Volcano Infrasound

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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

Kilauea Volcano (Courtesy HVO)

Tungurahua Volcano (Courtesy IG)

Infrasound – What is it?

Sound waves (pressure waves) below ~20 Hz

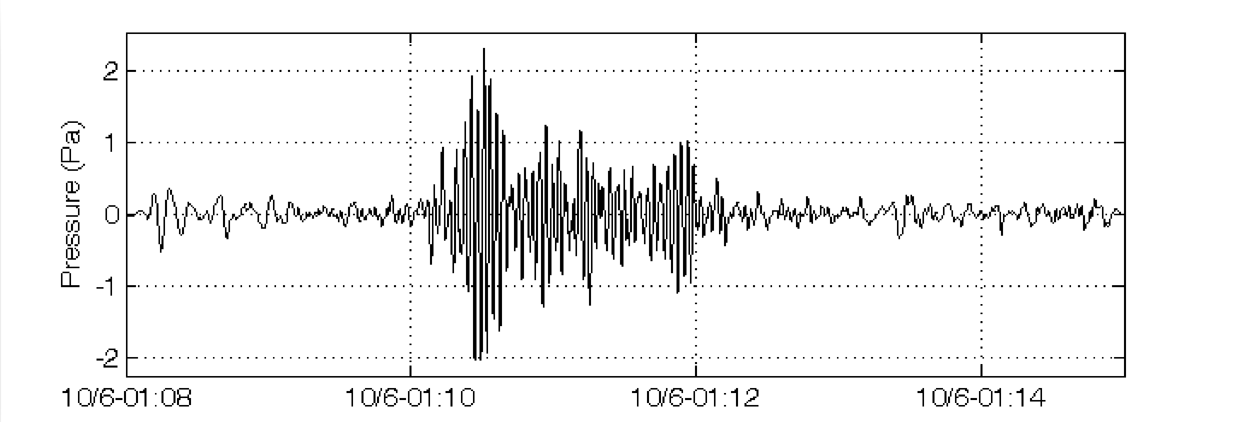
- Low amount of attenuation → propagate long distances

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

$$p(t) = s(t) * l(t) * g(t)$$

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

→ 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)

Infrasound Magnitudes - Amplitude

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 ($r_{red} = 1000\ m$).

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

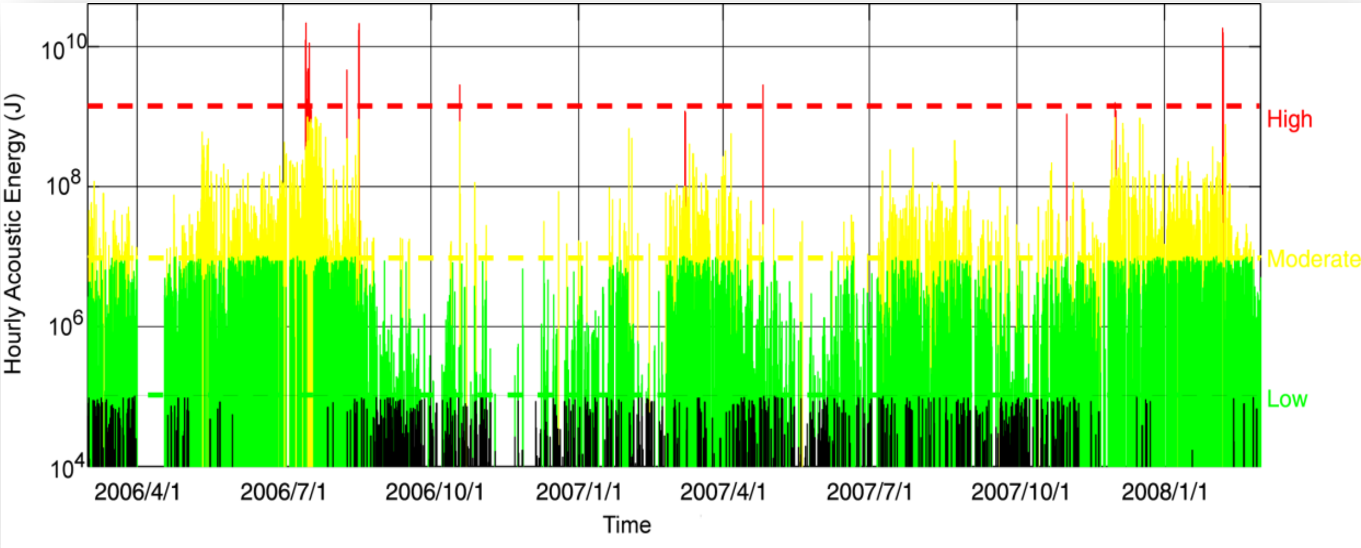
Infrasound Magnitudes - Energy

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, ρ=air density, c=sound speed, Δp=change in pressure

Acoustic Power: Energy/time



Fee et al., 2010

Tungurahua Eruption Notifcation - ASHE

Hourly Acoustic Energy

High: Significant eruption in progress

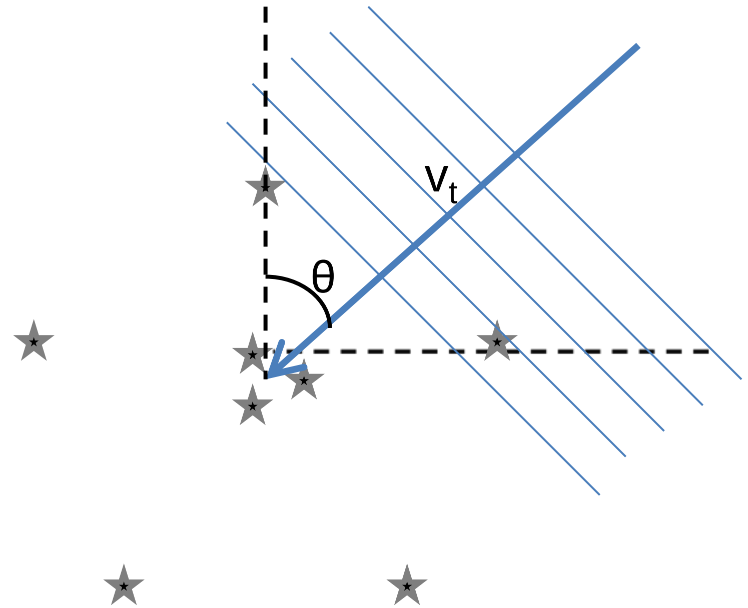
Moderate: Elevated activity, some ash

Low: Background tremor and/or explosions, minor ash emissions

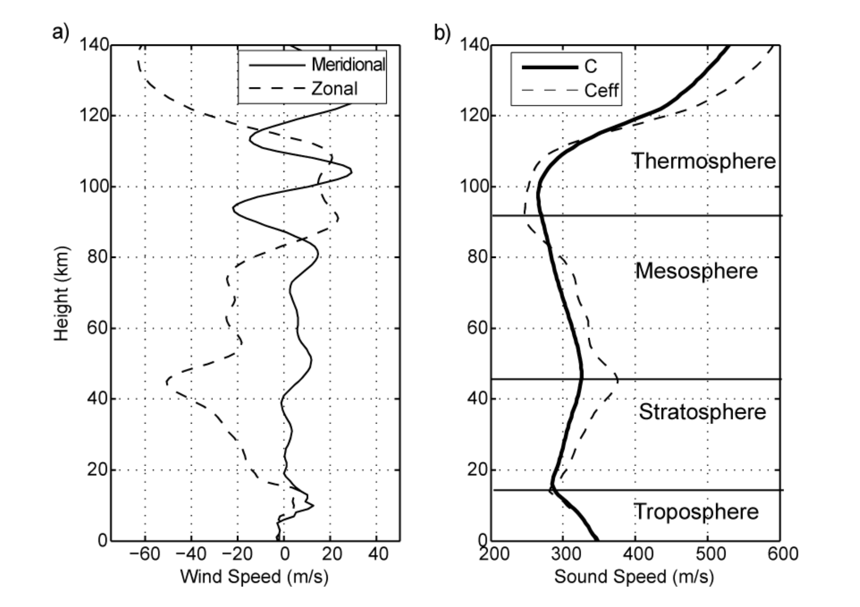
Infrasound Arrays and Array Processing

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 (θ), 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.)



Infrasound Propagation - Long Range (>200 km)



Strong zonal (east-west, positive easterly) wind jet changes c_{eff}

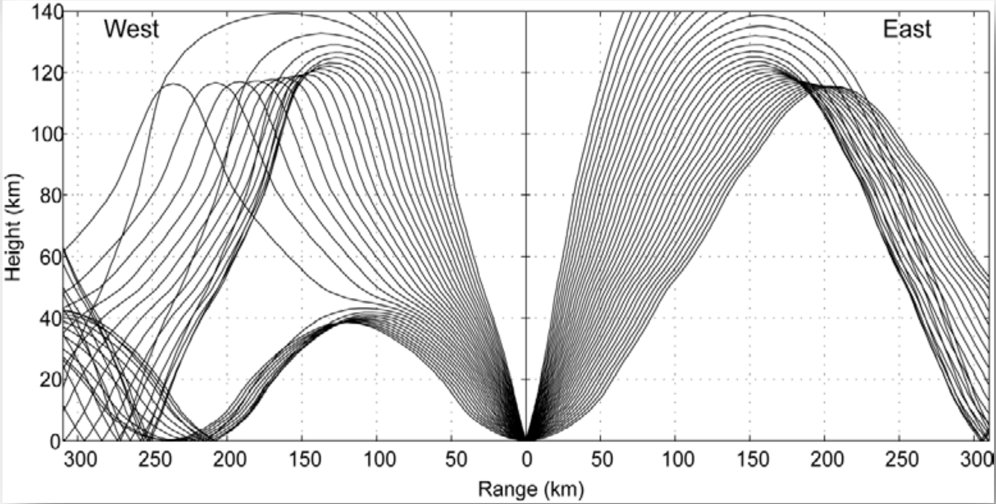
Sound propagating east refracted down around 115 km (thermospheric)

Sound propagating west refracted around 115 km (thermospheric) and 40 km (stratospheric)

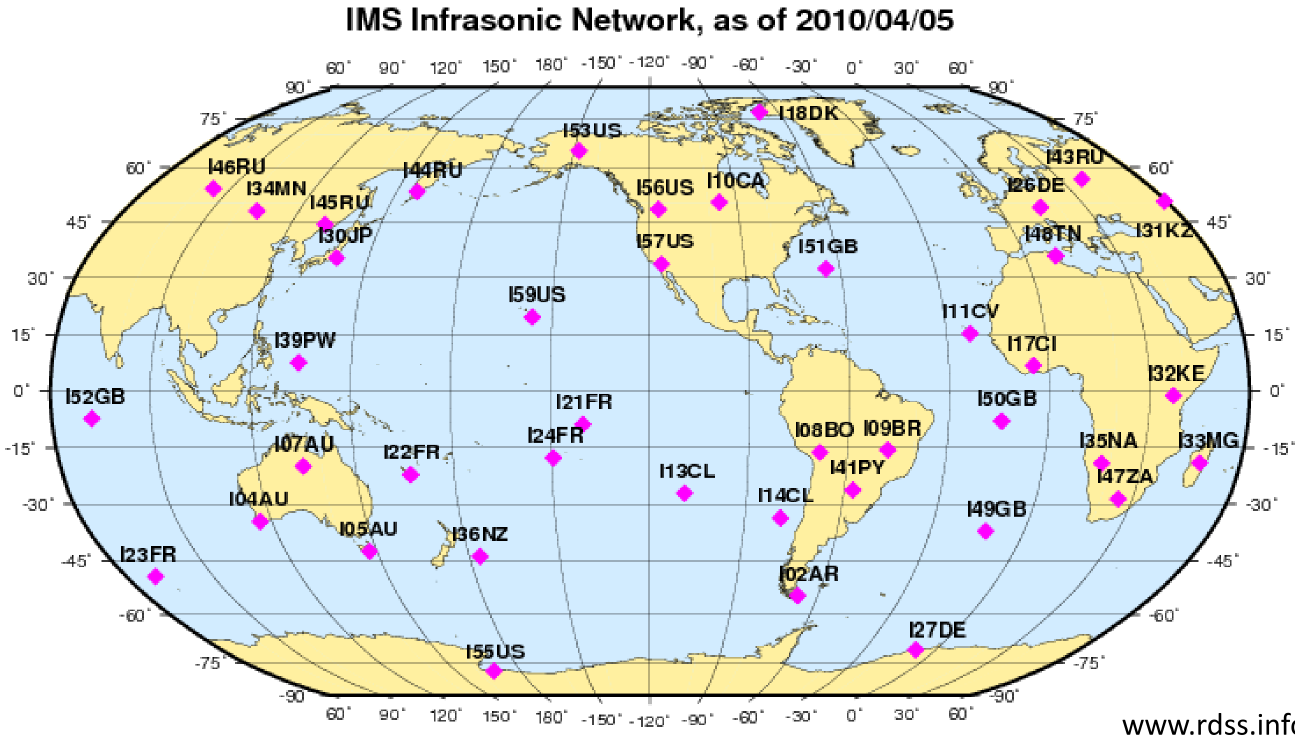
Sound energy can be represented as rays refracting according to Snell's Law

Rays often refract up, until c_{eff} exceeds that at the source

$$c = \sqrt{\gamma RT} \qquad c_{eff} = c + \vec{v} \bullet \vec{n}$$



Global Infrasound Network - CTBTO



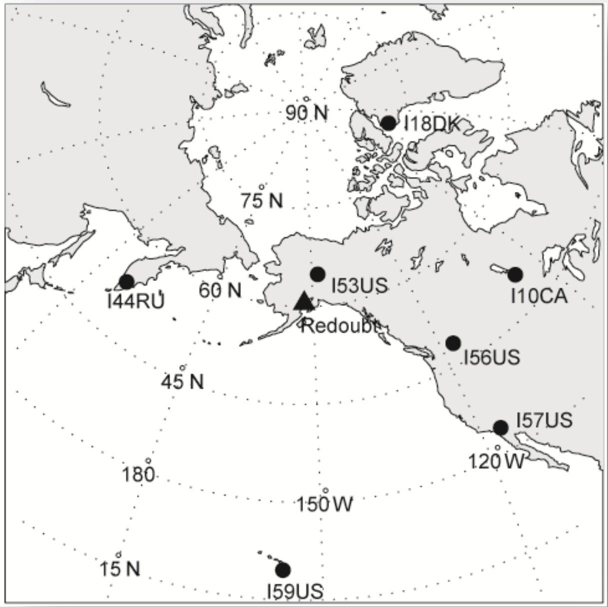
www.rdss.info

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

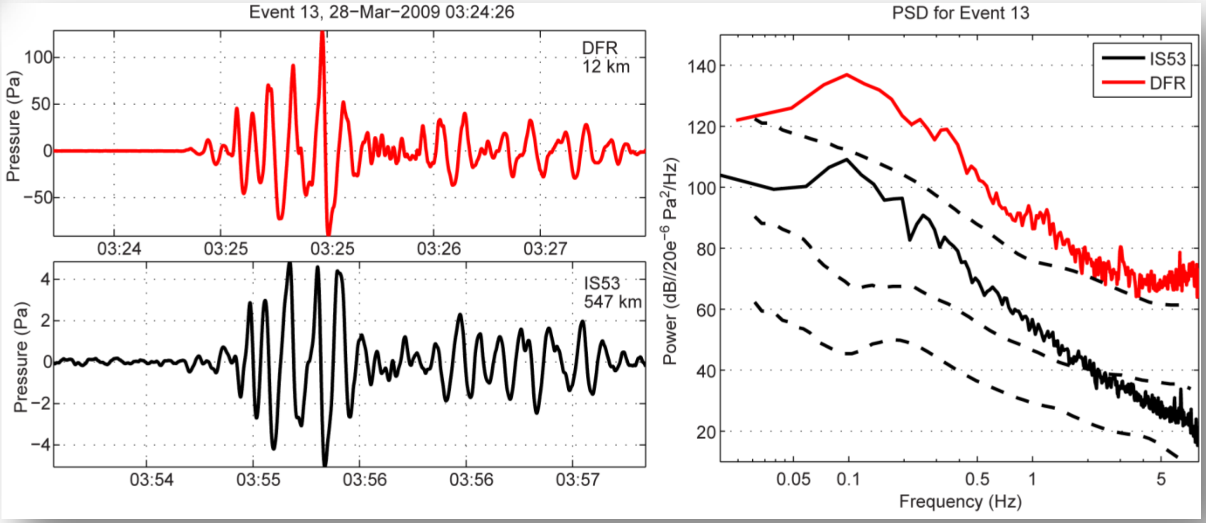
DFR: Single Microphone→12 km

IS53 : 8-element infrasound array → 547 km

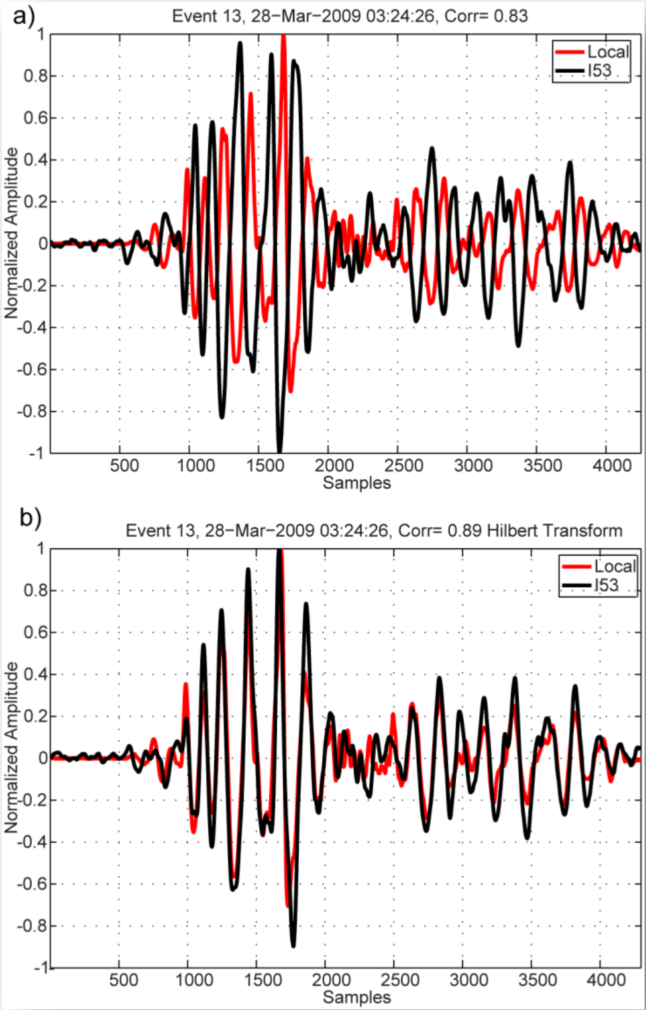
-also recorded at numerous other remote arrays (Kamchatka, Greenland, etc)

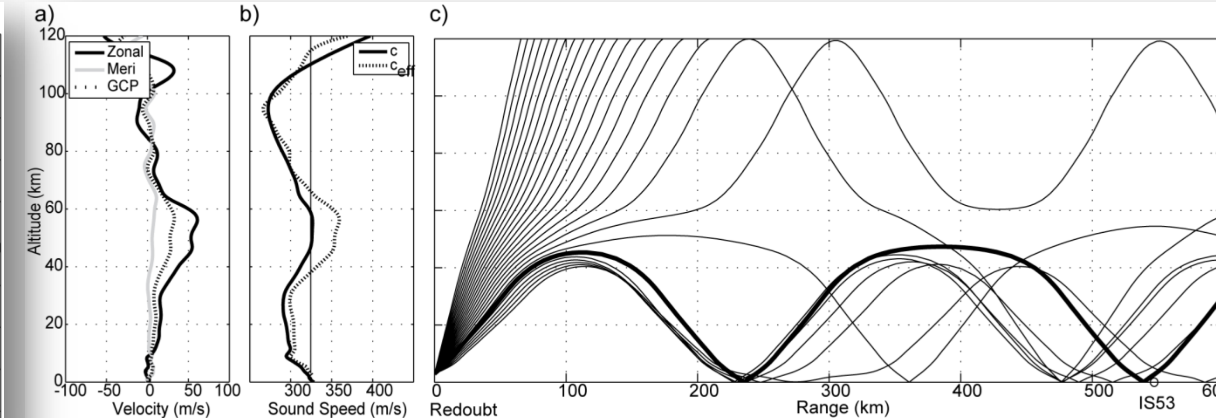
All significant explosive events clearly detected IS53

- 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

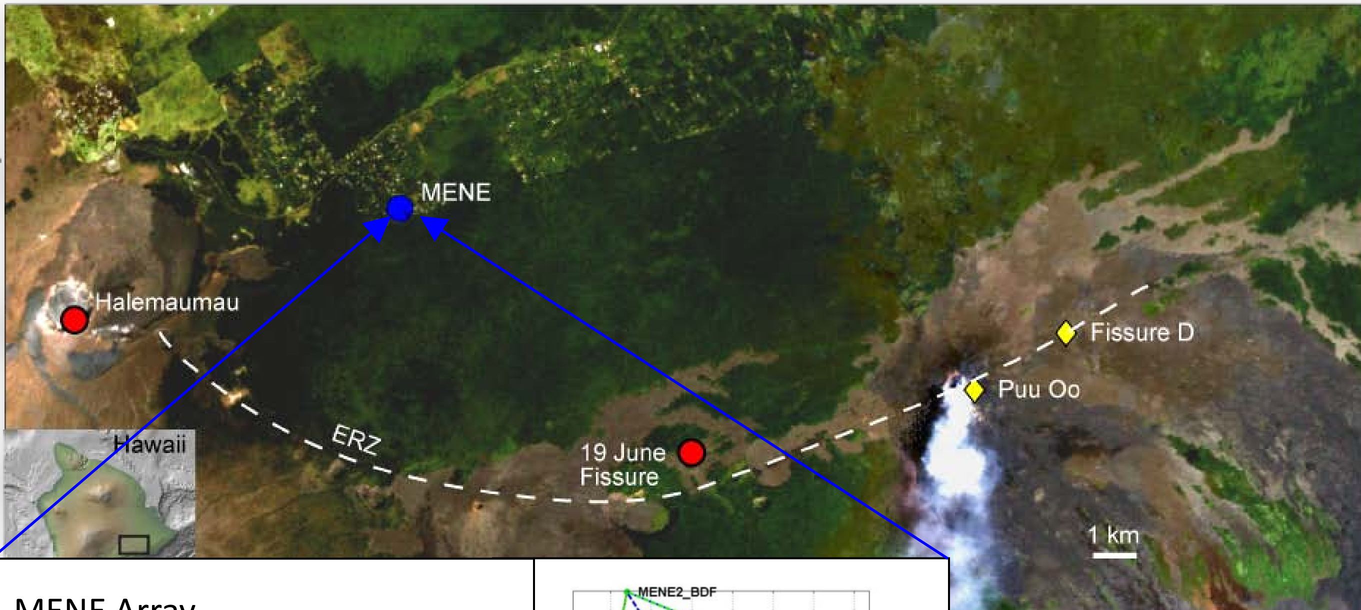
Reflections from craters, topography, etc.

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



Kilauea Volcano, Hawaii

2007 Puu Oo Crater

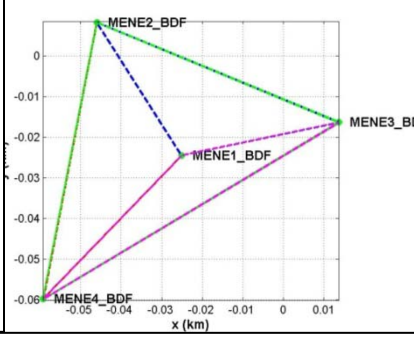
2007 East Rift Zone Fissure Eruptions

2008-mid 2009 Halema'uma'u Crater

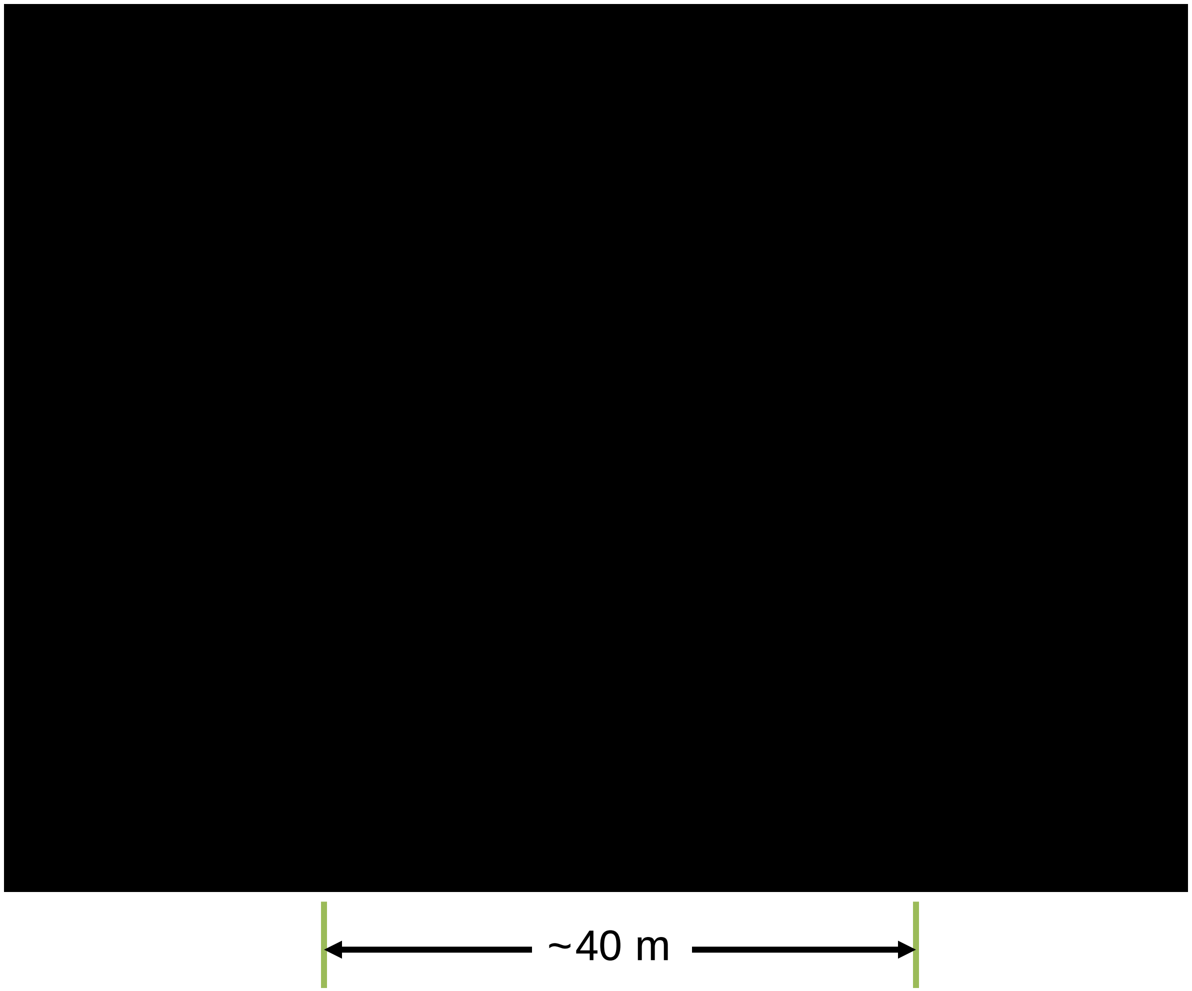
Local infrasound array

MENE Array

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



Helmholtz Resonance - Halemaumau



Video provided by Matt Patrick, HVO

2008 Halemaumau Crater, Hawaii

Visible and audible "breathing" during degassing

Dominant Oscillation Frequency:

~0.5 Hz (2 sec)

Agrees well with dominant infrasound frequency

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

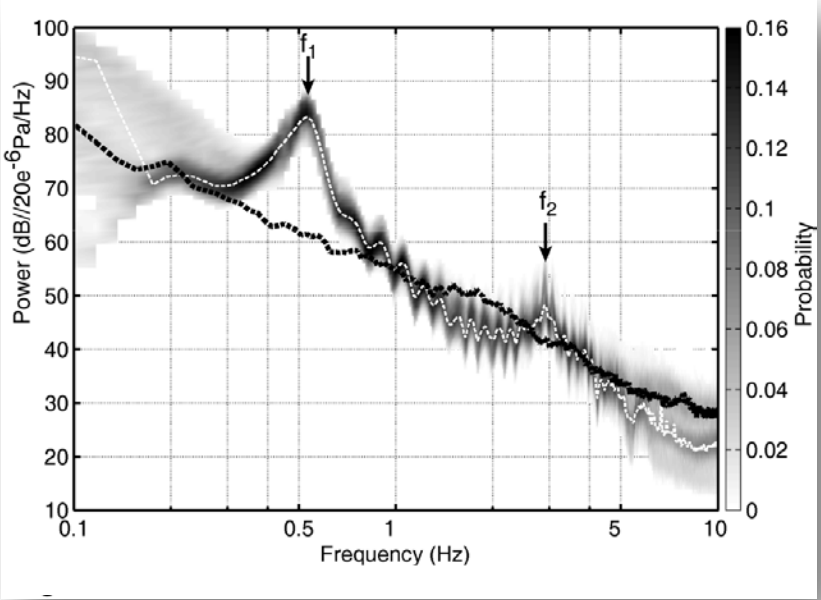
Persistent degassing magma at bottom of chamber excites volume into Helmholtz and acoustic resonance

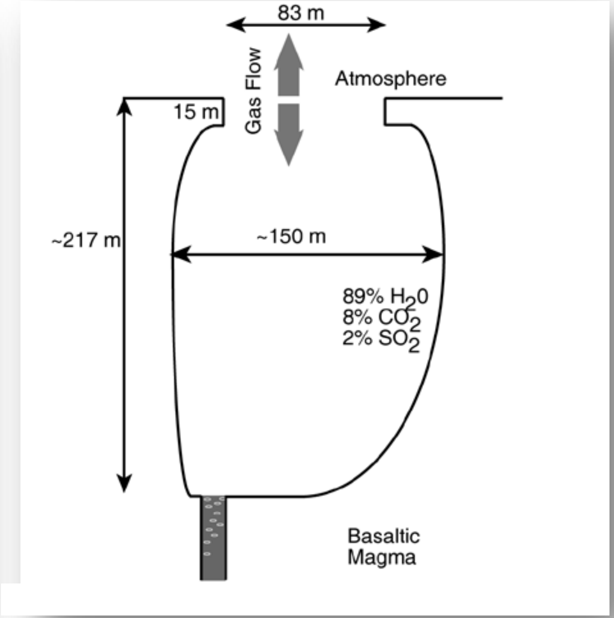
f_1: Helmholtz Resonance - Air forced in/out of a cavity through a "neck"

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

f_2: Standing Wave Resonance -Natural frequencies of vibration

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





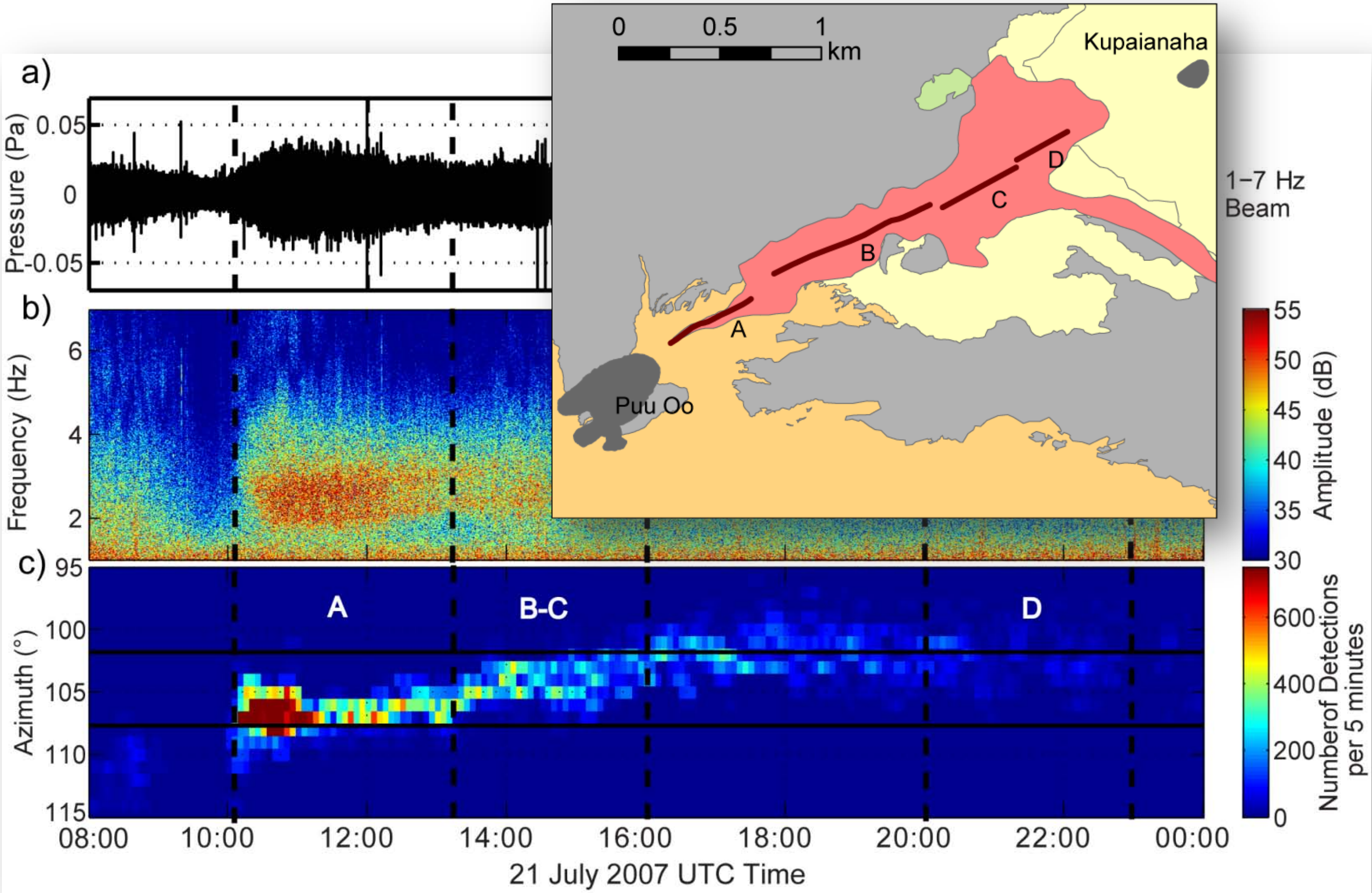
November 2008:

Volume estimated from f_1 (~3 × 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



Fee et al., 2011

Fissure Rupture

A:10:06-13:15
Most intense degassing

B-C: 13:15–16:00
~307 m/hr

D: 20:00-23:00

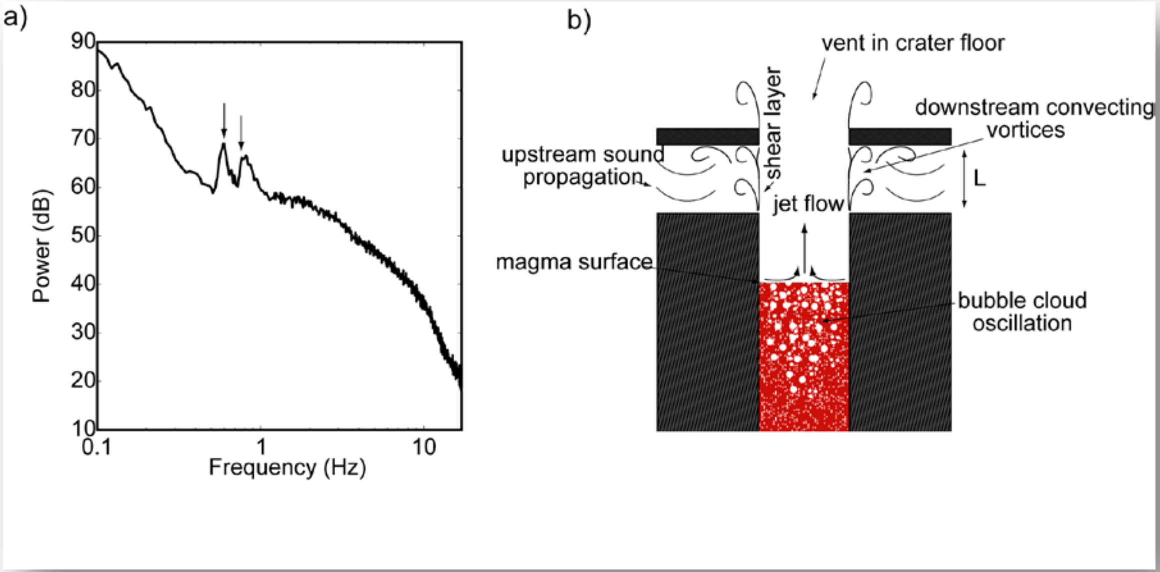
Total: ~13 hours and 164 m/hr

Consistent with visual and deformation data

Seismically quiet

Flow Induced Resonance

Pu‘u ‘Ō‘ō crater, April 2007



Matoza et al., 2010

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

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 Pu‘u ‘Ō‘ō 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→ "puffing". High overpressure→ bubble/slug burst and "explosion"

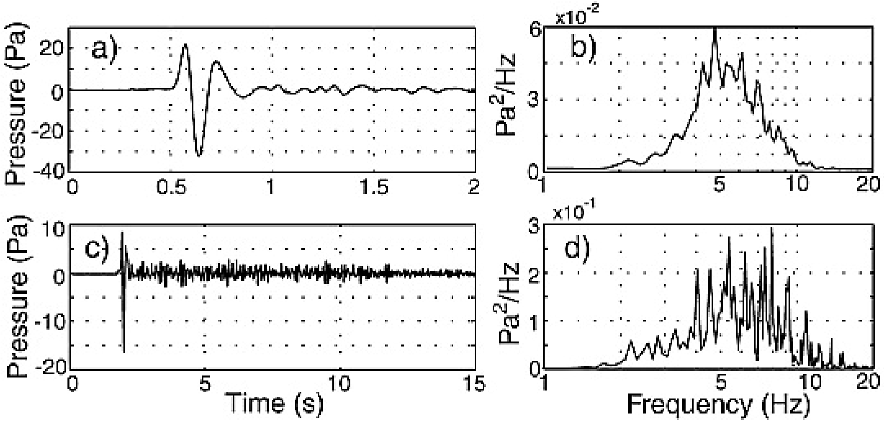
Stromboli:

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.)



[Ripepe and Marchetti, 2002]

Volcano Acoustic Source Modeling

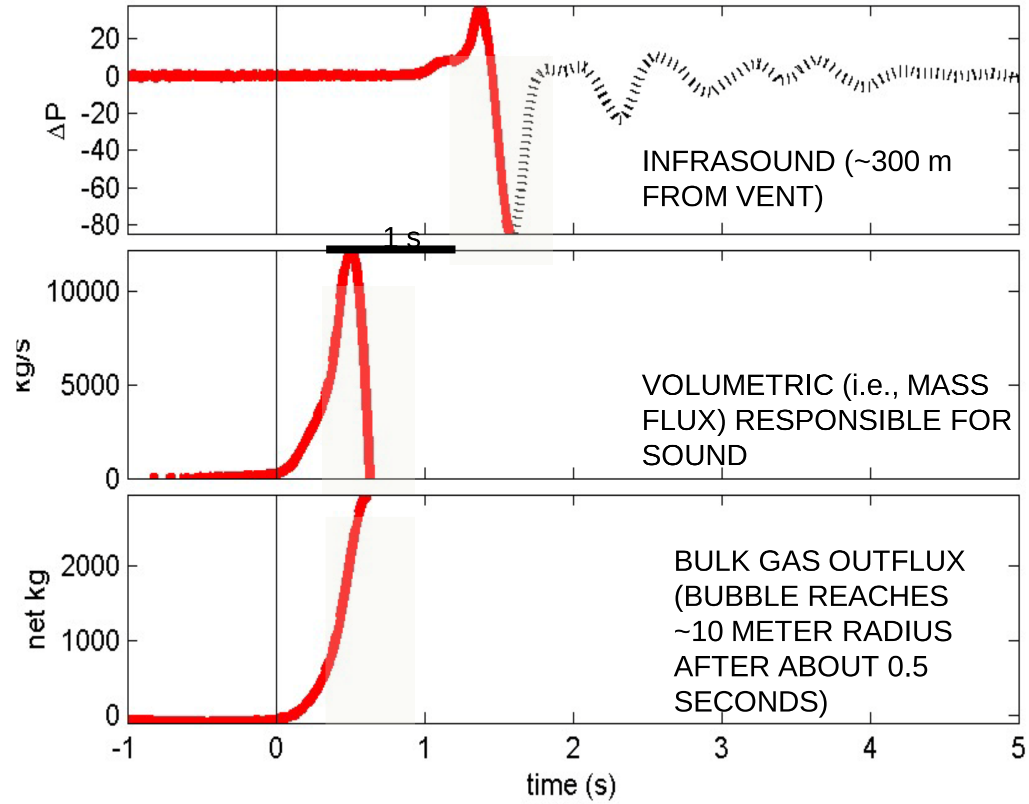
Lighthill's Acoustic Monopole Source (assuming compact source and linear wave propagation)

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

Where *p(r,t)* is the excess pressure (in Pa) and *Q* is the source strength, or density x "volumetric acceleration" (in kg/s^2) of the atmosphere

Not valid for Multipole/Anisotropic sources

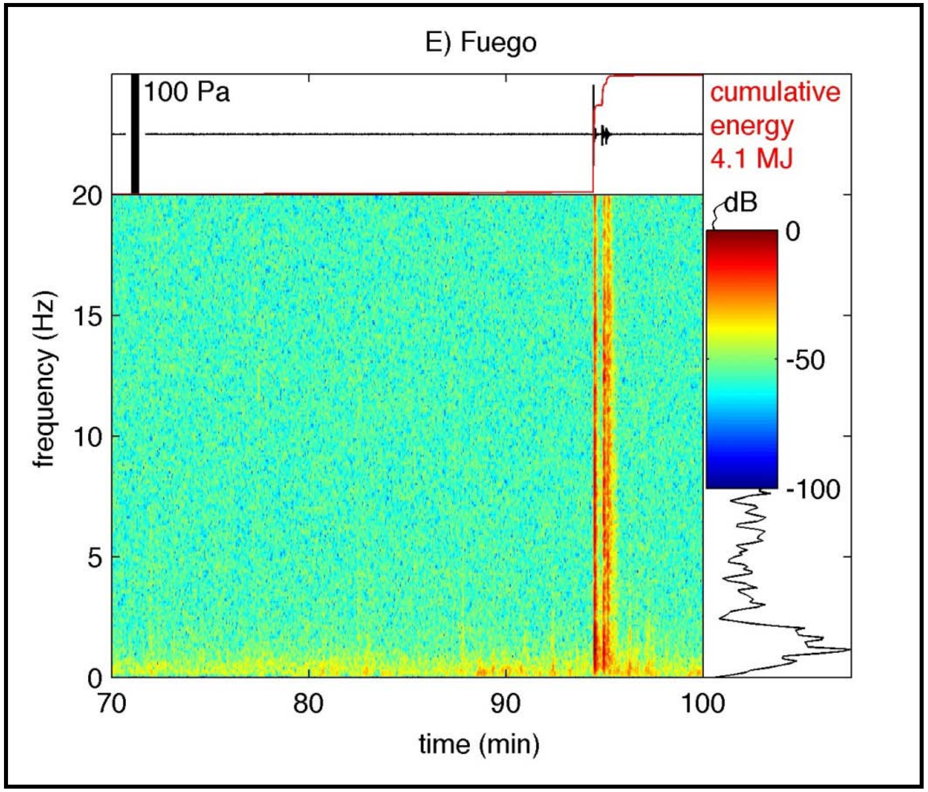
Erebus infrasound example… converting raw infrasound to volumetric flux and then bulk gas outflux

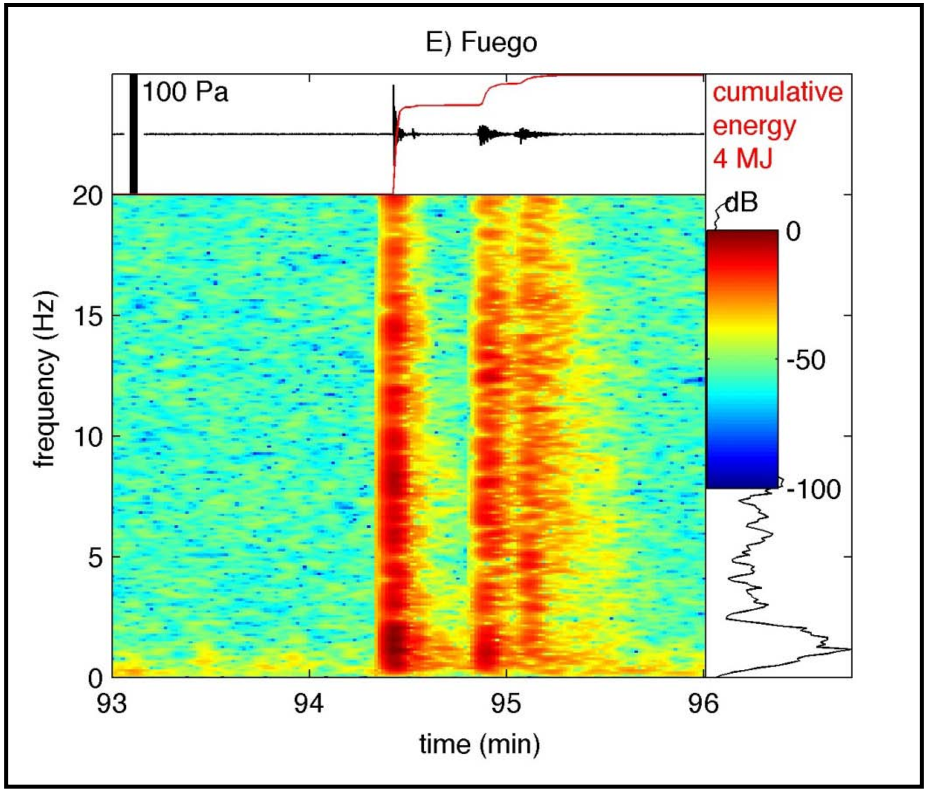


[Johnson et al., 2008]

Vulcanian Eruptive Activity

<u>Vulcanian:</u> discrete degassing episodes similar to Strombolian, but involve higher overpressure and degree of magma fragmentation

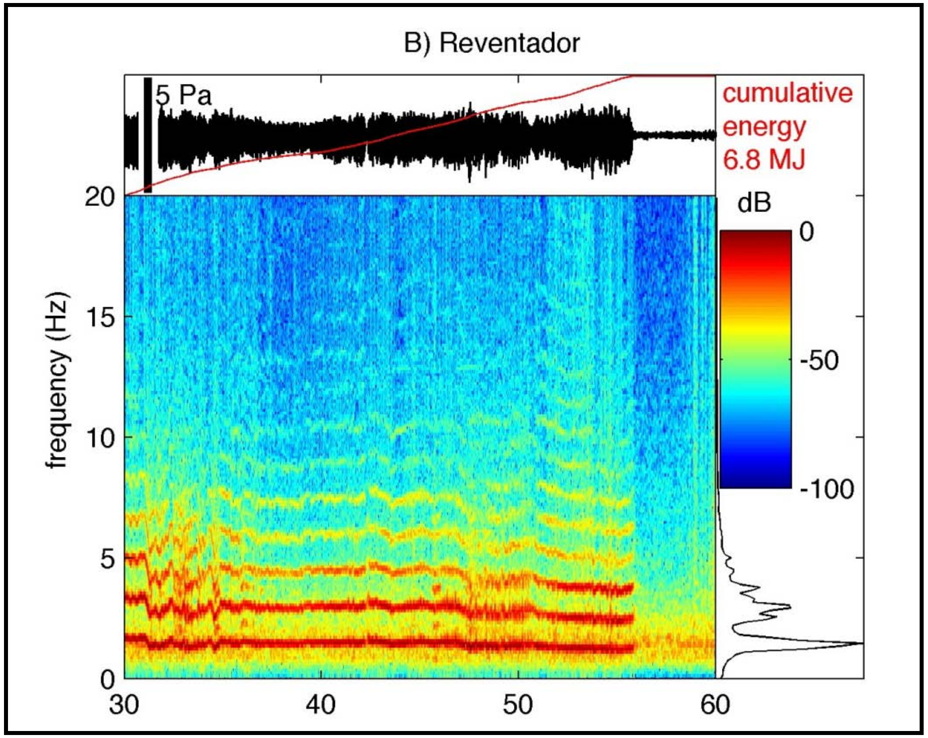


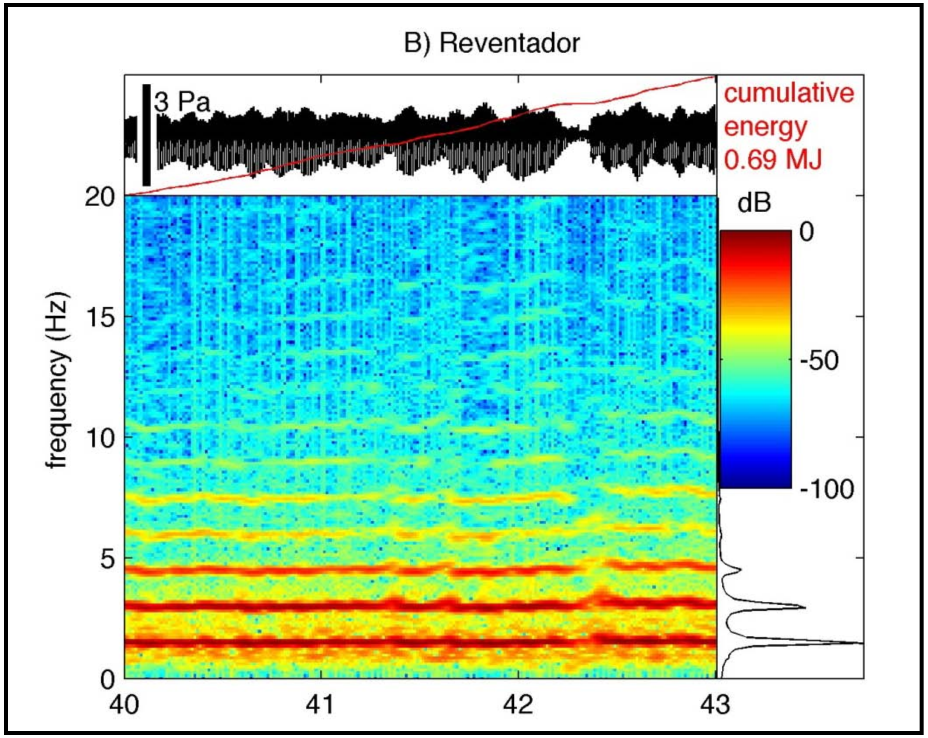


Fuego - short-duration Strombolian/Vulcanian explosions generate intense, short-lived infrasound transients, which are relatively broad band in character. Almost all acoustic energy is released during these short events when acoustic power reaches ~100,000 W. Long-term averaged acoustic power is ~2200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

Reventador, Ecuador

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

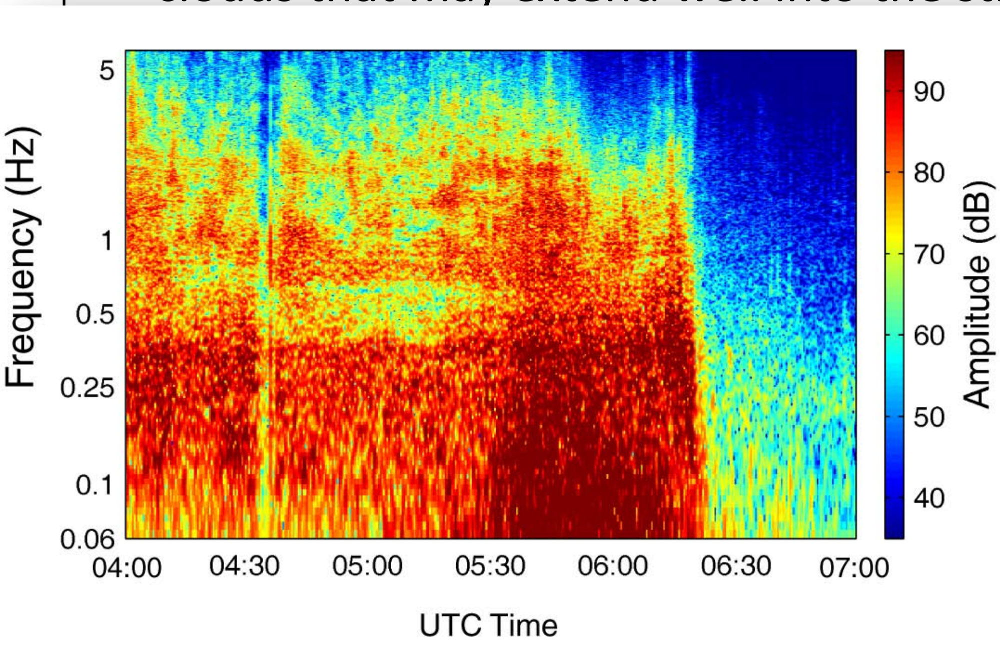


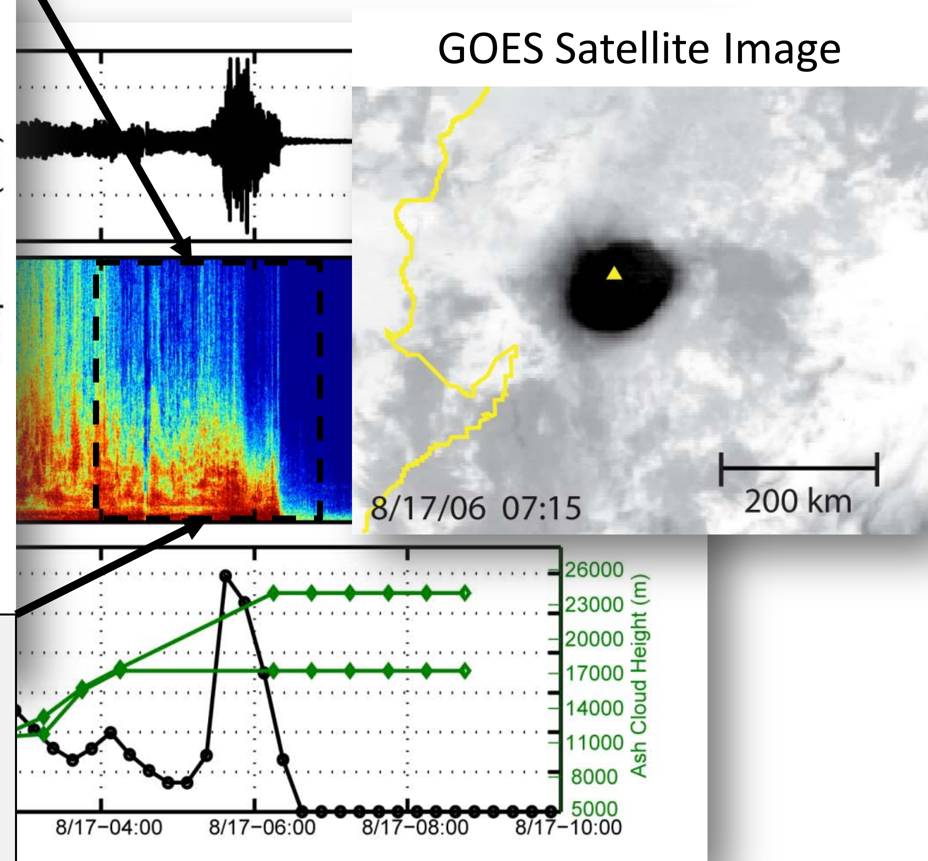


Reventador - continuous degassing giving rise to ~500-m-high vapor plume. Infrasound is dominated by harmonic tremor ('chugging'), which produces consistent levels of sound and sound power (~4000 Watts) until shutting off.

Subplinian-Plinian Eruptive Activity

<u>Subplinian-Plinian:</u> 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

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)

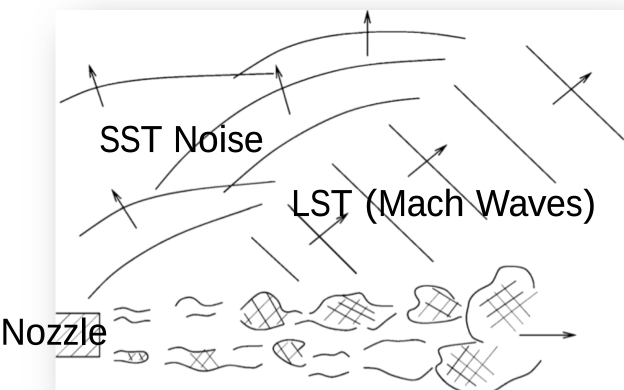
Spectrum scales with Strouhal number (*St*)

Strouhal Number:

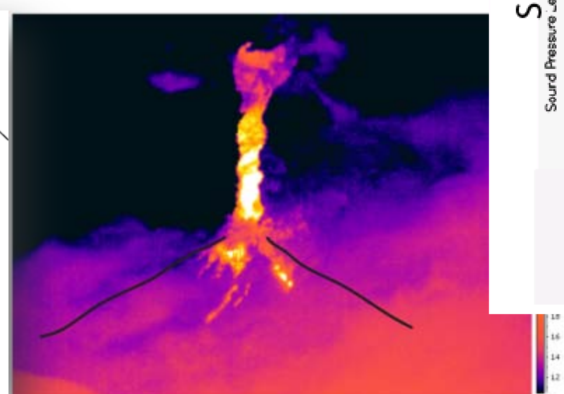
$$St = \frac{fD_j}{U_j}$$

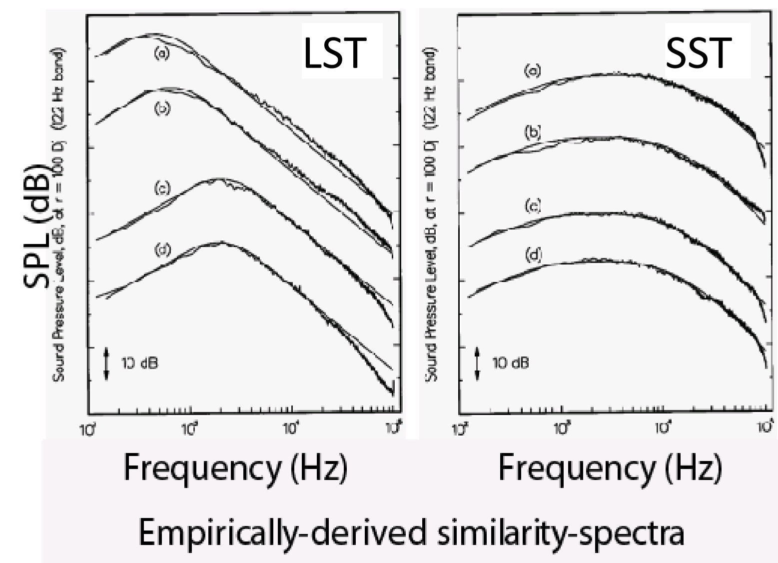
f=the peak jet noise frequency, D_j=expanded jet diameter, U_j=jet velocity

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



[Tam et al. 09]





[Tam et al. 96]

Volcanic Jetting Spectra

Mount St. Helens spectra resemble LST spectra

Tungurahua spectra similar for all 3 eruptions, LST fits best

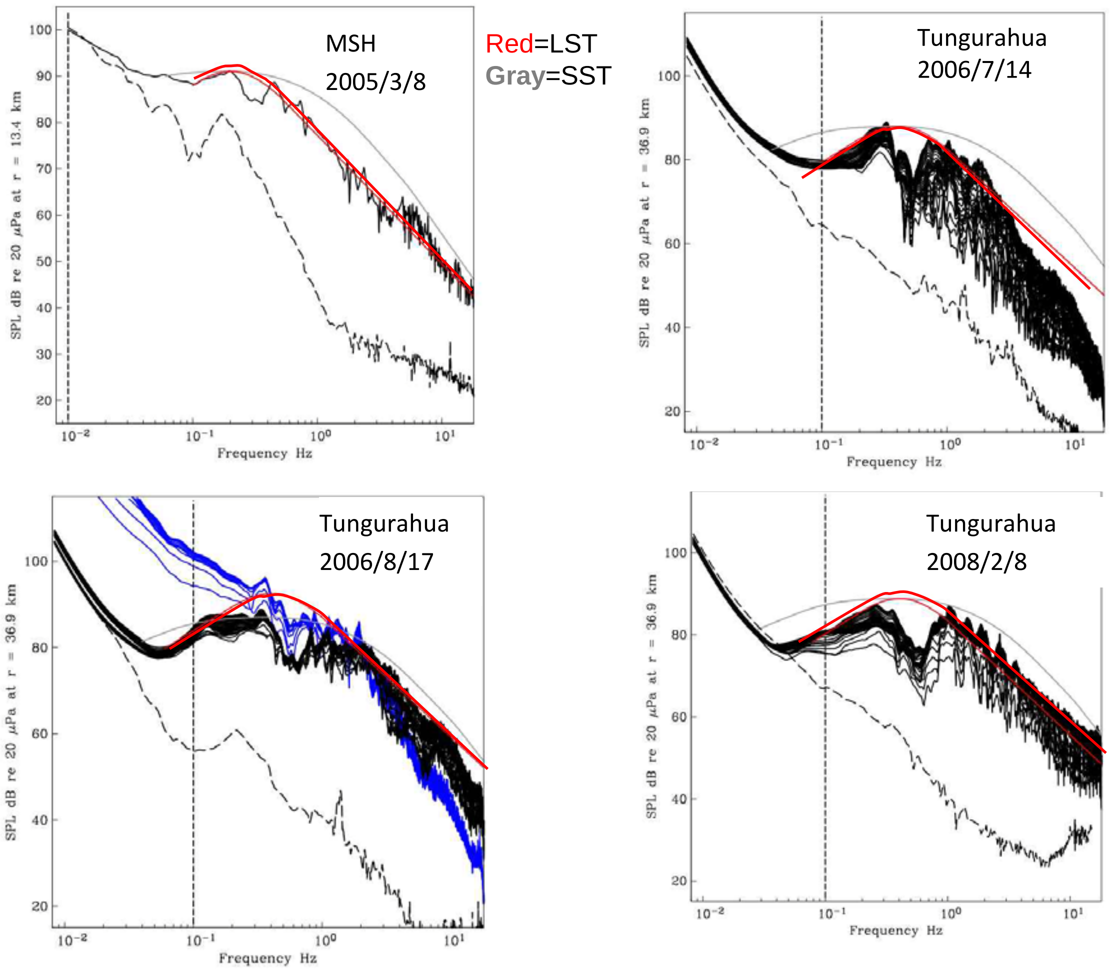
“Notch” in Tungurahua spectra

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

Complexities

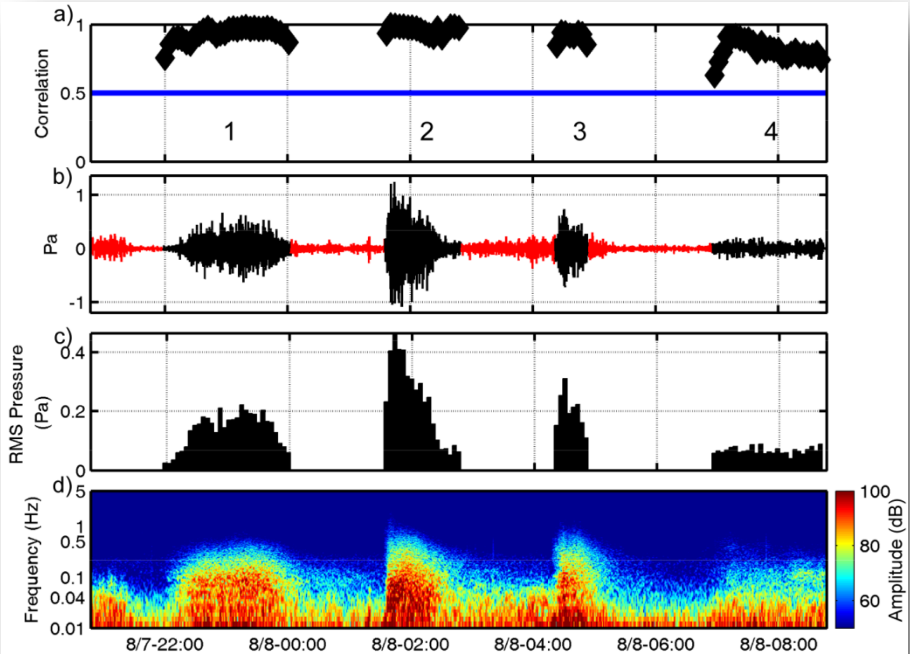
- -Interactions with crater
- -Volcanic jets multiphase, high temp
- -Propagation
- -Anisotropic source

<u>Jetting coincident with high-altitude ash emissions</u>



[Matoza et al., 2009]

2008 Kasatochi, Alaska Eruption



Fee et al., 2010

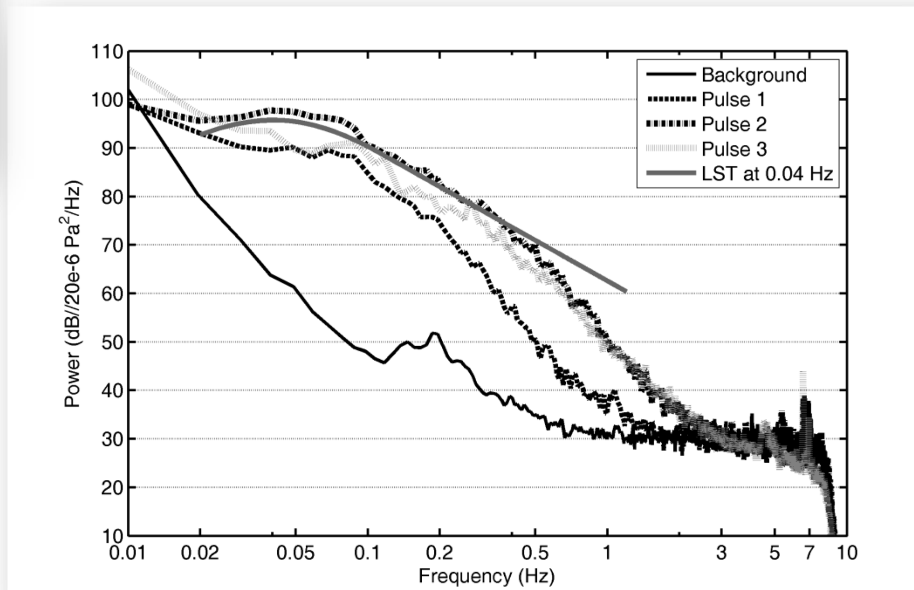
Spectra of three main pulses resemble that of man made jets (solid gray)

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



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

Pyroclastic Density Currents (PDC)

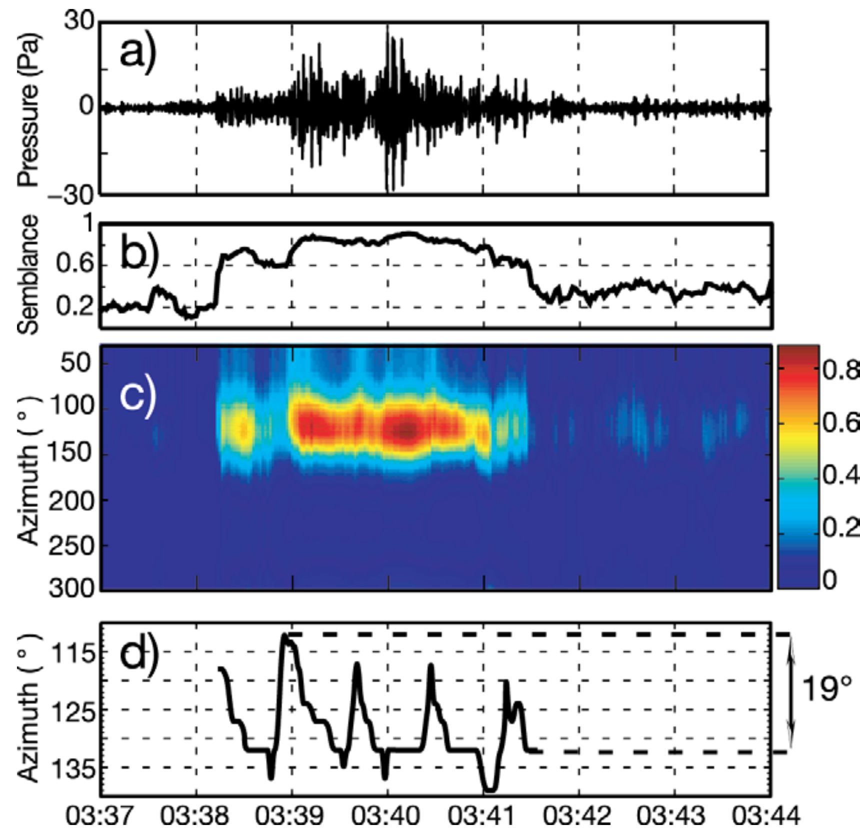
PDCs: dangerous lateral flows of hot gas and particles

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

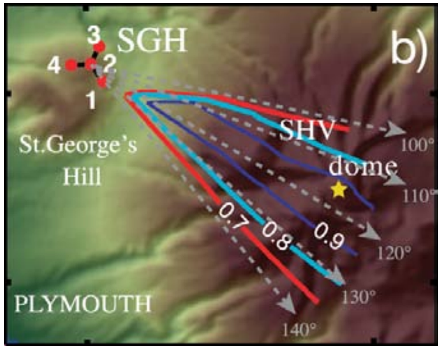
Turbulent flow likely produces sound (similar to jet noise?)

Relatively unstudied and unknown acoustic source models

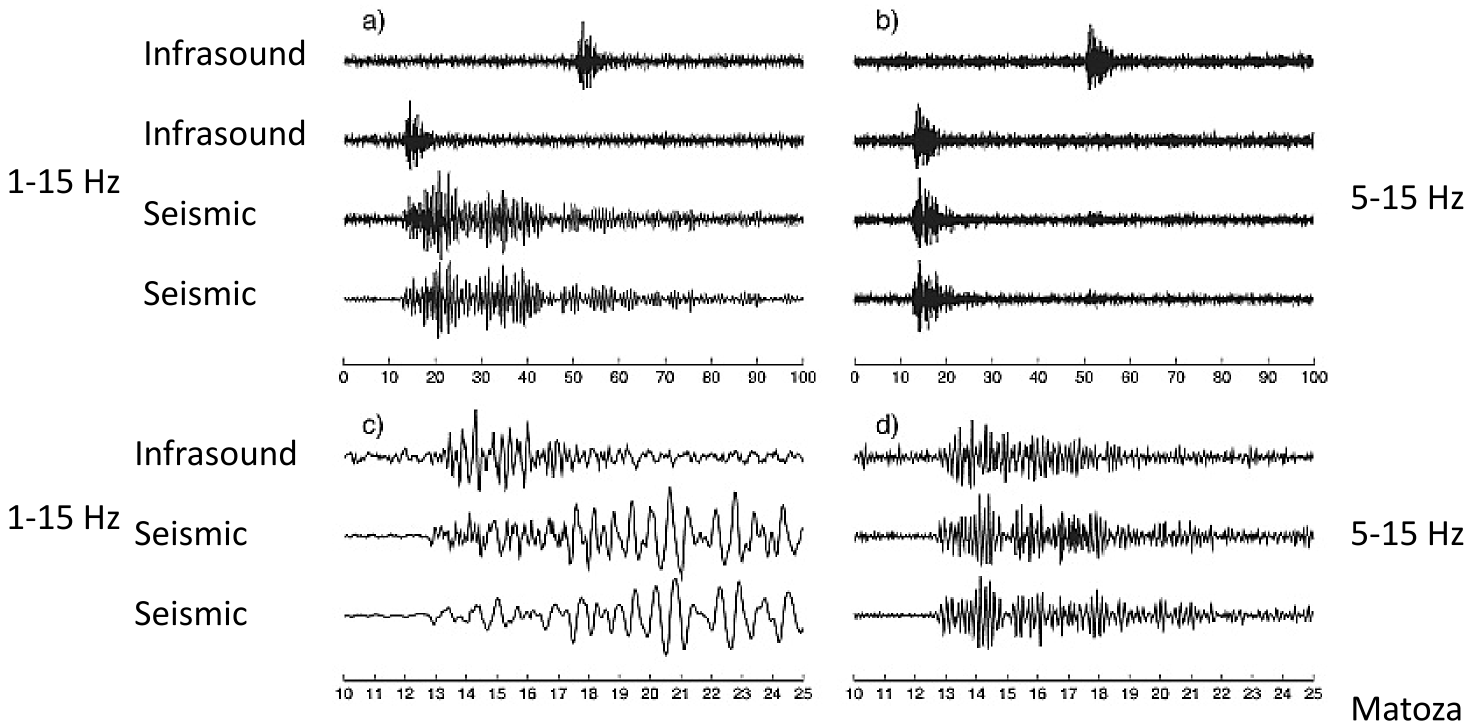
Often marked by concurrent jetting



Ripepe et al., 2010



LP (Long Period) Events – Mount St. Helens



Matoza et al., 2009

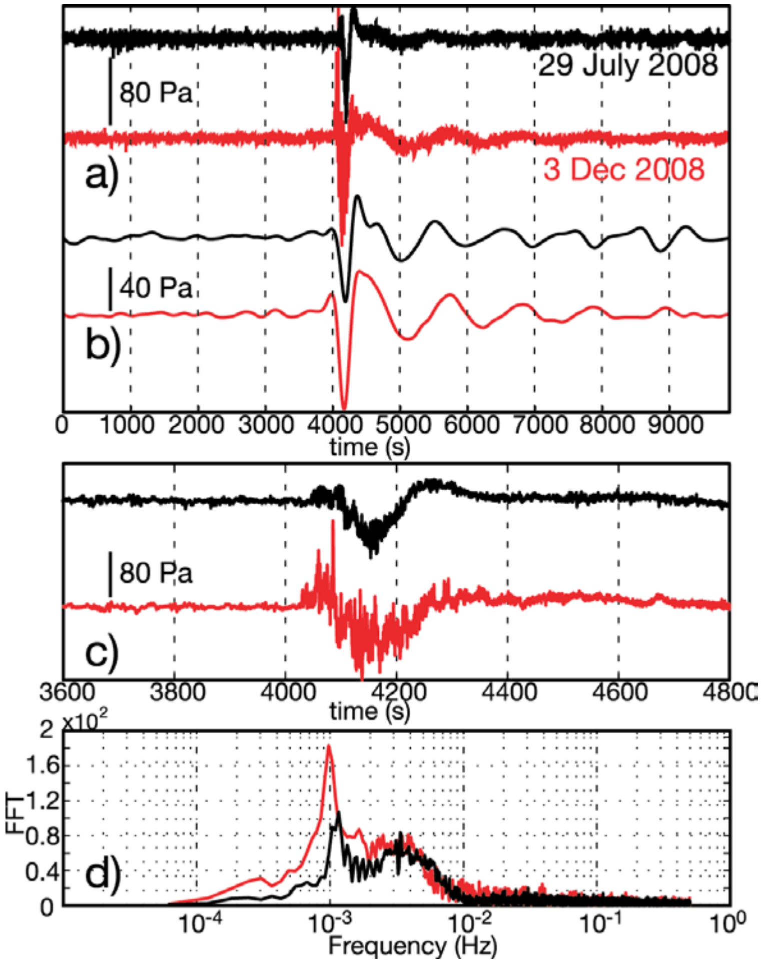
Seismic LP "drumbeat" events at MSH also produced acoustic counterparts

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.

Ultra Long Period (ULP) Infrasound and Acoustic-Gravity Waves

Soufriere Hills Volcano

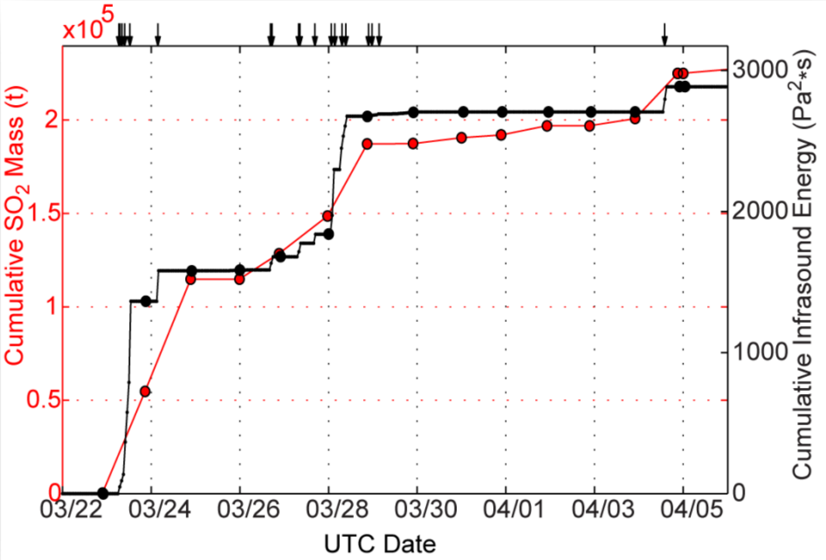


Ripepe et al., 2010

- 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.)

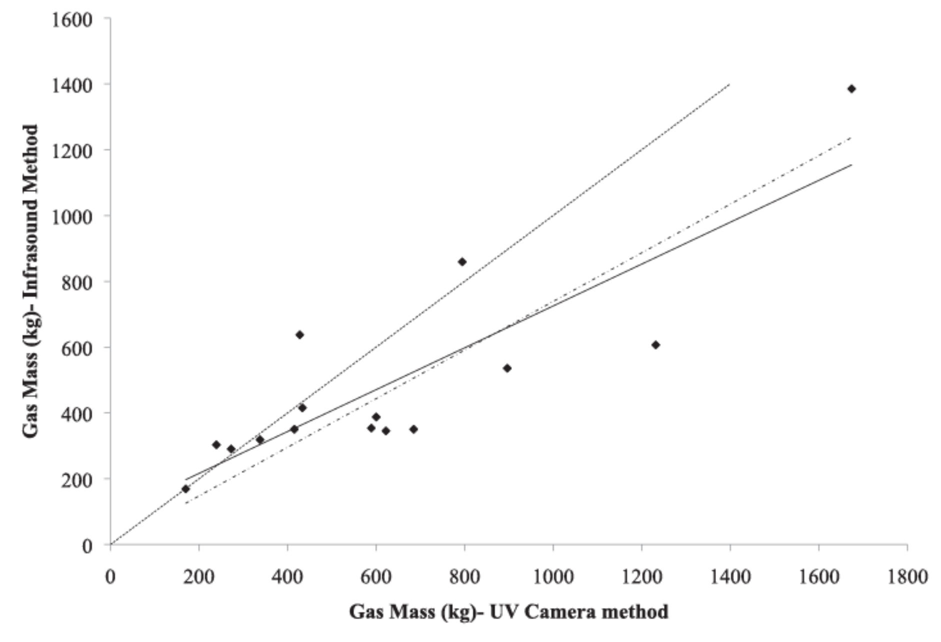
Infrasound and SO_2



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

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?)

References/Acknowledgements

Two upcoming review papers/book chapters:

Garces, M., D. Fee, and R. S. Matoza (in press), Volcano Acoustics, in *Modeling Volcanic Processes: The Physics and Mathematics of Volcanism*, edited by S. A. Fagents, T. K. P. a. Gregg and R. C. Lopez, Cambridge Univ Press.

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