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Modern Multispectral Sensors Help Track Explosive Eruptions

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Due to its massive air traffic impact, the 2010 eruption of Eyjafjallajökull was felt by millions of people and cost airlines more than U.S. $1.7 billion. The event has, thus, become widely cited in renewed efforts to improve real-time tracking of volcanic plumes, as witnessed by special sections published last year in *Journal of Geophysical Research,* (*117,* issues D20 and B9).

Adequately tracking and modeling plume dynamics requires measurement of a number of "source condition" parameters. Key parameters include mass discharge rate (MDR), exit velocity, particle size distribution, and ash concentration [*Bonadonna et al.*, 2011]. These must be measured as close to above the vent as possible and, due to variations in discharge over a few minutes, must be updated at similar rates.

A multitude of meetings have been convened since Eyjafjallajökull [e.g., *Bonadonna et al.*, 2011]. These have highlighted that scientists currently do not know, or cannot adequately measure, these key parameters. However, experts agree that coupling geophysical and field observations at targeted field sites and combining various remote-sensing methods can help volcanologists to converge on the provision of parameters that can be used as inputs into plume dispersion models. These experts also stress the need for better interfaces between modelers and observationalists.

Ground-based remote sensing thus needs to be tuned to measure and deliver the data required by modelers and real-time responders. The Clermont-Ferrand Centre for Volcano Research (ClerVolc), based at the Laboratoire Magmas et Volcans (LMV, in Clermont-Ferrand, France) and financed by the French Government Laboratory of Excellence (LabEx) initiative as well as other European funding bodies (e.g., Agence Nationale de la Recherche, Région Auvergne, Fonds Européen de Développement Régional), is tasked with pushing forward the understanding of volcanic systems and eruptions and, among other goals, aims to better measure and model plumes emitted during volcanic explosions. To this end, a multidisciplinary working group, spanning LMV as well as the Observatoire de Physique du Globe de Clermont-Ferrand and Laboratoire d'Informatique, de Modélisation et d'Optimisation des Systems, both based at Université Blaise Pascal in Clermont-Ferrand, was put together with the goal of merging modern remote sensing techniques for complete plume parameterization. The resulting instrument package, consisting of a suite of ground-based sensors measuring across the electromagnetic spectrum, was tested at Italy's Stromboli volcano in late 2012.

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Measuring Volcanic Plumes

Due to recent technological advances in field-based remote sensing, scientists now have the instrumentation and methodologies that, if coupled, make source term retrieval viable. These measurements involve techniques that span a broad range of the electromagnetic spectrum from ultraviolet to microwave and can be made as the plume leaves the vent, ensuring that the conditions at the source—before dilution, contamination, dispersal, and fallout—are recorded. Over the past decade, three ground-based remote sensing tools (thermal, ultraviolet, and radar imaging) have been developed. These tools offer great promise for source parameter measurements during explosive eruptions.

Initial efforts during the 1970s focused on use of traditional photographic methods for measuring plume ascent dynamics and trajectories. However, the advent of the commercial thermal camera in the late-1990s meant that thermal infrared imagery, now available at temporal resolutions of more than 200 frames per second with ever-improving spatial resolutions, came into use in extracting information regarding plume ascent velocity, MDR, and particle size distribution. Also, beginning in the late 1990s, Doppler radar was deployed to target explosive plumes, yielding data for particle velocity across the entire plume depth. During the 2000s, spectrometers were deployed for point-based measurements of volcanic sulfur dioxide (SO_2) fluxes; since 2006, SO_2 cameras have been added for full plume imaging.

While these methods have revealed a wealth of information regarding plume dynamics and particle and gas content, each alone can provide only a portion of the total information required. Thermal cameras, for example, are capable of giving information on particle velocities and sizes. They cannot, however, record in cloudy conditions. Nor can they look into the plume core, and data processing requires knowledge of particle density to convert particle volumes to masses. Doppler radar can record in cloudy conditions, provides data across the entire plume, and can provide velocities to complement those of the thermal camera. However, it requires knowledge of particle size distributions for derivation of mass fluxes. At the same time, the SO_2 camera allows information regarding the gaseous component of the emission to be retrieved but not the solid component. Until recently, these instruments also lacked the ability to record at high frame rates or sufficiently high spatial resolutions. While instruments also lacked portability, improvements in the efficiency and standardization of data output, format, storage, and processing have allowed researchers to move well beyond single-instrument deployments for short, experimental periods. However, to date, few attempts have been made to put all these sensors together.

The ClerVolc equipment array was thus designed to allow the velocity, size distribution, density, and mass of particles exiting the vent to be measured multiple times per second using this full instrument set. An example of the array output is given in Figure 1.

A New Instrument Package Tested at Stromboli

A package that combined the full range of modern remote sensing capabilities for plume measurement (see supporting information in the online version of this article for full technical detail) was put together by ClerVolc. The package includes two thermal infrared cameras, one for acquiring images for a window immediately above the vent at 200 hertz, the second capturing the entire plume at 30 hertz. Next to these are a Doppler radar, which scans at 24 hertz; an SO_2 camera that takes images every 6 seconds; a high-speed camera (imaging at 2000 frames per second); and two stereoscopic cameras. Sample videos of the various camera outputs are also given as online supplements to this article.

Stromboli was selected for a first test deployment of the array. The volcano is a reliable particle emitter where experimental plume measurement approaches can be tested and refined before operational deployment. Instruments took less than 48 hours to pack and ship from Clermont-Ferrand to Stromboli; setting them up on the volcano took about 45 minutes. Instruments were mounted on tripods within 500 meters of the erupting vent, and data collection lasted from 27 September to 7 October, 2012, spanning around 30 individual eruptions.

Data from the remote sensing array were complemented by the permanent geophysical array installed on Stromboli by *Ripepe et al.* [2004]. Finally, all particles landing in well-defined areas within the fallout zone during individual eruptions were collected and retrieved for analysis. Together, the package allowed the velocity, size distribution, density, and mass of particles to be retrieved, hence allowing tracking of MDR and gas fluxes over time windows of less than 10 seconds in duration (see supporting information). In total, deploying the equipment for this initial test cost €25,000 (about US $33,000).

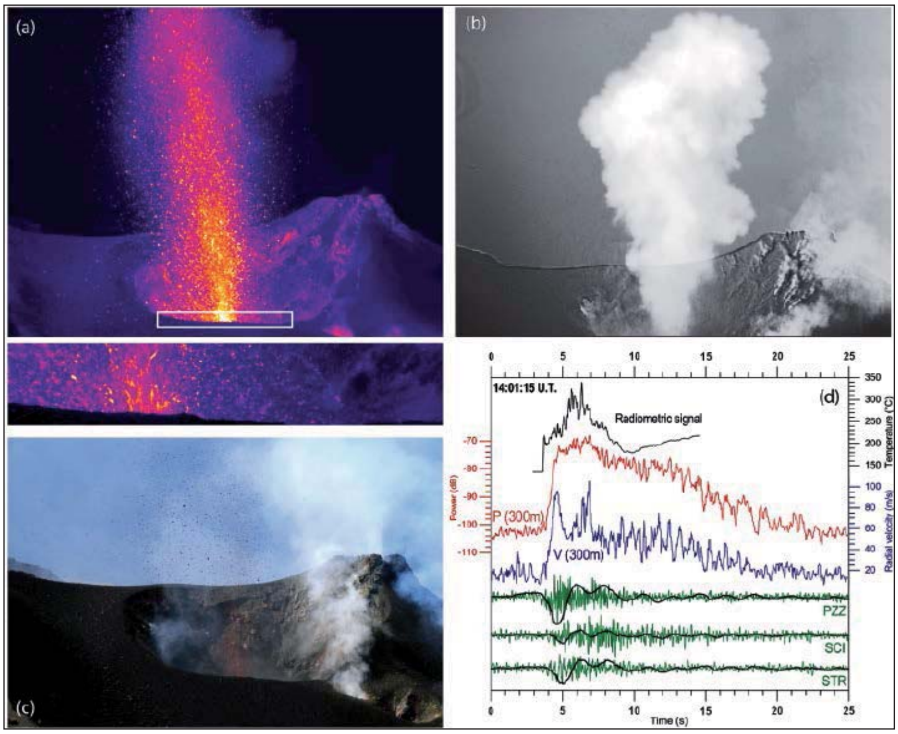

Fig. 1(a) Thermal, (b) sulfur dioxide (SO_2) and (c) visible images of plumes emitted during explosions at Stromboli during 27 September 2012, with (d) associated thermal, radar, and seismic waveforms. The white box in Figure 1a is the region tracked by the high speed thermal camera, an image from which is given below the main thermal image. Images were taken around 250 meters away from the plume. In (d), the red P is power; the blue V is velocity. Three green PZZ, SCI, and STR labels are the station names from which each seismic waveform is taken (see additional suporting information in the online version of this article for more details).

Moving Forward

Real-time measurements and model-based projections must connect well during crises to allow delivery of the best possible information to decision and policy makers. If the link between observers and modelers is to be effective, the volcanological measurement community needs to provide quality source term data in real time and in an agreed, standard, and stable format. The current suite of instruments developed to effectively monitor volcanic emissions has thus prioritized retrieval of exit velocity (in standard units of meters per second), particle size and density (in meters and kilograms per cubic meter), and MDR (in kilograms per second). This has been achieved through application of a full-waveband remote sensing approach that integrates modern ultraviolet, visible, infrared, and radar technologies with standard geophysical measurements and gas chemistry, plus textural and particle size analysis.

The system is fully operational and deployable in less than an hour after shipping to sites where monitoring is needed. Currently, data are stored onsite, necessitating retrieval after the instruments have been running for a few hours. However, software is being developed by ClerVolc to allow instruments to transmit data to processing stations for real-time analysis. Information output by the system will help researchers better model plumes during volcanic eruptions, potentially allowing scientists to warn communities and air spaces downwind of eruptions of the composition of the ash clouds headed their way.

Further, developers are testing the equipment on other small ballistic and/or ash-dominated plumes before moving to the more energetic cases that generate the plumes and clouds that pose a real and genuine aviation threat. ClerVolc's aim is to provide scientists with a method through which they can adequately and fully monitor volcanic plumes at the source and anticipate how the resulting clouds may evolve over time—information of vital importance to anyone whose livelihood takes them into the shadow of an explosive volcanic eruption.

References

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