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Capturing the Acoustic Fingerprint of Stratospheric Ash Injection

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More than 100 separate incidents of interactions between aircraft and volcanic ash were documented between 1973 and 2003. Incidents on international flight paths over remote areas have resulted in engine failures and significant damage and expense to commercial airlines. To protect aircraft from volcanic ash, pilots need rapid and reliable notification of ash-generating events. A global infrasound array network, consisting of the International Monitoring System (IMS) and other national networks, has demonstrated a capability for remote detection of Vulcanian to Plinian eruptions that can inject ash into commercial aircraft cruise altitudes (approximately 12 kilometers) near the tropopause. The identification of recurring sound signatures associated with high-altitude ash injection implies that acoustic remote sensing can improve the reliability and reduce the latency of these notifications.

Eruptions release excess pressure within volcanoes, and infrasound sensors capture the inaudible atmospheric pressure waves induced by eruptions. Seismometers record ground vibrations and are most responsive to subsurface volcanic activity, though the relationship between seismicity and volcanic ash emissions is complex and not fully understood. Satellite remote sensing techniques are currently the primary means of identifying and tracking volcanic ash, in conjunction with volcano observatories and aircraft pilot reports. Cloud cover and sampling interval limitations can interrupt satellite remote sensing data, while acoustic sensors record eruptive activity even when the volcano is visually obscured by clouds. A combination of seismic, satellite, and infrasound coverage can decrease ambiguity between subterranean and surface activity and reduce uncertainty in the timing and intensity of eruptions.

Volcano monitoring is one of various natural hazards applications of the technology developed for the IMS infrasound array network [*Hedlin et al.*, 2002]. As the IMS infrasound network has expanded to 39 operational arrays, it has captured a growing collection of acoustic signals from volcanoes tens to thousands of kilometers away from monitoring stations [e.g., *Le Pichon et al.*, 2005]. As a result, the International Civil Aviation Organization (ICAO) expressed an interest in the potential of global and regional infrasound networks to provide eruption notifications to the aviation community through the existing international Volcanic Ash Advisory Center (VAAC) framework (http://www.ssd.noaa.gov/VAAC/vaac.html). Because data distribution and latency issues may complicate the release of IMS data for practical operational use, international groups in the United States, Canada, Ecuador, France, and Australia are collaborating in the design of prototype low-latency infrasound surveillance systems specifically tailored to the needs of the aviation community [*Garcés et al.*, 2007].

Robust, Low-Latency Acoustic Monitoring Over Regional Distances

One of the key monitoring goals is to distribute operationally useful notifications

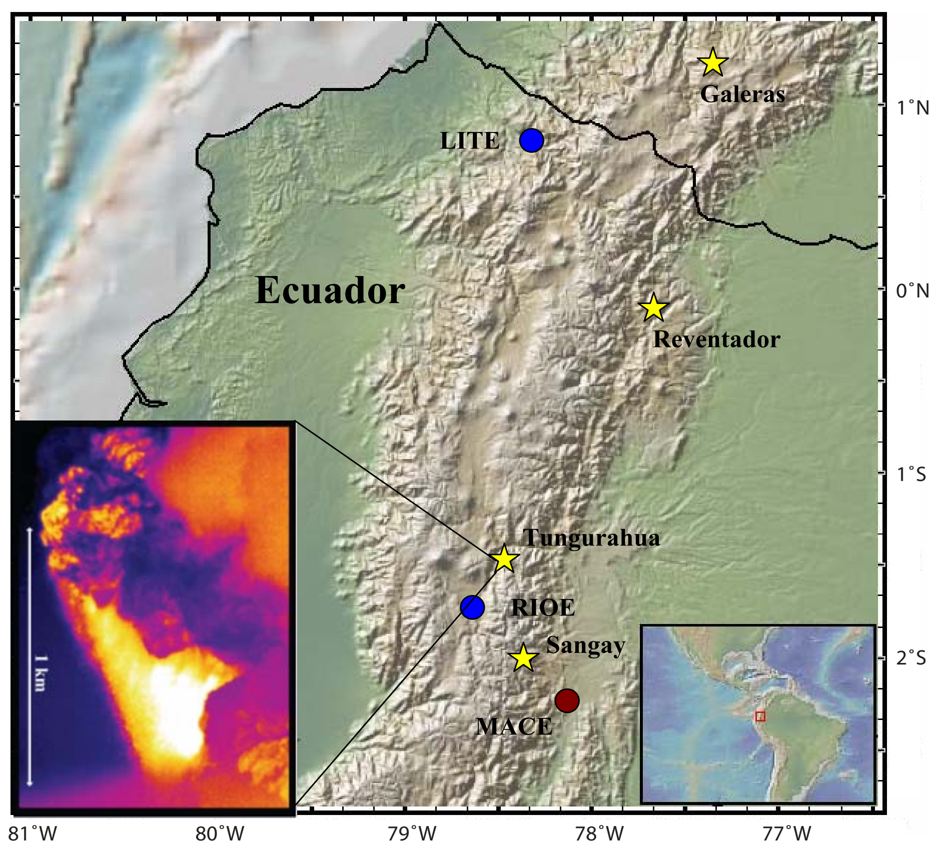

Fig. 1. Location of prototype seismoacoustic station deployments in Ecuador. The blue circles denote four-element infrasound arrays with colocated wind sensors and two components of a broadband seismometer. The red circle is a broadband seismometer. The yellow stars show the locations of recently active volcanoes. The inset to the left is an infrared image of Tungurahua volcano taken on 17 August 2006 at 0451:22 UT, showing the incandescent eruption column that injected volcanic ash into the stratosphere (image courtesy of the Instituto Geofísico, Escuela Politécnica Nacional).

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to VAACs within 5–20 minutes of an eruption that could threaten air traffic. In contrast to most ground-based volcano surveillance systems, infrasound arrays may be sited tens to hundreds of kilometers away from the devastation zones of erupting volcanoes, offering coverage over broad areas while improving personnel safety and operational continuity during eruptive episodes. On the basis of ongoing automatic data processing for stations at ranges of approximately 10, 40, and 250 kilometers, real-time processing can produce eruption notifications in 2.5, 4, and 17 minutes, respectively. Recent studies have shown that Vulcanian, sub-Plinian, and Plinian eruptions can be consistently detected by regional and distal stations in the global infrasound network (see http://www.isla.hawaii.edu/volcano/iwars06.php). For telesonic ranges, latency increases to about 1 hour per 1000 kilometers of distance of a station from a volcano.

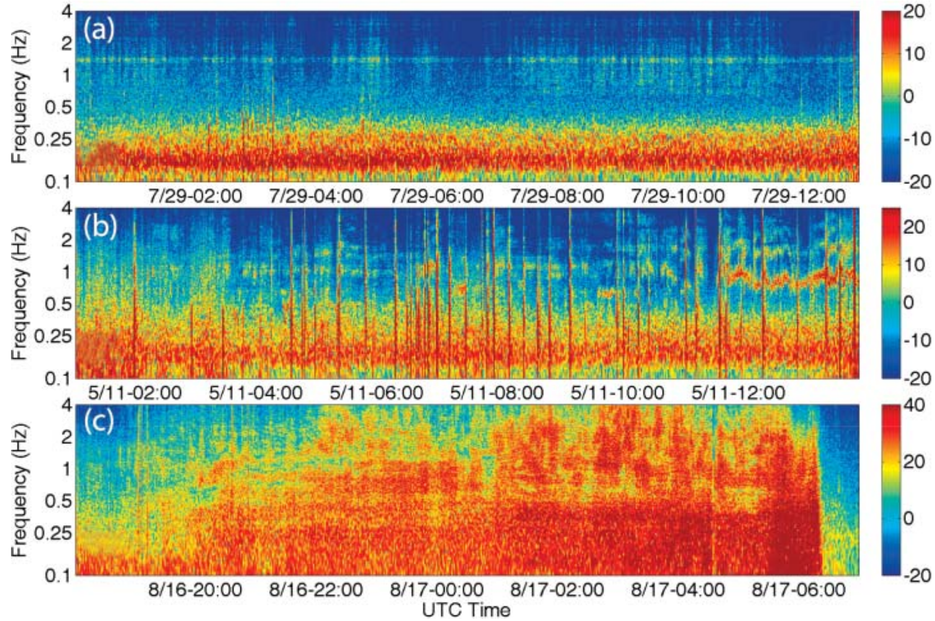

Fig. 2. Spectrograms for three different eruption styles seen at Tungurahua in 2006. The horizontal axis represents 13 hours of data, and the vertical scale shows frequency in a logarithmic scale from 0.1 to 4 hertz. The color denotes acoustic power in decibels referenced to 1 pascal squared per hertz. Ocean noise shows up in Figures 2a and 2b as a red band centered about 0.2 hertz; it is not of volcanic origin. Explosive events appear as intense vertical bands. Figure 2a shows the infrasonic levels for low activity, with continuous infrasonic tremor at 1.4 hertz. Figure 2b shows a moderate level of eruptive activity, corresponding to explosions and harmonic tremor during an ash-poor eruption. Figure 2c shows high activity levels, corresponding to the onset of a Vulcanian eruption after 1900 UT on 16 August 2006 and transitioning into Plinian after 0500 UT on 17 August 2006. Note the change in power levels in Figure 2c due to acoustic pressures an order of magnitude greater than low (Figure 2a) and moderate (Figure 2b) eruption levels.

Prototype System Design and Testing

Most acoustic studies have concentrated on Strombolian and mild Vulcanian eruptions [e.g., *Harris and Ripepe*, 2007] because of their relative abundance. However, a different approach would be used to target larger Vulcanian to Plinian ash-laden columns that may threaten aircraft. *Matoza et al.* [2007] describe prototype autonomous stations consisting of a four-element infrasound array with an aperture of about 100 meters, a broadband seismic sensor, and a wind sensor. A satellite dish sends real-time data from remote locations to collaborating parties. In October 2004, shortly after the onset of the latest activity of Mount St. Helens, two of these prototype stations were deployed approximately 13 and 250 kilometers away from the volcano. The remarkably aseismic eruption of 16 January 2005 and the explosive, steam-rich eruption of 8 March 2005 were captured in their entirety by the arrays [*Matoza et al.*, 2007], confirming the potential to monitor eruptive activity at regional distances.

Garcés et al. [2007] describe the deployment of similar stations in Ecuador (Figure 1). Two infrasound arrays were sited to permit detection within 15 minutes of volcanic eruptions in Ecuador and southern Colombia, and as early as 5 minutes for volcanoes within 40 kilometers of an array. In a period of 2 years, these two arrays recorded eruption signals from Tungurahua, Sangay, Reventador, Galeras, and Nevado del Huila volcanoes. However, the acoustic activity accompanying the destructive July and August 2006 eruptions of Tungurahua volcano was exceptionally relevant. Satellite imagery confirmed that both of these eruptions injected ash above a height of 14 kilometers. These Vulcanian to Plinian eruptions produced powerful infrasonic signals that were recorded clearly by both arrays in Ecuador, by near-field networks [*Kumagai et al.*, 2007], and by at least one IMS array. The distinct acoustic signatures produced by high-altitude ash injection were used to train detection algorithms, which successfully triggered automatic eruption notifications to the VAACs during the 6 February 2008 Vulcanian eruption of Tungurahua.

Acoustic Fingerprint of Stratospheric Ash Injection

Array processing is the most effective method for identifying sounds originating from the known direction of a volcano. To minimize the effects of geometrical spreading and topography, the acoustic energy estimated from the array detections can be compared with that of a selected reference event. The energy ratio between the signal of interest and the reference event is used to define an intensity threshold that activates an eruption notification to the VAACs. This method may be used to automatically trigger on eruptive events and produce near-real-time notifications of large explosions and changes in tremor levels, as well as to compile daily volcano infrasound summaries that include events below the notification threshold.

At least three distinct types of eruption signatures were characterized at Tungurahua in 2006 (Figure 2) and used to define event trigger levels. Observations from the Instituto Geofísico (IG), Escuela Politécnica Nacional, in Ecuador, and ash height information from satellite data and pilot reports were used to classify the eruptions. The first and most common eruption style is low ash-producing background tremor with a dominant frequency of 1.4 hertz (Figure 2a). Ash injection to the atmosphere during this eruptive stage is associated with atmospheric stability and plume convection.

During mid-May 2006, a second type of eruptive regime was exhibited when volcanic activity increased and transitioned toward large explosions followed by harmonic tremor (Figure 2b). This type of eruptive regime was characterized as ash-poor and gas-rich by the IG and satellite observations, and it represents a moderate level of activity.

The third eruptive type corresponds to intense Vulcanian to Plinian eruptions and defines the acoustic fingerprint of stratospheric ash injection. On 14 July 2006 a large Vulcanian eruption produced dangerous pyroclastic flows, substantial ash clouds, and a drastic increase in tremor. During 16–17 August 2006, a larger Vulcanian to Plinian eruption (Figure 2c) was characterized by lethal pyroclastic flows, a larger stratospheric ash cloud, and powerful infrasonic tremor. As the eruption intensified to Plinian, acoustic energy shifted to much deeper frequencies, reaching a peak power level of approximately 10 megawatts between 0.06 and 0.1 hertz during its paroxysmic stage. The acoustic fingerprints of the two major July and August 2006 eruptions are easily identifiable in infrasonic records due to the vast amount of energy present over a broad band of frequencies. The seismic records of the two major eruptions appear to have a significantly different spectral signature, suggesting seismoacoustic decoupling. These two eruptions injected a substantial amount of ash into the atmosphere. We used these eruption signals to define a high level of activity, which would automatically trigger an eruption notification to the VAACs.

Using the principles described in this article, a prototype autonomous notification system was successfully triggered on 6 February 2008 during a climactic Vulcanian eruption sequence at Tungurahua that had been preceded by months of explosive activity. Because of the relative proximity of the RIOE infrasound array to Tungurahua (37 kilometers; Figure 1) and lessons learned from previous eruptions, the capacity to deliver notifications within 5 minutes of substantial changes in eruptive activity was demonstrated.

The Future: Test Operations

This article describes how acoustic remote sensing may complement seismic observations and satellite remote sensing to improve continuous monitoring of wide regions of potential eruption hazard. The acoustic sensing techniques described have been used as prototypes by the Acoustic Surveillance for Hazardous Eruptions (ASHE) project [*Garcés et al.,* 2007]. The ASHE prototypes presently produce automated notification products on a test basis to a participating ICAO-designated VAAC for comparison against, and possible integration with, its existing warning systems. These notifications are coupled with more detailed real-time data products (presently provided in designated Web pages), and they could be used by volcano observatories to disseminate updated information.

On the basis of acoustic records captured during the Vulcanian to Plinian eruptions of Tungurahua volcano, source parameters that may be estimated during large eruptions include (but may not be limited to) the height probability, start time, and duration of an ash cloud injection that could pose a hazard to international carriers at cruising altitudes. The possibility of inferring these source parameters even at greater distances was suggested by the recognizable acoustic fingerprints of the summer 2008 eruptions of Okmok and Kasatochi volcanoes in the remote Aleutian Arc of Alaska. These eruptions were recorded at distances of 1700–4500 kilometers by infrasound arrays in Fairbanks, Alaska, Washington state; Hawaii; Russia, and Japan.

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