VALIDATING TWO THEORETICAL MODELS TO PREDICT THE EMISSIVITY OF A PURE QUARTZ SAMPLE BETWEEN 8-14 µm

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ABSTRACT

Emissivity is an intrinsic magnitude of Earth surfaces, which indicates the capacity of a surface to emit radiation at different ranges of the electromagnetic spectrum. In the Thermal InfraRed (TIR) range (8-14 µm) the accurate knowledge of the emissivity is of prime importance to obtain precise land surface temperatures, key magnitude in the surface-atmosphere energy budget studies.

There exist several methods to retrieve the emissivity, based on semi-empirical, multichannel or physical relationships. However, sometimes it is impossible to apply these techniques and it is needed to use a previous measured or modeled emissivity value. The present study is focused on the retrieval of TIR emissivity of a pure quartz sample by means of two different theoretical models, based on the Mie theory. These models need as inputs the particle size distribution and the complex refractive index. The emissivity spectrum of each model was calculated under three different conditions, one with the original Mie parameters, and the other two using different compactness corrections proposed by several authors. Results were validated with emissivity laboratory measurements obtained from the ASTER spectral library for a quartz soil with particle size ranging between 0-45 µm.

Results of the study showed that both models compared with laboratory measurements represent quite well the spectral variability of the quartz emissivity, including the fall of the emissivity at the so-called Reststrahlen spectral region (8-9 µm). The difference between measured and modeled emissivity is reduced when compactness corrections are applied to the Mie parameters of the models. The main results of this study suggested a promising use of these models in remote sensing applications.

1. INTRODUCTION

The knowledge of emissivity (ε) is of prime importance to understand the role of a surface in the radiative energy balance. Remote sensing techniques focused in the thermal infrared (TIR) region (8-14 µm) need the emissivity, as well as the atmosphere effect, to retrieve the temperature of the surfaces. However, the emissivity itself is useful to study and characterize the composition and development of the surfaces from the Earth or other planets.

Current methods like Temperature and Emissivity Separation (TES) applied to ASTER (1) or MODIS (2) sensors onboard TERRA platform; allow the retrieval of the TIR emissivity of surfaces at some specifics spectral ranges within the TIR domain. These discrete values of the emissivity can be useful to characterize the soil composition; however, a detailed knowledge of ε along the TIR range can be essential to establish the type of surface studied with optical remote sensors.

This work evaluated two different analytical models to simulate the emissivity of the non-vegetated surfaces, based on the Mie diffraction theory. Results of these models were confronted with emissivity measurements of a pure quartz sample, performed in laboratory conditions by a FTIR spectrometer. These laboratory emissivities are available in the ASTER Spectral Library database (ASL) (3).

The next sections describe the two theoretical models evaluated in this study to simulate the emissivity, as well as the soil compactness correction applied to these models (section 2), the main optical and granularity properties of the pure quartz sample used to test the models (section 3), the results and discussions drawn from the study (section 4) and the main conclusions (section5).

2. THEORETICAL EMISSIVITY MODEL

The two analytical models proposed in this study to simulate the emissivity are based in the Mie theory, which describes the light diffraction in a dense medium. The emissivity is simulated using an analytical expression which main inputs are the asymmetry factor (*g*) and the single-scattering albedo (ω).Both parameters are calculated by the Mie theory under the assumption of an isolated spherical particle which spectral value of the refractive index is well-known. The Mie parameters calculations can be extended to a dense medium, composed by several grains with different diameter. In this case it is necessary to know the particle size distribution (PSD) of the soil.

2.1 Warren-Wiscombe-Dozier (WWD) model

The first model presented is the proposed by (4) to calculate the reflectivity of the snow and converted to an analytical expression of the emissivity by (5). The model was intended to simulate the emissivity of multiple scattering mediums, and it is based on the δ-Eddington approximation proposed by (6), which considers the phase function as a δ-Dirac. The WWD model expresses the emissivity as follows:

$$\varepsilon(\lambda,\theta)=\frac{\xi\cos(\omega b+1+P)+1+P-\omega}{(1+P)(1+\xi\cos\theta)} \quad (1)$$

where $b=g/(1-\omega g)$, $\xi=(3(1-\omega g)(1-\omega))^{1/2}$, $P=2\xi/3(1-\omega g)$.

Mie parameters *g* and ω, as stated above, are representative of an isolated spherical particle, or a medium of isolated spherical particles (distance between particles of 3 times the particle radius). However, a soil surface is not composed by isolated particles, but rather the opposite. The grains of the soil are in contact and compacted, for that reason, the WWD model proposed a soil compactness correction of the Mie parameters, defined by the expressions:

$$g_\delta=\frac{g}{1-g} \quad (2)$$

$$\omega_\delta=\frac{(1-g^2)\omega}{1+g^2\omega} \quad (3)$$

2.2 Hapke model

The second model evaluated in this study was the proposed by (7). The emissivity analytical expression is only dependent on ω, as:

$$\varepsilon(\lambda,\theta)=\sqrt{1-\omega}\,\frac{1+2\cos\theta}{(1+2\cos\theta\sqrt{1-\omega})} \quad (4)$$

The soil compactness correction for the Hapke model was proposed by (8), expressed by the next corresponding equations:

$$g_w=\frac{2\omega g-1}{2\omega-1} \quad (5)$$

$$\omega_w = 2\omega - 1 \tag{6}$$

Both models were implemented in a computer code to simulate the emissivity between 8-14 μm. This emissivity was retrieved from each model under three different compactness conditions: first using the original Mie parameters for an isolated medium of isolated particles, second applying the δ-compactness by means of the corrected Mie parameters ω_δ and g_δ, and third applying the compactness correction proposed by (8) through the Mie parameters ω_w and g_w. The main goal was to evaluate which of these three compactness conditions showed the best emissivity modeled results compared to the laboratory emissivity measured by the ASL for a pure quartz sandy sample (3).

3. OPTICAL AND GRANULARITY PROPERTIES OF THE QUARTZ

The quartz is the most abundant mineral found in the Earth surfaces. For that reason we evaluated the two emissivity models for a pure quartz sample, with a PSD ranging between 0-45 µm. This sample was similar to that used by the ASL in the measurement of the emissivity carried out by a FTIR spectrometer.

A PSD analysis of our sample was performed with laboratory techniques. Results plotted in Figure 1, show a near Gaussian behaviour of the PSD in the quartz sample, with grains diameter ranging between 2 and 80 µm. It is worth to note that the emissivity measured in laboratory by the ASL, used in this work for evaluation purposes, corresponded to a sample which granularity ranged between 0-45 µm, but our sample fitted this requisite since 97% of the grains diameter are within this range, being the average diameter 18 µm.

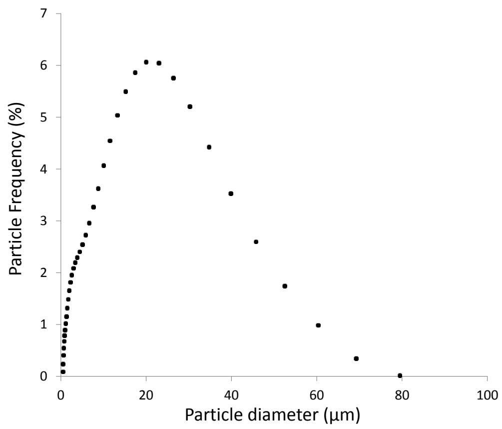

Figure 1. Particle size distribution of the Grains diameter of a pure quartz sample.

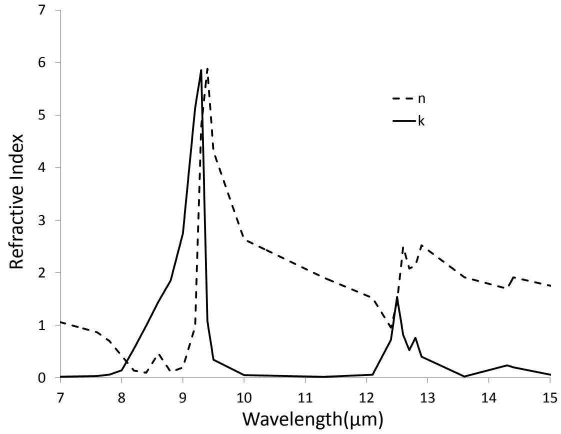

Figure 2. Spectral variation of the real (n) and imaginary (k) parts of the refractive index for the quartz mineral. Data extracted from (9).

Besides the grain radius, the other parameter needed to perform the Mie calculations is the spectral complex refractive index $m_\lambda = n_\lambda + i\ k_\lambda$ (being n and k the real and imaginary part, respectively). Quartz refractive index has been studied in numerous works, in this study the *m* used was that determined by (9), which spectral values of *n* and *k* between 7-15 µm are plotted in Figure 2.

4. RESULTS AND DISCUSSION

Figure 3 shows the comparison of simulated emissivities obtained from both models with the quartz emissivities measured in laboratory and available in the ASL (3).

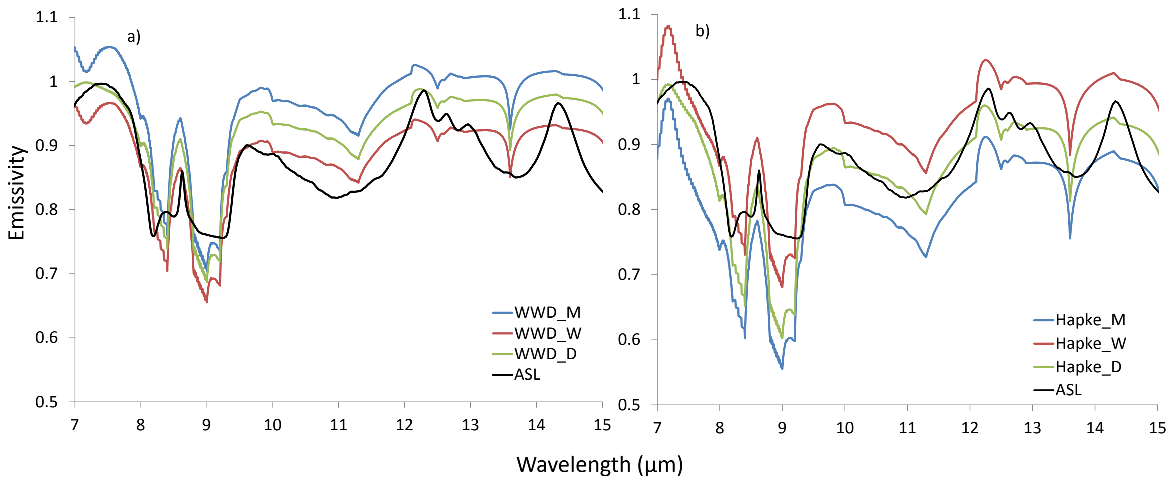

Figure 3: Emissivities calculated between 8-14 µm, with the WWD (a graph) and Hapke (b graph) models, considering the non-corrected Mie parameters (WWD_M and Hapke_M) and correcting these parameters with the compactness correction proposed in (4) (WWD_D and Hapke_D) and proposed by (8) (WWD_W and Hapke_W). Emissivity measured in laboratory and available in the ASTER Spectral Library (3) is also included in both graphs for validation purposes.

From results of Figure 3 it can be stated that independently of applying a compactness correction or not, both models represent satisfactorily the spectral shape of the quartz emissivity, even capturing the significant fall of emissivity between 8-9 µm, the so-called Reststrahlen bands. However, using original non corrected Mie parameters showed the worst results compared with ASL measured emissivity. This result was expected since the real medium is not composed by isolated particles, then it reinforces the application of the two proposed soil compactness corrections to both emissivity models, which reduces the difference with the measured emissivity, as can be seen in Figure 3. Finally, from Figure 3 is surprisingly observed a change in the roll of the compactness correction. The Wald compactness applied to WWD model improved the results obtained when the original was applied to this model (Figure 3a). On the other hand, δ-compactness applied to Hapke model also improves the results obtained when Wald compactness was applied to this model (Figure 3b).

Table 1 shows the average, maximum and minimum values of the difference between ASL emissivity and models simulated emissivity, with the corresponding compactness corrections. As observed, the non-compactness correction leads the models to present the large errors. The best results in the case of the WWD model were obtained applying the Wald correction, with an average difference of 0.03 and a maximum difference of 0.11. The Hapke models showed the best results applying the δ-compactness correction, showing an average difference of 0.03 and a maximum difference of 0.16.

Table 1: Average, maximum and minimum differences between the simulated (WWD and Hapke) and measured ASL emissivity. Difference presented for the non-corrected Mie parameters (MIE) and for the two proposed soil compactness corrections (WALD and δ), applied to both models.

	WWD			HAPKE		
	MIE	WALD	δ	MIE	WALD	δ
Average	0.09	0.03	0.06	0.07	0.07	0.03
Maximum.	0.16	0.11	0.13	0.21	0.14	0.16
Minimum.	0.000	0.000	0.000	0.000	0.001	0.000

The last test to check which of both models showed the best simulated emissivity was to compare directly predicted and measured emissivity. Figure 4 shows measured ASL emissivity compared with predicted emissivity with both models after applying their optimal compactness corrections in each one (Wald-compactness in WWD model and δ-compactness on Hapke model).

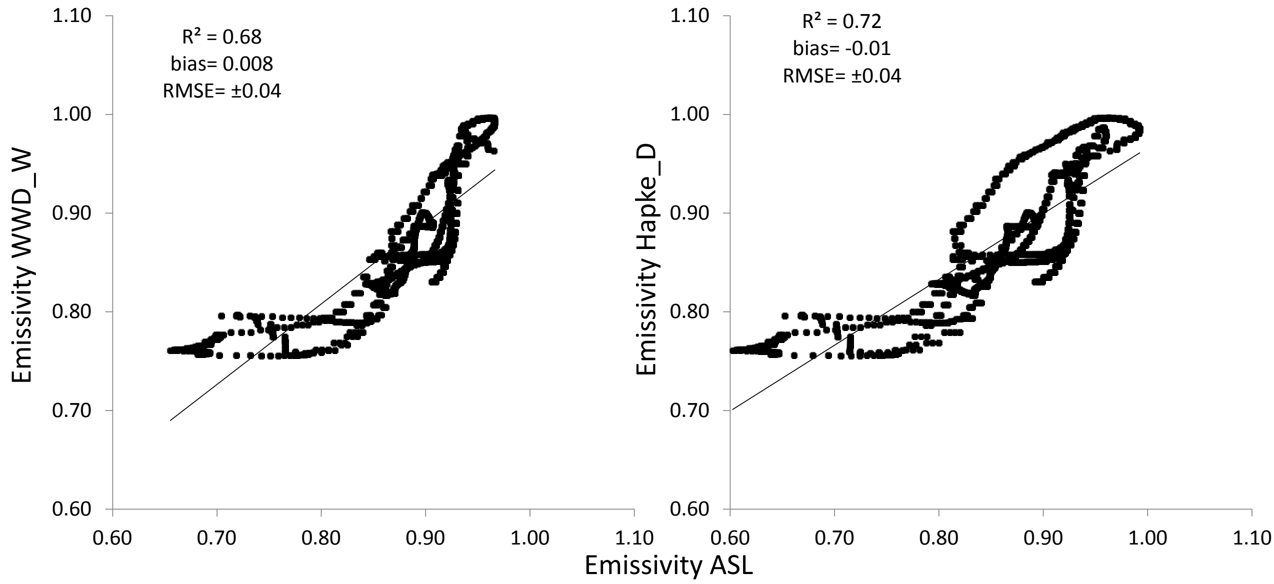

Figura 4. Comparison of emissivity simulated by the WWD model after applying the Wald-compactness correction (left graph) and Hapke model after applying the δ-compactness correction (right graph), with measured ASL emissivity values. It is also represented the correlation coefficient (R^2), the bias and the RMSE.

Results of Figure 4 show that WWD using Wald compactness correction is the best choice to simulate the quartz emissivity. The correlation is higher for Hapke model with δ-compactness correction and the RMSE is the same for both models, but the bias is slightly smaller for the WWD model.

In spite of WWD models showed the best results, both models showed significant deficiencies simulating a realistic value of the emissivity in the Reststrahlen band 8-9 µm of the quartz. Both models are promising for future works, but an exhaustive control both of the refractive index and the spectral emissivity will be of importance to reach more decisive conclusions.

5. CONCLUSIONS

The hyperspectral knowledge of the surfaces emissivity could be of prime importance to establish their composition, as well as their optical properties (e.g. refractive index). The present work evaluated two theoretical models to predict the emissivity of pure quartz sample in the TIR domain (8-14 µm), these models are based on the Mie diffraction theory. Results showed that both models represented satisfactorily the spectral shape of the quartz emissivity, even capturing the significant fall of emissivity between 8-9 µm, the so-called Reststrahlen bands. Results also showed that applying the soil compactness correction improves significantly the values of the simulated emissivity compared with the emissivity measured in laboratory. WWD model after applying the Wald-compactness correction, showed the best simulated emissivity compared with measured data, with an RMSE of ±0.03. However, both models showed deficiencies representing the emissivity of the Reststrahlen band of the quartz (8-9 µm).

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