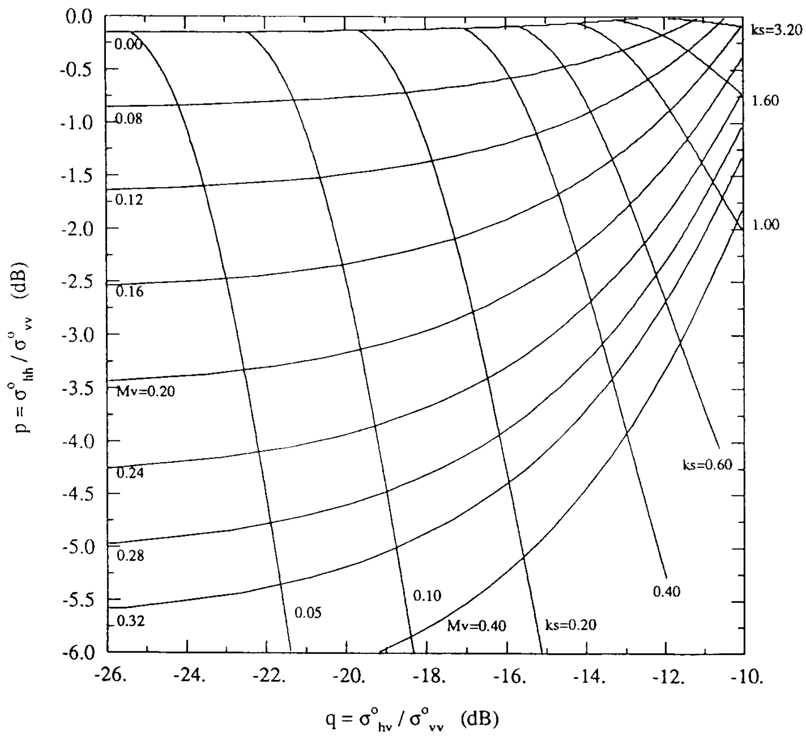


Figure 5. An inversion diagram to retrieve ks (k=wave number, s=rms height) and Mv (volumetric moisture content) from the ratios (p and q) of the backscattering coefficients (1.25 GHz, 40°).