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Condition for Precise Measurement of Soil Surface Roughness

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***Abstract*—Whereas it is well known that electromagnetic scattering by a randomly rough surface is strongly influenced by the surface-height correlation function, it is not clear as to how long a surface-height profile is needed and at what interval it should be sampled to experimentally quantify the correlation function of a real surface. This paper presents the results of a Monte Carlo simulation conducted to answer these questions. It was determined that, in order to measure the rms height and the correlation length with a precision of ± 10%, the surface segment should be at least $40\bar{l}$ long and $200\bar{l}$ long, respectively, where $\bar{l}$ is the mean (or true) value of the surface correlation length. Shorter segment lengths can be used if multiple segments are measured and then the estimated values are averaged. The second part of the study focused on the relationship between sampling interval and measurement precision. It was found that, in order to estimate the surface roughness parameters with a precision of ± 5%, it is necessary that the surface be sampled at a spacing no longer than 0.2 of the correlation length.**

I. Introduction

Extraction of soil moisture and vegetation biomass information from imaging radar data has been a subject of intense interest for a long time. However, the technique has not been very successful, in part because of the complexity of natural soil surfaces, specifically, the difficulty in estimating the surface roughness and the inhomogeneity of the soil moisture. Furthermore, theoretical and numerical models, while well suited for ideal rough surfaces, are not easy to implement for natural soil surfaces. An attempt has been made to retrieve soil moisture and surface roughness together from polarimetric radar scattering data through the use of an inversion algorithm [1]. Because the dynamic range of the backscattering coefficient associated with the surface roughness is comparable to or larger than that associated with the soil moisture, the surface roughness should be estimated accurately for retrieving the soil moisture with good accuracy. In this paper, the effect of surface roughness on radar scattering from soil surfaces is discussed and the results of a simulation study aimed at quantifying criteria for accurate estimation of surface roughness parameters are presented.

According to experimental observations [1], whereas the height distribution of natural soil surfaces is characterized by Gaussian density functions, the measured correlation functions of the surface height profiles more closely resemble exponential functions, as shown in Fig. 1(a). The "measured" correlation function shown in Fig. 1(a) was obtained by averaging more than 300 normalized correlation functions measured from natural soil surfaces. The angular responses of the vv-polarized backscattering coefficients for the exponential, Gaussian, and the measured correlation functions were computed and are shown in Fig. 1(b) for a surface with $s = 0.01$ m, $l = 0.1$ m, and $\varepsilon_r = (10, 2)$ at $f = 1.5$ GHz by using the small perturbation method (SPM), where s is the rms height and l is the correlation length. The large difference in trend between the exponential and Gaussian curves, particularly in the higher angular range, shows the importance of the shape of the correlation function on the backscattering coefficient.

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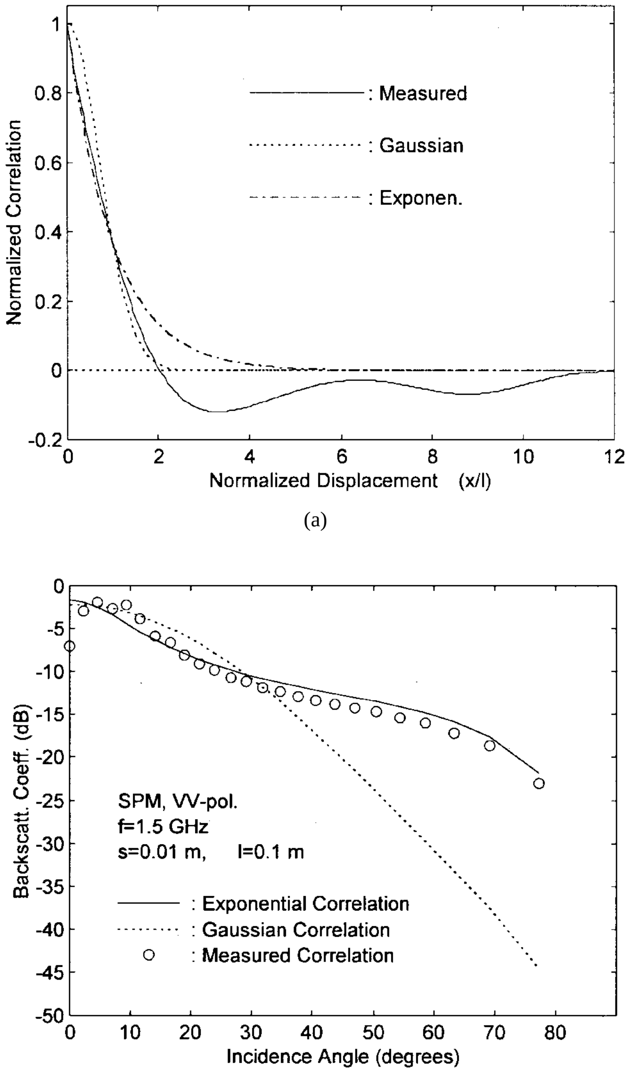


Fig. 1. Role of the surface correlation function of the surface-height profile. (a) comparison of the measured correlation function with Gaussian and exponential functions and (b) the effect of the correlation function on the backscattering coefficient.

II. Simulation Procedure

In order to examine the surface characteristics of random surfaces, several randomly rough surfaces are generated by using the technique given in [2], as follows:

$$Z(k) = \sum_{j=-M}^{M} W(j)X(j+k) \tag{1}$$

where $Z(k)$ is the surface height distribution, $X(i)$ is a Gaussian random deviate $N(0,1)$, and $W(j)$ is the weighting function given by

$$W(j) = F^{-1}\left[\sqrt{F[C(j)]}\right] \tag{2}$$

where $C(j)$ is the correlation function and $F[\,]$ denotes the Fourier transform operator. For a surface characterized by a Gaussian or an exponential correlation function, given respectively by

$$C_G(j) = s^2 \exp\left[-\left(\frac{j\Delta x}{l}\right)^2\right]$$

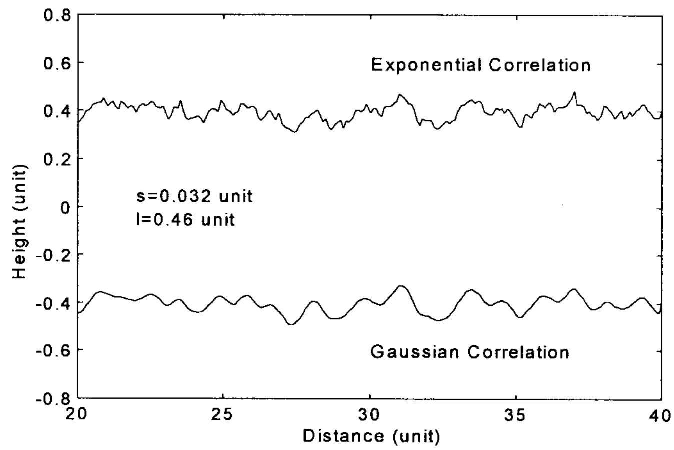


Fig. 2. Surface profiles generated for both a Gaussian and an exponential correlation function.

and

$$C_e(j) = s^2 \exp\left[-\frac{|j|\Delta x}{l}\right] \tag{3}$$

the corresponding weighting functions are given by

$$W_G(i) = \left(\frac{2\Delta x}{\sqrt{\pi} l}\right)^{1/2} s \exp\left[-2\left(\frac{i\Delta x}{l}\right)^2\right]$$

and

$$W_e(i) = \left(\frac{\sqrt{2\Delta x}}{\pi\sqrt{l}}\right) s K_0\left[\frac{i\Delta x}{l}\right] \tag{4}$$

where Δx is the sampling distance and $K_0[\,]$ is the modified Bessel function of the second kind. Using the above equations, randomly rough surfaces were generated. The profiles shown in Fig. 2 are for surfaces with $s = 0.032$ unit and $l = 0.46$ unit for Gaussian and exponential correlation functions, both with a Gaussian height distribution.

III. Simulation Results

The simulation procedure described in the preceding section was used to generate four profiles of different rms heights and correlation lengths. In each case, the profile was longer than $1000l$, where l is the correlation length. These profiles were then used to determine the following:

a) relationships between the measurement precision associated with estimating the surface roughness parameters (rms height s and correlation length l) and the length of the surface-height profile L (by using only specific segment lengths of the total generated profile);
b) improvement provided by averaging multiple segments on the estimates of s and l;
c) relationship between measurement precision and sampling interval Δx.

A. Dependence on Segment Length

Fig. 3(a) shows the plots of two correlation functions calculated, as given in [3], for the same surface, but on the basis of segments of different lengths. It is clear from the plots that the 2000-unit-long segment produces an exponential looking correlation function,

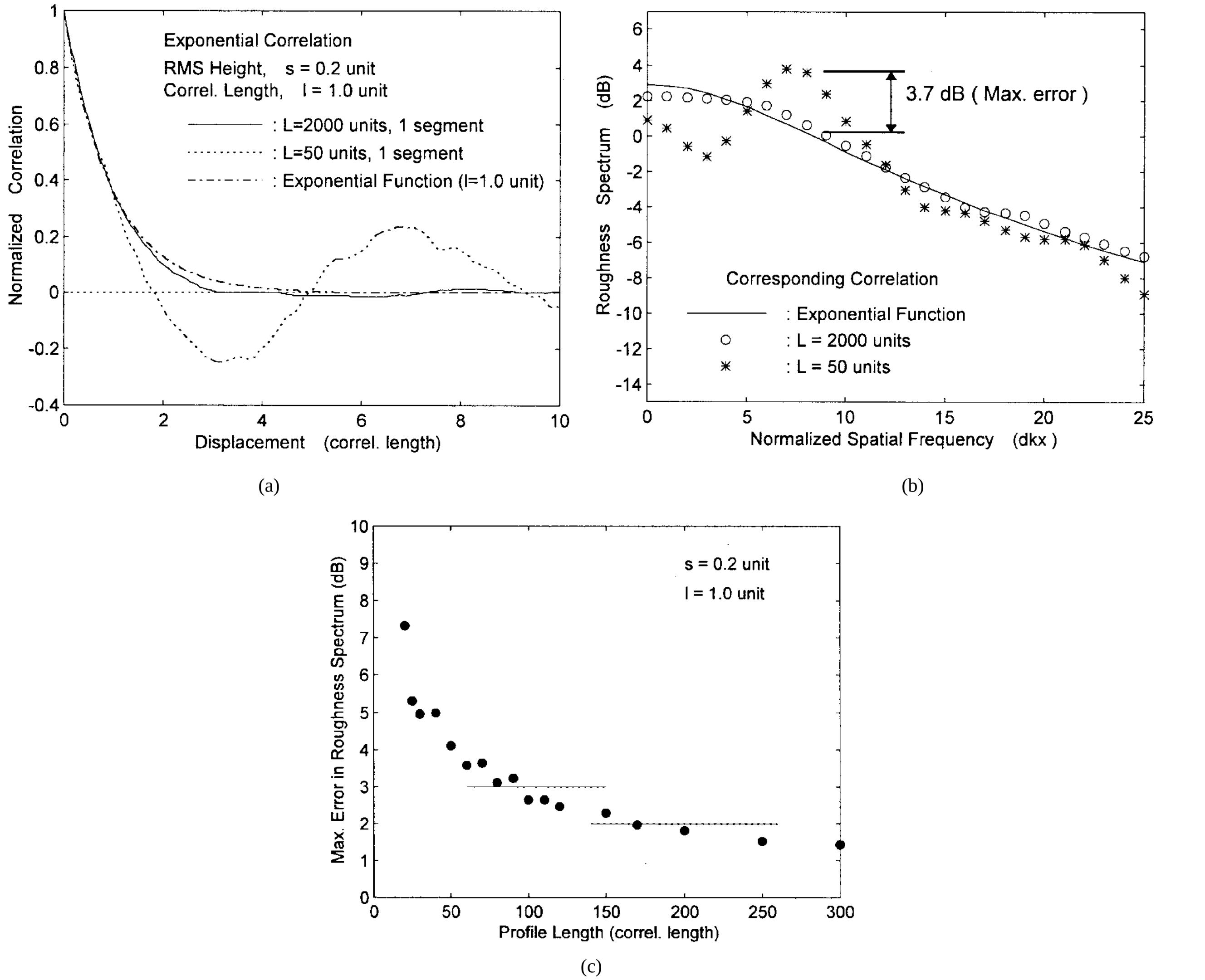


Fig. 3. Effect of the profile segment length on (a) the correlation functions, (b) the corresponding roughness spectrums, and (c) the maximum errors of the roughness spectrums.

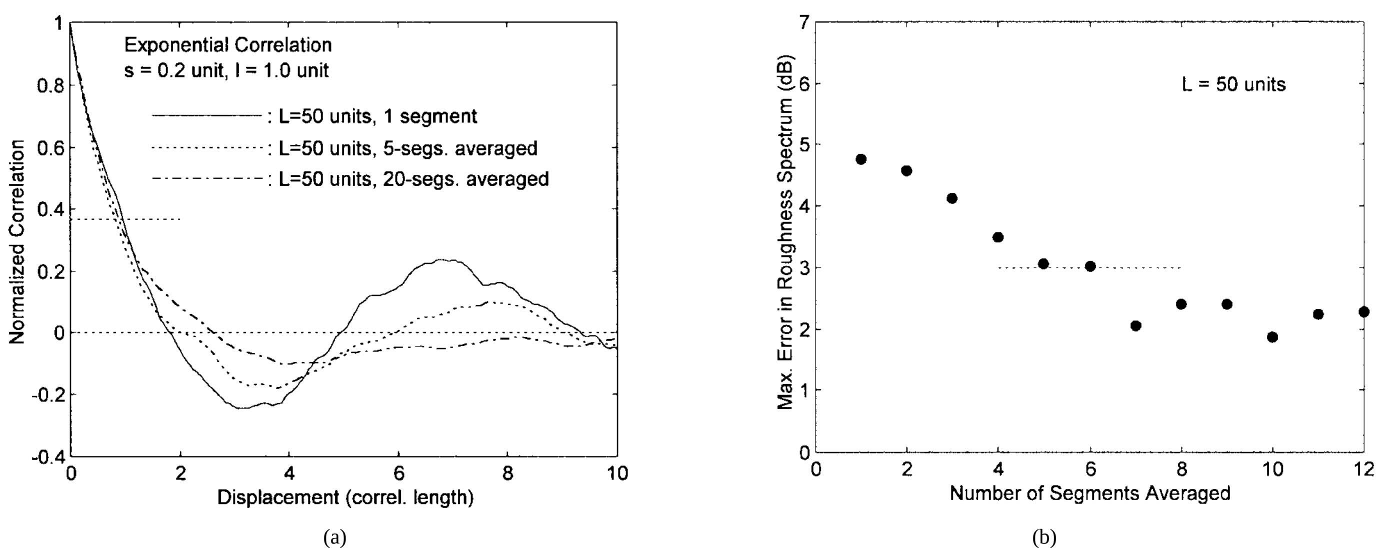
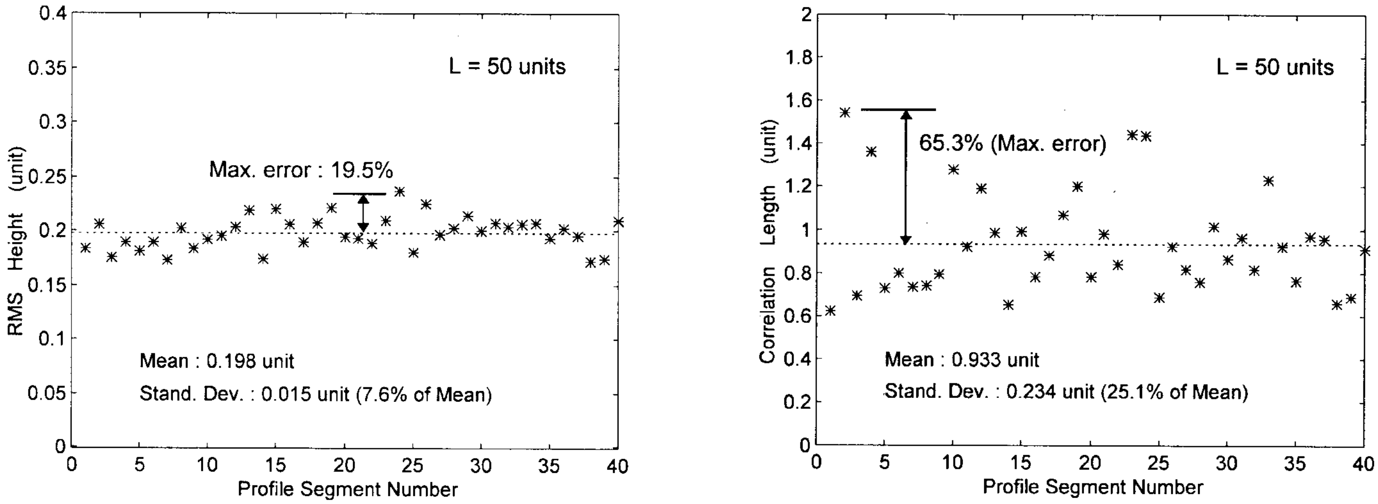
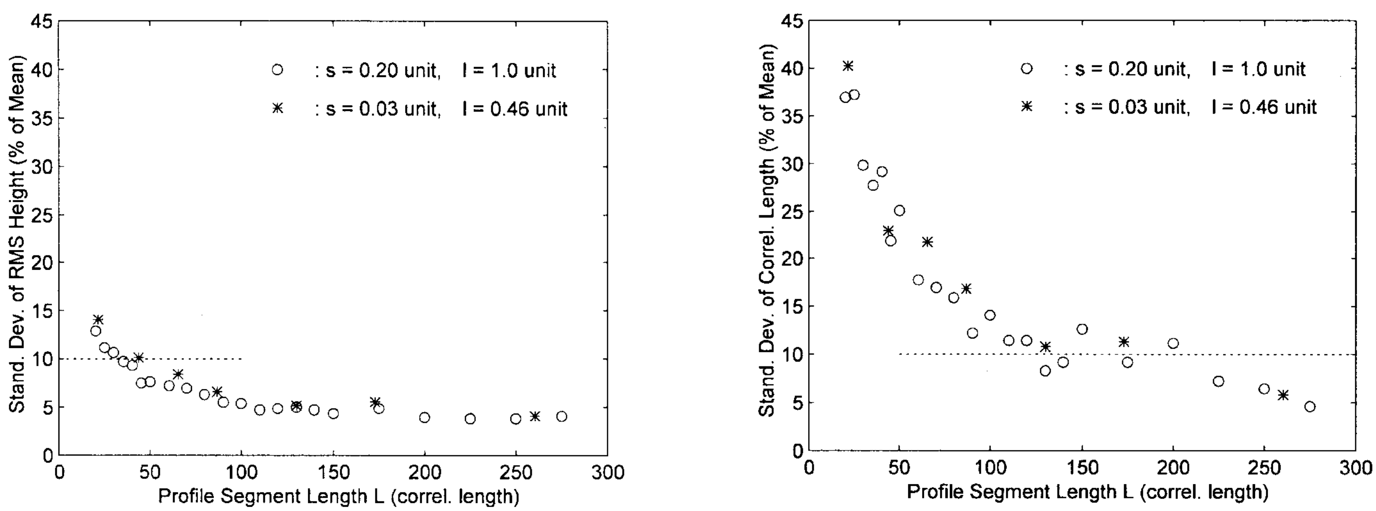


Fig. 4. Effect of averaging multiple segments on (a) the correlation functions and (b) the maximum errors in the roughness spectrums.



(a) (b)

Fig. 5. Rms height (a) and correlation length (b) computed from each profile segment.



(a) (b)

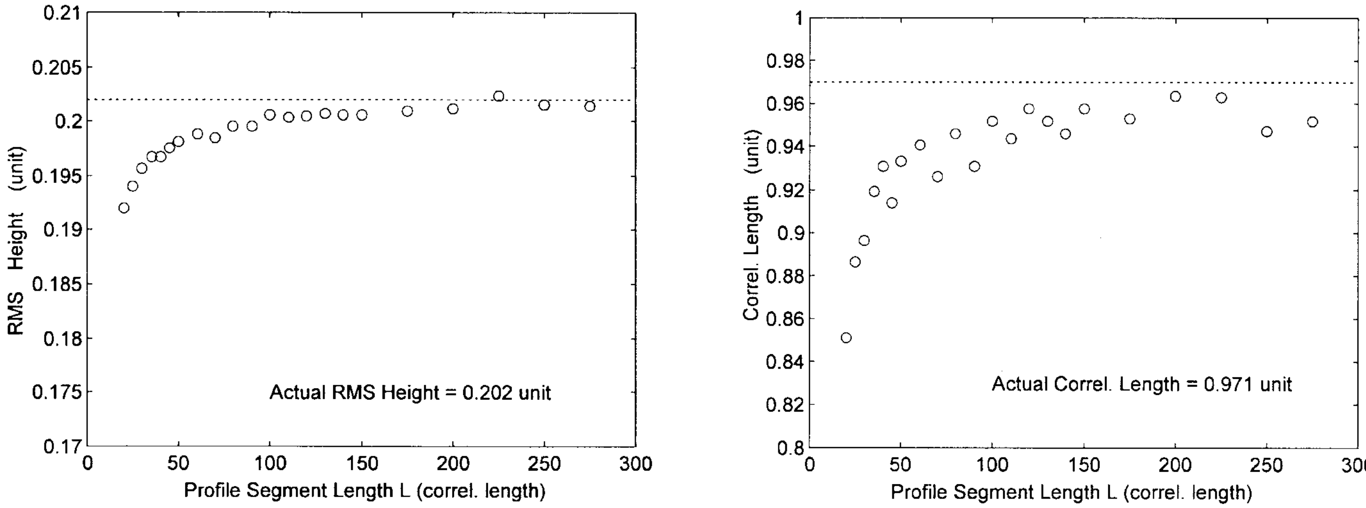
Fig. 6. Standard deviations of (a) rms height and (b) correlation length, as a function of profile segment length.

whereas the short segment ($L = 50$ unit) produces an oscillatory function and it is accurate only for displacements shorter than the correlation length (1.0 unit). The scattering coefficient is proportional to the Fourier transform of the correlation function, which is the roughness spectrum, in the SPM model and the dominant term in the physical optics (PO) model is also proportional to the roughness spectrum. Therefore, the roughness spectrums corresponding to the correlation curves in Fig. 3(a) are computed and shown in Fig. 3(b). The oscillatory behavior of the correlation curve for a profile segment of length $L = 50$ unit gives the maximum error of 3.7 dB, comparing with the exponential curve. In order to reduce a numerical and aliasing error, a Gaussian-type window was used and the averaged maximum error of ten segments in the roughness spectrum was computed for each segment length, as shown in Fig. 3(c). Fig. 3(c) shows that the profile length should be at least $200l$ long to get a precision of ± 2 dB in the roughness spectrum, where l is the profile correlation length.

Fig. 4(a) and (b) show the improvement in measurement precision provided by averaging multiple equal-length segments of the same profile. Figs. 3(c) and 4(b) show that averaging five $50l$-long segments is equivalent to a result from a single $100l$-long segment, in the sense of maximum error in the roughness spectrum.

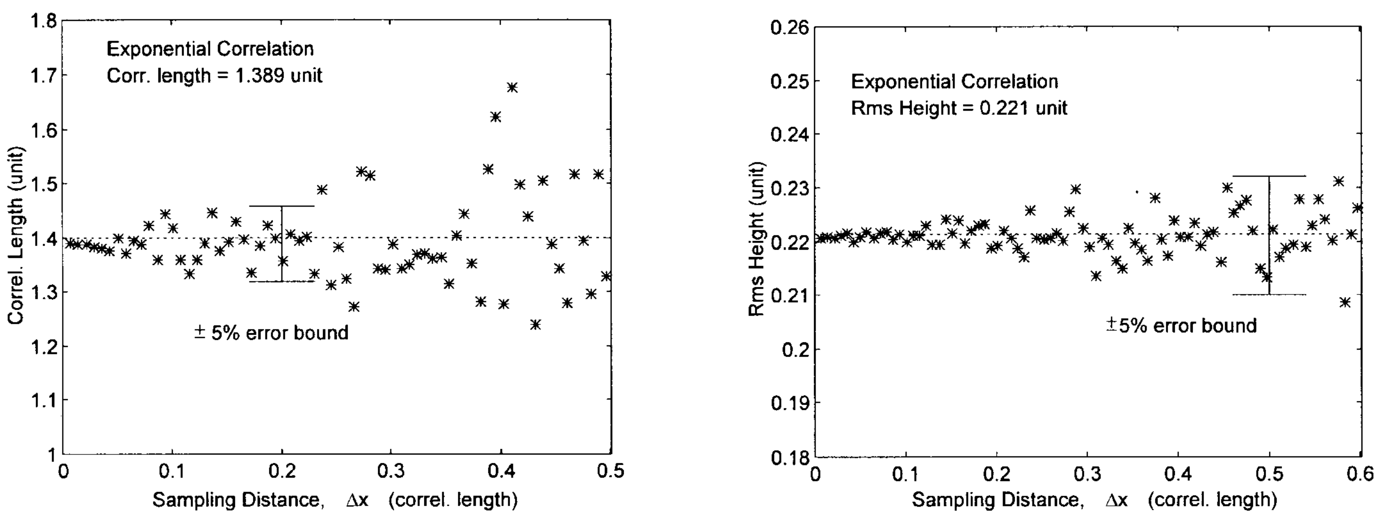
For 40 $50l$-long segments of the same profile, the rms height (standard deviation of surface height) and the correlation length (displacement $j\Delta x$, such that the normalized correlation function $C_e(j)/s^2 = e^{-1}$) are computed [3], as shown in Fig. 5(a) and (b). The standard deviations of the rms height and the correlation length are 7.6% and 25.1% of the mean values, respectively, as shown in Fig. 5(a) and (b). By repeating the process for many different profile segment lengths of the same profile, the standard deviations σ_s and σ_l, associated with the estimates of s and l (as percentages of the true means $\bar{s}$ and $\bar{l}$) are calculated. The results are displayed in Fig. 6(a) and (b), which show that σ_s and σ_l decrease in an exponential-like manner with segment length L. To determine s with $\sigma_s/\bar{s} \leq 0.1$, it is sufficient to use a single segment $40l$ in length, but to estimate l with $\sigma_l/\bar{l} \leq 0.1$, the segment length has to be at least $200l$ in length.

Averaging multiple segments does not necessarily result in the same correlation function, even when the total segment length is the same. The shorter the segment length, the shorter the estimated value



(a) (b)

Fig. 7. Dependence on the profile segment length L when calculating (a) averaged rms height and (b) averaged correlation length.



(a) (b)

Fig. 8. Effect of the sampling distance for (a) correlation length l and (b) rms height s.

of the rms height and the correlation length, as shown in Fig. 7(a) and (b).

B. Sampling Distance

The precision associated with the measurements of the roughness parameters s and l is also dependent on the sampling distance Δx. According to the results shown in Fig. 8, which displays the estimated values of l [in Fig. 8(a)] and s [in Fig. 8(b)], as a function of Δx (measured in units of $\bar{l}$) for a segment 2000 unit in length, Δx should be no more than $0.2\bar{l}$ to keep the error in estimating l to within $\pm 5\%$ and no more than $0.5\bar{l}$ for the same error bound when estimating s.

IV. Conclusion

Based on the simulation study involving the generation of random surfaces, it is recommended that, in order to measure the rms height and the correlation length of a rough surface with a precision of about $\pm 10\%$ of their mean values, the surface segment length should be $40\bar{l}$ and $200\bar{l}$, respectively. Shorter segments lengths can be used if multiple segments are measured and then the estimated values are averaged. And the sampling distance Δx should be no more than $0.2\bar{l}$ in length, where $\bar{l}$ is the true correlation length of the surface.

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