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Calculating radiant flux from thermally mixed pixels using a spectral library

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ABSTRACT

Hot surfaces associated with volcanoes, wild fires and geothermal areas are often thermally heterogeneous with respect to the spatial resolution of satellite sensors. A single pixel temperature derived from a satellite image can therefore represent a continuum of surface temperatures that may vary by hundreds of degrees Celsius. For thermally mixed pixels it is therefore more meaningful to estimate radiant flux [Watts] and/or radiant exitance [Watts per metre squared]. Here we introduce a new method for calculating radiant flux from thermally heterogeneous surfaces with temperatures in the 100 to 1100 °C range. It involves modelling radiance spectra using a spectral library. Two spectral libraries were created to represent two different sensor configurations i) a VNIR–SWIR imaging spectrometer and ii) a two channel SWIR imager, both characterized by a 30 m spatial resolution. We compare our approach against that of the "dual-band method". The spectral library approach was able to calculate radiant flux to within 30% of the actual value for targets radiating at or above 0.7 MW (i.e. when using an imaging spectrometer) or 7.1 MW (i.e. when using just two SWIR wavebands). The dual-band approach, on the other hand, required targets to be radiating at least 12 MW before a 30% accuracy level could be obtained. All of the approaches could accurately fit the spectral radiance values that they modelled. However, they could not reliably determine subpixel temperature distributions. This indicates that it might never be possible to retrieve subpixel temperature distributions reliably using short-wave infrared spectra alone. This finding has significant implications for the remote sensing of hot targets.

1. Introduction

Volcanic activity is typically associated with high surface heat flow. This can be measured from space using orbital sensors. Satellite based monitoring offers a number of advantages over ground-based techniques, including the synoptic views it provides of target areas, global coverage of subaerial volcanism, and the prospect of dispensing with potentially hazardous fieldwork and deployments.

An ideal metric of thermal activity should be both physically meaningful and consistent (i.e. regardless of the sensor used to measure it). Satellite sensors typically measure upwelling electromagnetic radiation in terms of in-band radiance [W/m^2/sr] or spectral radiance [W/m^2/sr/μm] based on pre-launch or in-orbit calibration. The dependence of spectral radiance, L, on wavelength, λ, and temperature, T, is given by Planck's formula; which can be modified to account for spectral emissivity, ε_λ, as follows:

$$L(\lambda, T) = \varepsilon_\lambda c_1 \lambda^{-5} / \left[\exp\left(\frac{c_2}{\lambda T}\right) - 1\right] \quad (1)$$

where c_1 and c_2 are the radiation constants (i.e., $c_1 = 1.19 \cdot 10^{-16}$ W m^2/sr and $c_2 = 1.439 \cdot 10^{-2}$ m K). Radiance is not an ideal metric of thermal activity. This is because different radiance measurements can be acquired from the same target depending on the spectral position and width of a sensor's wavebands. Furthermore, as volcanoes often display temperature ranges that are extreme relative to other terrestrial surfaces (i.e. 100–1100 °C), imagery of such targets often contain saturated pixels.

There exists therefore the need to process radiance measurements into an improved metric of thermal activity. In theory, temperature would be an ideal metric. Terrestrial targets can often be assumed to be isothermal at the pixel scale. This allows temperatures to be calculated remotely if the emissivity of the target can be accounted for, along with the radiative transfer along the atmospheric path. Volcanoes, however, typically exhibit a wide distribution of surface temperatures at the pixel scale. This thermal heterogeneity means that a single temperature obtained by solution of Eq. (1) provides little insight into the true surface temperature distribution. To account for this previous authors (e.g. Flynn, Mouginismark, & Horton, 1994; Oppenheimer, 1991; Rothery, Francis, & Wood, 1988; Wright & Flynn, 2003; Wright, Garbeil, & Davies, 2010) have attempted to calculate the size and

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temperature (and sometimes number) of subpixel thermal components using the following model.

$$L_{\lambda,pixel} = \varepsilon_\lambda \sum_{i=1}^{n} f_i L_{\lambda,i} \quad (2)$$

where $L_{\lambda,pixel}$ is the spectral radiance from a single pixel, n is the number of isothermal subpixel components, and f_i and $L_{\lambda,i}$ are the fractional area and spectral radiance of the ith component, respectively. Spectral emissivity is therefore modelled as constant for all subpixel components. This is assumed to be valid for volcanic targets (e.g. Oppenheimer, 1993). Typically the number of subpixel components is fixed into the model. Matson and Dozier (1981) and Dozier (1981) assumed that two subpixel components could reliably characterize active fires. By taking two different spectral radiance measurements they could then define and solve for the following simultaneous equations:

$$L_x = fL_{x,hot} + (1-f)L_{x,cold} \quad (3)$$

$$L_y = fL_{y,hot} + (1-f)L_{y,cold} \quad (4)$$

where L and f are spectral radiance and fractional area, the subscripts x and y denote different wavelengths and hot and cold denote relative temperature. There are therefore two equations and three unknowns (i.e. the temperature and fractional area of the hot component, and the temperature of the cold component). When using just two wavebands of data one of these unknowns must be assumed a priori. Initial applications of this technique used channels from the Advanced Very High Resolution Radiometer (AVHRR). These channels were situated in the mid infrared (MIR; 3–5 μm) and thermal infrared (TIR; 8–13 μm). The method was first applied to volcanic targets by Rothery et al. (1988) using two short-wave infrared (SWIR; 1–3 μm) channels from the Landsat Thematic Mapper. The approach became known as the bi-spectral method in the fire monitoring community and the dual-band method in the volcano monitoring community.

The dual-band method has been widely used over the last 25 years (see Harris, 2013, Electronic Supplement 5, for a historical review) and continues to be used to this day (e.g. Blackett & Wooster, 2011; Lombardo, Buongiorno, & Amici, 2006; Lombardo, Musacchio, & Buongiorno, 2012; Vaughan et al., 2010). Even so, the validity of the dual-band approach has been called into question a number of times (e.g. Harris, 2013; Oppenheimer, Rothery, & Francis, 1993; Wright & Flynn, 2003), primarily because volcanic temperature distributions cannot be well represented by just two isothermal components. Harris (2013) expressed his concern as follows:

> "…we need to be careful when extracting and using results from dual-band-based methodologies. As already discussed, the results may not be valid, but instead may be an artefact forced by having had to work with measurements at just one or two wavebands."

One can then pose the question: can subpixel temperatures be reliably resolved if measurements from more than two wavebands are used? Oppenheimer (1993) demonstrated that three infrared bands (i.e. any one or a combination of SWIR, MIR and TIR channels) could be used to solve for three-component subpixel models. Flynn et al. (1994) showed how a two-component model could be resolved without making any a priori assumptions about subpixel conditions using three channels. Wright and Flynn (2003) used a gradient solver to determine the subpixel characteristics of thermally mixed pixels, allowing the model fitting process to determine the optimum number of subpixel components.

Any approach to resolving a subpixel temperature distribution by using radiance spectra is based on two fundamental presuppositions: i) the model temperature distribution can meaningfully represent the actual temperature distribution of the volcanic target, and ii) it is possible to reliably resolve the actual temperature distribution from measurements of spectral radiance. To date, subpixel radiometry from space has almost exclusively involved the use of models with just two or three subpixel thermal components, thus the validity of the first presupposition has therefore repeatedly come under question (as mentioned above) because the continuous temperature distribution of volcanic surfaces is typically not well characterized by just a few thermal components. Furthermore, we show here, that the second presupposition is also probably not valid.

There remains, therefore, a need for a quantitative and reliable metric to describe thermal activity from volcanic targets. One potential candidate is radiant flux, Φ, which measures the total energy radiated from a given surface per unit time (i.e. measured in Watts or Joules per second). Applications in the volcano monitoring community include: i) mapping heat flux from individual volcanoes (e.g. Flynn et al., 1994; Wright et al., 2010, ii) calculating global volcanic thermal budgets (Wright & Flynn, 2004; Wright & Pilger, 2008, iii) differentiating between different eruptive styles (e.g. Coppola & Cigolini 2013; Coppola, Laiolo, Piscopo, & Cigolini, 2013; Coppola et al., 2012, iv) calculating lava discharge rate (e.g. Coppola & Cigolini 2013; Coppola et al., 2013; Harris, Steffke, Calvari, & Spampinato, 2011; Wright, Blake, Harris, & Rothery, 2001, v) constraining numerical lava emplacement models (e.g. Herault, Vicari, Ciraudo, & Del Negro, 2009; Vicari, Ciraudo, Negro, Herault, & Fortuna, 2009; Wright, Garbeil, & Harris, 2008, vi) calculating lava flow volumes (e.g. Coppola & Cigolini 2013; Coppola et al., 2013; Ganci, Harris, Del Negro, et al., 2012; Harris et al., 2011, and viii) use for operational volcano monitoring (e.g. Ganci, Vicari, Cappello, & Del Negro, 2012). The radiant flux from a blackbody can be expressed as follows.

$$\Phi = A\sigma \sum_{i=1}^{n} f_i T_i^4 \quad (5)$$

where A is the ground sampling area of a pixel, σ is the Stefan–Boltzmann constant ($5.67 \cdot 10^{-8}$ $W/m^2/K^4$), and f_i and T_i are the fractional area and temperature of the ith subpixel component. Paradoxically, even though radiant flux estimates from space require the modelling of subpixel temperature distributions, these model temperature distributions do not have to be accurate representations of the actual temperature distribution for the radiant flux estimate to be accurate. To explore this further it is useful to note that the radiant flux emitted from a given surface is equivalent to radiant exitance, M [W/m^2], multiplied by an area of interest, A (i.e. the ground sampling area of a pixel [m^2] in this case).

$$\Phi = A \cdot M \quad (6)$$

Radiant exitance from a Lambertian surface is equal to π multiplied by the integral of spectral radiance over all wavelengths.

$$M = \pi \int_0^\infty L_\lambda d_\lambda \quad (7)$$

The integral, by definition, is equal to the graphical area encapsulated below a spectral radiance curve, i.e. as produced when Eq. (1) is plotted as spectral radiance versus wavelength (Fig. 1). It follows, from Eqs. (6) and (7), that radiant flux is also proportional to this graphical area. Therefore, if the spectral radiance curve from a given subpixel model is similar in size and shape to the actual spectral radiance curve (i.e. from the target) then the model will provide an accurate radiant flux estimate. Crucially this can occur even if the subpixel model (i.e. used to create the model spectrum) is itself inaccurate. This paper explores the possibility of calculating radiant flux by modelling the size and shape of measured spectral radiance curves using three-component subpixel models.

When modelling spectra measured from real targets it is necessary to correct for spectral emissivity.

$$B_\lambda = \frac{L_\lambda}{\varepsilon_\lambda} \quad (8)$$