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M. Zribi[1], M. Sahnoun[12], N. Baghdadi[3], T. Le Toan[1], A. Ben Hamida[2]

[1]CESBIO (CNRS/UPS/IRD/CNES), 18 av. Edouard Belin, bpi 2801, 31401 Toulouse cedex9, France.

[2]ENIS/Université de Sfax, Route Soukra Km 3.5, Sfax, Tunisia.

[3]IRSTEA, UMR TETIS, 500 rue François Breton, 34093 Montpellier cedex 5, France.

Abstract

In this paper, the potential use of P-band radar signals for the estimation of soil roughness parameters is analyzed. The numerical moment method backscattering model is used to study the sensitivity to soil roughness parameters of backscattered P-band signals. Two roughness scales related to terrain microtopography and low frequency roughness structures are considered. In the case of microtopography, the rms height is shown to be the dominant influence in the relationship between radar signals and roughness. For low frequency structures, the parameter *Zs* is strongly correlated with the backscattered signals. An analysis of the behavior of P-band radar signals as a function of multi-scale soil roughness (microtopography and large-scale roughness structures) reveals the complexity of using P-band data for the study of bare surface soil parameters.

The Moment method model is then compared with the real data covering a large range of microtopographic roughness values, derived from experimental airborne P-band SAR campaigns made over agricultural fields, at two sites in France. The significant discrepancies observed between measurements and simulations confirm the limitations of an analysis based on microtopographic characterizations only.

Keywords: SAR, P-band, bare soil, roughness, moment method

1- Introduction

Soil moisture and roughness parameters play a key role in hydrological and climatic studies. In recent years, considerable effort has been devoted to the analysis of the backscattering characteristics of bare soils. Different backscattering models (theoretical (analytical or numerical), semi-empirical and empirical) were developed (Ulaby et al., 1986, Fung et al., 1992, Oh et al., 1992, Dubois et al., 1995, Chen et al., 2003, Zribi et al., 2006, Huang et al., 2010, Huang et al., 2012, Tsang et al., 2012). Recently, several studies have proposed various approaches to the improvement of roughness descriptions (Oh et al., 1998, Davison et al., 2000, Mattia et al., 2001, Zribi et al., 2003, Callens et al., 2006, Baghdadi et al., 2006, Verhoest et al., 2008, Lievens et al., 2009, Zribi et al., 2014a), which are essential to the accurate analysis and interpretation of backscattering behavior and soil moisture estimation. Almost all studies based on the interpretation of radar measurements make use of signals recorded in the L, C and X bands. For these different bands, which are generally derived from satellite or airborne measurements, various algorithms have been developed to estimate roughness and soil moisture for agricultural soils (Rahman et al., 2008, Paloscia et al., 2010, Pierdicca et al., 2010, Zribi et al., 2011, Gerboudj et al., 2011, Gorrab et al., 2015). Roughness is generally described by two parameters: the RMS height (*Hrms*), and the correlation length (*l*) of the soil, derived from its height correlation function, which is often considered to have a Gaussian or exponential shape. In the case of applications involving agricultural soils, this function is generally assumed to be exponential (Zribi et al., 1997). Fung et al. (1994), Shi et al. (1997) and Zribi et al. (2005) have also proposed different types of analytical correlation function to fit the experimental data. In a context where only a small number of radar configurations was available for the inversion of surface parameters, Zribi and Dechambre (2003) introduced a description based on the parameter $Zs = Hrms^2/l$. The strength of backscattered radar signals is sensitive to variations in surface roughness, especially in the case of low levels of roughness (rms height approximately <1 cm in the X-band, 1.5 cm in the C-band, and 2 cm in the L-band), (Baghdadi et al., 2006). The results obtained using L, C, and X-band data show that in the case of bare soils, the radar signal ($\sigma°$) has an exponential or logarithmic dependence on soil surface roughness (Baghdadi et al., 2002; Zribi et al., 2003), and increases linearly with the volumetric soil moisture (*mv*) when the latter lies in the range between approximately 5 and 35 Vol.% (e.g. Aubert et al., 2013). In the last years, different studies have also analyzed effects of low frequency roughness structures, particularly row directional effects (Ulaby et al., 1982, Rakotaoraivony et al., 1996, Davidson et al., 2002, Zribi et al., 2002, Blaes et al., 2008). However, because of large number of unknown surface parameters, they are often neglected in radar signal inversion.

Whereas the vast majority of research involving P-band radar measurements has been related to the mapping of forest characteristics, very few studies have investigated the characteristics of these signals over bare soils (Baghdadi et al., 2013). In this context, with the planned 2020 launch of the P-band SAR mission BIOMASS, devoted to the study of the biomass of the Earth's forests (Le Toan et al., 2011), there is a call to analyze the potential use of this frequency band for other applications - in particular roughness and moisture estimations for bare or covered soils. In the present study, we therefore discuss the application of P-band measurements to the estimation of these parameters. Our paper is organized in four sections. Section 2 presents our analysis of P-band backscattering behavior over rough soils, computed with the numerical moment method (MM). This section discusses the influence of microtopography and low frequency roughness structures, as well as that of multi-scale roughness surfaces on backscattering simulations. Section 3 presents an intercomparison of results produced by the numerical moment method and real radar data acquired over agricultural fields. Finally, our conclusions are presented in Section 4.

2- Analysis of backscattering behavior over rough soils

The aim of this section is to use exact numerical simulations to analyze the backscattering behavior of P-band radar signals, as a function of roughness. For this analysis, we consider two roughness scales: surface microtopography resulting from soil tillage (clods, etc), and low-frequency scale features that can be produced by small local variations in topography or directional tillage.

2-1 Moment method simulations

The backscattering computation is based on the numerical resolution of two integral equations, defined as follows:

- in air:

$$\vec{n}\times\vec{E}^{i}(\vec{r}) = -\frac{1}{2}\vec{K} + \vec{n}\times\int_{c}\left[j\omega\mu_0 G_1\vec{J} - \vec{K}\times\nabla G_1 - \frac{\nabla'.\vec{J}}{j\omega\varepsilon_1}\nabla G_1 \right] dl'$$

$$\vec{n}\times\vec{H}^{i}(\vec{r}) = -\frac{1}{2}\vec{J} + \vec{n}\times\int_{c}\left[j\omega\varepsilon_1 G_1\vec{K} + \vec{J}\times\nabla G_1 - \frac{\nabla'.\vec{K}}{j\omega\mu_0}\nabla G_1 \right] dl' \qquad (1)$$

- in soil, the corresponding integral equations are:

$$0 = -\frac{1}{2}\vec{K} - \vec{n}\times\int_{c}\left[j\omega\mu_0 G_2\vec{J} - \vec{K}\times\nabla G_2 - \frac{\nabla'.\vec{J}}{j\omega\varepsilon_2}\nabla G_2 \right] dl'$$

$$0 = -\frac{1}{2}\vec{J} - \vec{n}\times\int_{c}\left[j\omega\varepsilon_0 G_2\vec{K} + \vec{J}\times\nabla G_2 - \frac{\nabla'.\vec{K}}{j\omega\varepsilon_2}\nabla G_2 \right] dl' \qquad (2)$$

where μ_0 is the permeability of air, ε_1 and ε_2 are the dielectric constants of air and soil, respectively, and $\vec{n}$ is the unit outward normal to the surface. $\vec{J} = \vec{n}\times\vec{H}$ is the equivalent surface electric current density, and $\vec{J} = -\vec{n} \times \vec{E}$ is the equivalent surface magnetic current density.

The Green functions are defined in cylindrical coordinates, by the zeroth order Hankel function of the second kind, as:

$$G_i = -\frac{j}{4} H_0^{(2)}\left(k_i \left|\vec{\rho} - \vec{\rho}'\right|\right), i = 1,2 \qquad (3)$$

In order to implement these numerical simulations, a large number of surfaces with varying roughness parameters was generated. For this step, we consider the approach described by (Fung et al, 1985), in which the following procedure is applied:

the surface heights h are written as:

$$h(k) = \sum_{i=-M}^{i=M} W(i) X(i+k) \qquad (4)$$

where $X(i)$ is a Gaussian random variable $N(0,1)$, and $W(i)$ is the weighting function given by $W(i) = F^{-1}\left\lfloor \sqrt{F\left[C(i)\right]} \right\rfloor$, in which $C(i)$ is the correlation function and $F[]$ denotes the Fourier transform operator. In the numerical simulations, a Fast Fourier Transformation (FFT) is used to compute the corresponding values of $W(i)$.

Following several convergence tests, the profile length was set to approximately 20 λ, where λ is the wavelength corresponding to the radar frequency (f=0.43 GHz) used in the simulations, and the number of profiles was set to 50. For each profile, a small cell size was selected (λ/100), thus allowing an accurate analysis to be made of the contributions of microtopographic structures to the simulated backscattering behavior. Although our results are shown for the HH polarization only, very similar behaviors were observed in the VV polarization.

2-2 Analysis of the moment method model's sensitivity to soil roughness

In order to study the influence of soil roughness (small-scale, low frequency structures) on radar signal backscattering in the P-band, moment method simulations were run in the *HH* and *VV* polarizations, at 20° and 40° incidence angles.

The soil surfaces generated using this approach are considered to have an exponential correlation function, of the form $\rho(x) = Hrms^2 \exp\left(-\frac{x}{l}\right)$ for small roughness scales, and $\rho_G(x) = Sg^2 \exp\left(-\frac{x}{Lg}\right)$ for low spatial frequency roughness scales.

The dielectric constant is estimated as a function of the volumetric soil moisture and texture, using the empirical model of Pelinsky (Pelinski et al. 1995a, Pelinski et al., 1995b), developed for frequencies in the range between 0.4 and 1.3 GHz. Fig. 1 (a and b) show the simulated backscattering coefficients as a function of rms surface height (*Hrms*), computed in the P-band (0.43 GHz) at 20° and 40° incidence angles. Various surface roughness parameters corresponding to the ranges generally retrieved for agricultural soils were used: *Hrms* between 0.4 and 2 cm; correlation lengths (*l*) between 4 and 10 cm. These simulations show that the backscattered signal is well correlated with Hrms (R^2 equal to 0.97 and 0.99, at 20° and 40°, respectively), and that when *Hrms* remains constant only a small increase in backscattered radar signal is produced by variations in correlation length: a difference of approximately 1.0 ~ 1.5 dB is observed between the shortest and longest correlation lengths (4 cm and 10 cm). This increase in signal strength is in contradiction with the decrease observed in the C and X bands, using the same dynamic range for the roughness parameters retrieved (in general) from real agricultural soils (Zribi et al., 2003, Zribi et al., 2014a). This change in behavior between frequency bands is related to variations in the roughness spectrum, as shown in Fig. 2, where this function is plotted (in dB) as a function of wave number (k), using two different correlation lengths (4 and 10 cm), for the case of an exponential correlation function given by: $W = \dfrac{k^4 l^2 Hrms^2}{\left(1+(2k.l\sin\theta)^2\right)^{1.5}}$.

Firstly, it can be seen in Fig. 2 that the difference between the spectral power at these two correlation lengths undergoes a sign change, when the wave number increases beyond ~ 0.16 cm^{-1}. Secondly, with the MM simulations, the correlation length has a relatively minor influence on the roughness spectrum at low frequencies.

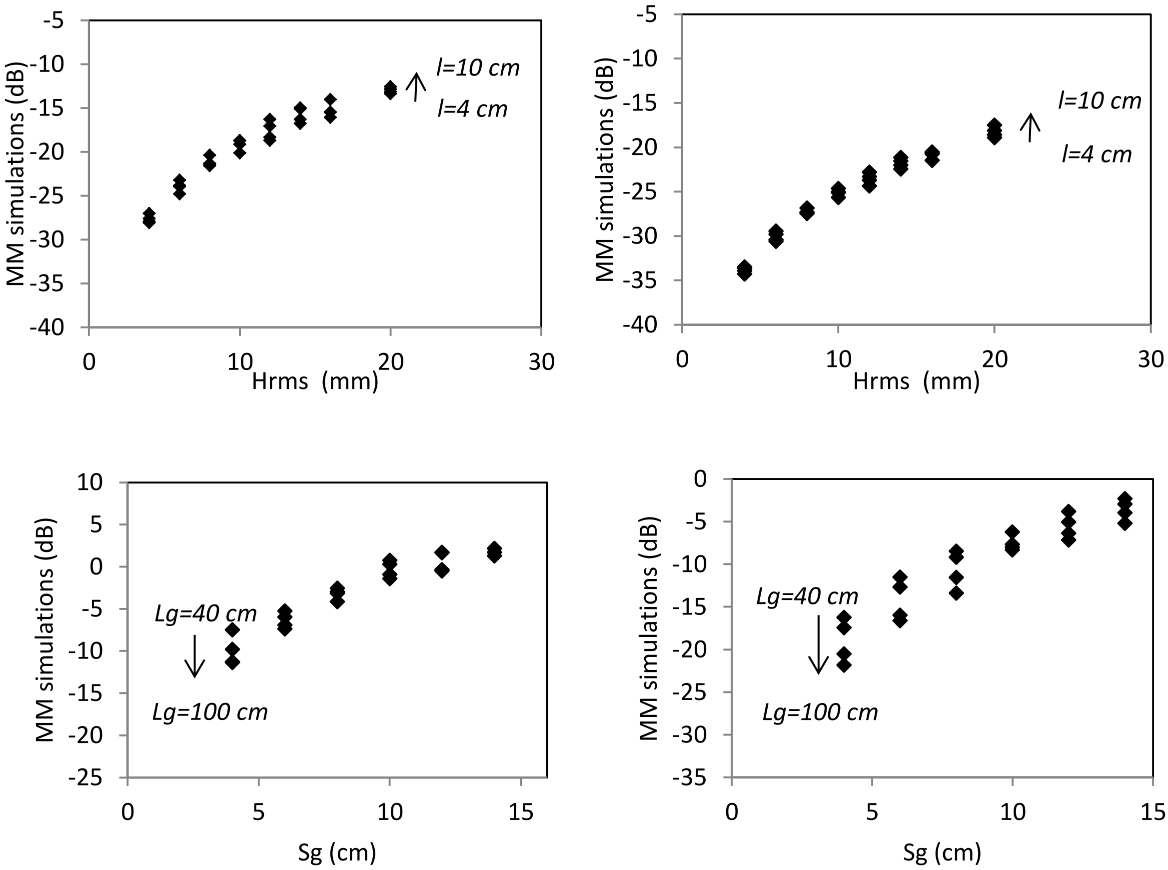


Figure 1: Backscattering simulations as a function of surface roughness, corresponding in the case of (a) and (b) to: microtopography (*Hrms)* with correlation lengths *l* equal to 4, 6, 8 and 10 cm, and in the case of (c) and (d) to: a low spatial frequency rms height (*Sg*), with correlation lengths *Lg* equal to 40, 60, 80 and 100 cm. All simulations are made in the HH polarization with a volumetric soil moisture value of 20 Vol.%. The simulations

in (a) and (c) are made at a 20° incidence angle, and those of (b) and (d) are made at a 40° incidence angle.

To a first approximation, the MM simulations thus show that a study of the role of microtopography roughness can be limited to variations in the parameter Hrms.

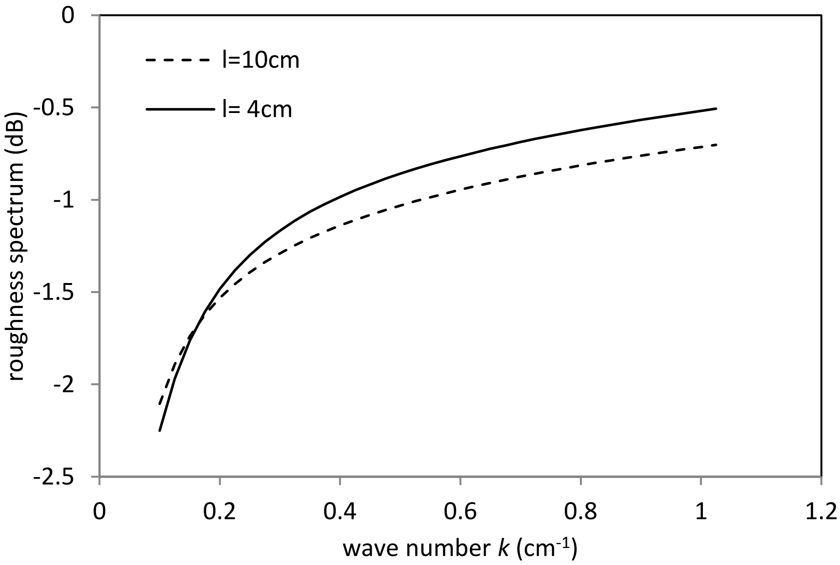


Figure 2: Exponential roughness spectrum as a function of wave number

Fig. 1 (c and d) plots the simulated backscattering MM signals as a function of the rms height *Sg*. Several surface parameters were chosen (*Sg* =4 cm, *Sg* =6 cm, *Sg* =8 cm, *Sg* =10 cm, *Sg* =12 cm, *Sg*=14 cm; *Lg*=40 cm, *Lg* =60 cm, *Lg* =80 cm and *Lg* =100 cm).

For these roughness values, we observe an increase in radar signal strength as a function of increasing rms height *Sg*, and a decrease in simulated radar signal as a function of increasing correlation length *Lg*.

The parameter *Zs*, defined by (Zribi et al., 2003) as $Zs = Sg^2 / Lg$ and tested with C and X bands data in other studies, is evaluated here. As shown in Fig. **3**, the relationship between *Zs* and the simulated radar signals is strongly correlated under all roughness conditions, with R^2

equal to 0.95 and 0.98 at angles of incidence equal to 20° and 40°, respectively. We thus consider that, at this scale it is sufficient to use *Zs* alone, to describe the radar signal's behavior as a function of the soil roughness.

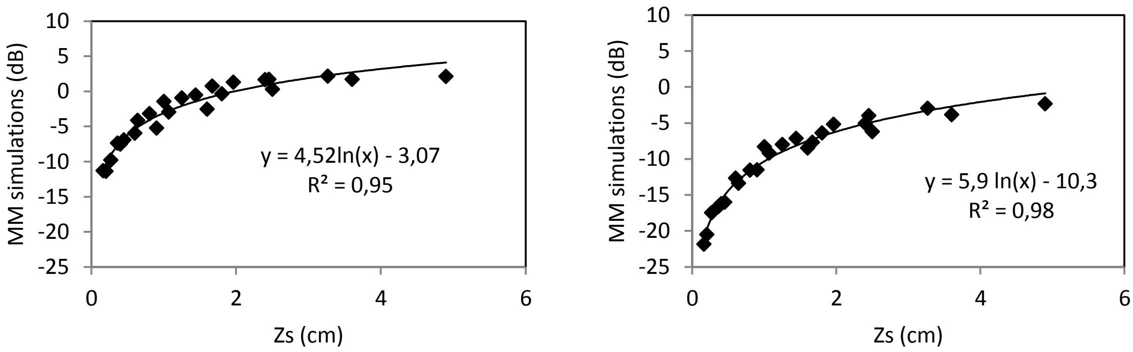


Figure 3: Backscattering simulations in the HH polarization, as a function of the parameter *Zs* (cm): *Sg* lies in the range between 4 and 14 cm, *Lg* between 40 and 100 cm, *mv* = 20 Vol.% (cm^3/cm^3) a) 20° incidence angle, b) 40° incidence angle.

2-3 Analysis of the effects of multi-scale roughness in moment method simulations

In general, when natural or agricultural soils are observed, two main roughness components are observed: small-scale roughness corresponding to soil microtopography tillage (cloddy structures), and large-scale roughness corresponding to local variations in terrain height, and/or directional effects (Rakotoarivony et al., 1996). For this reason, in the present section we analyze the radar signal's sensitivity to multi-scale roughness, including the effects of micro-topography and low frequency roughness structures. We thus consider synthetic soil profiles respecting the correlation function, with small and low roughness scales:

$$\rho(x) = Hrms^2 \exp\left(-\frac{x}{l}\right) + Sg^2 \exp\left(-\frac{x}{Lg}\right) \qquad (5)$$

Fig. 4 provides two examples of synthetic surface profiles: the first of these has small-scale roughness parameters only (*Hrms*=0.6cm, *l*=6cm), whereas the second is characterized by multi-scale roughness, combining the latter small-scale parameters with the additional effects of low frequency roughness structures (*Sg*=6 cm, *Lg*=100 cm).

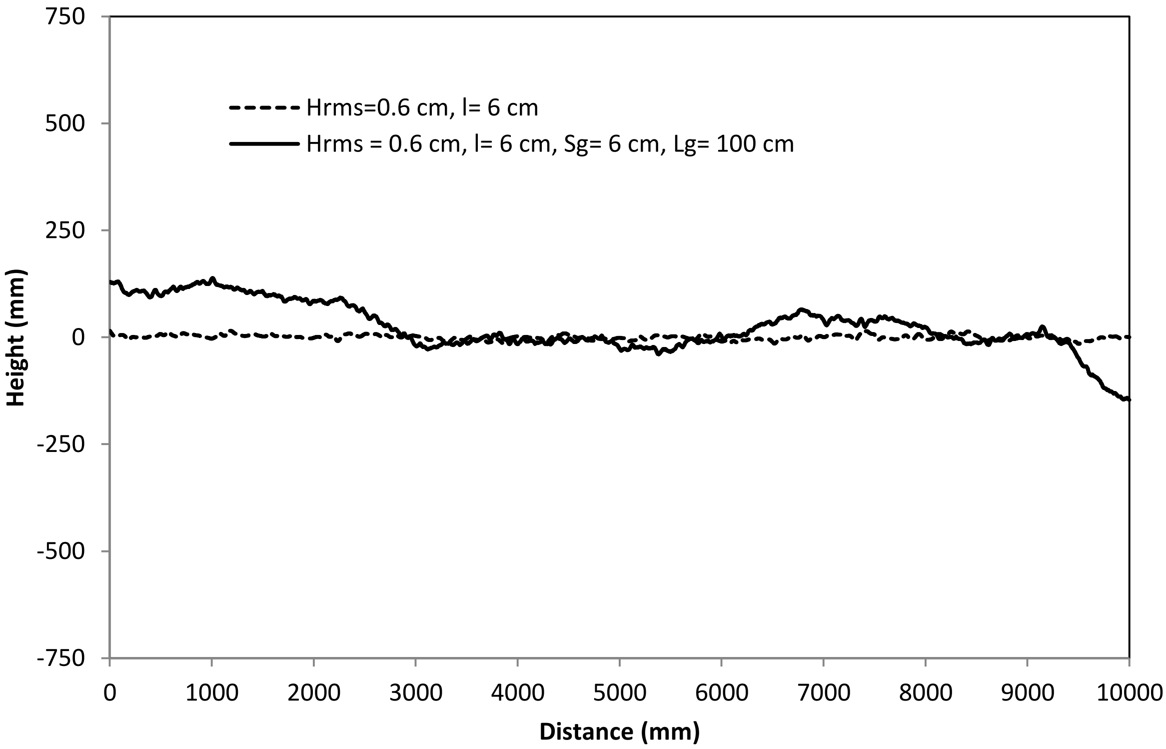
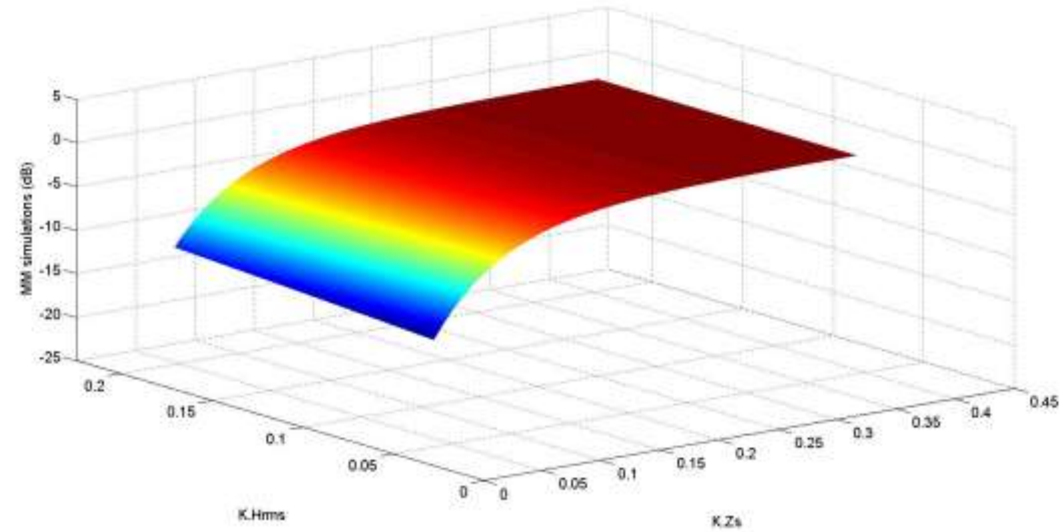


Figure 4: Synthetically generated surface profiles: micro-topography (*Hrms*=0.6cm, *l*=6cm) and multi-scale roughness (*Hrms*=0.6cm, *l*=6cm, *Sg*=6cm, *Lg*=100cm).

Two parameters, *Hrms* describing the terrain's micro-topography, and *Zs* describing low frequency roughness structures, can be used to analyze the behavior of radar signals under multi-scale roughness conditions.

Fig. 5 plots the results of radar signal simulations for these multi-scale surfaces, in the HH polarization at 20° and 40° incidences, as a function of the two roughness parameters: *k.Hrms* in the range between 0.036 and 0.19; and *k.Zs* between 0.015 and 0.45 (corresponding to *Sg* in the range between 4 and 14 cm and *Lg* in the range between 40 and 100 cm). The simulated backscattering coefficients increase when the values of the two roughness parameters *k.Zs* and *k.Hrms* increase.

For a constant value of *k.Zs*, only small variations (less than one decibel) in simulated radar signal are observed due to variations in *k.Hrms* (micro-topography). As shown in the preceding section, the radar signals with the highest dynamic range are produced by terrain having low frequency structures, with a difference of approximately 12 dB between the extreme values of *k.Zs*. As can be seen in Fig. 6, the MM backscattered signals come close to saturation at high values of *k.Zs* (>0.2).



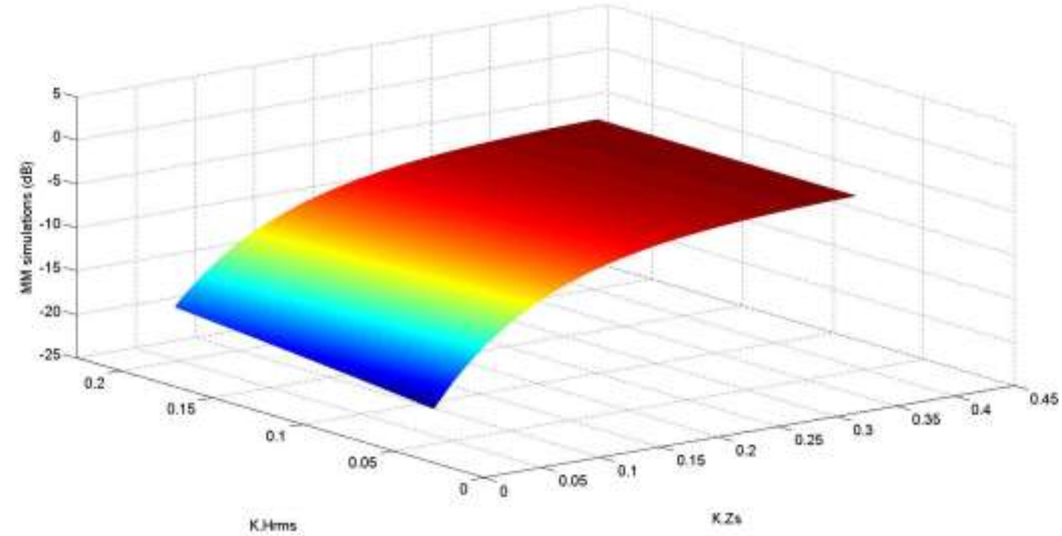


Figure 5: MM backscattering simulations (in decibels) as a function of the two roughness parameters (*k.Hrms*, *k.Zs*), at a) 20° incidence angle, b) 40° incidence angle.

In the previous discussions we consider a roughness spectrum produced by the sum of two independent exponential spectra corresponding to the small, and to the low spatial frequency, roughness scales described above. We thus retrieve two dominant roughness parameters for the backscattering simulations: *k.Zs* and *k.Hrms*. From these results, we propose to use the following roughness spectrum:

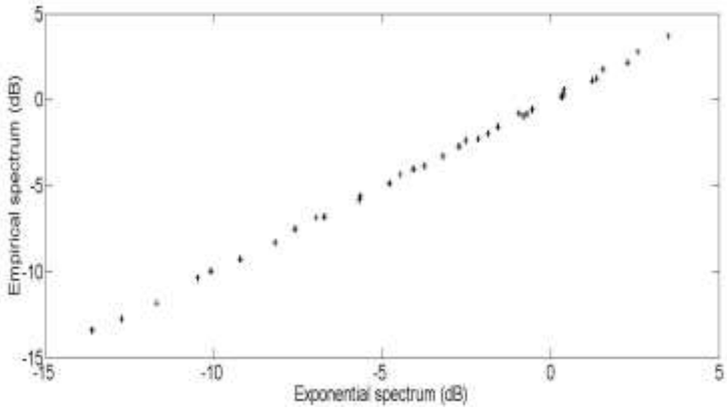
$$W(2k\sin\theta) = a_\theta (k.Hrms)^{b_\theta} + c_\theta (k.Zs)^{d_\theta} \qquad (6)$$

where a_θ, b_θ, c_θ, d_θ are empirical parameters retrieved, as shown in Table 1, by fitting this relationship to the two constituent exponential roughness spectra (corresponding to small and low spatial frequency scales).

Table 1: Empirical values of the roughness parameters a_θ, b_θ, c_θ and d_θ.

angle	a_θ	b_θ	c_θ	d_θ
20°	5.4	1.73	2.32	1.03
40°	3.6	2.95	0.42	0.98

Figure 6 compares the analytical and empirical exponential spectra proposed for all roughness combinations (more than 1000 different sets of conditions, covering the ranges considered for *Hrms*, *l*, *Sg* and *Lg*) used in the simulations described above. These are found to be in very good agreement, with RMS errors equal to 0.12 dB and 0.05 dB at incidence angles equal to 20° and 40°, respectively.



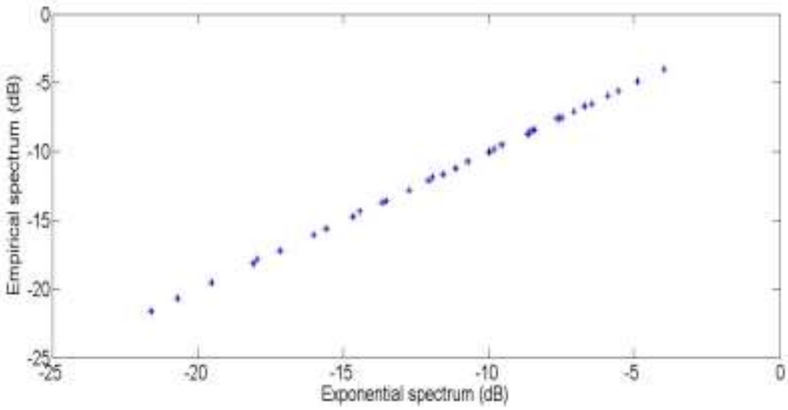


Figure 6: Intercomparison between roughness spectrum values retrieved with exponential spectrum and empricial relationship (6), for all roughness conditions considered for MM simulations (*Hrms* ranged between 0.4 cm and 2 cm, *l* ranged between 4 and 10 cm, *Sg* ranged between 4 and 14cm and *Lg* ranged between 40 and 100 cm), at incidence angle equal to: a) 20° incidence angle, b) 40° incidence angle.

From these results, we propose the following empirical relationship to express the backscattered radar signal as a function of the two variables (*k.Hrms* and *k.Zs*), for one polarization and one value of incidence angle:

$$\sigma^0 = \alpha_{\theta,p} + \beta_{\theta,p}\left(1 - e^{-\left(\mu_{\theta,p}\; k.Zs + \gamma_{\theta,p} k.Hrms\right)}\right) \qquad (7)$$

where σ^0 is expressed in dB, k in cm^{-1}, *Hrms* in cm and *Zs* in cm.

For incidence angles equal to 20° and 40°, the values of α, β, μ and γ are provided in Table 2. The value of α is related to soil moisture effects. In the absence of low scale surface roughness, μ is equal to zero. In the absence of microtopograhical soil roughness, γ is equal to zero.

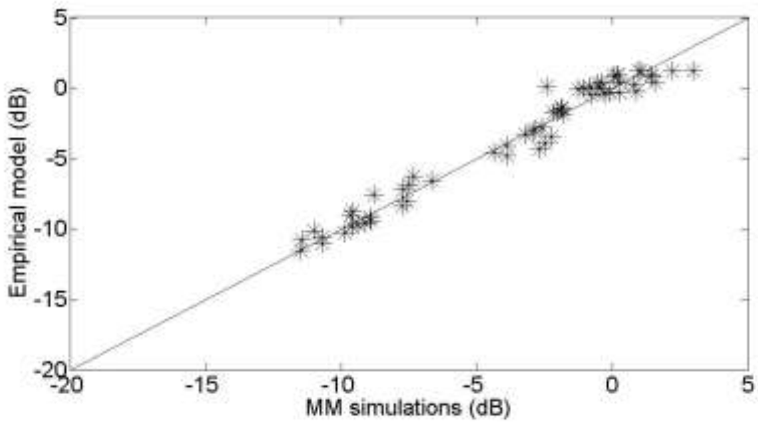
Table 2: Values of the empirical model parameters, for incidence angles equal to 20° and 40°, in the HH polarization.

Incidence angle	α	β	μ	γ
20°	-15.8	17.07	1.55	0.099
40°	-23.6	20.21	0.99	0.12

In Fig. 7 the backscattered signal strength given by the calibrated empirical model (Eq. 6) is compared to that predicted by the MM simulations, at incidence angle equal to 20° and 40° and for the same roughness conditions as those illustrated in Fig. 6. The two models are found to be in very good agreement, with an RMSE equal to 0.7 dB and 0.8 dB, and R^2 equal to 0.98 and 0.97, for incidence angle equal to 20° and 40° respectively. This outcome illustrates the usefulness of this empirical relationship, for the prediction of radar backscattering behavior as a function of soil roughness. The empirical model is validated for all of the roughness conditions analyzed by the moment method simulations, in which *k.Hrms* ranges between 0.036 and 0.18, and *k.Zs* ranges between 0.015 and 0.45.

The parameter *k.Zs* clearly dominates the relationship between roughness and radar signal strength. If the latter parameter is used alone in the empirical exponential relationship (i.e. the influence of *k.Hrms* is ignored in Eq. 6), the RMSE increases to 0.9 dB and 1.2 dB, at incidence angles equal to 20° and 40°, respectively.

This analysis, based on the implementation of only two independent parameters (*k.Hrms* and *k.Zs*), is very well adapted to the use of an inversion approach, which generally makes use of a limited number of radar configuration measurements (often just one or two). For the purposes of direct modeling, an analysis based on the use of all roughness parameters (*Hrms*, *l*, *Sg* and *Lg*) could be useful for a more detailed analysis of the role of roughness and soil surface characteristics.



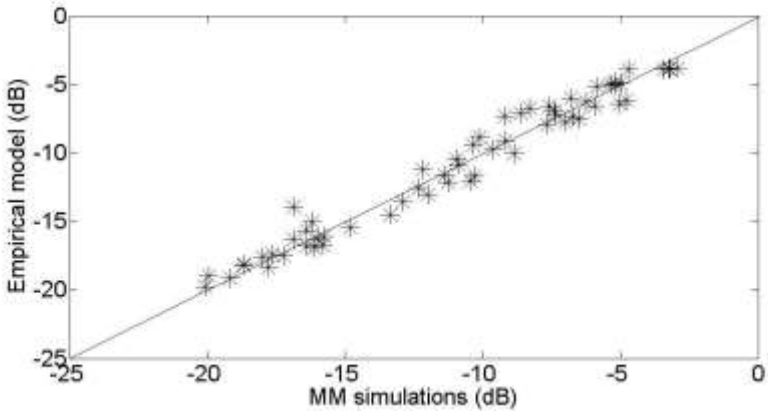


Figure 7: Comparison of radar backscattering predicted by the empirical model defined in equation (6), with the results predicted by MM simulations using the same set of roughness conditions as for the simulations shown in Fig. 5, at incidence angles equal to a) 20°, b) 40°.

The preceding description reveals the somewhat complex relationship between P-band radar signals and soil roughness: in the absence of an accurate knowledge of the soil's low frequency roughness structures, the backscattering analysis is likely to be affected by significant errors.

3- Comparison between MM backscattering simulations and experimental P-band data

3-1 Description of the database

Our database is comprised of fully polarimetric acquisitions recorded from airborne SAR (Synthetic Aperture Radar) sensors, together with ground measurements, corresponding to several agricultural study sites in France (Fig. 8, Table 3).

Bordeaux site: this site is located in the southwest of France (long. 0°50′W, lat. 45°17′N). The soil is comprised of approximately 19% silt, 29% clay, and 51% sand. On January 21, 2004, fully polarimetric P-band radar data (435 MHz) was acquired by the airborne RAMSES SAR, operated by the French Aerospace Research Center (ONERA). The spatial resolution of these SAR images was 2.5 m in range and azimuth.

Garons site: this site is located near to Nîmes in the South of France (long. 04°23'E, lat. 43°45'N). The soil is stony, and is comprised of 54% silt, 40% clay, and 6% sand. Fully polarimetric radar data were acquired in the UHF-band (360 MHz, spatial resolution approximately 0.75 m) on October 4th, 2011, using the new multispectral airborne SAR system known as SETHI, operated by the ONERA.

Figure 8: Location of two study sites in France (Bordeaux and Garons).

Ground truth measurements of soil moisture and surface roughness were carried out simultaneously with SAR sensor observations of eight reference plots, each of which has a surface area of at least one hectare. Only bare soils or soils with scattered short grass were selected. The soil roughness measurements were made using 1 m long needle profilometers with 2 cm sampling intervals. From ten roughness profiles measured on each reference field, the root mean square (*Hrms*) surface height and correlation length (Table 2) were computed from the mean values of all correlation functions. Gravimetric soil moisture samples were collected from the top 10 cm of soil at random locations in each field, and the volumetric water content at the scale of each field was taken to be the mean of the water content values of the individual samples (10 to 40 measurements per plot). In the case of the ground truth campaign made at the Bordeaux site, the four bare soil plots were very wet, with moisture contents ranging between 26.9 Vol.% and 46.9 Vol.%. However, the Garons site was very dry, with soil moisture contents ranging between 2.8 Vol.% and 4.4 Vol.% (Table 1).

The RAMSES and SETHI data were radiometricaly calibrated, and their polarimetric parameters were then extracted. Coherency matrices are frequently processed for speckle reduction, using a sliding window to compute the average values of several neighboring pixels.

The PolSARPro v4.2.0 software (http://earth.eo.esa.int/polsarpro/) was used to process the polarimetric SAR data. The backscattering coefficients in the HH and VV polarizations were averaged using a 15x15 pixel sliding window.

Table 3: Characteristics of the ground truth measurements. θ : Incidence angle, m_v: Volumetric soil moisture (0-10 cm), H*rms* : Root mean square surface height, *l* : Correlation length.

Study site	Plot number	θ (°)	m_v (Vol.%)	*Hrms* (cm)	*l (cm)*
Bordeaux	Bare soil (B1)	53°	26.9	1.89	4.33
	Bare soil (B2)	47°	46.9	0.88	3.22
	Bare soil (B3)	50°	32.9	1.31	3.95
	Bare soil (B4)	52°	39.4	1.69	4.30
Garons	Bare soil (G1)	43°	4	1.56	4.80
	Bare soil (G2)	45°	4.3	1.40	3.34
	Bare soil (G3)	34°	4.4	0.59	3.27
	Bare soil (G4)	46°	2.8	1.25	3.80

3-2 Intercomparison of real data and backscattering model simulations

In Fig. 9, the results produced with the MM model are compared with real radar data, for the *HH* and *VV* polarizations, respectively. For each individual test field, ground truth measurements (H*rms* height, correlation length, soil moisture) were used in the radar backscattering simulations. As can be seen in Fig. 9, considerable discrepancies are found between the measurements and simulations, for both HH and VV polarizations, with an RMSE equal to 13.4 and 11.2 dB, respectively. These differences cannot be explained by excursions from the validity domain of the (exact) MM model. As shown in the last section, low frequency structures have a dominant effect on backscattering signals. However, the terrain's low frequency roughness structures were not taken into account in our simulations, since they could not be measured with a simple 1 or 2 m pin profiler. This is one possible explanation for the large values of RMSE found with these results.

Another possible source of errors in the simulated radar signals is the heterogeneity of the vertical soil moisture profile. This effect has been discussed for the case of higher frequencies, in the L, C and X bands (Le Morvan et al., 2008, Zribi et al., 2014b). In these bands, soil moisture heterogeneity generally has a limited effect on the backscattered radar signals. In the P-band, the penetration depth defined by $\delta = \frac{\lambda\sqrt{\varepsilon'}}{2\pi\varepsilon''}$ (where $\varepsilon = \varepsilon' - i\varepsilon''$ is the relative dielectric constant) is greater. This effect has been analyzed in (Zribi et al., 2016) through the use of two multi-layer models, the SSA (Small Slope Approximation) and the SPM (Small Perturbation Model), applied to various different simulated moisture profiles. The results show that even relatively extreme conditions, characterized by dry surface soils and wet soils at greater depths, affect the radar signal by not more than 1.5 dB. Two types of extreme conditions were recorded in our database: very wet and very dry conditions (*mv*> 27 Vol.% and *mv*<4.5% Vol.%). In both cases, only small heterogeneities are observed in the vertical moisture profiles.

Volume scattering is a third possible cause of the aforementioned errors. Our database comprises wet and dry soils, and for both types we found nearly the same discrepancies between the simulations and radar measurements. However, it should be noted that volume scattering is negligible in the case of wet surfaces (*mv*>27 Vol.%), as a consequence of the radar signal's reduced penetration depth (Ulaby et al., 1986).

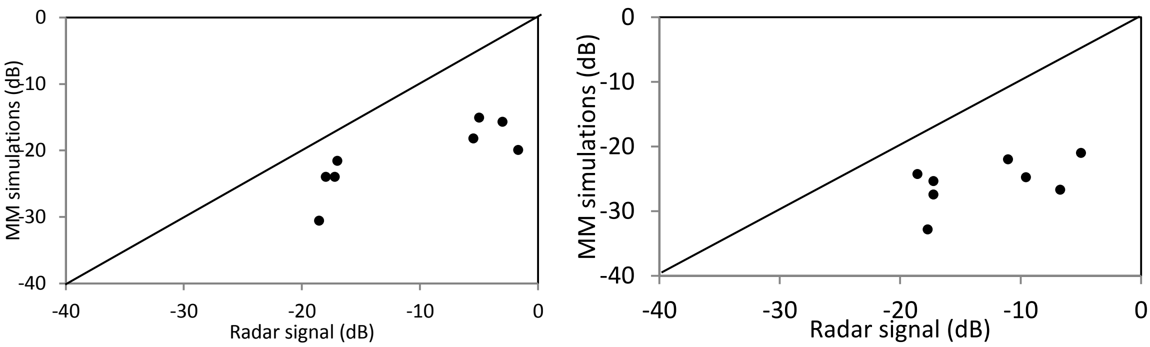


Figure 9: Simulated MM radar signals as a function of measured radar signals over agricultural fields, a) HH pol (b) VV pol

From this analysis, we assume that low frequency structures probably play the most significant role, in terms of induced errors, when they are not accounted for in the simulations.

3-3 Application of the proposed empirical inversion model

From the conclusions of the previous section, and in the absence of ground truth measurements allowing the real value of low spatial frequency roughness to be determined, the proposed empirical model described in Eq. (7) is used here, to retrieve the roughness parameter *Zs* corresponding to eight test fields.

When *Hrms* (microtopography) and the incidence angle are known, *Zs* can be retrieved from Eq. (7). Figure 10 plots the retrieved values of *Zs* as a function of *Hrms*, for the eight test fields. *Zs* can be seen to range between 0.3 and 3 cm, i.e. to the range of values considered in our simulations of agricultural soils. Four of the fields were selected at the Garons site, and have quite small values of *Zs*, between approximately 0.3 and 0.5 cm. This indicates a small level of low frequency variations, and is confirmed by the very flat characteristics of the studied site. Although ground truth measurements would be needed to verify this result, it confirms the robustness of the analyses described in the previous sections, based on numerical and empirical simulations.

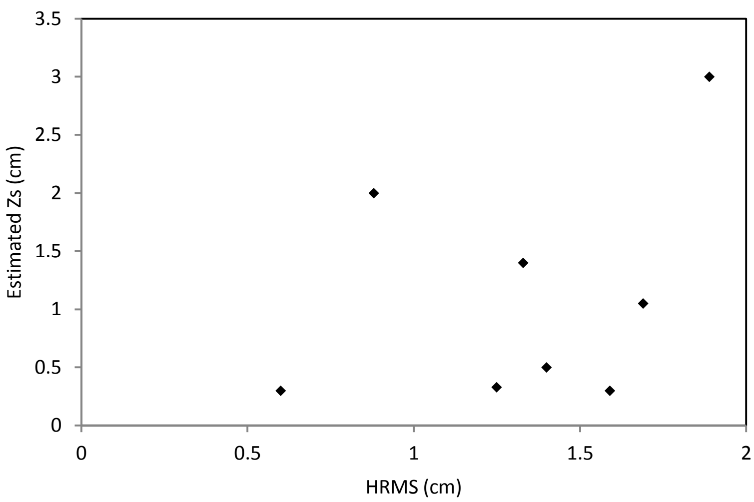


Figure 10: Estimated values of *Zs*, plotted as a function of the in situ values of *Hrms* measured on eight test fields

3-4 Numerical example of errors produced by ground measurement inadequacies

In this section, we use numerical simulations to show that the backscattering model is affected by increasingly strong errors, when the size of the ground measurement profile is decreased, in the presence of low frequency terrain structures. Ground measurements are generally based on the use of a pin profiler of limited length (one to two meters). The height correlation function is then estimated using the mean values of the roughness parameters derived from *n* profiles. In the following, we present the results of radar signal simulations (f=0.43 GHz) computed using different mean roughness values. The latter are derived from a numerically generated 150 m profile, which is subsequently divided into *n* profiles, having lengths ranging from 1 m (*n*=150) to 15 meters (*n*=10). Fig. 11 shows the simulated MM radar signal strength (using mean roughness values as input) as a function of the lengths of the *n* profiles. An initial increase in the value of the backscattering coefficient can be observed when the length of the profiles is increased, and convergence is nearly achieved when the length of the profiles reaches approximately 6 m. This result clearly illustrates the risk of generating large errors, when the profiles are not sufficiently long with respect to the low frequency structure of the terrain (Baghdadi et al, 2000). This threshold for the profile lengths may not be completely constant, and can depend on the nature of the low frequency structures present in the observed terrain.

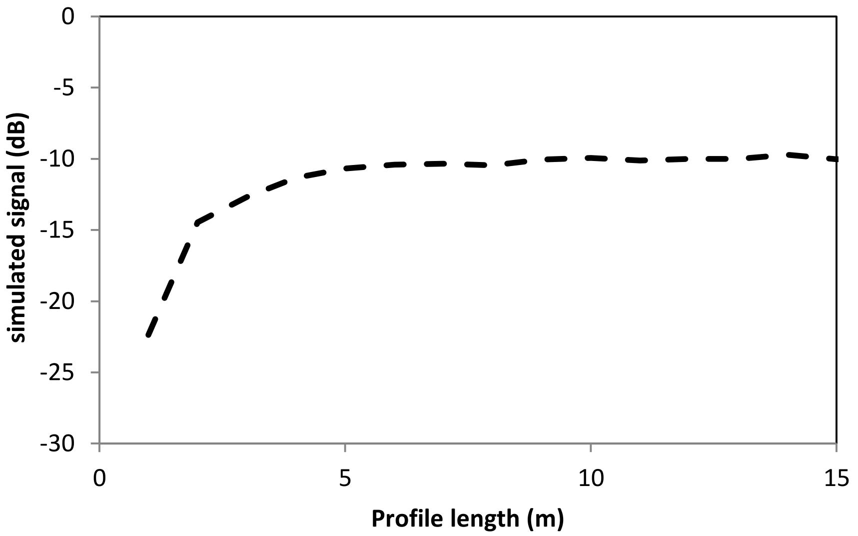


Figure 11: Variations in simulated radar signal as a function of the length of the soil profiles, including the effects of multiscale roughness (*Hrms*=0.6 cm, *l*=6 cm, *Sg*=6 cm, *Lg*=100 cm)

4- Conclusions

In the present study, we discuss the potential sensitivity of P-band radar signals, as well as their interpretation for the characterization of soil surface roughness (microtopography and low frequency structures), based on the analysis of backscattering simulations run with an exact numerical model (moment method). Simulations are first considered as a function of microtopography parameters (the *Hrms* and correlation length) of the soil surface. Roughness parameters typical of agricultural fields are considered in this analysis, which shows that the radar signal increases with Hrms and the correlation length of the soil. A strong correlation is found between the simulated signals and the soil's Hrms, with the correlation length having a relatively small influence on the results. To a first approximation, when studying the relationship between simulated radar backscattering and the microtopography of the soil, Hrms can be used alone to represent the terrain's physical structure. Backscattering simulations for a terrain having low frequency structures reveal a combined effect, in which both the rms height, and the structure's correlation length should be taken into account. The MM radar simulations are found to be strongly correlated with the parameter *Zs,* with R^2 equal to 0.95 at 20°, and 0.98 at 40°. A multi-scale roughness analysis using both roughness scales (*Hrms*, *Zs*) reveals the limited influence of small-scale roughness in radar simulations. An empirical roughness spectrum is proposed, based on the use of these two parameters, and is found to be in very good agreement with the previously used analytical (exponential) spectrum. An empirical relationship is proposed to describe the behavior of the backscattered signal as a function of these two parameters. These results illustrate the complexity of interpreting the behavior of P-band radar signals as a function of soil roughness. When the signals simulated with the MM model are compared with real experimental SAR data acquired over various agricultural fields, strong discrepancies are observed, with RMS errors equal to 13.4 dB and 11.2 dB, in the HH and VV polarizations, respectively. These discrepancies could be explained mainly by the absence of an additional roughness scale related to low frequency structures that are not accounted for in local roughness measurements with 2m pinprofiler, with which the MM simulations produce weaker signals. The proposed empirical model can be used to estimate *Zs*, lying in the range between 0.3 and 3 cm, for the low roughness description of the studied test fields.

Despite the usefulness of the parameter *Zs* in the description of low frequency structures, it still suffers from some limitations, which should be well understood. This parameter has been introduced in response to the difficulties that are encountered during the inversion of (in general) one or two radar configuration measurements. It must correspond to realistic surface parameters, retrieved from real natural surfaces. As shown by our simulations, under different realistic conditions characterized by approximately the same value of Zs, we retrieve nearly the same backscattered signal. However, when it is used independently of real data range, or is not used in an inversion process, the same value of Zs can be retrieved under conditions of extreme roughness leading to different simulations.

Backscattering simulations based on numerically generated profiles, making use of different profile lengths (from 1m to 15m) and including the effects of multi-scale roughness, show that the radar simulations become inaccurate when short profile lengths are used. This means that experimental campaigns involving roughness measurements made at the local scale only, for example through the use of a 1m or 2m pin profiler, are inadequate for a complete and accurate analysis of the influence of soil roughness on P-band radar signals. These conclusions are in agreement with studies proposed by Davidson et al., 2000 and Mattia et al., 2001 for higher radar frequencies. When the roughness of low scale structures, determined for example through the use of a fine digital elevation model, is not included in the analysis, significant errors can arise in the estimation of soil roughness and signal strength. This aspect could also concern the retrieval of row orientation, since this parameter is known to have a significant influence at low radar frequencies (Zribi et al., 2002). In the context of the planned BIOMASS space mission, the results presented in the present study highlight the need for further theoretical developments and experimental measurements, in order to improve our understanding of radar-soil interactions in the P band, in particular with respect to the role and characterization of soil roughness as well as the non-negligible effects of volume scattering.

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Figures and tables

Table 1: Empirical values of the roughness parameters a_θ, b_θ, c_θ and d_θ

Table 2: Values of the empirical model parameters, for incidence angles equal to 20° and 40°, in the HH polarization.

Table 3: Characteristics of the ground truth measurements. θ : Incidence angle, m_v: Volumetric soil moisture (0-10 cm), H*rms* : Root mean square surface height, *l* : Correlation length.

Figure 1: Backscattering simulations as a function of surface roughness, corresponding in the case of (a) and (b) to: microtopography (*Hrms)* with correlation lengths *l* equal to 4, 6, 8 and 10 cm, and in the case of (c) and (d) to: a low spatial frequency rms height (Sg), with correlation lengths Lg equal to 40, 60, 80 and 100 cm. All simulations are made in the HH polarization with a soil moisture value of 20 cm^3/cm^3. The simulations in (a) and (c) are made at a 20° incidence angle, and those of (b) and (d) are made at a 40° incidence angle.

Figure 2: Exponential roughness spectrum as a function of wave number

Figure 3: Backscattering simulations in the HH polarization, as a function of the parameter Zs (cm): Sg lies in the range between 4 and 10 cm, Lg between 40 and 100 cm, mv = 20 cm^3/cm^3, a) 20° incidence angle, b) 40° incidence angle.

Figure 4: Synthetically generated surface profiles: micro-topography (Hrms=0.6cm, l=6cm) and multi-scale roughness (Hrms=0.6cm, l=6cm, Sg=6cm, Lg=100cm).

Figure 5: MM backscattering simulations (in decibels) as a function of the two roughness parameters (K.Hrms, K.Zs), a) 20° incidence angle, b) 40° incidence angle.

Figure 6: Intercomparison between roughness spectrum values retrieved with exponential spectrum and empricial relationship (6), for all roughness conditions considered for MM simulations (Hrms ranged between 0.4 cm and 2 cm, l ranged between 4 and 10cm, Sg ranged

between 4 and 14cm and Lg ranged between 40 and 100cm), at incidence angle equal to: a) 20° incidence angle, b) 40° incidence angle.

Figure 7: Comparison of radar backscattering predicted by the empirical model defined in equation (7), with the results predicted by MM simulations using the same set of roughness conditions as for the simulations shown in Fig. 5, at incidence angles equal to a) 20°, b) 40°.

Figure 8: Location of two study sites in France (Bordeaux and Garons).

Figure 9: Simulated MM radar signals as a function of measured radar signals over agricultural fields, a) HH pol (b) VV pol.

Figure 10: Estimated values of Zs, plotted as a function of the in situ values of Hrms measured on eight test fields.

Figure 11: Variations in simulated radar signal as a function of the length of the soil profiles, including the effects of multiscale roughness (*Hrms*=0.6cm, *l*=6cm, Sg=6cm, Lg=100cm).