2. ROUGH SURFACE SCATTERING MODELS

Natural surfaces can be considered as rough, and the roughness is the dominant factor for the scattering behaviour of an EM wave. The roughness of any scattering surfaces is not an intrinsic property of that surface but depends on the properties of a wave being transmitted. Both, the frequency and the local angle of incidence of the transmitted wave, determine how rough or smooth any surface appears to be. The relation of the EM wave in terms of its wavelength λ to the statistical roughness parameter s is given by ks. Thus with increasing wavelength, the roughness term is decreasing, consequently, the indication of relative roughness for any surfaces is depending on the wavelength as $k = 2\pi / \lambda$. Also the local incidence angle plays an important role for defining the roughness condition of a surface. In the near field of the propagating EM wave, the surface appears rougher than in the far field, which can be compared with the reflection of the sunset over the sea. (BECKMANN & SPIZZICHINO 1963).

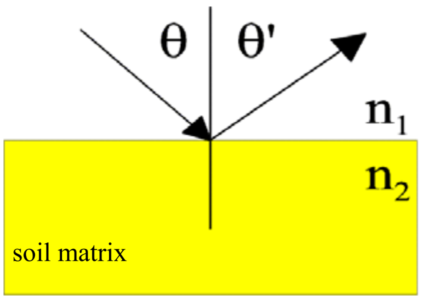


Figure 1 Fresnell reflection scheme

In case of an ideal smooth surface the characteristics of the reflection can be described by the well known Fresnel Reflectivity Γ. The Fresnel Reflectivity, named after the French Engineer and Physicist Augustin Jean Fresnel (1788-1827), characterises the reflection of a transmitted wave at the interface between two dielectric media n, for example the air n_1 and a homogeneous soil n_2. The Fresnel coefficient Γ is a function of the angle of the transmitted θ and reflected wave θ', and the dielectric constant of the scatterer.

$$\Gamma_h(\theta) = \frac{\mu\cos\theta - \sqrt{\mu\varepsilon - \sin^2\theta}}{\mu\cos\theta + \sqrt{\mu\varepsilon - \sin^2\theta}} \qquad \Gamma_v(\theta) = \frac{\varepsilon\cos\theta - \sqrt{\mu\varepsilon - \sin^2\theta}}{\varepsilon\cos\theta + \sqrt{\mu\varepsilon - \sin^2\theta}} \tag{1}$$

where Γ_h and Γ_v is the horizontal and vertical polarisation of the EM wave and μ is always for non-ferromagnetic media, as natural surfaces, equal to one. The response of the horizontal polarisation increases with increasing the local incidence angle. The vertical polarisation decreases to zero at a certain angle, the so called Brewster Angle - the angle under which the transmitted wave is completely absorbed by the dielectric medium - and increases then suddenly with further increase of the local incidence angle.

Considering a constant wavelength and fixed local incidence angle, the interaction of a transmitted EM wave with a surface of different roughness conditions can be in general treated as the rougher the surface, the more diffuse the scattering or the smoother the surface, the more directional the scattering. The Fresnel reflectivity, as described above, considers an ideal smooth surface boundary. In the natural environment the surface condition varies from medium to rough. The backscattered EM wave on a surface consists of two components, a reflected or coherent and a scattered or incoherent one. The coherent component reacts as a specular reflection on a smooth surface and thus in a case of a monostatic radar there is no scatter return. The incoherent component is a diffuse scatterer and distributes the scattering power in all directions. As the surface becomes rougher, the coherent component becomes negligible and the incoherent component consists of only diffuse scattering.

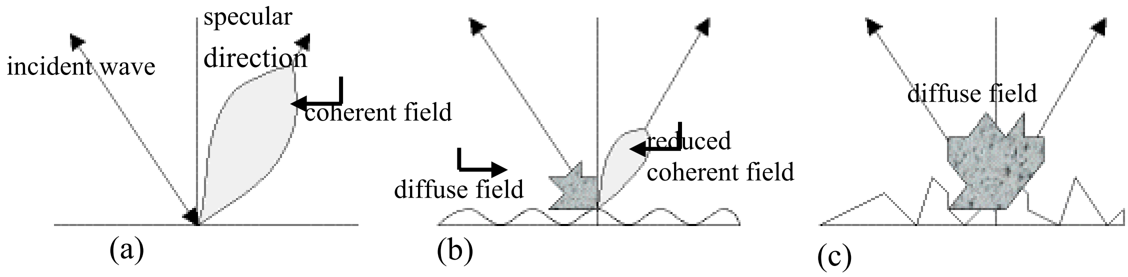


Figure 2 Insérer votre légende. Rates of roughness components demonstrated on a (a) smooth, (b) rough and (c) very rough surface.

Defining a surface from an electromagnetic point of view as smooth or rough, as before mentioned, is obviously somewhat arbitrary. Nevertheless two main criteria can be found to define a smooth surface, the Rayleigh and the Frauenhofer criterion, respectively. Considering a plane monochromatic wave transmitted at some angle θ onto a rough surface (see **Figure 3**), it is a simple matter to calculate the phase difference $\Delta\phi$ between two rays scattered from separate points on the surface:

$$\Delta\phi \quad = \quad 2h\frac{2\pi}{\lambda}\cos\theta \tag{2}$$

where h is the standard deviation of the roughness height regarding to a reference height and θ the local incident angle.

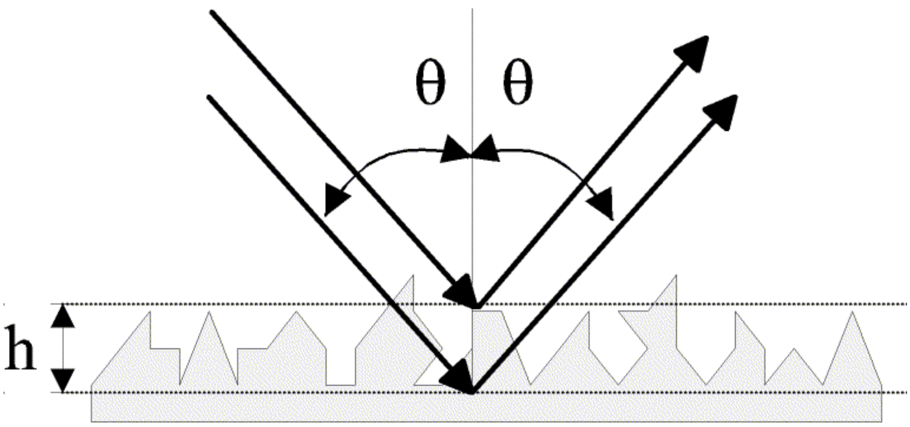


Figure 3 Diagram for determining the phase difference between two parallel waves scattered from different points on a rough surface (SCHANDA 1980).

The Rayleigh criterion states that if the phase difference $\Delta\phi$ between two reflected waves is less than $\pi/2$ radians, than the surface may be considered as smooth, and is defined by (3)

$$h < \frac{\lambda}{8\cos\theta} \tag{3}$$

The usage of a more stringent criterion, which is adapted to the EM wave region, is proposed in ULABY *et al*. (1982) and is called Frauenhofer criterion (4). This criterion considers a surface as smooth, if the phase difference is $\Delta\phi < \pi/8$

$$h < \frac{\lambda}{32\cos\theta} \tag{4}$$

2.1 Theoretical Scattering Models

Electromagnetic (EM) wave scattering on rough dielectric surfaces has been the subject of intensive studies for many decades. Many experimental measurements have been accumulated and many approaches have been developed in order to predict and interpret experimental data. Despite the large amount of research efforts the general surface scattering problem is analytically not completely solved. The following approaches can be categorised as approximate solutions, and hence with a more or less restricted applicability or exact but too general to be of practical importance (BECKMANN & SPIZZICHINO 1963).

One the earliest mathematical formulations of wave scattering from rough surfaces was that of Lord RAYLEIGH (1877). This work leads to the so-called Rayleigh criterion for determining the degree of surface roughness. The scattering of electromagnetic waves from statistically rough surfaces was further investigated by MANDEL'SHTAM (1913) with regard to the molecular scattering of light on liquid surfaces. In the early fifties the field of rough surface scattering began to expand, with FEINBERG (1944 - 1946) investigating the coherent component of scattered electromagnetic waves for small surface height irregularities; RICE (1951) applying his perturbation vector theory for the scattering of electromagnetic waves on a two-dimensional randomly rough surfaces, with DAVIES (1954) developing a simpler theory for scalar waves and ANTOKOL'SKII (1948), BREKHOVSKIKH (1951) and ISAKOVICH (1952) formulating the Kirchhoff tangent plane approximation. Further developments of the theory went along the lines of the *Small Perturbation Approximation (SPM*) and the *Kirchhoff Approximation (KA)* (SILVER 1947, SANCER 1968).

The most often quoted reference book on wave scattering from rough surfaces is that of BECKMANN & SPIZZICHINO (1963), providing a review of wave scattering theory from rough surfaces based on the Kirchhoff solution to the scalar wave scattering problem from periodic and random surfaces. Even though it was written close to half a century ago, this treatise is still concidered today as one of the most valuable text. Another review from BASS & FUKS (1979) considers both perturbation and Kirchhoff theory including more complicated problems such as surface self-shadowing and multiple scales of surface roughness, and provides an excellent summary of Soviet (SSSR) Russian contributions, unknown for a long time in the West. Further reviews on wave interactions with random media – as natural rough surfaces – are included in the books of ISHIMARU (1978) and ULABY *et al*. (1982). A more recent text from OGILVY (1991) provides a good numerical overview of wave scattering from random rough surfaces, and it includes simulation results. Finally, a more updated review of theoretical wave scattering models from random media, their extensions and applications can be found in the treatise by FUNG (1994). Due to the large amount of studies on this subject matter it is impossible to refer to all on what is available in the open literature. Therefore, only these major publications have been referenced in that they provide a good overview of the relevant literature.

As stated already before, the scattering problem of electromagnetic waves from randomly rough surfaces, which has been an actual research topic over decades, is still not satisfactorily solved and no exact closed-form solutions exist hitherto. However, for many practical applications, approximate solutions are sufficient. Various approximate methods for wave scattering at rough surfaces of a more or less general form have been developed. In the field of radar, the most common approximate methods have been the Kirchhoff Approximation (KA) and the Small Perturbation Model (SPM).

The KA is valid when the surface roughness dimensions are large compared to the wavelength, and is therefore more suitable for applications with short wavelengths, as for example at X- or C-band and for large surface correlation lengths ($kl > 6$). In this case, the scattering at a point on the surface may be considered as scattering at the tangential plane to this point. Even with this approximation it is not possible to obtain an analytic solution, and additional assumptions are necessary. Therefore, two modifications of the KA have been addressed: The Geometric Optics Model (GOM) and the Physic Optics Model (POM). The GOM represents the low frequency solution of the KA, the obtained scattering coefficients depend mainly on the surface slope, and is valid for high surface roughness conditions ($ks > 2$). In contrast, the POM represents the high frequency solution of the KA, where the obtained scattering coefficients depend on the surface roughness and the surface correlation length, and it is valid for high surface roughness $ks > 0.25$.

On the other hand, the SPM assumes that the variation in surface height is small compared to the wavelength and is therefore more appropriate for applications with long wavelengths, as at S-, L- or P-band. Although valid only within a limited range of rough surface parameters, it is one of the classical and most widely used solutions of the rough surface scattering. It has been used extensively in many practical applications and the analytic conditions for its validity have been investigated in detail in several studies (BECKMANN & SPIZZICHINO 1963, CHEN & FUNG 1988).

2.1.1.1 Small Pertubation Model

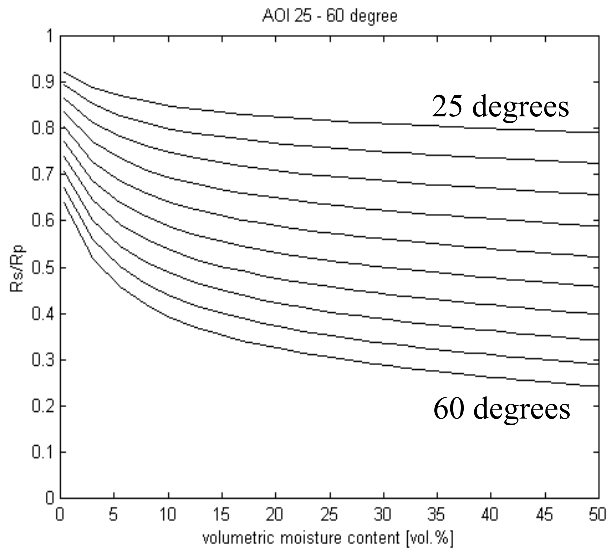
A perfectly smooth surface has zero backscatter at oblique incidence. However, in the Bragg scattering region, where the variation of surface height is small relative to the wavelength (i.e., for *ks* values << 0.3) the presence of roughness can be seen as a perturbation of the smooth surface scattering problem. In this case, the backscatter coefficients are obtained by the small perturbation or Bragg scattering model which is derived directly from Maxwell's equations (OH *et al.* 1992). According to this model, the random surface is decomposed into its Fourier spectral components, each one corresponding to an idealised sinusoidal surface. The scattering is mainly due to the spectral component of the surface which matches (i.e. is in resonance) with the incidence wavelength and angle of incidence (AOI). The scattering matrix [*S*] for a Bragg surface is of the form

$$[S]=\begin{bmatrix} S_{HH} & S_{HV} \\ S_{VH} & S_{VV} \end{bmatrix} = m_s \begin{bmatrix} R_S(\theta, \quad \varepsilon) & 0 \\ 0 & R_P(\theta, \quad \varepsilon) \end{bmatrix} \tag{5}$$

where m_s is the backscatter amplitude containing the information about the roughness condition of the surface, and R_S and R_P are the Bragg scattering coefficients perpendicular and parallel to the incidence plane, respectively. Both are functions of the complex permitivity ε and the local incidence angle θ

$$R_S = \frac{\cos\theta - \sqrt{\varepsilon - \sin^2\theta}}{\cos\theta + \sqrt{\varepsilon - \sin^2\theta}} \qquad R_P = \frac{(\varepsilon - 1)(\sin^2\theta - \varepsilon(1+\sin^2\theta))}{(\varepsilon\cos\theta + \sqrt{\varepsilon - \sin^2\theta})^2} \tag{6}$$

One of the most important statements of the SPM arrives directly from (6), the co-polarised ratio R_s $/R_p$ depends only on the complex permitivity and the local incidence angle, and is independent of surface roughness. **Figure 4** shows the dependency of the co-polarised ratio on the soil moisture content according to (6), for incidence angles ranging from 25 up to 60 degrees. For dry surfaces, the co-polarised ratio is high and decreases with increasing moisture content. A strong variation of the ratio for all incidence angles can be observed for soil moisture values ranging from $0 < m_v < 20$ [vol. %] which saturates for m_v values > 20 [vol %]. This indicates that the SPM is insensitive to very wet surfaces and therefore, its inversion yields prospectively too large uncertainties for moisture content estimates above the saturation level. Several studies have experimentally verified the sensitivity of R_s / R_p to soil moisture content in the case of slightly rough surfaces as well at its saturation above $m_v = 20$ [vol %] (CHEN & FUNG 1988).



e

Figure 4 Modelled co-polarised ratio versus soil moisture

However, for the most natural bare surfaces the validity range for roughness conditions of the SPM is too strict in order to be of practical importance. To demonstrate this, the roughness and moisture content values of all test fields from both test sites, Elbe-Auen and Weiherbach, are shown in **Figure 5**. The roughness values are plotted against the corresponding moisture values, measured in two depths of 0 - 4 cm and 4 - 8 cm. The fact that only one of the test fields lies in the Bragg region, indicates the limited applicability of the SPM for the inversion of surface parameters under realistic conditions in radar remote sensing.

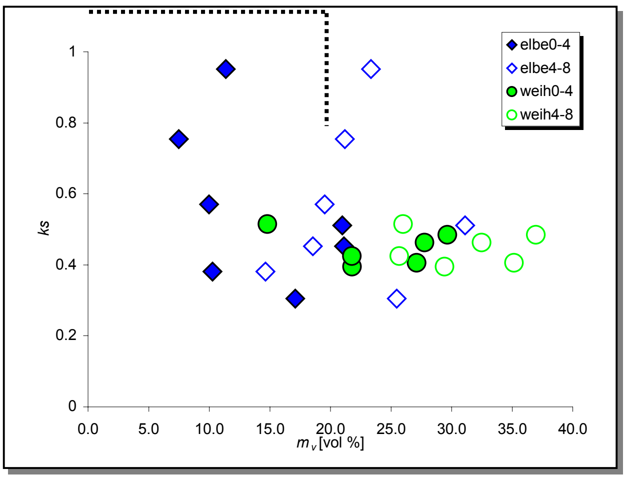


Figure 5 Validity range of the SPM, surface roughness versus soil moisture content, for two experimental data sets, the Elbe-Auen and Weiherbach test sites

2.2 Empirical Models

Semi-empirical and/or empirical approaches are based on theoretical models, which are extended or modified according to physical considerations or empirical observations in order to increase the performance of the original model to interpret experimental data. In this section, two extensions of the SPM used for the inversion of surface parameters from polarimetric radar data will be introduced and discussed. Compared to the SPM, these models are characterised by a wider validity range regarding surface conditions and, as it will be demonstrated, a higher estimation accuracy.

2.2.1.1 The Oh Model

Y. OH, K. SARABANDI, and F.T. ULABY developed this semi-empirical model at the University of Michigan, in 1992. The radar measurements used for its development were obtained by a truck-mounted scatterometer (LCX POLARSCAT) operating at three frequencies (1.5, 4.5 and 9.5 GHz) in a fully polarimetric mode with an incidence angle range from 10° to 70°.

On the basis of the scatterometer measurements and ground measurements, an empirically determined function for the co- and cross-polarised backscatter ratios was proposed (OH *et al.* 1992)

$$p = \frac{\sigma^0_{HH}}{\sigma^0_{VV}} = \left(1 - \left(\frac{2\theta}{\pi}\right)^{\frac{1}{3\Gamma^0}} \cdot e^{-ks}\right)^2 \qquad (7)$$

And

$$q = \frac{\sigma^0_{HV}}{\sigma^0_{VV}} = 0.23\sqrt{\Gamma^0}\left(1 - e^{-ks}\right) \qquad (8)$$

where p and q indicate the co- and cross polarised backscatter ratios, $\frac{\sigma^0_{HH}}{\sigma^0_{VV}}$ and $\frac{\sigma^0_{HV}}{\sigma^0_{VV}}$ respectively; θ the local incidence angle, *ks* is the RMS height normalised to the wavelength, and Γ° the Fresnel reflectivity coefficient at nadir (i.e., $\theta = 0$) and

$$\Gamma^0 = \left|\frac{1-\sqrt{\varepsilon'}}{1+\sqrt{\varepsilon'}}\right|^2 \qquad (9)$$

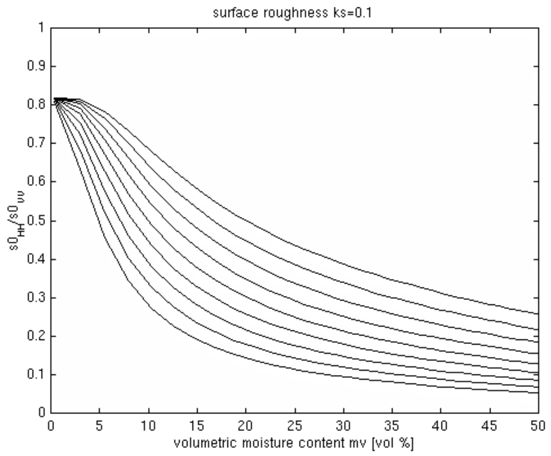
ε' is the relative dielectric constant. For a known angle of incidence, (7) and (8) constitute a system of two non linear equations with two unknowns: *ks* and ε'.

The main characteristics of the model are briefly summarised by the following three points:

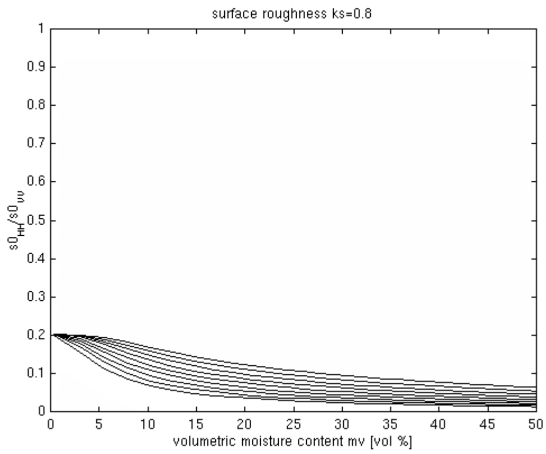
The co-polarised ratio *p is always* lower than one for all local incidence angles, surface roughness conditions and soil moisture contents, as shown in **Figure 6**. It increases monotonically with increasing *ks* up to $ks \cong 1$ and converges slowly to one, which finally reaches for $ks > 3$. On the other hand, for ks < 3, *p* decreases with increasing local incidence angle and/or with increasing soil moisture content. A significant sensitivity to soil moisture and incidence angle variations can be observed.

- The cross-polarised ratio q << 1, shows – as compared to the co-polarised ratio - a stronger sensitivity to ks variations and a weaker dependency to soil moisture variations. q increases with increasing ks up to ≅ 1 and converges slowly to a value, which depends on the soil moisture content and finally reaches it for $ks > 3$. A significant sensitivity of the quotient q to surface roughness and no dependency on the incidence angle can be observed, respectively, as shown in **Figure 7**.
- In general, the algorithm exhibits a good agreement to the ground measurements in the range of $0.1 \leq ks \leq 6$, $2.5 \leq kl \leq 20$, and $9 \leq m_v \leq 31$.

The fact that p and q are limited to $ks \leq 3$ and $p = \frac{\sigma^0_{HH}}{\sigma^0_{VV}} \leq 1$ makes the model more appropriate for applications at lower frequencies, as for example for the S-, L-, or P-band.



a)



b)

Figure 6 Co-polarised ratio versus volumetric moisture content for varying local incidence angle: a) for a smooth surface ks = 0.1 and b) for a rough surface ks = 0.8.

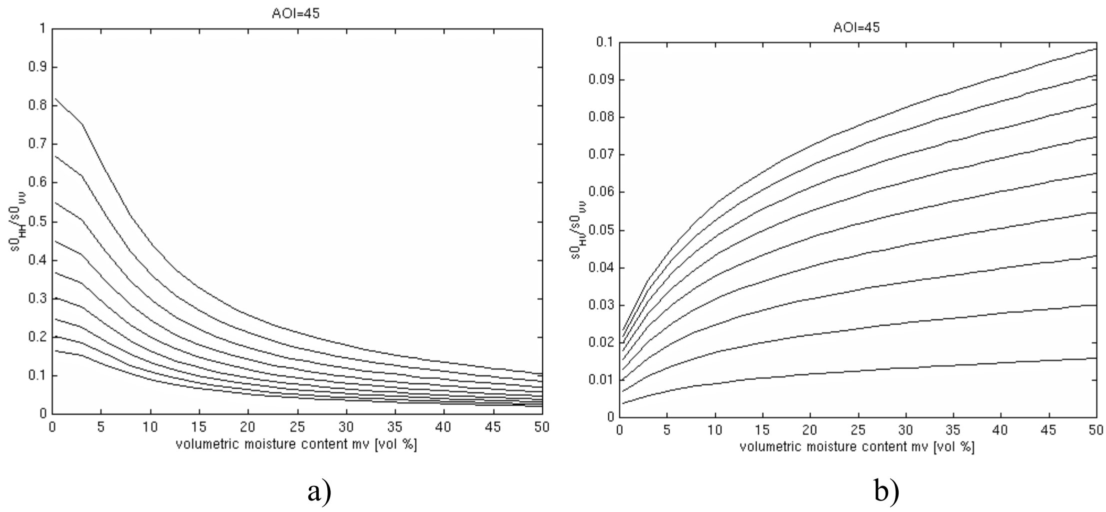


Figure 7 Co- and cross-polarised ratio versus volumetric moisture content for varying surface roughness (from *ks*=0.1 up to *ks*=0.8) for a local incidence angle of 45 °.

2.2.1.2 The Dubois Model

The empirical model developed by P. C. DUBOIS, J. VAN ZYL, and T. ENGMAN in 1995 is a simplification of the Oh-Model adressing only co-polarised backscatter coefficient. The data used in the original study, were collected with the scatterometer from the University of Michigan LCX as well as with the University of Bern scatterometer (RASAM) operating at six frequencies between 2.5 GHz and 11 GHz. In later investigations the algorithm was applied to SAR data (AIRSAR and SIR-C) in order to prove the robustness of the algorithm.

Using the scatterometer data and ground measurements, the empirically determined co-polarised backscatter coefficients, σ^0_{HH} and σ^0_{VV} for the horizontal and vertical polarisation, were expressed as a function of system parameters, as the local incidence angle and frequency, and soil parameters, such as dielectric constant and surface roughness. In a first elaborative step, the dependence of the backscattering coefficient ratio on different soil moisture conditions and the local incidence angle was investigated. It was found that the relationship resembles most closely to the tangent of the incidence angle. In a second step, the deviation caused by surface roughness was accounted for by an empirically derived expression for the roughness term $\log(ks \cdot \sin\theta)$. The resulting expressions are given by

$$\sigma^0_{HH} = 10^{-2.75} \frac{\cos^{1.5}\theta}{\sin^5\theta} 10^{0.028\varepsilon' \tan\theta} \left(ks \cdot \sin\theta\right)^{1.4} \lambda^{0.7} \tag{10}$$

$$\sigma^0_{VV} = 10^{-2.37} \frac{\cos^3\theta}{\sin^3\theta} 10^{0.046\varepsilon' \tan\theta} \left(ks \cdot \sin\theta\right)^{1.1} \lambda^{0.7} \tag{11}$$

where θ is the local incidence angle, ε' is the real part of the dielectric constant, ks the normalised surface roughness and λ the wavelength. For a known angle of incidence, (10) and (11) constitute a system of two non-linear equations with two unknowns: ks and ε'.

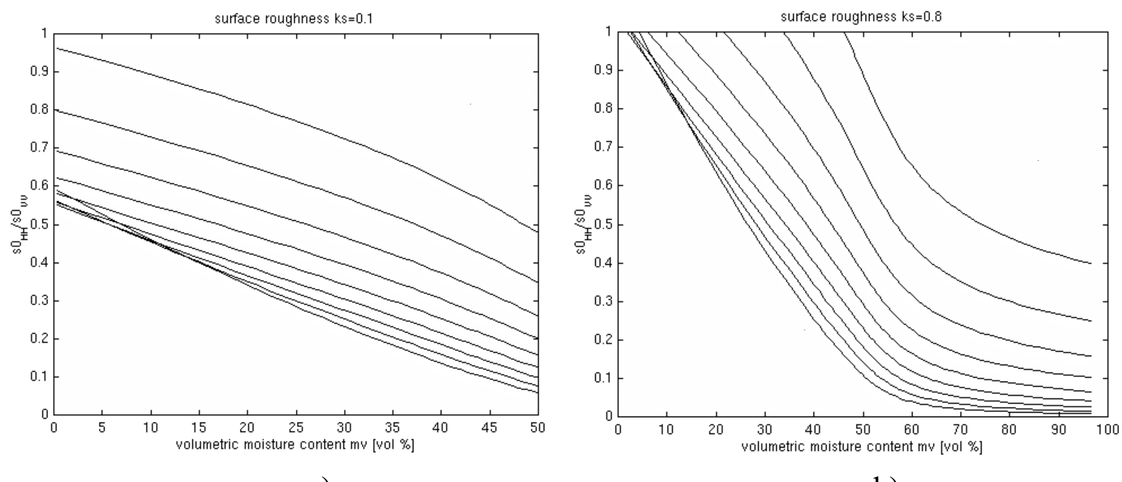
Similar to the prediction of the SPM, the backscatter coefficient of (10) and (11) decreases with increasing local incidence angle and/or with decreasing surface roughness. On the other hand, the backscatter coefficient increases with increasing soil moisture, stronger in σ^0_{VV} than in σ^0_{HH}. Furthermore, the sensitivity to moisture content decreases with increasing local incidence angle.

The empirically determined expressions predict that the ratio $\sigma^0_{HH}/\sigma^0_{VV}$ is roughness-dependent and increases with increasing surface roughness, due to the $\log(ks \cdot \sin\theta)$ term. This is different from the SPM, where the co-polarised term does not depend on roughness.

On the other hand, with increasing soil moisture content, the backscatter ratio $\sigma^0_{HH}/\sigma^0_{VV}$ is steadily increasing, while its sensitivity to moisture content decreases with a decreasing local incidence angle as shown in **Figure 8**.

The performance of the model may be briefly summarised by the following points (DUBOIS et al. 1995):

- The estimated validity range for the surface parameters are $m_v \leq 35$ % and $ks \leq 2.5$ and their accuracy is ranging for the soil moisture estimation by about 4.2 vol. % and for the surface roughness by about *ks* of 0.4 for a bare surface (NDVI < 0.4).
- For an inversion accuracy better than 4 vol. % the radar data should be calibrated to within 2 dB absolute and 0.5 dB relative accuracy between the two co-polarised channels.
- If the cross-polarised channel is available, it can be used to exclude disturbing vegetation impacts.



a) b)

Figure 8 Sensitivity plots of the co-polarised ratio to the volumetric moisture content for varying local incidence angles. a) for a smooth surface *ks* = 0.1; and b) for a rough surface *ks* = 0.8.

Important aspects which are not considered by the model as stated in (10) and (11), are:

- the influence of the tillage direction on the agricultural fields,

- the influence of the surface correlation length on the fields,
- the influence of topography on the accuracy of the estimated surface parameters.

There are several reasons why the model was developed to include only the co-polarised channels. Co-polarised backscattering coefficients are less sensitive to system noise and cross talk. Consequently, the calibration of the co-polarised returns is simpler to perform and more accurate. In the early 90's, the deployment of effective polarimetric calibration algorithms was still under development. Furthermore, they provide a robust performance to the algorithm even in the presence of sparse vegetation. Finally, the need of only two channels allows the application of the algorithm on data acquired using dual polarised systems instead of fully polarised systems, which are strictly required for the application of the Oh-Model.

