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First Testing of a Volcano Doppler Radar (Voldorad) at Mount Etna, Italy

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and J. Kornprobst¹

Abstract A medium-power (1 kW) Doppler radar of limited weight (110 kg) and working in the UHF band has been developed for active remote sensing of volcanic eruptions. Named Voldorad, this radar is designed to monitor eruptive activities of variable magnitude at medium distance range (~0.5-5 km), in any weather condition, and fills the gap between low- and high-power radar or sodar systems previously tested on volcanoes. Voldorad was operated for the first time during an eruption of Mt. Etna on October 11-12, 1998. Doppler spectra recorded at 1 km distance from the vent reveal powerful echoes during the eruption paroxysm (lava fountains), which gradually decreased along with declining activity. An average vertical velocity of 80-87 m s⁻¹ is inferred for the eruptive jets.

1. Introduction

Active remote sensing techniques such as radar or sodar (Sound Detection and Ranging) are commonly used to study the structure and dynamics of the atmosphere. These sensors also have a great potential for probing, at safe distance, the dynamics of volcanic eruptions but have scarcely been applied to this field yet. The few published measurements include i) non-Doppler meteorological radar surveys of the ash content and long range evolution of eruptive clouds from Mount St. Helens [Harris *et al.*, 1981; Harris and Rose, 1983] and Mt. Spurr [Rose *et al.*, 1995] volcanoes and ii) determinations of vertical velocities of explosive outbursts at Stromboli volcano using a Doppler sodar, [Weill *et al.*, 1992] and, recently, a portable FM-CW radar Doppler anemometer [Hort and Seyfried, 1998; Seyfried and Hort, 1999].

Moreover, the techniques used during these previous measurements have different intrinsic limitations. Powerful non-Doppler meteorological radars can successfully be operated several hundred kilometres away from a volcano but are heavy and cumbersome equipments, not adapted to the sounding of eruptive mechanisms. The sodar technique is lighter but requires to be operated at only a few hundred meters or so away from the eruptive vent and, for accurate determination of eruption velocity, requires the knowledge of sound speed at the temperature and gas composition of the jets, which is not at hand. The Doppler radar technique used

by Hort and Seyfried [1998] and Seyfried and Hort [1999] is more promising. The first tests were conducted 200-300 m away from the vent, but the operating range could be increased by using a parabolic mirror antenna with a small aperture [Seyfried and Hort, 1999].

Based on the UHF wind profiler technique [e.g. Ecklund *et al.*, 1990], we have developed and tested a medium-power pulsed Doppler radar specifically devoted to volcanic sounding [Dubosclard *et al.*, 1999]. Named Voldorad, this radar can operate at medium distance (~0.5 to 5 km) from a volcanic vent and is compact enough to be easily set up on a volcano. In the following, we describe this new instrument and report preliminary data recorded during an eruptive sequence of Mount Etna (Sicily) in October 1998.

2. Instrumentation

2.1 Radar description

The equipment (110 kg as a whole) consists of an antenna and four main units (transmitter, receiver, signal processor, power supply), each weighing around 20 kg, plus a PC for radar control, real time display and data storage. The power consumption of the radar is low (300 W) and can be supplied with a small electric generator. In order to increase the portability of our system, we have developed a 2x2 array of 24 elements Yagi antenna (10 kg total weight), with a 9° beamwidth. This antenna, set up on a tripod, is steerable both in azimuth and elevation. The main characteristics and operating parameters of Voldorad are summarized in Table 1.

After amplification and filtering, the received signal is digitized. Each digitized sample corresponds to a received echo at a selected time (i.e., selected range), thus defining the so-called range gates.

For each gate, signal processing first consists in a time integration of N_c (typically, 10 to 20) consecutive samples. This coherent integration improves the signal to noise ratio by N_c . The spectrum of resulting time series is then computed by Fast Fourier Transform. In order to improve the detectability of volcanic signals, a mean spectrum is further calculated from several (typically 5) consecutive spectra.

2.2. Radar data measurements

Based on radar meteorology background [e.g. Sauvageot, 1992], one can expect that, at UHF, a volcanic eruption will generate radar echoes by three mechanisms:

- Bragg scattering from spatial irregularities of the refractivity index induced by turbulence inside the eruptive jet,
- Rayleigh scattering by ejected particles whose size is smaller than the radar wavelength λ , and
- Mie scattering by particles whose size is greater than λ .

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Table 1. Radar Characteristics

Frequency	1238 MHz
Wavelength	24.2 cm
Peak power	1 kW
Pulse duration	0.75 or 1 μ s
Corresponding range resolution	112 or 150 m
Pulse repetition period	100 μ s
Antenna beamwidth	9°

For Bragg scattering the so-called radar reflectivity, η , deduced from the intensity of the echo power is given by [e.g. Sauvageot, 1992]:

$$\eta = 0.38 C_n^2 \lambda^{-1/3} \quad (1)$$

where C_n^2 , the structure parameter, is proportional to the variance of the refractive index. For Rayleigh scattering, η is expressed as:

$$\eta = \frac{\pi^5}{\lambda^4} \left| \frac{\varepsilon - 1}{\varepsilon + 2} \right|^2 Z \quad (2)$$

where ε is the dielectric constant of the target and Z the radar reflectivity factor generally expressed in dBZ (logarithmic) units.

For Mie scattering (target size $\ll 24$ cm in our case), one generally uses an equivalent radar reflectivity factor, i.e. the reflectivity of a small particle population satisfying the Rayleigh approximation that would produce the same received power.

Whatever the scattering mechanism, the radial velocity, V_r , of the target (the component of velocity along the antenna beam direction), is calculated from the Doppler shift Δf between the transmitted and received frequencies ($V_r = -\lambda/2\Delta f$). Note that a negative Doppler shift corresponds to a target moving away from the antenna (positive radial velocity) and *vice versa*.

3. Experimental Conditions

The first testing of Voldorad on a volcano was carried out at Mt. Etna in October 1998. Since mid-September the Southeast (SE) summit cone displayed almost periodic episodes of brief Strombolian eruption, culminating in lava fountains and separated by about a week of total quiescence. Our radar soundings were performed during the seventh of these episodes. The eruption started around 16:00 UT on October 11 and gradually intensified until 23:00, with jets of gas and lava sustaining a true eruptive column. The paroxysmal phase took place between 23:00 and 00:00, with lava fountains a few hundred meters high. Afterwards, the eruption gradually declined and finally ended at around 11:00 UT on October 12.

Prior to the event, Voldorad had been set up in an alpine shelter at Torre del Filosofo (2900 m a.s.l.), at a slanting distance of 1150 m from and a height of 300 m below SE crater rim (measured with a laser range binocular). Our radar soundings covered about 7 hours of the eruption, including its paroxysm. Most of the observations were made with an antenna elevation angle, θ , of 30°. The geometry of the experiment is illustrated in Figure 1. The returned signals were detected in four consecutive gates (G_1 to G_4) corresponding to slanting distance between 1118 and 1455 m from the radar (Table 2). Taking the crater centre as the origin and knowing ψ_i , the elevation angle from vertical of each gate G_i , shows that G_2 ($\psi_2 = +8^\circ$) and G_3 ($\psi_3 = -8^\circ$) could record

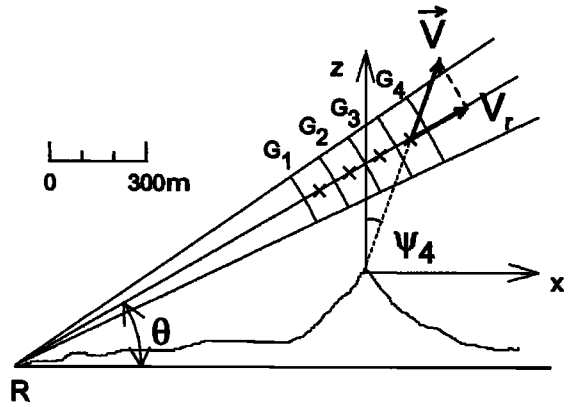


Figure 1. Radar sounding geometry and gate coordinate system. Relief is schematic. R: radar location, θ : antenna beam elevation. Crosses indicate the centre of each gate.

nearly vertical trajectories within about 350 m height above the crater rim. In these two gates, as well as in G_4 , an uprising target having a positive radial velocity (away from the antenna) should give a negative Doppler shift. Conversely, due to its negative radial component, a falling particle (downward velocity) give a positive Doppler shift. Trajectories passing through the centre of gate G_1 ($\psi_1 = 29^\circ$) are almost perpendicular to the radar beam direction. Due to the spatial extension of this gate, rising particles can thus induce positive, null or negative Doppler shifts, while falling particles will produce negative signal. Because of this ambiguity, data for G_1 are hardly interpretable.

4. Preliminary results

In order to illustrate the capabilities of Voldorad, we present preliminary results derived from the analysis of some Doppler spectra recorded in gates G_1 to G_4 during both the paroxysm (Fig. 2a) and the declining phase (Fig. 2b) of the eruption. As ground clutters produce a contamination of Doppler spectra at and around the zero frequency, the zero frequency power was forced to mean noise power

4.1. Doppler power spectra

On each spectrum one observes several peaks or undulations. These peaks suggest the contribution of several spectral components due to Rayleigh (and, possibly, Mie) back-scattering from ejected pyroclasts of different sizes and different velocities, as well as to Bragg scattering from turbulent eddies inside the hot jet.

During the eruption paroxysm, powerful echoes were recorded in the four gates G_1 to G_4 . From Figure 1 and Table 1 one deduces that the eruptive column axis was essentially vertical and that most ejected targets were confined within an inverted cone of about 48° width. Furthermore, the nearly symmetrical spectra observed in gates G_2 and G_3 , through which trajectories were roughly vertical, are consistent with a

Table 2. Coordinates of Gates G_1 to G_4 (Antenna Elevation Angle: 30°).

	G_1	G_2	G_3	G_4
x (m)	-142	-45	52	149
z (m)	259	315	371	427
ψ_i (°)	29	8	-8	-19

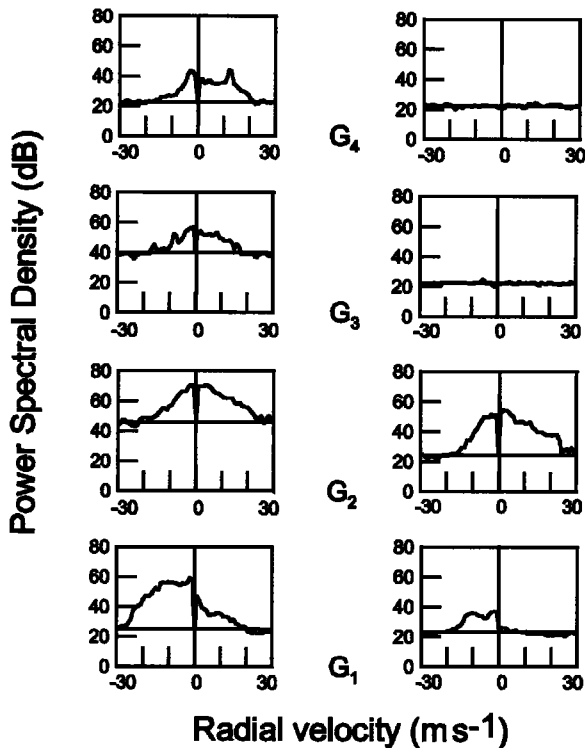


Figure 2. Doppler spectra for gates G₁ to G₄, integrated for one minute, as a function of radial velocity (positive for targets moving away from the radar). 2a (left): eruption paroxysm (00h03 UT); 2b (right): post-paroxysm (01h36 UT). Horizontal lines correspond to background noise level.

quasi-parabolic motion of the targets. Finally, we note that the noise level, which is the same for G₁ and G₄ and higher for G₂ and G₃, increases with the mean echo intensity in each gate. In fact, the digitized complex signal recorded at the output of the receiver presented large amplitude variations, sometimes leading to saturation despite a 30 dB attenuation of the receiver gain. Since this saturation is expected to increase the spectral noise, we outline that the signals recorded in gates G₂ and G₃ are likely to be minimal ones. This enhances the above indications that most of the erupted material was concentrated along and near the thrust axis, in qualitative agreement with photobalistic observations made at Stromboli volcano [Chouet et al., 1974; Ripepe et al., 1993].

From the intensity of the echoes and taking $\epsilon = 6$ [Adams et al., 1996] we estimate a high radar reflectivity factor of at least 55 dBZ during the eruption paroxysm. This is equivalent to a structure parameter $C_n^2 = 1.710^{-8} \text{ m}^{-2/3}$, which is far greater than values typical of most atmospheric conditions (from $\sim 10^{-16}$ to $10^{-13} \text{ m}^{-2/3}$). Because atmospheric attenuation is negligible at UHF band, we then emphasize that Voldorad is well suited to monitor volcanic activity in any weather condition.

During the decline of the eruption (Fig. 2b) echoes were essentially detected in G₁ and G₂ and, to some extent, in G₃. This agrees with field observations of both a gradual tilting of the eruptive jets towards the antenna and a reduced spreading of the pyroclasts (due to either a modified conduit geometry or/and a lower magma level). Comparison of G₂ spectra in Figures 2a and 2b furthermore evidences a drastic reduction of the echo power with declining activity.

Table 3. Mean Values of Measured Radial Velocity (V_{+mean}) and of Inferred Ejecta Velocity (V , at gate level) and Initial Eruptive Velocity (V_0) for Gates G₂ and G₃, before (ΔT_1 , 19:30-20:30), during (ΔT_2 , 23:00-00:30) and after (ΔT_3 , 01:00-02:30) the Eruption Paroxysm.

	ΔT_1	ΔT_2	ΔT_3
V_{+mean} (m s ⁻¹)	7.3 ± 0.7	7.8 ± 0.7	6.5 ± 0.4
G ₂ V (m s ⁻¹)	19.5	20.9	17.3
V_0 (m s ⁻¹)	80.9	81.3	80.4
G ₃ V_{+mean} (m s ⁻¹)	8.0 ± 0.7	10.4 ± 1.1	7.0 ± 0.4
V (m s ⁻¹)	13.0	16.9	11.4
V_0 (m s ⁻¹)	86.2	86.9	86

4.2. Vertical eruptive velocity

For a given Doppler spectrum, V_{+max} is the rightmost abscissa for which the signal to noise ratio is unity and V_{+mean} is the mean positive radial velocity calculated from the Doppler spectrum in the interval $0-V_{+max}$. Assuming that the target motion in the center of the fountain is purely ballistic [e.g. Wilson and Head, 1981], let consider a target rising through a range gate G_i (x, z) with a velocity V (as an example, see Fig. 1 for G₄). From the radial (Doppler) velocity V_r , measured by the radar in G_i, we can first deduce V [$V = V_r / \sin(\theta - \psi)$; see Fig. 1] and then the initial eruptive velocity V_0 , equal to: $V_0 = (V^2 + 2gz)^{1/2}$, where g is the acceleration due to gravity and z the height of the gate center.

From Doppler spectra we have successively determined V_{+mean} , V and V_0 for gates G₂ and G₃, the nearest to the jet axis, which provide the most reliable information. The results are reported in Table 3 for three time periods before (ΔT_1), during (ΔT_2) and after (ΔT_3) the paroxysm. Due to subsequent tilting of the eruptive jets, some spectra in G₃ have no Doppler signal during ΔT_3 (see above and Fig. 2b). The measured V_{+mean} in these two gates allow us to infer average eruptive velocities between 80 and 87 m s⁻¹. Interestingly, the average eruptive velocity in each gate remained similar within about two hours before and after the paroxysm (with only a slight maximum during the paroxysm itself), although the echo power of the volcanic jets was markedly different. This suggests that while the eruption rate was varying during this interval, the initial pressure conditions of the jets remained broadly constant.

The average eruption velocities determined with Voldorad at Mt. Etna are much higher than those inferred from either sodar (40 m s⁻¹ [Weill et al., 1992]) or radar (10 m s⁻¹ [Hort and Seyfried, 1998]) sounding during explosive outbursts at Stromboli. They are more comparable to the upper range of peak velocities during Strombolian explosions, as estimated

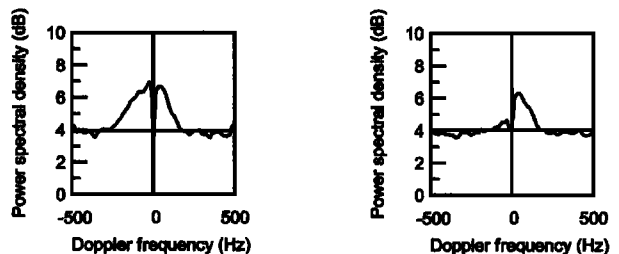


Figure 3. Power-frequency Doppler spectrum at the onset of an explosion (3a, left) and five seconds latter (3b, right). The zero frequency is forced to mean noise power. Negative frequencies correspond to rising targets.

from photoballistic studies (20–110 m s⁻¹ [Chouet *et al.*, 1974; Blackburn *et al.*, 1976; Ripepe *et al.*, 1993]). We note, however, that our V_{+max} values may include the contributions from small (non ballistic) particles and from turbulent eddies (acting as tracers of the gas velocity), which introduces some (unknown) uncertainty on the estimated velocity at gate level. Keeping the approximation of a ballistic motion, the maximum height reached by a target with an initial velocity V_0 is $z_{max} = (V_0)^2/2g$. For $V_0 = 86$ m s⁻¹ we find $z_{max} = 370$ m, in fair agreement with our field estimate of the upper height (≈ 300 m) reached by visible (sizeable) tephra during the paroxysm.

4.3. Short-term echoes evolution

One interesting aspect of Voldorad is its capability to observe the eruptive process with a fine time resolution (up to 63 ms). Moreover, the pulsed regime of the instrument allows the operator to trigger and synchronise radar recording with the volcanic events, which is particularly useful for detailed analysis of lava fountains. As an illustration, Figure 3 shows two Doppler spectra as a function of Doppler frequency obtained in gate G₂ with this procedure. On the first spectrum (Fig. 3a), measured at the time of the explosion, rising targets (left part of the graph) are associated with both high reflectivity and Doppler velocity. The explosive phase ends five seconds later (Fig. 3b), with no more rising material being detected by the radar. We note in the two sequences that the right (positive) parts of the spectra are similar, suggesting a steady and homogeneous process associated with falling material.

Conclusions

Our first experiment with Voldorad at Mt. Etna demonstrates the adequacy of this medium-power Doppler radar to investigate the dynamics of an eruption of mild intensity. The powerful echoes recorded during the paroxysmal phase indicate that Voldorad could be efficiently and safely operated at a few kilometres distance from a much stronger eruption (eruptive column of one to several kilometres high), although with some reduction in the vertical resolution. Moreover, the high pulse repetition frequency of this radar allows one to investigate the dynamics of eruptive processes at high temporal resolution, in contrast with sodar techniques. Combining Voldorad data with simultaneous recording of the seismic tremor [Dubosclard *et al.*, 1999, and in prep.] and modelling of volcanic jets [e.g. Blackburn *et al.*, 1976; Wilson and Head 1981] should provide useful insight into the source mechanism of periodical lava fountaining that occurred at Etna SE crater during the last part of 1998.

The signals recorded at Etna, which exceed by far those commonly observed in the atmosphere, emphasize that Voldorad is well suited to continuous volcano monitoring in any weather condition. Owing to its relatively low weight and small antenna, Voldorad is more versatile and economic to operate on such a volcano than more powerful radars. A still more compact (portable) version of our prototype is currently being designed.

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