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Observation of SO_2 degassing at Stromboli volcano using a hyperspectral thermal infrared imager

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ABSTRACT

Thermal infrared (TIR) imaging is a common tool for the monitoring of volcanic activity. Broadband cameras with increasing sampling frequency give great insight into the physical processes taking place during effusive and explosive event, while Fourier transform infrared (FTIR) methods provide high resolution spectral information used to assess the composition of volcanic gases but are often limited to a single point of interest. Continuing developments in detector technology have given rise to a new class of hyperspectral imagers combining the advantages of both approaches. In this work, we present the results of our observations of volcanic activity at Stromboli volcano with a ground-based imager, the Telops Hyper-Cam LW, when used to detect emissions of sulfur dioxide (SO_2) produced at the vent, with data acquired at Stromboli volcano (Italy) in early October of 2015. We have developed an innovative technique based on a curve-fitting algorithm to quickly extract spectral information from high-resolution datasets, allowing fast and reliable identification of SO_2. We show in particular that weak SO_2 emissions, such as inter-eruptive gas puffing, can be easily detected using this technology, even with poor weather conditions during acquisition (e.g., high relative humidity, presence of fog and/or ash). Then, artificially reducing the spectral resolution of the instrument, we recreated a variety of commonly used multispectral configurations to examine the efficiency of four qualitative SO_2 indicators based on simple Brightness Temperature Difference (BTD). Our results show that quickly changing conditions at the vent – including but not limited to the presence of summit fog – render the establishment of meaningful thresholds for BTD indicators difficult. Building on those results, we propose recommendations on the use of multispectral imaging for SO_2 monitoring and routine measurements from ground-based instruments.

1. Introduction

Volatiles are a crucial component of volcanic systems. The explosivity of an eruption in particular, depends in large part on the amount and composition of volatiles contained in the erupted magma, and the relative ease with which they can be exsolved from the melt and released at the surface. For that reason, measurements of volcanic degassing have been an integral part of monitoring networks at restless volcanoes for the past 40 years. Changes in degassing rates may reflect changes in magma supply rate and/or in the permeability of the system and help inform short-term forecast of ongoing or pending eruptions (e.g., de Moor et al., 2015; Fischer et al., 1994; Watson et al., 2000). In addition, the composition of volcanic gases offers insight into physical processes occurring at depth (e.g., Burton et al., 2007; Vergniolle and Jaupart, 1990). Although it usually constitutes <5% of the total gases emitted (Oppenheimer et al., 2013) sulfur dioxide (SO_2) is virtually absent from the background atmosphere, which makes it an ideal target gas to monitor volcanic emissions. The shallow exsolution depth of SO_2, compared to carbon dioxide (CO_2) for instance, makes it a good indicator of the presence of a degassing magmatic body near the surface, and therefore provides a tool to forecast eruptions. Molecular SO_2 presents absorption features in various regions of the electromagnetic spectrum. Particularly strong absorptions appear in the ultraviolet (UV) and thermal infrared (TIR) range. Therefore, a large variety of spectroscopic methods have been developed to detect and quantify volcanic SO_2 degassing in those spectral ranges.

The SO_2 absorption features in the UV are strong, and mainly associated with electronic transition. However, remote sensing measurements in the UV require the sun as a source of radiation, which limits their use to daytime only. A number of instruments onboard satellite platforms and operating in the UV can be used to detect emissions from space. They are typically instruments that were originally developed for ozone monitoring (which presents absorption features at similar wavelengths) such as the Total Ozone Monitoring Satellite (TOMS), and more recently the Ozone Monitoring Instrument (OMI), for which specialized algorithms have been developed (e.g., Krotkov et al., 2006) and used to quantify volcanic SO_2 loading worldwide (e.g., Carn et al.,

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2003, 2008, 2016). Ground-based instruments that exploit the same absorption features also exist, such as the Correlation Spectrometer (COPSEC) (Stoiber et al., 1983) and Differential Optical Absorption Spectroscopy methods (DOAS) (Galle et al., 2003) and are still extensively used (e.g., Arellano et al., 2008; Barrancos et al., 2008; Menard et al., 2014; Mori et al., 2013). In the last decade, UV imaging techniques have emerged, commonly referred to as SO_2 cameras (Bluth et al., 2007; Mori and Burton, 2006). They allow quantification of the SO_2 column amount for every pixel in a 2D image, and are quickly becoming a common tool for gas monitoring (e.g., Aiuppa et al., 2015; Barnie et al., 2015; Moussallam et al., 2016; Nadeau et al., 2015; Pering et al., 2014; Smekens et al., 2015).

At the other end of the electromagnetic spectrum, infrared spectroscopy is an invaluable diagnostic tool to determine the composition of solid and gaseous materials, and has also been used extensively for volcano monitoring. At typical eruption temperatures (1000–1500 K), most magmas emit electromagnetic radiation with a peak located at a wavelength of 3–4 μm, otherwise designated as the Middle Wave Infrared (MWIR) spectral range. At lower terrestrial or atmospheric temperatures (200–350 K), the maximum emission is located in the Thermal Infrared (TIR) region of the spectrum (7–14 μm). Those natural IR emitters are used opportunistically as radiation sources for the detection and quantification of SO_2. Indeed, the SO_2 molecule presents two distinct absorption features in the TIR spectral region caused by vibrational transitions: a weak feature centred around 1150 cm^{-1} (v2 ~ 8.6 μm) and a stronger feature centred around 1400 cm^{-1} (v3 ~ 7.3 μm). A very large number of sensors on-board satellite platforms operate at those wavelengths, and are used extensively to detect, track and quantify volcanic SO_2 emissions worldwide (e.g., Carn et al., 2005; Corradini et al., 2009; Karagulian et al., 2010; Prata and Kerkmann, 2007; Watson et al., 2004). Spaceborne measurements in the TIR, where radiation is of relatively low energy, offer a range of capabilities due to variable sensor characteristics and orbital specifications. However, the waveband with the stronger absorption feature (v3) sits outside the atmospheric window and cannot be exploited at low altitude, and is mostly relevant in the upper troposphere and lower stratosphere (UTLS). Given that the summit of Stromboli, our target volcano, stands at 926 m, we will focus on the v2 feature only, which lies within an atmospheric window with a high transmissivity factor (i.e., water vapor essentially), allowing SO_2 detection in the planetary boundary layer (PBL). Both wavebands and their associated retrieval methods have been widely used on SO_2 plumes either in the UTLS (e.g., Doutriaux-Boucher and Dubuisson, 2009; Thomas et al., 2011; Urai, 2004; Watson et al., 2004), or in the PBL (e.g., Pugnaghi et al., 2006; Urai, 2004). In parallel, many ground-based instruments operating in the TIR have been developed. While broadband infrared imaging has proved ineffective for SO_2 detection, hyperspectral instruments have shown very strong capabilities in that regard. Indeed, detailed studies of the composition of volcanic plumes have been conducted with Open-Path Fourier Transform Infrared (OP-FTIR) instruments that produce high-resolution spectra over a narrow field of view (e.g., Allard et al., 2005; Burton et al., 2007; Duffell et al., 2001; La Spina et al., 2015). Multispectral imaging instruments, although offering a good compromise between spectral and spatial resolution at a relatively low cost, are relatively new and uncommon in the field of volcanology. One existing example is the Cyclops camera, an instrument developed by Prata and Bernardo (2014), that uses bandpass filters (see Fig. 1) mounted on a wheel rotating ahead of a broadband TIR sensor (micro-bolometer array), providing near-simultaneous images of a scene at different wavelengths. This instrument has been successfully tested at Etna volcano for the detection and quantification of SO_2 emissions, and was later deployed at Karymsky volcano for use in a multi-disciplinary study of volcanic activity (Lopez et al., 2013). Note that we are currently developing a novel instrument at the Observatoire de Physique du Globe de Clermont-Ferrand (OPGC) for laboratory experiments, that consists of a synchronized dual camera system, each of which is equipped with a narrow bandpass filter, allowing simultaneous acquisition of two images at different wavelengths. Finally, a hyperspectral imager using an uncooled micro-bolometer array with the specific aim of measuring SO_2 in volcanic plumes has recently been tested, and has already shown promising capabilities (Gabrieli et al., 2016).

In this paper, we present results from the observation of SO_2 degassing during persistent volcanic activity at Stromboli volcano with the Telops Hyper-Cam, a commercially available hyperspectral imager. Stromboli is a basaltic stratovolcano in the Aeolian island chain, located north of Sicily. Its activity encloses a range of behaviors, from continuous passive degassing (Allard et al., 1994) to occasional larger eruptions with effusive episodes and Vulcanian paroxysmal explosions (Calvari et al., 2006; Pistolesi et al., 2011). The volcano, however, is better known for a style of eruption which has been persistent at Stromboli since at least 1000 CE, and consisting of intermittent small explosions every few tens of minutes (Rosi et al., 2000, 2013). Produced by a mechanism of bubble coalescence starting in the magma chamber (Jaupart and Vergniolle, 1988), these explosions can manifest in a variety of ways at the surface, from short fountains of incandescent ballistics to weak ash plumes (Patrick et al., 2007). The summit area is host to several active vents, each characterized by a distinct type of activity. At the time of our measurements, the Northeast craters (NE1 and NE2)

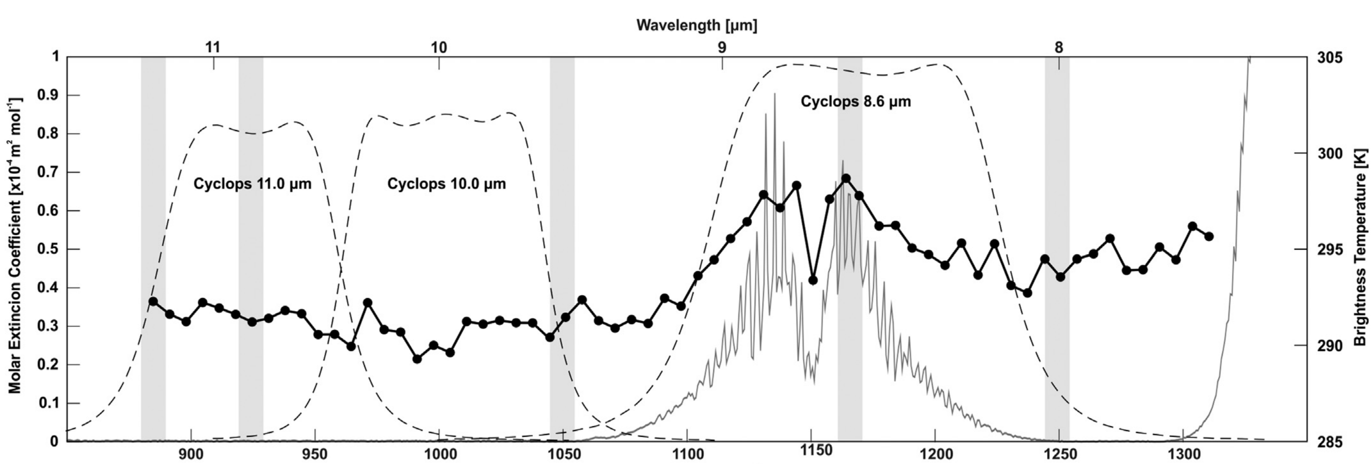

Fig. 1. SO_2 absorption spectrum and imaging instruments filter responses in the thermal infrared. Laboratory measurement of the molar absorption cross-section of SO_2 (Vandaele et al., 1994) (light gray, y-axis on the left) and brightness temperature spectrum of a typical SO_2-bearing pixel extracted from a Hyper-Cam data cube at moderate resolution (black circles, y-axis on the right). Also shown are the bandwidths of bandpass filters on the Cyclops ground-based camera operating at that wavelength range (dotted lines). Shaded areas represent the spectral bandwidths used for bi-spectral indices in this work.

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