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Acoustic source characterization of impulsive Strombolian eruptions from the Mount Erebus lava lake

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ABSTRACT

We invert for acoustic source volume outflux and momentum imparted to the atmosphere using an infrasonic network distributed about the erupting lava lake at Mount Erebus, Ross Island, Antarctica. By modeling these relatively simple eruptions as monopole point sources we estimate explosively ejected gas volumes that range from 1,000 m^3 to 24,000 m^3 for 312 lava lake eruptions recorded between January 6 and April 13, 2006. Though these volumes are compatible with bubble volumes at rupture (as estimated from explosion video records), departures from isotropic radiation are evident in the recorded acoustic wavefield for many eruptions. A point-source acoustic dipole component with arbitrary axis orientation and strength provides precise fit to the recorded infrasound. This dipole source axis, corresponding to the axis of inferred short-duration material jetting, varies significantly between events. Physical interpretation of dipole orientation as being indicative of eruptive directivity is corroborated by directional emissions of ejecta observed in Erebus eruption video footage. Although three azimuthally distributed stations are insufficient to fully characterize the eruptive acoustic source we speculate that a monopole with a minor amount of oriented dipole radiation may reasonably model the primary features of the recorded infrasound for these eruptions.

1. Introduction

Advancements in volcano monitoring and studies of eruption sources are increasingly facilitated by deployments of acoustic pressure sensors at diverse volcanoes worldwide (e.g., Matoza et al., 2007; Kumagai et al., 2007; Johnson, 2007). Acoustic pressure transients in the near-infrasound band (1–20 Hz), where most volcanoes appear to produce their most energetic sounds, provide valuable records of eruption dynamics arising from rapid expansion of gas and/or deflection of a rock/atmosphere or magma/atmosphere free surface (e.g., Firstov and Kravchenko, 1996; Yamasato, 1998; Garces et al., 1999; Hagerty et al., 2000; Ripepe and Marchetti, 2002; Johnson et al., 2003; Aster et al., 2004; Vergniolle et al., 2004; Gresta et al., 2004; Green and Neuberg, 2005; Ruiz et al., 2006; Petersen and McNutt, 2007). Unlike seismic signals, which are comprised of multiple wave types and which experience substantial path effects during propagation through volcanic or other highly heterogeneous structures, short-range atmospheric acoustic propagation is associated with relatively simple Green's functions and is thus more easily analyzed to reveal source information, particularly for surface or near-surface events (e.g., eruptions) that couple strongly with the atmospheric elastic wavefield. A useful first step is to characterize source mechanisms accounting for idealized Green's and transfer functions accommodating solely geometric spreading and instrument response (e.g., Ripepe et al., 1996, 2001; Vergniolle and Brandeis, 1996; Garces and McNutt, 1997; Garces et al., 2000; Johnson et al., 2004; Vergniolle et al., 2004). Ongoing development of infrasonic analysis techniques for heterogeneous media and topography promises to improve acoustic source modeling efforts (e.g., Fee and Garces, 2007; Ruiz, 2007).

In this study we assume negligible topographic effects and an homogeneous atmosphere for infrasonic propagation over short (hundreds of meters) distances, however we use near-source recordings to investigate volcano acoustic source directivity. This is a complication that has not been previously focused on in detail, but is shown here to affect infrasonic observations in an explicable and predictable manner. Our analysis demonstrates the tractability of incorporating infrasound source directivity in volcano acoustic studies utilizing infrasonic networks.

2. Background

Lava lake explosions from Mount Erebus are amongst the most straightforward type of volcanic eruptions for performing acoustic inversions for source properties owing to their relative simplicity of mechanism (Rowe et al., 2000; Johnson et al., 2004), high occurrence frequency and quasi-repeatability (Dibble, 1989; Aster et al., 2003; Gret et al., 2006; Henderson, 2007), and short and/or straight-line acoustic propagation paths between source and infrasonic transducers. In this

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context, the simplicity of the acoustic source arises from the short (few seconds) time duration of intense sound generation as well as from the small physical dimension of the source region. In 2006 the size of the primary Erebus lava lake was ~40 m in diameter, and both it and the large eruptive bubbles which ruptured its surface could be considered compact relative to the primary Erebus infrasound wavelengths (peak energy at 2 Hz is ~160 m wavelength). The short transit distances (typically hundreds of m) and unobstructed view into the crater provide for line-of-sight propagation of sound waves from source to several pressure transducers, resulting in minimal acoustic path effects. The persistently exposed conduit at Erebus also facilitates numerous corroborative observations, such as continuous telemetered time-stamped video (Aster et al., 2004) and Doppler radar (Gerst et al., 2008-this issue). These external data provide important additional constraints and verification of inferences made from infrasonic data.

3. Monopole and dipole source models

Infrasonic waves are generated when the atmosphere is accelerated. This can be accomplished through various means, including an infusion/extraction of volume and/or by an external force applied to the atmosphere (Dowling and Williams, 1983). An isotropic gas expansion, such as would be observed during a symmetric chemical explosion (Baker, 1973), or an idealized bursting of a balloon (Kulkarny, 1977), can, in certain instances, be described as a monopole source. Volumetric sources may be considered monopoles when they are confined to a small, or compact, isotropic source zone. In this case, the radiated acoustic waves from a compact source region are considered to be in phase, and sound propagation into a uniform atmosphere is radially symmetric. The excess pressure radiated from a monopole as a function of time t may be expressed as (Dowling and Williams, 1983):

$$\Delta P_m(r,t) = \frac{Q(t-r/c)}{4\pi r} \tag{1}$$

where c is sound speed, and r is propagation distance. Q is the monopole strength expressed in units of $\rho \mathrm{m}^3/\mathrm{s}^2$ where ρ is the fluid density in kg/m^3. Throughout this paper we choose to quantify source strength as the product of fluid density ρ and volumetric fluid acceleration m^3/s^2 because it is more intuitive and simpler to consider volume perturbations associated with eruptive emissions rather than mass fluxes. For our analyses, the coefficient $1/4\pi r$ in Eq. (1) is increased to $1/2\pi r$ to account for monopole radiation into a half space, such as would be produced from an isotropic source located a small distance above a reflective surface.

Dipole sources, in contrast, involve no net volumetric flux, but perturb the atmosphere through a change of momentum. A dipole may be modeled in the limit as two closely spaced monopoles that are 180° out of phase. A classic example of a simple dipole is the compact un-baffled speaker. One side of the speaker membrane compresses the atmosphere while the other side rarefies the atmosphere, with the resulting pressure variations being 180° out of phase. The resultant force induces an asymmetric acoustic radiation pattern with zero pressure disturbance orthogonal to the axis orientation and maximum pressure at a dipole axis angle (θ) of 0°. Dipole pressure radiation can be expressed as (Dowling and Williams, 1983):

$$\Delta P_d(r,\theta,t) = \frac{\cos\theta}{4\pi r}\left[\frac{1}{c}\frac{\partial F(t-r/c)}{\partial t} + \frac{F(t-r/c)}{r}\right] \tag{2}$$

where F is the vector force (ρm^4/s^2) applied to the fluid. The first (far-field) term is proportional to the time derivative of F and decays as $1/r$. The second (near-field) term is proportional to F and decays as $1/r^2$.

Higher order acoustic source characterization, such as quadrupole radiation has further been proposed for some types of volcano sound sources, such as fumeroles (e.g., Woulff and McGetchin, 1976). A quadrupole may be thought of as a limit-case dipole pair in close proximity, and is considered to be a useful characterization for jet noise (Lighthill, 1978). Quadrupole radiation is less efficient than dipole radiation as there is neither a net flux of fluid nor a net force exerted upon the fluid atmosphere. Although we do not consider higher order terms for our lava lake bubble bursts, we note that another vent active at Erebus in 2006 supported intermittent jetting emissions of gas and ash (Jones et al., 2008-this issue). Infrasound produced from this distinct narrow vent, situated some 80 m to the southwest of the lava lake, was prolonged in duration (several s to tens of s) and substantially lower in intensity (peak pressure amplitudes were 1–2 orders of magnitude smaller than from the lava lake). Considering the relatively low pressure amplitudes and eruptive style

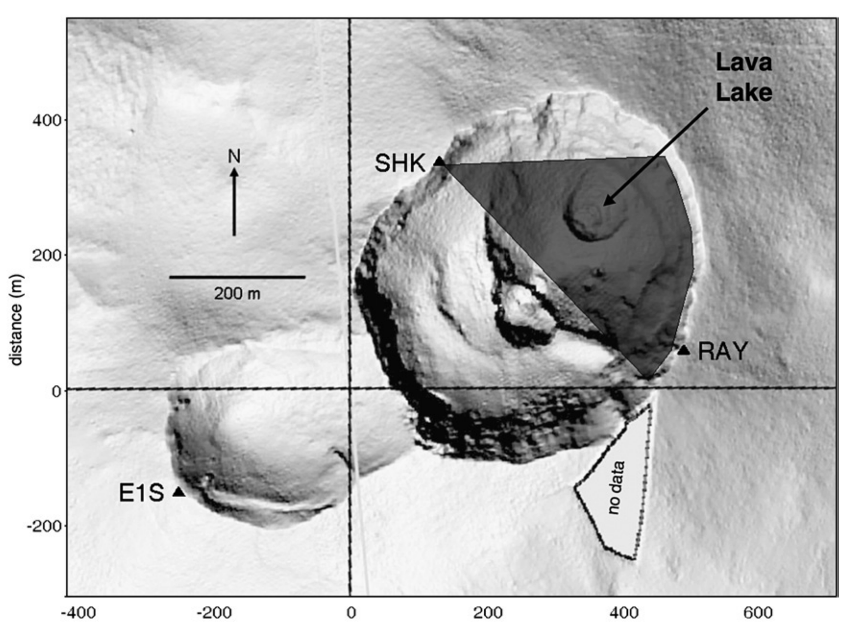

Fig. 1. Erebus crater region, showing infrasound stations SHK, E1S, and RAY used in this study. Approximate field of view (shaded triangle) of video camera, situated near SHK, is shown. Image is modified from digital elevation model of Csatho et al. (2005).