Numerical backscattering analysis for rough surfaces including a cloddy structure

M. Zribi\textsuperscript{1}, A. Le Morvan\textsuperscript{2}, M. Dechambre\textsuperscript{2}, N. Baghdadi\textsuperscript{3}

\textsuperscript{1} IRD-CESBIO, 18 av. Edouard Belin, bpi 2801, 31401 Toulouse cedex 9, France
\textsuperscript{2} LATMOS/IPSL/CNRS, 10-12 av. de l'Europe, 78140 Vélizy, France
\textsuperscript{3} CEMAGREF, UMR TETIS, 500 rue François Breton, 34093 Montpellier cedex 5, France
E-mail: Mehrez.Zribi@ird.fr; Tel.: 33 1 39 25 48 23; Fax: 33 1 39 25 49 22,

Abstract

In recent years, the presence of a new type of agricultural surface tillage, used for the sowing of wheat and \textbf{corn}, has been observed with increasing frequency. It illustrates less roughly ploughed soils, with a greater quantity of small clods distributed over the soil surface. In this paper, a new description of such rough agricultural surfaces is proposed. It is based on a composite model, including a classical surface, represented by an exponential correlation function, together with \textbf{random cloddy structure}. This description enables volumetric structures to be introduced over the soil’s surface. A numerical moment modelling method, based on integral equations, is used to evaluate the contribution of \textbf{clods} to the radar backscattering behaviour of agricultural surfaces. It is found that the presence of clods explains the very small correlation lengths which are often found in cloddy agricultural fields. The classical approach, in which the surface is described by a correlation function only, based on two statistical parameters, \textit{rms} height and correlation
length, over-estimates the backscattering coefficients when compared to an approach that includes the clods. This over-estimation is often observed with real radar data for such fields.

I. Introduction

In the last two decades, considerable effort has been devoted to the study of radar backscattering responses from natural surfaces [1-4]. Electromagnetic backscattering models (Kirchoff models, the small perturbation Model) and more recently, the Integral Equation Model (IEM), [1], [5] have been used in order to estimate roughness and moisture parameters. Each model has its domain of validity. SPM, for example, is better adapted to smooth surfaces, the IEM model is suited to small and medium surface roughness, and the Kirchoff approach is more suited to medium or high surface roughness. Despite improvements achieved in backscattering simulations, through the development and improvement of various analytical models ([6-8]), it is still difficult to correctly retrieve radar signals, particularly for medium to rough surfaces, even within their validity domains. The latter are often tested using simulations made with Gaussian surfaces, and are thus not necessarily representative of realistic, natural surfaces, having more complicated surface roughness descriptions. On the other hand, many experimental and theoretical studies have sought to improve roughness measurements and descriptions [9-11]. Various axes of research have been discussed ([1], [12-15]). Concerning roughness measurements, different experimental campaigns have shown a high variability of statistical roughness parameters even for homogeneous soil surfaces, particularly as a function of profile length ([16-18]). Different measurement protocols have been proposed
in order to improve precision of statistical parameters ([14], [19]). In order to measure the rms height and the correlation length with a precision of ±10%, (Oh et al. [19]) have shown that the surface segment should be at least 40 \( l \) and 200 \( l \) long, respectively, where \( l \) is the mean value of the surface correlation length. Concerning roughness description, different types of analytical correlation function have been proposed to fit the experimental data ([1]). Very often, an exponential correlation function is used to describe a natural surface. Analyses based on fractal descriptions have also been proposed ([20-22]). These permit a multi-scale description to be used, rather than one limited to a unique scale, by a single correlation length parameter. Li et al. [23] proposed a generalized power-law spectral density, with a new form of parameterisation, for surfaces considered to be stationary. Other studies have proposed an approach, using an empirical relationship between correlation length and \( rms \) height, in order to fit IEM simulations with observed radar data ([11]). All of these studies have enabled improvements to be achieved in backscattering simulations. However, some difficulties still remain when it comes to correctly simulating radar signals for medium and highly rough surfaces, as illustrated in [24]. In recent years, using different experimental measurements, these authors have observed the generalisation of a new type of tillage corresponding to sowing bed, with less strongly ploughed soils and clods covering the soil surface. For these surfaces, we observe generally an over-estimation of backscatter by analytical models in comparison to real radar data [24]. In this study, we propose to understand the behaviour of these cloddy soil surfaces, with the development of a new composite surface roughness model. We have analysed the influence of this more complex description, by means of numerical backscattering simulations involving integral equations, using the development of the moment method.
Our paper is organised as follows: in Section II, the generation of a surface with a cloddy structure is presented. Description of the proposed moment method, discussions and results are provided in Section III. Finally, our conclusions are presented in Section IV.

II. Statistics of Soil Surfaces with Cloddy Structure

A. Introduction

As presented in the three illustrations of figure 1, corresponding to agricultural fields in Orgeval basin [25], we observe in the last years a generalisation of this new tillage of surfaces prepared to sowing. We note the presence of clods with different sizes superposed over soil surface, with different discontinuities in surface profile. As said in introduction, our objective is to propose a new modelling of this type of surface, considering these clods structures. [26] has presented a close approach for rock-strewn surfaces description, with identification of discrete objects for rocks.

B. Soil surface generation

*Introduction*

In this section, we propose a new composite roughness description for a type of soil surface. It comprises two distinct roughness structures:

- An exponentially correlated random surface, referred to as the ‘substrate’ surface. The choice of an exponential form is motivated by the general use of this type of function for surface characterisation.

- The addition of clods on top of the substrate surface
Exponentially correlated profile generation

For an exponential correlation profile [27], we first generate independent Gaussian variables \(X_k\) with a mean value equal to zero, and a standard deviation equal to 1. The profile heights \(C_k\) are computed as:

\[
C_k = \sum_{j=-M}^{j=M} W_j X_{j+k}
\]  

(1)

with \(W_j\) the filter weights are determined:

\[
E[C_k C_{k+j}] = \sum_j \sum_n W_j W_n \{X_{j+k} X_{n+k+i}\}
\]  

(2)

since \(\{X_i\}\) are independent:

\[
E[X_{j+k} X_{n+k+i}] = 0, j \neq n + i
\]

\[
= 1, j = n + i.
\]  

(3)

then

\[
E[C_k C_{k+i}] = \sum_j W_j W_{j-i}
\]  

(4)

The correlation function of the filtered points is equal to the convolution of the weights, such that the Fourier Transform of the correlation function (the topographic power spectral density function) is equal to the square of the Fourier transform of the weights. We thus obtain a filter, which corresponds to the inverse Fourier transform of the square root of the spectral density.

For the exponential correlation function, \(W_j\) has an analytical expression equal to
where $\Delta x$ is the sampling distance and $K_0[\cdot]$ is the modified Bessel function of the second kind, $s$ is the $rms$ height and $l$ is the correlation length.

Figure 2 provides an example of **exponentially correlated** profile generation. In this case, the surface has an $rms$ height $(s)$ equal to 8mm and a correlation length $(l)$ of 80mm for a profile length of 1000mm. We note, as described by [20], an increase of correlation length value with profile length due to the introduction of low frequency roughness.

**Introduction of clods**

It is proposed to add clods to the **exponentially correlated** profile of the substrate, through the use of a Monte Carlo approach. Two Gaussian distributions are considered: one for the size of the clods, and another for the distance between any two adjacent clods. These can be written as:

$$p_s(x) = \frac{1}{\sigma_s \sqrt{2\pi}} \exp\left(-\frac{(x - S_c)^2}{2\sigma_s^2}\right) \text{ for the clod sizes}$$ (6)  

Where $S_c$ is the mean clod size, $\sigma_s$ is the standard deviation and $x$ is the size of clods.

and

$$p_d(x) = \frac{1}{\sigma_d \sqrt{2\pi}} \exp\left(-\frac{(x - D_c)^2}{2\sigma_d^2}\right) \text{ for the separation between clods}$$ (7)
Where $Dc$ corresponds to the mean distance between adjacent clods, $\sigma_d$ represents the standard deviation and $x$ is the separation distance.

We consider $hc$, the height of the clod profile, in the absence of the exponential substrate.

For each clod, a simple shape is proposed. If we consider $x_k$ to be the mean abscissa of the $k^{th}$ clod of size $S_k$, then for $x$ lying between $x_k-S_k/2$ and $x_k+S_k/2$,

$$hc(x) = \sqrt{\left(\frac{S_k}{2}\right)^2 + (x_k - x)^2}$$  \hspace{1cm} (8)

Outside the clods:

$$hc(x) = 0$$  \hspace{1cm} (9)

Our proposed surface geometry is based on the sum of the exponential substrate surface, together with the cloddy surface.

Therefore, for each point of the resulting surface profile, the total height can be written as:

$$h(x) = h_{\text{exp}}(x) + hc(x)$$  \hspace{1cm} (10)

where $h_{\text{exp}}$ represents the heights generated by the exponentially correlated profile of the substrate.

Figure 3 shows three examples of surfaces generated in this manner, having different surface parameters. For these three surfaces, in order to illustrate clearly clods structure, we consider in each case a presentation of just 200 mm long from soil profile,
for which the exponential substrate is characterised by the same parameters, i.e. an $rms$ height of 7 mm, and a correlation length of 80mm. On the other hand, we simulate three different clod distributions, with different mean clod sizes: $Sc = 17$ mm, 22 mm and 34 mm, and approximately the same mean value for the characteristic distance between adjacent clods: $Dc = 83$ mm, 72 mm and 71 mm. The three profiles shown in Figure 2 show the presence of clods on top of the relatively smooth substrate surface, with an overall profile varying from smooth to rough. The results obtained using this surface generation method are analysed in the following sections of our paper. In all discussions, we consider exponentially correlated profiles with relatively small $rms$ heights, because, by adding clods, we can produce medium or high $rms$ heights for the overall profile.

C. Correlation function estimation

In this section, we estimate the correlation functions corresponding to the proposed surfaces, generated by the addition of clods on top of an exponentially correlated substrate with $s=5$mm and $l=80$mm. The first objective is to analyse the influence of the proposed ‘cloddy’ surface generation method on the correlation function behaviour. Figure 4 shows the correlation function estimations corresponding to the three surface profiles. The shapes of these functions are fitted to an expression of the form:

$$\rho(x) = s^2 \exp\left(-\left(\frac{x}{l}\right)^\alpha\right)$$

(11)

where $\alpha$ lies, in general, between 1 and 2.
Firstly, for the first and second examples, characterised by clod distributions with small to medium clods sizes ($Sc = 17\text{mm}$ and $Sc = 18\text{mm}$), on top of the smooth substrate, we observe a nearly exponential ($\alpha = 1.02$) correlation function with respectively roughness parameters: global $rms$ height ($sg$) equal to $6.6\text{mm}$ and $6.9\text{mm}$, and global correlation length ($lg$) equal to $28\text{mm}$ and $26\text{mm}$.

In the case of the third example, for which a higher roughness value is used, the shape of this function approaches that of a Gaussian ($\alpha = 1.65$), with roughness parameters: $sg$ equal to $8.6\text{mm}$ and $lg$ equal to $22\text{mm}$. This trend is often observed in experimental measurements, in which the parameter $\alpha$ increases with roughness [15].

Secondly, the three examples are found to have a strong decrease in correlation length, when compared to those used for the exponentially correlated profile generation ($l = 80\text{mm}$): the correlation lengths of the composite surfaces lie between $20$ and $40\text{mm}$. This decrease in correlation length is produced by the cloddy structure, which when added to the exponentially correlated profile, limits the correlation between relatively distant points on the soil surface.

It is important to note that, in general, we use a pin profiler for surface geometry measurements, with the distance between successive pins often being equal to $0.5$ or $1\text{ cm}$ ([28]).

In order to evaluate the influence of our proposed new soil surface description on radar backscattering behaviour, we propose to apply an exact numerical model calculated directly over generated surfaces, based on the moment method.
III. Results and discussions

A. Numerical backscattering modelling

In this section, we provide a limited description of the numerical approach used to compute radar backscattering behaviour, well detailed in ([29-30]), from surfaces generated using the approach defined in section II.

The backscattering computation is based on the solving of integral equations. We consider firstly the integral equations in air ([30-31]):

\[
\bar{n} \times \vec{E}^{i}(\vec{r}) = -\frac{1}{2} \vec{K} + \bar{n} \times \int_{c} \left[ j \omega \mu_{0} G_{1} \vec{J} - \vec{K} \times \nabla G_{1} - \frac{\nabla' \vec{J}}{j \omega \epsilon_{1}} \nabla G_{1} \right] d\vec{l} \tag{12}
\]

\[
\bar{n} \times \vec{H}^{i}(\vec{r}) = -\frac{1}{2} \vec{J} + \bar{n} \times \int_{c} \left[ j \omega \epsilon_{0} G_{1} \vec{K} + \vec{J} \times \nabla G_{1} - \frac{\nabla' \vec{K}}{j \omega \mu_{0}} \nabla G_{1} \right] d\vec{l} \tag{13}
\]

next, the integral equations for a soil medium are given by:

\[
0 = -\frac{1}{2} \vec{K} - \bar{n} \times \int_{c} \left[ j \omega \mu_{0} G_{2} \vec{J} - \vec{K} \times \nabla G_{2} - \frac{\nabla' \vec{K}}{j \omega \epsilon_{2}} \nabla G_{2} \right] d\vec{l} \tag{14}
\]

\[
0 = -\frac{1}{2} \vec{J} - \bar{n} \times \int_{c} \left[ j \omega \epsilon_{0} G_{2} \vec{K} + \vec{J} \times \nabla G_{2} - \frac{\nabla' \vec{K}}{j \omega \mu_{2}} \nabla G_{2} \right] d\vec{l} \tag{15}
\]

Where \( \mu_{0} \) is air permeability, \( \epsilon_{1} \) and \( \epsilon_{2} \) are dielectric constants of air and soil mediums, \( \bar{n} \) is the unit outward normal to the surface, \( \vec{J} = \bar{n} \times \vec{H} \), the equivalent surface electric current density, and \( \vec{K} = -\bar{n} \times \vec{E} \) is the equivalent surface magnetic current density.
The Green functions defined in cylindrical coordinates by the zeroth order Hankel function of the second kind:

\[ G_i = -\frac{j}{4} H_0^{(2)}(k_i |\vec{\rho} - \vec{\rho}'|), i = 1, 2 \] (14)

For horizontal polarisation, the resulting integral equations can then be transformed into a matrix system, of the form given in the following expression:

\[
\begin{bmatrix}
Q^{11} & Q^{12} \\
Q^{21} & Q^{22}
\end{bmatrix}
\begin{bmatrix}
E_x \\
J_y
\end{bmatrix}
= 
\begin{bmatrix}
E_x' \\
0
\end{bmatrix}
\] (15)

Details of the various matrix terms are given by [30].

By solving for this system, the electrical field and electrical density can be estimated over the studied surface. The backscattered electric field is computed from:

\[
E_x' = -\int c \left[ j \omega \mu_0 G_t J_y + E_y (\vec{n}' \nabla G_i) \right] \, dl' ,
\] (16)

and the backscattered signal can then be written as:

\[
\sigma^0 = \frac{2 \pi \rho}{P L_{\text{eff}}} \left[ \sum_{j=1}^{P} \left| E_j^s \right|^2 - \frac{1}{P} \left( \sum_{j=1}^{P} E_j^s \right)^2 \right]
\] (17)

Where \( L_{\text{eff}} \) is the effective illumination length of the antenna pattern.
For the vertical polarisation, the approach is similar, requiring only minor modifications [30].

Based on convergence of numerical computations, the profile length is assumed to be longer than twenty correlation lengths (or wavelengths). The number of profiles is sufficiently high to ensure that the backscattered signals are estimated with a high precision. In the present analysis, we used 250 profiles, and the soil cells used for numerical sampling were considered equal to \( \lambda/10 \), where \( \lambda \) is the wavelength of the radar signal.

**B. Influence of clods on the backscattering behaviour**

In this section, we study the soil’s backscattering characteristics, as a function of the presence of clods on top of an exponentially correlated surface, using the simulation algorithm proposed in section III-A. Numerical computations are realized directly over generated surfaces. As shown in Figure 5, scattering simulations based on the moment method are performed for two examples, with three types of surface. Firstly, exponential substrate profiles are simulated without clods \( (s = 5\text{mm}, \ l = 80\text{mm}, \text{and} \ s = 7\text{mm}, \ l = 80\text{mm}) \) and secondly, the same substrate profiles are simulated with the addition of two different clod distributions: mean clod sizes of \( Sc = 17\text{mm} \) and \( Sc = 34\text{mm} \), and identical characteristic inter-clod distances, i.e. \( Dc = 100\text{mm} \). The simulations are carried out in the C band \( (5.3\text{GHz}) \), for both polarisations, with a large range of incidence angles: from 0 to 60 degrees. The influence of the clods is clearly visible. When the clod size is increased, the backscattered radar signal level increases for all incidence angles. For example, we find a difference of approximately 11.5 dB, at
40 degrees in HH polarisation, between surfaces without clods (exponentially correlated profile only, with \( s = 5 \text{mm} \) and \( l = 80 \text{mm} \)), and surfaces with the largest clods on top of the same exponential substrate. Figure 5 also shows that the presence of clods leads to a reduction in the difference between backscattered power in the vertical and horizontal polarisations, for example from 6 dB to 2.4 dB at 40° incidence, for the same surfaces.

Figure 6 provides two examples, using different characteristic inter-clod distances: \( (D_c = 100 \text{mm}, \text{ and } D_c = 57 \text{mm}) \), assuming the same clod size \( (Sc = 34 \text{mm}) \), for the two exponentially correlated profiles described in Figure 4 \( (s = 5 \text{mm}, \text{ and } s = 7 \text{mm}, \text{ and } l = 80 \text{mm}) \). The simulations show firstly a decrease in backscattering signal, with increasing inter-clod distance. We observe, for example, a difference of approximately 3 dB between these two inter-clod distances, for the case of the first exponentially correlated profile, at HH polarisation and high incidence angles.

The simulations also reveal increased backscattering signal oscillations, as a function of incidence angle, for small inter-clod distances. This effect is due to the presence of a more complex distribution of local surface slopes, with higher slopes for the surfaces with smaller inter-clod distances. Figure 7 presents three slope distributions, for the three surfaces corresponding to: exponential substrate profile only, and the exponential substrate with two different inter-clod distance distributions. The slope distribution is computed using mean local values computed for 5mm cell sizes.

C. Analysis of backscattering behaviour difference as a function of surface generation method
In this section, having analysed the contribution of the clods to the backscattering signal, we investigate the role of the type of surface description on the computed signal level, by comparing the classical approach (based on an exponential description) with that including the presence of clods.

This comparison is carried out in different steps:

- firstly, we generate various cloddy surfaces as described above, from which we compute the correlation function, and corresponding $rms$ height and correlation lengths,

- secondly, we generate correlated surfaces with the same roughness characteristics: correlation function, $rms$ height and correlation length estimated from generated surfaces, as described in section II-C.

- lastly, we compare the backscattering simulations derived from the surfaces generated by these two different methods.

The numerical simulations for the HH and VV polarisations are illustrated in Figure 8, for the two studied exponential substrate profile examples ($s = 5\text{mm}$, $l = 80\text{mm}$, and $s = 7\text{mm}$, $l = 80\text{mm}$), and for the same substrates with a cloddy distribution characterised by $Sc = 34\text{mm}$, and $Dc = 100\text{mm}$. For each of these cases, and for almost all incidence angles, the backscattering coefficient is over-estimated when the simulated surfaces are those with no representation of the cloddy structure. This over-estimation, by about 1 to 2 dB, is almost invariant as a function of incidence angle for the HH polarisation. For the VV polarisation, the backscattering coefficient is also
over-estimated, except at low incidence angles, below 10°. This observed difference in backscattered signal strength is due, in particular, to the assumption (or not) of a surface description based on only one horizontal scale parameter (the correlation length). This result could provide one explanation of over-estimation of Integral Equation Model often observed in comparison with real radar data over agricultural soils ([15]-[32]).

IV. Conclusion

In the present paper, we propose a new approach for the description of surface roughness in backscattering behaviour. This is found to be more appropriate for the modelling of cloddy agricultural soils, which have become increasingly common in recent years. The developments are based on a numerical algorithm using the moment method, and assume composite surfaces with clods, on top of exponentially correlated substrate profiles. The clods are characterised by two Gaussian distributions, based on two parameters: the characteristic clod size, and the characteristic distance between clods.

Firstly, we observe that the introduction of clods leads to a decrease in the correlation length of the generated surfaces, relative to that of the exponential correlation profiles alone. This influence of cloddiness on the correlation length has often been observed in agricultural soils with small experimental correlation lengths.

Through numerical modelling of simulated surfaces, we observe that an increase in clod size induces an increase in backscattered signal level, in both HH and VV polarisations, at medium and high incidence angles. It also leads to a reduction in the difference between
backscattered power for the VV and HH polarisations. A decrease in the average distance between clods leads to an increase in the simulated backscattering coefficient, for medium and high incidence angles, and to increased oscillations (backscattered power variations) as a function of incidence angle.

We have compared the backscattering levels, resulting from the proposed surface generation method, with those found using the more ‘traditional’ approach.

Soil surfaces, making use of a correlation function only, have been generated to match those simulated with cloddy characteristics. Numerical backscattering simulations for the different tested surfaces show that the signal is often over-estimated, for surfaces created using this classical approach.

This over-estimation can be explained, in particular, by the use of a single equivalent ‘horizontal correlation length’ roughness parameter, which is strongly reduced from that of the slightly rough background terrain by the presence of clods.

The proposed roughness description and numerical simulations clearly show the significance of clods in backscattering simulations. In forthcoming studies, this analysis will be validated by experimental campaigns over different types of agricultural soils.
References


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Figures

Figure 1: Illustration of three examples of cloddy soils

Figure 2: Surface generation based on an exponential correlation function \((s = 8\text{mm}, l = 80\text{mm})\)

Figure 3: Composite surfaces generated by adding clods to an exponentially correlated ‘substrate’ surface.

Figure 4: Correlation functions calculated for computer-generated cloddy surfaces.

Figure 5: Simulation of backscattering coefficients, using the moment method, for simulated cloddy surfaces, based on two different exponentially correlated profiles \((s = 5\text{mm}, l = 80\text{mm} \text{ and } s = 7\text{mm}, l = 80\text{mm})\), and clod with two different clod size distributions.

Figure 6: Simulation of backscattering coefficients, using the moment method, for simulated cloddy surfaces, based on two exponentially correlated profiles \((s = 5\text{mm}, l = 80\text{mm} \text{ and } s = 7\text{mm}, l = 80\text{mm})\), and clod with two different clod distance distributions.
Figure 7: Illustration of the surface slope distributions corresponding to various surface characteristics.

Figure 8: Comparison between computed backscattering coefficients for simulated cloddy surfaces, and for equivalent surfaces simulated by correlation function statistics.
Figure 1
Figure 2
Figure 4
HH polarisation
- exponential profile (s=5mm, l=80mm)
- exponential profile and clods (Sc=17mm, Dc=100mm)
- exponential profile and clods (Sc=34mm, Dc=100mm)

VV polarisation
- exponential profile (s=5mm, l=80mm)
- exponential profile and clods (Sc=17mm, Dc=100mm)
- exponential profile and clods (Sc=34mm, Dc=100mm)

Figure 5
HH polarisation

- exponential profile ($s=7\text{mm}, l=80\text{mm}$)
- exponential profile and clods ($Sc=34\text{mm}, Dc=100\text{mm}$)
- exponential profile and clods ($Sc=34\text{mm}, Dc=57\text{mm}$)

VV polarisation

- exponential profile ($s=7\text{mm}, l=80\text{mm}$)
- exponential profile and clods ($Sc=34\text{mm}, Dc=100\text{mm}$)
- exponential profile and clods ($Sc=34\text{mm}, Dc=57\text{mm}$)
Figure 6

Incidence angle (degrees)
Backscattering coefficient (dB)
Figure 7

- exponential profile (s=7mm, l=80mm)
- exponential profile and clods (Sc=34mm, Dc=100mm)
- exponential profile and clods (Sc=34mm, Dc=57mm)
HH polarisation

exponential profile (s=5mm, l=80mm) and clods (Sc=34mm, Dc=100mm)

simulated profile (s=9.2mm, l=28mm)

VV polarisation

exponential profile (s=5mm, l=80mm) and clods (Sc=34mm, Dc=100mm)

simulated profile (s=9.2mm, l=28mm)
Figure 8