Microwave response of rough surfaces with auto-correlation functions, RMS heights and correlation lengths using active remote sensing

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The radar backscattering coefficient of three types of soil surfaces at observation angles (10°- 60°) have been calculated using integral equation model (IEM) for different values of root mean square (RMS) roughness heights and correlation lengths. The surfaces are represented by isotropic autocorrelation functions (exponential, 1.5 power and Gaussian). The dielectric constant ($\varepsilon$) of the soil, an input parameter for the calculation of backscattering coefficient by IEM model, has been determined using wave guide cell method at a single microwave frequency of 9.78 GHz and room temperature 34°C. A positive correlation has been observed between co-polarized (horizontal - horizontal) radar backscattering coefficient and RMS roughness height of the soil surface. Further, the radar backscattering coefficient of soil surface decreases as the angle of observation increases. The variation of backscattering coefficient with correlation length of surface depends on the auto-correlation function and observation angle.

\textbf{Keywords:} Surface roughness, Autocorrelation function, Backscattering coefficient, Correlation length, RMS roughness height

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1 Introduction

Active microwave remote sensing describes the surface characteristics through backscattering coefficient ($\sigma^0$) of a particular surface. Surface roughness is one of the important target characteristics that influence the strength of backscatter. The backscattering response is mainly dependent on: (i) surface roughness, (ii) vegetation cover, (iii) radio frequency interference, (iv) atmospheric conditions, and (v) ionospheric disturbances. But at X-band microwave frequencies, surface roughness is a major limiting factor for active microwave remote sensing inferences. Because active sensors have the capability to provide high spatial resolution of the order of tens of meters and are more sensitive to surface roughness, topographic features and vegetation than passive systems\textsuperscript{1,2}. To obtain genuine inference from remote sensing observations, the removal of perturbing effects are essential. Since, it is difficult to develop a removal method without the knowledge of surface characteristics. According to the theory of remote sensing, $\sigma^0$ is the function of geometrical and dielectric properties of the target and sensor properties like frequency and polarization of microwaves. The backscattering coefficient of a non-periodic random surface can be expressed as the product of two functions\textsuperscript{3} as given by the equation:

$$\sigma^0 = f_s(\varepsilon),f_r(\rho(\xi),\theta)$$  \hspace{1cm} (1)

where, $f_s(\varepsilon)$, is the dielectric function; and $f_r(\rho(\xi),\theta)$, the roughness function with $\xi$ and $\theta$, the roughness character of the surface and observation angle, respectively. Soil roughness can be considered as a stochastic varying height of the soil surface towards a reference surface. This reference surface can either be unperturbed surface of a periodic pattern or mean surface if only random variations exist. Surface roughness characteristics generally have been described in terms of three important parameters, namely:

(i) RMS surface height or standard deviation of height ($\sigma$);
(ii) Roughness correlation length ($l$); and
(iii) A correlation function ($\rho$) of rough surface.

The $\sigma$ and $l$ are statistical parameters commonly used in the description of surface roughness and correspond to the vertical-scale roughness and horizontal-scale roughness, respectively and their ratio is proportional to the RMS slope of the surface.
1.1 Roughness characteristics of soil surface

1.1.1 RMS surface height

The root mean square (RMS) height describes the variation in surface elevation above an arbitrary plane. Obviously, the greater spread of height measurements means the greater value of RMS height. It represents the standard deviation of the distribution of surface heights. Thus, it is an important parameter to describe the surface roughness by statistical methods. This parameter is more sensitive than the arithmetic average height. It is an estimation of the variance of the vertical dimension in the test surface. For discrete one-dimensional surface roughness profiles consisting of surface height $Z_i$, the RMS height $\sigma$ is calculated using Eqs (2) and (3):

$$\sigma = \sqrt{\frac{1}{N} \sum_{j=1}^{N} z_i^2 - N\bar{z}^2} \quad \ldots(2)$$

where, $\bar{z} = \frac{1}{N} \sum_{i=1}^{N} z_i \quad \ldots(3)$

The RMS height (σ) of a surface can be measured by pin profilometer for agricultural areas and its value generally is in the range 0.25 cm (sown fields) - 4.0 cm (ploughed fields). In the present investigations, the RMS height and correlation length of soil surface have not been measured experimentally, but the values determined by other workers for agricultural soils have been used.

1.1.2 Correlation length

Correlation length describes the uniformity of the height over finite distances along the surface. The maximum distance over which significant correlation occurs is known as correlation length ($l$). In other words, the correlation length can be defined as the distance between two statistically independent points. For natural surfaces, as the distance increases, autocorrelation decreases. It gives us a measure of the slope of the terrain. In radar scattering models, the roughness of surfaces is defined as the ratio of RMS height $\sigma$ to autocorrelation length $l$ or some variant of this ratio. Campbell & Gravin suggested that this ratio is termed as effective slope of the surface. Hence, autocorrelation can be used to measure the slope of the terrain. Smoother surfaces generally have large correlation lengths while rougher surfaces have low values of correlation lengths. A profile of white noise (perfectly rough surface such that two nearly located points have not any correlation) has correlation length equal to zero while a straight horizontal line has correlation length equal to infinity. The correlation length ($l$) describes the horizontal distance over which the surface profile is autocorrelated with a value larger than $1/e$ $(\approx 0.368)$. Correlation length in agricultural areas generally varies from 2.0 to 20.0 cm. Using a 1-m profiler, Álvarez-Mozos et al. measured average correlation lengths in the range 2.44 (for rolled surfaces) - 7.41 cm (for ploughed fields). For radar remote sensing studies, the laser profiler is the non-contact technique that is mostly used for measuring the RMS height (σ) and the correlation length ($l$) (ref. 11).

1.1.3 Autocorrelation function

If the surface roughness is independent of the view direction, the correlation coefficient is said to be isotropic, depending on a single parameter ($\xi$). The normalized autocorrelation function (ACF) for lag ($\xi$) is related to the spatial resolution of the profile and is given by Eq. (4):

$$\rho(\xi) = \frac{\sum_{i=1}^{N-j} z_i z_{i+j}}{\sum_{i=1}^{N} z_i^2} \quad \ldots(4)$$

where, lag($\xi$) represents a roughness character of a step of surface or segment. For isotropic surfaces, $\xi$ is a function of a single horizontal parameter $x$ or $y$. Generally for real surface, $\xi$ is a function of $x$ and $y$. Thus, $\xi = j\Delta x$, where, $\Delta x$ is the spatial resolution of the profile, and $j$ is particular number of profile of extended surface.

The ACF can be calculated as the inverse Fourier transformation of the power spectral density. In backscatter models, often two types of ACFs are used, i.e. exponential and Gaussian. The exponential ACF describes the smooth natural surfaces while the Gaussian ACF correlates rough surfaces and the 1.5 power ACF is an important roughness function suitable for real surfaces. The roughness spectrum of the surface $W^{(n)}$ is the Fourier transformation of the $n$th power of the surface autocorrelation function $\rho(\xi)$.

$$W^{(n)}(k) = \int \rho^n(\xi) J_0(K\xi) d\xi \quad \ldots(5)$$
where, \( J_0 (K \xi) \), is the zero-order Bessel function. The surface correlation function\(^{13} \) \( \rho(\xi) \) with exponential distribution is given by \( \rho(\xi) = \exp\{-(\xi/\ell)\} \) or \( p(x, y) = \exp\{-(x^2+y^2)/\ell^2\} \) and the surface correlation with Gaussian distribution is given by \( \rho(\xi) = \exp\{-(\xi/\ell)^2\} \) or \( p(x, y) = \exp\{-(x^2+y^2)/\ell^2\} \). Here, \( \ell \) is correlation length.

The three commonly used autocorrelation functions for natural surfaces with corresponding roughness spectrum are given in Table 1. For agricultural fields, however, different studies reveal that the ACF was well approximated by exponential correlation functions. Wegm"uller et al.\(^{14} \) have shown that the exponential correlation function usually gives a better agreement with the observed correlation function than the Gaussian correlation function for agricultural fields. The observed correlation function for natural surfaces is Gaussian while for agriculture surfaces, it is exponential. The surface roughness, described in the present study, is defined as the topographic expression of surface at horizontal and vertical scale of millimeters to a few centimeters. These are the scales with which the agriculturists are most familiar. The same scales also have the greatest effect on the behaviour of scattered microwaves in active microwave remote sensing. The relationship between roughness and environmental variables such as tillage and soil texture has been extensively studied in past\(^{15} \). For smooth surfaces, geometrical variation of surface irregularities and volume discontinuities are small in comparison to wavelength of microwaves. The roughness of agricultural soil surfaces is in decimeter to millimeter range. The roughness of the order of millimeter to decimeter range has the greatest effect on the behaviour of scattered microwaves (radar) and is therefore, of interest to interpret radar remote sensing data of agriculture. Thus, the present study on the effect of surface roughness at X-band microwave frequencies will be useful for agricultural purposes in the microwave remote sensing.

### 1.2 Backscattering models and their validity

Three different modeling approaches have been presented in the literature for the calculation of radar backscattering coefficients (\( \sigma^b \)), viz. empirical, semi-empirical, and theoretical. The empirical and semi-empirical backscattering models may not be applicable for data sets other than those used in their development. Hence, the lack of consistency and universality in their applications is observed. Theoretical backscattering model is derived from the theory of electromagnetic wave scattering from a randomly rough conducting surface. Thus, the theoretical backscattering models are preferable than empirical and semi-empirical backscattering models because theoretical backscattering models provide site independent relationships that are valid for different sensor configurations and the effects of different surface parameters on backscattering are taken into account. Hence, inspite of their complexity, only theoretical models can yield a significant understanding of the interaction between the electromagnetic waves and the earth’s surface. The standard theoretical backscattering models are the Kirchhoff Models (KM) which consists of the Geometrical Optics Model (GOM), Physical Optics Model (POM) and the Small Perturbation Model (SPM). The scattering pattern of an SPM surface is dominated by the coherent component, whereas the patterns for a KM surface are dominated by the diffuse (incoherent) component. The small perturbation approximation requires small surface RMS height and slope with respects to the wavelength. So, that for a smooth surface, whose standard deviation and correlation length are much smaller than the wavelength, the Small Perturbation Model (SPM) can be used to estimate the backscattering contribution. These models having different validity restrictions for the frequency and roughness ranges concerned are given in Table 2. These two models, which are commonly used to calculate surface scattering, involve limited domains of applicability. Because according to the validity conditions of other theoretical backscattering models, the GOM is best suited for very rough surfaces, POM is suited for surfaces with intermediate roughness while and SPM is suited for surfaces with small roughness\(^{16} \). Thus, no single model is applicable for all types of rough surfaces. Hence, these models have limited domains of applicability.

### Integral equation model (IEM), developed by Fung et al.\(^{17} \), is a backscattering model for scattering from a randomly rough surface.
randomly rough dielectric surface that is based on an approximate solution of a pair of integral equations for the tangential surface fields. The IEM unite the KM and SPM. Hence, IEM is applicable to a wider range of roughness conditions or frequencies. In its complete version, the model describes the backscattering behaviour of a randomly rough and bare surface without any limitation on the roughness scale or frequency range and accounted for both the single and the multiple surface scattering of a rough surface. Hence, the IEM circumvents the limitations or restrictions on GOM, POM and SPM. As most natural terrains have a small height, it has been suggested by Fung et al.\(^{17}\) that the single scattering terms should dominate over multiple scattering terms in most of the situations. So, neglecting the multiple scattering and assuming surface correlation function to be isotropic, an approximate version of the IEM is possible. This is valid for surfaces with small to moderate surface RMS heights and is useful for the most of the natural surfaces. The validity expression for this model may be expressed\(^ {17}\) as \(k_0\sigma < 3\), where \(k_0 = 2\pi/\lambda_0\) is the free space wave number, and \(\lambda_0\) the free space wavelength (cm).

In the present investigations, backscattering coefficient of bare soil surface has been calculated using approximate version of the IEM. Because of its complexity, it is not practical to use the complete version of the IEM and hence, in applications, the approximate solutions are frequently considered, as used by Altese et al.\(^{18}\) which is valid for surfaces with small to moderate surface RMS heights. Altese et al.\(^{18}\) used only the single scattering component of the IEM and further, made simplified assumptions by using only the real part of the relative permittivity with the assumption that the surface correlation function is isotropic and can be represented by either the Gaussian or exponential models. In the present study, the three values of RMS heights used are: \(\sigma = 0.15, 0.31\) and 0.62 cm and the value of correlation length varies from 1 to 3 cm. The autocorrelation functions for surfaces, used in the present study, are represented by the exponential, Gaussian and 1.5 power. For these ACFs, the roughness spectrum is computed analytically using Eq. (5). The roughness spectrum of the surfaces (\(W^m\)) is the Fourier transformation of the \(n^{th}\) power of the surface isotropic autocorrelation function \(\rho(\xi)\). But in general, the real surfaces do not follow such simple functions and the spectrum must be computed numerically. The possibility of performing the numerical integration due to the oscillating characteristics of \(J_n(2k_0\sigma\cos\theta)\) has been rejected.

In IEM, roughness spectrum \(W^n(-2k_0\sin\theta, 0)\) is required. Thus, \(W^n(-2k_0\sin\theta, 0)\) is calculated by Eq. (6) as used by other researchers\(^5\):

**Roughness spectrum,**
\[
W^n(-2k_0\sin\theta, 0) = (l/\lambda_0)^2 [1 + (k_0l/\lambda)^2]^{-1.5}
\]  …(6)

\(W^n(-2k_0\sin\theta, 0)\) has been calculated for the values of \(n\) varying from 1 to 7, followed by summation and used in IEM equation. The real surfaces can not be defined by such simple isotropic autocorrelation functions and the spectrum may be computed numerically for real surfaces. Hence, in the present study surfaces defined by different functions have been considered.

2 Experimental procedure and Theory

The real and imaginary parts of dielectric constant (\(\varepsilon'\) and \(\varepsilon''\)) of soil at 34°C have been determined for a terrain characterized by fairly standard values of volumetric moisture (0.030) and dry soil density (1.39 g m\(^{-3}\)) at a single microwave frequency 9.78 GHz in Alwar district. The fractions of sand and clay are equal to 58.5 and 12.8%, respectively. Dielectric constant (real and imaginary parts) of the soil are measured using shift in minima of the standing wave pattern inside the slotted section of a X-band rectangular wave guide excited in TE\(_{10}\) mode. The experimental set up, theory and procedure for the present work is the same as used earlier by other researchers\(^{19-20}\). The dielectric constant (\(\varepsilon'\)) and dielectric loss (\(\varepsilon''\)) of soil samples have been determined using Eqs (6) and (7), respectively:
\[ \varepsilon^\prime = \left( \frac{\lambda_0}{k_0} \right)^2 + \left( \frac{\lambda_0}{k_\sigma} \right)^2 \left[ 1 - \left( \frac{\alpha_d}{\beta_d} \right)^2 \right] \]  \hspace{1cm} \ldots (7)

\[ \varepsilon^* = 2 \left( \frac{\lambda_0}{k_0} \right)^2 \left[ \frac{\alpha_d}{\beta_d} \right] \]  \hspace{1cm} \ldots (8)

where, \( \lambda_0, \lambda_\sigma, \) and \( k_\sigma \) are the free space wavelength, cut off wavelength \( (\lambda_\sigma = 2a) \) and wave length in the dielectric medium, respectively for the wave-guide excited in TE\(_{10}\) mode; \( \alpha_d, \) the attenuation introduced per unit length (napers per meter) of the material inside the wave-guide; \( \beta_d, \) the phase shift introduced by per unit length of the material (in radian per meter).

Magnitude of the complex dielectric permittivity of the soil is given by Eq. (9):

\[ \varepsilon_r = |\varepsilon^\prime| = |\varepsilon^\prime - j \varepsilon^\prime| \]  \hspace{1cm} \ldots (9)

The IEM\(^{17}\) used for the backscattering coefficient (horizontal-horizontal) is given by Eqs (10-14):

\[ \sigma^0_{pq} = \frac{k_0^2}{2} \exp(-2k_\sigma^2\sigma^2) \sum \sigma^2 n |I^n_{pq}|^2 \frac{w^n}{n!} \]  \hspace{1cm} \ldots (10)

where, \( \sigma^0_{pq} \) is polarized backscattering coefficients; \( \sigma \) the RMS surface height; \( k_0, \) free space wave number; \( k_\sigma \) and \( k_{x_0}, \) the z component and \( x \) component of the free space wave number given by \( k_\sigma = k_0 \cos \theta \) and \( k_{x_0} = k_0 \sin \theta, \) respectively having \( k_0 = 2\pi/k_0 \) (free space wave number of microwaves). The quantity \( w^n \) is the surface spectrum corresponding to Fourier transform of the surface correlation coefficient raised to its \( n \)\(^{\text{th}} \) power. The quantity \( |I^n_{pq}| \) is the function of the incidence angle, dielectric constant of the soil and the Fresnel reflection coefficient and is given by Eq. (11):

\[ |I^n_{pq}| = (2k_\sigma)^n f_{pq} \exp(-\sigma^2k_\sigma^2) + k_\sigma^n |F_{pq}(-k_{x_0},0) + F_{pq}(k_{x_0},0)| \]  \hspace{1cm} \ldots (11)

where, \( n \), has values varying from 1 to 7 and summation is taken for the values of \( n \). As the value of \( n \) increases, the RHS of Eq. (11) diminishes quickly, so it is sufficient to use the values of \( n \) upto 7.

The first term of the Eq. (11) is the Kirchhoff’s term; and the second term is the complementary term. Horizontal-horizontal polarization, the Kirchhoff coefficient \( f_{pq} \) and complementary filed coefficient \( F_{pq} \) are obtained by Eqs (12) and (13), respectively

\[ f_{hh} = -\frac{2R_h}{\cos \theta} \]  \hspace{1cm} \ldots (12)

\[ F_{hh}(-k_{x_0},0) + F_{hh}(k_{x_0},0) = -\frac{2\sin^2 \theta (1 + R_h)^2}{\cos \theta} \]  \hspace{1cm} \ldots (13)

where, \( \varepsilon_r, \mu_r \) and \( \theta \) are the relative permittivity, relative magnetic permeability and observation angle, respectively. \( R_h, \) the horizontal Fresnel reflection coefficients, is given by the Eq. (14) as:

\[ R_h = \frac{\cos \theta \sqrt{\varepsilon_r - \sin^2 \theta}}{\cos \theta + \sqrt{\varepsilon_r - \sin^2 \theta}} \]  \hspace{1cm} \ldots (14)

The two terms in the \( |I^n_{pq}| \) together provide a very good estimate of the induced field on the surface and lead to a backscattering coefficient that is in good agreement with the small perturbation model in the low frequency region. In the high-frequency region, the contribution from the complementary term becomes negligible and the backscattering coefficient provides good agreement with the Kirchhoff model. \( \mu_r \) is usually equal to unity for soil. Because, in the low frequency region\(^{12}\), the Kirchhoff’s term is negligible and complimentary term becomes important, while in high frequency region, the complimentary term becomes negligible and Kirchhoff’s term becomes important and thus, the backscattering coefficient is in good agreement with Kirchhoff’s model making first term important\(^{12}\).

Behaviour of the IEM is highly dependent on the choice of the correlation function. For the roughness spectrum, Fourier transform of the \( n \)\(^{\text{th}} \) power of Gaussian, exponential and 1.5 power correlation functions have been used in this study. In the present work, the local angle in the Fresnel reflection coefficient in the complementary field coefficients \( (F_{hh}) \) has been approximated by the incident angle (flat surface approximation). Fung\(^{12}\) has shown that the approximation by the incident angle is good for the low to intermediate frequency regions.
Actually, the angle of incidence depends on the slope of the scattering surface. Inclined surfaces imply an elevated horizon with variation depending on the azimuth. The local angle of incidence of an inclined surface depends on the orientation of the surface with respect to the view direction of the sensor. Transformation from the global to the local plane of incidence affects both the scattering geometry and the polarization. The local angle of incidence \( \theta_l \) given by Robinson can be written as Eq. (15):

\[
\cos \theta_l = \cos \theta \cos \alpha + \sin \theta \sin \alpha \cos (\phi - \beta)
\]  

(15)

where, \( \theta_l \) is the local angle of incidence; \( \alpha \), the slope of the facet or pixel; \( \theta \), is incident angle of the remote sensing system defined as the angle between the sensor and the normal to the horizontal surface; \( \phi \) the actual flight track of the remote sensing system which is same as the azimuth direction of the satellite; \( \beta \) the aspect angle of the inclined surface. The variables \( \phi \) and \( \beta \) are defined to be zero towards the north and increases in counter clockwise direction.

The local observation angle takes into account the local slope of the terrain in relation to the radar direction. This is the angle between the normal direction on inclined surface and the radar direction. Surface normal \( \hat{n} \) used to define as perpendicular on the plane of incidence deviates from the vertical direction by a slope angle \( \alpha \), oriented by an aspect angle \( \beta \). While studying about the topography of a surface, the important surface analysis functions are slopes \( \alpha \) and aspect \( \beta \). The slope is defined as the topographic gradient in the direction of steepest descent and aspect is the cardinal direction of steepest descent. The observation direction or satellite sky position may be described by zenith or observation angle \( \theta \) and azimuth angle \( \phi \).

Fung noted that for dielectric surfaces, there are two approximations that have been made to the local angle in the Fresnel reflection coefficients \( R_h \) and \( R_v \) to be used in the Kirchhoff coefficient \( f_{pq} \) of IEM. One approximation replaces the local angle by the incident angle and the other by the angle along the specular direction. The local angle in the Fresnel reflection coefficients in the complementary field coefficients \( F_{pq} \) is always approximated by incident angle. Fung has shown that the approximation by the incident angle is good for low to intermediate frequency regions while the other approximation is good at high frequencies.

3 Results and Discussion

The backscattering coefficients \( \sigma_{hh}^0 \) computed for the co-polarized (horizontal-horizontal) microwaves at different view angles (sensor position) varies from 10° to 60° for three surfaces at RMS heights (\( \sigma = 0.15, 0.31, 0.62 \) cm) and correlation lengths (\( l = 1.0, 2.0, 3.0 \) cm) have been shown in Figs (1-3). \( \sigma_{hh}^0 \) is computed for the co-polarized (horizontal-horizontal) microwaves only to avoid the discrepancy in the calculation of \( \sigma_{hv}^0 \) (Brewster angle), \( \sigma_{vh}^0 \) (polarization mixing).

An intense examination of Figs (1-3) leads to the following inferences:

(i) The backscattering coefficient (\( \sigma \)) decreases as the angle of observation increases for all values of RMS heights and correlation lengths of surfaces. This is because of the fact that for small levels of roughness, at low observation angles, the contribution of the coherent component to the backscattering is found dominant and this contribution diminishes.

Fig. 1 — Variations of \( \sigma_{hh}^0 \) with observation angle at RMS heights (0.15, 0.31 and 0.62 cm) and correlation lengths (1, 2 and 3 cm) for exponential surfaces.
as the angle of observation increases. Hence, $\sigma^0$ decreases with increasing angle of observation.

(ii) $\sigma^0$ increases as the RMS height of surface increases for all three types of surfaces (exponential, 1.5 power and Gaussian) and at all values of correlation length ($l = 1, 2$ and $3$ cm) and always exist in the order $\sigma^0(0.62) > \sigma^0(0.31) > \sigma^0(0.15)$. The reason behind this behaviour is that the RMS height of a certain surface is directly proportional to the roughness of the surface. The backscattering coefficient increases as the roughness of the surface increases. The scattering pattern of a rough surface consists of both the specular (coherent component) and the diffused (incoherent) component. Smooth surfaces behave as specular reflectors and have strong backscattering only at near-zero incidence angles, whereas, rough surfaces act as diffused reflectors. For the surfaces with small levels of roughness at low observation angles, the contribution of the coherent component to the backscattering is found dominant and this contribution diminishes as the angle of observation increases. As the observation angle increases, the backscattering decreases due to contribution of diminished coherent component. Thus, at small levels of roughness the backscattering coefficient decreases as the observation angle increases. Hence, as the RMS height increases, backscattering coefficient ($\sigma^0$) increases because of an increase in incoherent or diffuse component of backscattering and the rough surface becomes lambertian.

(iii) $\sigma^0$ varies with type of correlation function of the surface and with the correlation length in a typical manner. The relation $\sigma^0$ (Gaussian) > $\sigma^0$ (1.5 power) > $\sigma^0$ (exponential) holds at all RMS heights and at correlation length $l = 1$ cm only. At correlation length $l = 2$ and $3$ cm, the $\sigma^0$ (1.5 power) is greater than $\sigma^0$ (Gaussian) and $\sigma^0$ (Exponential). Gaussian surfaces correspond to rougher surfaces while exponential surfaces correspond to smoother surfaces and exponential surfaces are related to agricultural surfaces having intermediate roughness. Thus, at correlation length $l = 1$ cm, the roughness of the surfaces is in the order of (Gaussian) > (1.5 power) > (exponential). Hence, $\sigma^0$ exist in the order of $\sigma^0$ (Gaussian) > $\sigma^0$ (1.5 power) > $\sigma^0$ (exponential), at correlation length ($l = 1$ cm). But at correlation lengths $l = 2$ and $3$ cm, the roughness of the 1.5 power surface becomes more rough than that of Gaussian and exponential and hence, $\sigma^0$ varies as $\sigma^0$ (1.5 power) > $\sigma^0$ (Gaussian) > $\sigma^0$ (exponential).
(iv) For exponential and Gaussian surfaces at all RMS heights, the variations of $\sigma^0$ with correlation lengths are highly dependent on observation angles. The relation $\sigma^0 (l = 3) < \sigma^0 (l = 2) < \sigma^0 (l = 1)$ holds at higher values of observation angle but at lower values of observation angle, the order $\sigma^0 (l = 1) < \sigma^0 (l = 2) < \sigma^0 (l = 3)$ is obtained. The change in trend of variations of backscattering coefficient $\sigma^0$ with observation angle for certain correlation lengths takes place at lower observation angles. The backscattering coefficient ($\sigma^0$) depends on various factors like surface roughness, RMS height, correlation length, observation angle, etc. Generally, the smooth surfaces have large correlation lengths while rough surfaces have low values of correlation lengths resulting into higher values of backscattering coefficient ($\sigma^0$) at low values of correlation lengths and at higher values of observation angle. But at lower observation angles, the contribution of coherent components backscattering are strong in comparison to incoherent components. The coherent and incoherent components of backscattering respond to coherent length in different manner. Further, at low values of observation angles roughness of surface is not only defined by coherence length and other factors given above but various factors such as micro relief, three dimensional surface geometry, tilt, etc. are also effective.

(v) For 1.5 power surfaces, the variations of $\sigma^0$ with respect to correlation lengths are observed in the manner $\sigma^0 (l = 3) > \sigma^0 (l = 2) > \sigma^0 (l = 1)$. This is due to the reason that for 1.5 power surfaces, the RMS height effect and roughness spectrum have dominant contribution towards backscattering coefficient ($\sigma^0$) resulting into the relation $\sigma^0 (l = 3) > \sigma^0 (l = 2) > \sigma^0 (l = 1)$.

(vi) At higher observation angles ($0 > 50^0$), the $\sigma^0$ decreases slowly with an increase in the RMS height of the surface. The roughness effect is not more significant at high values of observation angle.

There are many factors, like air present, humidity in soil, constituents of soil (minerals and rocks), impurities in soil and texture of the soil (sand, silt and clay) which affect the dielectric parameters of the soil. As Alwar is situated in the region of Aravali mountains, the geographical and climatic conditions of this region are very different. The soil formation in this region is very different due to presence of rocks, salts and other impurities. The vegetation canopy, present in the Alwar region, is different and contributes differently in the soil formation. Thus, the dielectric parameters of soil and vegetation canopy are different, which affect greatly the remote sensing properties of the region. This makes the soil of Alwar region of a special type. Hence, the soil of Alwar has different microwave response.

The parameters like RMS height, correlation length and observation angle are considered to obtain results suitable for agricultural fields of Alwar. The RMS height and correlation length are comparable to the wavelength of X-band microwaves because RMS height and correlation length of agricultural fields vary between millimeters and few centimeters. The X-band microwaves are used in microwave remote sensing of top layer soil. These studies are useful for active microwave remote sensing of agricultural fields.

4 Conclusions

The study is aimed to assess the microwave response of surface roughness of bare agricultural fields using the IEM model. The values used for RMS heights and correlation lengths are best suitable for agricultural fields. The results of this study indicate that $\sigma^0$ increases as roughness of the surface increases. Roughness of surface corresponds to high values of RMS height and low values of correlation length. Further, variations of $\sigma^0$ with respect to correlation length and auto correlation function are interrelated and are dependent on observation angle. The complication in the estimation of $\sigma^0$ increases as surfaces are represented by Gaussian ACF. The $\sigma^0$ decreases as the angle of observation increases. The relationship between RMS height, correlation length and environmental variables such as tillage and soil texture has been extensively studied in the past. Álvarez-Mozos et al.\textsuperscript{10} measured average correlation lengths ranging 2.44 (rolled surfaces) - 7.41 cm (ploughed fields). Similar results were obtained by Davidson et al.\textsuperscript{15}. The correlation length of 1.8 cm to 6.4 cm was measured by Morvan et al.\textsuperscript{24}
for agricultural fields. For agricultural soils, however, different studies show that the ACF was well approximated by exponential correlation functions. In the present work, three values of correlation lengths \( l = 1, 2 \) and 3 cm which are correlated with agriculture fields, have been used. Although, the backscattering coefficient for surfaces defined by Gaussian, exponential and 1.5 power correlation functions have been determined, but the exponential correlation function is related with agriculture fields. The values of correlation lengths and RMS heights for determination of backscattering coefficient are comparable with the X-band microwaves used for the present investigations. Also, roughness parameters used in the study are suitable for agricultural fields. Hence, the present studies are useful for microwave remote sensing applications in agriculture.

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