RELATIONSHIP BETWEEN THE SURFACE ROUGHNESS PARAMETERS AND THE RADAR BACKSCATTER OF A BARE SURFACE

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ABSTRACT: Whereas it is well known that the surface roughness parameters, the RMS height and the correlation length, of a natural soil surface are underestimated with a short surface profile, it is not clear how much the underestimated surface parameters affect the backscattering coefficients of the surface for various incidence angles and polarizations. The backscattering coefficients of simulated and measured surface profiles are computed using the integral equation method (IEM) and analyzed in this paper to answer this question. It is shown that the RMS error of the backscattering coefficients between 5-*m*- and 1-*m*-long measured surface profiles is 1.7 dB for vv-polarization and 0.5 dB for hh-polarization at a medium range of incidence angle ($15° \le \theta \le 70°$), while the surface roughness parameters are significantly reduced; from 2.4 *cm* to 1.5 *cm* for the RMS height s and from 35.1 *cm* to 10.0 *cm* for the autocorrelation length l. This result is verified with numerous simulations with various roughness conditions and various wavelengths.

KEY WORDS: Surface roughness parameters, radar backscatter, soil surface, integral equation method

1. INTRODUCTION

Surface roughness is commonly characterized as a stationary random function with a Gaussian probability density function (PDF), which is proper to represent a natural surface height distribution. Natural soil surfaces however show various types of autocorrelation functions, even though measured autocorrelations fit more likely to exponential functions. One of the main difficulties to predict accurate backscattering coefficients is how to represent a natural soil surface with an accurately characterized autocorrelation function. Among others, a Gaussian or an exponential or a function between the Gaussian and the exponential, or a rational correlation function is frequently assumed in scattering models because of easy manipulation [Ulaby et al., 1982]. Then the RMS height s (measure of vertical roughness) and the autocorrelation length l (measure of horizontal roughness) can simply represent the surface roughness in scattering models.

Measurement errors in the estimation of the surface height autocorrelation can be caused by finite (short) profile length (outer scale) or coarse sampling distance (inner scale) [Oh and Kay, 1998]. Because most sensors have enough horizontal resolution satisfying $\Delta x < 0.2l$ (where Δx is the sampling distance and l is the correlation length), the error by the sampling distance is usually negligible. A numerical simulation shows that both the RMS height and autocorrelation length increase as the profile length increases, and those parameters asymptotically reach constant values with long profiles[Dierking, 1999]. Accurate estimates of the RMS height and correlation length that deviate less than 5% from the true values can be obtained at profile lengths longer than $50\bar{l}$ and $200\bar{l}$, respectively ($\bar{l}$ here is the true correlation length). Therefore, the consideration of the profile length is important for the validation of scattering models and the development of inversion algorithms.

The scattering coefficient is proportional to the Fourier transform of autocorrelation function (or its n*th* power) in scattering models, such as the small perturbation method (SPM), the physical optics (PO) model, and the integral equation method (IEM) [Fung, 1994]. The IEM is widely used to predict the backscattering coefficients of soil surfaces because its validity region is much wider than the classical models, such as the SPM and the PO models [Ulaby et al, 1982]. While most correlation functions of agricultural soil surfaces are well approximated by exponential correlation functions, some of the agricultural fields deviate from the exponential correlation functions especially at the tails of the correlations.

This paper aims to contribute to a better understanding of the effect of the profile length on the microwave backscattering coefficient of natural soil surfaces, by computing the backscattering coefficients with the IEM for the measured and simulated surface profiles with various profile lengths.

2. MEASUREMENT

A bare field was prepared by cleaning a natural tall-grass field at a suburban area of Seoul in September 2005. The backscattering coefficients of a bare surface were collected using a network analyzer-based scatterometer mounted on a 4.8-m tower. The scatterometer system is designed to measure the fully polarimetric backscattering coefficients (*i.e.*, collect vv-, hh-, vh-, and hv-polarized backscatter signals) at R-band. The center frequency of the measurement was 1.85 GHz with the frequency bandwidth of 0.5 GHz, which allowed us to use the time domain gating capability of the network analyzer. The polarimetric response of a conducting trihedral corner reflector was measured to achieve absolute calibration of the scatterometer system.

In addition to the backscattering coefficient measurements, height profiles and soil samples of the soil surface were collected. The surface profiles are measured using a pin-board profiler, which consists of a 1.1-m long thick acryl plate with a grid paper attached, a 1.1-m long aluminium rod with 201 holes 0.005 m apart where the needles slide through, 20-cm long 201 needles, and supports of this system. When the pin-board profiler is placed on a soil surface, the upper tips of the needles well represent the profile of the soil surface below the profiler. The profile delineated by the needle tips was pictured by a digital camera, and a discrete surface profile was obtained by a digitization process. The repeat process with careful alignment of the pin-board profiler with a level provides 5-m long profiles.

The measurement shows that the PDF of the surface height distribution can be assumed as a Gaussian PDF with a zero-mean and a standard deviation of 2.35 cm. The measurement also shows the first part of measured autocorrelation function (when the displacement is smaller than the correlation length of the surface, l=0.35 m) agrees quite well with an exponential function, while the tail of the autocorrelation function deviates a lot from the theoretical correlation functions.

The soil moisture content of the soil field was 0.23 cm^3/cm^3 when the scatterometer data were collected. For a preliminary examination of the measurement, the measured backscattering coefficients were compared with the polarimetric semi-empirical model (PSEM) reported by [Oh *et al.*, 2002]. The RMS height s and the correlation length l of 2.5-m long surface profiles were used in the PSEM model, because the model was developed based on the profile data measured with the 1-m long laser profiler and the 3.75-m long mesh-board profiler. Fig. 1 shows that the measurements agree very well with the PSEM especially for vv-polarized backscattering coefficients, and also agrees fairly well with both hh- and vh-polarizations.

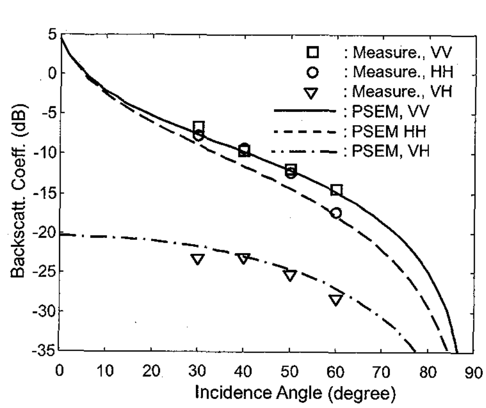

Fig. 1. Comparison among measurements and the PSEM model.

Because it is not able to examine the effect of correlation function with the PSEM, we selected the IEM model to examine the effect of the correlation function (consequently, the effect of the profile length) on the backscattering coefficient of a bare soil surface.

3. COMPUTATION OF BACKSCATTERING COEFFICIENTS

The IEM for rough surfaces with small to moderate roughness (*e.g.*, ks<2) is given in [Fung, 1994] by

$$\sigma_{qp}^{o} = \frac{k^2}{2} \exp[-2(k_z s)^2] \sum_{n=1}^{\infty} \left| I_{qp}^{n} \right|^2 \frac{W^{(n)}(-2k_x,0)}{n!}, \quad (1)$$

where $k_z = k\cos\theta$, $k_x = k\sin\theta$, p, q = v or h and s is the RMS height,

$$I_{qp}^{n} = (2k_z s)^n f_{qp} \exp[-(k_z s)^2] + \frac{(k_z s)^n}{2}\left[F_{qp}(-k_x,0) + F_{qp}(k_x,0)\right], \quad (2)$$

with $f_{vv} = 2R_{//}/\cos\theta$, $f_{hh} = -2R_{\perp}/\cos\theta$, and $f_{vh} = f_{hv} = 0$.

$R_{//}$, $R_{\perp}$ are the Fresnel coefficients for vertical and horizontal polarizations and F_{qp} is the field coefficient at qp – polarization, which is given in [Fung, 1994, p. 249-250]. The symbol $W^{(n)}(-2k_x,0)$ is the Fourier transform of the n[th] power of the surface autocorrelation,

$$W^{(n)}(-2k_x,0) = \int_0^{\infty} \rho^n(r) J_o(2kr\sin\theta)\, r\, dr, \quad (3)$$

where $\rho(r)$ is the normalized surface autocorrelation function and $J_o(\cdots)$ is the 0[th] order Bessel function of the first kind. Since the dielectric constant is an input parameter in the IEM, the dielectric constant is computed from the measured soil moisture content with an empirical formula with the measured soil texture (sand 33.9%, silt 42.9% and clay 23.2%).

The roughness spectrum can be numerically computed from the measured autocorrelation with the 0[th] order Bessel function of the first kind. We should take extra care with the numerical integration, with dividing the integration interval with enough number of subsections and using high precision to avoid numerical errors, because of an oscillatory behaviour of the integrand in (3).

4. EXAMINATION OF THE EFFECT OF SURFACE PROFILE LENGTH

It is well known, however, that the roughness parameters depend on the length of a measured surface profile; *i.e.*, both the RMS height and autocorrelation length decreases as the profile length decreases. Now we arrived at a question, "How much does the backscattering coefficient for a correlation function differ from the one for another correlation function with a different profile length?" The autocorrelation function of the surface for each profile length was computed by dividing the measured 5-m long surface profile into N sections (N=5/L, where L is the profile length), and used in the computation of the backscattering coefficient for each profile length to answer this question.

Fig. 2 shows the RMS heights and correlation lengths of the measured profiles with different profile length. Both the RMS height and the correlation lengths decrease with a decrease in the profile length, with higher decrease rate for the correlation length than for the RMS height It was also shown that at this roughness condition, the RMS height reaches a constant (true) value at the profile length of 5-m while the correlation length does not reach a constant value yet.

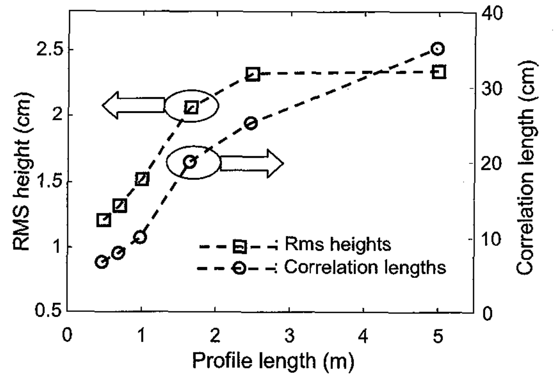

Fig. 2. The RMS heights and correlation lengths for various profile lengths.

Fig. 3 shows the vv-polarized backscattering coefficients for various profile lengths from 5 *m* to 0.5 *m* for the measured surface profiles. It is shown that the vv- and hh-polarized backscattering coefficients increase with an increase in the profile length at low incidence angles and reach constant values at a long profile length, *e.g.*, the data at 10° in Fig. 3.

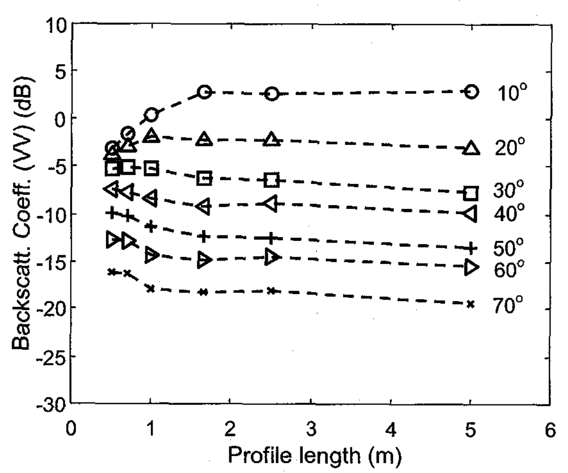

Fig. 3. Backscattering coefficient versus profile length at various incidence angles for vv-polarization.

On the other hand, at large incidence angles, the backscattering coefficients decrease with an increase in the profile length before reaching constant values at $L \geq 1.67$ *m* for vv-polarization. The effect of the profile length on the backscattering coefficient is negligible (less than about 1 dB) if the profile length is larger than 1.67 *m* (about five times the correlation length) as shown in Fig. 3. Moreover, the effect of the profile length is less than about 2 dB even for very small profile length ($L = 1.5\,l \sim 3.0\,l$) at 20°< θ <60° for vv-polarization for the measured surface profiles. As an example, the difference of the backscattering coefficients between 5-*m* and 1-*m* long measured surface profiles is 1.67 dB for vv-polarization and 0.48 dB for hh-polarization (within a measurement error bound) in an RMS sense at a medium range of incidence angle ($15° \leq \theta \leq 70°$) as shown in Fig. 3, while the surface roughness parameters are significantly reduced; *i.e.*, from 2.4 *cm* to 1.5 *cm* for the RMS height *s* and from 35.1 *cm* to 10.0 *cm* for the autocorrelation length *l* as shown in Fig. 2.

5. VERIFICATION WITH A NUMERICALLY GENERATED SURFACE PROFILE

We numerically generated a long surface profile ($L = 4000\bar{l}$ where L is the profile length and $\bar{l}$ is the true correlation length) in order to verify the conclusion obtained in the previous section. The randomly rough surface has a sampling distance of $0.05\,\bar{l}$, a Gaussian PDF of height distribution with an RMS height s=$0.1\,\bar{l}$, and an exponential correlation function with a correlation length l=1 unit. At first, the surface is divided into twenty $200\,\bar{l}$ long profiles, and the correlation functions are computed for each $200\,\bar{l}$ long profiles, and 20 correlation functions are averaged. Then, the process was repeated for various profile lengths from $200\,\bar{l}$ to $1.5\,\bar{l}$. The shape of correlation function of the numerically generated surface profile approaches the exponential function with increase of the profile length, because the rough surface has an exponential autocorrelation. Fig. 4 shows the variations of both the RMS height and correlation length due to profile lengths, which are similar results with the measured surface profile.

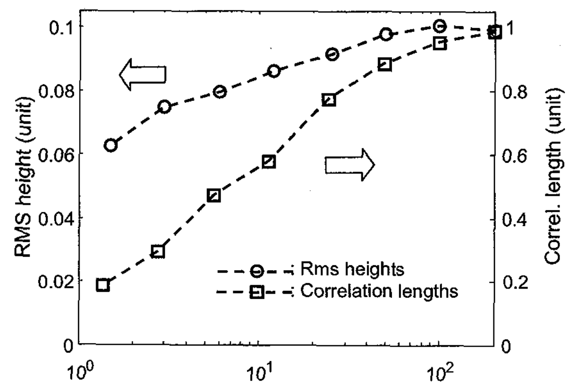

Fig. 4. RMS height and correlation length versus profile length.

Both the RMS height and correlation length increase with an increase of the profile length and reach the true values at large profile length; *i.e.*, about 50 $\bar{l}$ for the RMS height and about 200 $\bar{l}$ for the correlation length. The increase rate is much higher for the correlation length than the RMS height, with variations of the profile length, as shown in Fig. 4.

The numerically generated rough surface was divided into 20 smaller sections for each profile length, and the averaged autocorrelation of the 20 divided surfaces was computed for each profile length. The effects of the profile length at various incidence angles are shown in Fig. 5 for the vv-polarized backscattering coefficients. The backscattering coefficients at low incidence angles increase with an increase in the profile length, and reach constant values for both polarizations. On the other hand, with increase in the profile length, the backscattering coefficients at large incidence angles decrease for vv-polarization, and show no variations for hh-polarization as shown in Fig. 5.

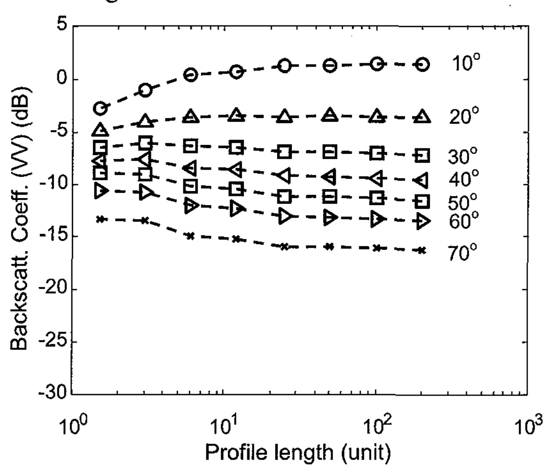

Fig. 5. Backscattering coefficient versus profile length at various incidence angles for vv-polarization.

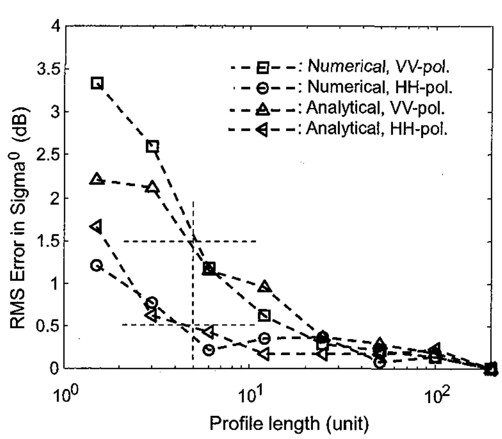

Fig. 6. RMS errors in the backscattering coefficients at $15^\circ \le \theta \le 70^\circ$ compared with the backscattering coefficients of the 200 $\bar{l}$ surface.

Fig. 6 shows the RMS errors in the backscattering coefficients at various profile lengths compared with those of the 200 $\bar{l}$ long surface. The RMS error at $15^\circ \le \theta \le 70^\circ$ is less than 1.5 dB for vv-polarization and 0.5 dB for hh-polarization, if the profile length is larger than 5 $\bar{l}$ for the rough surface as shown in Fig. 6.

6. CONCLUDING REMARKS

The backscattering coefficients of measured and simulated rough surfaces with various profile lengths were computed with the IEM and analyzed to examine the effect of the profile length on the microwave backscattering coefficient of the natural soil surface. It was shown that even though both the RMS height and autocorrelation length vary significantly with variations of the profile length, the minimal variations of the backscattering coefficients were observed. The computations with a measured surface profile showed us that the difference of the backscattering coefficients between 5-*m* and 1-*m* long measured surface profiles is 1.7 dB for vv-polarization and 0.5 dB (within a measurement error bound) for hh-polarization in an RMS sense at a medium range of incidence angle ($15^\circ \le \theta \le 70^\circ$), while the surface roughness parameters are significantly reduced; *i.e.*, from 2.4 *cm* to 1.5 *cm* for the RMS height *s* and from 35.1 *cm* to 10.0 *cm* for the autocorrelation length *l*. This small effect of the profile length on the backscattering coefficients at the medium range of incidence angle is verified with numerically generated rough surfaces.

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