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ACOUSTIC SOUNDER MEASUREMENTS OF THE VERTICAL VELOCITY OF VOLCANIC JETS AT STROMBOLI VOLCANO

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Abstract. We have used a Sodar (acoustic doppler sounder) to characterize the behavior of volcanoes, and in particular, to measure the vertical velocities of volcanic jets. We have analyzed more than 100 explosions on Stromboli volcano (Eolian islands). First results show vertical speeds close to the vent ranging from 20 m/s to 80 m/s. The uncertainty in the measurements is close to 10 %, due mainly to the inaccurate knowledge of the sound speed in volcanic jets. This is small, compared to other volcanological methods. This method is well suited for monitoring temporal variations during an eruption and should be particularly interesting for the study of the eruptive dynamics of lava fountains. The Doppler spectrum in explosions appears to be related to different types of echoes and contains information on particle sizes in the jet.

Introduction

Several theoretical models of volcanic eruption regimes and volcanic plumes have been proposed in the literature in the last ten years [Wilson and Head, 1981; Sparks, 1986; Vergniolle and Jaupart, 1990 among others], but few direct constraints have been made available to test them. Until now, vertical velocities of volcanic jets have only been measured from photoballistics of particles in photographic studies [Chouet et al, 1974].This method gives a good estimate of the velocity of large particles but may not measure the velocity of very small ejecta, which is closest to the gas velocity. Remote sensing techniques such as radar systems have been used for observations of ash clouds from volcanic eruptions at Mount St Helens in 1980 [Harris and Rose, 1983]. Estimates of the particle size and total ashfall mass have been obtained. However, they are related to the broader part of the plume, at which height the largest particles are not visible because of the large distance (>1km) between the radar and the volcano. Further, this technique was not use to infer velocities.

Physicists in atmospheric sciences used Sodar (Sound Detection and Ranging) to characterize the velocity of atmospheric and industrial plumes as well as energetic hot experimental jets [e.g. Brown and Hall, 1978]. This method is based on the Doppler effect for particles in motion in the plume. Volcanic jets are hot and energetic, and hence we have applied this technique to measure their vertical velocity.

Principle

A monostatic Sodar is an instrument which sends an acoustic wave and receives an acoustic backscattered one at the same location (collocated transmitter and receiver). The Doppler shift Δf between the acoustic transmitted wave of frequency f and the backscattered one is directly related to the vertical velocity w inside the jet. In the absence of any horizontal component :

$$\Delta f/f = -2\ w \sin \alpha / C \qquad (1)$$

where α is the angle between the antenna axis and the horizontal and C the sound speed at the temperature of the jet. C is function of temperature T and composition. Assuming T=1000°C and a normal atmospheric composition, $C \approx 718$ m/s. The acoustic wave frequency is 2000 Hz. Assuming an angle $\alpha=45°$, and a vertical velocity of 50 m/s [Chouet et al, 1974], the Doppler shift is equal to 197 Hz. This is sufficient to allow the determination of vertical velocities if the acoustic backscattered intensity is high enough.

The acoustic intensity σ of the reflected wave in the volcanic jet may be estimated as follows. Reflections from both eddies and particles in the jet contribute to the backscattered signal. For a monostatic Doppler acoustic antenna when no particles are present, the intensity is proportional to C_T^2/T^2 where C_T^2 characterises the level of turbulence in the jet and is the structure function of temperature fluctuations in the jet and T is the mean temperature in °K [Tatarski, 1961]. The parameter C_T^2 for volcanic jets is very high as it varies with the temperature difference between the jet and the ambient air (~1000°C) and the temperature gradient in the jet. The temperature profile across the jet can be considered as a top hat function with a very thin gradient localized at the edge of the jet [Turner, 1973]. Considering the turbulent kinetic energy budget [Wyngaard, 1973], and assuming that the mean turbulent dissipation rate is close to half the buoyancy, one gets :

$$C_T^2 \sim K_\theta\ (\Delta\theta / \Delta z)^2 / [\ 0.5\ g/\theta\ (\Delta\theta/\Delta z)\ ]^{1/3} \qquad (2)$$

where K_θ is the temperature turbulent exchange coefficient, $\Delta\theta$ the temperature jump at the interface Δz, θ the mean potential energy and g gravity. K_θ can be estimated to be:

$$K_\theta \sim W \times \Omega \qquad (3)$$

where W is the vertical velocity scale (~ 40 m/s) and Ω the turbulence scale. Taking the turbulence scale of the order of the jet dimension (~5m), this yields $K_\theta \sim 200$. This corresponds to very strong thermal turbulence. The potential temperature gradient is always greater than $\Delta\theta/2R$ where R is the half conduit dimension and $\Delta\theta$ the temperature difference between the jet and the ambient medium. Taking the minimum value for the gradient, we obtain $C_T^2 \approx 8 \times 10^6\ K^2\ m^{-2/3}$. Thus, the estimated level of turbulence in volcanic jets is 4×10^8 larger than what is generally observed in atmospheric studies. The acoustic backscattered intensity is proportional to $C_T^2/T^2 \sim 5$, hence a strong echo can be expected, although some energy may be lost in the jet by absorption or along the antenna beam.

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The second effect on the backscattered signal is due to Rayleigh scattering on the particles in the jet. Following Little [1972], Weill et al [1986], Coulter et al [1989], the acoustic backscattered cross-section η in a monostatic mode may be expressed for Rayleigh scattering on particles of dimension D much smaller than the wavelength λ ($\lambda=C/f=0.17$ m), as:

$$\eta = H\ \lambda^{-4}\ 1/V\ \Sigma_V\, D^6 \qquad (4)$$

where H is a constant ~ 2×10^{10}, and V the gate scattering volume. Following Little [1972], the backscattered acoustic σ intensity can be expanded into:

$$\sigma = P\ \lambda^{-4}\ 1/V\ \Sigma_V\, D^6 + Q\, C_T^2\, \lambda^{-1/3}\, T^{-2} \qquad (5)$$

where P and Q are coefficients to be determined and are a priori unknown in volcanic jets. However, for conditions similar to atmospheric conditions as in clouds, the contribution to the reflectivity due to particles is larger than the turbulence contribution. In conclusion, since the turbulence effect has been estimated to be large, a strong echo can be expected in volcanic jets.

Measurements

We have tested this technique on Stomboli volcano (Eolian Islands, Italy). This volcano has shown a remarkable steady-state activity for the last 2000 years, according to historical records. Its eruptive pattern consists of series of explosions, interspersed with periods of quiescence. The explosions are due to large gas pockets bursting at the vent [Blackburn et al, 1976; Jaupart and Vergniolle, 1988]. Explosions from the western vent project fragments following parabolic trajectories with a large spread of initial angles. This suggests the bursting of a "spherical" gas pocket. Explosions from the eastern vent propel ejecta almost vertically in the atmosphere, and resemble a powerful gas jet. The largest explosions project gas, particles and larger lava clots to heights which can be greater than 100m above the vent. Most of the explosions are very short (typically 10-15s). The major gas constituent is H_2O (~80%) with minor amounts of CO_2 (10%), SO_2 (5%) and Cl_2 (5%) [P. Allard, 1991, pers. comm.]. The temperature of the gas jet can be estimated to be close to the liquidus of the lava, i.e. ~1000°C [Clocchiatti, 1981].

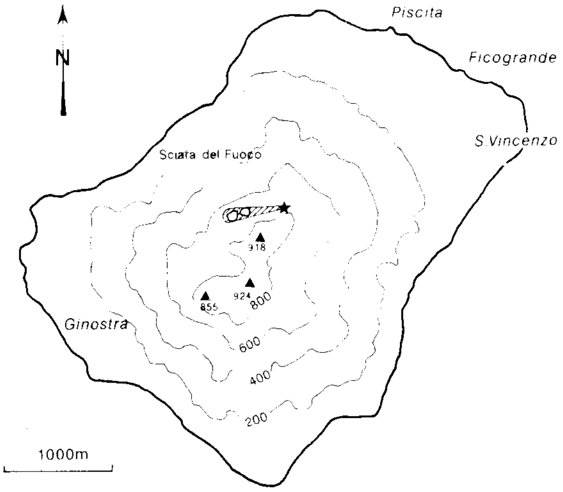

Fig. 1 Map of Stromboli volcano. The eastern and western craters are indicated. Level contours are in meters. The location of the antenna is showed by the star, as well as that of the antenna main lobe . The antenna was in direct sight of the Eastern crater.

The first Sodar measurements on Stromboli have been performed in September 1991 during 5 days (9/23 to 9/27) and almost continuously (~17 hours per day). The equipment was emplaced by helicopter on a safe site, on the ridge at the height of 800m and at 340m from the ridge of the vent in the Eastern crater (Figure 1). This distance was measured by triangulation of the observation site with a theodolite.

A slanting monostatic acoustic antenna has been used to detect in the Doppler spectrum the vertical component related to the gas vertical velocities [Weill, 1991]. As the updraft speed in explosions is relatively large and associated with a high reflectivity level (high echo level), the distinction between gas vertical velocity from the horizontal component of atmospheric wind was obvious. Although the wind speed was not estimated during our experiment, its projection along the horizontal was always observed. Data were stored on a Digital audio-tape recorder and the wave form analysis was processed in the laboratory on a window of 100 Hz which yields a spectral resolution of 3.1 Hz.

The operating parameters for the antenna were chosen as follows in order to interpret the returned signal (equation 2-6). The pulse frequency is f=2000Hz, its repetition period is 4s and its length τ=50ms. After a blinding period of 30ms, the signal is analyzed over time intervals or gate durations equal to 50ms. This corresponds to spatial lengths along the beam or gate widths equal to $C.\tau/2$ ~8.5m in the atmospheric part out of the jet. The maximum range for measurements is ~600m. The half antenna beam angle is ≥5° since the parabolic antenna was not protected by an acoustic foam cylinder. We had built an antenna for which the angle α could be changed degree by degree, from -45° up to 45° to insure flexibility in the field. As a Doppler shift ≥ 200 Hz was expected, two 400 Hz band-pass quartz filters, depending on the sign of α, were designed for the acoustical signal analysis in order to be able to estimate large velocities (equation 1) and a drastic filtering outside the signal analysis filters was performed in order to eliminate contamination of the signal by impulsive explosions. Finally, a previous acoustic recording made in June 1990 on the Stromboli had shown that acoustic harmonics of explosions at frequencies close to f were non existent.

We measured the velocity as close as possible to the exit of the vent, in order to obtain the most representative estimate of the volcanic gas velocity. Further up from the vent, turbulent mixing with ambient air takes place. This increases the section of the plume and thus, changes the velocity of the volcanic gas [Woods, 1988] Because of the field geometry at the site of measurements, acoustic sounding was operated with α=6° and on September 27th with α=7.5°. With these angles, the height of measurements in the jet is ~ 20 m above the exit of the conduit. Explosions were expected near gate 44 at a distance of 370 m from the antenna. Most of the time, the explosion appears on 2 or 3 gates, therefore, the horizontal dimension of the volcanic jet varies from 17 to 30 m. This is in good agreement with visual observations of vent diameters [Chouet et al, 1974].

Results and Conclusion

During 5 days, more than 117 explosions were identified and analyzed. As an example, continuous measurement of the average vertical velocity is reported on Figure 2. The velocity for the explosions is equal to 40 and 45 m/s and is much above the "noise" level. Figure 3 represents a sequence of successive Doppler spectra in and outside explosions obtained for the single gate 44. Before the explosion, spectral line stays close to 26 which is the frequency of the acoustic transmitted wave. The Doppler shift and hence the velocity are small. During the explosion, there is a drastic shift of the spectrum with a large spectral broadening. Vertical velocity varies between 20 to 80 m/s with an average of 41.5 m/s and a standard deviation of 8 m/s. In a single gate of width 8.5 m,

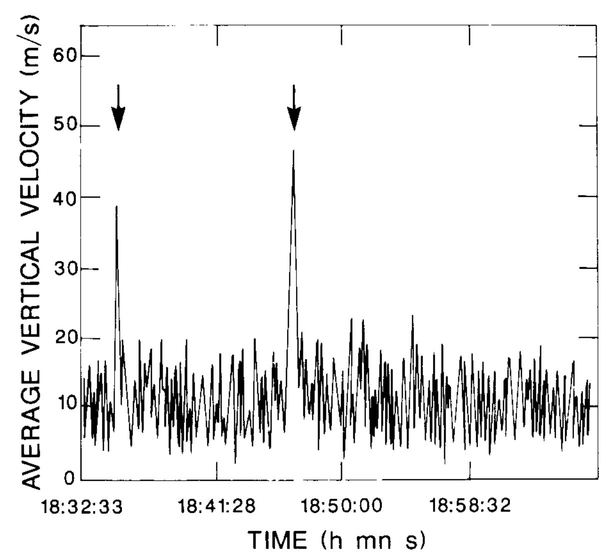

Fig. 2 Example of average vertical velocities estimates calculated in a single gate 44 during a period of 35min on September 24. Two explosions that are indicated by arrows, have been identified and correspond to visual observations. The "noise" outside explosions is a combination between wind speed and vertical velocities of plumes upon the volcano vents. It is calculated assuming the same sound speed than during explosions and hence must be lower of a factor 2 to that indicated here.

the highest velocities are for gas or very small particles, the smallest for the large particles. Note also that the reflectivity level upon the mouth remains always relatively high with a slight Doppler shift outside the explosions, and is probably related to turbulence in the air above the vent due to high temperature.

The only parameter which is not measured is the sound speed C in the jet (equation 1). We have taken C = 700 m/s, assuming a temperature of 900°C and the composition given above. Taking into account realistic variation of compositions and temperature, this implies a maximum uncertainty of 10 % on C, hence 10% uncertainty on radial velocities. Particle size distribution should also have some effect on the sound speed in the jet [Soo, 1967]. Particles on Stromboli are coarse and have a mean diameter ~1cm with very few particles under 1mm [Chouet et al., 1974]. There are no data showing a bimodal size distribution with very fine particles such as those observed on Mount St Helens [Carey and Sigurdsson, 1982]. Since the physics of fragmentation of acid magmas is different from that of basaltic ones, the amount of very fine particle is expected to be small. With a mass ratio of particles to gas <0.5, the sound speed in the jet is close to that measured in a pure gas at the frequency of the transmitted acoustic wave [Soo, 1967]. Further, considering the spectral resolution of 3 Hz and an inclination of 7°, the statistic uncertainty is ~ 4 m/s. We must also note the following limits of the method. Since an explosion is very short (typically ~ 10-15 s), there is a limited number of acoustic pulses in the explosive jet (<4). We may not measure the maximum velocity during an explosion, since pulses are not synchronized with the explosions.

Doppler spectrum also contains some information on particle size (Figure 3). In case of the explosive jet, we notice some "wing" in the spectrum, probably corresponding to falling particles. Its interpretation in terms of particle dimensions and turbulence is not yet possible. Relationships between particle dimensions and fall speed in a high temperature medium is not known and echo level calibration needs knowledge of sound absorption in and outside the jet.

We observed that the velocity systematically increased during the period of measurements (Figure 4). We suggest that this variation is related to a decrease of the concentration of particles in the jet, as observed visually. There was more gas and less lava clots towards the end of the experiment.

Our measurements gave the same order of magnitude than those measured by Chouet et al [1974] and Blackburn et al [1976] from their photographic studies. The advantage of our method over photoballistic studies lies in the fact that it is continuous and can be performed both night and days except

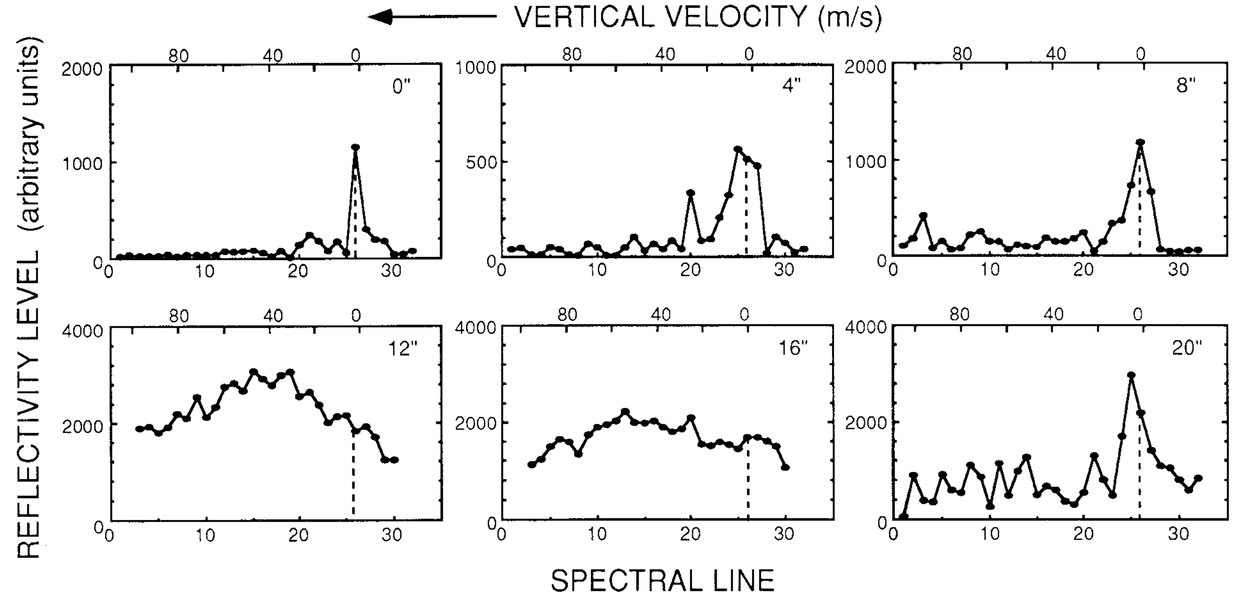

Fig. 3 Sequence of Doppler spectra in and outside explosion in September 25 at 15:31. The explosion occurs between 8" and 12" and continues until ~18". The lower abscissa indicates the spectral line (maximum 32). Spectral line 26 indicated by dotted line is the frequency of the transmitted wave. The reflectivity level is the same for all spectra and is in arbitrary units. Spectra during the explosion have been smoothed to remove oscillations. Is also indicated on the upper scale the vertical velocity, which is calculated from equation 1 assuming C=700m/s and Δf=3.1Hz.

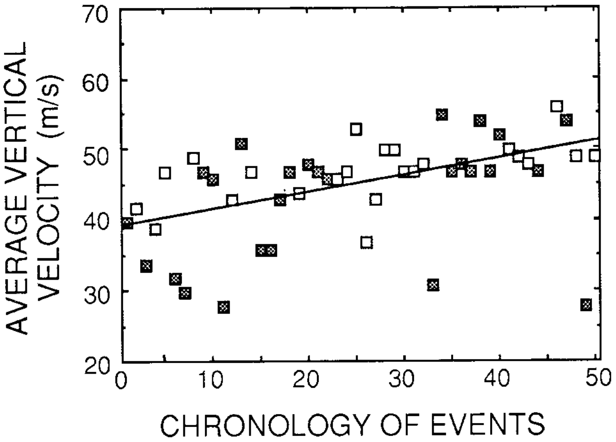

Fig. 4 Average vertical velocities versus time as recorded during 4 days (September 24 to 27). Events are represented in a chronological order. Black squares represent explosions with many lava clots and gaz. Open squares represent explosions with mainly gaz as observed visually.

for periods of too strong wind. Spectral analysis could also be performed in the field, giving access in real time to the vertical velocity. Thus, it is well suited for monitoring temporal variations of the velocity during an eruption. This technique can be applied to any basaltic volcano and should be particularly interesting for the study of lava fountains such as those observed in Hawaii.

In conclusion, we have shown that remote sensing techniques can be used to sound basaltic volcanic explosions and to reliably estimate their vertical velocities. The Doppler spectrum also contains information on particle size, but the interpretation requires studies on falling speeds of particles in hot turbulent jets which are beyond the scope of this paper. More accurate measurements could be obtained in future experiments of acoustic sounding, using a multifrequency antenna giving several independent estimates of the Doppler shift for the same signal.

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