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Analysis of the relationship between backscattered P-band radar signals and soil roughness

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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.

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 and Tsang, 2012). Recently, several studies have proposed various approaches to the improvement of roughness descriptions (Oh and Kay, 1998, Davidson et al., 2000, Mattia et al., 2001, Zribi and Dechambre, 2003, Callens et al., 2006, Baghdadi and Zribi, 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, Gherboudj 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 (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 and Zribi, 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 and Dechambre, 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, Rakotoarivony et al., 1996, Davidson et al., 2000, Zribi et al., 2002, Blaes and Defourny, 2008). However, because of

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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:

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

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

-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 $\vec{K}=-\vec{n}\times\vec{E}$ 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 and Chen, 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.

$W(i)=F^{-1}[\sqrt{F[C(i)]}]$, 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 $W(i)$.

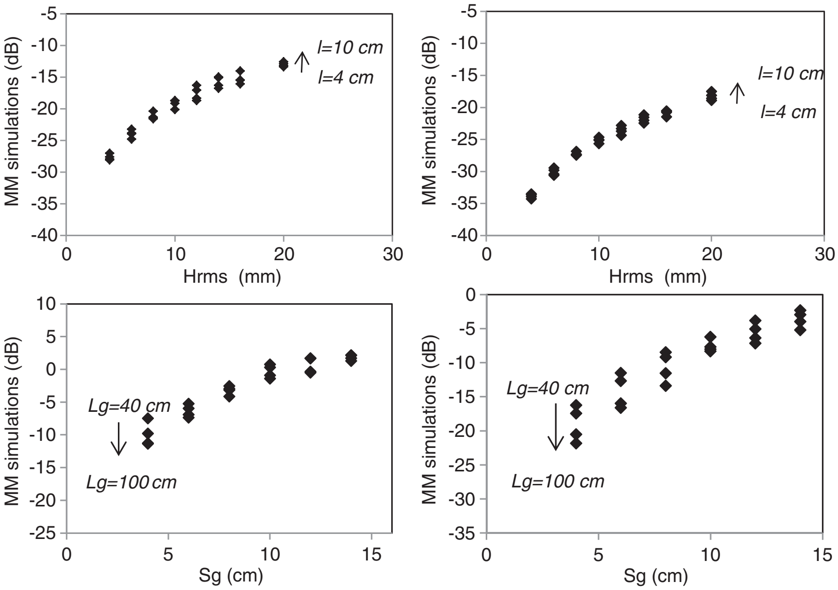

Fig. 1. Backscattering simulations as a function of surface roughness, corresponding in the case of (a) and (b) to: microtopography (*Hrms)* with correlation lengths *l* equal to 4, 6, 8 and 10 cm, and in the case of (c) and (d) to: a low spatial frequency rms height (*Sg*), with correlation lengths *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.