SOIL MOISTURE ESTIMATION USING MULTI-INCIDENCE AND MULTI-POLARIZATION ASAR DATA

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ABSTRACT

The potential of Advanced Synthetic Aperture Radar (ASAR) for the retrieval of surface soil moisture over bare soils was evaluated for several ASAR acquisition configurations: (1) one date/single channel (one incidence and one polarization), (2) one date/two channels (one incidence and two polarizations), (3) two dates/two channels (two incidences and one polarization), and (4) two dates/four channels (two incidences and two polarizations). The retrieval of soil moisture from backscattering measurements is discussed, using empirical inversion approaches. When compared with the results obtained with a single polarization (HH or HV), the use of two polarizations (HH and HV) does not enable a significant improvement in estimating soil moisture. For the best estimates of soil moisture, ASAR data should be acquired at both low and high incidence angles. ASAR proves to be a good remote sensing tool for measuring surface soil moisture, with accuracy for the retrieved soil moisture that can reach 3.5% (RMSE).

INTRODUCTION

Soil moisture and surface roughness are significant indicators for hydrologic studies and the monitoring of agricultural environments. These parameters play an important role in the distribution of precipitation between runoff and infiltration. The possibility of retrieving these soil parameters has been investigated by using scatterometers, satellites, space shuttles, and airborne synthetic aperture radars [1,2,3,4,6,7,8,9,12]. The launch of the new European Environmental Satellite (ENVISAT) in March 2002, carrying the C-band Advanced Synthetic Aperture Radar (ASAR), should enable the scientific community to improve and increase its ability to retrieve physical parameters, based on ENVISAT's capability of providing images in HH, HV, and VV polarizations (two polarizations are possible simultaneously) and at various incidence angles between 15° and 45°. The objective of the present study is to investigate empirical inversion approaches in order to retrieve volumetric soil moistures for bare soil from ASAR images acquired at various incidence angles and in HH and HV polarizations. This work will enable us to evaluate the potential of the new ASAR sensor for extracting surface soil moisture.

DATA SET

The image data used in this study were acquired by the ASAR SAR between 9 February 2003 and 20 April 2004 over two study sites (16 images, HH and HV polarizations, incidence angle between 20° to 43°). The first lies to the west of Paris, near Villamblain, France (latitude 48° 00` N, longitude 01° 34` E). The second is located near Toulouse in the Touch catchment basin (latitude 43° 27` N, longitude 01° 02` E). The sites are composed mainly of agricultural fields intended for growing wheat and corn. Simultaneously with the radar acquisition, ground truth measurements including soil moisture, surface roughness, and bulk density were performed on several bare soil test fields. Soil moisture content was measured using the gravimetric method (upper 0-5 cm soil layer, 10 locations within each test field). The volumetric soil moistures range from 5.4% to 47.3% with a standard deviation of about ±1.7%. The soil bulk density ranges from 0.86 to 1.66 with a standard deviation of about 0.06. Most of the *in situ* ground measurements of soil moisture were made within ± 2 h of the ASAR overpasses. Soil roughness measurements were also carried out, using a 2 meter-long needle profilometer with a 1-cm sampling interval (10 roughness profiles for each test field : 5 parallel and 5 perpendicular to the row direction). On the basis of these measurements the roughness parameters, such as the root mean square (*rms*) surface height and the correlation length (*L*) were calculated using the mean of all experimental auto-correlation functions, both parallel and perpendicular. The *rms* values fluctuate between 0.5 cm and 3.56 cm; the lowest ones correspond mainly to wheat-sown fields and the highest ones to recently ploughed fields. The data set available for this study consists of about 400 triplets of backscattering coefficient, soil moisture, and surface roughness.

METHODOLOGY

The retrieval of volumetric soil moisture by means of an empirical inversion procedure requires the establishment of experimental calibration relationships between the backscattering coefficient and the soil moisture. ASAR data acquired in various configurations of polarization and incidence angle were used, together with ground measurements conducted over bare soil. The objective of this study was to use empirical approaches to investigate the accuracy of estimates of soil moisture (*mv*). The contributions of polarization and incidence angle (θ) were studied, as well as the combination of multi-incidence and multi-polarization data. Four cases are considered in this study:

- ASAR images acquired on one date, with only one channel: one incidence angle (20°-24°, 34°-37°, 40°-43°) and one polarization (HH, HV).
- ASAR images acquired on one date, with two channels: one incidence (20°-24°, 34°-37°, 40°-43°) and two polarizations (HH, HV).
- ASAR images acquired on two dates, with two channels: two incidences (20°-24°, 34°-37°, 40°-43°) and one polarization (HH, HV).
- ASAR images acquired on two dates, with four channels: two incidences (20°-24°, 40°-43°) and two polarizations (HH, HV).

To retrieve volumetric soil surface moisture (*mv*) from a single radar configuration, it is necessary to establish a relationship between the radar backscattering coefficient ($\sigma°$) and *mv* alone, without having any knowledge of the *rms* surface height. Many studies have found a linear relationship between the radar signal acquired over bare soil surfaces and the soil moisture, up to values of *mv* of around 35% [5]. As a first approximation, the radar backscattering coefficient (in decibels, dB) may be expressed as follows:

$$\sigma^0_{dB} = \delta\, mv + \xi \qquad (1)$$

This simplified relationship ignores the surface roughness. For a given radar frequency, the coefficient δ was observed to be dependent on both radar incidence angle and polarization [5]. The coefficient ξ is primarily controlled by incidence angle, polarization, and surface roughness. The coefficients δ and ξ are often found to be dependent on the catchment basin, and thus different from one basin to another. However, for the same catchment, the slope of the observed linear relationship between radar signal and soil moisture is consistent [6].

To take the surface roughness into account, the radar backscattering coefficient $\sigma°$ (in decibels) of a bare soil can be expressed as the sum of two functions: the first one, *f* (linear), describes its dependence on volumetric surface soil moisture, while the second, *g* (exponential), illustrates the dependence of σ° on *rms* surface height [11,12]:

$$\sigma^0_{dB} = f(mv,\theta,mn,\lambda)_{dB} + g(rms,\theta,mn,\lambda)_{dB} = \delta\, mv + \mu\, e^{-krms} + \tau \qquad (2)$$

where *mn* is the polarization, and k the wave number (≈1.11 cm^{-1} for ASAR).

The data set was divided equally into a calibration set and a validation set. First, empirical relationships between the backscattering coefficients and the ground truth volumetric soil moisture were established for the calibration set. Then the inversion procedure was applied to the validation set to estimate the soil moisture. The validity of this procedure was verified by comparing the output from the inversion procedure with the experimental data. The various cases that were studied for the purpose of estimating *mv* were:

- One date characterized by one incidence and one polarization:

$$mv = \alpha\sigma^0_{mn}(\theta) + \beta \qquad (3)$$

- One date characterized by one incidence and two polarizations (HH and HV). This case allows the benefits of the multi-polarization ASAR configuration to be tested. Solving equation (2) for two polarizations gives:

$$mv = \alpha\sigma^0_{HH}(\theta) + \beta\sigma^0_{HV}(\theta) + \gamma \tag{4}$$

- Two dates characterized by one low incidence and one high incidence, and a single polarization (HH or HV). Solving equation (2) for two incidences leads to:

$$< mv > = \alpha\sigma^0_{mn}(\theta_{low}) + \beta\sigma^0_{mn}(\theta_{high}) + \gamma \tag{5}$$

Several studies have used the ratio $\sigma^0_{HH}(20°)/\sigma^0_{HH}(40°)$ in formulating the inversion procedure, because of the extreme sensitivity of this ratio to surface roughness [10,12]:

$$< mv > = \alpha\sigma^0_{mn}(\theta_{low} \ or \ \theta_{high}) + \beta\left(\frac{\sigma^0_{mn}(\theta_{low})}{\sigma^0_{mn}(\theta_{high})}\right)_{dB} + \gamma \tag{6}$$

This last equation is obtained by combining the σ° described by equation (2) and the ratio of σ° at low and high incidence angles, which follows an exponential function of the *rms* surface height.

where <*mv*> is the mean moisture for two different dates, *mn* = HH or HV, θ is the radar incidence = 20°-24° (θ_{low}), 34°-37°, or 40°-43° (θ_{high}).

- Two dates characterized by two incidence angles (20° and 40°), and two polarizations (HH and HV). In this case, we solve the set of equations based on equation (2):

$$\begin{cases} \sigma^0_{HH}(20°) = \alpha_1\, mv + \beta_1 e^{-krms} + \gamma_1 \\ \sigma^0_{HV}(20°) = \alpha_2\, mv + \beta_2 e^{-krms} + \gamma_2 \\ \sigma^0_{HH}(40°) = \alpha_3\, mv + \beta_3 e^{-krms} + \gamma_3 \\ \sigma^0_{HV}(40°) = \alpha_4\, mv + \beta_4 e^{-krms} + \gamma_4 \end{cases} \tag{7}$$

The various calibration relationships defined by equations (3) to (7) are fitted to the calibration database by using the least squares method.

DISCUSSION

The results obtained in the validation phase with one incidence and one polarization show inversion errors in the estimation of *mv* of about 6% for HH polarization and incidence angles of 20°-24° and 34°-37°. The use of HV polarization for incidence angles of 34°-37° gives slightly poorer results (RMSE about 7%). In contrast, large errors in the retrieved soil moisture are observed for incidences of 40°-43° (RMSE of 9.6% and 9.1% for HH and HV polarizations respectively). This is due to the fact that the radar signal is much more sensitive to surface roughness at high incidence angles. It is therefore preferable to use radar observations at the lowest available incidence angle to estimate the soil moisture of a bare soil surface. The use of both HH and HV polarizations does not improve on the inversion results obtained from a single polarization. Indeed, the RMSE is reduced by about 1% at most for incidence angles of 20°-24°, and remains relatively unchanged for 34°-37° and 40°-43°.

The accuracy of estimates of soil moisture can be improved by about 2% by using ASAR multi-incidence data. In fact, the use of ASAR images at low and high incidence angles allows *mv* estimates with RMSEs of 3.5% to be obtained. Since the data set containing two incidences angles is small (between 17 and 21 points), we used all the points for the calibration phase. Figure 1 shows scatter plots for the estimated and measured *mv* values.

These results appear promising for the development of simplified algorithms for retrieving soil moisture from ASAR data. In the light of this study, the ASAR sensor does not seem to offer any advantage compared to the mono-polarization and multi-incidence RADARSAT-1 sensor. In the future, ASAR images at VV and VH polarizations will be necessary for a comprehensive study of the potential for extracting soil moisture by inversion of ASAR images.

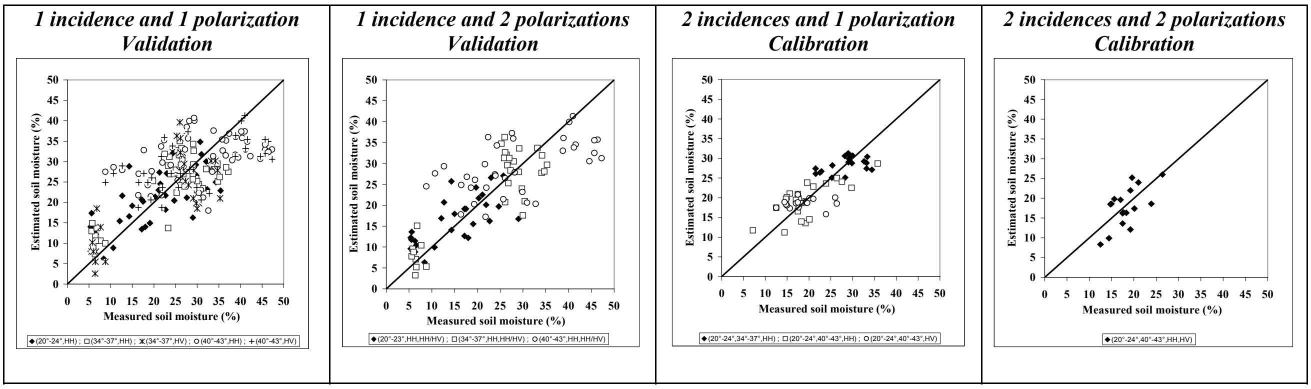

Fig. 1. Comparison between the estimated *mv* values and those measured *in situ*.

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