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Analysis of TerraSAR-X data and their sensitivity to soil surface parameters over bare agricultural fields

Nicolas Baghdadi [a,*], Mehrez Zribi [b], Cécile Loumagne [c], Patrick Ansart [c], Thais Paris Anguela [b]

[a] CEMAGREF, UMR TETIS, 500 rue François Breton, F-34093 Montpellier, France
[b] CETP/CNRS, 10/12 avenue de l'Europe, 78140 Vélizy, France
[c] CEMAGREF, UR HBAN, Parc de Tourvoie, BP 44, 92163 Antony Cedex, France

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ABSTRACT

The sensitivity of TerraSAR-X radar signals to surface soil parameters has been examined over agricultural fields, using HH polarization and various incidence angles (26°, 28°, 50°, 52°). The results show that the radar signal is slightly more sensitive to surface roughness at high incidence (50°–52°) than at low incidence (26°–28°). The difference observed in the X-band, between radar signals reflected by the roughest and smoothest areas, reaches a maximum of the order of 5.5 dB at 50°–52°, and 4 dB at 26°–28°. This sensitivity increases in the L-band with PALSAR/ALOS data, for which the dynamics of the return radar signal as a function of soil roughness reach 8 dB at HH38°. In the C-band, ASAR/ENVISAT data (HH and VV polarizations at an incidence angle of 23°) *are* characterised by a difference of about 4 dB between the signals backscattered by smooth and rough areas.

Our results also show that the sensitivity of TerraSAR-X signal to surface roughness decreases in very wet and frozen soil conditions. Moreover, the difference in backscattered signal between smooth and rough fields is greater at high incidence angles. The low-to-high incidence signal ratio ($\Delta\sigma° = \sigma_{26°-28°}/\sigma_{50°-52°}$) decreases with surface roughness, and has a dynamic range, as a function of surface roughness, smaller than that of the backscattering coefficients at low and high incidences alone. Under very wet soil conditions (for soil moistures between 32% and 41%), the radar signal decreases by about 4 dB. This decrease appears to be independent of incidence angle, and the ratio $\Delta\sigma°$ is found to be independent of soil moisture.

1. Introduction

Soil surface characteristics, namely the soil moisture content and roughness, play an important role in hydrological studies. Floods, excess runoff, and soil erosion are, among others, key factors controlled and influenced by soil surface conditions. Spatial remote sensing is a vital tool for measuring and mapping soil parameters, thanks to its capacity to provide permanent coverage over large areas. In active microwave remote sensing, Synthetic Aperture Radars (SAR) provide measurements day and night, whatever the meteorological conditions, with high to medium spatial resolutions (1 m to 1 km), whereas scatterometers provide data with a spatial resolution of a few tens of kilometers (ERS and ASCAT). Moreover, the SAR technique is very sensitive to soil surface conditions, especially roughness and moisture content in the first few centimeters of soil (Bruckler et al., 1988).

The radar signal, which depends on various radar parameters (polarization, incidence angle and frequency), is also correlated with (1) the slope, i.e., the topography; (2) the surface roughness; and (3) the dielectric properties related mainly to soil moisture (*e.g.* Dobson & Ulaby, 1986; Ulaby et al., 1986; Fung, 1994). In recent years, many researchers have demonstrated the potential of microwave remote sensing for the estimation of surface roughness and soil moisture (*e.g.* Baghdadi et al., 2002, 2006, 2007; Le Hégarat et al., 2002; Satalino et al., 2002; Zribi & Dechambre 2002; Oh, 2004; Alvarez et al., 2005; Mattia et al., 2006; Rahman et al., 2008; Zribi et al., 2008**)**. For natural surfaces, the statistical properties of surface roughness can be summarized using two parameters: the standard deviation of surface height (root mean square, *rms*) which specifies the vertical scale of roughness, and the correlation length (L) representing the horizontal scale over which similar (correlated) roughness conditions are detected. The relation between the radar wavelength λ and the statistical roughness parameter *rms* is given by $k \cdot rms$ ($k = 2\pi/\lambda$). Thus, with increasing wavelength, the roughness parameter is decreasing. Also, the local incidence angle plays an important role for defining the roughness condition of a soil. At low incidences, the surface appears rougher than at high incidences. The Frauenhofer criterion proposed in Ulaby et al. (1982) considers a soil surface as rough when the phase difference between two rays scattered from separate points on the surface ($\Delta\phi = 2 \cdot k \cdot rms \cdot \cos\theta$) exceeds $\pi/8$ ($rms > \lambda/(32 \cdot \cos\theta)$).

* Corresponding author. Tel.: +33 4 67 54 87 24; fax: +33 4 67 54 87 00.
E-mail address: baghdadi@teledetection.fr (N. Baghdadi).

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Roughness parameters can be determined from surface height profiles obtained by means of a laser scanner (Davidson et al., 2003), or a needle profilometer with photographic recording of the relative needle elevations (Ulaby et al., 1986). Zribi and Deschambre (2002) proposed a new roughness parameter *Zs*, defined by rms^2/L, which is given by the product of the *rms* height and the slope of the soil surface (*rms/L*). Smooth soils correspond in general to small values of Zs (<0.1 cm) whereas ploughed soils correspond to large values of Zs (>0.1 cm). Previous results show that radar signals are strongly dependent on surface roughness, when the latter has small values (*e.g.* Fung, 1994; Baghdadi et al., 2002; Zribi & Deschambre, 2002; Baghdadi et al., 2008). In addition, the sensitivity of radar signals to surface roughness increases with incidence angle. Baghdadi et al. (2002) have shown that high incidence angles (>45°) are best suited to the discrimination between smooth and rough areas, under which conditions it has been shown that the backscattered signal has an exponential dependence on surface roughness (*e.g.* Zribi & Deschambre, 2002; Baghdadi et al., 2008). They also observe that the dependence of the radar signal on surface roughness in agricultural areas is mainly significant for low levels of roughness and it is difficult to discriminate between roughnesses greater than around 1.5 cm with C-band SAR sensors. It is for this reason that Baghdadi et al. (2002) proposed mapping roughness according to three classes: smooth ($rms \leq 1$ cm), moderately rough (1 cm$<rms<$2 cm) and rough ($rms \geq 2$ cm). Concerning the influence of radar wavelength on the backscattered signal, Ulaby et al. (1986) have shown that the discrimination between various roughness classes is significantly better in the L-band than in the C-band or the X-band.

The SAR technique can be used to derive the soil moisture content corresponding to the degree of saturation in the near surface layer. Given that the presence of dense and high vegetation cover prevents X- and C-band radar signals (wavelengths between 3 and 6 cm) from reaching the ground (Ulaby et al., 1986; Fung, 1994), soil moisture mapping is often carried out exclusively on bare soils or zones with little vegetation cover (*e.g.* Baghdadi et al., 2002, 2006, 2007; Le Hégarat et al., 2002; Zribi & Dechambre 2002; Zribi et al., 2008**).** The arrival of the ALOS SAR (L-band) has enabled soil moisture mapping based on SAR data to be extended from bare soils to soils with vegetation (depending on the density and height of the vegetation).

Several methodologies have been developed to map soil moisture at local, regional and global scales, using remote sensing techniques. Scatterometers and passive systems which provide low spatial resolutions (>10 km), but which have a wide spatial coverage and high temporal resolution (daily to weekly), are used for soil moisture mapping on regional and global scales only (*e.g.* Wigneron et al., 1995; Magagi & Kerr, 1997; Wagner & Scipal, 2000; Owe et al., 2008; Zribi et al., 2008), whereas SAR sensors with their fine spatial resolution are used at the watershed scale. The currently operational SAR sensors are PALSAR/ALOS, ASAR/ENVISAT, RADARSAT-1/2, ERS-2, TerraSAR-X, and CosmoSkyMed. ERS, RADARSAT-1, and ASAR, all of which have been widely used for retrieving soil moisture (*e.g.* Le Hégarat et al., 2002; Satalino et al., 2002; Zribi & Dechambre, 2002; Alvarez et al., 2005; Baghdadi et al., 2006, 2007, 2008; Zribi et al., 2007). The most recent SAR sensors (ALOS, RADARSAT-2, TerraSAR-X and Cosmo-SkyMed) are in their evaluation phase. The increasing number of SAR satellites and the short revisit interval of new sensors (TerraSAR-X and Cosmo-SkyMed) now make it possible to map soil moistures with high temporal frequencies (daily to weekly).

Many semi-empirical and physical models have been developed for the estimation of soil moisture and surface roughness from SAR data (*e.g.* Fung, 1994; Dubois et al., 1995; Weimann et al., 1998; Le Hégarat et al., 2002; Oh, 2004; Baghdadi et al., 2006; Zribi et al., 2007). The physical approach uses a backscattering model capable of reproducing the radar signal from radar parameters (wavelength, polarization, and incidence angle) regardless of soil characteristics (soil moisture and surface roughness for bare soils). The Integral Equation Model (IEM) (Fung, 1994) is one of the models most widely used in inversion procedures for retrieving soil moisture and/or roughness parameters. It is applicable to a wide range of the surface roughness values encountered on agricultural soils. The second approach is empirical, based on a large set of experimental data, in order to establish experimental relationships linking the backscattering coefficient to soil surface characteristics and to the instrumental parameters of the radar sensors (*e.g.* Dubois et al., 1995; Weimann et al., 1998; Le Hégarat et al., 2002; Oh, 2004; Baghdadi et al., 2006; Zribi et al., 2007).

Soil moisture retrieval from single frequency, single incidence, and single polarization backscattering observations requires the data to have a minimal sensitivity to other soil surface parameters (mainly surface roughness). Several studies using SAR in the C-band have shown that when using only one radar channel, the best soil moisture estimations are obtained with images acquired at low and medium incidence angles, ≤35° (*e.g.* Zribi & Dechambre 2002; Srivastava et al., 2003; Baghdadi et al., 2006). Such optimal incidence angle conditions can be attained with current SAR sensors several times per week. The combination of two SAR images, acquired at respectively low (~20°) and high (~40°) incidence angles, makes it possible to eliminate the effects of roughness and thus to improve the accuracy of soil moisture estimations (*e.g.* Zribi & Dechambre, 2002; Srivastava et al., 2003; Baghdadi et al., 2006). The root mean square error (RMSE) in soil moisture estimation is approximately 6% for data taken at a single angle of incidence, as opposed to about 3.5% for data taken at two incidence angles. Orbiting SAR sensors are not able to provide simultaneous acquisition of images of the same surface area, at two different incidence angles. However, the new sensors TerraSAR-X and Cosmo-SkyMed can acquire two SAR images within an interval of one day, compared with one week for ASAR and RADARSAT-1 (in high spatial resolution mode). Finally, the very high spatial resolution (metric) of recent SAR sensors (TerraSAR-X, Cosmo-SkyMed) offers great potential in terms of improving the quality with which surface soil characteristics can be mapped. These new sensors can provide a diagnosis suited to catchment basins where the parcels are of small size, and can enable improved characterization at the inter-parcel scale.

Table 1
Main characteristics of SAR images, and summary of ground-truth measurements used in this study

Date (dd-mm-yy)	Time UTC	Sensor	Site	Incidence angle	Polarization	Number of measurements	Range of *mv* (%)	Range of ρ (g/cm^3)	Range of *rms* (cm)	Range of *L* (cm)
15-01-08	17:51	TerraSAR-X	Villamblain	52°	HH	10 *rms* ;8 *mv*	[27.1–32.0]	[1.12–1.24]	[0.42–3.01]	[2.32–8.51]
16-01-08	17:34	TerraSAR-X	Villamblain	28°	HH	10 *rms* ;8 *mv*	[27.8–32.4]	[1.12–1.24]	[0.42–3.01]	[2.32–8.51]
06-02-08	17:51	TerraSAR-X	Villamblain	52°	HH	15 *rms* ;12 *mv*	[26.7–34.5]	[1.06–1.18]	[0.42–3.11]	[2.32–9.13]
07-02-08	17:34	TerraSAR-X	Villamblain	28°	HH	15 *rms* ;12 *mv*	[26.7–34.5]	[1.06–1.18]	[0.42–3.11]	[2.32–9.13]
03-02-08	10:12	ASAR	Orgeval	23°	HH , VV	12 *rms*	–	–	[0.55–3.29]	[3.99–9.30]
12-02-08	17:43	TerraSAR-X	Orgeval	50°	HH	12 *rms* ;12 *mv*	[31.3–40.9]	[1.23–1.43]	[0.55–3.29]	[3.99–9.30]
12-02-08	22:04	PALSAR	Orgeval	38°	HH	12 *rms* ;12 *mv*	[31.3–40.9]	[1.23–1.43]	[0.55–3.29]	[3.99–9.30]
13-02-08	17:26	TerraSAR-X	Orgeval	26°	HH	12 *rms* ;12 *mv*	[30.9–40.4]	[1.23–1.43]	[0.55–3.29]	[3.99–9.30]
15-02-08	06:09	TerraSAR-X	Orgeval	26°	HH	12 *rms* ;12 *mv*	[30.5–39.5]	[1.23–1.43]	[0.55–3.29]	[3.99–9.30]

rms and *L* represent the *rms* surface height and the correlation length, respectively. *mv* is the volumetric soil moisture measured at a depth of 5 cm, and ρ is the dry soil bulk density.