INFRASOUND

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Rebirth of infrasound

A new global network of microbarometers is breathing life into a once dormant branch of acoustics: the study of infrasound. The nascent study of sub-audible sounds is shedding new light on a great variety of man-made and natural phenomena in the atmosphere, including Mount Saint Helens, pictured on the front cover of this issue. The re-emergence of this field is due largely to the Comprehensive Nuclear-Test-Ban Treaty (CTBT), which was opened for signatures in New York City in September of 1996. The CTBT held the promise of limiting the spread of nuclear weapons. In the process, the treaty created the International Monitoring System (IMS). The International Monitoring System consists of seismic, hydroacoustic, radionuclide, and sixty infrasound stations spread over the globe to provide almost uniform coverage (Fig. 1). Never before has there been a global system designed to listen for acoustic waves in the atmosphere connected via modern communications to allow for real time monitoring and correlation of signals. The International Monitoring System stations employ modern electronics that allow for real time digitization of signals and archiving signals from the global constellation of stations at a single location.

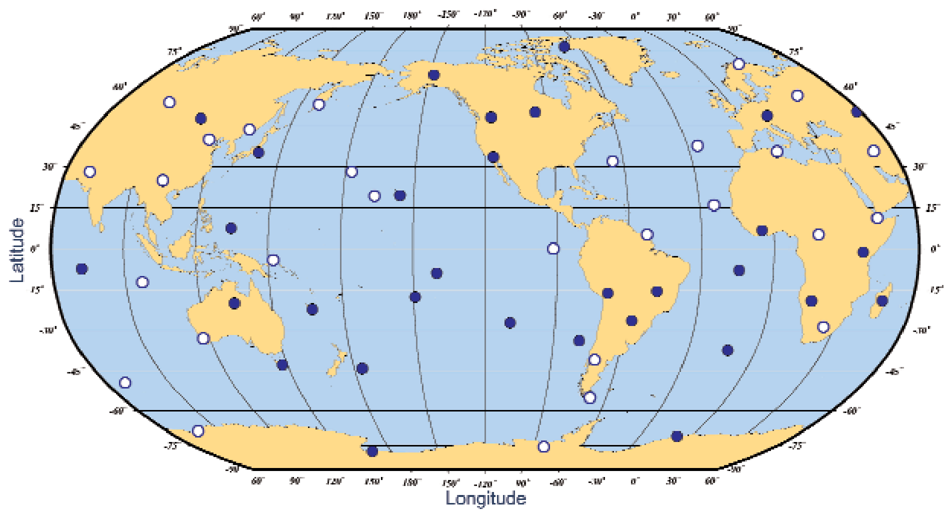

Fig. 1. Map showing the existing locations (blue circles) and planned locations (clear circles) of the 60-station IMS infrasound network.

Because the absorption of sound in the atmosphere decreases with frequency, the low-frequency infrasound band holds the promise of signal detection over long distances. One of the earliest reports of infrasound propagation over long distances was from the cataclysmic 1883 explosion of Krakatoa. Barometric records of the explosion observed throughout the US, Europe, Russia, and reports of cannon-like sounds in surrounding islands (as far as Diego Garcia and Rodrigues Islands) demonstrated for the first time the ability of low-frequency sound to propagate for thousands of kilometers. Preliminary studies of data from the International Monitoring System reveal a large number of signals detectable because of the low noise characteristics of modern stations and atmospheric conditions that often allow infrasound to travel great distances with little loss in amplitude. Interpretation of these signals challenges even the most advanced propagation and atmospheric models.

Infrasound stations and data analysis

The heart of a modern infrasound station is the highly sensitive microbarometers that measure the absolute or differential pressure variations in a frequency band of roughly 0.02 to 10 Hz. These instruments, acting as extremely sensitive microphones, measure the minute pressure fluctuations associated with acoustic energy propagating through the atmosphere. The pressure fluctuations reach the microbarometers through spatial filters that are designed to suppress wind noise by spatial averaging. Most wind noise is incoherent across distances of several meters, while infrasonic signals can be coherent over distances in excess of 100 meters. The wind filter averages pressure fluctuations over an area larger than the coherence limit of noise but smaller than the coherence limit of signals. In this manner, the effects of wind-induced noise are minimized while the signal is preserved.

A common form of wind filter is the pipe rosette—a modern version of the linear pipe array wind filters first used in the 1950s to make long distance recordings of atmospheric nuclear tests[1]. A pipe rosette[2] consists of plastic or metal pipes arranged in a hub-and-spoke configuration (Fig. 2). The outer ends of the pipes are open to the atmosphere (through screens that resemble shower heads) and at the hub, all the pipes are connected together in a summing manifold. The hubs of multiple rosettes are then connected via pipes to a central summing manifold to create a single large rosette. The microbarometer is connected to this central manifold, so it effectively averages the pressure fluctuations over the entire circular surface area covered by the rosette (anywhere from 18 m to 70 m in diameter).

Fig. 2. Partially installed infrasound site in Warramunga, Australia. The pipe rosette will be buried so that only the intakes (white "shower heads") will be above ground and the four rosettes will be connected to the microbarometer located in the cement vault. (Photo by D. Christie).

Data from the IMS infrasound network are recorded on low noise 24-bit digitizers at sample rates of 10 to 40 samples per second. Data packets from a central recording computer are then transmitted in near real-time to national and international data centers using satellite communications systems. Local meteorological conditions and state-of-health data channels are transmitted along with the infrasound data.

A typical infrasound station actually consists of an array of microbarometers providing improved signal detection and processing capability over that of a single sensor. There are typically four to eight individual microbarometers comprising an array, and each is connected to its own wind-filtering pipe rosette. The spacing between microbarometers is anywhere from tens of meters to one or two kilometers.

Infrasound arrays are typically used to observe signals from sources hundreds to thousands of kilometers away from the station. Detection of weak signals from distant sources requires a sophisticated approach to data processing. The signals from the array of microbarometers are processed together, using a variety of standard techniques, such as beamforming and frequency-wavenumber analysis that are designed to enhance weak signals and provide improved directional response. Most infrasound signal detection algorithms require a combination of signal power and correlation of the signal across array elements to identify a signal. Most signal detectors use strategies to avoid detector "capture" wherein strong signals from a single direction are detected while simultaneous, but weaker, signals from another direction are missed. This is particularly critical in infrasound processing, since signals from noise or clutter sources can be quasi-continuous, coherent and larger than signals from sources of interest. Infrasound investigators have used a variety of detection algorithms. These range from correlation detection to the F-statistic estimator[3] and the Progressive Multi-Channel Correlation (PMCC) method[4].

Once signals are detected, additional processing is used to locate and characterize the source. A frequency-wavenumber (*f-k*) analysis of the array elements can be used to determine the azimuth of incoming signals (the bearing from the station to the signal source). Source location processing utilizes the triangulation of bearings and arrival times of signals observed at two or more stations. In some cases, the infrasound observations are combined with seismic observations of the same source to generate a fused event location.

Source characterization is a very active area of study since the rapidly expanding global infrasound network is providing many new observations. Sources are characterized through the analysis of signal features such as duration, peak amplitude, and frequency content.

Sources of infrasound in nature

A broad suite of natural phenomena in Earth's surface and atmosphere produce infrasound. While the sources we review in this article are natural, infrasound can also be generated by anthropogenic (man-made) sources including large chemical or nuclear explosions, rockets and aircraft.

Earthquakes

Earthquakes may produce infrasound in various ways. Acoustic-gravity waves from strong vertical ground displacements can propagate thousands of kilometers from their source[5]. Under certain earthquake source conditions, and when the shear speed of the ground is commensurate with the atmospheric sound speed, ground-coupled airwaves propagating at acoustic velocities may be produced[6]. Infrasonic waves may also be radiated by topography when seismic surface waves travel through mountainous regions[7]. Le Pichon et al.[8] performed the first acoustic estimates of fault rupture speeds from the June 23, 2000 Arequipe earthquake. Olson et al.[9] also estimated fault rupture dynamics from infrasound signals from the magnitude 7.9 Denali Fault earthquake of November 3, 2002. Analysis of the azimuth of arrival and trace velocity of the acoustic waves associated with the earthquake indicated that the source of the waves moved eastward along the Denali Fault. These observations were in agreement with the description by local seismologists of a propagating rupture along the fault. As the rupture moved along the Denali Fault it produced large, local ground motions and these motions produced infrasound waves that were detected at the Fairbanks, Alaska array I53US. Despite the large displacements, the infrasonic sources were not attributed to the horizontal motions of the ground, but rather to the motion of the mountains in the Alaska Range associated with the Denali Fault. Submarine earthquakes may also produce infrasound through the displacement of the ocean surface. This subject will be discussed in more detail in the Tsunami section.

Auroral infrasound

Researchers at the Geophysical Institute, University of Alaska have identified two forms of infrasound associated with visible auroras. Early work, dating to the 1960s, found large "bow waves" associated with the passage of auroral curtains in the overhead ionosphere[10]. The ground footprint of these waves produces an impulse in the infrasound record as they sweep across the array. Recently, a new form of auroral infrasound has been discovered at the Geophysical Institute. These infrasound signals are associated with pulsating auroral forms that are common after magnetospheric substorms. The pulsating auroral forms appear stationary in the sky with intensity fluctuations that are quasi-periodic in the period range from 10 – 30 seconds. When adjusted for propagation delays from the ionosphere to the ground, the infrasound signals show good correlation with the fluctuations in auroral intensity. Presumably, the precipitating auroral electrons that produce the optical auroras also deposit enough heat to produce detectable pressure variations. However, the details of the energy transfer have yet to be delineated.

Meteors

Sensitive infrasound sensors[11] can routinely detect the rumble of hypersonic objects tearing through the atmosphere. A meteor entry may generate sound either as a shock wave radiating from a near-cylindrical Mach cone, or from the explosion of the meteor. Approximately ten thousand small meteors hit the Earth's atmosphere each year with sufficient energy to generate an acoustic signal, while several bolides per year have explosive energies that are comparable to a thousand tons of dynamite. Such kiloton bolide bursts occur approximately once per year and can cause significant damage[12]. Because of their unpredictable arrivals, high speeds, and sometimes-unknown compositions, meteors are difficult to model. Substantial improvements have been recently made (e.g., References 13 and 14) by using a combination of multiple monitoring technologies, more realistic atmospheric specifications, and hydrodynamic source models.

Volcanoes

Eruptions are driven by the excess pressure of volcanic fluids[15]. These fluids may consist of a combination of magma, water, gas, rock particles, and in some cases, mud. When the fluids breach the surface of a volcano, the pressure release

"Infrasound, A new frontier in monitoring the Earth"

may be recorded by microphones as distinct explosions or bursts[16], jet noise, or as a continuous vibration of the atmosphere known as tremor. Landslides and pyroclastic flows at volcanoes also produce a distinct acoustic signature that may be used for tracking the flow deposits. The forecasting potential[17] and usefulness[18] of volcano-acoustic monitoring has been well documented for explosive as well as effusive eruptions, and efforts are underway to test the ability of infrasound to provide regional, low-latency eruption warnings to the airline industry[19]. The proof of concept for this application can be readily found in the tomographic study of Reference 20, where persistent volcanic eruptions near New Caledonia have been used to infer the seasonal variability of the atmospheric wind structure. Of all the geophysical monitoring applications for infrasound, volcano surveillance is the most mature and the closest to the IMS aim of listening to explosions at large distances. However, the physics of volcanic eruptions involve pressurized, high-temperature multi-phase mixtures that may be moving at supersonic speeds through conduits of unknown geometry and stability. Infrasound usually measures the pressure at the vent, so inferring the eruptive source processes at depth requires multidisciplinary observing systems and modeling.

Ocean swells

Microbaroms are coherent infrasonic signals in the 0.1 to 0.5 Hz frequency band that may be observed anywhere in the world and are related to strong storm and ocean wave activity (e.g., Reference 21). Reference 22 showed that these microbaroms signals could also depend strongly on the atmospheric wind conditions during the year. Microbaroms are believed to originate from the nonlinear interactions of ocean waves traveling in nearly opposite directions with similar frequencies (e.g., Reference 23). Theoretical acoustic models can be coupled with global ocean wave spectra to estimate the acoustic source pressure spectra induced by microbaroms near the ocean surface[21]. The predicted acoustic source values exhibit peaks in wake regions of marine surface lows, and show a large number of weaker source regions at a distance from wave-generating storms. Comparison of microbarom observations with surface weather, ocean wave charts, and predicted acoustic sources suggests that microbarom source regions occur in locations that contain opposing wave trains, instead of exclusively from regions of marine storminess. In addition to allowing the tracking of large swells in the open oceans, microbaroms may be used for passive acoustic tomography of the atmosphere[24].

Infrasonic stations located near ocean shores routinely record infrasound from breaking waves. Reference 25 recognized a clear relationship between infrasonic amplitude in the 1-5 Hz range and breaker height, and postulated that a breaking wave may generate infrasound by barreling (plunging), slamming against a cliff, or by impacting against dry reef. Reference 26 corroborated the relationship between infrasonic and ocean wave amplitudes and located active surf regions along the coastline of Tahiti. Reference 27 reported surf infrasound propagating over 200 km inland under favorable wind and swell conditions. Recent experimental results[28] suggest that low-frequency sound can be used to monitor the energetics, spatial distribution, and temporal variability of different types of breaking ocean waves. These experiments confirmed that infrasound may be produced by plunging waves as well as by surf impinging against cliffs and exposed reefs, and demonstrated the possibility of extracting the height and period of breaking waves from single-sensor infrasound data. These new capabilities could allow more extensive oceanographic studies and monitoring of the surf zone.

Tsunamis

Infrasonic measurements of recent tsunamis[29,30] strongly suggest that low-frequency atmospheric sound may be combined with other technologies as a discriminator for tsunami genesis. Infrasonic signatures associated with the December 26, 2004 Great Sumatran Earthquake were captured by the IMS station in Diego Garcia that recorded (1) seismic arrivals from the earthquake, (2) tertiary arrivals (T-waves), propagated along sound channels in the ocean and coupled back into the ground, (3) infrasonic arrivals associated with either the tsunami generation mechanism near the seismic source or the motion of the ground above sea level, and (4) deep infrasound (with a dominant frequency lower than 0.06 Hz) originating from the Bay of Bengal. A similar sequence was observed during the March 28, 2005 Nias earthquake and tsunami. These events off the coast of Sumatra were ~3000 km to the closest infrasound station in Diego Garcia. The large ranges, coupled with the fact that all infrasound stations used in those studies were transverse to the axis of Sumatra, caused uncertainty in the ability to discriminate between sounds potentially produced during tsunami genesis at the ocean surface and the sounds produced by the earthquake-induced vibration of mountains and islands. In contrast, IMS infrasound station IS30 in Japan (Fig. 1) is optimally situated to recognize the different source regions of infrasound associated with the Miyagi-Oki earthquake and tsunami. The magnitude 7.2 event occurred August 16, 2005 at 02:46:28 UTC (Fig. 3), and the epicenter was less than 400 km from the station. Therefore, all arrivals must be stratospheric except for the furthermost sources. The earthquake produced a minor tsunami. There was no deep infrasound component suggesting that very low infrasonic frequencies are produced only by the largest tsunamis. T-waves are also absent, possibly due to the shallow bathymetry at the epicenter. However, the infrasonic arrival sequence is similar to that observed during the Sumatra events, with infrasound originating from nearby mountains, the epicentral region in the ocean, and a shallow bay that may resonate in response to the water displacement. Note that shallowest parts of the bay also appeared to produce infrasound.

The aforementioned studies suggest that tsunami-associated infrasound may be radiated from the ocean surface or be excited by the interaction of the ocean waves with the coastline and bathymetry. The effective propagation speeds of tsunami (~50-200 m/s) and sound waves (~300 m/s) yield an advance warning time of at least 1.7 s/km. At 100 km, sound

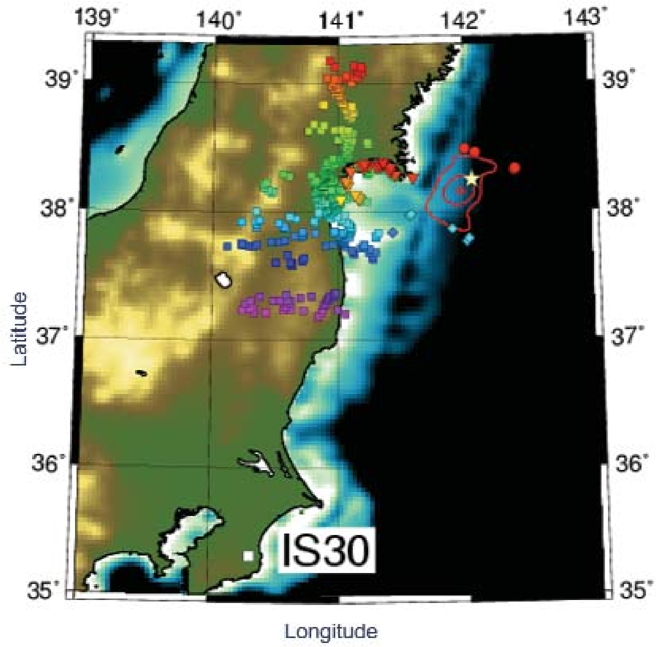

Fig. 3. Estimated infrasonic source locations associated with ground vibration, tsunami genesis, and the interaction of the tsunami with the coastline. The squares represent stratospheric arrivals with a celerity of 0.3 km/s. The diamonds are also stratospheric arrivals but with the celerity of 0.32 km/s predicted for that azimuth. The circles are thermospheric arrivals with a celerity of 0.27 km/s. The triangles are stratospheric arrivals with a celerity of 0.3 km/s, but with an additional delay time of ~250 s. The color of the symbols indicates the arrival time in seconds (~700–1450s, purple to red) since the earthquake's origin time. The topography is from the National Oceanic and Atmospheric Administration (NOAA) ETOPO2 data.

leads the tsunami by at least 170 s, but some of this time would be taken up by signal processing and identification, leaving less than one minute to issue an alert. However, infrasound may offer substantial advance warnings to areas greater than a few hundred kilometers from the tsunami source region.

Effects of the atmosphere

As infrasound propagates from source to receiver, the atmosphere has a dramatic effect on the amplitude and frequency content. In general terms, as sound propagates, the amplitude decreases exponentially with an absorption coefficient α that is proportional to the ratio of the frequency, f, squared divided by the ambient pressure, P. Absorption also depends on relative humidity. At sea-level, a signal at 100 Hz experiences absorption near 300 dB/1000 km while a signal at 1 Hz is absorbed at a rate of 0.03 dB/1000 km—a huge difference favoring low-frequency propagation. At an altitude of 30 km, characteristic of the stratosphere, the atmospheric pressure is typically about 1/100th that at sea level that would give rise to absorption of 3dB/1000 km at 1 Hz. At 120 km, in the thermosphere, the absorption increases to near a 1000 dB/1000 km. For all practical purposes, a 1 Hz signal cannot get to the thermosphere and back[31].

The other atmospheric factor that influences infrasound propagation is the variation of wind and temperature with altitude. Under typical conditions, as the altitude increases from sea level, the speed of sound decreases due to decreasing atmospheric temperature (the adiabatic lapse). This trend (Fig. 4) reverses at the stratosphere when the temperature begins to increase. These variations give rise to a propagation duct that can trap sound. As sound moves in this duct, its amplitude decreases as 1/r, characteristic of cylindrical spreading rather than $1/r^2$ characteristic of spherical spreading. Since the ducts that are formed are not rigid, sound leaks out of the duct back to the ground and sound propagating from the surface of the Earth can be diverted back to the surface by the duct boundaries. As a result, where rays can propagate upward to the duct and are reflected back to the ground, shadow zones and hot spots are formed. At greater altitudes there is another duct at the thermosphere that is always present regardless of winds. That duct is so high that high-frequency sound is absorbed prior to reflecting from the upper part of that duct. Only very low-frequency sound can make it back to the ground so signals received after reflection from the thermosphere are very low in frequency content.

The speed at which sound propagates is also affected by the winds. If sound is propagating against prevailing winds, the increase in sound speed above the stratosphere can be negated by winds destroying the ducted propagation in a direction against the wind while retaining ducted propagation with the wind.

Non-linear effects arise as sound propagates over long distances and at high altitudes. As a sound wave propagates upward, the amplitude decreases as 1/r or $1/r^2$ modified by

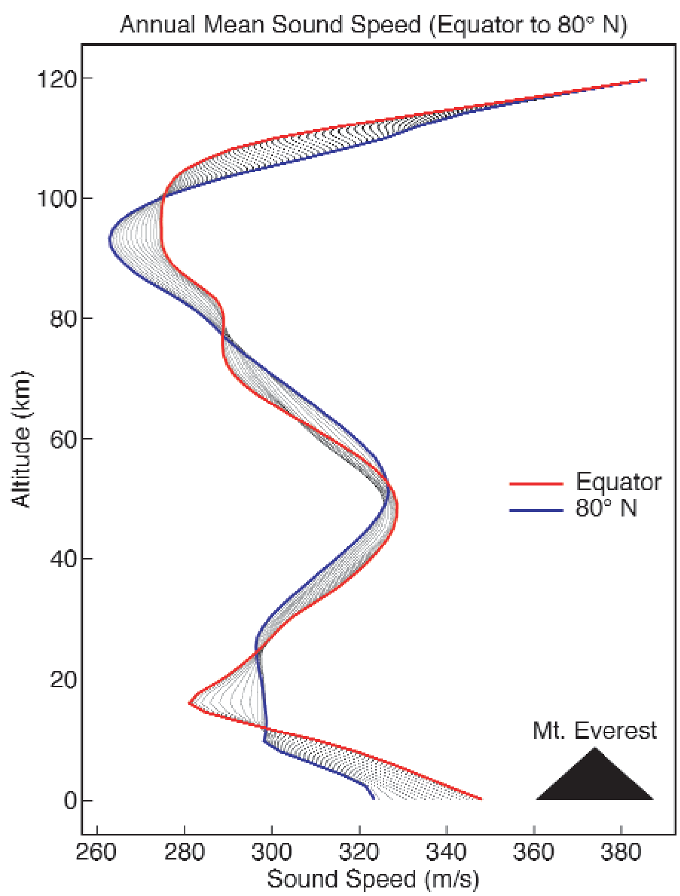

Fig. 4. Annual mean sound speed in the northern hemisphere from the equator to 80° North. These curves are based on an empirical model of atmospheric temperature provided by the Committee on Space Research (COSPAR) in 1986 (CIRA-86).

atmospheric absorption. At the same time, the atmospheric pressure decreases exponentially with a halving distance of about 5 km. As the sound waves reach higher altitudes, the ratio of the sound pressure, Δp, to the ambient pressure, p, increases and non-linear effects become more important. One such effect is the creation of harmonics or a shift of energy from low frequency to high frequency. Since high frequencies are absorbed more rapidly, this has the effect of distorting waveforms and increasing overall attenuation of sound.

These combined effects make propagation predictions quite complex. Add in the effect of ground bounces and turbulence and the overall physics is challenging. The individual elements of propagation have been studied for decades and are well understood. Recently there have been quite successful attempts to combine all the effects that impact signal amplitudes and frequency content into a single algorithm. Although that effort is a work in progress, the software package InfraMAP[32] does a reasonable job including all relevant physics as well as modern meteorological models. The ability to correct for atmospheric effects has now reached the point where researchers feel confident using measurements of received signals at different directions and distances from a source to infer the conditions of the intervening atmosphere using acoustic tomography. This ability promises to provide a tool to continuously measure the wind speeds of the upper atmosphere in near real time globally.

Limitations imposed by wind noise

Wind is the dominant source of noise recorded by infrasound stations and can readily overwhelm signals of interest[33]. A quick glance at a raw infrasound record clearly reveals the strong diurnal wind pattern that characterizes most locations on the Earth (Fig. 5). The large pressure fluctuations created by the wind obscure the weak signals from distant infrasound sources. This is especially striking given that, where possible, most infrasound stations have intentionally been sited in low wind locations. In fact, a recent study of the wind speeds observed at infrasound stations showed that most stations have mean annual wind speeds of roughly 3 m/s or less (a "light breeze" on the Beaufort scale).

Many strategies have been explored to reduce the impact of wind-generated infrasound noise. Pipe-rosettes, as described above and by References 2 and 34 are perhaps the most common form of wind filter used today. A variant uses porous hose, rather than non-porous pipe, to construct the rosette. Regardless of the materials used, these strategies all attempt to exploit the incoherence of wind-induced pressure fluctuations over length scales of tens of meters. Another effective wind mitigation strategy is the wind fence[35] that surrounds a microbarometer in much the same way a foam windscreen surrounds a microphone.

New instruments and approaches are also being developed to provide alternatives to mechanical wind suppression techniques. For example, a distributed sensor[36] consisting of numerous individual microphones allows signals to be summed electronically rather than mechanically (such as in the summing manifolds of pipe rosettes). The clear advantage of this approach is that these data can be summed adaptively to optimally reduce the noise and preserve the signal. The recently developed optical fiber infrasound sensor[37] is another approach to electronic, and thus instantaneous, averaging of wind noise. In this instrument optical fibers wrapped around a sealed, compliant tube measure the total deformation of the tube, sensing the coherent deformations of the tube induced by acoustic waves and averaging out the incoherent deformations along the length of the tube that are due to wind fluctuations. Several optical fiber infrasound sensors (OFIS) distributed in a fan configuration have been used to characterize the signal as well as remove incoherent noise.

Current research on the physical mechanisms responsi-

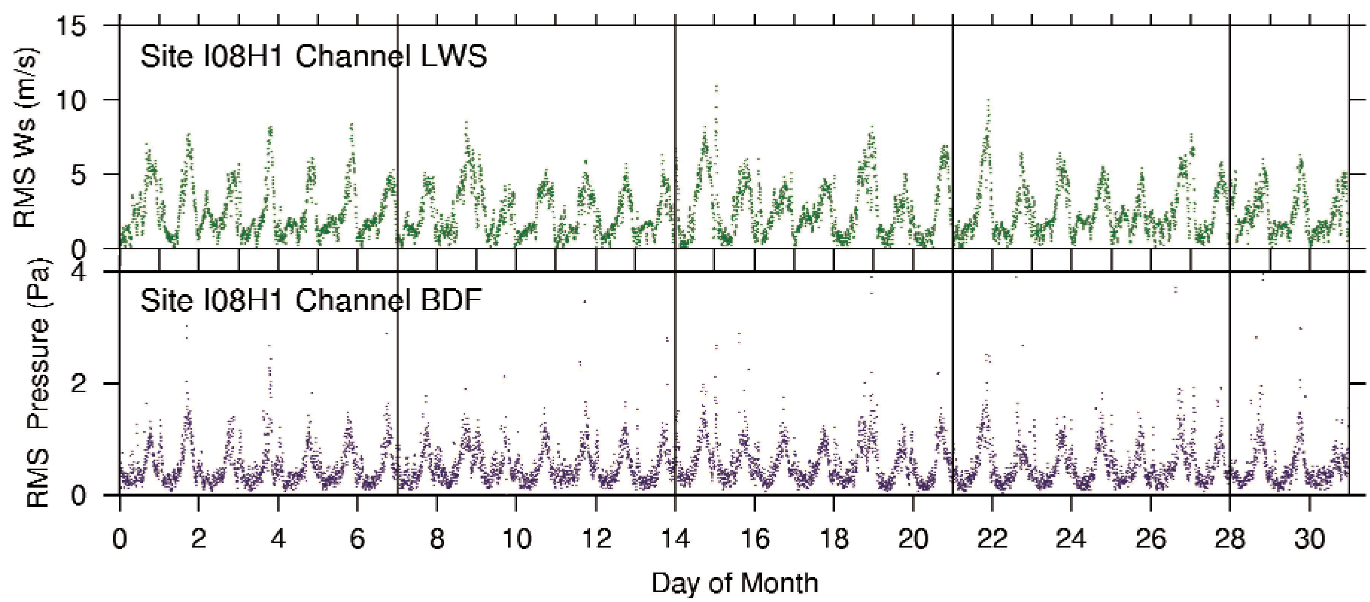

Fig. 5. A one month time series showing root-mean-square (RMS) infrasound variations (bottom) and RMS wind speed (top) for October 2004 for an infrasound station near Lake Titicaca in Bolivia. A clear diurnal variation in the wind speed, peaking at about 5-6 m/s, is obvious and is strongly correlated to the pressure variations.

ble for wind-induced infrasound noise may provide another means of mitigating wind noise. Figure 6 illustrates the general characteristics of the functional relationship between wind and infrasound noise. We see that at low wind speeds the wind has relatively little effect on the observed infrasound noise. However, above some threshold wind speed, typically around 1-2 m/s, the infrasound noise increases dramatically with increasing wind speed. As Fig. 6 demonstrates, the relationship between infrasound noise and wind speed varies with seasons, even for the same wind speed. The likely explanation for this observation is the wind filtering effect of seasonal vegetation. Since most pipe rosettes are deployed at ground level even low growing vegetation will have an impact on the wind experienced by the infrasound sensors in this "boundary layer" regime. By exploiting the relationship between wind and infrasound noise, such as shown in Fig. 5, it may be possible to use wind observations to essentially subtract or "cancel" the wind noise that contaminates the infrasound observations.

Taken together, the new developments in sensor and wind-filter design, combined with our improving understanding of the physical mechanisms responsible for wind-generated noise, are providing important new tools for mitigating the impact of wind noise on infrasound observations.

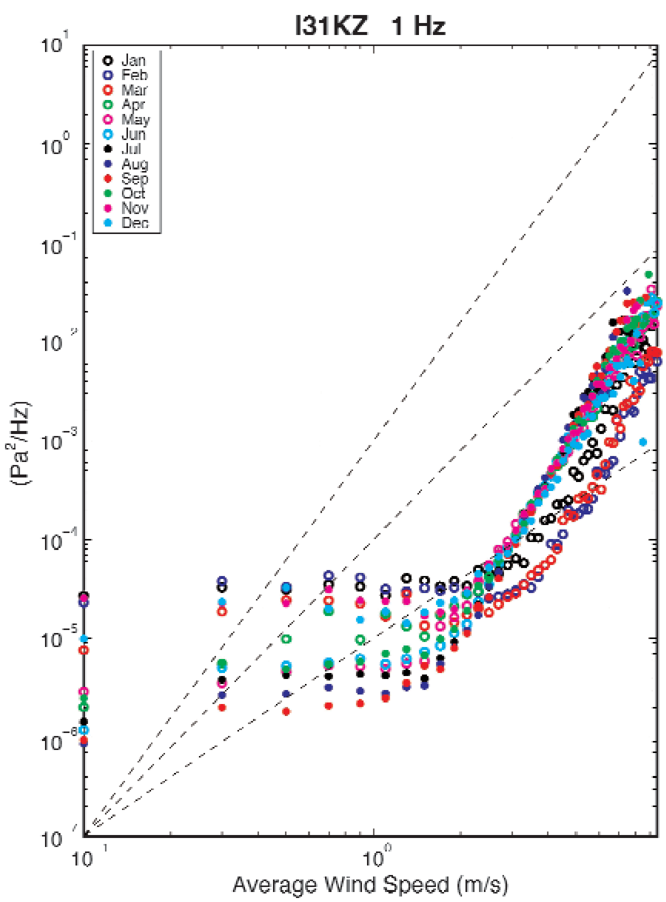

Fig. 6. Infrasound noise, as a function of average wind speed during 2004 for a station in Kazakhstan. The different colored symbols show the average values for different months of the year. Dashed lines are for reference and have slopes of 2, 3, and 4.

Shuttle investigation

Acoustic emissions from space shuttle missions on their return to Earth have been routinely observed at infrasound stations located at several locations in continental North America. As sound passes through the atmosphere, stratification of winds and temperature as well as turbulence modifies the received signal. Sound propagating from source to receiver along different paths can arrive at the receiver at different times giving rise to time-separated signals. Below and to each side of the shuttle path, there is a sonic boom carpet, defined by the Mach cone of the shuttle intersecting the Earth's surface. Outside the carpet, signals similar to those from subsonic sources were observed that can be predicted if atmospheric conditions are well established[38]. The infrasound array stations can determine the direction of the signal that when combined with the trajectory of the re-entry and the arrival times, allows us to identify the approximate location of the source of the infrasound emission.

The ill-fated STS-107 *Columbia* shuttle mission is probably one of the best studied infrasound events. Infrasound signals recorded by ten stations during the reentry have been analyzed in an attempt to better understand this tragedy[38,39]. Data from stations in Texas and New Mexico clearly show more than one arrival. Other stations have suggestions of multiple arrivals, probably due to multiple paths through the atmosphere though it is possible that some come from fragments or debris from the break-up of the shuttle. Without explicitly identifying the size and location of debris, based on our current limited experience with such datasets, it is difficult to unambiguously separate these two hypotheses.

Infrasound arrays that clearly detected the re-entry of this mission were located at Pinon Flat, CA, Newport, WA, at Lac du Bonnet, Manitoba of the International Monitoring System, from experimental infrasonic arrays operated by Los Alamos National Laboratory at St. George, UT, Los Alamos, NM, and Pinedale, WY, from arrays operated by Southern Methodist University at Mina, NV and Lajitas, TX, a National Oceanic and Atmospheric Administration (NOAA) array located near Boulder, CO, and a temporary array at White Sands Missile Range operated by the Army Research Laboratory. Figure 7 shows the location of these stations in relation to the known trajectory of the shuttle, along with the signals associated to the re-entry[38]. The primary conclusions from analyzing the infrasound signals are: (a) no signals could be detected at the arrays in Hawaii and Alaska; (b) signals detected at the other stations were quite simple for recording sites close to the trajectory and increasingly complex at greater distances from the path of the *Columbia*; (c) these signals were largely from the direction of the closest approach of the *Columbia* to each recording array, with some information from other directions; (d) stations Mina, St. George and Los Alamos that are all within 100 km of the trajectory, detected clear bow or N waves; and, (e) atmospheric propagation modeling using InfraMAP[32] could sufficiently predict the arrival times at the nearest stations, but did not account for all signal complexity at the more distant stations. Further comparison of infrasound signals to those for flights STS-77, STS-78, and STS-90 that had similar re-entry trajectories suggests that other than an hour-long acoustic emission following the bow-wave, STS-107 signals are not anomalous.

Summary

The rebirth of interest in infrasound resulting from the International Monitoring System has provided a cadre of personnel and experimental stations capable of monitoring the Earth for sources of infrasound. In an era where hazard warning is an important element of mitigation, infrasound provides one more monitoring tool. Use of the global system to provide information on nuclear treaty violations is certainly important but the most probable use of the system over the next decade will be in the nature of infrasound sources and hazard warnings. As a global monitoring tool, infrasound requires the cooperation of scientists from all countries. The extent of this effort exceeds that associated with the ocean warming experiments envisioned during the past decade. Never in our lifetime has there been an effort to conduct acoustics research on such a large scale. This article offers glimpses of what might be learned from this vast array but the full realization of the potential of this investment relies on participation of the entire acoustics community.**AT**

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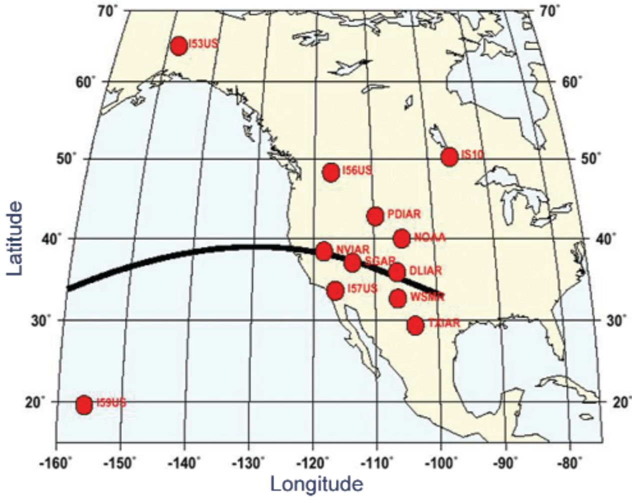

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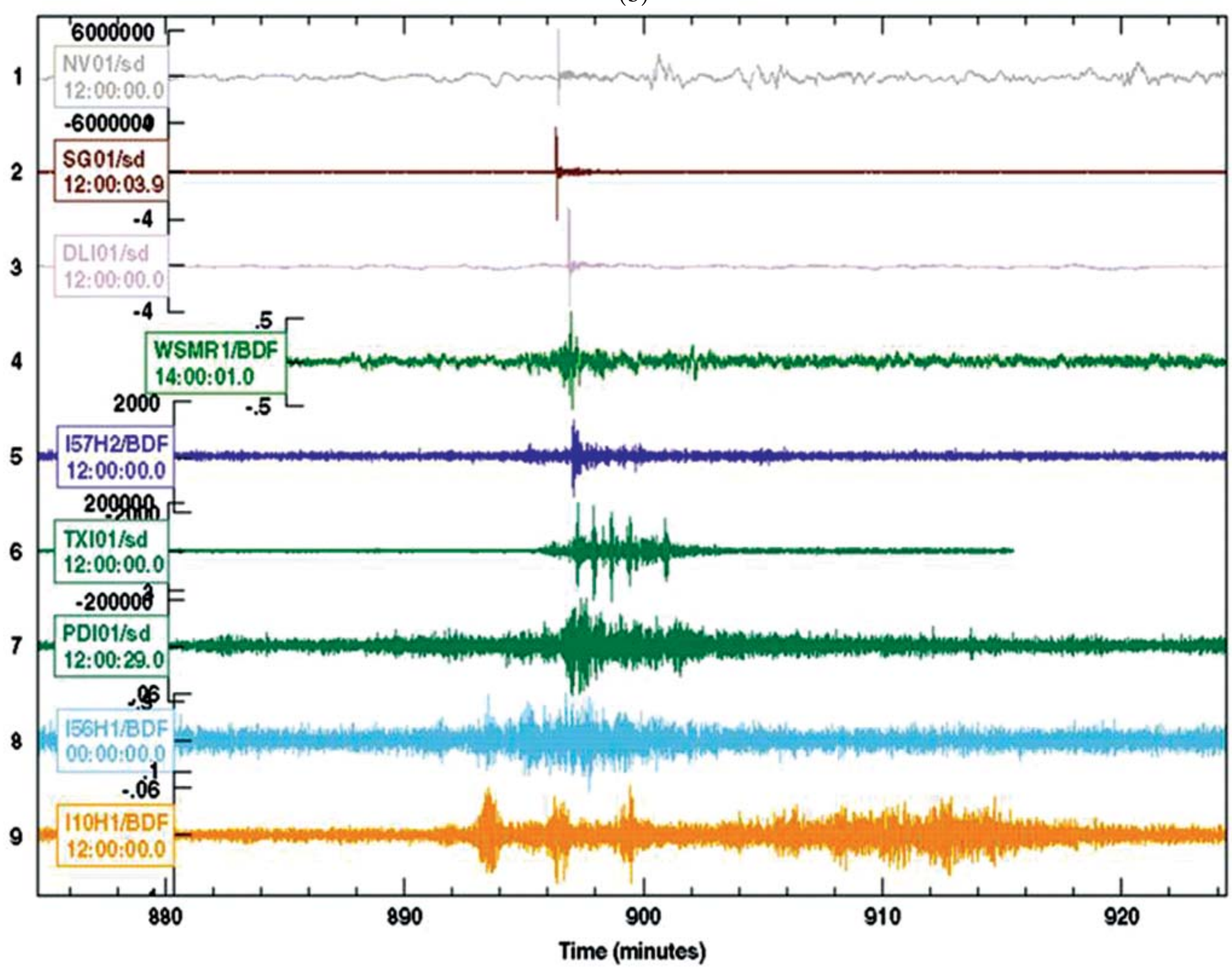

Fig. 7. Results of infrasound analysis of the Columbia shuttle (STS-107) re-entry on February 1, 2003. (a) Projected track and the locations of the infrasonic stations (circles) whose data have been analyzed (after Reference 38). (b) Single-channel traces from each of the infrasound arrays which clearly detected infrasonic signals from the Shuttle re-entry. The traces are aligned on the first detected infrasonic arrival, and ordered by distance of closest approach of the nominal trajectory to the recording location.

References for Further Reading

1. G.B. Olmsted, "Detection of airborne low-frequency sound from atomic explosion of operations Buster and Jangle,"

Headquarters, US Air Force, Office for Atomic Energy, 15 March 1952.

2. A. Alcoverro and A. Le Pichon, "Design and optimization of a noise reduction system for infrasonic measurements using elements with low acoustic impedance," J. Acoust. Soc. Am. **117**, 1717-1727 (2005).

3. R.H. Shumway, "On detecting a signal in N stationarily correlated noise series," Technometrics **13**, 499 (1971).

4. Y. Cansi, "An automated seismic event processing for detection and location: The P.M.C.C. method," Geophys. Res. Lett. **22**, 1021-1024 (1995).

5. B.A. Bolt, "Seismic air waves from the great 1964 Alaskan earthquake," Nature **202**, 1095–1096, (1964).

6. J.P. Mutschlecner and R.W. Whitaker, "Infrasound from earthquakes," J. Geophys., Res. **110**, doi:10.1029/2004JD005067 (2005).

7. A. Le Pichon, J. Guilbert, A. Vega, M. Garcés, and N. Brachet, "Ground-coupled air waves and diffracted infrasound from the Arequipa earthquake of June 23, 2000," Geophys. Res. Lett. **29**(18), 1886, doi:10.1029/2002GL015052 (2002).

8. A. Le Pichon, J. Guilbert, M. Vallée, J.X. Dessa, and M. Ulziibat, "Infrasonic imaging of the Kunlun Mountains during the great 2001 China earthquake," Geophys. Res. Lett. **30**(15), 1814, doi:10.1029/2003GL017581 (2003).

9. J.V. Olson, C.R. Wilson, and R.A. Hansen, "Infrasound associated with the 2002 Denali fault earthquake, Alaska," Geophys. Res. Lett. **30**(23), 2195, doi:10.1029/2003GL018568 (2003).

10. C.R. Wilson, "Auroral infrasonic waves," J. Geophys. Res. **74**, 1812–1836 (1969).

11. M. Garcés, C. Hetzer, H. Bass, M. Hedlin, K. Lindquist, J. Olson, C. Wilson, D. Drob, and M. Picone, "Forensic studies of infrasound from massive hypersonic sources," EOS **85**(43), 433–440 (2004).

12. P. Brown, R.E. Spalding, D.O. ReVelle, E. Tagliaferri, and S.P. Worden, "The flux of small near-Earth objects colliding with the Earth." Nature **420**, 294–296 (2002).

13. A. Le Pichon, J.M. Guerin, and E. Blanc, "Trail in the atmosphere of the 29 December 2000 meteor as recorded in Tahiti: Characteristics and trajectory reconstitution," J. Geophys. Res. **107**, No. D23, 4709, doi:10.1029/2001JD001283 (2002).

14. D.O. ReVelle, P.G. Brown, and P. Spurny, "Entry dynamics and acoustics/infrasonic/seismic analysis for the Neuschwanstein meteorite fall," Meteoritics and Planetary Sci. **39,** 1605–1625 (2004).

15. M.A. Garcés, M.T. Hagerty, and S.Y. Schwartz, "Magma acoustics and time-varying melt properties at Arenal Volcano, Costa Rica," Geophys. Res. Lett. **25**, 2293–2296 (1998).

16. M. Ripepe, P. Poggi, T. Braun, and E. Gordeev, "Infrasonic waves and volcanic tremor at Stromboli," Geophys. Res. Lett. **23**, 181–184 (1996).

17. M. Garcés, 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).

18. J.B. Johnson, 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. Volc. Geotherm. Res. **121**, 15–63 (2003).

19. D. McCormack, H. Bass, M Garcés, and H. Yepes, "Acoustic surveillance for hazardous eruptions (ASHE)," J. Acoust. Soc. Am. **117**, 2419 (2005).

20. A. Le Pichon, E. Blanc, D. Drob, S. Lambotte, J.X. Dessa, M. Lardy, P. Bani, and S. Vergniolle, "Infrasound monitoring of volcanoes to probe high-altitude winds," J. Geophys. Res. **110**, D13106 (2005).

21. M. Willis, M. Garcés, C. Hetzer, and S. Businger, "Infrasonic observations of open ocean swells in the Pacific: Deciphering the song of the sea," Geophys. Res. Lett. **31,** L19303, doi:10. 1029/2004GL020684 (2004).

22. M. Garcés, M. Willis, C. Hetzer, and D. Drob, "On using ocean swells for continuous infrasonic measurements of winds in the lower, middle, and upper atmosphere," Geophys. Res. Lett. **31**, L19304, doi:10.1029/2004GL020696 (2004).

23. S. Arendt and D. Fritts, "Acoustic radiation by ocean surface waves," J. Fluid Mech. **415**, 1-21 (2000).

24. A. Le Pichon and D. Drob, "Contribution of infrasound monitoring for atmospheric investigations," J. Acoust. Soc. Am. **117**, 2420 (2005).

25. M. Garcés, C. Hetzer, M. Merrifield, and J. Aucan, "Observations of surf infrasound in Hawai'i," Geophys. Res. Lett. **30**, 2264, doi:10.1029/2003GL018614 (2003).

26. A. Le Pichon, V. Maurer, D. Raymond, and O. Hyvernaud, "Infrasound from ocean swells observed in Tahiti," Geophys. Res. Lett. **31**, L19103, doi:10.1029/2004GL020676 (2004).

27. S.J. Arrowsmith and M.A.H. Hedlin, "Observations of infrasound from surf in southern California," Geophys. Res. Lett. **32**, L09810, doi:10.1029/2005GL022761 (2005).

28. M. Garcés, P. Caron, C. Hetzer, A. Le Pichon, H. Bass, D. Drob, and J. Bhattacharyya, "Deep infrasound from the Sumatra earthquake and tsunami," EOS, (2005).

29. M. Garcés and S. McNamara, "Infrasound from the 2005 Miyagi-Oki tsunami," Geophys. Res. Lett. (2005) (submitted).

30. A. Le Pichon, P. Herry, P. Mialle, J. Vergoz, N. Brachet, D. Drob, M. Garcés, and L. Ceranna, "Infrasound associated with large Sumatra earthquakes and tsunami," Geophys. Res. Lett. (2005) (in press).

31. L.C. Sutherland and H.E. Bass, "Atmospheric absorption in the atmosphere up to 160 km," J. Acoust. Soc. Am. **115**, 1012–1032 (2004).

32. D. Norris and R. Gibson, "Advanced Tools for Infrasonic Modeling," InfraMatics, No. 5, 13–19 (2004).

33. M.A.H. Hedlin, B. Alcoverro, and G. D'Spain, "Evaluation of rosette infrasonic noise-reducing spatial filters," J. Acoust. Soc. Am. **114**, 1807-1820 (2003).

34. A. Alcoverro and A. Le Pichon, "Design and optimization of a noise reduction system for infrasonic measurements using elements with low acoustic impedance," J. Acoust. Soc. Am. **117**, 1717–1727 (2005).

35. M.A.H. Hedlin and R. Raspet, "Infrasonic wind-noise reduction by barriers and spatial filters," J. Acoust. Soc. Am. **114**, 1379-1386 (2003).

36. F.D. Shields, "Low-frequency wind noise correlation in microphone arrays," J. Acoust. Soc. Am. **117**, 3489-3496 (2005).

37. M. Zumberge, J. Berger, M.A.H. Hedlin, E. Husmann, S. Nooner, R. Hilt, and R. Widmer-Schnidrig, "An optical fiber infrasound sensor: A new lower limit on atmospheric pressure noise between 1 and 10 Hz.," J. Acoust. Soc. Am. **113**, 2474-2479 (2003).

38. H.E. Bass, et al., Report to the Department of Defense on Infrasonic Re-entry Signals From the Space Shuttle Columbia (STS-107) (Revision 3.0), Eos Trans. AGU, **84**(46), Fall Meet. Suppl. (2003).

39. M. Garcés, C. Hetzer, H. Bass, M. Hedlin, K. Lindquist, J. Olson, C. Wilson, D. Drob, and M. Picone, "Forensic studies of infrasound from massive hypersonic sources," EOS, **85**(43), 433–440 (2004).

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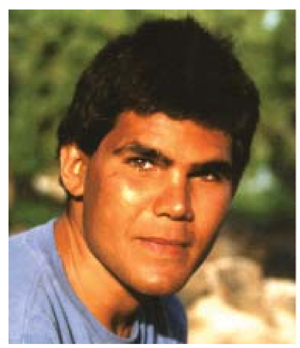

Milton A. Garcés has expanded his early interest in volcano acoustics to the study of global infrasound from natural and man-made sources, and founded the Infrasound Laboratory (ISLA) of the University of Hawai'i for the development of infrasound research and technology. One of his primary projects involves the operation of stations in the Pacific and Indian Oceans that are part of the global infrasound network of the International Monitoring System. Under Dr. Garcés' direction, the ISLA has collaborated with national and international organizations in the analysis of signals associated with the April 23, 2001 superbolide explosion, the February 2003 *Columbia* disaster, and the December 26, 2004 Sumatra earthquake and tsunami. In addition to the nuclear monitoring projects, ongoing projects include the development of acoustic monitoring techniques that provide low-latency volcanic eruption warnings to the aviation community, the identification and modeling of low frequency sound from ocean processes, community building efforts in the formation of an International Infrasound Consortium, and education and outreach in the Geosciences.

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