

ACCURATE ASSESSMENT OF LAND SURFACE THERMAL EMISSIVITY

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ABSTRACT

The emissivity of natural surfaces is a required parameter in high accuracy land surface temperature (LST) determinations. Then, it is of great importance to know how thermal infrared (TIR) emissivity changes with the different factors. Soil type influence on emissivity is well known from experimental studies, whereas the effect of soil moisture (*SM*) on emissivity is one of the pending issues in thermal remote sensing. It is seen that the *SM* variation may cause a high systematic error in emissivity, e.g., about +0.1 in emissivity for an increase from 0.04 to 0.10 g/cm³ in *SM* for sandy soils. This study reveals a common emissivity increase with soil water content, higher for larger sand content and in the 8 to 9 μm range, but always significant considering the experimental uncertainty ($\delta\varepsilon \sim \pm 0.5\%$). The emissivity increase is understood because of both the quartz contribution to decrease the emissivity of the material chiefly between 7.7 and 9.7 μm, and the decrease of the reflectivity by the water film on the soil particles. Emissivity-*SM* relationships were obtained with the aim of using them together with *SM* estimates from remotely sensed data in order to improve the TIR emissivity estimations and thus, the LST determination. Furthermore, the study showed the possibility of retrieving *SM* from TIR emissivities with a standard estimation error of about $\pm 0.08 \text{ m}^3 \text{ m}^{-3}$, when considering the OM content.

INTRODUCTION

The surface emissivity is an important parameter for determining the long-wave surface energy balance, which is strongly affected by the difference between the land surface temperature (LST) and the sky brightness temperature. This difference is small outside the atmospheric window region (7-14 μm) and any changes in the emitted radiation caused by emissivity variability are mostly compensated for changes in the reflected sky radiance (1).

The soil texture influence on emissivity is well-known from experimental studies (2,3,4,5). However, up to now, few published works analyse the variation of TIR emissivities with soil moisture (*SM*) (6,7,8). Mira et al. (9) recently assessed the importance of an accurate determination of the TIR emissivity variation with soil water content to permit accurate temperature retrievals. The study showed systematic errors from 0.1 to 2 K due to *SM* influence on emissivity. In (9), TIR (8-13 μm) emissivities of six soil samples with different textures were measured under controlled *SM* content in order to obtain quantitative relationships between *SM* and spectral emissivities. The best determination coefficients ($R^2 \sim 0.90$ in average) were achieved when using particular equations for each spectral band and soil sample, following a quadratic function of emissivity with *SM*. The measurements showed an emissivity increase up to 16% when water content increased by 24% in the 8.2-9.2 μm region, with the larger increases at low water contents and high sand contents. In this work the study is completed by providing the results of emissivity variation with *SM* for an additional set of eight new soil samples of different textures. A general relationship to define the *SM* dependence of thermal emissivities of soils will be obtained. Furthermore, the possibility of retrieving *SM* estimates from TIR emissivities is analysed.

METHODS

A set of eight soil samples with a diversity of soil types were selected to complement the previous work by Mira et al. (9). They included one sample from White Sands desert in New Mexico (USA), four soils sampled in the Little Washita River Experimental Watershed (LWREW) in south central

Oklahoma (USA), and three soils from a rural area in São Paulo (Brazil). The soil composition for the total set of soils ranged from 14% to 100% for sand, 0% to 54% for clay, 0.0% to 8.9% for organic matter (OM), 1% to 100% for quartz, and 0% to 46% for carbonates content. The quartz abundance in most samples is highlighted due to the low emissivity values at the reststrahlen bands at 7.7 μm , 9.7 μm , and near 12.6 μm (4). The main soil features are summarised in Table 1.

Table 1: Soil sample properties, including location, soil texture and bulk mineralogy.

Samples	Location	Texture (USDA)	Sand (%) Silt (%) Clay (%)	OM (%)	Quartz (%)	CaCO ₃ (%)
WS	32°49'26"N 106°16'23"W	sand	100.0 0.0 0.0	0.21±0.01	1	0.0
LW03	34°57'51"N 98°4'34"W	loamy sand	77.2 17.6 5.2	0.73±0.04	53.7	0.0
LW13	34°55'16"N 97°57'11"W	loam	50.8 35.6 13.6	1.61±0.09	76.0	0.0
LW45	34°55'37"N 98°18'14"W	silty loam	29.2 53.6 17.2	1.15±0.08	72.4	0.0
LW52	34°47'49"N 98°6'54"W	sandy clay loam	62.4 15.2 22.4	1.71±0.10	58.4	0.0
BR1	21°57'43"S 47°50'34"W	clay	40 6 54	2.93±0.08	37.9	0.0
BR2	22°56'11"S 47°43'24"W	sandy loam	69 15 16	1.47±0.09	82.3	0.0
BR3	22°45'18"S 47°53' 75"W	sand	92 2 6	1.69±0.10	100.0	0.0

The measurement strategy and the configuration details of the container designed to keep the soils and allow water drainage and a practical execution of emissivity measurements are given in (9). In that study, the gravimetric method was chosen for measuring the *SM*, since it is considered the most accurate technique. However, it is a laborious and destructive method since small amounts of soil are removed from the total sample when *SM* measurements are done. For these reasons and because models usually require volumetric *SM*, which implies less precisely measured densities, we calculated volumetric *SM* measurements using time domain reflectometry (TDR) in this study. Volumetric *SM* is defined as the ratio of the volume of water contained to the total volume of the soil sample, and can be obtained from gravimetric *SM* by considering the bulk density of the sample. In our experiment, the soil moisture sensor Delta-T SM200 was used, which has a calibration uncertainty of $\pm 0.03 \text{ m}^3 \text{ m}^{-3}$ for *SM* determinations according to the manufacturers.

The emissivities were determined through the two-lid variant of the Box method (10)-(11) and using a CIMEL CE-312 thermal infrared radiometer (7). It has four spectral channels: one broad, 8.0-13.3 μm (channel 1), and three narrow channels, 8.3-9.3, 10.2-11.3, 11.5-12.4 μm (channels 4, 3, and 2 respectively). A calibration of CE-312 with a Landcal Blackbody Source (Type P80P) within the temperature range -10 to 50°C was done during our experiment and uncertainties of about $\pm 0.10 \text{ K}$

were obtained. The sensitivity analysis performed by Mira et al. (8) for the Box method showed that such radiometric errors yield uncertainties in emissivity of about ± 0.012 , and no systematic errors.

According to the two-lid variant of the Box method, the emissivity of a sample is obtained from a sequence of measurements of radiance in which a bottomless box with specular reflective walls is used in four different configurations. Two interchangeable lids with different spectral response are used as tops. One of them (the cold lid) has an emissivity $\varepsilon_c=0.03$, whereas the other (the hot lid) has an emissivity $\varepsilon_h=0.98$ and its temperature is kept 15-20°C over that of the sample. A thick insulating material covers the outer walls and lids of the box to insure the thermal homogeneity of the system. For additional details on the measurement technique, the reader is referred to (9).

For each soil sample and a given *SM* value, a series of 30 emissivity measurements per spectral channel was carried out. Afterwards, the average value of the spectral channel emissivity of each soil and *SM* condition was obtained from these series. The sequence of soil saturation and drying was repeated at least two times in order to ensure the validity and reproducibility of emissivity measurements as well as to obtain intermediate values of emissivity along the *SM* range. For further details on the experimental set up, see (9).

RESULTS

The experimental results are summarised in Figure 1, which shows the influence of soil water content on the TIR emissivity at the different spectral channels. As expected, there is a common increase of TIR emissivities with *SM*. The increase is clearly larger than the standard uncertainty of the measurements, which is about $\pm 0.3\%$. The emissivity error is the estimated standard deviation of the set of 30 emissivity measurements taken for each sample, *SM* value and band. Quantitatively, the highest variation of emissivity with soil water content is observed in channel 4 (8.3-9.3 μm), followed by variations in channel 1 (8.0-13.3 μm), and finally channel 2 (11.5-12.4 μm) and channel 3 (10.2-11.3 μm). From our measurements, it is seen that a large increase of emissivity at low water content is observed, whereas there is almost no change in emissivity for moisture levels above the field capacity (FC) of the soils. A soil is at FC point when, after saturation, all water drained from macropores by gravity. We conclude that soils with *SM* higher than its FC have thermal emissivities close to one as a result of the water spectrum, since water is retained in the soil macropores. Besides, it is seen that the increase of soil water content results in a sharp decrease in the spectral contrast since water is very strongly absorbing in the region of the quartz reststrahlen bands (2).

It is of great interest to find a general relationship that explains how TIR emissivities of soils with any soil texture change with *SM* content. If it is assumed that no knowledge is available about the soil type, except its *SM*, the best results are obtained with equation:

$$\varepsilon_i = a_i + b_i\theta_v + c_i \ln(\theta_v) \quad (1)$$

where ε is the emissivity, θ_v (m^3m^{-3}) is the volumetric soil moisture, and a , b , c are the regression coefficients for each spectral channel i ($i=1$ to 4). R^2 and σ take values from 0.36 to 0.66, and from $\pm 0.7\%$ to $\pm 3\%$, respectively, leading to LST errors up to ± 1.1 K (at 11 μm and for a LST of about 300 K). Results are summarised in Figure 1. Note that channels 1 and 4 do not depend on θ_v , but only on $\ln(\theta_v)$.

To improve the results, a more complex relationship has to be considered since there are other parameters influencing the emissivity spectrum such as soil composition or particle size. A statistical analysis of our data showed which are the main soil properties affecting the emissivity, besides *SM* content. First, the *OM* content, which is highly absorbing in the 8-14 μm region and reduces the apparent spectral contrast of the quartz reststrahlen bands. According to Salisbury and D'Aria (2), soils that contain more than 1.5-2% extractable *OM* tend to display low ratios between bands 8.3 μm and 11.3 μm , regardless of the particle size. Second, the quartz content, which exhibits fundamental molecular absorption features in the TIR: it contributes to increase the reflectance of the material, which means an emissivity decrease, between 7.7 and 9.7 μm , and near 12.6 μm , due to the presence of the quartz reststrahlen bands (4). And third, the carbonates content, whose

spectrum is distinctive because of the presence of a weak absorption feature centred near 11.2 μm and otherwise generally flat spectra (4). Both quartz and carbonates content data improve the estimate of the 8.82 μm band (channel 4) and the wide band (channel 1) emissivities. However, they are not essential for emissivity estimates at 11.96 μm (channel 2) and 10.80 μm (channel 3). The fitting regression relationships presenting the best results for each band when considering not only *SM* but also *OM*, quartz (*Q*) and carbonates (*C*) content is:

$$\varepsilon_i = a_i + b_i\theta_v + c_i \ln(\theta_v) + d_iOM + e_iOM^2 + f_iQ + g_iC \quad (2)$$

where *a* to *g* are the regression coefficients for each spectral channel *i* (*i*=1 to 4), and *OM*, *Q* and *C* content are given in percent. The results of this analysis are summarised in Table 2. Since the minimum *SM* value is usually different from zero in real conditions, the logarithmic function in Eq. (3) should not present divergence problems. As expected, the consideration of ancillary data in relationship (2) significantly improved the emissivity estimation. Quantitatively, R^2 took an average value of 0.78, and σ was lower than $\pm 1.9\%$, leading to *LST* errors lower than ± 0.7 K (at 11 μm and for a *LST* of about 300 K). Here σ represents the minimum achievable error, which will be larger as far as the estimations of parameters (i.e., θ_v , *OM*, *Q*, and *C*) become less accurate.

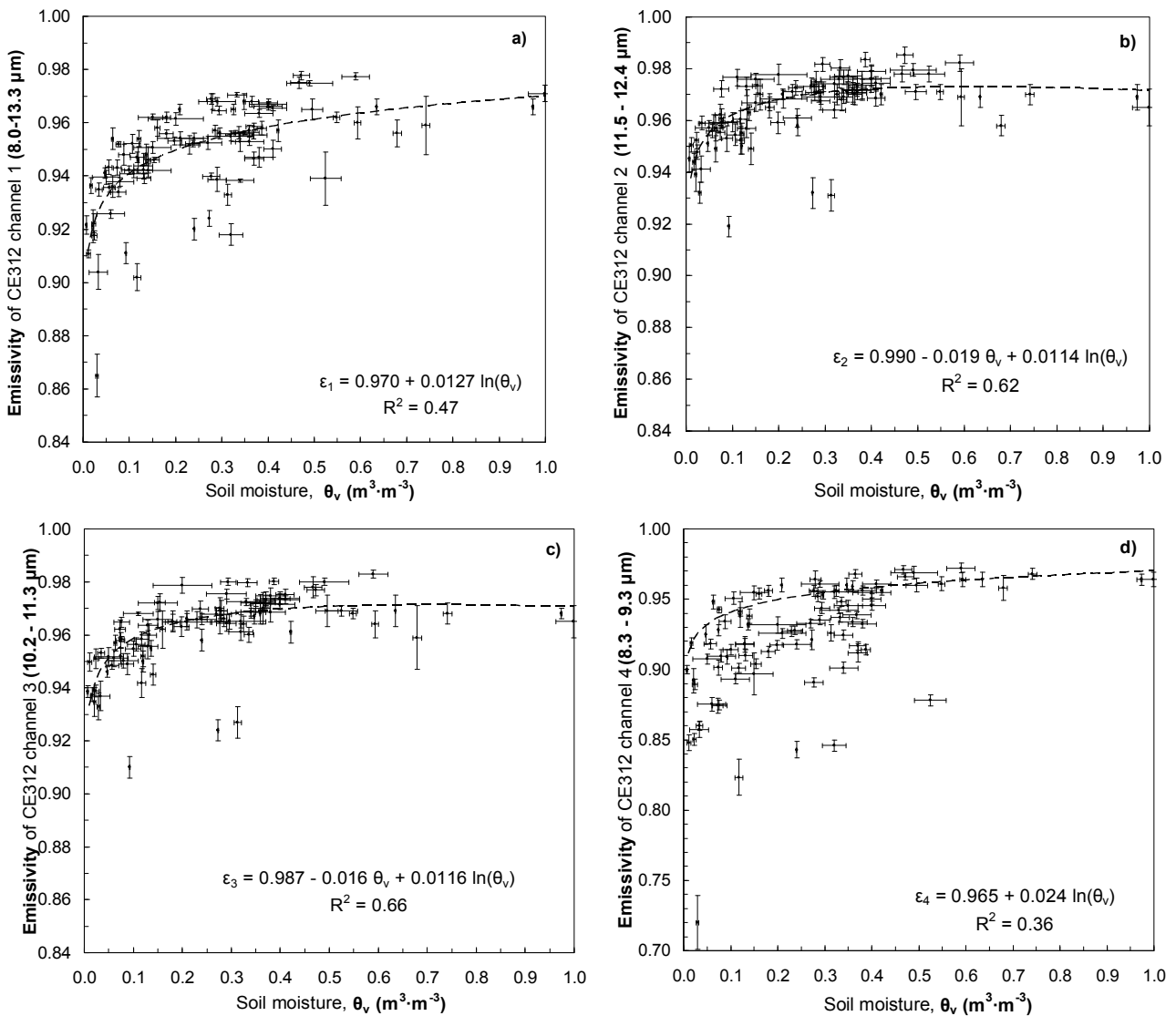


Figure 1: Soil emissivity measurements for CE-312 channels, at various moisture contents. Dashed lines represent the fitting curves of emissivity against soil water content for each channel, according to Eq. (1) and coefficients given in each plot.

Table 2: Fitting curves of emissivity, ϵ , against volumetric water content, θ_v , and other soil properties, for each spectral band of CE-312, when considering all soils together, including samples from (ix). OM: organic matter content, %; Q: quartz content, %; C: carbonates content, %; a to g: regression coefficients; R^2 : determination coefficient; σ : standard estimation error.

	$\epsilon_i = a_i + b_i\theta_v + c_i \ln(\theta_v) + d_iOM + e_iOM^2 + f_iQ + g_iC$			
	CE321 ch1 (8-13 μm)	CE321 ch2 (12.0 μm)	CE321 ch3 (10.8 μm)	CE321 ch4 (8.8 μm)
$a \pm \delta(a)$	0.964 ± 0.003	0.968 ± 0.004	0.970 ± 0.004	0.930 ± 0.007
$b \pm \delta(b), (\text{m}^3\text{m}^{-3})^{-1}$	0 ± 0	0.027 ± 0.007	0.025 ± 0.007	0 ± 0
$c \pm \delta(c)$	0.0124 ± 0.0010	0.0060 ± 0.0013	0.0065 ± 0.0013	0.020 ± 0.002
$d \pm \delta(d)$	0.0186 ± 0.0019	0.0033 ± 0.0009	0 ± 0	0.050 ± 0.004
$e \pm \delta(e)$	-0.00198 ± 0.00019	-0.00078 ± 0.00011	-0.00045 ± 0.00004	-0.0047 ± 0.0004
$f \pm \delta(f)$	-0.00022 ± 0.00004	0 ± 0	0 ± 0	-0.0005 ± 0.00008
$g \pm \delta(g)$	-0.00052 ± 0.00010	0 ± 0	0 ± 0	-0.0013 ± 0.0002
R^2	0.77	0.79	0.77	0.79
σ	0.009	0.006	0.006	0.019

A complementary approach was considered in this study, i.e., the possibility of retrieving the soil water content from TIR emissivity estimates. The best estimates of SM were retrieved through the following equation:

$$\theta_v = A + B \exp(\epsilon_3) + C \exp(\epsilon_4) + D(\epsilon_4) + E OM + F(OM)^2 \quad (3)$$

where A to F are the regression coefficients, OM is the organic matter content given in percent, and ϵ_i is the emissivity of channel i ($i=3, 4$) of the CE-312 radiometer. The results of the analysis, summarised in Table 3, showed that R^2 was about 0.85, being the standard estimation error (σ) of SM of about $\pm 0.08 \text{ m}^3\text{m}^{-3}$, which can be larger if emissivity estimates are less accurate. Note that retrievals of low SM contents have large errors. Therefore, this approach could be considered as a way to roughly estimate SM when the emissivity spectrum of the soil is known. Then, the advantage of this method with respect to SM retrievals from microwave-based sensors is the possibility of working with a higher spatial resolution, while the disadvantages are the loss of precision in the SM retrievals and the fact that only the soil water content from the skin of the surface can be retrieved by TIR remote sensing.

Table 3: Fitting curves of volumetric water content, θ_v , against TIR emissivities of channel 3 (10.8 μm) and channel 4 (8.8 μm), and organic matter (OM) content, when considering all soils together (including samples from (9)). A to F: regression coefficients; R^2 : determination coefficient; σ : standard estimation error.

$\theta_v = A + B \exp(\epsilon_3) + C \exp(\epsilon_4) + D(\epsilon_4) + E OM + F(OM)^2$	
$A \pm \delta(A), \text{m}^3\text{m}^{-3}$	-15.9 ± 1.2
$B \pm \delta(B), \text{m}^3\text{m}^{-3}$	2.8 ± 0.3
$C \pm \delta(C), \text{m}^3\text{m}^{-3}$	29 ± 5
$D \pm \delta(D), \text{m}^3\text{m}^{-3}$	-70 ± 12
$E \pm \delta(E), \text{m}^3\text{m}^{-3}$	-0.113 ± 0.018
$F \pm \delta(F), \text{m}^3\text{m}^{-3}$	0.0166 ± 0.0017
R^2	0.85
$\sigma, \text{m}^3\text{m}^{-3}$	0.08

CONCLUSIONS

As reported by previous studies, the experimental measurements demonstrated that there is a common increase of emissivity with *SM*. A large increase of emissivity is observed at low water contents, while there is almost no change in emissivity for moisture levels above the soil field capacity. The scope of the study was to model the emissivity dependence on soil water content. A general retrieval procedure applied to any soil retrieved rough estimates of the emissivities with a standard estimation error from $\pm 0.7\%$ to $\pm 3\%$. The study also indicated that the consideration of ancillary data (i.e., organic matter, quartz and carbonates content) significantly improved the results from a general fitting curve applicable to any soil, providing the emissivity with a standard estimation error lower than $\pm 1.9\%$. Furthermore, the possibility of retrieving the soil water content from emissivity estimates was also analysed. *SM* was obtained with a standard estimation error of about $\pm 0.08 \text{ m}^3\text{m}^{-3}$ when the OM content was considered. This could be obtained when the TIR emissivity spectrum can be measured with high precision and no data of the soil water content is available or it has a poor spatial resolution. The uncertainty in surface temperature associated with such emissivity errors took values of about $\pm 0.2 \text{ K}$ and $\pm 1.1 \text{ K}$ (at $11 \mu\text{m}$ and for a LST of about 300 K) from the specific and general relationships, respectively. An important feature of the retrieval relationships is that if the soil composition is known, accurate retrievals of TIR emissivities from *SM* are possible.

This study, which includes data from (9), provides the first database on soil moisture effects on emissivity. Thus, this work could be used to estimate thermal emissivities of moist soils with a wide variety of textures, which has been difficult up to now due to the lack of published data. Therefore, in further work we will explore the feasibility of this approach using Soil Moisture and Ocean Salinity (SMOS) data and compare the retrieved emissivities with those coming from other sources, e.g., emissivities from the Moderate Resolution Imaging Spectroradiometer (MODIS) and the Advanced Spaceborne Thermal Emission and Reflection (ASTER) sensors onboard the National Aeronautics and Space Administration (NASA)'s Terra satellite.

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