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Characterization of the gas–magmatic outflow at a volcanic vent through integral-equation based inverse acoustics

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ABSTRACT

A methodology to set up and solve a 3D inverse problem in volcano acoustics is developed. The method is used to estimate the acceleration of the gases at the volcanic vent from acoustic recordings at a microphone located on the erupting volcano. The assumption of linear acoustic propagation outside the volcanic vent is made. The Boundary Element Method (BEM) is used to extract the matrix transfer function relating the pressure at the location of the microphone to the acoustic acceleration at the volcano's outlet. The BEM transfer function includes the complete scattering effect of the volcano topography under the assumption of acoustically rigid surface. The spectrum of the acoustic acceleration at the vent is obtained in two different fashions: (i) by inversion of the matrix transfer function; (ii) through the minimization of the deviation with respect to the measurements. The method was tested on the Stromboli volcano using the simplifying assumption of an axially symmetric orographic profile. The problem was also solved using a bi-objective optimization to maximize the matching of the simulations with the measurements. Both the techniques produced satisfactory results. The method could be used to optimize the distribution of pressure transducers around the vent.

1. Introduction

In the last decades, the use of pressure sensors to detect the infrasonic signal emitted during explosive eruptions has got a worldwide diffusion. An extensive review of the literature concerning volcano acoustics is beyond the scope of the present paper, and the interested reader is addressed to Johnson and Ripepe [1]. Nevertheless, the collocation of the present work with respect to the state-of-the-art is briefly addressed in the present section.

One of the main advantages of using infrasonic signals related to an active volcano lies in the possibility to perform a real-time continuous monitoring of the explosive activity in all weather conditions, evidencing the activity status of volcanoes as far as tens of kilometers away: that enables a safe and continuous remote sensing, even during violent eruptions. Furthermore, sensible and calibrated pressure transducers can be used as a probe for the activity status of a volcano, detecting the presence of extremely low signals related to passive degassing [2,3]. At present, many active volcanoes around the world are monitored by means of infrasonic stations, sometimes in array configuration. The wide use of this technique lies in the ample spectrum of informations obtainable on the source dynamics. Compared to seismic signals, pressure recordings are less affected by the propagation scattering effects, since the infrasound travels in atmosphere: so at least for short distances (<50 km), pressure at microphones may be directly connected to the source, in the approximation of homogeneous and isotropic atmosphere [1]. Considering this assumption, many authors tried to extract from infrasound recordings quantitative information concerning the physics related to the gas–magma outflow at the volcanic vent. Woulff and McGethcin [4] performed the first gas velocity measurement from acoustic recordings (in the audible-band), considering the classic multipole expansion [5]. Such methodology has had a wide use in the last decades, and many authors tried to relate the eruptive style of a volcano to one of these acoustic sources. Some authors [6–14] assumed that a strombolian explosion can be associated to a simple acoustic source. If the monopole model can fit a sudden explosion at the top of a magma column, the dipole has been used mostly to model prolonged eruptions. Woulff and McGetchin [4] considered the dipole source as the product of interaction of a gas flow with the solid boundaries of the conduit wall [15], and used it to analyze some fumaroles of Acatenago volcano (Guatemala). Some authors

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used it in analyzing sub-plinian plumes and thermals [12], others for vulcanian explosions [16]. Johnson et al. [14] considered the explosion of gas bubble at the surface of the lava lake of Erebus volcano having the nature of a monopole with dipolar asymmetries connected to the film rupture. The third kind of elementary source, the quadrupole, is strictly connected to the turbulence inside the gas jet [17,18]. Matoza et al. [19] and Fee et al. [20], made a comparison between the large scale turbulence similarity spectrum [21] and some frequency spectra from different volcanic eruptions, in order to detect the presence of quadrupole as a source of acoustic radiation. Despite the large diffusion of volcano infrasound, the actual source process is still not clear. As a matter of fact the choice between the elementary (monopole, dipole and quadrupole) acoustic sources is still debated. Furthermore, the interaction with the terrain have to be considered, since it affects the free-field propagation of these three sources. In this view, numerical simulations of the source condition and the propagation effects nearby the vent can provide an accurate method to study what really happens in the first instants (<0.2 s) of the explosion. Moreover it will be possible to study also the effect of some physical parameters (such as magma density or vent radius) that in most cases are poorly constrained. Kieffer and Sturtevant [22] performed laboratory experiments on the behavior of volcanic jet in supersonic conditions. Some authors studied the propagation of acoustic waves by numerical simulations considering as source mechanism the resonance of the magma column induced by an explosion [23–25]. Pelanti [26] studied a multicomponent compressible flow at the base of wave propagation by numerical methods. Johnson et al. [14] tried to identify the most plausible source by means of numerical simulations and source directivity. Ogden et al. [27] performed numerical simulations on volcanic jets to investigate both the gas-thrust region and the convective plume generated by a supersonic shock. Kim and Lees [28] and Lacanna and Ripepe [29] used a bi-dimensional Finite Difference Time Domain (FDTD) approach to numerically study the effect of terrain scattering and atmospheric absorption on the signal shape.

In the present paper, we propose a method to relate the pressure recorded at a set of microphones to the source conditions at the volcanic vent through the inverse solution of the three-dimensional acoustic propagation problem including the scattering effects of the orographic profile [30]. The methodology is based on a Boundary Integral Equation (BIE) formulation of the acoustic problem, numerically solved with the Boundary Element Method (BEM). The solution has been obtained by using two different methods: (i) a sound-matching-based bi-objective optimization; (ii) a linear system coming from the inversion of the matrix transfer function. The relationship between the pressure measured at the microphones and the boundary conditions at the volcanic vent is described in Section 2, with the two different approaches to the solution in SubSections 2.2 and 2.3. In Section 3, the features of the infrasonic signal used for our analysis are described. Finally, numerical results are illustrated in Section 4, with a validation of the methodology performed by means of a Finite Element Method (FEM).

2. Methodology

2.1. The inverse problem set-up

Since a volcanic eruption is a complex physical phenomenon, the generation of infrasonic waves during an explosion is strictly connected to the dynamics of a multiphase fluid moving inside the volcanic conduit: a pressurized volcanic gas mixture and magma at a certain degree of fragmentation [31]. The equations of linear acoustics are valid in most cases for infrasound emitted by volcanic explosions [1]. But at the very onset of the process these approximations could be no more valid, and the sound pressure and corresponding fluid velocity amplitudes can be large enough to make the nonlinear terms be significant. As a consequence, the terms of viscous friction and heat conduction could play a significant role inside the equations of motion, and neglecting these terms in the equations could be a source of error [32,33]. Another problem arises if the acoustic source moves during the process of sound generation. This could occur during volcanic explosions, where the gas–magma mixture moves inside the conduit before escaping in the free air. Furthermore, the acoustic source can be the flow itself, interacting with the solid wall of the volcanic conduit [15], and producing a prolonged rumbling noise. For all these reasons the actual process of generation of acoustic waves is still not completely known. Nevertheless, the assumption of linear acoustic propagation immediately outside the volcanic conduit appears to be acceptable, even if there can be a transitional zone where residual nonlinear effects could be of some importance. The existing literature, and the results presented in Section 4 corroborate this assumption.

The starting point of the present method is to consider the acoustic source as located on a virtual surface corresponding to the outflow section of the volcanic vent. Indeed, this section is here considered as a radiating surface without any a priori assumption on the nature of the acoustic singularities used to model the source. The degassing process, associated to a sudden expansion of an over-pressurized gas jet, can occur inside the volcanic conduit; in such a case, the generated pressure perturbation is forced to propagate inside a duct before expanding in the free air. In order to avoid any problems connected to the propagation inside the duct (nonlinear effects, resonance of the tube, and energy trapping due to the acoustic impedance contrast at the open-end conduit) we put our surface at the volcanic vent, considering only the propagation outside the volcanic conduit. In this preliminary work, the effects of atmospheric turbulence, wind, and thermal gradients have been neglected, because the attention is here focused on the overall capacity of the method in reproducing the basic features of the phenomenon.

The BEM is a numerical technique for solving a wide range of physical and engineering problems. Like other computational techniques as the FEM, the BEM is a method for solving Partial Differential Equations, expressed in form of integral equations. The main advantage of the BEM is that the geometry is defined only by meshing the surfaces, in such a way, the method provides a complete solution in terms of boundary values. Especially in linear acoustics, the BEM reveals powerful for problems where the acoustic domain is so large that can it be realistically approximated as having infinite dimension (external problem). This can be the actual case of acoustic propagation in free air, where by using the BEM only a mesh of the surface of the body is required. The integral equations that the BEM has to solve assume a boundary integral form, relating the solution at any points of the domain to functions defined only on the boundary of the bodies. Such Boundary Integral Equations are discretized by representing surfaces as panels, and defining the boundary function on each panel of the mesh. To solve the acoustic propagation from the volcanic vent to the microphones we used the code AcouSTO (Acoustic Simulation TOol) [34], an open source BEM solver for the Kirchhoff–Helmholtz Integral Equation (KHIE) in three dimensions released under GPLv3.0 (http://acousto.sourceforge.net/). The code is written in the language C and enables parallel computing in order to solve numerical calculations on a distributed environment. The acoustic problem is studied in the Fourier domain, and equations can be written in terms of pressure perturbation inside a domain $\mathcal{V}$:

$$\nabla^2 \tilde{p}(\mathbf{x}) + k^2 \tilde{p}(\mathbf{x}) = \tilde{q}, \qquad \text{for } \mathbf{x} \in \mathcal{V} \tag{1}$$