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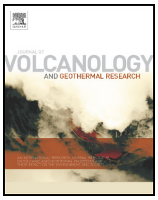

Volcanic plume characteristics determined using an infrared imaging camera

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ABSTRACT

Measurements of volcanic emissions (ash and SO_2) from small-sized eruptions at three geographically dispersed volcanoes are presented from a novel, multichannel, uncooled imaging infrared camera. Infrared instruments and cameras have been used previously at volcanoes to study lava bodies and to assess plume dynamics using high temperature sources. Here we use spectrally resolved narrowband (~0.5–1 μm bandwidth) imagery to retrieve SO_2 and ash slant column densities (g m^{-2}) and emission rates or fluxes from infrared thermal imagery at close to ambient atmospheric temperatures. The relatively fast sampling (0.1–0.5 Hz) of the multispectral imagery and the fast sampling (~1 Hz) of single channel temperature data permit analysis of some aspects of plume dynamics. Estimations of SO_2 and ash mass fluxes, and total slant column densities of SO_2 and fine ash in individual small explosions from Stromboli (Italy) and Karymsky (Russia), and total SO_2 slant column densities and fluxes from Láscar (Chile) volcanoes, are provided. We evaluate the temporal evolution of fine ash particle sizes in ash-rich explosions at Stromboli and Karymsky and use these observations to infer the presence of at least two distinct fine ash modes, with mean radii of <10 μm and >10 μm. The camera and techniques detailed here provide a tool to quickly and remotely estimate fluxes of fine ash and SO_2 gas and characterize eruption size.

1. Introduction

Ground-based thermal infrared (IR) remote sensing has become a primary tool for volcano monitoring in recent years. High temporal resolution broadband thermal imaging cameras deployed in both ground-based and airborne configuration have been used at active volcanoes to monitor changes in surface temperature (Carter et al., 2007; Wessels et al., 2013), estimate lava effusion rates (Harris et al., 2007), evaluate changes in lava lake surfaces (Oppenheimer and Yirgu, 2002), image plume degassing (Ripepe et al., 2002; Harris and Ripepe, 2007b; Patrick, 2007), characterize explosive eruptions (Ripepe et al., 2005a, b; Patrick et al., 2007; Marchetti et al., 2009; Lopez et al., 2013), constrain emission velocities and plume dynamics (Harris and Ripepe, 2007a; Patrick et al., 2007; Delle Donne and Ripepe, 2012), and quantify eruption and emission masses (Delle Donne and Ripepe, 2012; Harris et al., 2013). Additionally, multichannel thermal IR instruments, such as the airborne NASA Thermal Infrared Multispectral Scanner (TIMS) (Realmuto et al., 1994, 1997), and the nicAIR camera (Prata and Bernardo, 2009; Lopez et al., 2013), discussed here, exploit the characteristic IR absorption features of SO_2 gas, ice, and silicate ash, to allow SO_2 and very fine silicate ash to be detected and quantified. Here we describe methods for using nicAIR camera data to constrain ash and SO_2 slant column densities (SCDs), quantify plume ascent speeds, determine SO_2 and fine ash masses for individual explosions, and estimate mass fluxes of fine ash and SO_2. We apply these techniques at three active volcanoes exhibiting various styles of degassing and explosive eruptive activity: Stromboli (Italy), Karymsky (Russia), and Láscar (Chile). We include brief descriptions of the nicAIR camera and the retrieval methods for detection and quantification of ash and SO_2 and refer readers to Prata and Bernardo (2009, 2014) for further details.

The purpose here is not to provide new insights on volcanic processes, but rather to show the potential applications of the nicAIR camera to characterize volcanic plumes containing fine ash and/or SO_2 gas. The restriction to fine ash retrievals is emphasized as the results presented do not include ash mass estimates for particles with radii greater than approximately 50 μm. Here we aim specifically to illustrate what can be determined from thermal imagery, to present some basic methods

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for processing these data, and to report on the limitations and difficulties associated with this type of measurement.

2. The nicAIR infrared imaging camera

The nicAIR is a multispectral IR imaging camera designed for portable field deployment at volcanoes and in industrial settings (Prata and Bernardo, 2009, 2014). The system is capable of detecting and quantifying SO_2 gas and particulates at sample rates of 0.1–0.5 Hz (or up to 1 Hz for single channel thermal data). The camera measures thermal radiation emitted and absorbed by gases and particles in plumes and clouds, and by using specialized software, the image data can be transformed into SCDs of SO_2 or ash (in gm^{-2}, also referred to as ash mass loading in the literature). These SCDs can be used with feature tracking in the plumes to calculate SO_2 and ash fluxes (in kg s^{-1}). The sensitivity of the camera detector array is usually assessed by the Noise Equivalent Temperature Difference (NEDT), in Kelvin. For the broadband channel the NEDT $\approx$ 50 mK, but for the filtered channels this increases to 100–500 mK depending on the scene temperature and filter. Apart from NEDT limitations, the ability of the camera to provide quantitative estimates of SO_2 or ash SCDs depends on pixel size, distance to target, the transparency of the atmosphere between the camera and the plume, plume optical depth, the presence of interfering species (*e.g.* gases that absorb or emit in the waveband of 8–12 μm) and problems associated with non-synchronicity of the multispectral imagery due to movement of the filter wheel. The minimum errors have been assessed to be ~20% for SO_2 by Prata and Bernardo (2014), but a full assessment of the error for ash retrieval has not yet been made. It is likely that due to inaccurate knowledge of the refractive indices of the ash and of the size and shape distributions of the particles, in addition to the problems mentioned above, the retrieval error will be somewhat larger than that for SO_2. The error associated with ash retrievals from satellites is typically 40–60% (Wen and Rose, 1994), and this size of error can be expected from the ground-based thermal camera retrievals described here for translucent plumes.

In Section 3, the methods used to process the data and obtain retrievals of SO_2 SCDs and fluxes are provided and their accuracies assessed. Ash retrievals are also presented for several cases and an estimate of the flux of fine ash particles ($r < 50$ μm) is made in the case of Stromboli. The system has a 24 h capability and can be deployed in an automated manner to provide volcano observatories with continuous information on SO_2 and ash fluxes, and the maximum plume height of individual explosions. This last parameter may be useful as an input parameter to initialize dispersion models for forecasting the movement of volcanic ash clouds.

2.1. Technical specifications and deployment scenarios

Table 1 provides detailed technical specifications of the nicAIR camera system. An example of a typical camera deployment in which the camera is viewing SO_2 degassing from Láscar volcano (see Section 4.3) is shown in Fig. 1. In this example the camera is located ~6.5 km from the degassing vent and tilted slightly upwards to view the plume and some clear sky. In addition to viewing and quantifying daytime emissions, the nicAIR has the significant advantage over ultraviolet (UV) instruments (*e.g.* Kern et al., 2014) of also being able to measure emissions at night. During the Stromboli Workshop (the main topic of this Special Issue), the nicAIR camera was set up to measure continuously and to view both ash and gas emissions during both day and nighttime conditions. Fig. 2 shows a sequence of 20 broadband IR images, each separated by ~20 s that capture discrete explosions from Stromboli Volcano. These explosions could be easily detected and tracked for periods of several minutes using the camera during the day and/or night. Table 2 lists the locations and important deployment logistics of the nicAIR cameras at the three volcanoes studied.

Table 1
nicAIR technical specifications.

Total field-of-view	26° × 20°
Optics	35 mm F1.4 Ge lens
Image size	640 × 512 pixels
Number of filters	Up to 4
Channel 1 (SO_2)	8.6 μm
Channel 2 (plume temperature)	10.0 μm
Channel 3 (ash)	11.0 μm
Channel 4 (ash)	12.0 μm or 8–13 μm (broadband)
Sampling rate (max for single channel)	~1 Hz
Detector	Uncooled microbolometer
NEΔT filter 1	500 mK @ 250 K
NEΔT filter 2	200 mK @ 250 K
NEΔT filter 3	200 mK @ 250 K
NEΔT filter 4	200 mK @ 250 K
NEΔT broadband	50 mK @ 250 K
Requirements	12 V, 3 A, 40 W peak
Accuracy (SO_2)	$\pm 0.2\ \text{g m}^{-2}$ (or ±20%, whichever is higher)
Accuracy (silicate particles)[a]	$\pm 0.5\ \text{g m}^{-2}$ (or ±40–60%, whichever is higher)
Detection range	~10 km
Operating temperature range	−10 °C to +50 °C
Weight	8 kg
Dimensions	300 mm × 160 mm × 160 mm (L × W × H)

[a] For particles in the range 1–16 μm radius.

3. Quantifying SO_2 and ash slant column densities and fluxes

3.1. SO_2 retrievals

SO_2 gas has a strong IR absorption feature situated near 8.6 μm. This absorption band has been used by Realmuto et al. (1997) among others

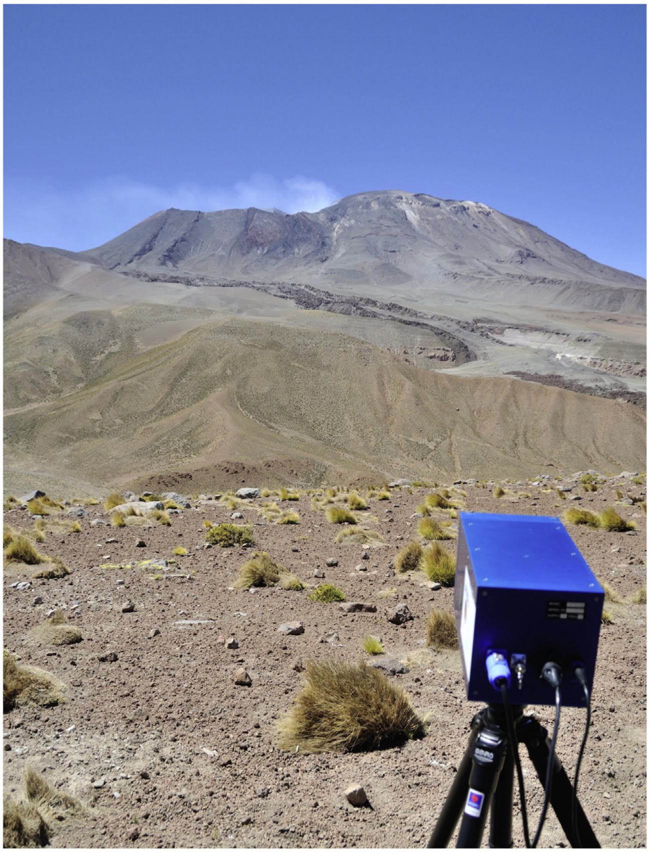

Fig. 1. Photograph of the nicAIR camera viewing the SO_2 plume from Láscar. The character of the plume, low altitude and close to the volcano was typical of its behavior during the measurements on 29–30 November 2012.

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