A new parameterization of the effective temperature for L band radiometry

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[1] An accurate value of the effective temperature is critical for soil emissivity retrieval, and hence soil moisture content retrieval, from passive microwave observations. Computation of the effective temperature needs fine profile measurements of soil temperature and soil moisture. The availability of a two year long data set of these surface variables from SMOSREX (Surface Monitoring Of the Soil Reservoir EXperiment) makes it possible to study the effective temperature at the seasonal to interannual scale. This study shows that present parameterizations do not adequately describe the seasonal variations in sensing depth. Therefore, a new parameterization is proposed that is stable at the seasonal to interannual scales while retaining simplicity. **Citation:** Holmes, T. R. H., P. de Rosnay, R. De Jeu, R. J.-P. Wigneron, Y. Kerr, J.-C. Calvet, M. J. Escorihuela, K. Saleh, and F. Lemaître (2006), A new parameterization of the effective temperature for L band radiometry, *Geophys. Res. Lett.*, *33*, LXXXXX, doi:10.1029/2006GL025724.

1. Introduction

[2] Measurements of passive microwave brightness temperature quantify the intensity of the soil microwave radiation. According to the Rayleigh-Jeans approximation, the emitted energy from the soil in the microwave domain is proportional to the thermodynamic temperature and the brightness temperature can be expressed as the product of the emissivity and the effective temperature.

[3] The whole soil layer contributes to the soil thermal emission. From the point of origin to the soil surface, the intensity is attenuated by the intervening soil, whose absorption is related to the moisture content. The net intensity at the soil surface, called the effective temperature, is a superposition of the intensities emitted at various depths within the soil [*Choudhury et al.*, 1982].

[4] The effective temperature is used to normalize the measured brightness temperature and obtain values of surface emissivity. Especially at L band (1.4 Ghz), the contributing layer is thick and varies strongly through the year. An accurate computation of the effective temperature is thus critical for obtaining relevant values of the soil emissivity from brightness temperature measurements. The soil emissivity values may then be used in (non) coherent models to retrieve soil moisture [*Njoku and Kong*, 1977; *Whilheit*, 1978; *Schneeberger et al.*, 2004].

[5] The theoretical formulation of the effective temperature requires fine vertical profile information on both soil moisture and soil temperature. Required information is not available from remote sensing and only a few test sites provide a sufficiently fine measurement of the vertical profiles in the soil. To estimate the effective temperature with minimum soil profile information, several parameterizations have been developed for use with L band radiometry. *Choudhury et al.* [1982] showed that for short time periods, the effective temperature can be described as a linear function of the soil temperature at two depths. *Wigneron et al.* [2001] improved this parameterization, making it suitable for seasonal studies, by taking into account the influence of soil moisture on the attenuation of microwave energy.

[6] As part of the preparation for SMOS (Soil Moisture and Ocean Salinity) mission [*Kerr et al.*, 2001], the intensive field campaign SMOSREX (Surface Monitoring Of the Soil Reservoir EXperiment) has been ongoing in Southern France [*de Rosnay et al.*, 2006]. SMOSREX began in 2001 with ground measurements, and it was expanded in 2003 to include L band and multi-spectral remote sensing measurements. It is expected to last until the end of 2006. Designed to improve radiative modeling over land at L band, the measurements include dense profiles of soil temperature and moisture sensors. This study uses the two-year 2003–2004 data set of the profile data to calculate the theoretical effective temperature and compare it to Wigneron's parameterization. The long duration of the field campaign makes it possible to study its behavior at annual to interannual time scales. Based on the results of this study we will propose a new parameterization of the effective temperature.

2. Theory

[7] The effective temperature (T_{eff}) is controlled by the soil dielectric and temperature profiles. From radiative transfer theory [*Ulaby et al.*, 1986], the effective temperature can be expressed as:

$$T_{eff} = \int_0^\infty T_s(z) \cdot W(z) \cdot dz \qquad (1)$$

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where $T_s(z)$ is soil thermodynamic temperature at depth z, $W(z)$ is a temperature weighting function of the contribution of each soil layer to the T_{eff}. $W(z)$ is defined as:

$$W(z) = \alpha(z) \cdot \exp\left[-\int_0^z \alpha(z') \cdot dz'\right] \quad (2)$$

where

$$\alpha(z) = (4\pi/\lambda) \cdot \epsilon''(z)/2(\epsilon'(z))^{0.5} \quad (3)$$

$\alpha(z)$ is an attenuation coefficient related to the soil dielectric constant, λ is the observation wavelength, and ϵ' and ϵ'' are the real and imaginary part of the soil dielectric constant.

[8] The shape of the weighting function is determined only by the soil moisture profile through its effect on the dielectric constant. The higher the soil moisture content, the higher the attenuation and the more rapid the weighting function declines with depth. The result is a smaller sensing depth. This effect is illustrated for L band in Figure 1, which shows examples of a dry (July) and a wet (March) soil moisture profile (Figure 1a) and their corresponding normalized temperature weighting functions (Figure 1b). It clearly illustrates that a wetter soil profile results in a smaller sensing depth, and that for L band the difference can be several tens of centimeters.

3. Material and Methods

[9] Soil temperature and moisture data are measured on a bare soil as part of the SMOSREX campaign [*de Rosnay et al.*, 2006]. Thermistors are installed at 1 cm, 5 cm, 20 cm 50 cm and 90 cm. Soil moisture is measured by theta probes, installed at 0–6 cm (4x), 10 cm (x3), 20 cm (x3) 40 cm (x2), 50 cm (x2), 60 cm (x2), 70 cm, 80 cm and 90 cm. Soil texture can be characterized as a loam soil, with a porosity of 40%. Wilting point and transition moisture values are calculated to be 0.15 and 0.238 $m^3\ m^{-3}$ respectively, based on the work by *Wang and Schmugge* [1980].

[10] Using equations (1)–(3), the theoretical effective temperature is computed based on the SMOSREX data of 2003 and 2004. The dielectric constant is calculated using the model of *Wang and Schmugge* [1980], for a wavelength of 21cm (L band). This model is shown to be highly suitable to represent both the real and imaginary part of the dielectric constant for a large range of soil moisture and temperature conditions. The recent Monitoring Underground Soil Experiment (MOUSE) confirms its suitability for different soil texture types [*Vall-llossera et al.*, 2005]).

[11] Despite of uncertainties in the measured soil moisture and temperature profiles, as well as in the corresponding dielectric constant, the theoretical approach is considered to provide a good approximation of the effective temperature. It is used in the following as the "true" effective temperature.

4. Parameterization of Effective Temperature

[12] The calculation of the effective temperature by equations (1)–(3) needs detailed information on temperature and water content profiles. For application studies at a larger scale, it will be necessary to use a simple parameterization. The most straightforward parameterization was proposed by *Choudhury et al.* [1982]:

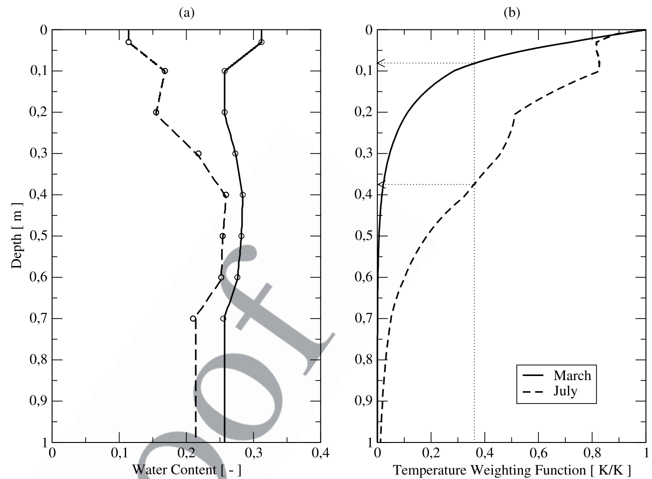

Figure 1. (a) Water content profiles and (b) corresponding normalized weighting functions for L band, for March and July 2003. Circles indicate measured values.

$$T_{eff} = T_{Deep} + (T_{Surf} - T_{Deep}) \cdot C \quad (4)$$

where T_{Deep} is the deep soil temperature, ranging from 50 to 100 cm and T_{Surf} the surface soil temperature between 0 to 5 cm. C is a fitting parameter, defining the depth of the soil layer that best represents T_{eff}. Because C is described to be constant in this formulation, this parameterization can only properly describe small term field experiments, with limited change in soil moisture content.

[13] To take into account the sensing depth variation with the soil moisture content, *Wigneron et al.* [2001] proposed a parameterization for low frequency radiometry:

$$T_{eff} = T_{Deep} + (T_{Surf} - T_{Deep}) \cdot C(w_{Surf}) \quad (5)$$

where $C(w_{Surf})$ is a function of the surface soil moisture, w_{Surf}, given as:

$$C(w_{surf}) = (w_{Surf}/w_0)^b \quad (6)$$

where the fitting parameters w_0 and b are positive. For dryer soils, $C(w_{Surf})$ is lower and T_{eff} is closer to T_{Deep} than for wet soils. This parameterization proved to be robust at the seasonal scale.

4.1. Interseasonal Calibration

[14] To test Wigneron's parameterization [Wig] at the interseasonal scale, the parameterization was calibrated using the values of the calculated "true" effective temperature for the first year of the measurements at the SMOSREX site. This calibration was carried out for different choices of T_{Surf}: using the infrared temperature, or the 1 cm or 5 cm soil temperature. Best results were obtained using T_{Surf} at 5 cm and T_{Deep} at 50 cm, and this configuration will be used hereafter. The calibration was first performed separately for three time periods in order to analyze the stability of the parameterization at interseasonal

Table 1. Results of the Calibration of the Two Parameterizations[a]

Parameterization	Period	Parameter 1	Parameter 2	rmse, *K*	Emax, K	Freq, %
[Wig]		w_0	b			
Wigneron et al. [2001]	2003 winter	0.34	0.62	0.42		
	2003 summer	0.47	0.56	0.51		
	2003	0.36	0.70	0.478	2.38	4
	2004	0.32	0.58	0.592	2.64	4
	2003 applied to 2004	0.36	0.70	0.734	2.22	6
	2003 and 2004	0.33	0.63	0.573	3.11	10
[New]		ϵ_0	b			
	2003 winter	0.09	0.52	0.42		
	2003 summer	0.08	0.98	0.37		
	2003	0.08	0.95	0.412	2.50	2
	2004	0.08	0.81	0.482	1.67	2
	2003 applied to 2004	0.08	0.95	0.515	2.00	4
	2003 and 2004	0.08	0.87	0.458	2.43	6

[a]The best fitting parameters are listed for both parameterizations as well as the associated rmse compared to the theoretical value of effective temperature. Maximum error (Emax) and occurrence (Freq in %) of errors larger than 1 K are indicated for each case. The calibration was performed for different periods: 2003 winter (Jan–Mar, Nov–Dec), 2003 summer (May–Oct), 2003, 2004, 2003–2004. The case 2003 applied to 2004 is an evaluation of the best 2003 fitting parameters to the year 2004. This test addresses the robustness of each parameterization for temporal extrapolation.

and annual temporal scales: For the winter and summer of 2003, and for the whole year 2003.

[15] The calibrated parameters for these different temporal scales are listed in Table 1, as well as the averaged error (rmse) with the theoretical effective temperature. These results show that Wigneron's parameterization describes the theoretical effective temperature well, with an rmse of 0.48 K for the year 2003. However, the results for the seasonal time periods indicate that the fitting parameters are not stable throughout the year.

4.2. New Parameterization

[16] The unstable calibration results for Wigneron's parameterization shows that the effect of soil moisture on the sensing depth is not yet sufficiently accounted for in the parameterization. In the theoretical formulation of T_{eff} (equations (1)–(3)), the influence of water on the attenuation of microwave energy is represented by the use of the ratio of the real and imaginary parts of the soil dielectric constant. From this it is expected that a parameterization that uses the soil dielectric constant, in the form of (ϵ''/ϵ'), instead of the water content would be able to describe the yearly trends better.

[17] This approach is tested by calculating C and comparing this to water content and the dielectric properties. Because T_{eff} becomes very insensitive to the sensing depth when the soil temperature profile is almost vertical, we remove the data where $(T_{Surf} - T_{Deep})^2$ is less than 5 K. The remaining C-values are plotted for 2003 against water content (Figure 2a) and against ϵ''/ϵ' (Figure 2b). These plots clearly show a much better correlation between C and ϵ''/ϵ' (0.9) than with water content (0.84).

[18] Much of this improvement in the correlation is a result of the different dielectric behavior of the soil before and after the transition moisture. Initially, the dielectric constant increases slowly with moisture content. After reaching a transition moisture value (0.238 for this soil), the dielectric constant increases steeply with moisture content [*Wang and Schmugge*, 1980]. The inconsistencies that occur in the high moisture levels in Figure 2b are not yet explained but are probably related to gradients in the surface soil moisture and temperature profiles. This feature is also observed when, as suggested by equation (3), we consider the relationship between C-values and the ratio $(\epsilon''/(\epsilon')^{0.5})$ (not shown). However, C is slightly better correlated to (ϵ''/ϵ') (0.9) than to $(\epsilon''/(\epsilon')^{0.5})$ (0.89). Based on these results we propose the following parameterization of the effective temperature:

$$T_{eff} = T_{Deep} + \left(T_{Surf} - T_{Deep}\right) \cdot C(\epsilon) \quad (7)$$

where $C(\epsilon)$ is a function of the dielectric properties of the surface:

$$C(\epsilon) = \left((\epsilon''/\epsilon')/\epsilon_0\right)^b \quad (8)$$

with the fitting parameters ϵ_0 and b. (ϵ''/ϵ') is calculated from w_{Surf}, according to the dielectric mixing model [*Wang and Schmugge*, 1980]. This extra step needs information about soil texture and the soil temperature at the same depth as the soil moisture measurements.

[19] The calibration results for this new parameterization are also shown in Table 1. These results show that the rmse for the calibrations on the year 2003 are improved from 0.48

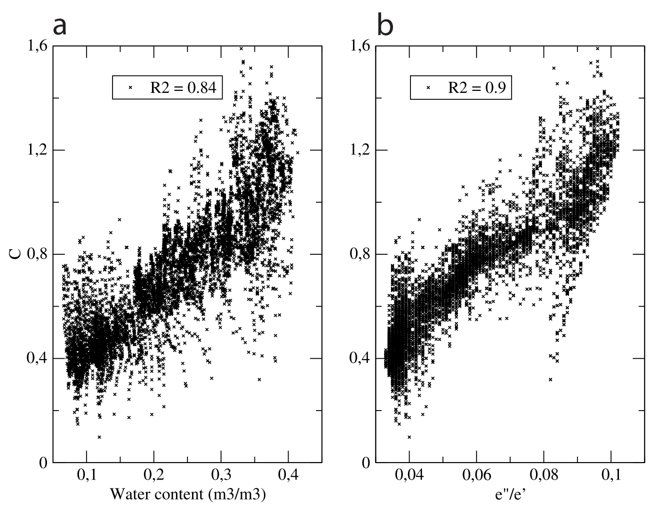

Figure 2. Scatterplots of (a) C versus surface water content and (b) C versus the ratio of the soil dielectric constant. For data where $(T_{Surf} - T_{Deep})^2 > 5K$.

to 0.41 K. The rmse for the summer periods is improved especially, from 0.51 to 0.37 K. However, the higher correlation between C and ϵ''/ϵ' is not reflected in more stable calibration at the interseasonal scale. This can be attributed to the inconsistencies in Figure 2b at the high moisture levels. The following section will test the two parameterizations further at the interannual scale.

4.3. Interannual Calibration

[20] In order to compare the stability and robustness of the new parameterization [New] and Wigneron's parameterization [Wig] at annual and interannual temporal scales, the calibration is now extended to two years of the SMOSREX data set. The calibration is repeated for the year 2004 and for the years 2003 and 2004 combined. The calibration was also tested for 2004 with the optimized parameters obtained for 2003.

[21] The best fit parameters for the different temporal scales and the rmse between the parameterized and the theoretical effective temperature are listed in Table 1. It also indicates, for each time period, the maximum error and the occurrence of errors larger than 1 K. This provides a quantitative assessment of the percentage of situations where the model is not able to reproduce effective temperature with a 1 K accuracy.

[22] Table 1 shows that the new parameterization indeed improves upon the results with Wigneron's method. The rmse are lower than those obtained with [Wig] at the annual and interannual scales. At the interannual scale (2003–2004), the rmse decreases from 0.573 with [Wig], to 0.458 K with [New]. Maximum error decreases from 3.11 with [Wig] to 2.43 K with [New] and the occurrence of errors larger than 1 K is 10 and 6 for the two models respectively. The 1 K accuracy is thus ensured at this interannual scale in 90% with [Wig] and 94% with [New]. The stability of the calibrated parameters for [New] is particularly noteworthy. With only one parameter (ϵ_0 is shown to be almost constant at any time scale) the parameterization is able to describe the variations of the effective temperature encountered at different temporal scales.

[23] These results indicate that the [New] parameterization takes into account the main processes that govern the thermal sampling depth. For intermediate soil moisture conditions, such as in April 2004, the two parameterizations provide similar results which are in good agreement with the theoretical formulation. The differences between the two parameterizations are more significant in more extreme conditions, such as soil freezing in February 2003 and a very warm period in August 2003. In these conditions, the relevance of the model is strongly dependent on the approach used to account for the effects of soil moisture in the computation of the effective temperature. The [New] model which represents this effect through the modifications of the dielectric constant, is closer to the theoretical effective temperature than the [Wig] parameterization. These results underscore that the soil moisture influences the thermal sampling depth through the soil dielectric profile.

5. Conclusion

[24] Because of the availability of a two year-long data set of fine soil moisture and temperature profiles, it was possible to clearly show the effect of changes in soil water content through the year, on the effective temperature. The change from saturated surface conditions in January to below wilting point in July results in a strong expansion of temperature sensing depth for L band.

[25] This strong variation in the temperature sensing depth is not fully reflected in the parameterization by Wigneron of T_{eff}. This results in unstable values for the calibration parameters at the interseasonal scale.

[26] The correlation of the sensing depth with ϵ''/ϵ' is shown to be better than the correlation with water content. Therefore a new parameterization is proposed in which the effect of water content on the sensing depth is accounted for by means of the ratio of the soil dielectric constant. This incorporates the effect of the transition moisture and agrees better with the theoretical formulations for T_{eff}. This parameterization is an improvement on Wigneron's parameterization in terms of rmse, and it describes the variations of sampling depth at the seasonal to interannual temporal scale.

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