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Volcanological applications of SO_2 cameras

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ABSTRACT

Ground-based volcanic gas and ash imaging has the potential to revolutionise the way in which volcanoes are monitored and studied. The ability to track and quantify volcanic emissions in space and time with unprecedented fidelity opens the door to integration with geophysical measurements, allowing breakthroughs in our understanding of the physical processes driving volcanic activity. In May 2013 a European Science Foundation funded Plume Imaging workshop was conducted in Stromboli, Italy, with the objective of bringing the ground-based volcanic plume imaging community together in order to examine the state of the art, and move towards a 'best-practice' for volcanic ash and gas imaging techniques. A particular focus was the development of SO_2 imaging systems, or SO_2 cameras, with six teams deploying and testing various designs of ultraviolet and infrared-based imaging systems capable of imagining SO_2. One conclusion of the workshop was that the term 'SO_2 camera' should be applied to any SO_2 imaging system, regardless of wavelength of radiation used.

This Special Issue on Volcanic Plume Imaging is the direct result of the Stromboli workshop, and together the papers presented here represent the state of the art of ground-based volcano plume imaging science and technology. In this work, we examine in detail the volcanological applications of the SO_2 camera, reviewing previous works and placing the new research contained in this Special Issue in context. The development of the SO_2 camera, and future developments extending imaging to other volcanic gases, is one of the most exciting and novel research frontiers in volcanology today.

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1. Introduction

In May 2013 a European Science Foundation-funded Plume Imaging workshop was conducted on Stromboli, Italy, with the objective of bringing the ground-based volcanic plume imaging community together in order to examine the state of the art, and move towards a 'best-practice' for volcanic ash and gas imaging techniques of volcanic ash and gas imaging techniques. A particular focus was the development of SO_2 imaging systems, or SO_2 cameras, with six teams deploying and testing various designs of ultraviolet and infrared-based imaging systems capable of imaging SO_2 (Kern et al., 2015a, b). This special issue is a direct product of that workshop, and represents the state of the art in volcanic gas and ash imaging research.

The recent development of gas and ash imaging systems has opened up new frontiers in volcanology. The ability to detect rapid changes in gas and ash emissions allows a whole new series of phenomena to be examined over a range of scales, with a particular focus on explosive volcanism and the dynamics of passive degassing. Volcanologists may now combine comprehensive studies of gas emissions with seismic signals, producing unprecedented new constraints on the underlying physical processes that drive both geochemical and geophysical observations. Compared to earlier plume scanning technologies (e.g. Edmonds et al., 2003; Burton et al., 2007; Burton et al., 2009; Salerno et al., 2009; Galle et al., 2010) SO_2 cameras allow more precise and much faster measurement of gas fluxes.

Clearly, however, direct interdisciplinary comparisons also place great demands on the quality of data produced by each discipline. When used to make truly quantitative inferences on a physical process we require data that is both accurate, in order to e.g. compare with mass fluxes of lava, and precise, in order to distinguish real variations in flux from uncertainties. Furthermore, we begin a natural progression from short-term experimental field studies by research teams towards permanent and automatic data acquisition and analysis by volcano observatories. These demands require a rapid maturation of methodology, and the ongoing efforts of the community to ensure comparability of standards.

In this paper we examine the role of the SO_2 camera in volcanology and discuss what steps need to be made to fully realise the potential of the approach, highlighting how the papers in this special issue and previously published SO_2 camera research have contributed to this goal. A detailed review of SO_2 camera technologies is presented by Platt et al., 2015, and therefore in this work we focus on three main subjects: (i) Quantification of gas emission rates, (ii) volcanic processes which

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can be investigated with the SO_2 camera, and (iii) implementation of SO_2 cameras in monitoring networks. Platt et al. (2015) highlight that whilst the majority of SO_2 cameras developed to date are based on ultraviolet spectroscopy, infrared spectroscopy offers tangible advantages, particularly in terms of night-time viewing. One conclusion of the workshop was the term 'SO_2 camera' which should be applied to any SO_2 imaging system, regardless of wavelength of radiation used.

2. Quantification of gas emission rates

The majority of SO_2 camera systems used to date (and 1-D plume scanning systems) are based on ultraviolet absorption spectroscopy using scattered sunlight as a source of radiation. This approach has been a staple of volcano observatories looking to monitor SO_2 emissions from active volcanoes since the 1980s. As we discuss in more detail in Section 4, volcano observatory personnel are generally focussed on the interpretation of signals generated by their instruments, and tend to trust the results obtained by them. However, frequently it is overlooked that direct trace gas column measurements can be misleading unless appropriate corrections are applied (e.g. Lübcke et al., 2013). Light scattering below volcanic plumes can dilute the SO_2 signal measured at the ground. This may be quite a significant problem, particularly when the distance between the instrument and the plume is large or the plume is ash-rich; unfortunately SO_2 fluxes during eruptions are of great interest to volcano observatories. A theoretical treatment of these multiple scattering issues is described by Kern et al. (2013). Campion et al. (2015) use the brightness of the volcanic edifice to determine how much 'light dilution' is occurring, and use this to correct for the effect. Burton and Sawyer (2013) present an intensity-based spectrum analysis approach to solve the issue. Also, care has to be taken that the SO_2 camera correctly calibrated, Lübcke et al. (2013) describe possible pitfalls in calibration and how problems can be avoided. More work is required to fully understand and resolve this challenging problem.

A further major challenge in derivation of gas emission rates from SO_2 camera data is the conversion of sequences of images of SO_2 slant column amounts into a time series of SO_2 flux. This was dealt within the first papers (e.g. Mori and Burton, 2006) by defining a line orthogonal to the plume advection direction and integrating the SO_2 slant column amounts along that line, before multiplying by a plume velocity derived from the cross-correlation lag between parallel lines. This approach works well when the plume movement is quite uniform, which is a good approximation when the SO_2 camera is far from the plume. However, one of the strengths of the SO_2 camera is its spatial and temporal resolutions, which make it very often attractive to deploy it close to a source of gas, where the plume direction is far from uniform. In this case it is non-trivial to determine a flux, as there is no single velocity for the gas. Peters et al. (2015) address this problem using motion detection algorithms to find the overall flux of gas passing through a user-defined line or curve, allowing accurate determination of gas fluxes even close to the gas source. Kern et al. (2015a, b) report a very similar approach, used to help automate SO_2 flux calculations on Kilauea. Validation of SO2 fluxes measured with the SO2 camera can also be obtained using a calibrated emission source, and such a test is reported by Smekens et al. (2015).

A key element in the evolution of the SO_2 camera is the intercomparison of the diverse approaches that have developed since the inception of the technique. The May 2013 plume imaging workshop on Stromboli provided the ideal vehicle for such an intercomparison, and the results from this are reported by Kern et al. (2015a, b).

3. Volcanic and degassing processes which can be investigated with the SO_2 camera

Magmatic degassing is one of the main drivers of volcanic processes, coupling with crystallisation and viscosity variations to determine the style and intensity of volcanic activity (Sparks, 2003). The magnitude of gas release is related to the mass of magma ascending in the volcanic system, allowing inferences on magma dynamics from mass balance considerations. In the following we review how SO_2 cameras can improve our understanding of volcanic processes.

3.1. SO_2 imagery and geophysical signals associated with volcanic activity

One of the greatest strengths of the SO_2 camera is its ability to measure fast changes in degassing rates at source, thanks to both, a potentially fast frame rate (cameras can collect up to 18 frames per second in ideal conditions) and the fact that each two-dimensional image records the history of degassing captured within the frame, like a ticker-tape timer. This ability makes the camera ideal for investigating the rates of degassing during explosions (see Section 3.2, below) and for studying the links between degassing and seismic and acoustic signals. Quantitative inversion of very long period (VLP) seismic events allows the volume change associated with the passage of a gas slug to be estimated (Chouet et al., 2003; Zuccarello et al., 2013). This information can be directly compared with results from the SO_2 camera, in order to test our understanding of the physical processes which link gas slug ascent with VLP events. Volcanic tremor, an almost ubiquitous seismic signal on active volcanoes, is linked with magma and gas flow (e.g. Tamburello et al., 2013; Zuccarello et al., 2013), and therefore comparisons with gas flux data can deepen our understanding of the processes driving this seismic signal as well. We summarise the work performed to date comparing SO_2 imagery with geophysical parameters below, and in Table 1.

SO_2 is typically a minor gas component in magmatic degassing, which is instead dominated by H_2O and CO_2. VLP signals are generated by magmatic gas, not just the SO_2 component, and therefore the composition of the explosion gas must be known in order to convert from SO_2 masses measured with the SO_2 camera to total gas masses. In the future, technological developments may permit multiple gases to be imaged with a single instrument (see Platt et al., 2015).

Dalton et al. (2010) were the first to study the relationship between acoustic signals and explosive gas release measured with an SO_2 camera at Pacaya volcano, Guatemala. They found that gas masses derived from gas and acoustic datasets agreed to the same order of magnitude, and that the infrasound explosion records correlate with small pulses in degassing, but that longer-term degassing trends were probably controlled by a deeper process.

The first SO_2 camera comparisons with VLP signals were conducted by Kazahaya et al. (2011) and Nadeau et al. (2011), on Asama (Japan) and Fuego (Guatemala) volcanoes, respectively. Both authors found a linear correlation between SO_2 amounts released in each explosion and VLP amplitude. Furthermore, Nadeau et al. (2011) found a clear correlation between volcanic tremor and gas emission rate, and suggested that decreases in gas emission rate may be the result of rheological stiffening in the upper conduit of Fuego.

Tamburello et al. (2012) performed SO_2 camera measurements on Stromboli, finding again a linear relationship between the VLP amplitude and explosion gas mass (2009) and extended their investigation to include thermal signals, which were also well-correlated with gas emissions. SO_2 camera investigations of the degassing rate from Etna, Italy, show a correlation with volcanic tremor amplitude during passive degassing (Tamburello et al., 2013).

Lopez et al. (2013) used an infrared imaging system, NicAIR, to measure SO_2 and ash emission rates at Karymsky volcano, Kamchatka, which produced a wide range of degassing and explosive behaviours during their observation period. The NicAIR SO_2 camera was used to quantify pulsatory magmatic degassing, but in this case no clear correlation with infrasound pressure or thermal variations were detected, probably due to the temporal delay between gas emission at the vent and SO_2 detection downwind.

In what is probably the most detailed study of the relationship between SO_2 degassing rates measured with an SO_2 camera and geophysical signals during explosive volcanic activity, Waite et al. (2013)

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