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Remotely Monitoring Volcanic Activity with Ground-Based Doppler Radar

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Concern about hazards that volcanic plumes pose, especially to aviation safety, has led scientists for about two decades to use satellite sensors in different wavelengths for the detection and study of volcanic activity. Together with ground-based meteorological radars, these techniques now enable tracking the ascent and dispersal of large eruptive clouds, making reflectivity mapping, determining plume heights, measuring gas (SO_2) and aerosols content, and estimating particle sizes and total mass of gas and fine ash [e.g., *Harris and Rose*, 1983].

However, there is still a crucial need for direct measurements of particle velocities, especially near an emission vent, to constrain physical and numerical models of eruption dynamics, which in turn should improve our predictive capacity regarding plume behavior.

In recent years, compact Doppler radar systems have been developed for ground-based remote sounding of the dynamics of volcanic jets. The main advantage of these active remote sensing methods is to allow the monitoring of the eruptive jets in successive sample volumes (range gates) inside the beam just above the crater, close to the outbursts. Furthermore, the radar system's high sampling rate and good spatial resolution provide two data sets related to the echo power (backscattered by particles and received by the antenna), and the velocity of the ejecta, respectively; these data sets can be used to quantify the relative intensity of an eruption. The Ultra High Frequency radar signal can be transmitted through overcast weather or at night when direct observations of the volcanic activity are difficult.

Advanced techniques like Doppler radar remote sensing, therefore, have advantages over photogrammetric and video analysis methods, and are more powerful and suitable for continuous monitoring of volcanic activity. Ground-based radar soundings can complement satellite observations of volcanic clouds at high altitude by providing simultaneous near-vent measurements. They also allow the probing of the dynamics of less explosive activities, such as Strombolian explosions and lava fountains, details of which are not detectable from space.

A mobile ground-based Doppler radar system, named VOLDORAD (Volcano Doppler Radar, Figure 1), has been designed at the Observatoire de Physique du Globe de Clermont-Ferrand (OPGC, in France). Aimed at gaining insight into the dynamics of jets and plumes, it also provides volcanologists with a new tool for real-time continuous monitoring of explosive volcanic activity of variable intensity.

A Doppler Radar Designed for Volcano Monitoring

The VOLDORAD systems are medium-power, pulsed Doppler radars operating in the L band of frequencies, unlike the frequency-modulated continuous wave radars used by *Seyfried and Hort* [1999] at Stromboli volcano. The first prototype Doppler radar, working at 1238 MHz, was tested successfully at Mount Etna in 1998 [*Dubosclard et al.*, 1999, 2004]. The lighter, current version, operating at 1274 MHz, has been used to record five episodes of Strombolian to lava fountain activity at Mt. Etna in 2001, and to monitor the eruptions of Arenal volcano during eight days in 2004.

The 24-cm wavelength was chosen to avoid attenuation by fog, clouds, and rain, and to enable signal transmission through a dense, ash-laden plume. The wavelength results from a compromise between the equipment size/weight and the variable range of operation (0.4 to several kilometers) imposed by field conditions.

The VOLDORAD radar acquisition, reception, and processing units are housed in a cubic metal box (60 cm) weighing about 50 kg. They are controlled by a personal computer, synchronized on Global Positioning System time, which is also used for real-time PC screen monitoring and data storage. The radar antenna is a 2 × 2 array of Yagi uni-directional antennas, which is set up on a tripod adjustable in azimuth and elevation. The beam width is 9°, equivalent to a vertical resolution of about 150 m at a slant distance of 1 km. The relatively low average power consumption (200 W) is supplied by a small electric generator or by alternating current power. The whole system, readily and quickly set up, is held in a four-wheel-drive vehicle.

Every 100 μs or, alternatively, 50 μs, a pulsed signal of selectable duration 0.4–1.5 μs is transmitted with a peak power of 60 W. The received echoes, stemming mainly from the power backscattered by reflectors inside the antenna beam, are amplified, filtered, digitized, and then sampled at time intervals identical to the pulse duration. The different samples then correspond in distance to successive range gates along the beam, with a chosen resolution in the beam direction of 60–220 m. A number of coherent integrations of successive received signals are usually made to improve the signal-to-noise ratio, providing every ~0.1 s or less a spectrum of radial velocities with the associated power backscattered by volcanic ejecta moving in each range gate.

Insights Into Eruptive Processes

The time variations of the backscattered power, which depends on an eruption's particle size distribution and concentration, were found to be a good indicator of the long-term evolution of eruptions at Etna and followed the overall trend of the volcanic tremor during Strombolian activity culminating in lava fountains (Figure 2a). The measured maximum velocities stem from the finest particles, which are directly entrained by gas, and therefore may provide an estimation of gas velocity [*Dubosclard et al.*, 2004].

Radar maximum velocities appear particularly well correlated to the abrupt variations of the tremor amplitude. This correlation emphasizes the shallow control of the volcanic tremor by the dynamics of gas bubbling in the magmatic conduit at Etna. Thus, combining Doppler radar with other geophysical techniques brings up insightful perspectives on conduit magma processes as well.

During the most violent lava fountain episode of Etna's southeastern crater preceding the summer 2001 flank eruption, on 13 July, maximum radial velocities of 90 m/s were measured for over 20 min (Figure 2a), corresponding to vertical velocities of over 230 m/s

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Fig. 1. The VOLDORAD (Volcano Doppler radar) antenna aimed at the summit of Arenal volcano 2.5 km away; the operating radar is in a four-wheel-drive vehicle (left inset) and provides signal real-time screen monitoring during an explosion (right inset).

inferred from the sounding geometry. Vertical jet velocities of 350–400 m/s were even reached during the explosive activity of Etna's Laghetto cone at 2570 m, on 31 July.

Comparatively, the strongest of a series of 31 Strombolian outbursts of Arenal volcano recorded in February 2004 produced a small ash plume 500 m high with maximum radial velocities of 90 m/s (Figure 2b), equivalent to 200 m/s in the vertical direction. In addition to providing data for plume numerical models, measuring maximum velocities may help to infer the amount of gas released during an eruptive episode and the source processes leading to an eruption [e.g., *Vergniolle and Jaupart*, 1990].

Measurements of particles and gas velocities and of total backscattered echo power thus provide a quantitative assessment of the relative intensity of an eruption. In addition to the high sampling rate being well suited for the continuous monitoring of eruptive episodes lasting hours or more, the sampling rate allows the radar signal to be analyzed at the time-scale of more short lived phenomena lasting a few seconds.

As jet particles follow nearly ballistic trajectories during Strombolian and lava fountain activity, it is possible to discriminate ascending and falling particles crossing the range gates above the vent because they generate positive and negative velocities, respectively, in the Doppler spectra. For example, lava fountains at Etna exhibit cyclic behavior, with periodic peaks in the echo power associated with uprising particles indicating feeding by jet outbursts every 5–6 s during a paroxysm. The spectrum acquisition rate around 10 Hz even enables the measuring of the evolution of particle and gas velocity during a single outburst, with initial peaking values followed by a rapid decrease in a matter of seconds (Figure 2c).

Radar Surveillance of Etna

The Italian Gruppo Nazionale di Vulcanologia (INGV) funded the construction by the OPGC of a surveillance radar similar to VOLDORAD that will be installed permanently on Etna in the coming year in order to monitor the summit crater's activity in real time from the INGV operational center in Catania. The long-term scientific collaboration between the OPGC and INGV should lead to the achievement of a database of radar signals characterizing different eruptive regimes, and thus improve the knowledge of jet dynamics.

The surveillance radar will help to track wind-drifted ash plumes commonly generated at Etna, and provide an early warning on any shift in the evolution of the explosive activity, even at night or during poor weather. This has important bearings on civil protection decisions regarding hazard alert bulletins, possible air traffic disruption, airport closure, and actions to limit the discomfort of the inhabitants of Catania and villages surrounding Etna. VOLDORAD'S near-source measurements on Etna's large plumes also could be usefully combined with satellite data collected by the Volcanic Ash Advisory Center in Toulouse (France).

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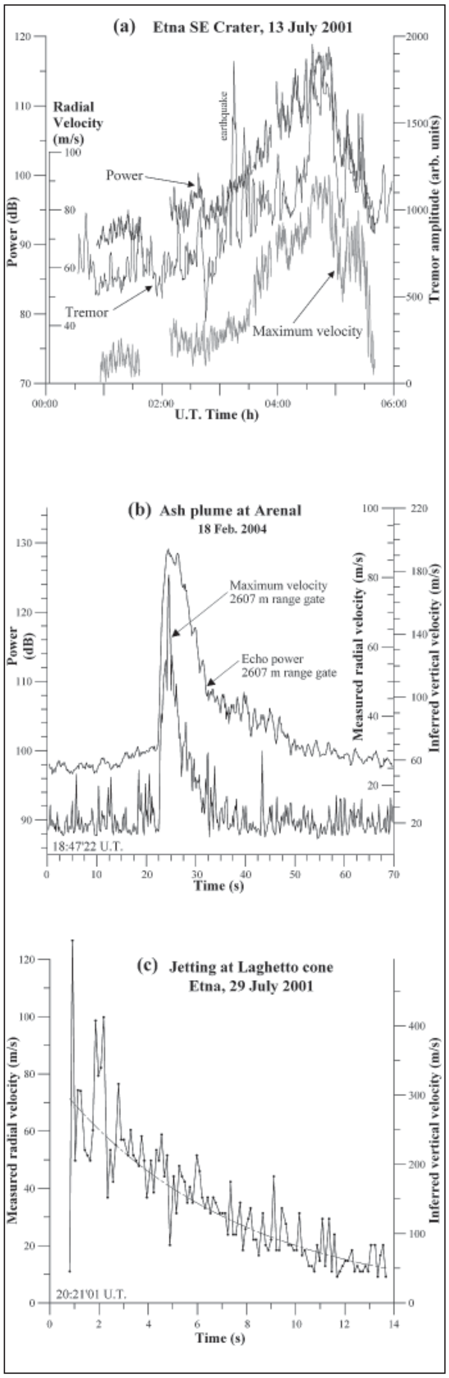

Fig. 2. Radar measurements of backscattered power and maximum velocity at (a) 1 km from Etna's southeastern crater during Strombolian and lava fountain activity, on 13 July 2001, and (b) 2.5 km west of the Arenal summit during the largest explosion of the observation period, on 18 February 2004. Figure 2c details an outburst at 800 m west of Etna's newly formed Laghetto cone during lava fountain, on 29 July 2001.

References

Dubosclard, G., R. Cordesses, P. Allard, C. Hervier, M. Coltelli and J. Kornprobst (1999), First testing of a volcano Doppler radar (Voldorad) at Mount Etna, Italy, *Geophys. Res. Lett.*, 26, 3389–3392.

Dubosclard, G., F. Donnadieu, P. Allard, R. Cordesses, C. Hervier, M. Coltelli, E. Privitera, and J. Kornprobst (2004), Doppler radar sounding of volcanic eruption dynamics at Mount Etna, *Bull. Volcanol., 66*(5), 443–456.

Harris, D. M., and W. I. Rose Jr. (1983), Estimating particle sizes, concentrations, and total mass of ash in volcanic clouds using weather radar, *J. Geophys. Res., 88,* 10,969–10,983.

Seyfried, R., and M. Hort (1999), Continuous monitoring of volcanic eruption dynamics: A review of various techniques and new results from a frequency-modulated radar Doppler system, *Bull. Volcanol., 60*(8), 627–639.

Vergniolle, S., and C. Jaupart (1990), Dynamics of degassing at Kilauea volcano, Hawaii, *J. Geophys. Res., 95,* 2793–2809.

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