ELSEVIER

A Simple Algorithm to Retrieve Soil Moisture and Vegetation Biomass Using Passive Microwave Measurements over Crop Fields

Jean-Pierre Wigneron, André Chanzy,† Jean-Christophe Calvet,‡ and Nadine Bruguier**

A simple algorithm to retrieve soil moisture and vegetation water content from passive microwave measurements is analyzed in this study. The approach is based on a zeroth-order solution of the radiative transfer equations in a vegetation layer. In this study, the single scattering albedo accounts for scattering effects and two parameters account for the dependence of the optical thickness on polarization, incidence angle, and frequency. The algorithm requires only ancillary information about crop type and surface temperature. Retrievals of the surface parameters from two radiometric data sets acquired over a soybean and a wheat crop have been attempted. The model parameters have been fitted in order to achieve best match between measured and retrieved surface data. The results of the inversion are analyzed for different configurations of the radiometric observations: one or several look angles, L-band, C-band or (L-band and C-band). Sensitivity of the retrievals to the best fit values of the model parameters has also been investigated. The best configurations, requiring simultaneous measurements at L- and C-band, produce retrievals of soil moisture and biomass with a 15% estimated precision (about 0.06 m^3/m^3 for soil moisture and 0.3 kg/m^2 for biomass) and exhibit a limited sensitivity to the best fit parameters.

*INRA / Bioclimatologie, Montfavet, France
†INRA / Science du Sol, Montfavet, France
‡Météo-France / CNRM, Toulouse, France

Address correspondence to Jean Pierre Wigneron, INRA / Bioclimatologie, 84914 Avignon Cedex 9, France.
Received 1 May 1994; revised 5 September 1994.

REMOTE SENS. ENVIRON. 51:331–341 (1995)

655 Avenue of the Americas, New York, NY 10010

INTRODUCTION

Numerous studies have shown that passive microwave radiometers can be used to estimate surface soil moisture and vegetation biomass (Jackson and Schmugge, 1989; Choudhury et al., 1990; Paloscia and Pampaloni, 1992; Wegmüller, 1993; Wigneron et al., 1993a). Over bare fields, the measured microwave emissivity is almost linearly related to the moisture content of a soil layer whose thickness is dependent on the frequency of the observation [between 1 cm and 5 cm at 5 GHz and 1.4 GHz (Wang, 1987)]. The slope and intercept of this relationship is dependent on the configuration of the observation system (in terms of frequency, incidence angle, and polarization) and on the characteristics of soil (in terms of soil texture and surface roughness) and vegetation. The vegetation cover attenuates soil emission and adds its own contribution to the emitted radiation. In order to reduce the effect of vegetation when estimating soil moisture, low-frequency observations can be used (between 1 GHz and 5 GHz). Nevertheless, for crop fields with dense vegetation coverage the contribution of vegetation can be very important even for L- and C-band observations. The depolarization of the soil-vegetation emissivity increases as the vegetation density increases (depolarized vegetation emission increases whereas polarized soil emission is attenuated by the vegetation layer). The index PDI (polarization difference index) quantifies this effect and can be used to monitor vegetation biomass. Therefore, the low-frequency microwave emissivity of vegetation-covered surfaces contains information about both the vegetation canopy and the underlying soil layer.

Several approaches can be used to retrieve this information. Over a given area, a linear relationship between emissivity and soil moisture can be calibrated

0034-4257 / 95 / $9.50
SSDI 0034-4257(94)00081-W

based on ground measurements (Jackson et al., 1993). Based on satellite data, Teng et al. (1993) estimate the effect of vegetation on this relationship using the polarization difference index PDI. Simple or complex models of the microwave emission of vegetation-covered surface can also be used (Kerr and Wigneron, 1993). The τ–ω model is a simple approach based on two parameters: τ, which represents the optical thickness of the vegetation layer, and the single scattering albedo ω, which models scattering effects inside the canopy. This approach is a zeroth-order solution of the radiative transfer equations since the phase matrix P, which models the effects of multiple scattering, is neglected ($P=0$). It is valid in a low-frequency range where scattering effects inside the vegetation canopy are low (1–5 GHz). More complex models take into account the phase matrix in the radiative transfer equations, based on continuous or discrete modeling of the vegetation medium (Wigneron et al., 1993a,b). These latter approaches have a larger frequency range, up to 20 GHz. Yet, calculations of the phase matrix require several input parameters. Therefore, the use of these approaches to implement retrievals of surface characteristics is more complex.

Several studies have analysed the relationships between the parameters (τ, ω) and the vegetation characteristics for different canopy types (Kirdyashev et al., 1979; Jackson et al., 1982; Brunfeldt and Ulaby, 1984; 1986; Pampaloni and Paloscia, 1986; Mätzler, 1990; Jackson and Schmugge, 1991; Wegmüller et al., 1993). From the literature it can be seen that values of retrieved single scattering albedo are usually less than 0.15 and the time variations of ω are weak during the vegetation growing cycle. The opacity τ is almost linearly related to the integrated vegetation water content W_c (kg m^{-2}) using a factor b_p which is mainly dependent on frequency and on crop type (Jackson and Schmugge, 1991). Using satellite observations over semiarid areas and ancillary data about soil moisture, van de Griend and Owe (1993) found that the retrieved τ is well related to the time variations of vegetation index NDVI. Conversely, Chanzy et al. (1994) used microwave radiometric observations over crop fields and ancillary information about vegetation characteristics (W_c and b) to retrieve soil moisture with a 0.03 m^3/m^3 precision error.

In this study, the ability of the τ–ω model to retrieve *simultaneously* information about both soil moisture and vegetation biomass is analyzed. The algorithm requires very little ancillary information. It requires an estimate of the surface temperature (inferred from thermal infrared observations) and information about crop type. The analysis is based on two sets of radiometric observations which monitored the entire growing cycle of a wheat and a soybean crop. The two canopies have a very different vegetation structure and can be considered as well representative of a variety of agricultural crops. The accuracy of the retrievals of soil moisture and vegetation water content based on simultaneous measurements for different configurations of the observation system (frequencies of 1.4 GHz and 5 GHz and look angles of 8–38°) is investigated.

Therefore, the multiple angle observations over a given area are considered as simultaneous in this study. Spaceborne microwave radiometers with aperture synthesis in the cross- or along-track dimension could acquire such multiple angle measurements. A given region could be viewed at various look angles from distinct orbits (if cross-track measurements are used) or from a single orbit (if along-track measurements are used). For cross-track measurements as reported by Le Vine et al. (1989), the surface parameters would generally change (especially surface temperature and soil moisture) during the time interval between observations for different look angles. In such a case, the multiple angle measurements are not simultaneous and the time interval between the two observations is dependent on the characteristics of both the radiometer and the satellite orbit. Conversely, if the multiple angle observations over a given area by electronically scanned thinned array radiometer are made in the along-track dimension, the measurements could be considered as simultaneous. Also, the present study is based on observations over agricultural fields using ground-based measurements. This situation is quite different from large scale satellite observations over natural areas. However, the results obtained in this work may contribute to better evaluate the potential interest of the L- and C-band to monitor both soil moisture and biomass at a global scale.

MATERIALS AND METHODS

Experimental Data

The study is based on two sets of radiometric data acquired over a soybean and a wheat crop. The measurements monitored the whole vegetation development during a 2.5-month period. Therefore, a large range of soil moisture and vegetation density conditions were observed. Both experiments were conducted on a plot located on the INRA (Institut National de Recherches Agronomiques) Avignon test site (43°55 N, 4°53 E). The plot consists of silty clay loam soil with 62% silt, 11% sand, and 27% clay. The measurements over the soybean field (PORTOS-1991 experiment) were acquired during the summer of 1991 from day of year (DoY) 205 (sowing day) to DoY 273. The radiometric measurements over the wheat field (PORTOS-1993 experiment) were performed during the spring of 1993 from DoY 109 (shortly after seeding on DoY 78) to DoY 189 (shortly before harvest). The observations were acquired using the multifrequency passive microwave radiometer PORTOS (1.4 GHz, 5.05 GHz, 10.65 GHz, 23.8 GHz, 36.5 GHz, and 90 GHz) designed by CNES (Centre

National d'Études Spatiales, France) and Matra Marconi Space in 1990. The radiometer was mounted on a 20-m crane boom and observations were carried out at different incidence angles (from 0° to 50°). The look direction of the radiometer was parallel to the row direction for both crops. During both experiments, absolute calibrations were made over calm water surfaces and over ecosorb slabs either at surrounding temperature or immersed into liquid nitrogen. In 1991, the measured brightness temperatures appeared to be sensitive to the surrounding air temperature. This problem was related to the lack of efficiency of the radiometer thermal control system, which did not maintain a constant internal temperature. In 1992, the thermal control system has been improved and the temperature inside the radiometer was regulated within a 0.5 K error range (Grosjean and Sand, 1994). At 1.4 GHz and 5 GHz, the radiometer absolute accuracy was only about 5–7 K in 1991 and was about 3 K in 1993 based on a single calibration rule for the whole campaign.

During both campaigns, soil and vegetation characteristics were sampled regularly. Twice a week, measurements of dry and wet biomass, water content, height, volume fraction, and geometry of the vegetation canopy have been performed. Measurements of soil moisture content, soil and vegetation temperatures were performed concurrently with the radiometric measurements. Description and analysis of the time variations of the soybean microwave emission and of the ground data have been reported in Wigneron et al. (1993a). A similar analysis of ground data and of wheat microwave emission at 23.8 GHz during the PORTOS-1993 experiment has also been reported (Wigneron et al., 1994). More attention will be paid in this study to the PORTOS-1993 data set, since the radiometric measurements were more numerous and more accurate, and the range of variations of vegetation water content and soil moisture was wider than for the PORTOS-1991 data set. For the wheat field, two periods of time will be considered: [DoY-110 DoY-186] and [DoY-110 DoY-167]. The first period includes all dates of radiometric measurement; the second one includes dates before vegetation dries up in relation with fruit maturity (the gravimetric vegetation moisture content is below 65% after DoY 170).

Retrieval Algorithm

Model Description

The retrieval algorithm is based on the τ–ω model. Using this radiative transfer approach, which neglects the phase matrix, the emitted p-polarized brightness temperature T_{Bp} ($p=v$ for the vertical polarization and $p=h$ for the horizontal polarization) can simply be written as a function of p-polarized terms: ω_p, τ_p, and soil reflectivity $\Gamma^s(\theta,p)$ and of the soil and vegetation temperatures (T_s and T_v):

$$T_{Bp}=(1-\omega_p)(1-\gamma_p)(1+\Gamma^s(\theta,p)\gamma_p)T_v + \{(1-\Gamma^s(\theta,p))T_s+T_{B\mathrm{sky}}\Gamma^s(\theta,p)\gamma_p\}\gamma_p, \quad (1)$$

where γ_p ($p=v$ or $p=h$) is the p-polarized transmissivity of the vegetation layer which can be expressed as a function of the optical thickness τ_p and of the incidence angle θ:

$$\gamma_p=\exp(-\tau_p/\cos\theta). \quad (2)$$

$T_{B\mathrm{sky}}$ is the sky radiometric temperature. At 1.4 GHz and 5 GHz, this term is in a 4–8 K range and a simple approximation of $T_{B\mathrm{sky}}$ can be obtained as a function of the incidence angle, the surface air temperature, and water-vapor density (Ulaby et al., 1981). To account for soil roughness, a modified Fresnel reflection formulation is used to calculate the soil reflectivity $\Gamma^s(\theta,p)$ (Wang and Choudhury, 1981). This formulation is based on two semiempirical parameters, h_r and Q, which model the intensity of the roughness effects and the polarization-mixing effects, respectively:

$$\Gamma^s(\theta,p)=[(1-Q)\Gamma^{\mathrm{spc}}(\theta,p)+Q\Gamma^{\mathrm{spc}}(\theta,q)]\exp(-h_r\cos^2\theta), \quad (3)$$

where $\Gamma^{\mathrm{spc}}(\theta,p)$ is the p-polarized specular reflectivity, which is derived from computations of the soil dielectric properties using a dielectric mixing model (Dobson et al., 1985).

In the present study, the optical thickness τ_p will be considered as linearly related to the vegetation water content W_c (kg m^{-2}):

$$\tau_p=b_p\cdot W_c, \quad (4)$$

where b_p ($p=v$ or $p=h$) is a factor which is mainly dependent on the frequency, the canopy type, and the vegetation dielectric constant (Jackson and Schmugge, 1991). The dependence of b_p on polarization and look angle is not often discussed in the literature. However, for vegetation canopies with a structure dominated by vertical stalks (corn, wheat . . .), γ_p was shown to be a strongly polarized parameter (Ulaby and Wilson, 1985; Brunfeldt and Ulaby, 1986; Ulaby et al., 1987). In such a case, the dependence of γ_p (and therefore of τ_p and b_p) on polarization and look angle should be considered. If scattering interactions between the leaves and the stalks are neglected, the transmissivity of a vegetation canopy can be expressed as the product of stalk and leaf transmissivities:

$$\gamma_p=\gamma_p^{\mathrm{st}}\cdot\gamma_p^{l} \quad (5)$$

where the superscripts st and l stand, respectively, for stalks and leaves. Considering that the leaf transmissivity γ_p^l is almost independent on the polarization p leads to

$$\gamma_v/\gamma_h=\gamma_v^{\mathrm{st}}/\gamma_h^{\mathrm{st}}. \quad (6)$$

Based on a modeling of the vertical stalk layer as a uniaxial crystal (Allen and Ulaby, 1984; Ulaby and Wilson, 1985), the ratio γ_v/γ_h (with γ_v and γ_h expressed in units of dB) can be calculated as a function of the incidence angle θ and of a polarization correction factor C_{pol}:

$$\gamma_v / \gamma_h \,\mathrm{dB} = \gamma_v^{st} / \gamma_h^{st} \,\mathrm{dB} = \cos^2\theta + C_{pol}\sin^2\theta \qquad (7)$$

with

$$C_{pol} = |\mathrm{Im}\{(\varepsilon_z)^{1/2}\}| \,/\, |\mathrm{Im}\{(\varepsilon_x)^{1/2}\}|, \qquad (8)$$

where the dielectric terms ε_x and ε_z are function of the geometric and dielectric properties of the vegetation canopy. The uniaxial crystal model applies to a canopy with thin stalks in comparison with the wavelength of the radiation inside the stalk. The applicability of this model is therefore limited to the lower frequencies (<10 GHz approximately).

From Eqs. (2) and (7), the following expression is obtained:

$$\tau_v / \tau_h = \gamma_v / \gamma_h \,(\mathrm{dB}) = \cos^2\theta + C_{pol}\sin^2\theta. \qquad (9)$$

Note that if $C_{pol} = 1$, the canopy optical thickness is not dependent on polarization and look angle ($\tau_v = \tau_h$). Also, the uniaxial crystal approximation states that τ for H-polarization is not dependent on the incidence angle θ. This result, which is consistent with radiometric observations performed over wheat and corn canopies (Ulaby and Wilson, 1985; Ulaby et al., 1987), will be used in the present study.

Retrieval Methodology

The radiometric data used in this retrieval problem are acquired at 1.4 GHz (L-band) and 5.05 GHz (C-band). Using a simple modeling approach, it was difficult to fit the simulated data to the observations for a large range of look angles. Therefore, the range of incidence angles has been limited to 0–40°, and four specific incidence angles are used in this study (θ = 8°, 18°, 28°, and 38°). Several configurations of the retrieval problem are tested based on the use of:

- A1. two frequencies (1.4 GHz and 5 GHz) and four incidence angles,
- A2. two frequencies (1.4 GHz and 5 GHz) and one incidence angle (38°),
- B1. one frequency (1.4 GHz) and four incidence angles,
- B2. one frequency (1.4 GHz) and one incidence angle (38°),
- C. one frequency (5 GHz) and four incidence angles.

For all the above configurations, both vertical (V) and horizontal (H) polarizations are used. For configurations (A2) and (B2), θ = 38° was chosen in preference to θ = 8° in order to use the information about the depolarization effects due to the above-ground vegetation cover.

During the inversion process, two parameters are retrieved simultaneously: soil moisture m_v (1.4 GHz) and the optical thickness for H polarization τ_h [at 1.4 GHz or at 5 GHz, according to the configuration (A1), . . . (C)]. These two parameters are retrieved for all the dates of radiometric observations. The inversion process is performed through a minimization procedure of the rms error (RMSE^e, where the superscript e stands for emissivity) between the measured and simulated microwave emissivities for every incidence angle and every frequency given by the retrieval configuration. The procedure is based on an iterative optimization routine by the Simplex method, as given by the NAG Fortran library (Numerical Algorithms Group, 1990). Also, note that in this study a 300 K normalizing factor is applied to the values of both measured and simulated emissivity. The 300 K factor is introduced to provide a more concrete estimate of the dynamic range of vegetation emissivity. Measured emissivity is derived from the measured brightness temperature divided by the surface effective temperature T_{eff}. In the present study, an estimate of T_{eff} is inferred from thermal infrared observations. Therefore, ancillary data about surface temperature are required by the inversion algorithm.

The retrieved soil moisture m_v (1.4 GHz) is the moisture content of the soil surface layer which contributes to the passive microwave emission at 1.4 GHz. At 5 GHz, the soil layer which contributes to the emission is thinner and its moisture content m_v (5 GHz) is slightly different of m_v (1.4 GHz). It is possible either to calibrate an approximate relationship between m_v (1.4 GHz) and m_v (5 GHz), or to consider that these two terms are equal. In this study, an empirical polynomial relationship is used, based on the data acquired during the PORTOS-1993 experiment. In order to calibrate this relationship, it is considered that m_v (1.4 GHz) is the moisture content of the 30-mm top layer and that m_v (5 GHz) is the moisture content of the 20-mm top layer:

$$m_v(5\,\mathrm{GHz}) = (-2.9041\,M^2 + 1.7723\,M + 0.7491)\cdot M, \qquad (10)$$

where

$$M = m_v(1.4\,\mathrm{GHz}).$$

The retrievals of τ were carried out for H polarization. The optical thickness for this polarization was considered to be independent of the incidence angle, as discussed in the subsection *Model Description.* In configurations (A1) and (A2), the optical thickness at 5 GHz for H polarization is retrieved [τ_h(5 GHz)]. The other optical thickness [τ_v(5 GHz), τ_v and τ_h(1.4 GHz)] are derived from τ_h(5 GHz). First, considering Eq. (4) is valid at both 1.4 GHz and 5 GHz, τ_h(1.4 GHz) can be derived from τ_h(5 GHz) using a single parameter r_{tau}:

$$\tau_h(1.4\,\mathrm{GHz}) = r_{tau}\cdot\tau_h(5\,\mathrm{GHz}). \qquad (11)$$

Thus, for configurations (A1) and (A2), the choice to retrieve τ_h(5 GHz) rather than τ_h(1.4 GHz) is arbitrary since these two terms are considered as proportional. Second, at L- and C-band the optical thickness for V polarization can be derived from the optical thickness for H polarization using Eq. (9):

$$\tau_v(1.4\,\text{GHz}) = (\cos^2\theta + C_{\text{pol}}(1.4\,\text{GHz})\sin^2\theta)\cdot\tau_h(1.4\,\text{GHz}), \quad (12)$$

$$\tau_v(5\,\text{GHz}) = (\cos^2\theta + C_{\text{pol}}(5\,\text{GHz})\sin^2\theta)\cdot\tau_h(5\,\text{GHz}). \quad (13)$$

For configurations (B1), (B2), and (C) a similar approach is used based on Eqs. (12) and (13). The vegetation water content (W_c) is derived from the optical thickness [τ_h(1.4 GHz) or τ_h(5 GHz) according to the retrieval configuration] using Eq. (4). In this equation, b_p is a free parameter which is fitted. In summary, for every configuration (A1), . . . , (C), the soil moisture content (of a 3-cm top layer) and the vegetation water content are retrieved. The retrieved values are compared with the measured data by calculating the mean rms error (RMSE^r, where the superscript r stands for retrieval) and the mean bias between the measured and retrieved surface parameters.

Several parameters must be known to perform the retrievals: the soil roughness parameters h_r and Q, the single scattering albedos ω(1.4 GHz) and ω(5 GHz), the correction factors C_{pol}(1.4 GHz) and C_{pol}(5 GHz), the ratio r_{tau} [$r_{\text{tau}} = \tau_h(1.4\text{ GHz}) / \tau_h(5\text{ GHz})$], and the factor b_h relating the optical thickness for H polarization to the vegetation water content ($b_h = \tau_h / W_c$). The soil roughness parameters are calibrated using radiometric measurements performed when the crop biomass is very low (at the beginning of the canopy development). The other parameters are fitted in order to minimize RMSE^r and the bias between the measured and retrieved surface parameters during the whole experiment. Best results have been obtained using $\omega(1.4\text{ GHz}) = 0$, for both the wheat and soybean data sets. Plant geometry remains basically the same during the entire growing cycle and the parameters ω(5 GHz), C_{pol}, r_{tau}, and b_p will be considered constant with time.

RESULTS

Wheat Data

Model Parameters

The retrievals of soil moisture m_v(1.4 GHz) and wheat water content W_c were performed for the different configurations (A1), (A2), . . . , (C). As was explained above, the model input parameters were fitted in order to obtain best match between the measured and retrieved surface parameters. For all the configurations, the soil roughness effects could be neglected ($h_r = Q = 0$). This result is consistent with the smooth soil surface. At 5 GHz, the single scattering albedo ω(5 GHz) can be derived from the radiometric measurements over a dense well-developed canopy. Indeed, from Eq. (1) it can be seen that, for high values of the vegetation biomass,

$$\gamma \approx 0 \Rightarrow e_p \approx (1-\omega_p). \quad (14)$$

Using this equation for the wheat data set at nadir ($\theta = 0°$) leads to

$$\omega_h = \omega_v \approx 0.03, \quad (15)$$

and for $\theta = 38°$

$$\omega_v \approx 0.04 \text{ and } \omega_h \approx 0.06. \quad (16)$$

As no simple formulation was found to describe the dependence of ω on polarization and incidence angle, a single approximate value, $\omega_v = \omega_h = 0.04$, is used in this study at 5 GHz. The single scattering albedo together with the other input data: C_{pol}, r_{tau}, and b_p are given in Table 1 for the different configurations. For configurations (A1) and (A2), b_h (5 GHz) is a best-fit parameter and b_h(1.4 GHz) is derived from Eq. (11). No result presented for configurations (B2) and (C) for the retrieval process fails whatever the model parameters. The set of input data of these two configurations includes microwave data acquired at a single frequency (at L- and C-band). In the present study, a failing retrieval attempt will refer to a case when the *retrieval process cannot distinguish the high microwave emission of a dry sparsely vegetated surface from the high emission of a fully developed green vegetation.* Further analyses showed that if the dependence of τ on look angle and polarization is not taken into account at L-band [using configuration (B1) with C_{pol} set equal to 1], the retrieval process fails too. At C-band, the time variations of soil moisture and biomass could hardly be distinguished when the wheat canopy is well developed, due to the high attenuation of soil emission by the dense vegetation layer.

Employing the set of input parameters given in Table 1, the τ–ω model can produce results that match the time variations of wheat emissivity. In Figures 1a–d, the time variations of simulated and measured emissivities are compared at the incidence angle $\theta = 38°$ during the whole PORTOS-1993 campaign (a 300 K normalizing factor is applied to the values of both measured and simulated emissivities). The input parameters for configuration (A1) are used in Figures 1a–b. Figures 1c–d are presented to show the dependence of τ at 1.4 GHz and of ω at 5 GHz on polarization and look angle. At 1.4 GHz, the dependence of τ on polarization and look angle is not taken into account in Figure 1c [$C_{\text{pol}}(1.4\text{ GHz}) = 1$]. It can be seen that the emission for H polarization is overestimated whereas that for V polarization is underestimated. Therefore, the simulations cannot match correctly the observations when using a single value of τ for both polarizations and for all look angles. At 5 GHz, the simulations match much better to the observations than for configuration (A1) if the dependence of ω on polarization and incidence angle is taken into account ($C_{\text{pol}} = 1$, $\omega_v = 0.04$, and $\omega_h = 0.06$ is employed in Fig.

Table 1. Best Fit Model Parameters (Wheat Field)

Configuration	ω(5 GHz)	C_{pol} 1.4 GHz	C_{pol} 5 GHz	r_τ	b(5 GHz)	b(1.4 GHz)
(A1)	0.04	2.6	2.0	0.22	0.57	0.125
(A2)	0.04	2.6	2.0	0.30	0.40	0.12
(B1)	0.04	2.6	–	–	–	0.132

1d whereas $C_{pol}=2$ and $\omega_v=\omega_h=0.04$ in Fig. 1b). For configuration (A1), the mean RMSE^e between measured and simulated emissivities as summed over two frequencies (L- and C-band), four incidence angles, two polarizations, and 43 observation dates is 6.7 K over the period DoY 110–DoY 186. Over the period DoY 110–DoY 167 the error slightly decreases to RMSE^e = 5.4 K. If the dependence of τ on look angle and polarization is not taken into account at L-band [using configuration (A1) with C_{pol} set equal to 1], the error is higher (RMSE^e = 8.4 K and 7.6 K, respectively, for the two periods considered above).

These results show that satisfactory simulations have been obtained, especially if the polarization effects on wheat optical thickness are accounted for. Nevertheless, it can be noted that for L- and C-band, the simulated data overestimate measured wheat emissivity at the end of the wheat growing cycle, during the vegetation drying-up (DoY 165 / DoY 186), especially in Figures 1a and 1d for H polarization. This result can be attributed to the fact that b_h is not constant with time, but slightly decreases as vegetation dries up, probably in relation with the decrease of vegetation dielectric permittivity. In addition, it can be observed in Figures 1a–b that during the period DoY 110 / DoY 125, when the vegetation biomass is very low, the match between the measured and simulated data is not satisfactory. Therefore, part of the rms error given by RMSE^e is also due to the description of soil emission.

Retrieval of the Surface Parameters

Results of the retrievals for the configurations (A1), (A2), and (B1) are given in Table 2. In Table 2, the values of RMSE^r and of the bias between the measured and retrieved surface parameters are calculated for two periods of time: DoY 110–DoY 167 (before the vegetation drying up) and DoY 110–DoY 186 (the entire growing cycle). Good retrievals are obtained for configurations (A1) and (A2). Considering the range of variations is 0.→0.40 (m^3/m^3) for the soil moisture content m_v(1.4 GHz) and 0.→2.6 (kg/m^2) for the vegetation water content W_c (Figs. 2a–b), the retrieval precision error is about 15% for both m_v(1.4 GHz) and W_c. Best results are obtained for configurations (A1) when the radiometric data set includes two frequencies (1.4 GHz and 5 GHz) and four incidence angles (8°, 18°, 28°, 38°). If the observation period is limited to dates before vegetation drying-up (up to DoY 167 approximately), the precision error is minimum for configuration (B1) which includes the sole L-band (RMSE^r≈10%). Therefore, it appears that the simple retrieval algorithm based on the sole L-band is able to monitor vegetation growth as long as the general characteristics of the vegetation canopy do not change much (in terms of structure and moisture content). If these general characteristics change significantly, the assumption that b_h(1.4 GHz) is constant is not valid and the precision error of the retrieval increases.

Sensitivity Analysis

Another aspect of the retrieval must also be studied in order to better analyze the potential interest of the different configurations. The best fit parameters (C_{pol}, r_{tau}, ω, and b_h) are characteristics of the wheat canopy. However, from one field to another within a single crop type, slight variations of these parameters will occur. Therefore, it is also important to investigate to what degree the retrievals are dependent on the value of the best fit parameters. The albedo ω is not fitted since it was derived from Eq. (14). Also, the parameter b_p can be considered as a second-step parameter: it is used to compute the vegetation water content from the retrieved optical thickness τ, but it does not determine if the retrieval process fails or not. Therefore, the sensitivity analysis is carried out only for C_{pol} and r_{tau}. In this study, an estimate of the sensitivity of the retrieved parameter A (A = MV for soil moisture m_v(1.4 GHz) or A = WC for vegetation water content W_c) to the best fit parameter X ($X=C_{pol}$ or $X=r_{tau}$) is provided by the parameter $S_A(X_0)$ defined as follows:

$$S_A(X_0)=[1/\mathrm{RMSE}_A^r(X_0)]\cdot\max(|\mathrm{RMSE}_A^r(X_0)-\mathrm{RMSE}_A^r(X_0+0.2X_0)|,|\mathrm{RMSE}_A^r(X_0)-\mathrm{RMSE}_A^r(X_0-0.2X_0)|), \quad (17)$$

where RMSE$_A^r$ is the rms error between the retrieved and measured parameters A, X_0 is the value (given in Table 1) of the best fit parameter X, which minimizes the function RMSE$_A^r$ (A = MV or A = WC); RMSE$_A^r(X_0)$ is calculated using the best fit parameter X_0 and RMSE$_A^r$ ($X_0 \pm 0.2\ X_0$) is calculated using a 20% increase or decrease in the value of the parameter X_0.

Therefore, $S_A(X_0)$ evaluates the sensitivity of the retrieved parameter A to a ±20% change in the value of the best fit parameter X_0. Results of this sensitivity analysis are given in Table 3. For all the configurations, the sensitivity of the retrieval process to r_{tau} appears to be very important [a 20% change in the value of r_{tau} can lead to a 85% [configuration (A2)] or 46% [configuration

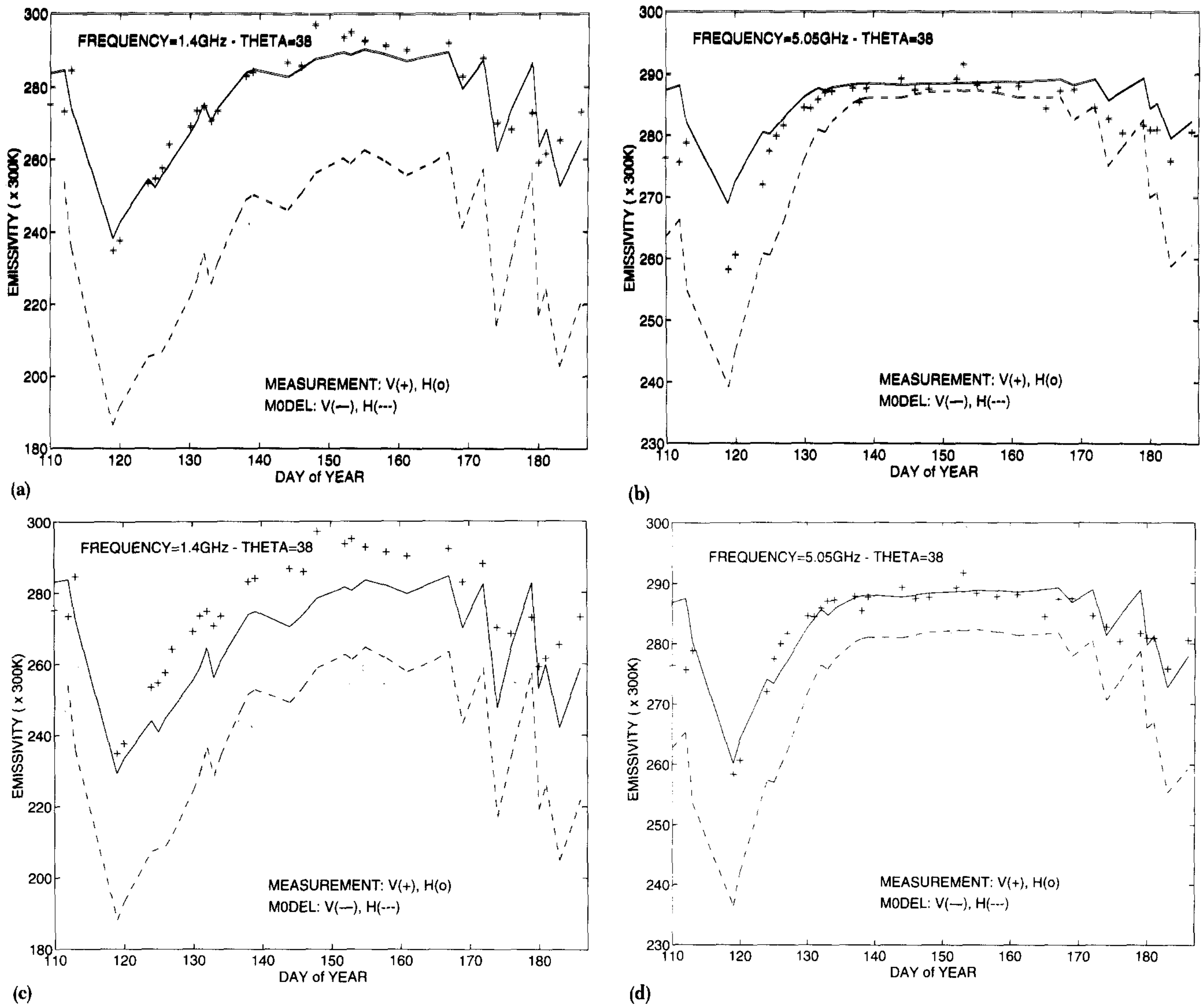

Figure 1. Comparison between simulated and measured wheat emissivities during the PORTOS-1993 campaign using model parameters for configuration (A1) at 1.4 GHz (a), 5 GHz (b), 1.4 GHz with C_{pol} (1.4 GHz) = 1 (c), and 5 GHz with $\omega_v = 0.04$ and $\omega_h = 0.06$ (d).

(A1)] change in the value of $RMSE^r$ for the surface parameters $m_v(1.4)$ and W_c}. The sensitivity of the retrieval process to $C_{pol}(1.4\text{ GHz})$ is important for configurations including a limited set of radiometric data: for configuration (A2), $S_{MV}(X_0) = 35\%$; for configuration (B1) the retrieval process fails if $C_{pol}(1.4\text{ GHz})$ is set equal to 1. Conversely, the effect of the parameter $C_{pol}(5\text{ GHz})$ on the retrieval process is weak for all the configurations.

Soybean Data

The same analysis as that described for the wheat canopy is presented in this section for the soybean canopy.

Table 2. rms Difference and Bias between the Measured and Retrieved Surface Parameters (Wheat Field)

	Soil Moisture [DoY 110–186]		*Vegetation Water Content [DoY 110–186]*		*Soil Moisture [DoY 110–167]*		*Vegetation Water Content [DoY 110–167]*	
Configuration	*RMSE*	*Bias*	*RMSE*	*Bias*	*RMSE*	*Bias*	*RMSE*	*Bias*
(A1)	0.053	0.004	0.242	0.024	0.043	0.015	0.240	0.001
(A2)	0.055	0.004	0.314	0.017	0.044	0.014	0.340	0.019
(B1)	0.061	0.016	0.290	0.011	0.032	0.012	0.200	0.052

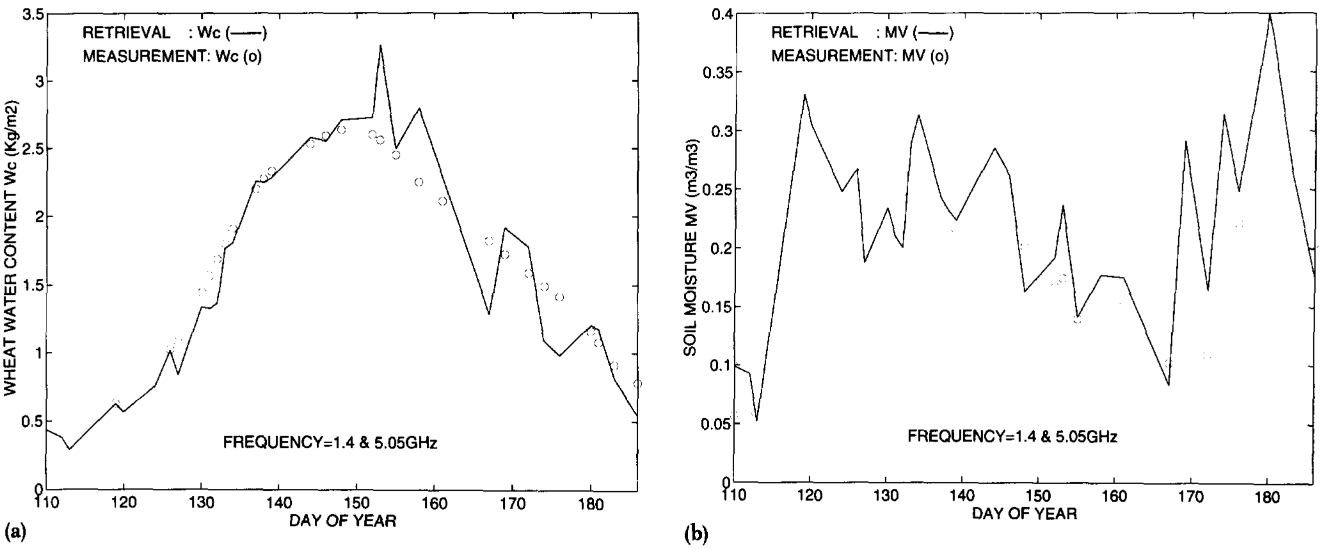

Figure 2. Retrieval for configuration (A1) of wheat vegetation water content W_c (a) and soil moisture m_v (1.4 GHz) (b), during the entire wheat growing cycle (PORTOS-1993 experiment).

Table 3. Sensitivity $S_A(X_0)$ of the Retrieval of the Surface Parameter A to the Model Parameter $X(C_{pol}$ or $r_\tau)$ Based on the Wheat Data Set

Configuration		*Soil Moisture* $S_{MV}(X_0)$ (%)	*Vegetation* W_c $S_{WC}(X_0)$ (%)
(A1)	r_τ	26.1	46.3
	C_{pol}(1.4 GHz)	1.8	2.8
	C_{pol}(5 GHz)	0.0	2.6
(A2)	r_τ	84.2	6.0
	C_{pol}(1.4 GHz)	35.5	14.3
	C_{pol}(5 GHz)	0.7	2.3
(B1)	C_{pol}(1.4 GHz)	14.5	24.0

Results for two configurations are given [configurations (A1) and (A2)]. As for wheat, the retrieval process fails for the configurations including observations for a single frequency. Best-fit parameters for soil roughness are $(h_r, Q)_{\text{L-band}} = (0.1, 0.2)$ and $(h_r, Q)_{\text{C-band}} = (0.1, 0.1)$. Best-fit model parameters for soybean are listed in Table 4. For this leafy vegetation with randomly oriented vegetation scatterers, the optical depth τ was found to be polarization independent [$\tau_v = \tau_h$ at 1.4 GHz and 5 GHz, and therefore $C_{pol}(5\text{ GHz}) = C_{pol}(1.4\text{ GHz}) = 1$]. The ratio $r_{tau} = \tau_h(1.4\text{ GHz}) / \tau_h(5\text{ GHz})$ is higher for soybean than for wheat [for configuration (A1): $r_{tau} = 0.55$ for soybean and $r_{tau} = 0.22$ for wheat]. At L-band, the attenuation effect of vegetation is higher for soybean; at C-band, the result of the comparison is dependent on the configuration which is used [four look angles for (A1) or a single look angle for (A2)]. Scattering effects at 5 GHz are found to be higher for soybean than for wheat ($\omega = 0.11$ for soybean whereas $\omega = 0.04$ for wheat, at C-band). The low value of ω(5 GHz) for wheat can also be interpreted as a result of the strong forward-scattering pattern of the vertical stalks (Mo et al., 1982; Pampaloni and Paloscia, 1986). Using the set of model parameters given by configuration (A1), good visual agreement can be observed between measured and simulated emissivities during the soybean growing season (Figs. 3a–b at L- and C-band for $\theta = 38°$) and RMSE^e between measured and simulated emissivities as summed over 29 observation dates is 6.9 K.

The values of the rms error (RMSE^r) and of the bias between the measured and retrieved surface parameters are presented in Table 5. Again, best retrievals of surface parameters are obtained when both frequencies and four incidence angles are used. For soil moisture retrieval, better results have been obtained for wheat than for soybean. It is likely that this is related to the lower accuracy of the radiometric measurements during the PORTOS-1991 experiment over the soybean field. The

Table 4. Best Fit Model Parameters (Soybean Field)

Configuration	ω*(5 GHz)*	C_{pol} *1.4 GHz*	C_{pol} *5 GHz*	r_τ	*b(5 GHz)*	*b(1.4 GHz)*
(A1)	0.11	1.0	1.0	0.55	0.37	0.20
(A2)	0.11	1.0	1.0	0.40	0.45	0.18

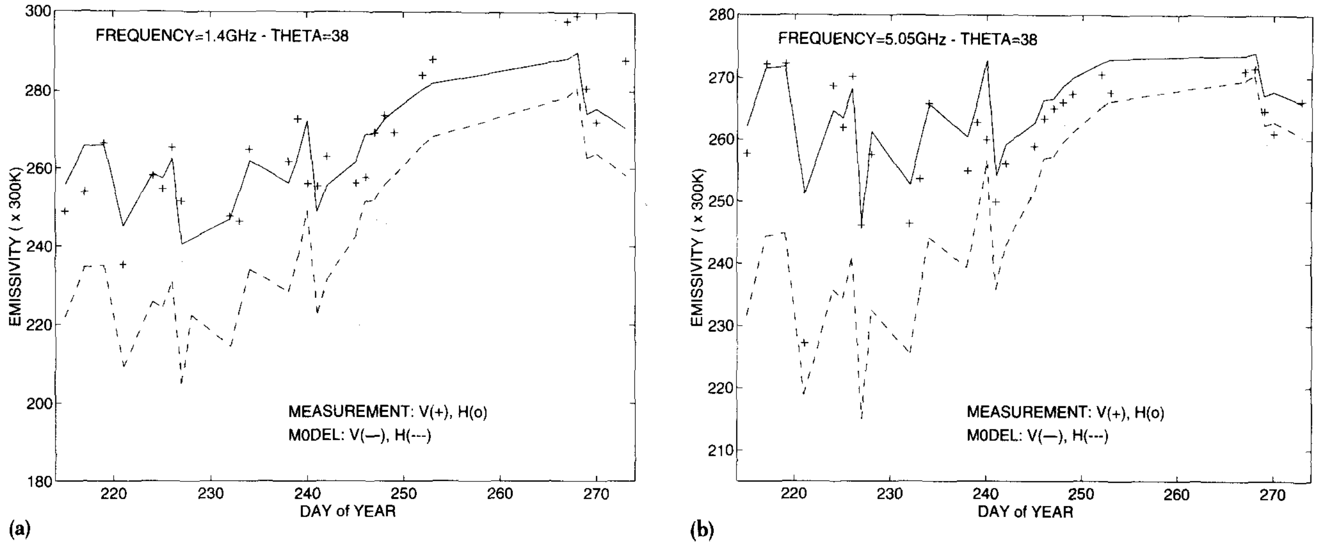

Figure 3. Comparison between simulated and measured wheat emissivities during the PORTOS-1991 campaign using model parameters for configuration A1 at 1.4 GHz (a) and 5 GHz (b).

precision error of the retrievals of W_c for soybean is similar to that of wheat, but the dynamic range of this variable is lower (Fig. 4a–b). When the sole L-band is used, the retrieval attempt fails. Therefore, it appears that, when using only one frequency, the retrieval process is more sensitive to the precision error of the radiometric measurement and to the values of the model input parameters. Though the precision error between the measured and retrieved surface parameters is higher for soybean than for wheat, the stability of the retrieval process confirms the applicability of the algorithm for a leafy vegetation cover.

DISCUSSION AND CONCLUSION

An algorithm developed to retrieve both soil moisture m_v and vegetation water content W_c, and based on simultaneous measurements at L- and C-band, was tested in this study for different configurations of the observation system. The retrieval model is based on a simple zeroth-order radiative transfer approach (τ–ω model). The algorithm requires preliminary calibrations of several input parameters which are considered constant throughout the inversion process. These parameters account for scattering effects [single scattering albedo ω(1.4 GHz) and ω(5 GHz)] and for vegetation attenuation [ratio of the optical thickness at L- and C-band: $r_{tau} = \tau_h(1.4\ \text{GHz}) / \tau_h(5\ \text{GHz})$]. For crops with dominant vertical structure, the effects of polarization and look angle on attenuation are also accounted for using a correction parameter (C_{pol}). These model input parameters are fitted in order to obtain best match between measured and retrieved surface parameters. They are mainly dependent on the canopy structure and have been calibrated for two crops (wheat and soybean). The value of the single scattering albedo ω can be simply derived from observations over well-developed dense canopy. As low incidence angle observations are used ($\theta < 40°$), low values of the albedo ω have been estimated (Mo et al., 1982). In this study, scattering effects could be neglected at L-band. At C-band, the values $\omega = 0.04$ and $\omega = 0.11$ were obtained for wheat and soybean, respectively. For the wheat canopy, it is important to account for the dependence of the optical depth τ on polarization and look angle. For instance, if only the L-band observations are used, the retrieval process failed if C_{pol} was set equal to 1. For the soybean field, the dependence of the attenuation on polarization is much lower due to the random distribution of orientation of leaves and petioles. The values of b appear to be consistent with previously published data sets. For instance, based on previous research, Jackson and Schmugge (1991) reported that b_h is greater for soybean than for wheat and $b_h \approx 0.15$ at 1.4 GHz (at $\theta = 0°$). At 5 GHz, they obtained $b_h \approx 0.15$ for wheat and $b_h \approx 0.35$ for soybean. In this study [$\theta = 38°$, configuration (A2)], the values of b_h are 0.12 and 0.18, respectively, for wheat and soybean at 1.4 GHz. At 5 GHz, $b_h \approx 0.4$ for both crops.

Using best fit values for C_{pol}, r_{tau}, and b_h, the precisions of the retrieval of the surface parameters are compared for different configurations of the microwave

Table 5. rms Difference and Bias between the Measured and Retrieved Surface Parameters (Soybean Field)

	Soil Moisture [DoY 213–273]		*Vegetation W_c [DoY 213–273]*	
Configuration	*RMSE*	*Bias*	*RMSE*	*Bias*
(A1)	0.065	0.016	0.300	−0.009
(A2)	0.080	0.029	0.310	0.003

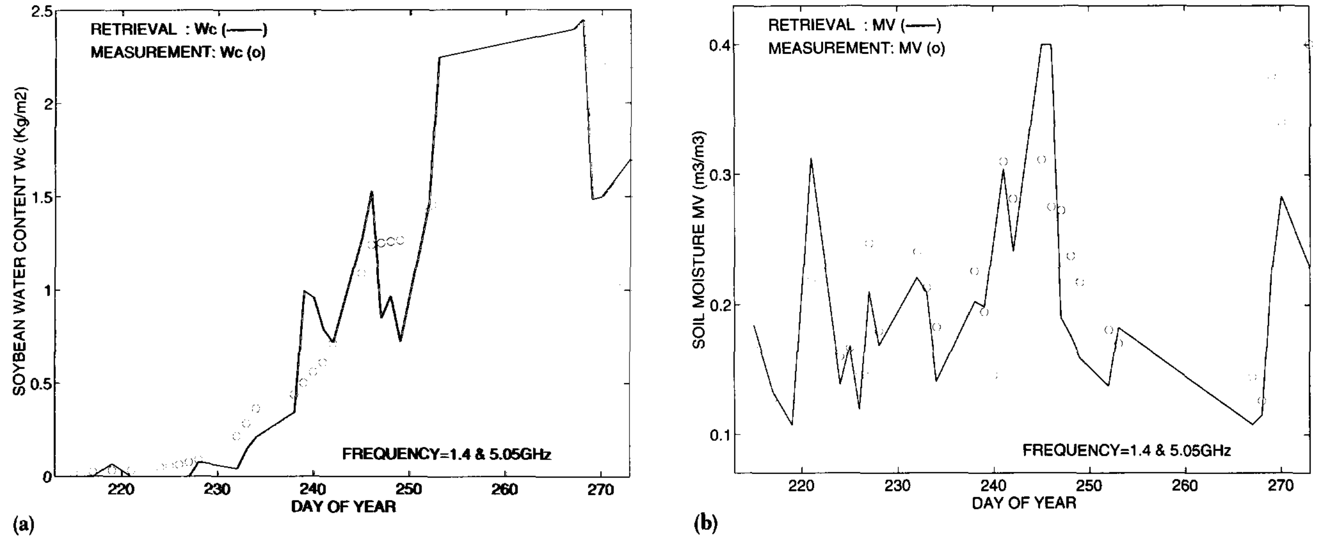

Figure 4. Retrieval for configuration (A1) of soybean vegetation water content W_c (a) and soil moisture m_v (1.4 GHz) (b), during the soybean growing season (PORTOS-1991 experiment).

observations in terms of frequency channels (L- and C-band) and look angles. It is shown that using simultaneous measurements at both L- and C-band for a range of incidence angles between approximately 10° and 40°, good retrievals can be obtained (the precision error is about 15% for both m_v and W_c). If less microwave data are used [using only the L-band (configuration B1), or using only the look angle $\theta = 38°$ (configuration A2)], the retrievals are still possible. Yet, the results are found to be more sensitive to the accuracy of both the microwave data and the calibrated parameters. Therefore, the results obtained in this study illustrate the synergism between the microwave measurements performed for different configurations of the microwave sensor. It is possible to estimate soil moisture using only L-band observations if the measurements are acquired over a range of look angles (from 8° to 38° in this study). For this configuration of the retrieval problem, it is necessary to account for the effect of polarization and incidence angle on the crop optical thickness. If simultaneous microwave data are also acquired at C-band, the retrieval process is more stable (it is less dependent on the best fit model parameters), and the precision of the retrievals of both soil moisture and biomass increased. Conversely, over well-developed crops, the retrievals could not be carried out in the case of the following configurations (if the whole vegetation cycle is considered):

- at C-band,
- at L-band for a single look angle ($\theta = 38°$ in this study).

Further investigations are required to analyze the dependence of the retrieval process on the best-fit parameters. For instance, it is important to know whether a set of input parameters derived from measurements over a given wheat canopy is also appropriate for all wheat fields, whatever the experimental conditions (relative direction of the radiometer look and of the canopy rows, stalk density, canopy height, etc.). Also, the results have been derived from measurements over dense crop canopies. For surfaces with sparse vegetation cover, a similar algorithm might also be constructed from measurements at smaller wavelengths (C- and X-band for example).

This study has shown that simultaneous bi-polarized measurements at L- and C-band have the potential of monitoring both soil moisture and vegetation biomass. Furthermore, if multiple angle measurements are available, the retrieval process appears to be more accurate and more stable. Ancillary data are also required. They include an estimate of the surface temperature, which can be inferred from thermal infrared observations, and information about the crop type. Electronically thinned array radiometers, could be capable of meeting at these configuration requirements. Therefore, in view of the future spaceborne remote sensing platforms that are being developed to obtain data needed to understand the global scale processes that govern the Earth's environment (Earth Observing System), this study supports the use of low-frequency (L- and C-band), bipolarized, and multiple-angle passive microwave observations.

This study was enabled thanks to the financial support of the Programme National de Télédétection Spatiale (PNTS) and of the Centre National d'Etudes Spatiales (CNES), France. The authors gratefully acknowledge the assistance of O. Grojean and the PORTOS team (CNES) during the microwave observation campaigns. The authors also with to thank the anonymous reviewers for their useful comments and corrections.

REFERENCES

Allen, C. T., and Ulaby, F. T. (1984), Modeling the polarization dependence of the attenuation in vegetation canopies, in *IEEE Int. Geosci. Remote Sens. Symp. IGARSS'84 Dig.*, Strasbourg, France, 27–30 Aug.

Brunfeldt, D. R., and Ulaby, F. T. (1984), Measured microwave emission and scattering in vegetation canopies. *IEEE Trans. Geosci. Remote Sens.* 22:520–524.

Brunfeldt, D. R., and Ulaby, F. T. (1986), Microwave emission from two crops. *IEEE Trans. Geosci. Remote Sens.* 24:353–359.

Chanzy, A., Haboudane, D., Wigneron, J.-P., Calvet, J.-C., and Grosjean, O. (1994), Radiométrie micro-onde sur divers types de couverts végétaux: influence de l'humidité du sol, in *Proceedings of the 6th International Symposium Physical Measurements and Signatures in Remote Sensing*, Jan., Val d'Isère, France.

Choudhury, B. J., Wang, J. R., Hsu, A. Y., and Chien, Y. L. (1990), Simulated and observed 37 GHz emission over Africa, *Int. J. Remote Sens.* 11:1837–1868.

Dobson, M. C., Ulaby, F. T., Hallikainen, M. T., and El-Reyes, M. A. (1985), Microwave dielectric behavior of wet soil—Part II: Dielectric mixing models, *IEEE Trans. Geosci. Remote Sens.* 23:35–46.

Grosjean, O., and Sand, A. (1994), Etalonnage du radiomètre hyperfréquence PORTOS et méthode de correction des mesures, in *Proceedings of the 6th International Colloquium Physical Measurements and Signature in Remote Sensing*, Val d'Isère, France.

Jackson, T. J., and Schmugge, T. J. (1989), Passive microwave remote sensing system for soil moisture: some supporting research, *IEEE Trans. Geosci. Remote Sens.* 27:225–235.

Jackson, T. J., and Schmugge, T. J. (1991), Vegetation effects on the microwave emission of soils, *Remote Sens. Environ.* 36:203–212.

Jackson, T. J., Schmugge, T. J., and Wang, J. R. (1982), Passive microwave sensing of soil moisture under vegetation canopies, *Water Resour. Res.* 18:1137–1142.

Jackson, T. J., Le Vine, D. M., Griffis, A. J., et al. (1993), Soil moisture and rainfall estimation over a semiarid environment with the ESTAR microwave radiometer, *IEEE Trans. Geosci. Remote Sens.* GE-31(4):836–841.

Kerr, Y. H., and Wigneron, J.-P. (1993), Vegetation models and observations—a review, In *Proceedings of the ESA / NASA International Workshop on Passive Microwave Remote Sensing Research Related to Land-Atmosphere Interactions* 11–15 Jan., Saint-Lary, France, forthcoming.

Kirdiashev, K. P., Chukhlantsev, A. A., and Shutko, A. M. (1979), Microwave radiation of the earth's surface in the presence of vegetation cover, *Radiotekhnika* 24:256–264; also NASA Tech. Trans. TM-75469.

Le Vine, D. M., Wilheit, T. T., Murphy, R. E., and Swift, C. T. (1989), A multifrequency microwave radiometer of the future, *IEEE Trans. Geosci. Remote Sens.* 27(2):193–199.

Mätzler, C. (1990), Seasonal evolution of microwave radiation from an oat field, *Remote Sens. Environ.* 31:161–173.

Mo, T., Choudhury, B. J., Schmugge, T. J., Wang, J. R., and Jackson, T. J. (1982), A model for microwave emission from vegetation-covered fields, *J. Geophys. Res.* 87:11,229–11,237.

Numerical Algorithms Group Inc. (NAG) (1990), NAG Fortran Workstation library handbook, NAG Ltd., Oxford, United Kingdom.

Paloscia, S. and Pampaloni, P. (1992), Microwave vegetation indexes for detecting biomass and water conditions of agricultural crops, *Remote Sens. Environ.* 40:15–26.

Pampaloni, P., and Paloscia, S. (1986), Microwave emission and plant water content: a comparison between field measurements and theory, *IEEE Trans. Geosci. Remote Sens.* GE-24:900–905.

Teng, W. L., Wang, J. R., and Doraiswamy, P. C. (1993), Relationship between satellite microwave radiometric data, antecedent precipitation index, and regional soil moisture, *Int. J. Remote Sens.* 14(13):2483–2500.

Ulaby, F. T., and Wilson, E. A. (1985), Microwave attenuation properties of vegetation canopies, *IEEE Trans. Geosci. Remote Sens.* 23:746–753.

Ulaby, F. T., Moore R. K., and Fung, A. K. (1981), *Microwave Remote Sensing—Active and Passive*, Addison-Wesley, Reading, MA, Vol. I.

Ulaby, F. T., Tavakoli, A., and Senior, T. B. A. (1987), Microwave propagation constant for a vegetation canopy with vertical stalks, *IEEE Trans. Geosci. Remote Sens.* 25:714–725.

van de Griend, A. A., and Owe, M. (1993), Determination of microwave vegetation optical depth and single scattering albedo from large scale soil moisture and Nimbus / SMMR satellite observations, *Int. J. Remote Sens.* 14(10):1875–1886.

Wang, J. R. (1987), Microwave emission from smooth bare fields and soil moisture sampling depth, *IEEE Trans. Geosci. Remote Sens.* 25:616–622.

Wang, J. R., and Choudhury, B. J. (1981), Remote sensing of soil moisture content over bare field at 1.4 GHz frequency, *J. Geophys. Res.* 86:5277–5282.

Wegmüller, U. (1993), Signature research for crop classification by active and passive microwaves, *Int. J. Remote Sens.* 14(5):871–883.

Wegmüller, U., Mätzler, C., and Njoku, E. (1993), Canopy opacity models, in *Proceedings of the ESA / NASA International workshop on Passive Microwave Remote Sensing Research Related to Land-Atmosphere Interactions*, 11–15 Jan., Saint-Lary, France, forthcoming.

Wigneron, J.-P., Kerr, Y. H., Chanzy, A., and Jin, Y. Q. (1993a), Inversion of surface parameters from passive microwave measurements over a soybean field, *Remote Sens. Environ.* 46:61–72.

Wigneron, J.-P., Calvet, J.-C., Kerr, Y. H., Chanzy, A., and Lopes, A. (1993b), Microwave emission of vegetation: sensitivity to leaf characteristics, *IEEE Trans. Geosci. Remote Sens.* GE-31(3):716–726.

Wigneron, J.-P., Calvet, J.-C., and Chanzy, A. (1994), A composite Discrete-Continuous approach to model the microwave emission of vegetation, *IEEE Trans. Geosci. Remote Sens.* GE-33:201–211.