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Estimates of eruption velocity and plume height from infrasonic recordings of the 2006 eruption of Augustine Volcano, Alaska

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ABSTRACT

The 2006 eruption of Augustine Volcano, Alaska, began with an explosive phase comprising 13 discrete Vulcanian blasts. These events generated ash plumes reaching heights of 3–14 km. The eruption was recorded by a dense geophysical network including a pressure sensor located 3.2 km from the vent. Infrasonic signals recorded in association with the eruptions have maximum pressures ranging from 13–111 Pa. Eruption durations are estimated to range from 55–350 s. Neither of these parameters, however, correlates with eruption plume height. The pressure record, however, can be used to estimate the velocity and flux of material erupting from the vent, assuming that the sound is generated as a dipole source. Eruptive flux, in turn, is used to estimate plume height, assuming that the plume rises as a buoyant thermal. Plume heights estimated in this way correlate well with observations. Events that exhibit strongly impulsive waveforms are underestimated by the model, suggesting that flow may have been supersonic.

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1. Introduction

On January 11, 2006, after 20 years of quiescence and several months of volcanic unrest, Augustine Volcano erupted. In the two weeks that followed, Augustine released 13 discrete Vulcanian blasts, discharging gas and ash to heights exceeding 14 km. The eruption was exceptionally well monitored by a dense array of seismic and geodetic instruments as well as satellite data, near real time photography and visual observations (Power et al., 2006; Cervelli et al., 2006). Among the instruments located on the volcano itself was an infrasonic microphone which recorded all of the eruptive blasts as well as the continuous eruptive phase that followed. While the infrasonic signals accompanying the eruptions exhibited wide variations in peak amplitude and duration (Petersen et al., 2006), these signals did not correlate with the height of associated eruptive plumes.

In recent years, infrasonic recordings have been used to study a host of volcanic processes. Because path effects are less significant for atmospheric waves, infrasonic and acoustic signals are thought to be more informative about the eruptive source process and have been used by a multitude of researchers to investigate eruption source mechanics. Most infrasonic analysis has focused on discrete explosions such as Strombolian bubble bursts and gas eruptions (Vergniolle and Brandeis, 1994; Vergniolle and Brandeis 1996; Ripepe et al., 1996; Firstov and Kravchenko, 1996; Johnson and Lees, 2000; Vergniolle et al., 2004). Researchers have used infrasound to estimate the size and volume of magma bubbles (e.g. Vergniolle and Brandeis, 1996; Vergniolle et al., 2004), or to examine conditions during the uncorking of a volcanic conduit (Morrissey and Chouet, 1997; Johnson et al., 1998; Johnson and Lees, 2000). In some cases, infrasound has been critical in examining eruptions that could not be observed (Caplan-Auerbach and McNutt, 2003; Vergniolle and Caplan-Auerbach, 2006; Matoza et al., 2007; Moran et al. 2008).

While infrasound has been effective in studying signals such as magma bubble bursts, less use has been made of infrasonic signals recorded in association with ash eruptions. Infrasonic signals from ash bursts are typically prolonged, diffuse, and substantially more complicated than those associated with discrete blasts.

Woulff and McGetchin (1976) were among the first to investigate the acoustic signals associated with gas release at volcanoes. In their seminal paper, Woulff and McGetchin (1976) described a relation between acoustic pressure and the velocity of gases ejected from volcanic fumaroles. This formalism represents the base of the work presented here. We first discuss the method used to determine velocity from acoustic pressure and show how the method may be used to calculate eruption velocity and flux for Augustine eruptions. Finally we discuss how volume flux may be used to estimate plume heights, given certain assumptions about the mechanics of plume formation. Note that although the term "infrasound" specifically refers to signals below 20 Hz, the signals here carry some energy in the audible range (>20 Hz). Thus we use both "infrasonic" and "acoustic" in our discussion of the pressure signals recorded here.

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2. Augustine Volcano and monitoring network

Augustine Volcano is an andesitic–dacitic stratovolcano that forms an island in Alaska's Cook Inlet. Although Augustine Island is unpopulated, it is located within 100 km of several population centers and its eruptions pose a significant hazard to aircraft and local shipping and oil refineries (Waythomas and Waitt, 1998). Augustine's recent eruptions, occurring in 1976, 1986, and 2006, all exhibited similar progressions. Each event initiated as a series of discrete Vulcanian blasts, after which the volcano entered phases of continuous eruptive activity followed by effusion and dome growth (Coombs et al., in press; Waythomas and Waitt, 1998).

The Alaska Volcano Observatory has monitored seismic activity at Augustine since 1970. The 2006 eruption was recorded by a dense seismic and geodetic network (Cervelli et al., 2006). A Chaparral Model 21 infrasonic microphone was co-located with short period seismic station AUE at a distance of 3.2 km due east of Augustine's vent. A network of eight porous hoses was connected to the microphone to reduce noise. The microphone has a flat response at frequencies between 0.1 and 50 Hz and records both high and low gain channels with a dynamic range of 119 dB. This allows identification of small signals while also keeping large pressure signals on scale. All of the signals presented in this paper are a combination of these two channels: the high gain channel is used except where signals clipped (~13.5 Pa), in which case the data were replaced by values recorded on the low gain channel. Although the data are digitized at 16 bits, the combination of two channels gives the instrument an effective resolution of ~20 bits. The response of the Chaparral Model 21 has been tested at pressures exceeding 100 Pa, so we are confident that the signals recorded during the Augustine eruption are within the range for which the instrument was designed and for which its response is known.

The discrete blast phase of the 2006 eruption comprised 13 Vulcanian explosions accompanied by pyroclastic and debris flows (Coombs et al., in press). Each of the blasts was recorded on scale by the pressure sensor and the seismic network (Table 1). Maximum amplitudes range from 13 to 111 Pa at the pressure sensor, for sound pressure levels (SPL) of 117–133 dB (Petersen et al., 2006). Following the 13 blasts of the explosive phase, Augustine switched into a phase of continuous eruption, generating more or less constant block and ash flow activity for a period of 4 days (Coombs et al., in press). Background infrasound levels are substantially higher for events 10 and 11, making the onset and coda of these events difficult to distinguish. This may be due to high winds, or to the volcano's transition near that time from discrete to continuous eruption. Thus, for consistency in the analysis we consider only the first 9 eruptive blasts in this study.

Waveforms for each of the nine eruptive events are presented in Fig. 1. Durations of the acoustic signals vary from ~55–350 s. Some events exhibit impulsive onsets while others have a more extended beginning. In most cases the event consists of a single burst of energy, although events 6 and 7 have a secondary amplitude increase several hundred seconds after the event begins.

3. Methodology

Fluctuations in air pressure recorded at a distance from a volcanic vent may be directly related to acoustic power, which in turn depends on flux at the volcanic vent (Woulff and McGetchin, 1976; Lighthill, 2001; Vergniolle and Caplan-Auerbach, 2006). The relation between eruptive flux and acoustic power, however, is complicated by uncertainties in the dynamics of the sound source. Woulff and McGetchin (1976) presented relations between velocity and power for three source types: monopole, dipole and quadrupole. A monopole source is one in which fluctuations in pressure are due entirely to the rate of change of mass flux, and is best envisioned as an exploding source. A steady gas jet or gas that interacts with solid walls is best described by a dipole source, the preferred model used by Woulff and McGetchin (1976) for describing gas release from volcanic fumaroles. Finally, gas sources that generate noise through turbulence, such as a jet engine, are modeled as quadrupoles.

For a source that radiates sound as a hemisphere of radius r, the relation between recorded pressure p and acoustic power Π is given by

$$\Pi = \frac{\pi r^2}{\rho_{\text{air}} c \tau} \int_0^\tau |p - p_{\text{air}}|^2 dt \quad (1)$$

where ρ_{air} is air density, c is the speed of sound, τ is the duration of the source function and $p - p_{\text{air}}$ is the excess pressure (Table 2). The acoustic power depends strongly on the source function (monopole, dipole or quadrupole) and may be determined by one of the following functions (Woulff and McGetchin, 1976):

$$\begin{aligned} \Pi_m &= K_m \frac{4\pi R^2 \rho_{\text{air}} u^4}{c} \\ \Pi_d &= K_d \frac{\pi R^2 \rho_{\text{air}} u^6}{c^3} \\ \Pi_q &= K_q \frac{\pi R^2 \rho_{\text{air}} u^8}{c^5} \end{aligned} \quad (2)$$

where K_m, K_d and K_q are empirically derived constants, R is the source radius (here taken to be the radius of the volcanic conduit), u is the velocity of material at the source and c is the speed of sound in air (Table 2). The value of K_m is on the order of 1 while K_d and K_q are approximately 10^{-2} and 10^{-5} respectively (Vergniolle and Caplan-Auerbach, 2006). Thus, despite the exponential effect of velocity, for gas flowing at a given velocity, less sound will be generated by a quadrupole source than by a dipole or monopole. In an alternate view,

Table 1
Parameters for the nine discrete eruptive blasts.

Event	Date/time (UTC, 2006)	Maximum pressure (Pa)	Duration (s)	Max velocity (m/s)	Max flux (m^3/s)	Eruptive volume ($\times 10^7 m^3$)	Modeled thermal height (km)	Sustained plume height (4% magma) (km)	Observed plume height (km)
1	Jan 11, 13:44	96	55	196	5.5×10^5	1.0	6.8	17.0	9
2	Jan 11, 14:12	13	270	100	2.8×10^5	3.5	9.1	15.3	9
3	Jan 13, 13:24	22	350	93	2.6×10^5	3.4	9.1	14.2	10
4	Jan 13, 17:47	35	250	135	3.8×10^5	3.9	9.4	16.2	9
5	Jan 13, 20:22	44	180	149	4.2×10^5	4.1	9.5	17.8	11
6	Jan 14, 01:40	33	270	132	3.7×10^5	6.1	10.5	17.8	10
7	Jan 14, 03:58	50	270	177	5.0×10^5	6.5	10.6	18.2	9
8	Jan 14, 09:14	62	150	189	5.3×10^5	4.5	9.7	19.1	N/A
9	Jan 17, 16:58	111	220	220	6.2×10^5	5.8	10.3	18.4	14

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