Experimental Tests on TIR Multispectral Images for Temperature-Emissivity Separation by Using the MaxEnTES Algorithm [†]

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Abstract: Satellite images in the TIR are relevant for several Earth Observation applications. The retrieval of temperature and emissivity from the emitted radiance, however, requires the use of suitable algorithms, such as the MaxEnTES that uses the concept of maximum entropy to solve the Temperature-Emissivity Separation problem. Here we discuss the performance of MaxEnTES when applied to TIR images with a limited number of channels, specifically simulated HypsIRI multispectral images and real multispectral images by ASTER. The results were respectively compared with the original temperatures used for the simulations and with the temperatures obtained by using the ASTER TES algorithm.

Keywords: temperature-emissivity separation; maximum entropy; thermal infrared; multispectral images; earth observation

1. Introduction

Images of the Earth surface, acquired in Thermal Infrared (TIR), provide relevant information for climatological studies, meteorology and surface characterization. Radiance emission in the TIR is modelled by Planck's law that relates the emitted spectral radiance to the target's temperature and emissivity. The retrieval of temperature and emissivity from the emitted radiance—the Temperature/Emissivity Separation (TES)—is an ill-posed problem since the number of available measurements ' n ' is less than the number of unknowns, that are ' $n + 1$ '. Several approaches have been proposed to solve the so-called TES problem [1–4]. All these approaches rely on a-priori assumptions to solve the TES problem. Following the work of Jaynes [5], new methods of inverse-modelling for such cases, in which the number of unknowns exceeds the number of measurements, were suggested. These procedures take the collective name of Maximum Entropy formalism (MaxEnt) [5]. Following MaxEnt methodology, the MaxEnTES algorithm retrieves temperature and spectral emissivity as expectation values of the corresponding random variables [6]. Thus, TES is turned into the problem of assessing the Probability Density Function (PDF) of the corresponding random variables that maximize the entropy. The MaxEnt is the less committal approach for bridging the gap between measurements and estimates. MaxEnTES approach, however, requires the availability of several measurements (spectral channels) to provide a good estimate and, in general, its performance improves as the number of measurements increases [6].

In this paper we discuss the performance of MaxEnTES when applied to images featuring a limited number of measurements. Here MaxEnTES was first tested on simulated HypsIRI-like

multispectral images (7 spectral bands in the TIR) and the results compared with the original ones used for the simulations. Secondly, MaxEntTES was applied to real multispectral images acquired by ASTER (5 spectral bands in the TIR) and the results compared with those obtained by using the ASTER-TES algorithm [2].

2. Materials and Methods

2.1. The MaxEntTES Algorithm

Spectral radiance in the TIR can be expressed as:

$$L_i = \varepsilon(\lambda_i)B(T, \lambda_i), \quad (1)$$

where λ_i is the wavelength of the i -th channel with $i = 1, \dots, n$, $B(T, \lambda_i)$ is the Planck function, and $\varepsilon(\lambda_i)$ is the emissivity. The entropy H is an estimate of information content. Given a PDF $= p(x_i)$, the entropy H can be written as:

$$H = -\sum_i p(x_i) \log p(x_i) \quad p(x_i) = \frac{\exp(l_1 f_1(x_i) + \dots + l_m f_m(x_i))}{Z(l_1, \dots, l_m)} \quad (2)$$

PDF is expressed as a function of the measurements $f_i(x)$, of the partition function $Z(l_1, \dots, l_m)$ and the Lagrange multipliers $(l_1, \dots, l_m)$. Lagrange multipliers result from the constrained maximization of the entropy. The MaxEnt approach consists in finding the optimal value of Lagrange multipliers $(l_1, \dots, l_m)$ that matches the expectations $E[f_i(x)]$ to the available measurements L_i .

The MaxEnt method applied to TES problem can be summarized with the following statement: “finding the PDF with maximum information entropy that maximizes the probability to obtain the available experimental results L_i when measuring $f_i(x)$ ”. The goal is the estimation of both temperature T and emissivity spectrum ε_i , calculated in the generic i -th channels, as expectation values of the corresponding aleatory variables e_i , t . Setting temperature and emissivity as $T = E\{t\}$, $\varepsilon = E\{e_k\}$: the spectral radiance L_i can be retrieved as:

$$f_i(\vec{e}, t) = e_i B(t, \lambda_i) \quad ; \quad L_i = E\{f_i(x)\} = \int_{\mathfrak{R}} p(x) f_i(x) dx \quad ; \quad \forall i \quad (3)$$

2.2. Simulated Data

The simulated data used for testing the MaxEntTES algorithm were generated according to the parameters of an acquisition performed by the HypsIRI TIR instrument [7]. The instrument has a spatial sampling of 60 m and acquires images in 7 spectral bands between 7 and 12 μm , as reported in Table 1. The HypsIRI-like image was simulated selecting 19 different classes of targets from the ECOSTRESS spectral library [8,9] Figure 1. The selected classes were used for generating a HypsIRI-like image of surface emitted radiance, that was used as an input for the MaxEntTES algorithm. White noise was considered in the simulation.

Table 1. HypsIRI TIR spectral bands.

Band	λ (μm)	Bandwidth (μm)
Band 1	7.35	0.320
Band 2	8.28	0.340
Band 3	8.63	0.350
Band 4	9.07	0.360
Band 5	10.53	0.540
Band 6	11.33	0.540
Band 7	12.05	0.520

Figure 1. HypsIRI-like simulated image: (a) thematic map with 19 classes; (b) Simulated ground-truth temperature image.

2.3. Real Satellite Data

The ASTER surface radiance (A09 product) image used for testing the MaxEnTES was acquired over the Fucino plains (Abruzzo, Italy) on 8 August 2018 at 10:55 local time (Figure 2a). ASTER is a multispectral imager with 5 spectral bands in the $8\ \mu\text{m}$ – $11\ \mu\text{m}$ spectral range, as shown in Table 2. Figure 2b shows the temperature image as provided by ASTER A08 product.

Figure 2. ASTER acquisition over Fucino area, Abruzzo, Italy: (a) ASTER A09 product—Ground emitted radiance image at $10.657\ \mu\text{m}$, (b) ASTER A08 product—Temperature image.

Table 2. ASTER TIR spectral bands.

Band	$\lambda\ \text{min}\ (\mu\text{m})$	$\lambda\ \text{max}\ (\mu\text{m})$
Band 10	8.12	8.47
Band 11	8.47	8.82
Band 12	8.92	9.27
Band 13	10.25	10.95
Band 14	10.95	11.65

3. Results

The MaxEnTES algorithm was applied to the HypsIRI-like simulated data in order to retrieve the temperature image (not shown) and the retrieved temperature values were compared with those used for the simulation. The histogram of their differences is plotted in Figure 3a. The error—estimated as Full Width Half Maximum—in retrieved temperature ΔT is equal to $\pm 1.5\ \text{K}$.

As far as real satellite data are concerned, the differences between MaxEnTES and ASTER-TES retrieved temperatures exhibit a $\Delta T \approx \pm 2.5\ \text{K}$ at FWHM. Figure 3b shows the scatter plot between temperatures retrieved by using MaxEnTES and ASTER-TES, respectively. R^2 is equal to 0.78.

Figure 3. MaxEnTES applied to simulated and real data: (a) Simulated data: histogram of the differences between the temperatures retrieved using MaxEnTES and those used for the simulation. (b) Real data: scatterplot of ASTER A08 temperatures vs the temperatures retrieved using MaxEnTES.

4. Discussion and Conclusions

Although MaxEnTES provides an optimal performance when applied to hyperspectral images that feature a large number of channels (>10 channels) as already demonstrated in [4], the results obtained in this paper showed good performance of the algorithm even when applied to multispectral images in the TIR, at least when the number of channels of the image is close to 10. The performance, in fact, apparently deteriorates when applied to the ASTER data featuring only 5 channels, although the results are still consistent with those obtained using the standard ASTER-TES algorithm. Next actions of the research aim to apply MaxEnTES to real multispectral images in the MIR-TIR featuring a larger number of channels.

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