Sensitivity of Passive Microwave Observations to Soil Moisture and Vegetation Water Content: L-Band to W-Band

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***Abstract*—Ground-based multifrequency (L-band to W-band, 1.41–90 GHz) and multiangular (20°–50°) bipolarized (V and H) microwave radiometer observations, acquired over a dense wheat field, are analyzed in order to assess the sensitivity of brightness temperatures (T_b) to land surface properties: surface soil moisture (m_v) and vegetation water content (VWC). For each frequency, a combination of microwave T_b observed at either two contrasting incidence angles or two polarizations is used to retrieve m_v and VWC, through regressed empirical logarithmic equations. The retrieval performance of the regression is used as an indicator of the sensitivity of the microwave signal to either m_v or VWC. In general, L-band measurements are shown to be sensitive to both m_v and VWC, with lowest root mean square errors (0.04 $\mathrm{m^3 \cdot m^{-3}}$ and 0.52 $\mathrm{kg \cdot m^{-2}}$, respectively) obtained at H polarization, 20° and 50° incidence angles. In spite of the dense vegetation, it is shown that m_v influences the microwave observations from L-band to K-band (23.8 GHz). The highest sensitivity to soil moisture is observed at L-band in all configurations, while observations at higher frequencies, from C-band (5.05 GHz) to K-band, are only moderately influenced by m_v at low incidence angles (e.g., 20°). These frequencies are also shown to be very sensitive to VWC in all the configurations tested. The highest frequencies (Q- and W-bands) are shown to be moderately sensitive to VWC only. These results are used to analyze the response of W-band emissivities derived from the Advanced Microwave Sounding Unit instruments over northern France.**

***Index Terms*—Microwave radiometry, soil moisture, vegetation.**

I. Introduction

PASSIVE microwave remote sensing techniques have applications in monitoring the terrestrial surfaces or the atmosphere, depending on frequency. However, it is not clear to what extent higher frequency observations can be used for soil moisture monitoring. The main motivation of this study is to consolidate previous investigations on the sensitivity of microwave emission at different frequencies, polarizations, or incident angles to soil moisture and vegetation water content (VWC). Clearly, low frequencies (L-band in particular) are sensitive to surface soil moisture m_v [1] and have been selected as the frequency of choice for such measurements. The Soil Moisture and Ocean Salinity mission is a dedicated soil moisture mission using L-band radiometry. However, the extremely high frequencies (e.g., Q- and W-bands) that are routinely used to characterize the atmosphere may also contain useful information on soil moisture content that is hitherto underutilized. For example, over continental areas, brightness temperatures (T_b) at extremely high frequencies require correction for land emissivity in order to retrieve relevant atmospheric information [2], but this land information has not been assessed for its soil moisture information.

For bare soil, microwave brightness temperatures are sensitive to soil moisture at frequencies ranging from L-band to extremely high frequencies, e.g., 90 GHz at W-band [3]. However, vegetation canopies tend to mask the soil microwave emission, with this effect increasing at higher frequencies. While many studies have shown that L-band radiometry is able to retrieve soil moisture over relatively dense canopies (up to 3–5 $\mathrm{kg \cdot m^{-2}}$), it has also been shown that C- and X-band observations can be used over areas where vegetation is not too dense (for a review, see [4]). However, microwave brightness temperatures may become dominated by vegetation characteristics at higher frequencies. For example, Wigneron *et al.* [5] have shown that observations over pine forests at 90 GHz are related to the density of trees, and Prigent *et al.* [6] have suggested that passive microwave observations at K-band (19 GHz) and higher frequencies are sensitive to the vegetation alone, and not to the underlying soil moisture.

The objective of this study is to assess the extent to which C-band and higher frequencies are sensitive to surface soil moisture under dense vegetation and to compare the soil moisture sensitivity with the sensitivity to the VWC. Since the findings of Prigent *et al.* [6], showing a lack of sensitivity to soil moisture for observations at K-band and higher frequencies, are based on the analysis of satellite data, the use of ground-based microwave observations in this paper, measured under controlled m_v and VWC conditions, can contribute to consolidate those results. The Portos-93 experiment [1] is used for this

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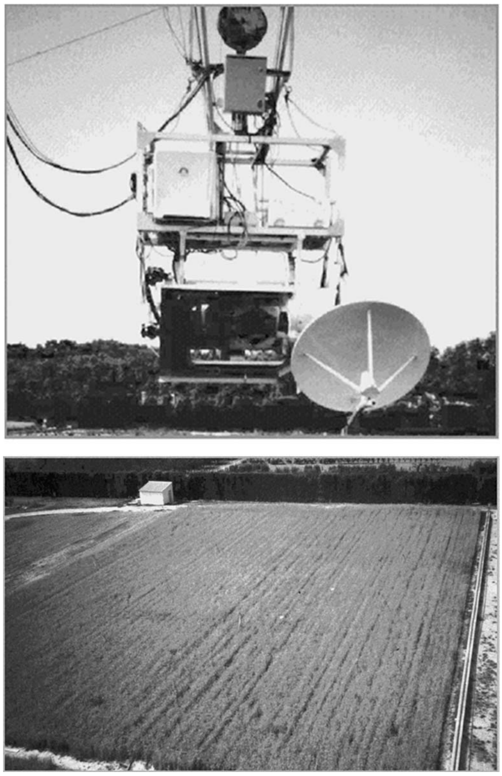

Fig. 1. PORTOS-93 experiment. (Top) PORTOS multifrequency microwave radiometer, mounted on a crane. (Bottom) Dense wheat field observed by the PORTOS instrument from April to July 1993.

purpose, which gathered microwave brightness temperatures over several surface types at various frequencies and at various incidence angles. In this study, the sensitivity of ground-based passive microwave observations from the Portos-93 database to m_v and VWC is assessed for a dense wheat field.

II. Portos-93 Data

The Portos-93 experiment [1] was carried out from April 1, 1993 to July 10, 1993 at Avignon, France $(43°55' \mathrm{N}, 4°53' \mathrm{E})$. The Portos instrument was a multifrequency (1.41, 5.05, 10.65, 23.8, 36.5, and 90 GHz, or L-, C-, X-, K-, Q-, and W-bands, respectively) dual-polarized (V and H polarizations) microwave radiometer. Portos was set up on the boom of a mobile crane (20 m high), and the microwave emissions of different surface types were observed at several incidence angles, from 0° to 60°. During the experiment, soil and vegetation samples were regularly collected in order to monitor m_v and VWC by gravimetric techniques. The data examined in this study were acquired on a wheat field (Fig. 1). The wheat field was monitored during the growing period and during the senescence. At the end of the growing period, the VWC of the crop reached a value close to $3\ \mathrm{kg} \cdot \mathrm{m}^{-2}$.

Fifty-one variables are used in this study: VWC, surface (0–0.5 cm) soil moisture (m_v), V- and H-polarized brightness temperatures (T_b) at six frequencies and four incidence angles (20°, 30°, 40°, and 50°), and the infrared temperature (T_{IR}). T_{IR} was measured with a Heiman KT15 infrared thermometer fixed to the Portos instrument, at the same incidence angles (20°, 30°, 40°, and 50°). T_{IR} varies between 17 °C and 38 °C across the four-month experiment.

Since the microwave observations are performed on a crane, 20 m above the surface, rather than from a satellite, weather conditions have little impact on the brightness temperatures. However, it must be noted that T_b's include, apart from the direct emission of the surface, a downwelling atmospheric and cosmic emission term, reflected by the surface. During the PORTOS experiment, it was not possible to measure the downwelling sky brightness with the radiometer. An attempt was made by Calvet *et al.* [3], [7] to estimate the contribution of atmospheric and cosmic emissions, over relatively specular surfaces (smooth bare soil with little or no vegetation), based on simulations of the atmosphere characteristics from a numerical weather prediction model and from *in situ* observations of the cloud coverage. In this study, a more complex surface is considered, and it is difficult to quantify the exact reflected component of the sky emission. Therefore, the sky emission was not removed from the T_b. For a large proportion (85%) of the PORTOS observations, the look direction of the radiometer was parallel to the row direction of the wheat field. In this study, all the observations were used, irrespective of the look direction. However, separate analysis (not shown) has concluded that using the observations with parallel look and row directions had little difference on the results to using all the results together. It was not possible to assess the results obtained using the observations with orthogonal look and row directions only, as those observations did not cover the range of configurations considered in this study.

In order to illustrate the time variations of these variables, Fig. 2 shows m_v and VWC throughout the experiment, together with the V-polarized T_b measured by Portos at six frequencies, for two contrasting incidence angles (20° and 50°). In this data set, no correlation is observed between m_v and VWC.

III. Methods

Biophysical variables can be retrieved from microwave T_b. The use of bipolarization and multiangular observations permits simultaneous retrieval of several variables, e.g., m_v and VWC [1], [8]. The vegetation effects can be modeled with the $\tau-\omega$ model [1], [9], [10]. The retrieval method may be based either on a physical model (e.g., the $\tau-\omega$ model associated to a soil emission model), to be inverted through optimization methods [11], or on linear combinations of T_b indices [12]. Wigneron *et al.* [13] have shown that the $\tau-\omega$ model can be used to build semiempirical statistical relationships between m_v and microwave emissivities observed at two contrasting incidence angles and that these relationships may be used for retrieval purposes.

Saleh *et al.* [14] performed a comparison of index-based methods and semiempirical regression methods at L-band. The semiempirical regression methods consisted of either single configurations (one incidence angle, one polarization) or multiple configurations (one polarization and two angles, or two polarizations and one angle). The best m_v retrievals were obtained with the multiple configuration regressions (either biangular or bipolarization). In addition, Saleh *et al.* [14] showed that the multiple configuration regression method

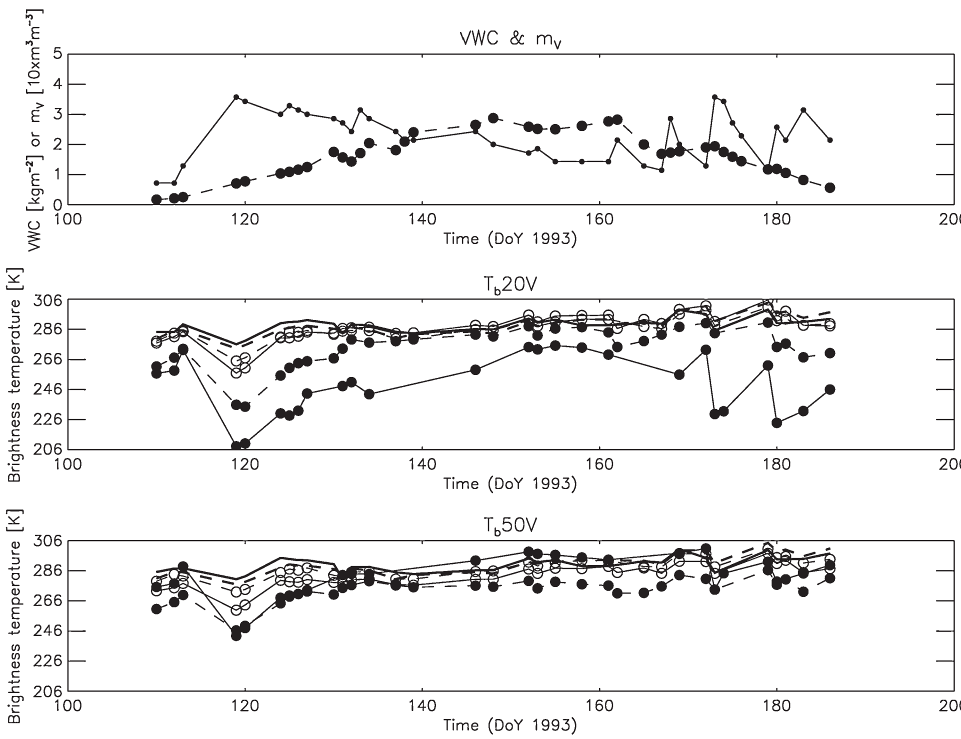

Fig. 2. Example of variables observed over a wheat field during the PORTOS-93 experiment. From top to bottom: VWC and surface soil moisture measured at 2.5 cm (m_v) and V-polarized brightness temperatures (T_b) at two incidence angles of 20° and 50° for six frequencies (1.41 GHz, closed circles and solid line; 5.05 GHz, closed circles and dashed line; 10.65 GHz, open circles and solid line; 23.8 GHz, open circles and dashed line; 36.5 GHz, solid line; 90 GHz, dashed line).

may be used to retrieve the optical depth of the canopy, which is dependent on the VWC.

In this study, the multiple configuration regression method is used to assess the sensitivity of the Portos microwave observations to either m_v or VWC at various frequencies. The following equations (adapted from [14]) are used:

$$VWC = \exp\left(A_{VWC}\ln\left(1-\frac{T_b(\theta_1,p)}{T_{\rm IR}}\right)\right.$$
$$\left.+B_{VWC}\ln\left(1-\frac{T_b(\theta_2,q)}{T_{\rm IR}}\right)+C_{VWC}\right) \quad (1)$$

$$m_v = \exp\left(A_{m_v}\ln\left(1-\frac{T_b(\theta_1,p)}{T_{\rm IR}}\right)\right.$$
$$\left.+B_{m_v}\ln\left(1-\frac{T_b(\theta_2,q)}{T_{\rm IR}}\right)+C_{m_v}\right). \quad (2)$$

Equations (1) and (2) are used in either biangular $(\theta_1 \neq \theta_2, p = q)$ or bipolarization $(\theta_1 = \theta_2, p \neq q)$ configurations. The regression coefficients $A_{VWC}, B_{VWC}, C_{VWC}$ and $A_{m_v}, B_{m_v}, C_{m_v}$ may vary from one configuration to another and may depend on the soil and vegetation characteristics [14]. It must be noted that wheat is a crop presenting a marked vertical structure (vertical stems in particular) which influences the response of the canopy scattering effects to polarization and to incidence angle [1]. Four biangular approaches are considered, with $\theta_1 = 50°$ or $\theta_1 = 40°$, and $\theta_2 = 20°$, and $p = q = \mathrm{V}$ or $p = q = \mathrm{H}$ (denoted as 50V20V, 40V20V, 50H20H, and 40H20H, respectively). Four bipolarization approaches are considered, with $\theta_1 = \theta_2 = 50°$, 40°, 30°, or 20° (denoted as 50VH, 40VH, 30VH, and 20VH, respectively). The regression coefficients are not derived from simulations of the τ–ω model as in [13]. Instead, the regressions are based on the observed m_v, VWC, T_b, and $T_{\rm IR}$. The quality of the regression is used as an indicator of the sensitivity of the microwave observations to either m_v or VWC. Three scores are considered: the squared correlation coefficient (r^2), the root mean square error (rmse), and the Fisher's F-test p-value.

IV. RESULTS

Table I and Figs. 3 and 4 present the results obtained for the 50V20V biangular configuration.

1) The VWC retrievals from (1) are significantly correlated to the observations (p-value < 0.05) at all the frequencies. The rmse ranges between 0.5 and 0.8 kg $\cdot$ m^{-2}. The best scores (denoting the highest sensitivity to VWC) were obtained at C-, X-, and K-bands, with rmse values close to 0.5 kg $\cdot$ m^{-2} and r^2 values higher than 0.6.
2) The m_v retrievals from (2) are significantly correlated to the observations (p-value < 0.05) at L- and C-bands only. The best correlation was obtained at L-band $(r^2 = 0.65)$. At L- and C-bands, rmse values of 0.054 and 0.076 m$^3 \cdot$ m^{-3} were obtained, respectively. At higher frequencies, the correlation was not significant.

The use of the horizontal polarization, instead of the vertical polarization, in the 50H20H configuration (Table II)

TABLE I

RESULTS FOR BIANGULAR APPROACH AT V POLARIZATION, 50V20V AND 40V20V, OVER A DENSE WHEAT FIELD AT SIX MICROWAVE FREQUENCIES. RETRIEVAL OF THE VWC AND OF THE SURFACE SOIL MOISTURE: REGRESSION COEFFICIENTS (A_{VWC}, B_{VWC}, C_{VWC} AND A_{m_v}, B_{m_v}, C_{m_v}) AND SCORES (SQUARED CORRELATION COEFFICIENT, F-TEST p-VALUE, AND ROOT MEAN SQUARE DIFFERENCE)

Approach	Variable	Statistics	1.41GHz (L-band)	5.05GHz (C-band)	10.65GHz (X-band)	23.8GHz (K-band)	36.5GHz (Q-band)	90GHz (W-band)
50V20V		n	26	33	33	32	32	33
	VWC	A_{VWC}	-1.282	-0.660	-0.226	-0.359	0.499	0.178
		B_{VWC}	2.001	-0.665	-0.599	-0.714	-1.154	-1.026
		C_{VWC}	-0.296	-3.186	-2.601	-3.429	-2.037	-2.779
		r^2	0.39	0.66	0.62	0.60	0.27	0.18
		p-value	<0.001	$<10^{-6}$	$<10^{-6}$	$<10^{-6}$	<0.01	<0.05
		RMSE (kg m^{-2})	0.68	0.49	0.51	0.51	0.70	0.77
	m_v	A_{VWC}	-0.370	-0.960	-0.114	-0.318	-0.316	-0.092
		B_{VWC}	1.481	0.633	0.185	0.451	0.157	0.044
		C_{VWC}	-0.004	-2.363	-1.275	-1.193	-2.243	-1.793
		r^2	0.65	0.18	0.12	0.09	0.06	0.00
		p-value	$<10^{-6}$	<0.05	NS	NS	NS	NS
		RMSE (m^3 m^{-3})	0.054	0.076	0.080	0.082	0.083	0.085
40V20V		n	26	33	33	32	32	33
	VWC	A_{VWC}	-1.477	-0.814	-0.202	-0.158	0.359	0.159
		B_{VWC}	2.141	-0.429	-0.574	-0.809	-1.017	-0.979
		C_{VWC}	0.222	-3.041	-2.493	-3.048	-2.080	-2.691
		r^2	0.31	0.67	0.64	0.54	0.21	0.22
		p-value	<0.01	$<10^{-6}$	$<10^{-6}$	$<10^{-5}$	<0.01	<0.01
		RMSE (kg m^{-2})	0.82	0.48	0.50	0.57	0.73	0.75
	m_v	A_{VWC}	-0.313	-0.682	-0.018	-0.113	0.082	-0.056
		B_{VWC}	1.276	0.653	0.149	0.273	-0.218	0.028
		C_{VWC}	0.028	-1.673	-1.119	-1.070	-2.086	-1.711
		r^2	0.67	0.14	0.12	0.08	0.01	0.00
		p-value	$<10^{-6}$	<0.05	<0.05	NS	NS	NS
		RMSE (m^3 m^{-3})	0.047	0.078	0.079	0.082	0.085	0.084

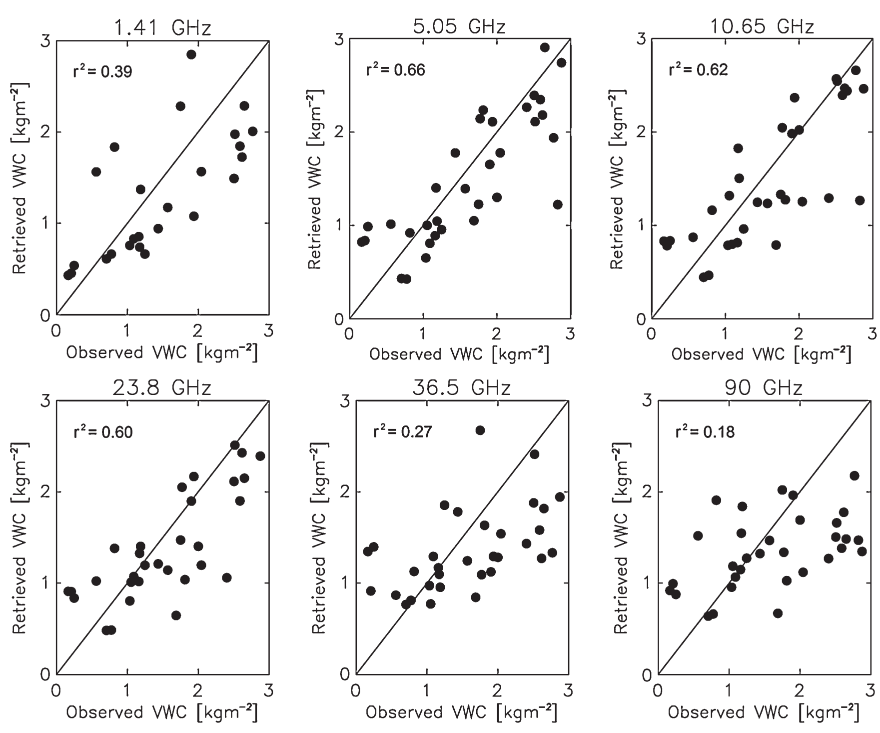

Fig. 3. Retrieved versus observed VWCs at the six frequencies observed, using a biangular approach (50° and 20°) at V polarization, i.e., 50V20V.

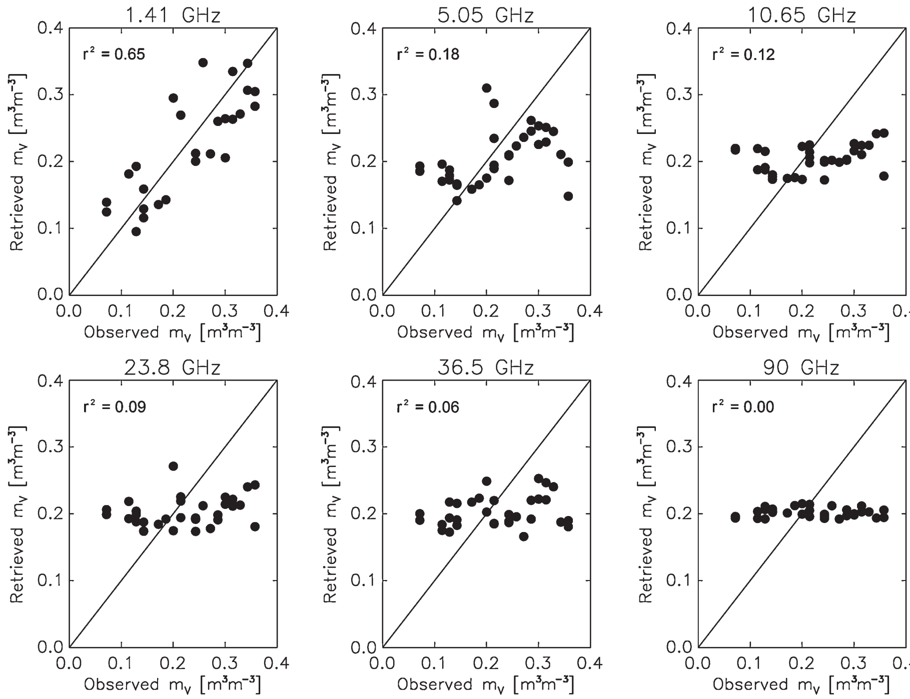

Fig. 4. Same as in Fig. 3 but for surface soil moisture (m_v).

TABLE II
SAME AS IN TABLE I BUT FOR H POLARIZATION, 50H20H AND 40H20H

Approach	Variable	Statistics	1.41GHz (L-band)	5.05GHz (C-band)	10.65GHz (X-band)	23.8GHz (K-band)	36.5GHz (Q-band)	90GHz (W-band)
50H20H		n	16	33	33	32	32	33
	VWC	A_{VWC}	-6.647	-2.982	-0.608	-0.153	-0.022	-0.055
		B_{VWC}	4.745	0.911	-0.455	-0.718	-0.551	-0.881
		C_{VWC}	-0.953	-3.707	-3.022	-2.547	-1.755	-3.085
		r^2	0.48	0.68	0.59	0.45	0.14	0.26
		p-value	<0.01	$<10^{-6}$	$<10^{-6}$	$<10^{-4}$	<0.05	<0.01
		RMSE (kg m^{-2})	0.52	0.47	0.54	0.59	0.75	0.72
	m_v	A_{VWC}	-3.667	-1.611	-0.205	-0.106	-0.267	-0.137
		B_{VWC}	3.732	1.114	0.320	0.333	0.128	0.137
		C_{VWC}	-0.394	-1.967	-1.076	-0.810	-2.084	-1.606
		r^2	0.75	0.28	0.17	0.13	0.04	0.00
		p-value	$<10^{-4}$	<0.01	<0.05	<0.05	NS	NS
		RMSE (m^3 m^{-3})	0.039	0.071	0.077	0.075	0.079	0.084
40H20H		n	20	33	33	32	32	33
	VWC	A_{VWC}	-6.253	-2.696	-0.510	-0.273	-0.321	-0.148
		B_{VWC}	5.311	1.064	-0.413	-0.556	-0.286	-0.736
		C_{VWC}	-0.203	-3.206	-2.750	-2.420	-1.897	-2.918
		r^2	0.15	0.66	0.61	0.43	0.16	0.30
		p-value	NS	$<10^{-6}$	$<10^{-6}$	$<10^{-4}$	<0.05	<0.01
		RMSE (kg m^{-2})	0.78	0.48	0.52	0.61	0.74	0.71
	m_v	A_{VWC}	-3.091	-0.862	-0.136	-0.021	-0.100	-0.068
		B_{VWC}	3.562	0.801	0.308	0.252	-0.401	0.073
		C_{VWC}	-0.217	-1.389	-0.963	-0.798	-2.090	-1.587
		r^2	0.73	0.19	0.17	0.13	0.01	0.00
		p-value	$<10^{-5}$	<0.05	<0.05	<0.05	NS	NS
		RMSE (m^3 m^{-3})	0.042	0.076	0.077	0.075	0.081	0.084

enhanced the sensitivity to soil moisture, with significant correlations from L-band to K-band. In particular, at C-band, a relatively high correlation was obtained ($r^2 = 0.28$ and p-value < 0.01). However, the rmse (of about 0.07 $\mathrm{m}^3 \cdot \mathrm{m}^{-3}$) is relatively poor at C-band. Very similar results were obtained with $\theta_1 = 40°$, instead of $\theta_1 = 50°$, apart from the lack of sensitivity to VWC observed at L-band in the 40H20H configuration.

TABLE III

RESULTS FOR BIPOLARIZATION APPROACH AT INCIDENCE ANGLES OF 50° AND 40° (50VH AND 40VH, RESPECTIVELY) OVER A DENSE WHEAT FIELD AT SIX MICROWAVE FREQUENCIES. RETRIEVAL OF THE VWC AND OF THE SURFACE SOIL MOISTURE: REGRESSION COEFFICIENTS (A_{VWC}, B_{VWC}, C_{VWC} AND A_{m_v}, B_{m_v}, C_{m_v}) AND SCORES (SQUARED CORRELATION COEFFICIENT, F-TEST p-VALUE, AND ROOT MEAN SQUARE DIFFERENCE)

Approach	Variable	Statistics	1.41GHz (L-band)	5.05GHz (C-band)	10.65GHz (X-band)	23.8GHz (K-band)	36.5GHz (Q-band)	90GHz (W-band)
50VH		n	13	36	36	35	35	36
	VWC	A_{VWC}	-0.910	-0.582	1.445	-1.196	0.123	1.789
		B_{VWC}	2.072	-1.142	-2.366	0.433	-0.464	-2.216
		C_{VWC}	0.126	-3.741	-2.000	-2.458	-0.873	-0.855
		r^2	0.35	0.73	0.33	0.34	0.03	0.16
		p-value	<0.05	$<10^{-6}$	$<10^{-3}$	$<10^{-3}$	NS	<0.05
		RMSE (kg m^{-2})	0.61	0.41	0.72	0.63	0.78	0.82
	m_v	A_{VWC}	-0.207	-0.535	-0.616	-0.320	-0.194	-0.046
		B_{VWC}	1.898	0.515	0.686	0.356	-0.019	-0.023
		C_{VWC}	0.418	-1.812	-1.519	-1.507	-2.370	-1.839
		r^2	0.58	0.06	0.05	0.04	0.05	0.00
		p-value	<0.01	NS	NS	NS	NS	NS
		RMSE (m^3 m^{-3})	0.059	0.080	0.081	0.078	0.077	0.083
40VH		n	21	36	36	35	35	36
	VWC	A_{VWC}	-0.871	-0.690	0.238	-0.788	-0.029	2.004
		B_{VWC}	1.447	-0.683	-1.000	0.077	-0.457	-2.470
		C_{VWC}	-0.001	-3.225	-2.067	-2.173	-1.455	-1.065
		r^2	0.27	0.70	0.26	0.30	0.11	0.22
		p-value	<0.05	$<10^{-6}$	<0.01	$<10^{-3}$	NS	<0.01
		RMSE (kg m^{-2})	0.68	0.44	0.79	0.66	0.73	0.79
	m_v	A_{VWC}	0.126	-0.388	-0.094	-0.249	0.105	-0.170
		B_{VWC}	0.679	0.545	0.187	0.345	-0.243	0.117
		C_{VWC}	-0.181	-1.293	-1.299	-1.273	-2.045	-1.800
		r^2	0.69	0.10	0.06	0.06	0.02	0.00
		p-value	$<10^{-5}$	NS	NS	NS	NS	NS
		RMSE (m^3 m^{-3})	0.043	0.078	0.081	0.077	0.079	0.083

Tables III and IV present the results obtained for the bipolarization configurations at 50° and 40° (Table III) and at 30° and 20° (Table IV).

1) In the bipolarization configurations, the sensitivity to VWC retrievals was similar to the biangular configurations presented in Tables I and II. For the 20VH configuration, the best scores were obtained at C-, X-, and K-bands, with rmse values close to 0.5 $\mathrm{kg \cdot m^{-2}}$ and r^2 values higher than 0.6. At higher incidence angles (i.e., 30°, 40°, and 50°), the best scores were obtained at C-band only. The best VWC retrieval was obtained at C-band in the 50VH configuration, with an r^2 value of 0.73 and an rmse of 0.41 $\mathrm{kg \cdot m^{-2}}$. It seems that C-band was good at retrieving VWC in all the configurations (r^2 was always higher than 0.64), whereas at L-band, the best VWC retrievals were obtained at low incidence angles (20VH and 30VH configurations) and with the 50H20H biangular configuration.
2) In the 20VH configuration, the sensitivity to m_v was similar to that observed for the 50H20H configuration, with significant correlations from L-band to K-band. At higher incidence angles (i.e., 30°, 40°, and 50°), the sensitivity of C-band to K-band to soil moisture decreased, and at 50°, only L-band was sensitive to m_v.

Table V summarizes the sensitivity to m_v and VWC based on the p-values obtained for each configuration. At L-, C-, and K-bands, in general, the use of low incidence angles (e.g., 20°) allows a higher sensitivity to both m_v and VWC. At L-band, the biangular approach at H polarization (50H20H) was particularly efficient for m_v retrieval. In addition, at C- and K-bands, the use of H polarization (50H20H or 40H20H) was more efficient. C-band to K-band observations are more sensitive to VWC than to m_v, but a moderate sensitivity to m_v was still observed, particularly at C- and X-bands provided that observations at low incidence angles are available. The extremely high frequencies (Q- and W-bands) are not sensitive to soil moisture over a dense vegetation canopy and are only moderately sensitive to VWC.

V. DISCUSSION

The sensitivities were assessed with the logarithmic relationships in (1) and (2). This assumption may impact the results. The regression method of Saleh *et al.* [14] is based on log-transformed variables, consistent with the $\tau-\omega$ model, and verified at L-band over grass. Wigneron *et al.* [13] have verified the method over wheat and soybean. In the case of wheat, Wigneron *et al.* [13] were able to estimate soil moisture with 0.05 $\mathrm{m^3 \cdot m^{-3}}$ accuracy after calibrating a biangular regression with L-band synthetic data generated by the $\tau-\omega$ model for a large range of soil and vegetation conditions. A wheat canopy has anisotropic attenuation properties caused by the nonuniform orientation distribution of the scattering elements [13], and the equations derived from the $\tau-\omega$ model may not

TABLE IV
SAME AS IN TABLE III BUT FOR 30° AND 20° (30VH AND 20VH, RESPECTIVELY)

Approach	Variable	Statistics	1.41GHz (L-band)	5.05GHz (C-band)	10.65GHz (X-band)	23.8GHz (K-band)	36.5GHz (Q-band)	90GHz (W-band)
30VH		n	21	36	36	33	33	36
	VWC	A_{VWC}	-2.762	-0.783	-0.062	-0.916	-0.305	1.903
		B_{VWC}	3.876	-0.282	-0.767	0.116	-0.274	-2.573
		C_{VWC}	0.089	-2.639	-2.510	-2.477	-1.842	-1.927
		r^2	0.44	0.67	0.54	0.39	0.18	0.18
		p-value	$<10^{-3}$	$<10^{-6}$	$<10^{-6}$	$<10^{-4}$	<0.05	<0.01
		RMSE (kg m^{-2})	0.61	0.46	0.57	0.61	0.70	0.84
	m_v	A_{VWC}	-0.205	-0.316	-0.211	-0.572	0.255	-0.161
		B_{VWC}	1.288	0.484	0.356	0.658	-0.366	0.114
		C_{VWC}	-0.029	-1.146	-1.136	-1.329	-1.951	-1.767
		r^2	0.58	0.13	0.09	0.08	0.03	0.00
		p-value	$<10^{-4}$	<0.05	NS	NS	NS	NS
		RMSE (m^3 m^{-3})	0.054	0.077	0.079	0.077	0.079	0.083
20VH		n	16	33	33	31	31	33
	VWC	A_{VWC}	-6.593	-1.257	-0.401	-0.741	-1.370	1.401
		B_{VWC}	7.883	0.278	-0.345	-0.189	0.727	-2.319
		C_{VWC}	0.645	-2.279	-2.376	-2.828	-2.014	-2.936
		r^2	0.39	0.64	0.64	0.63	0.21	0.31
		p-value	<0.01	$<10^{-6}$	$<10^{-6}$	$<10^{-6}$	<0.05	$<10^{-3}$
		RMSE (kg m^{-2})	0.65	0.50	0.50	0.47	0.70	0.73
	m_v	A_{VWC}	-1.517	-0.282	-0.826	-0.404	-0.182	-0.514
		B_{VWC}	2.755	0.455	1.114	0.614	0.027	0.472
		C_{VWC}	0.115	-1.045	-0.757	-0.894	-2.135	-1.780
		r^2	0.61	0.16	0.21	0.13	0.01	0.02
		p-value	$<10^{-3}$	<0.05	<0.01	<0.05	NS	NS
		RMSE (m^3 m^{-3})	0.054	0.077	0.075	0.077	0.082	0.083

TABLE V
SUMMARY OF THE RESULTS FOUND IN THIS STUDY ON THE PASSIVE MICROWAVE RESPONSE TO SURFACE SOIL MOISTURE AND VWC, FROM L-BAND TO W-BAND, FOR A DENSE WHEAT FIELD. FOUR LEVELS OF SENSITIVITY ARE INDICATED BASED ON THE F-TEST p-VALUES OF TABLES I–IV FOR EIGHT BIPOLARIZATION OR BIANGULAR CONFIGURATIONS: "***" CORRESPONDS TO p-VALUES $< 10^{-3}$, "**" CORRESPONDS TO p-VALUES < 0.01, "*" CORRESPONDS TO p-VALUES < 0.05, AND "NS" MEANS "NONSIGNIFICANT"

Variable	Configuration	1.41GHz (L-band)	5.05GHz (C-band)	10.65GHz (X-band)	23.8GHz (K-band)	36.5GHz (Q-band)	90GHz (W-band)
m_v	50H20H	***	**	*	*	NS	NS
	40H20H	***	*	*	*	NS	NS
	50V20V	***	*	NS	NS	NS	NS
	40V20V	***	*	*	NS	NS	NS
	20VH	***	*	**	*	NS	NS
	30VH	***	*	NS	NS	NS	NS
	40VH	***	NS	NS	NS	NS	NS
	50VH	**	NS	NS	NS	NS	NS
VWC	50H20H	**	***	***	***	*	**
	40H20H	NS	***	***	***	*	**
	50V20V	***	***	***	***	**	*
	40V20V	**	***	***	***	**	**
	20VH	**	***	***	***	*	***
	30VH	***	***	***	***	*	**
	40VH	*	***	**	***	NS	**
	50VH	*	***	***	***	NS	*

represent these properties well. The use of a simple linear regression did not alter the conclusions of this paper. However, very significant m_v correlations (p-values $< 10^{-3}$) were obtained for the biangular configurations at C-band (as at L-band). In the 50H20H configuration, very good rmse scores were achieved at C-band for both m_v and VWC (0.055 $m^3 \cdot m^{-3}$ and 0.47 $kg \cdot m^{-2}$, respectively).

For bare soil, microwave brightness temperatures are sensitive to soil moisture from L-band to W-band. This study confirms that, over dense vegetation canopies, L-band is the most appropriate wavelength for soil moisture sensing, with an rmse value lower than 0.04 $m^3 \cdot m^{-3}$ in the 50H20H configuration. However, multiangular observations also permit a moderate sensitivity to m_v to be achieved at higher frequencies, particularly at C-band. Over the studied wheat field, applying the regression method without log-transforming the variables permitted significant correlations to be achieved at C-band in biangular configurations (e.g., rmse of 0.055 $m^3 \cdot m^{-3}$ in the 50H20H configuration). At higher frequencies, rmse values were always higher than 0.072 $m^3 \cdot m^{-3}$. As the currently available soil moisture products derived from satellite microwave radiometry use high incidence angles only, it is concluded that the good agreement of these products with *in situ* observations in highly vegetated agricultural areas is due to the presence of a significant fraction of bare soil and/or dry vegetation, caused by the crop rotation practices. Consequently, the presence of bare soil may allow a significant sensitivity of radiometric observations at extremely high frequencies to soil moisture that would otherwise be completely masked by the vegetation canopy.

Indeed, passive microwave observations from a number of spaceborne radiometers are available at only high incidence angles (close to 50°). The results obtained from the Portos-93 data set show that, at high incidence angles, no sensitivity to soil moisture is to be expected over dense vegetation canopies, except for L-band observations. On the other hand, C-, X-, and K-band observations are sensitive to VWC, even at high incidence angles.

Soil moisture products can be derived from either passive or active microwave observations, for example, from the Advanced Microwave Scanning Radiometer for the Earth Observing System (AMSR-E) onboard NASA's Aqua satellite or from the scatterometers onboard the European Remote Sensing satellites (ERS-1 and -2) and onboard ESA's METOP satellite (ASCAT). Recent studies [15]–[18] showed that soil moisture products derived from C- and/or X-band satellite microwave observations (either passive or active) correlate well with *in situ* observations and model estimates of the surface soil moisture, over agricultural regions in France, characterized by dense crop fields. Gruhier *et al.* [16] showed that the agreement of AMSR-E products with *in situ* observations is as good in France as in Mali, a semiarid area with low vegetation cover. In the context of the Portos-93 findings, this result may denote a spurious correlation with vegetation status.

However, as far as the European scatterometers (onboard ERS-1, ERS-2, and METOP) are concerned, they provide C-band backscattering coefficients (σ^0) at V polarization and at distinct incidence angles. Wagner *et al.* [19] proposed a method to account for the effects of the vegetation phenology, based on this multiangular observation capability. Scaled surface soil moisture estimates are then derived from this simple σ^0 change detection approach. This study shows that C-band multiangular observations allow a moderate sensitivity to soil moisture in the case of dense vegetation canopies. In particular, the biangular configuration at H polarization seems to be most favorable to soil moisture retrieval. However, the wheat field considered in this study is characterized by a marked vertical structure, and V polarization might present a higher sensitivity to soil moisture for other vegetation types.

This explanation does not hold for the AMSR-E passive microwave observations, available at high incidence angles only. Although France is not considered as a semiarid area, bare soil surfaces are quite common in agricultural areas: In France, annual crops represent about one-third of the land use, and in many agricultural areas, crop rotation systems generate a rather high permanent fraction of bare soil and/or mature (dry) crops. This might explain why AMSR-E observations at high incidence angles are found to be sensitive to soil moisture.

Prigent *et al.* [6] suggested that K-band has no overall sensitivity to soil moisture, based on observations from the Special Sensor Microwave/Imager, with an incidence angle close to 53°. For high incidence angles, this study confirms that no sensitivity to m_v is to be expected over dense vegetation canopies, from C-band to W-band. Even at L-band, soil moisture retrieval is difficult (with rmse of 0.059 $m^3 \cdot m^{-3}$ in the 50VH configuration, Table III). However, Prigent *et al.* [6] showed that, over specific agricultural sites in Illinois, Russia, and India, high correlations between polarization differences are indeed observed. They attribute this correlation to the seasonal variability of the vegetation density. The recent findings showing that C- and X-band AMSR-E observations correlate well with soil moisture in agricultural regions tend to confirm the hypothesis that the microwave brightness temperatures actually respond to soil moisture, in spite of the vegetation and high incidence angle of AMSR-E. Again, the presence of bare soil in agricultural areas might be an explanation for this finding, but this needs further confirmation.

The presence of bare soil in agricultural areas may also allow a significant response of the land emissivities at extremely high frequencies (e.g., W-band). A way to assess this hypothesis is to investigate the impact of precipitation events on emissivities retrieved from the Advanced Microwave Sounding Unit-A (AMSU-A) and AMSU-B observations, over an agricultural area where a dense rain gauge network is available. The AMSU sensors are operational, onboard many satellites (NOAA-15, NOAA-16, NOAA-18, METOP, and AQUA). Land surface emissivities from AMSU usually vary in time and with surface type, roughness, observation frequency, and incidence angle (which goes from $-58°$ to $+58°$). Moreover, the AMSU-retrieved emissivities are a mixture between emissivities in the vertical and the horizontal polarizations since AMSU measurements are made with a system of rotating antenna. Karbou *et al.* [20] showed that emissivity angular dependence can be neglected for incidence angles smaller than 40°.

Fig. 5 shows daily mean AMSU-A and AMSU-B emissivities at 89 GHz, for an eight-month period, over a relatively flat area in northern France ($0.5°$ W$-4°$ E and $46°$ N$-49°$ N) covered to a large extent by annual crops. The mean daily emissivity estimates at 89 GHz are shown together with the average daily accumulated precipitation measured *in situ* at about 810 stations. On average, 152 emissivity observations are available each day within the considered area, including observations from AMSU-A NOAA-15, NOAA-16, NOAA-18, METOP, and AQUA and observations from AMSU-B, NOAA-16, NOAA-17, and NOAA-18. The emissivity departure from its average value of 0.95 ranges from -0.04 to $+0.02$. Fig. 5 shows that, when rain occurs, the emissivity may drop by 0.02–0.04. For instance, an increase in precipitation in early September corresponds to a decrease of the emissivity of more that 0.02. Similarly, soil freezing may affect the emissivity. De Rosnay *et al.* [21] showed that soil freezing may lead to

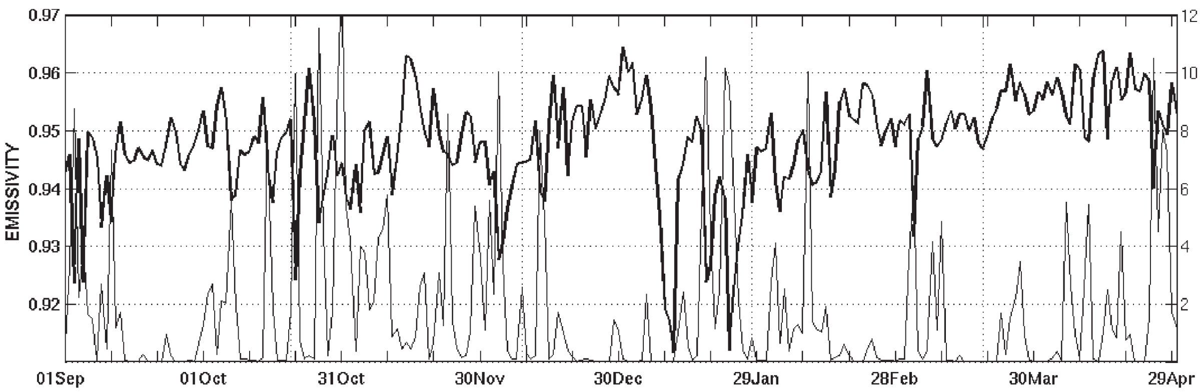

Fig. 5. (Dashed line) Daily mean AMSU-A emissivities at 89 GHz in northern France (0.5° W–4° E and 46° N–49° N) from 01/09/2008 to 30/04/2009 and (solid line) daily precipitation measured *in situ*.

contrasting effects on microwave emission (i.e., decreasing or increasing emissivities), depending on the vegetation cover. This effect is visible in mid-January 2009, with a drop in emissivity which is not associated with a precipitation event. Indeed, January 2009 was particularly cold in northern France: The mean minimum air temperature ($T_{\min}$) observed in Paris was negative, $-0.2\ ^\circ$C, much lower than the median value for January, $+2.5\ ^\circ$C, and negative $T_{\min}$ values were observed from January 1 to 12. Overall, the land surface emissivity at 89 GHz appears to be negatively correlated with precipitation. The Pearson, Kendall, and Spearman statistics are -0.43, -0.20, and -0.29, respectively, with p-values lower than 10^{-5}. However, more in-depth studies are required to arrive at final conclusions. In particular, examining the effect of rain on emissivities derived from other sensors (which provide measurements at V and H polarizations) would be instructive.

VI. Conclusion

This paper has investigated the sensitivity of passive microwave observations at various frequencies, from L-band to W-band, to both surface soil moisture and VWC. The Portos-93 observations over a dense wheat field were used. The performance of simple logarithmic statistical regression equations relating m_v and VWC to the microwave emissivities was used as an indicator of the sensitivity to the microwave observations to either m_v or VWC.

L-band observations were found to be very sensitive to m_v in all the configurations tested. Conversely, higher frequencies tended to be more sensitive to VWC than to m_v. However, multiangular observations permitted a moderate sensitivity to m_v be achieved at higher frequencies, particularly at C-band. At high incidence angles, no sensitivity to m_v was found from C-band to W-band. As the currently available soil moisture products derived from satellite microwave radiometry use high incidence angles only, it is concluded that the good agreement of these products with *in situ* observations in highly vegetated agricultural areas is due to the presence of a significant fraction of bare soil or dry vegetation, caused by the crop rotation practices. The presence of bare soil may allow a significant sensitivity of radiometric observations at extremely high frequencies to soil moisture. This hypothesis seems to be confirmed by the high correlation found between W-band emissivities of AMSU-A and AMSU-B with precipitation observations in northern France.

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