

Infrasonic tremor observed at Kīlauea Volcano, Hawai'i

M. Garcés, A. Harris, C. Hetzer, J. Johnson, and S. Rowland

HIGP, SOEST, University of Hawai'i at Mānoa, Hawai'i, USA

E. Marchetti

Dipartimento di Scienze della Terra, Università di Firenze, Firenze, Italy

P. Okubo

U.S. Geological Survey, Hawaiian Volcano Observatory, Hawai'i Volcanoes National Park, Hawai'i, USA

Received 23 June 2003; revised 22 August 2003; accepted 15 September 2003; published 16 October 2003.

[1] Infrasonic array data collected at Kīlauea Volcano, Hawai'i, during November 12–21, 2002 indicate that the active vents and lava tube system near the Pu'u 'Ō'ō vent complex emit almost continuous infrasound in the 0.3–10 Hz frequency band. The spectral content of these infrasonic signals matches well that of synchronous seismic tremor. In sites protected from wind noise, significant signal to noise ratios were recorded as far as ~13 km from the crater of Pu'u 'Ō'ō. The infrasonic recordings suggest that one or more tremor sources may be close to the surface. In addition, these results demonstrate that adequate site and instrument selections for infrasonic arrays are essential in order to obtain consistent and reliable infrasonic detections. *INDEX TERMS:* 8409 Volcanology: Atmospheric effects (0370); 8419 Volcanology: Eruption monitoring (7280); 8414 Volcanology: Eruption mechanisms. **Citation:** Garcés, M., A. Harris, C. Hetzer, J. Johnson, S. Rowland, E. Marchetti, and P. Okubo, Infrasonic tremor observed at Kīlauea Volcano, Hawai'i, *Geophys. Res. Lett.*, 30(20), 2003, doi:10.1029/2003GL018038, 2003.

1. Introduction

[2] Infrasonic sound consists of sound waves with frequencies below the 20 Hz hearing threshold of the human ear. Infrasonic monitoring methods have been used extensively and successfully at various volcanoes throughout the world [Garcés *et al.*, 1999; Johnson *et al.*, 2003; Liszka and Garcés, 2002; Ripepe *et al.*, 2002; Sakai *et al.*, 1996; Yamasato, 1997]. With the revitalization of the field of infrasound during the ongoing deployment of the International Monitoring System (IMS) [Hedlin *et al.*, 2002; Vivas Veloso *et al.*, 2002], new methods are being developed to improve infrasonic monitoring robustness and enhance station sensitivity. Some of these improvements were implemented during a multidisciplinary field campaign that took place from November 12 to 21, 2002 at Pu'u 'Ō'ō, the active crater at Kīlauea volcano, Hawai'i. This experiment involved the deployment of an infrasonic array, two near-crater pressure sensors, five thermal infrared thermometers, and one broadband seismometer around the active crater (Figure 1) with the aim of detecting subtle fluctuations in activity levels over time scales of seconds to days [e.g., Ripepe *et al.*, 2002]. During the experiment continuous

effusion occurred through an active tube system located on the southwest flank of Pu'u 'Ō'ō. Three of the thermal sensors are not shown on Figure 1 because they were placed at various skylights along the lava tube system. Spectrograms for the Steam Cracks seismic station, operated by the Hawai'i Volcano Observatory ~2.5 km west of Pu'u 'Ō'ō, showed a persistent seismic tremor peak between 1 and 2 Hz for the duration of the experiment.

[3] Here we focus on the infrasonic component of the experiment that consisted of a four-element infrasonic array at a range of ~2 km from the active vents and two thermal and infrasonic channels at a range of ~100 m from the active vents (Figure 1). On the last day of the experiment, we also deployed a very small aperture array ~13 km from the vent. Although a four-element array can provide a factor of two gain in the signal to noise ratio, the main advantage of an array is that it permits the discrimination of coherent signals from noise. Within the Pu'u 'Ō'ō crater there were seven open, degassing vents and numerous skylights could also be seen along the upper ~200 m of the lava tube feeding the flow that at the time extended to the shoreline. Although low-intensity sound could be heard a few meters from the skylights and carlitos in the lava tube system, the volcano appeared fairly quiescent to the human ear.

2. Selection of Infrasonic Sites

[4] Erupting volcanoes are often in windy and corrosive field environments. Pu'u 'Ō'ō is no exception to this rule due to the near-shore environment, prevalent trade winds and persistent acid plume emitted by the vents. Corrosion can be reduced by the selection of proper materials and enclosures, but the reduction of wind noise presents a more challenging problem. Without protection, strong winds can essentially deafen an infrasonic monitoring station. There are at least three levels of defense against direct wind noise. The first recourse is to select a site that blocks the prevalent wind direction. IMS stations in Kona, Hawai'i, and Windless Bight, Antarctica, are located in the lee of large mountain masses, and as a result have very low ambient noise levels [Vivas Veloso *et al.*, 2002]. The second level of protection is the selection of a densely forested site. This specification cannot be met in some environments, but should be considered even at the expense of a larger distance from the source. The third level of defense is a spatial wind noise reducing system, which can be an integral part of the sensor design [Hedlin *et al.*, 2003].

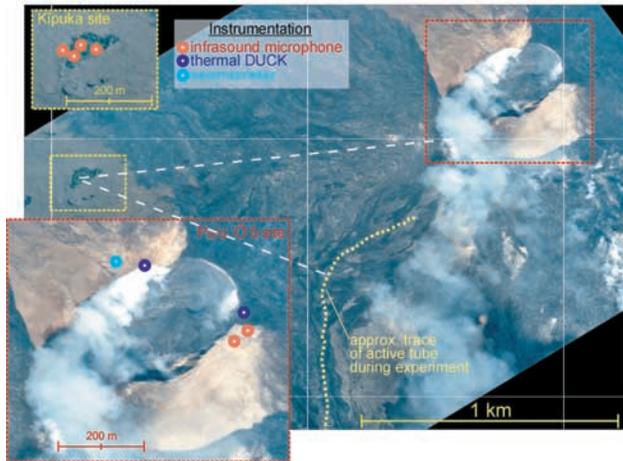


Figure 1. Location of infrasound, thermal, and seismic sensors during the experiment. The dashed white lines show the range of azimuths for infrasonic tremor energy arriving at the acoustic array deployed at the Kipuka site. Base image is scanned vertical air photo kindly provided by C. Heliker, USGS Hawaiian Volcano Observatory.

[5] The infrasonic deployment during the November experiment at Pu'u 'Ō'ō consisted of a 4-element array in the nearest available forest (~ 2 km west of the crater center, hereafter referred to as the Kipuka array) and a 2-element site ~ 100 m south of the southern crater rim. At the forested site three of the array elements (NEMO1-NEMO3) were deployed in dense vegetation, and the fourth (NEMO4) was placed on a tephra bed just outside the edge of the forest. In addition, two infrasound sensors (LOGO1 and LOGO2) were placed close to the rim of Pu'u 'Ō'ō, at a distance of ~ 0.1 km from the active vents. Both were placed within crevices in an 'a' flow, but LOGO2 had more shelter from the wind than LOGO1.

3. Instrumentation

[6] The low-cost eXpendable InfraSonic (XIS) microphones used for this experiment have been developed by the Infrasound Laboratory of the Hawai'i Institute of Geophysics and Planetology. Each sensor consists of 14 Panasonic WM034BY electret condenser microphones whose buffered outputs are summed in parallel. The nominal frequency response of the sensors has -3 dB points at 0.9 Hz and 20 Hz, with a peak sensitivity of 150 mV/Pa at 5 Hz. Each sensor was connected to an 18 m long porous (soaker) hose deployed as a spiral to act as a wind noise reducing filter. Two six-channel Geotech DL 24-bit digitizers ingested the infrasonic and thermal data, as well as wind speed and direction data from a Met-One ultrasonic wind sensor. All channels were recorded at 100 samples per second.

4. Characterization of the Infrasonic Tremor Signal

[7] With the exception of aircraft and earthquakes, no clear transient signals were observed from Pu'u 'Ō'ō. For frequencies greater than 1 Hz, the ambient acoustic field

near the volcano appeared to be dominated by wind noise and volcanic tremor, which coexisted in the same frequency band. Wind turbulence at 1 Hz would have relatively small eddy dimensions which would not show up as coherent pressure signals across the array, but can dramatically increase the background noise levels. Figure 2 shows the power spectral density for one element of the near-crater and two elements of the forest sites near Pu'u 'Ō'ō. For comparison, Figure 2 also shows the power spectral density during the same time period at permanent IMS station I59US sited on the slopes of Hualalai Volcano, ~ 80 km from Pu'u 'Ō'ō. The passband of I59US is 0.02–10 Hz, and due to its favorable location in the leeward side of the island and within a thick forest, has one of the lowest ambient noise levels in the IMS. At ~ 0.2 Hz we can clearly see the microbarom peak [Kibblewhite and Wu, 1996] in I59US and NEMO1 and NEMO4, but this feature is completely obscured in LOGO1 by wind noise. Above the microbarom peak, the most prominent spectral feature in the Pu'u 'Ō'ō data is the relatively large spectral levels between 0.5 and 10 Hz. Figure 3 shows the power spectral density for the same temporary stations but at higher wind speeds, with a clear increase in background noise at all sites. NEMO4, at the edge of the forest, shows a higher rise in wind noise than NEMO1, in the midst of the forest. Although LOGO1 is heavily affected by the wind, we can observe a broad spectral peak between 1 and 2 Hz. However, note that the low-frequency spectral levels at LOGO1 and NEMO4 increase substantially at higher wind speeds, suggesting

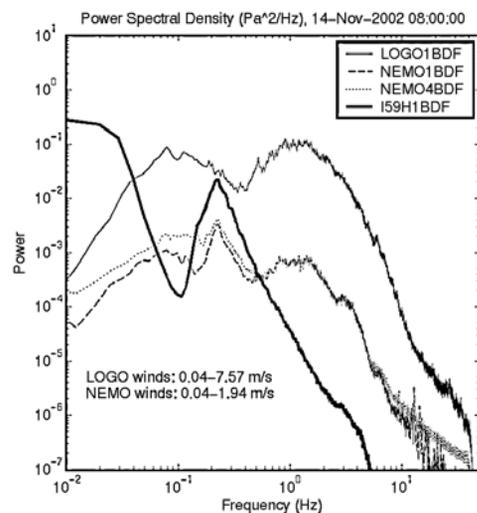


Figure 2. Power spectral density of infrasonic pressure for three microphones deployed temporarily near the Pu'u 'Ō'ō crater under relatively low wind conditions. The minimum and maximum wind speeds are shown in the figure. LOGO1 was located at the exposed crater rim and ~ 0.1 km from the active vents. NEMO1 was located ~ 2 km from the vent within a forested section. NEMO4 was on the outskirts of the forested patch (westernmost array element in Figure 1), and more vulnerable to wind. The tremor signal coexists with wind noise as a broad peak with maximum between 1 and 2 Hz. For reference, the background noise levels observed at I59US (range of ~ 80 km) are shown for the same time period.

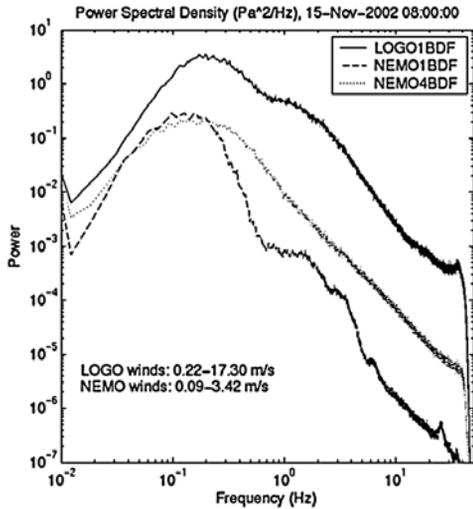


Figure 3. Power spectral density of infrasonic pressure for three microphones deployed near Pu'u Ō'ō volcano, Hawai'i, under higher wind conditions. Note the exposed area near the vent has peak winds that are five times stronger than in the forested site. Distinct frequency peaks are still observed at NEMO1, but this spectral structure is buried in the wind noise at NEMO4.

some of the energy between 1 and 2 Hz is due to wind noise. In contrast, spectral levels at NEMO1 within the 1–10 Hz frequency band are fairly stable. Although it is possible that much of the energy in this band is volcanic in origin and the difference in acoustic power between NEMO1 and LOGO1 are due to the increased range from the source, LOGO1 would be vulnerable to wind, weather, lava flows, and crater wall collapse, and would not be able to provide a long baseline of data essential for volcanic monitoring and eruption forecasting.

[8] By examining the coherence of incident acoustic energy across the array it is possible to discriminate wind noise from tremor noise, where we note that under high wind conditions (>10 m/s), only the array elements in the forest (NEMO 1–3) could consistently observe the tremor peak. We used the Progressive Multi-Channel Correlation (PMCC) [Cansi, 1995; Garcés and Hetzer, 2002] detection algorithm to determine the features of coherent acoustic energy across the Kipuka array in the frequency range of 1 to 10 Hz. The cross-correlation function of the data from two stations determines a time delay Δt_{ij} . PMCC is a time-domain detector that uses the correlation between various groupings of three sensors, i, j, k , to obtain an estimate of the consistency of the closure relation

$$r_{ijk} = \Delta t_{ij} + \Delta t_{jk} + \Delta t_{ki} \quad (1)$$

where Δt_{ij} is the time delay between the arrival of a signal at sensors i and j [Cansi and Klinger, 1997]. If the consistency is below a certain threshold, a detection is registered. The mean quadratic residual of the closure relations (Equation 1) of the sub array triplets yields the consistency of the signal. A subset of the array elements can be used for an initial time-delay calculation, which yields an initial value of arrival azimuth and slowness. Additional elements are progressively included in the calculation. If the point of

maximum correlation requires a significant variance in azimuth, velocity, or time, the arrival is discarded. This optimizes computation time over a large array, and also reduces the occurrence of false alarms. [Cansi, 1995].

[9] During the PMCC calculation, each time window is filtered into a number of frequency bands, and the results are analyzed individually for similarity in azimuth, slowness, and consistency. A detection must also satisfy specified trace velocity limits, arrival azimuth variation limits and duration limits, and must appear on a specified minimum number of sensors. The final detections, named families, are the result of nearest-neighbor grouping in time-frequency-feature space. Families that conform to a specified range of sizes are tabulated.

[10] We used the PMCC method for all the array data, and found the primary signals were from tremor and from helicopter flights. We select a period with low wind noise (Figure 2) so that we can use all four elements of the array to best advantage. Figure 4 shows that coherent energy arrives at the array from the east, the direction from Pu'u Ō'ō's crater and lava tube system (Figure 1). The azimuth plot in Figure 4 shows a range of variability that exceeds the expected value for azimuth deviations induced by the wind. For the light wind case, the maximum wind speed was ~ 8 m/s with a NNW direction. Using a sound speed of 340 m/s, the travel time for a 2 km range is ~ 6 s, and thus the maximum deflection perpendicular to the

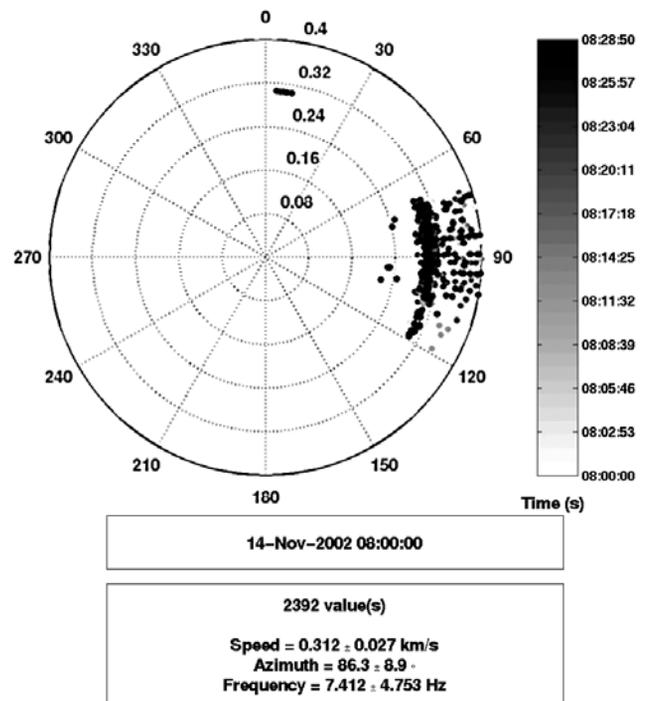


Figure 4. Progressive Multi-Channel Correlation (PMCC) results for a 4-element quadrilateral array with a maximum inter-element distance of 100 m and a minimum distance of 50 m. The correlation across the array is greater than 0.5 below 10 Hz and the azimuth points towards the active crater and lava tube system. The low apparent horizontal phase speed may be due to 3 m uncertainties in the sensor locations of the small aperture array and differences in the phase response between the electret microphones.

propagation path would be ~ 50 m, corresponding to an angular deviation of 1.4° . This angular variability is far smaller than what we observe in Figure 1. Although small errors in the azimuth and speed estimates are expected because of the 3-m accuracy of the sensor positions, these errors should be relatively invariant in time.

[11] The arrival azimuths of the infrasonic signals suggest that the infrasonic source is extended and possibly distributed along part of the lava tube system that feeds to the ocean. One possible explanation for the infrasonic tremor may be the acoustic excitation of the lava-gas mixture inside the tube system, although it may also be possible to excite infrasonic from fluid flow instabilities inside the convoluted magma plumbing. Although a vertical lava conduit with an open vent can generate infrasound efficiently even from sources at depth, a horizontal conduit would only be able to radiate efficiently into the atmosphere if it is within tens of meters of the surface. This is because the acoustic radiation would be from the ends (which would be buried,) or from openings on the conduit side, which manifest themselves as skylights. Thus the relatively high infrasonic tremor amplitude levels, the arrival direction of the signal, and the high variability of the arrival azimuths suggest that the source of the tremor signal is near the surface. This observation is consistent with seismic interpretations, which placed the tremor source within the surface layers at a depth ranging from 0–100 m [Chouet, 1996]. Ongoing seismic observations of the lava tube system [Hoblitt et al., 2002] also suggest that it can efficiently generate low-frequency vibration.

[12] A similar infrasonic array was deployed at a range of ~ 13 km in the nearby town of Volcano to confirm the arrival azimuth and test range of propagation of the tremor signal. Although the observed infrasonic tremor amplitude was lower, the arrival azimuth was consistent with energy originating from the Pu'ū 'Ō'ō area. It is likely that the continuous eruption of Pu'ū 'Ō'ō has been generating infrasound since activity began in 1983, and the correct combination of dynamic range, site selection, array design and wind noise reduction have allowed the discovery of these coherent signals.

5. Concluding Remarks

[13] Infrasonic tremor levels near Pu'ū 'Ō'ō are relatively high in the 1–10 Hz band, and appear to originate from a shallow and possibly distributed source originating near the active crater complex and extending into the upper lava tube system. Detectable volcanic signals appear to be restricted to ranges that are within a few tens of kilometers of the volcano, as IMS station I59US is located ~ 80 km away and does not observe the tremor. During low wind conditions, installation of infrasound sensors in a volcanic slope may be valuable for the detection of low-amplitude volcanic signals. However, barren volcanic slopes usually expose equipment to wind, corrosion, and potential damage or

destruction. More robust and accessible infrasonic monitoring stations may be installed in protected forests a few kilometers from an active vent. In our experiment, the reduced noise conditions at greater ranges improved our detection capabilities. With proper site selection, such sites can provide higher and more reliable signal to noise levels, allowing consistent acoustic measurements of changes in gas and magma flow conditions during an eruption.

[14] **Acknowledgments.** This work has been funded by the University of Mississippi and the National Science Foundation (grant EAR-0106349) and NASA (grant NAG5-10640). Many thanks to David Sherrod, Frank Truesdell, Jim Kauhikaua, and others on the staff of the Hawaiian Volcano Observatory, as well as David Okita and Peter Mouginiis-Mark for essential field support.

References

- Cansi, Y., An automatic seismic event processing for detection and location: The P. M. C. C. method, *Geophys. Res. Lett.*, 22, 1021–1024, 1995.
- Cansi, Y., and Y. Klinger, An automated data processing method for mini-arrays, *Newslett. Europn.-Medit. Seismolog. Cntr.*, 11, 2–4, 1997.
- Chouet, B. A., New methods and future trends in seismological volcano monitoring, in *Monitoring and mitigation of volcanic hazards*, edited by Scarpa and R. Tilling, pp. 23–97, Springer-Verlag, New York, 1996.
- Garcés, M., and C. Hetzer, Evaluation of infrasonic detection algorithms, paper presented at 24th Annual DTRA/NSA Seismic Research Review, Ponte Vedra, FL, 17–19 September 2002.
- Garcés, M., M. Iguchi, K. Ishihara, M. Morrissey, Y. Sudo, and T. Tsutsui, Infrasonic precursors to a Vulcanian eruption at Sakurajima volcano, Japan, *Geophys. Res. Lett.*, 26, 2537–2540, 1999.
- Hedlin, M., B. Alcoverro, and G. D'Spain, Evaluation of rosette infrasonic noise-reducing spatial filters, *J. Acoust. Soc. Am.*, (in press), 2003.
- Hedlin, M., M. Garcés, H. Bass, C. Hayward, E. Herrin, J. Olson, and C. Wilson, Listening to the secret sounds of Earth's atmosphere, *Eos Trans. AGU*, 83, 557, 564–565, 2002.
- Hoblitt, R. P., J. Battaglia, J. P. Kauhikaua, and P. G. Okubo, Lava tube seismicity at Kilauea, *Eos Trans. AGU*, 83(47), Fall Meet. Suppl., Abstract V71A-1259, 2002.
- Johnson, J. B., R. C. Aster, M. C. Ruiz, S. D. Malone, P. J. McChesney, J. M. Lees, and P. R. Kyle, Interpretation and utility of infrasonic records from erupting volcanoes, *J. Volcanol. Geotherm. Res.*, 121, 15–63, 2003.
- Kibblewhite, A., and C. Y. Wu, Wave interactions as a seismo-acoustic source, *Lecture Notes in Earth Sciences*, Springer-Verlag, New York, 1996.
- Liszka, L., and M. Garcés, Infrasonic observations of the Hekla eruption of February 26, 2000, *J. Low Frequency Noise, Vibr., Active Control*, 21, 1–8, 2002.
- Ripepe, M., A. Harris, and R. Carniel, Thermal, seismic, and infrasonic evidences of variable degassing rates at Stromboli volcano, *J. Volcanol. Geotherm. Res.*, 118, 285–297, 2002.
- Sakai, T., H. Yamasato, and K. Uhira, Infrasound accompanying C-type tremor at Sakurajima volcano, *Bull. Volcanol. Soc. Japan*, 41, 181–185, 1996.
- Vivas Veloso, J., D. Christie, T. Hoffmann, E. Demirovic, P. Campus, M. Bell, A. Molero, A. Langlois, P. Martysevich, J. Carvalho, and A. Kramer, Status of the IMS Infrasound Network, paper presented at the Infrasound Technology Workshop, De Bilt, Netherlands, October 28–31, 2002.
- Yamasato, H., Quantitative analysis of pyroclastic flows using infrasonic and seismic data at Unzen volcano, Japan, *J. Phys. Earth*, 45, 397–416, 1997.

M. Garcés, A. Harris, C. Hetzer, J. Johnson, and S. Rowland, HIGP, SOEST, University of Hawai'i at Mānoa, Hawai'i, USA. (milton@isla.hawaii.edu)

E. Marchetti, Dipartimento di Scienze della Terra, Università di Firenze, Firenze, Italy.

P. Okubo, U.S. Geological Survey, Hawaiian Volcano Observatory, Hawai'i Volcanoes National Park, Hawai'i, USA.