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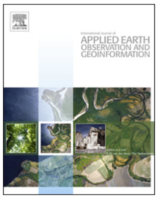

Auto-correcting for atmospheric effects in thermal hyperspectral measurements

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ABSTRACT

Correct estimation of soil and vegetation thermal emissivities is of huge importance in remote sensing studies. It has been shown that the emissivity of leaves retrieved from field observations show subtle spectral features that are related to leaf water content. However, such field measurements provide additional challenges before leaf water content can be successfully obtained, specifically atmospheric correction. The aim of this research was to investigate how information within hyperspectral thermal observations can be used to auto-correct the atmospheric influence. Hyperspectral thermal measurements were taken over a large variety of soil and vegetation types (including vineyard and barley) during ESA's REFLEX campaign in 2012 using a MIDAC FTIR radiometer. Using MODTRAN simulations, a simple quadratic model was constructed that emulates the atmosphere radiative transfer between the target and the sensor. Afterwards, this model was used to estimate the concentrations of H_20 (g) and CO_2 (g) while simultaneously correcting for these gas absorptions. Finally, a temperature-emissivity separation was applied to estimate the emissivities of the different land surface components.

The uncertainty of the approach was evaluated by comparing the retrieved gas concentrations against parallel measurements of a LICOR 7500. It was found that most measurements of gas concentrations were successfully retrieved, with uncertainties lower than 25%. However, absolute correction of the absorption features proved more difficult and resulted in overestimations of the correction-terms. This was mainly due to overlapping of spectral features with the observations in the simulations that proved troublesome.

1. Introduction

Correct estimation of soil and vegetation thermal emissivities is of huge importance in remote sensing studies. Applications such as estimating the land surface temperature (Prata et al., 1995; Sun et al., 2000; Zhang et al., 2004; Sobrino and Jimenez-Munoz, 2005; Wan, 2008), retrieving the surface radiative fluxes (Sobrino et al., 1994; Yamaguchi et al., 1998; Payan and Royer, 2004; Zhang et al., 2004; Liu et al., 2007; Sobrino et al., 2007) and estimating the land-atmosphere interaction by means of evaporation (Bastiaanssen, 2000; Su, 2002; Cleugh et al., 2007; Maes and Steppe, 2012) require accurate values of the thermal emissivity of the surface, as larger uncertainties will propagate into these applications.

Limitations in the current estimations of thermal emissivity, from either ground or remote sensing acquisitions, create significant uncertainties. Ground retrievals of emissivity involve radiative measurements of thermal radiation; usually performed using 'box' measurements (Sobrino and Caselles, 1993). However, such box measurements are very time-consuming and cannot easily be expanded to large areas because the approach requires sampling of the target with several lids of varying reflectivity/temperature. In contrast, remote sensing retrievals focus on estimating the thermal emissivity for large extended objects. These retrieval algorithms rely on the relationship between the emissivity and optical indices, such as NDVI (Su, 2002; Jimenez-Munoz et al., 2006). However, this relationship imposes limitations as it does not account for the variations found in the emissivity values (Salisbury and D'Aria, 1992) for different soil types and water content levels.

Alternatively, remote sensing approaches exist that perform temperature emissivity separation (TES) (Payan and Royer, 2004) using multiple thermal bands (Yamaguchi et al., 1998; Payan and Royer, 2004; Sobrino et al., 2007). However, these investigations were limited to retrieving spectrally averaged emissivity values (Sobrino and Caselles, 1993; Olioso, 1995; Chen et al., 2004; Jimenez-Munoz et al., 2006; Lopez et al., 2012) due to lack of equipment with appropriate spectral sampling, signal to noise ratios, and spatial resolutions. However, recent research has shown that it is possible to discriminate spectral emissivity features of leaves (Ribeiro da Luz and Crowley, 2007). Such investigations are now feasible due to new instruments

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capable of hyperspectral acquisitions of the thermal spectral response (Vaughan et al., 2003; Liu et al., 2007; Hecker et al., 2010; Hecker et al., 2011; Schlerf et al., 2012).

Such thermal hyperspectral emissivities can be used to enhance the retrieval of vegetation traits. While in the past only optical (0.4 m–2.5 m) hyperspectral measurements were possible, for retrieval of leaf constituents based on PROSPECT (Jacquemoud et al., 1996; le Maire et al., 2004; Colombo et al., 2008; Jacquemoud et al., 2009), these new thermal hyperspectral sensors (using the spectral absorption/emission behavior between 2.50 μm and 15.00 μm), provide the possibility to species identification (Ribeiro da Luz and Crowley, 2010; Ullah et al., 2012; Rock et al., 2016), and to estimate plant constituents (Elvidge, 1988; Salisbury and md, 1998). Specifically, research has focused on estimating leaf chemistry (Ribeiro da Luz and Crowley, 2007) and leaf water content (Fabre et al., 2011; Ullah et al., 2014) from the lab thermal hyperspectral acquisitions. The lab-based approaches have limitations that limit applicability. Specifically, they require that the samples be heated to a temperature above ambient conditions and that the leaves are cut from the plant (Ribeiro da Luz and Crowley, 2007); thereby disturbing the natural behavior of the leaves (such as the opening and closing of the stomata). In order to minimize this effect, additional measurements should be considered on live plants in the field.

Field measurements provide additional challenges before leaf constituents can successfully be retrieved. In particular, the radiative path between sensor and target needs to be considered. While in the laboratory the influence of the atmospheric conditions can be controlled by flooding the integrating sphere with nitrogen (Hecker et al., 2011), in field experiments this cannot be done. As a consequence, the radiative measurements should be atmospherically corrected (Su et al., 2005; Su et al., 2008). This is generally performed using simulations from dedicated atmospheric radiative transfer models such as MODTRAN (Berk et al., 1998) using a priori information about concentrations of atmospheric constituents. In most cases such concentrations are not known. This is because measurements by gas-analyzers, such as the LICOR 7500 (LICOR Biosciences, Nebraska, USA), are very expensive. The objective of this research is therefore to develop an approach to auto-atmospherically correct thermal hyperspectral emissivity measurements.

2. Materials and methods

For the hyperspectral measurements, a thermal radiometer from the MIDAC Corporation (MIDA, Costa MESA, CA, USA) was used, see Fig. 1. This MIDAC spectrometer uses a Mercury Cadmium Telluride (MCT) detector in a Fourier-transform Interferometer (FTIR) setup. The instrument is capable of thermal acquisitions from 3 m to 20 m with a maximum spectral resolution of 0.5 cm^{-1}, see Table 1. While the sensor itself is cooled with Liquid Nitrogen to improve signal to noise ratio levels, the housing of the instrument is not thermally controlled. Instead its thermodynamic properties are assumed to be ‘semi-static’ due to the thickness of the aluminium casting (providing a weight of 16 kg).

Table 1
MIDAC-API technical specifications.

Name	Specification
Interferometer type	High performance Michelson, HeNe laser, gold coated mirrors
Detector	MCT (M4401), LN2 cooled
Spectral range	3–20 micrometer
Spectral resolution	0.5 cm^{-1}–4.0 cm^{-1}
FOV	20 mrad
Spot size	7.1 cm (3.5 + 3.6) at 1.2 m
Blackbody sources	2 (0–70 °C)

The spectrometer has been modified in order to look down at the specific targets, as the instrument was initially designed by MIDAC for open path atmospheric measurements (Hecker et al., 2011). This is accomplished by a gold-plated folding mirror in the fore-optics (built by the Advanced Photonics Internal Corporation), see Fig. 1. In addition to the gold-plated mirror, two blackbodies required for the calibration of the system were also mounted on the fore-optics. These are set to temperatures ‘higher than target’ and ‘lower than target’ (Hecker et al., 2011). An additional modification was implemented to enable multi-directional observations similar as in a goniometer (Li et al., 2004; Timmermans et al., 2009), with 5° incremental steps from 0 up to 90° view direction.

2.1. Study area

The MIDAC setup was used during ESA’s REFLEX field campaign in 2012 at the Las Tiesas agricultural test farm in Barrax, Spain. In total, 13 types of target in 6 locations were measured in a period of 5 days (22-07-2012 till 26-07-2012), see Table 2.

2.2. Processing steps

In field spectrometry, radiometric measurements are not only influenced by the reflected incoming atmospheric radiation, but also attenuated by the atmosphere, as shown in following radiative transfer equation.

$$L^m_{target}(\lambda) = \tau_{atm}(\lambda)[L_{target}(\lambda, T_{target}) - (\varepsilon_{target}(\lambda) - 1)L_{inc}(\lambda) + L_{out}(\lambda)]$$

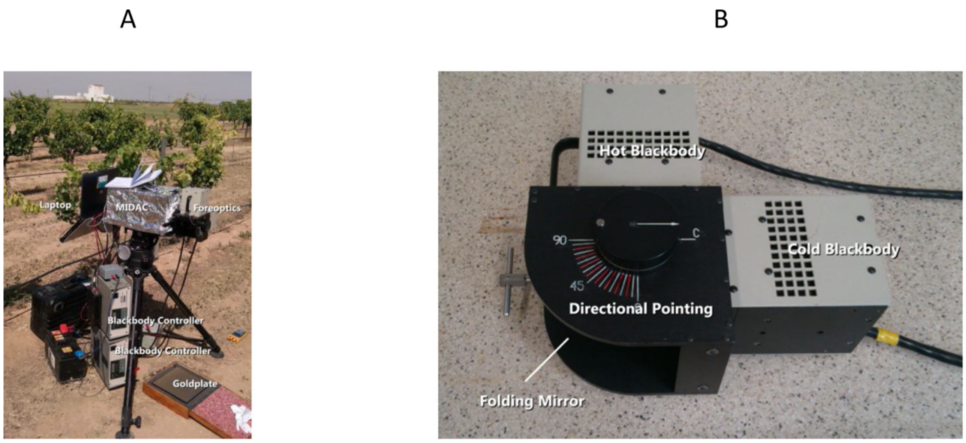

Fig. 1. The overview of the MIDAC setup. In the panel A the experimental MIDAC setup is shown over the vineyard at the Las Tiesas (Barrax, Spain) agricultural test farm. In panel B, the ITC-modified fore-optics is shown in detail. External components in both panels are labeled.