Effect of Surface Profile Length on the Backscattering Coefficients of Bare Surfaces

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***Abstract*—The root mean square (rms) height s and autocorrelation length l are commonly used as the surface roughness input parameters to surface scattering models. Whereas it is well known that the surface roughness parameters 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. In this paper, the backscattering coefficients of simulated and measured surface profiles are computed using the integral equation method and analyzed to answer this question. A $4000\bar{l}$-long rough surface is generated numerically, where $\bar{l}$ is the true correlation length of the surface, and the backscattering coefficients of the surface are computed and analyzed for various conditions. The rms error of the backscattering coefficient at a medium range of incidence angles 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 a surface with $ks = 1.0$, $kl = 10.0$, and $\varepsilon_r = (10.0, 2.0)$. Similar results are obtained from numerous simulations with various roughness conditions and various wavelengths. It is also shown that the rms error of the backscattering coefficients between 5- 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 $(15^\circ \leq \theta \leq 70^\circ)$, whereas the surface roughness parameters are significantly reduced from 2.4 to 1.5 cm for the rms height s and from 35.1 to 10.0 cm for the autocorrelation length l.**

***Index Terms*—Backscattering coefficient, bare soil surface, correlation length, root mean square (rms) height, surface profile length.**

I. Introduction

THE RETRIEVAL of soil moisture from synthetic aperture radar images has been extensively investigated in the past decades. A drawback, however, is the equal or even greater sensitivity of the backscattering coefficient to soil surface roughness than soil moisture. Therefore, a considerable amount of effort has been dedicated to retrieve both soil moisture and soil surface roughness at the same time based on empirical or theoretical scattering models. 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 more likely fit exponential functions.

One of the main difficulties in predicting accurate backscattering coefficients is how to represent a natural soil surface with an accurately characterized autocorrelation function. Among others, a Gaussian, an exponential, an intermediate function between these two, or a rational correlation function is frequently assumed in scattering models because of its easy manipulation [1], [2]. Then, the root mean square (rms) height s, which is the measure of vertical roughness, and the autocorrelation length l, which is the measure of horizontal roughness, can simply represent the surface roughness in scattering models. Sometimes, radar scattering from a natural surface is described in terms of the power spectrum based on fractal geometry [3] from which the surface roughness is characterized by two parameters, namely: 1) the fractal dimension D, which is the measure of surface roughness, and 2) the parameter s, which is the measure of the mean square slope [4].

Soil surface profiles have been collected using two general groups of profiling instruments, namely: 1) mechanical sensors and 2) optical sensors. A laser-based optical sensor has an advantage over a mechanical profiler, because a surface profile can be measured without direct contact to the soil surface [5]. The laser profiler, however, has a disadvantage over the mechanical profiler, because the laser reflects from dry vegetation elements across the beam path, which are not soil topography [6]. Mesh boards and pin boards are typical mechanical profilers, which contact physically with the soil surface to measure a surface profile. A mesh-board profiler is much more inexpensive and easier to install than a laser profiler. The mesh-board profiler, however, disturbs the soil surface when it is inserted in the soil and consequently underestimates the rms height of the soil surface [7]. A pin-board profiler can be simply consisted of an aluminum plate with an aluminum rod having holes where needles slide through. The pin-board profiler can also produce errors due to the imperfect parallelism between needles and finite dimensions of the needle tip. The errors from the pin-board profiler measurements, however, are negligible compared to the optical reflection errors of the laser profiler caused by dry vegetation elements and the errors of the mesh-board profiler from surface disturbance caused by its insertion into soil.

In addition to the measurement errors associated with instruments, another error in the estimation of the surface height autocorrelation can be caused by finite profile length (outer scale) or coarse sampling distance (inner scale) [8]. Because most sensors have enough horizontal resolution satisfying $\Delta x < 0.2l$ (where Δx is the sampling distance, and l is the correlation

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length), the error by the sampling distance is usually negligible [9]. A numerical simulation shows that both the rms height and autocorrelation length increase as the profile length increases, and these parameters asymptotically reach constant values with long profiles [9]. 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, where $\bar{l}$ is the true correlation length [10]. 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 the autocorrelation function (or its nth power) in scattering models, such as the small perturbation method, the physical optics model, and the integral equation method (IEM) [1]. The IEM is widely used to predict the backscattering coefficients of soil surfaces because of its wider validity region [2], [11]. Whereas most correlation functions of agricultural soil surfaces are well approximated by exponential correlation functions [8], [9], some of the agricultural fields deviate from the exponential correlation functions, especially at the tails of the correlations. An empirical calibration of the IEM with an exponential correlation was attempted in [12] to cope with the difficulty in determining the autocorrelation function type and/or assessment of the correlation length. Dierking [10] determined the rms height and the correlation length as functions of profile length and used the estimated values to examine the effect of profile length on the backscattering coefficient using the IEM.

This paper is aimed 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 simulated and measured surface profiles with various profile lengths. The autocorrelation functions for various profile lengths of a long numerically generated surface are computed in Section II. The computation of the backscattering coefficients using the IEM with the autocorrelation functions is presented in Section III, which is followed by the effect of profile length on the backscattering coefficients in Section IV. The results of Section IV are verified with a measured surface height profile of a natural bare soil surface in Section V, and the conclusions drawn from these computations are summarized in Section VI.

II. Autocorrelation of a Simulated Rough Surface

At first, we numerically generated a long surface profile with a stationary and isotropic random roughness. The surface has the height distribution of a Gaussian pdf with an rms height $s = 0.1\bar{l}$ and the autocorrelation of an exponential function with a correlation length $\bar{l} = 1$ unit. The total length of the surface is $4000\bar{l}$, and the sampling distance of the surface is $0.05\bar{l}$, where $\bar{l}$ is the true correlation length. Fig. 1 shows a typical profile section for this numerically generated randomly rough surface. The correlation functions shown in Fig. 2 are normalized with rms heights as displacements are also normalized with correlation lengths. Fig. 2 shows the correlation functions with four different profile lengths along with the exponential correlation function. The shape of the correlation function approaches the exponential function with an increase of the profile length, because the rough surface was generated with an exponential autocorrelation.

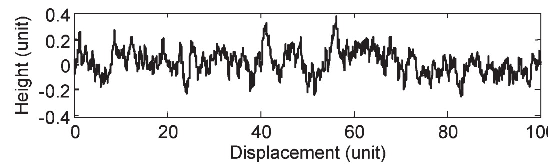


Fig. 1. Typical surface profile section.

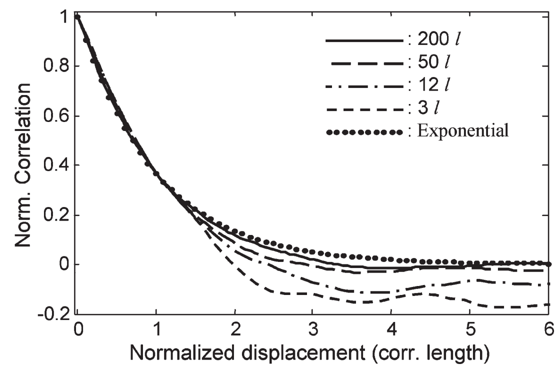


Fig. 2. Correlation functions normalized with both rms height and correlation length for various profile lengths.

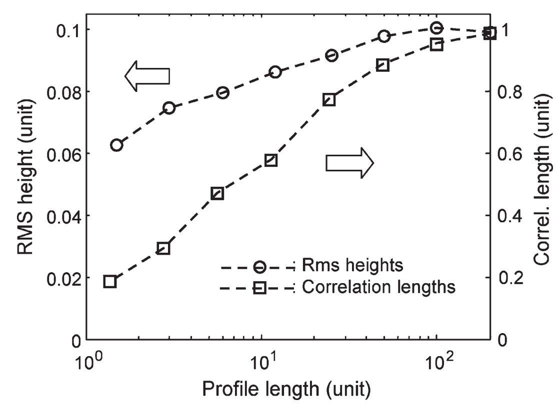


Fig. 3. RMS height and correlation length versus profile length.

Then, the numerically generated rough surface was divided into 20 smaller sections for eight different profile lengths ($200\bar{l}$, $100\bar{l}$, $50\bar{l}$, $25\bar{l}$, $12\bar{l}$, $6\bar{l}$, $3\bar{l}$, and $1.5\bar{l}$), and the averaged autocorrelation of the 20 divided surfaces was computed for each profile length. The rms height s (the standard deviation of the surface height) and the normalized autocorrelation function of a rough surface are computed using the equations in [1, p. 823]. Fig. 3 shows the variations of both the rms height and correlation length as functions of profile length. Both the rms height and correlation length increase with an increase of the profile length and reach the true values at a large profile length, which is about $50\bar{l}$ for the rms height and about $200\bar{l}$ for the correlation length [9], [10]. The increase rate, with variations of the profile length, is much higher for the correlation length than that of the rms height, as shown in Fig. 3. The rms height and correlation length shown in Fig. 3, as well as the

TABLE I
RMS HEIGHTS, CORRELATION LENGTHS, AND rms SLOPES WITH AVERAGE FOR 20 SAMPLES

Length (unit)	rms height (unit)	correl. length (unit)	rms slope
200	0.0992	0.962	0.103
100	0.1003	0.931	0.108
50	0.0977	0.864	0.113
25	0.0915	0.756	0.121
12	0.0860	0.566	0.152
6	0.0794	0.459	0.173
3	0.0747	0.284	0.263
1.5	0.0626	0.181	0.346

TABLE II
RMS HEIGHT AND CORRELATION LENGTH FOR A SINGLE SAMPLE

Length (unit)		rms height (s)	Correlation length (l)	Mean heights
100		0.0989	0.939	0.0189
25	1	0.0920	0.638	0.0253
	2	0.0910	0.648	0.0426
	3	0.1108	1.164	0.0502
	4	0.0682	0.461	-0.0427
	Avg.	0.0905	0.728	

rms slope ($m = s/l$ for exponential correlation), are tabulated in Table I for eight different profile lengths.

The rms height and the correlation length of a stationary Gaussian height distribution are not dependent on the profile length, provided that the profile length is very large compared to the correlation length (e.g., $L > 200\bar{l}$) and the sampling distance is sufficiently small (e.g., $\Delta x < 0.2\bar{l}$). However, these parameters will be reduced for a short surface profile by "mean and trend removal" in the surface height data, even for a stationary random height distribution. As an example, the rms height and correlation length of the surface profile $(L = 100\bar{l})$ shown in Fig. 1, as well as those parameters for four subsections with $L = 25\bar{l}$, are computed, as shown in Table II. The magnitudes values of mean heights (0.0253, 0.0426, 0.0502, and -0.0427) of short profiles are much higher than the mean height (0.0189) of a longer profile, as shown in Table II. Therefore, the "mean removal" for a short profile occurs by the relation $s^2 = \langle z^2 \rangle - \langle z \rangle^2$, where s is the rms height, and $\langle z \rangle$ is the mean height. This "mean removal" results in a reduction of the rms height for a short profile. The correlation length for a short profile $(L = 25\bar{l})$ is also reduced when profile length decreases from $100\bar{l}$ to $25\bar{l}$ because of the "trend removal" (i.e., large-scale roughness trends are filtered out to some extent) and the effect of finite length in the computation of the autocorrelation function [1, p. 823], as shown in Table II.

It was shown that the autocorrelation function of a randomly rough surface depends on the profile length of the surface; i.e., both the rms height and autocorrelation length decrease as the profile length decreases [9]–[10]. The increase rate of the correlation length is higher than that of the rms height, which gives an increase of the rms slope with a decrease in the profile length. As the profile length decreases, the roughness parameters of the surface correspond to a smoother surface in the vertical direction (i.e., the rms height decreases) and to a rougher surface in the horizontal direction (i.e., the correlation length decreases). Now, we arrive 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 IEM is used in the computation of the backscattering coefficient with various profile lengths to answer this question.

III. COMPUTATION OF BACKSCATTERING COEFFICIENTS

The IEM for rough surfaces with small to moderate roughness (e.g., $ks < 2$) is given in [2] and [11] by

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

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

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

with $f_{\mathrm{vv}} = 2R_{\parallel}/\cos\theta$, $f_{\mathrm{hh}} = -2R_{\perp}/\cos\theta$, and $f_{\mathrm{vh}} = f_{\mathrm{hv}} = 0$. $R_{\parallel}$ and $R_{\perp}$ are the Fresnel coefficients for vertical and horizontal polarizations, and F_{qp} is the field coefficient at qp-polarization, which is given in [2, pp. 249–250]. The symbol $W^{(n)}(-2k_x, 0)$ is the Fourier transform of the nth power of the following surface autocorrelation function [2, p. 117]:

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

where $\rho(r)$ is the normalized surface autocorrelation function, and $J_o(\cdots)$ is the zeroth-order Bessel function of the first kind.

The roughness spectrum can be computed numerically from the measured autocorrelation with the zeroth-order Bessel function of the first kind given in [13]. We should take extra care of the numerical integration because of an oscillatory behavior of the integrand in (3). The nth-order roughness spectrum in (3) can be computed analytically for an exponential autocorrelation function using

$$W_e^{(n)}(-2k\sin\theta, 0) = \frac{l^2}{n^2}\left[1 + \left(\frac{2kl\sin\theta}{n}\right)^2\right]^{-1.5} \qquad (4)$$

where l is the correlation length, and the integer n represents the power of the correlation function.

The backscattering coefficients of the numerically generated rough surface are computed using the IEM with the numerical integration of (3) and the analytical computation of (4), and these two computation results are compared with each other at vv- and hh-polarizations for the $L = 200l$ surface, as shown in Fig. 4. In these computations, the roughness parameters were set to be $ks = 1.0$ and $kl = 10.0$, corresponding to $\lambda = \pi/5$ unit (or $\lambda = \pi\bar{l}/5$, where $\bar{l}$ is the true correlation length of the surface) and the dielectric constant $\varepsilon_r = (10.0, 2.0)$. When the vv-polarized backscattering coefficients were computed with the autocorrelation data, the angular data points were scattered at large incidence angles because of a numerical artifact from

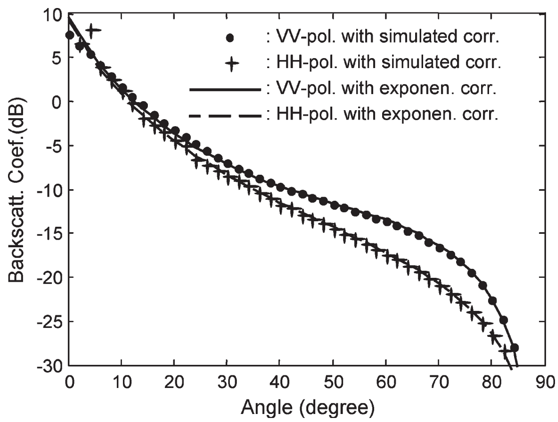


Fig. 4. Comparison between the backscattering coefficients for the autocorrelation of the simulated surface and those for an exponential correlation for vv- and hh-polarizations.

the highly oscillatory shape of the Bessel function, especially by the tail of the autocorrelation function. For a clear view of the angular trend of the data, the tail of the autocorrelation function is tapered with a Gaussian-type window function. Fig. 4 shows that the analytical computation results agree very well with the numerical results for the $L = 200l$ surface except at very low incidence angles of $0^\circ \leq \theta \leq 5^\circ$.

When we compute the backscattering coefficients from many independent profile sections using the IEM, we can consider two methods to compute the "averaged" scattering coefficients, namely: 1) averaging the measured autocorrelation function (method 1) and 2) averaging the roughness spectra of the surface profiles (method 2) [14]. A randomly rough $400\bar{l}$-long surface is divided into sixteen $25\bar{l}$-long surface profiles. The backscattering coefficients for the $25\bar{l}$-long surface profiles were computed at various angles with the following roughness spectra:

$$W^{(n)}(-2k_x, 0) = \int_0^\infty \left\langle \rho^n(r) \right\rangle J_o(2kr \sin\theta) r dr \tag{5}$$

for method 1 and

$$W^{(n)}(-2k_x, 0) = \left\langle \int_0^\infty \rho^n(r) J_o(2kr \sin\theta) r dr \right\rangle \tag{6}$$

for method 2, where $\langle \cdots \rangle$ denotes an ensemble average. The backscattering coefficients of method 1 agree very well with those of method 2 for both vv- and hh-polarizations at all incidence angles, as shown in Table III. In this paper, method 1 is used to compute the backscattering coefficients from 20 independent surface profiles for each profile length.

IV. Examination of the Effect of Surface Profile Length

In Section III, we computed the backscattering coefficients with the averaged autocorrelation function instead of simply using the correlation length l. Fig. 5 shows the angular responses of the vv-polarized backscattering coefficients for four different profile lengths, which were computed numerically using the autocorrelation functions. The angular trends of the numerically computed backscattering coefficients in Fig. 5 are the same as those of the analytically computed backscattering coefficients. Fig. 6 shows the numerically computed backscattering coefficients for hh-polarization as well as the same angular response with the analytical computation results. The backscattering coefficients decrease with a decrease in the profile length at lower incidence angles $(0^\circ \leq \theta \leq 20^\circ)$ for both polarizations, because the effect of the tail of the correlation function is alleviated for a short profile length. The backscattering coefficients increase with a decrease in the profile length at larger incidence angles $(\theta \geq 20^\circ)$ for the vv-polarization, whereas they do not

TABLE III
Comparison Between the Backscattering Coefficients With Averaged Correlation and Those With Averaged Spectrum

Angle (deg.)	VV-pol.			HH-pol.		
	$400l$	$25l$		$400l$	$25l$	
		Eq.(5) (avg. corr.)	Eq.(6) (avg. spec.)		Eq.(5) (avg. corr.)	Eq.(6) (avg. spec.)
10	1.95	1.84	1.83	1.67	1.50	1.50
30	-6.81	-6.54	-6.55	-7.73	-7.67	-7.68
50	-11.71	-11.69	-11.73	-14.48	-14.48	-14.56
70	-16.33	-16.29	-16.29	-20.88	-21.03	-20.99

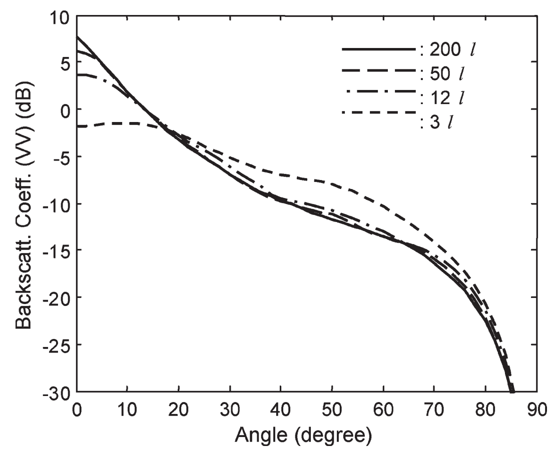


Fig. 5. Angular response of the backscattering coefficients at various profile lengths for vv-polarization.

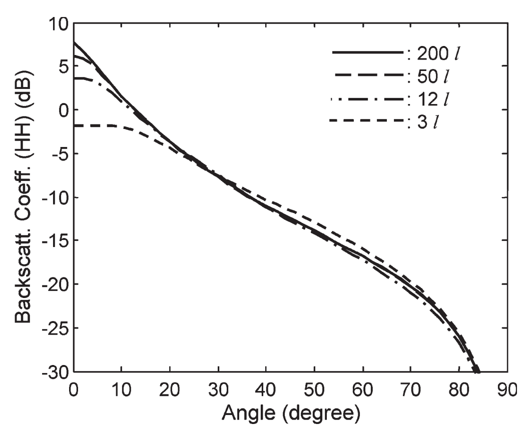
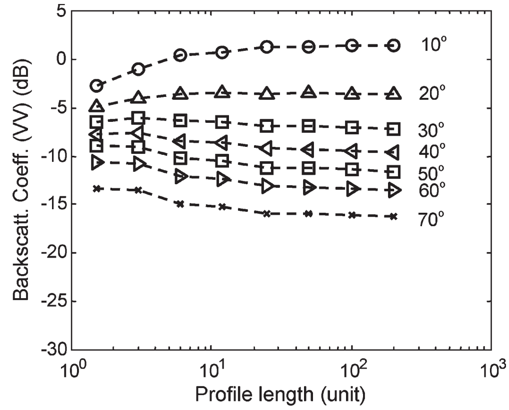


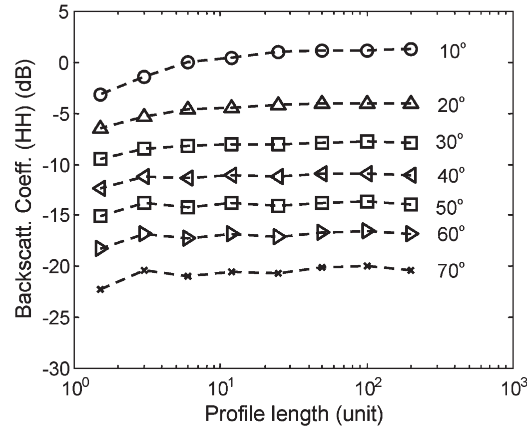
Fig. 6. Angular response of the backscattering coefficients at various profile lengths for hh-polarization.

vary much with variations of the profile length at $\theta \geq 20°$ for hh-polarization, as shown in Figs. 5 and 6.

The computation results in Figs. 5 and 6 are rearranged to show the effects of the profile length at various incidence angles, as shown in Fig. 7(a) and (b) for the vv- and hh-polarized backscattering coefficients, respectively. As shown in Fig. 7, 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 an increase in the profile length, the backscattering coefficients decrease for vv-polarization at large incidence angles and show no variations for hh-polarization. Fig. 8 shows the rms errors in the backscattering coefficients at various profile lengths compared with those of the $200\bar{l}$-long surface, which were obtained from the data of Figs. 5 and 6 at $15° \leq \theta \leq 70°$. The rms errors at $15° \leq \theta \leq 70°$ are less than 1.5 dB for vv-polarization and 0.5 dB for hh-polarization when the profile length is larger than $5\bar{l}$ for the rough surface, as shown in Fig. 8. Two more rough surfaces are generated numerically with different roughness parameters ($\bar{l} = 2.0$ units and $\bar{l} = 0.5$ units), and the backscattering coefficients are computed for those surfaces at various profile lengths. Computation results similar to the previous results were obtained. We also computed the backscattering coefficients for incidence waves with two different wavelengths ($ks = 0.5$ and 1.0) to generalize the effect of the profile length for rough surfaces. The simulation results with different wavelengths are also similar to the previous computations, except that the backscattering coefficients at low incidence angles decrease more rapidly at a larger wavelength.



(a)



(b)

Fig. 7. Backscattering coefficient versus profile length at various incidence angles for (a) vv- and (b) hh-polarizations.

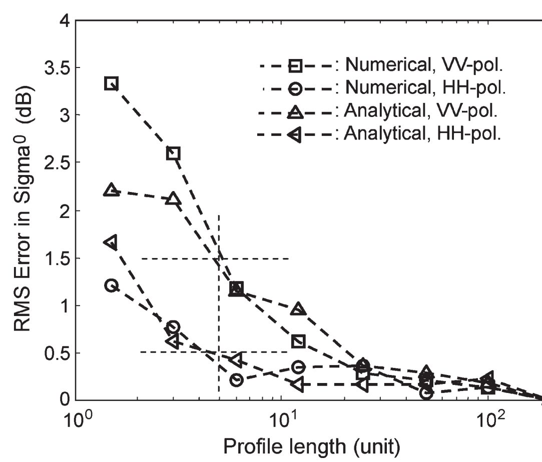


Fig. 8. RMS errors in the backscattering coefficients at $15° \leq \theta \leq 70°$.

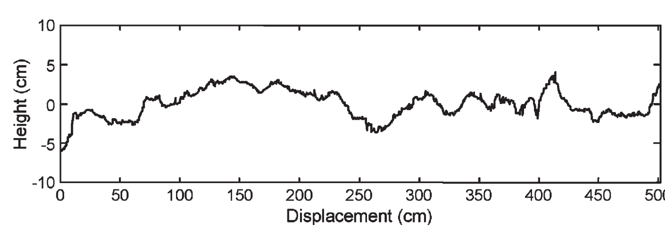


Fig. 9. One of the measured surface profiles.

V. Verification With Measurements

The surface height distribution, as well as the backscattering coefficients and the soil moisture contents of a natural bare soil surface, was measured to verify the conclusion obtained in Section IV; i.e., the deviation of the backscattering coefficients caused by using a "short" surface profile is negligible at a medium range of incidence angle, even though the rms height and correlation length are reduced significantly for the short profile. The polarimetric backscattering coefficients of a bare surface were collected at R-band (1.85 GHz) at vv-, hh-, vh-, and hv-polarizations using a network-analyzer-based scatterometer mounted on a 4.8-m tower.

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 [6], which is consisted of a 1.1-m-long thick acryl plate with a grid paper attached, a 1.1-m-long aluminum rod with 201 holes 0.005 m apart where the needles slide through, and two hundred one 20-cm-long needles. 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 photographed by a digital camera, and a discrete surface profile was obtained by a digitization process. The measurement process is repeated with a careful alignment of the pin-board profiler to provide 5-m-long profiles, as shown in Fig. 9. The pdf of the surface height distribution is very similar to a Gaussian pdf with a zero

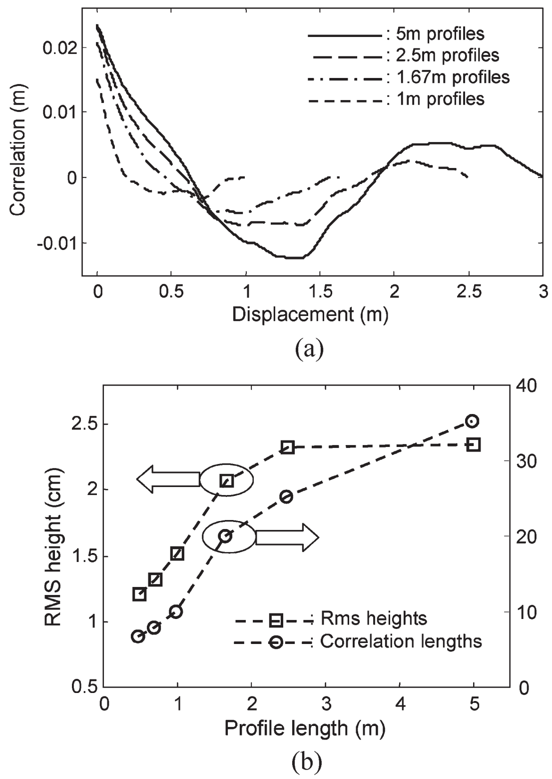


Fig. 10. Effect of profile length. (a) Comparison of measured autocorrelations. (b) rms heights and the correlation lengths versus profile length.

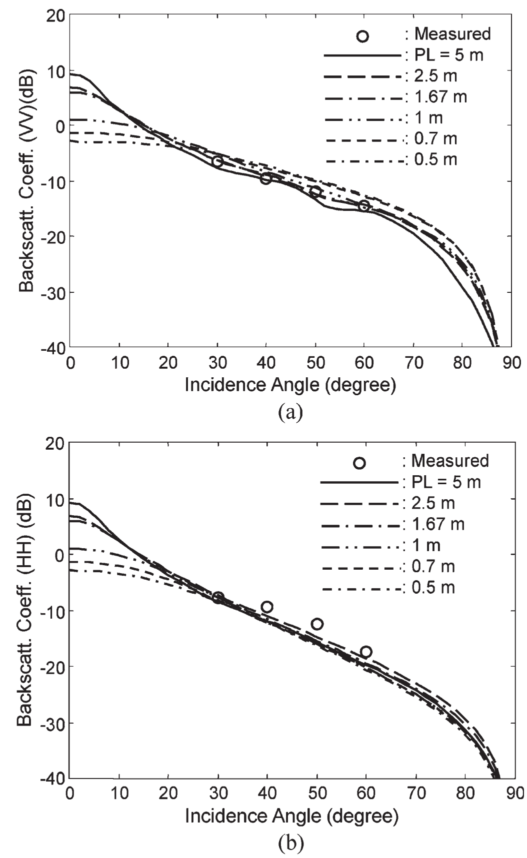


Fig. 11. Angular plots of the backscattering coefficients at various profile lengths for (a) vv- and (b) hh-polarizations.

mean and a standard deviation of 2.35 cm. The first part of the measured autocorrelation function is similar to an exponential correlation function with a correlation length of $l = 0.35$ m.

The soil moisture content of a soil field, which was obtained by taking three soil samples from the top 5-cm layer, was 0.23 $\mathrm{cm}^3/\mathrm{cm}^3$. For a preliminary examination of the measurement, the measured backscattering coefficients were compared with the polarimetric semiempirical model (PSEM) reported by Oh *et al.* [15]. 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 in [15]. The measured backscattering coefficients agree well with those of the PSEM for vv-, hh-, and vh-polarizations. Since the dielectric constant is an input parameter in the IEM, it is computed from the measured soil moisture content using the empirical formula given in [16] with a measured soil texture (sand 33.9%, silt 42.9%, and clay 23.2%).

Fig. 10(a) shows the averaged autocorrelation functions for four different profile lengths (5, 2.5, 1.67, and 1 m), which are obtained by dividing the 5-m-long measured surface profiles. Fig. 10(b) shows the rms heights and correlation lengths of the measured profiles with different profile lengths. Both the rms height and the correlation lengths decrease with a decrease in the profile length, with a higher decrease rate for the correlation length than for the rms height, as shown in Fig. 10(b). It was also shown that at this roughness condition, the rms height reaches a constant (true) value at the profile length of 5 m, whereas the correlation length does not yet reach a constant value.

Fig. 11(a) and (b) shows the vv- and hh-polarized backscattering coefficients of the measured surface for various profile lengths from 5 to 0.5 m. The vv-polarized backscattering coefficient decreases at $\theta < 20^\circ$ and increase at $\theta > 20^\circ$ with a decrease in profile length, as shown in Fig. 11(a). The hh-polarized backscattering coefficient also decreases with a decrease in the profile length at the lower angle $\theta < 20^\circ$, but the profile length does not affect the hh-polarized backscattering coefficient at large incidence angles $\theta > 20^\circ$.

It was 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. 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, whereas the backscattering coefficients for hh-polarization are not affected much by the profile length even for a short profile. The effect of the profile length on the backscattering coefficient is negligible (less than approximately 1 dB) if the profile length is larger than 1.67 m (about five times the correlation length), as shown in Fig. 11(a) and (b). Moreover, the effect of the profile length is less than approximately 2 dB even for very small profile length $(L = 1.5l{-}3.0l)$ at $\theta > 20^\circ$ for hh-polarization and at $20^\circ < \theta < 60^\circ$ for vv-polarization for the measured surface profiles. As an example, the rms error of the backscattering coefficients between 5- and 1-m-long measured surface profiles is 1.67 dB for vv-polarization and 0.48 dB for hh-polarization at a medium range of incidence angle $(15^\circ \leq \theta \leq 70^\circ)$, as shown in Fig. 11(a) and (b), whereas the surface roughness parameters are significantly reduced from 2.4 to 1.5 cm for the rms height s and from 35.1 to 10.0 cm for the autocorrelation length l, as shown in Fig. 10(b).

VI. Conclusion

The backscattering coefficients of simulated and measured rough surfaces with various profile lengths were computed with the IEM, and the computation results were analyzed to examine the effect of profile length on the microwave backscattering coefficient of a natural soil surface. It was shown that even though both the rms height and autocorrelation length vary significantly with variations of the profile length, minimal variations of the backscattering coefficients were observed. The computations with a simulated surface profile showed us that the rms error of the backscattering coefficients at $15^\circ \leq \theta \leq 70^\circ$ is less than 1.5 dB for vv-polarization and 0.5 dB for hh-polarization when the profile length is larger than $5\bar{l}$ for a surface with $ks = 1.0$, $kl = 10.0$, and $\varepsilon_r = (10.0, 2.0)$. We obtained similar results from numerous simulations, which were conducted for other surfaces with various roughness conditions and other incidence waves with various wavelengths. This small effect of the profile length on the backscattering coefficients at the medium range of incidence angle is verified with the measurement of a natural soil surface. As the profile length increases, the backscattering coefficients increase and reach constant values at a large profile length at low incidence angles for both polarizations, and at large incidence angles, the backscattering coefficients even decrease before reaching the constant value for vv-polarization. It was also shown from the measured surface profile that the rms error of the backscattering coefficients between 5- 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 $(15^\circ \leq \theta \leq 70^\circ)$, whereas the surface roughness parameters are significantly reduced from 2.4 to 1.5 cm for the rms height and from 35.1 to 10.0 cm for the autocorrelation length.

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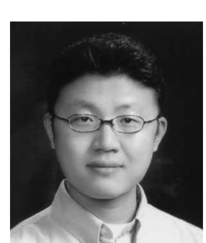

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