Volcano Infrasound

David Fee – University of Alaska Fairbanks
Jeff Johnson – New Mexico Tech
Overview

1) Infrasound Background

2) Volcano Infrasound Background
   a. Nomenclature
   b. Amplitude/Energy Estimation
   c. Array Processing

3) Propagation

4) Types of volcanism and associated infrasound case studies
   a. Source models
   b. Various types of infrasonic signals
   c. Implications understanding eruption dynamics
   d. Hazard Mitigation
Infrasound – What is it?

Sound waves (pressure waves) below ~20 Hz
- Low amount of attenuation → propagate long distances

Sound wave similar to P-wave in seismology
- Similar frequency range
- Less path effects, No shear or surface waves – only compressional

Sources: open ocean waves, surf, atmospheric nuclear tests, earthquakes, avalanches, meteors, tornadoes, auroras, jets...and volcanoes!

Not restricted by clouds, but affected by wind and temperature gradients
Infrasound Sensors

Electret condenser elements

- Pro – nice signal-to-noise.
- Pro – cheap..
- One dollar a piece!
- Con – frequency response rolls off in zone of interest

Machined silicon pressure transducer

- Pro – response is linear down to DC.
- Pro – relatively cheap - $100 a piece
- Con – doesn’t filter out barometric pressure fluctuations
- Con – Inferior signal-to-noise

Microbarometer (MB2000) & Differential Mic (Chaparral)

- Pro – flat response
- Pro – very low noise
- Con – a bit pricey (~$3-10,000)
- Con – difficult to manage for field deployments (big)
Volcano Infrasound

As magma depressurizes, gas comes out of solution and perturbs the atmosphere. Majority of pressure oscillations infrasonic due to large source length scales (10’s of m). Recorded at distances of meters to thousands of kilometers. Provides insight into eruptive activity and useful for hazard mitigation.

\[ p(t) = s(t) \ast l(t) \ast g(t) \]

- \( p(t) \) = observed pressure (acoustic) signal
- \( s(t) \) = source time function (pressure-time history at volcano)
- \( l(t) \) = local resonance effects, e.g. resonance in fluid-filled cavities, cracks, conduits, etc.
- \( g(t) \) = propagation from source to recording site, including atmospheric propagation effects (winds, absorption, etc.); seismic-acoustic coupling when applicable

\( \rightarrow \) We record \( p(t) \) and we want \( s(t) \), so we need to characterize \( l(t) \) and \( g(t) \).
Volcano Infrasound Nomenclature

**Explosion**: rapid, short-duration release of pressure with compressional onset, followed by rarefaction

**Degassing burst**: relatively short duration degassing events; durations 10’s of seconds to minutes; may have rarefactional (decompressional) onset

**Tremor**: continuous vibration of the air lasting minutes to years
- Harmonic - multiple spectral peaks
- Spasmodic - amplitude variations
- Episodic - cyclical
- Broadband - covering a wide frequency range
- Monotonic - single spectral peak

**Jetting**: sustained, aerial source from momentum-driven gas jet

**Classification by period**:
- Ultra Long Period (ULP): ~>100 s (<0.01 Hz)
- Very long period (VLP): ~2-100 s (0.01-0.5 Hz)
- Long period (LP): ~0.2-2 s (0.5-5 Hz)
- Short period (SP): ~<0.2 s (>5 Hz)
**Amplitude**: Excess pressure ($p$) amplitudes are most frequently measured in pascals (Pa) and are often scaled back to a common distance, e.g. 1 km or 1 m, to indicate the equivalent excess pressure that *would* be recorded at 1 km ($r_{red} = 1000 \text{ m}$).

Local reduced pressure:

$$p_{red} = p \times \frac{r}{r_{red}}$$

At local distances ($r$), where sound propagation is approximated as spherical and pressure decays as $1/r$

Reduced pressure can be used to infer vent (source) overpressure

At regional or global distances atmospheric ducting (waveguide) causes a less rapid reduction in amplitude that is more like $r^{1/2}$.

Absorption (loss of energy into heat) is important at higher frequencies, longer distances, and various heights in the atmosphere.
Acoustic source energy: integrate acoustic intensity over time and surface through which it passes (e.g. sphere, hemisphere)

\[ E_a = \frac{4\pi r^2}{\rho c} \int_{0}^{T} \Delta p^2(t) dt \]

- \( r \) = source-receiver distance,
- \( \rho \) = air density,
- \( c \) = sound speed,
- \( \Delta p \) = change in pressure

Acoustic Power: Energy/time

**Tungurahua Eruption Notification - ASHE**

- **High**: Significant eruption in progress
- **Moderate**: Elevated activity, some ash
- **Low**: Background tremor and/or explosions, minor ash emissions

Fee et al., 2010
Array Processing → Detect coherent acoustic waves propagating across an array

- Deploy groups of microphones in systematic configuration
- Time delays between sensor pairs are then computed from waveform cross-correlation
- Determine signal azimuth ($\theta$), trace velocity ($v_t$), and other parameters
- Increase signal-noise ratio
- PMCC (Progressive Multi-Channel Cross Correlation)
  - Performed over multiple time segments and frequency bands
- Other methods used as well (MCCM, Fisher Statistic, Semblance, etc.)
Sound energy can be represented as rays refracting according to Snell’s Law. Rays often refract up, until $c_{\text{eff}}$ exceeds that at the source.

\[ c = \sqrt{\frac{\gamma RT}{\rho}} \quad c_{\text{eff}} = c + \vec{v} \cdot \hat{n} \]
Global network of infrasound arrays built to monitor for clandestine atmospheric nuclear tests
Detection of moderate-large volcanic eruptions common at multiple arrays
More permanent arrays being added
2009 Redoubt Eruption

>19 significant explosive events in 2009

DFR: Single Microphone → 12 km
IS53: 8-element infrasound array → 547 km
-also recorded at numerous other remote arrays (Kamchatka, Greenland, etc)

All significant explosive events clearly detected IS53

Very large amplitudes (>100 Pa at 12 km)
Many events have emergent onsets
High waveform similarity between local (red) and remote (black) stations
Principal source features apparent at 547 km (IS53) for most events
Redoubt – Strongly Ducted Infrasound

Deep atmospheric duct (waveguide) between ~40-60 km, likely responsible for high waveform similarity

Propagation influenced by stratospheric winds and source temperature (sound speed)

Ray tracing predicts a single ground reflection between source and receiver

- Sound energy passes through single caustic where rays intersect
- Hilbert transform (90 deg phase shift) improves cross-correlation up to 0.89
Local Infrasound Deployments (<10 km)

**Pros:**
- Wind/temperature gradients not as important → predictable propagation paths
- $1/r$ decay in pressure, essentially no loss to absorption
- Acoustic travel time is low
- Higher signal levels

**Cons:**
- Nonlinearity a possibility
- Anisotropic sources
- Reflections from craters, topography, etc.
- Often higher noise (windy) environments
- Increased chance of instrument loss during eruption
Hawaiian (Kilauea) Eruptive Activity

Hawaiian (Kilauea): long lived, low-level, least-explosive (effusive); also fountaining/fissure eruptions

MENE Array
- 4 infrasound elements
- 6.75 km → Halema`uma`u
- 12.5 km → Pu`u O`o
- Dense Jungle

Kilauea Volcano, Hawaii
- 2007 Puu Oo Crater
- 2007 East Rift Zone Fissure Eruptions
- 2008-mid 2009 Halema'uma'u Crater
- Local infrasound array
Helmholtz Resonance - Halemaumau

2008 Halemaumau Crater, Hawaii

Visible and audible "breathing" during degassing

Dominant Oscillation Frequency: ~0.5 Hz (2 sec)

Agrees well with dominant infrasound frequency

Video provided by Matt Patrick, HVO

~40 m
Halemaumau Tremor and Resonance

**Tremor Frequency Spectra**

Very stable tremor peaks at 0.55 Hz ($f_1$), secondary at 3 Hz ($f_2$)

Dominant tremor frequency ($f_1$) matches the oscillation frequency of the gas emanating from the vent observed by video

**Cavity Resonance**

Persistent degassing magma at bottom of chamber excites volume into Helmholtz and acoustic resonance

$f_1$: Helmholtz Resonance - Air forced in/out of a cavity through a “neck”

$$f_H = \frac{c}{2\pi} \sqrt{\frac{S_a}{L_H}}$$

$f_2$: Standing Wave Resonance - Natural frequencies of vibration

$$f_m = \frac{mc^2}{2L}$$

### November 2008:

Volume estimated from $f_1$ (~$3 \times 10^6$ m$^3$)

Depth estimated from $f_2$ (~217 m), consistent with LIDAR (T. Ericksen, pers. communication)

Fee et al., 2010
21 July 2007: Kilauea ERZ Fissure Eruption

Fissure Rupture
A: 10:06-13:15
   Most intense degassing
B-C: 13:15–16:00
   ~307 m/hr
D: 20:00-23:00
   Total: ~13 hours
   and 164 m/hr
Consistent with visual and deformation data
Seismically quiet

Fee et al., 2011
Flow Induced Resonance

Puʻu ʻŌʻō crater, April 2007

Aeroacoustic loop frequency \( f_a \)

\[
\frac{L}{U} + \frac{L}{c} = \frac{1}{f_a}
\]

\( L \) = distance between the jet nozzle and solid boundary
\( U \) = jet velocity
\( c \) = sound speed

Matoza et al., 2010

Broadband tremor (>1 Hz) can be modeled by oscillating bubble clouds.
Spectral peaks may result from low velocity gaseous jet impinging on a boundary with a hole.
   - The boundary acts to disrupt the gas flow and create self-sustaining vortices.
   - Realistic degassing parameters at Puʻu ʻŌʻō crater in early 2007 gives frequencies consistent with those recorded (~0.2-1 Hz).

Numerous other types of flow-induced resonance may be present at volcanoes.
Strombolian Eruptive Activity

Strombolian: episodic release of discrete gas accumulations. Lower overpressure at surface $\rightarrow$ “puffing”. High overpressure $\rightarrow$ bubble/slug burst and “explosion”

Stromboli:

a) short-duration explosions (~3-5 s) with relatively large amplitudes (20-80 Pa at 350 m)

b) longer duration (5-15 s), more complex explosions with lower peak amplitudes (10-30 Pa at 350 m) [Ripepe and Marchetti, 2002].

Both explosive styles occur on a periodic basis and have repeatable (stable) waveforms primarily in the LP band.

Similar short duration, impulsive, relatively low amplitude signals observed at other volcanoes (Erebus, Villarica, Karymsky, etc.)
Volcano Acoustic Source Modeling

Lighthill’s Acoustic Monopole Source (assuming compact source and linear wave propagation)

\[ p(r,t) = \frac{Q(t - r/c)}{2\pi r} \]

Where \( p(r,t) \) is the excess pressure (in Pa) and \( Q \) is the source strength, or density x “volumetric acceleration” (in kg/s²) of the atmosphere

Not valid for Multipole/Anisotropic sources

Erebus infrasound example... converting raw infrasound to volumetric flux and then bulk gas outflux

[Johnson et al., 2008]
Vulcanian: discrete degassing episodes similar to Strombolian, but involve higher overpressure and degree of magma fragmentation.

Fuego - short-duration Strombolian/Vulcanian explosions generate intense, short-lived infrasound transients, which are relatively broad band in character. Almost all acoustic energy is released during these short events when acoustic power reaches ~100,000 W. Long-term averaged acoustic power is ~2200 W.
Reventador, Ecuador

Tremor is commonly recorded from volcanoes that display strombolian/vulcanian activity.

Reventador - continuous degassing giving rise to ~500-m-high vapor plume. Infrasound is dominated by harmonic tremor (‘chugging’), which produces consistent levels of sound and sound power (~4000 Watts) until shutting off.
**Subplinian-Plinian Eruptive Activity**

**Subplinian-Plinian:** high-energy, sustained eruptions producing massive eruption clouds that may extend well into the stratosphere and cause extensive ashfall.

- Spectrum shifts to low frequency (<0.1 Hz) during stratospheric ash emission.
- Ash plume >25 km high and over 200 km wide.
- Acoustic power/energy scales with ash height.

Fee et al., 2010

GOES Satellite Image
Jet Noise

Sound from large volcanic jets similar to turbulence-related sound from man-made jets [Matoza et al. 2009]

Tam et al. [1996]: two empirically derived similarity spectra to fit two characteristic spectra

- Small Scale Turbulence (SST) – dominant in subsonic jets (broad spectrum)
- Large Scale Turbulence (LST) – instability waves moving downstream generating mach waves (sharper frequency roll-off)

Spectrum scales with Strouhal number (St)

Strouhal Number: 

\[ St = \frac{f D_j}{U_j} \]

\( f = \) the peak jet noise frequency, \( D_j = \) expanded jet diameter, \( U_j = \) jet velocity

Peak St similar for pure-air, experimental jets (~0.19)
Volcanic Jetting Spectra

Mount St. Helens spectra resemble LST spectra
Tungurahua spectra similar for all 3 eruptions, LST fits best

“Notch” in Tungurahua spectra

Roll-off for Tungurahua 7/14 and 8/17 does not match as well

Complexities
- Interactions with crater
- Volcanic jets multiphase, high temp
- Propagation
- Anisotropic source

Jetting coincident with high-altitude ash emissions

[Red=LST, Gray=SST]

[Matoza et al., 2009]
Signal focused in VLP (0.01-0.1 Hz) band

Four pulses detected:
1: 2159 UTC, 123 min
2: 0135 UTC, 59 min
3: 0420 UTC, 33 min
4: 0654 UTC, 112 min

Significant low frequency infrasound coincident with high altitude ash emissions

Spectra of three main pulses resemble that of man made jets (solid gray)

Minor variations in spectra between eruption pulses
- Negligible effect of ash particles in jet

Highly correlated at three stations with similar spectral shape
- Frequency-dependent propagation effects similar between stations

Fee et al., 2010
Pyroclastic Density Currents (PDC)

PDCs: dangerous lateral flows of hot gas and particles

PDCs have been detected and tracked at Mt. Unzen, Japan [Yamasato et al., 1997] and Soufriere Hills Volcano, Montserrat [Ripepe et al., 2010]

Turbulent flow likely produces sound (similar to jet noise?)

Relatively unstudied and unknown acoustic source models

Often marked by concurrent jetting
Seismic LP “drumbeat” events at MSH also produced acoustic counterparts.

Seismic LP modeled as the resonant response of a fluid-filled cavity excited by an impulsive broadband pressure excitation.

Infrasonic LP modeled as a record of the broadband pressure excitation (trigger) mechanism initiating the resonance. Resonant component weakly couples to atmosphere through dome/uncosolidated material into atmosphere.
Historically large eruptions (Pinatubo, Mount St. Helens) produced pressure oscillations $>100$ s

Thought to result from large input of mass or thermal energy into atmosphere

Often seen as concentric cloud patterns in satellite imagery

Recent improvements in instrumentation and greater diversity of recordings show moderate eruptions capable of producing ULP signals (SHV, Redoubt, etc.)
Infrasound and SO$_2$

2009 Redoubt:
Very good correlation between cumulative infrasound energy (black) and daily SO$_2$ estimates (red)
Relationship between SO$_2$ production and infrasound energy not well understood
Potential to use remote infrasound arrays as real-time detector of elevated SO$_2$ (and ash?)

Pacaya
Degassing estimates from UV camera agreed to an order of magnitude with infrasound-derived SO$_2$ estimates
Longer term degassing rates did not agree as well

Dalton et al., 2010
References/Acknowledgements

Two upcoming review papers/book chapters:


Selected volcano infrasound papers cited here:


