RECENT PROGRESS AND FUTURE OPPORTUNITIES IN VOLCANO MONITORING USING INFRASOUND

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INFRA SOUND – WHAT IS IT?

• Sound waves (pressure waves) at frequencies lower than humans can hear
• Similar to P-wave in seismology, except through the atmosphere
• Low amount of energy loss and atmospheric winds permit long-range propagation
• Not restricted by clouds, but affected by wind and temperature in the atmosphere
INFRASOUND RECORDING AND PROCESSING

- Bearing and wave velocity estimate
- Remote detection
- Often part of global network

>5 km

200 m

Array

- High-resolution detection and localization
- Typically close to source (low latency)
- Determine eruption source parameters

Network
Goal: detect and locate atmospheric explosions of at least 1 kt TNT-equivalent yields with >2 stations
**VOLCANO INFRA SOUND**

- Infrasound produced by flux of material into atmosphere
- Used to detect, locate, characterize, and quantify eruptive activity
- Infrasound signals indicative of eruption mechanisms
- Readily combined with other datasets

![Infrasound Diagram](brittanica.com)
SHORT DURATION EXPLOSIONS

Pressure (Pa)

- Mount St. Helens
  - r = 13.4 km

- Mount St. Helens
  - r = 13.4 km

- Karymsky
  - r = 3.8 km

- Tungurahua
  - r = 36.9 km

- Augustine
  - r = 3.2 km

[Fee and Matoza, 2013]
SUSTAINED ERUPTIONS - VOLCANIC JET NOISE

- Similarities between sustained infrasound from large volcanic eruptions with the sound from jet engines [e.g. Matoza et al., 2009; Fee et al., 2013]
- Spectral shape and frequency can potentially be used to derive jet velocity, diameter, composition, etc.

Jet Engine
Volcanic Jet

[Tam et al. 2009]  [Mt. Spurr- 1992]

[Jet Engine]  [Volcano]

[Matoza et al., 2009]
**UNIQUE INFRASOUND SIGNATURES**

<table>
<thead>
<tr>
<th></th>
<th>Ash Explosions</th>
<th>Pulsatory Degassing</th>
<th>Gas Jetting</th>
<th>Explosive Eruption</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak T (°C)</td>
<td>230</td>
<td>160</td>
<td>80</td>
<td>&gt;350</td>
</tr>
<tr>
<td>IS Pressure (Pa)</td>
<td>±5.4</td>
<td>±0.13</td>
<td>±0.05</td>
<td>&gt;125</td>
</tr>
<tr>
<td>IS Waveform</td>
<td>Impulsive Discrete</td>
<td>Emergent Discrete</td>
<td>Emergent Continuous</td>
<td>Impulsive Discrete</td>
</tr>
<tr>
<td>IS Frequency</td>
<td>0.3-10 Hz</td>
<td>0.5-10 Hz</td>
<td>~10-100 Hz</td>
<td>0.1-10 Hz</td>
</tr>
<tr>
<td>SO₂ ER (kg/s)</td>
<td>0.63±0.4</td>
<td>*1.40±0.1</td>
<td>1.0±0.3</td>
<td>0.71±0.6</td>
</tr>
<tr>
<td>Ash Mass (kg)</td>
<td>NA</td>
<td>0</td>
<td>0</td>
<td>&gt;69,000</td>
</tr>
</tbody>
</table>

- Lopez et al. [2013] identified 4 main types of eruptive activity at Karymsky Volcano, Kamchatka
- Each type had distinguishing features
- Future work will attempt to quantitatively identify and model these sources
ERUPTION MONITORING: ACOUSTIC SURVEILLANCE FOR HAZARDOUS Eruptions (ASHE)

- Test viability of monitoring remote volcanic regions using infrasound
- Multiple collaborators teamed with local institute (IG) and Washington VAAC

[Fee et al., 2010]

- Intense, low frequency, sustained infrasound coincident with high-altitude ash emissions
- Identifiable based on spectral shape and frequency content (jet noise)
- Autonomous ASHE notification system successful in detecting and notifying authorities during 6 February 2008 Tungurahua eruption
ERUPTION MONITORING: CLEVELAND VOLCANO, AK

- One of the most active and remote volcanoes in the Aleutian arc
- Mostly small, ash-producing eruptions <9 km
- Before 2014:
  - no real-time, local, seismic network due to logistical challenges (closest seismic station is 75 km)
  - primarily monitored using remote sensing

Okmok: 150 km, 245°
Akutan: 315 km, 245°
DLL (Dillingham): 992 km, 230°
IS53 (Fairbanks): 1827 km, 233°

Photo courtesy Cyrus Read, AVO
From: David Fee dfee@gi.alaska.edu
Subject: Cleveland Volcano Dillingham Infrasound Detection Alert: 13-Apr-2012 1600 - 13-Apr-2012 1700 UTC
Date: April 13, 2012 10:08:14 AM PDT
To: David Fee <dfee@gi.alaska.edu>, volcanodoctor@gmail.com, Silvio De Angelis <silvio.deange@gmail.com>, 9073478599@txt.att.net, 9079782561@txt.att.net, 9073220676@txt.att.net, Colin Rowell <rownell.colinr@gmail.com>

Cleveland Volcano Dillingham Infrasound Detection Alert
Dillingham Infrasound Array, 992 km from source
Dillingham Detection Time: 13-Apr-2012 16:54:27 UTC
Approx. Origin Time: 13-Apr-2012 16:02:47 UTC
Max Pressure Amplitude: 0.143 Pa
Max Fisher Ratio: 237

Dec 2011 – Aug 2012 Detections:
~7/20 in satellite imagery
19/20 events with infrasound

Automated detections trigger alerts to AVO personnel

[De Angelis et al., 2012]
Matoza et al. [2011] found remote infrasound arrays (640-6400 km) provide most detailed eruption chronology.

Correlates well with eruption chronology from satellite data.

High signal-noise at IS44, Kamchatka (640 km northeast).
Dabrowa et al. [2011]: comprehensive study on IMS volcano infrasound observations

1) recorded distance increases with ash plume height

2) lowest detected infrasonic frequency decreases with increasing plume height

3) total acoustic energy and distance-corrected amplitude increase as a function of plume height
2009 REDOUBT VOLCANO ERUPTION

• Erupted 23 March - 4 April 2009
• >19 explosive eruptions (events)
• Ash plumes to 19 km
• Significant pyroclastic flows, lightning, and seismicity
• Relative proximity to Anchorage and North Pacific air routes

• DFR: Single infrasound sensor @ 12 km
• IS53: 8-element infrasound array @ 547 km
• All significant explosive events clearly detected IS53
• Unique opportunity to compare local and remote data and examine long-range propagation

[Fee et al., 2013]
• Compute cross-correlation between local and remote data
• Propagation modeling predicts 90° phase shift, improves cross-correlation to 0.89
• Remote infrasound can provide good representation of local infrasound

[Fee et al., 2013]
• Very good correlation between cumulative infrasound energy (black) and daily SO$_2$ estimates (red)

• Relationship between SO$_2$ production and infrasound energy still being explored

• Potential to use remote infrasound arrays as real-time detector of elevated SO$_2$ (and ash?)

[Fee et al., 2013]

[Lopez et al., 2013]
CURRENT PROGRESS: GLOBAL CATALOGING OF EXPLOSIVE VOLCANISM

- Goal: Search infrasound data from multiple infrasound arrays to identify volcanic signals recorded consistently (associated) across multiple stations
- Method: Association and location via brute force grid-search cross-bearings approach
- Project led by Robin Matoza (UCSB)

Example location: ± 5° longitude, latitude
CURRENT PROGRESS: GLOBAL CATALOGING OF EXPLOSIVE VOLCANISM

- Example: Sarychev Peak
  - 4 stations
  - 11-16 June 2009

- Example: Eyjafjallajökull
  - 14 stations
  - 14 April - 1 June 2010
Simplified view of an infrasonic signal:

\[ p(x, t) = G_0(x, t; x_0, t_0) \cdot Q(t) \]

- **Acoustic pressure**
- **Green’s Function** (propagation)
- **Volume flux** (monopole source strength)

\[ M = Q \]

- **Mass flux** (kg/s)
- **Volume Flux** (m^3/s)
- **Flow Density** (kg/m^3)

- Time-dependent flow density needed to convert volume flux to mass flux
- Waveform inversion to solve for volume flux [e.g. Ohminato et al., 1998]
- 3-D Finite Difference Time Domain modeling needed to solve Green’s function

[Sakurajima Volcano, Japan](#)

[Kim and Lees, 2014]
Excellent waveform fit to observations
Source time history (volume flux)
  - 3-D Green's function: smoothly decreasing
  - Half-space Green's function: oscillatory curve
First acoustic inversion with computed, 3-D Green’s functions
Volume/mass flux critical parameter for hazard mitigation

Using 3-D numerical Green's function

Using half-space Green's function

[Kim et al., 2015]
CONCLUSIONS

• Explosive volcanoes produce prodigious, varied infrasound signals indicative of the style of eruption
• Infrasound is produced by flux of material out of the vent
  ➡Permits real-time estimate of volume flux
• Infrasound correlates qualitatively (and quantitively) with plume height
• Proper understanding of acoustic propagation and the atmosphere is necessary to model the acoustic source
• Readily combinable with other datasets

NEXT STEPS?

• More and better understood quantitative models: source and propagation
• Real-time volume (and mass?) flux
• Better integration of regional infrasound with IMS infrasound. Data fusion.
• Local networks required for low-latency, high-resolution source studies and monitoring
• Integrate with remote sensing and hazard monitoring community
Previous work has shown similarities between sustained infrasound from large volcanic eruptions with the sound from jet engines [e.g. Matoza et al., 2009]

- IS19 (Djibouti): 264 km, 323°
- IS32 (Kenya): 1708 km, 18°
Nabro (high-amplitude)

• Asymmetric waveform with shock-like compression
• Nabro (blue) PDF differs substantially from Gaussian (black)
• PDF has positive tail

[Fee, Matoza, Gee, Nielsen, and Ogden, 2013]
Nabro (high-amplitude)

F/A-18E at afterburner

- Nabro and F/A-18E have similar waveforms and PDF
- High positive skewness
- F/A-18E data from [Gee et al., 2007]

[Fee, Matoza, Gee, Nielsen, and Ogden, 2013]
All three waveforms have high positive skewness values
PDFs all have long positive tails
Rocket and Nabro show strongest similarity
Rocket data from [Gee et al., 2009]

Nabro (high-amplitude)
F/A-18E at afterburner
GEM-60 Solid fuel rocket
TOPOGRAPHIC EFFECTS

[Kim et al., 2015]
Kasatochi Volcano

- Erupted August 7th-9th, 2008
- Previously unmonitored
- Ash to ~55,000’ (17 km)
- Extensive SO2 and ash
- Disrupted N Pacific air travel
GOES Imagery: high temporal resolution (30 min), low spatial resolution

Pulse 1-2 steam-rich

Pulse 3 ash-rich

- Compare plume top temperatures with atmospheric model temperatures
- Plume heights roughly the same for all three pulses: ~16-17 km
- Stratospheric emissions

[Fee et al., 2010]
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
- Winds characterized by easterly wind jet at ~20 km and westerly wind jet at ~60 km.
- 0.5 Hz PE modeling and ray tracing show rays and sound are primarily guided in the troposphere at 15-20 km and the thermosphere at ~120 km.
- Transmission loss (TL) is the accumulated loss in amplitude predicted by the PE, where warmer colors indicate lower transmission loss or higher amplitudes.
Increased attenuation due to thermospheric propagation path energy refracted down around

Acoustic Travel Time: ~7968 s (2 h 12 min) 90-110 km (thermospheric)
No stratospheric arrivals predicted
• 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
• Need detailed and accurate atmospheric specifications

The atmosphere varies spatially and temporally!
Mount St. Helens, 1 July 2012

Zonal Winds: east-west
Meridional Winds: north-south
PROPAGATION EXAMPLE

[Fee and Matoza, 2013]