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ATMOSPHERIC INFRASOUND

The search for ways to monitor compliance with the Comprehensive Test Ban Treaty has sparked renewed interest in sounds with frequencies too low for humans to hear.

Alfred J. Bedard Jr and
Thomas M. Georges

Imagine a world in which you could hear not just nearby conversations and the noise of traffic a few blocks away, but also the sound of blasting in a quarry in the next state, the rumblings of an avalanche or volcano a thousand miles away, and the roar of a typhoon halfway around the world. Fortunately, nature has spared our senses from direct exposure to this incessant din. But our relentless quest to extend our senses has yielded instruments that can do just that—and more. Waves of infrasound, sounds at frequencies too low for us to hear, permeate the atmosphere and offer us insights into natural and human-made events on a global scale.

The term infrasound was coined by following the convention adopted nearly two centuries ago for light waves. The invisible, longer waves below the red end of the visible spectrum were called infrared, and shorter waves beyond the violet end were called ultraviolet. ("Infra" and "ultra" are from the Latin, meaning "below" and "beyond," respectively.) The nominal range of human hearing extends from about 20 Hz to 20 000 Hz, so the inaudible sound waves with frequencies below 20 Hz were dubbed infrasound, while those above the upper limit of 20 000 Hz were named ultrasound. (Many animals can hear beyond the human limits, as described in the box on page 35.) Following the optical convention even further, frequencies just below 20 Hz are known as near-infrasound, and frequencies below about 1 Hz are often called far-infrasound. Near-infrasound, if sufficiently intense, is often felt rather than heard—as you might have experienced when you pass cars equipped with "mega-bass" audio systems. (See figure 1 for two examples of low-frequency sound sources.)

Interest in atmospheric infrasound peaked during the Cold War as one of several ways to detect, locate, and classify nuclear explosions at global distances. Now, the Comprehensive Test Ban Treaty calls for a more sophisticated global sensor network to monitor compliance.[1] There is a need to ensure that tests of clandestine, low-yield nuclear devices can be detected under conditions of noise, cloud cover, or other masking situations underground, underwater, or in the atmosphere. An integrated global sensor array now being deployed would address this problem by coordinating observations from multiple ground-based sensor types, including seismic, hydroacoustic, and infrasonic arrays, working in concert. (See Jeremiah Sullivan's article on the Comprehensive Test Ban Treaty, PHYSICS TODAY, March 1998, page 24.)

In anticipation of a CTBT monitoring system, infrasound research has returned full circle to its origins. In this article, we review the science and technology of atmospheric infrasound, beginning with a brief history of its Cold War origins. Our focus, however, is on the richness of Earth's infrasonic environment, unheard and unknown until instruments were built to detect and record it. Practical applications of this new science are just now being contemplated.

A little history

Pressure waves from very powerful explosions may be detected after traveling several times around the Earth. Two famous pre-nuclear instances were the explosion of the Krakatoa volcano in 1883 and the Great Siberian Meteorite of 1909. Following each of these events, sensitive barometers around the world recorded impulsive pressure fluctuations as traces on paper charts. Later, meteorologists collected these charts from stations around the world and, by comparing arrival times, were able to reconstruct the progress of pressure waves radiating outward from the source at the speed of sound, sometimes passing an observing station two or three times.

But these disturbances pale when compared with the political shock waves from the explosion of the first Soviet atomic bomb in 1949. Cold War fears stimulated a flurry of "remote-sensing" research—much of it classified—to detect and locate nuclear explosions halfway around the world. Among the technologies explored during those early years of the Cold War were seismic arrays, electromagnetic (radio to gamma-ray) sensors, and arrays of microphones to listen to very-low-frequency sound waves in the atmosphere.

In the early 1950s, a number of institutions contributed to the successful deployment of a global infrasonic monitoring network. Lewis Strauss, in his book, *Men and Decisions*, describes recording low-frequency air waves at the National Bureau of Standards in Washington, DC, following a 1954 nuclear test in the Pacific. He took the recording to President Eisenhower and played a sped-up version that made the recording audible. Strauss emphasizes the strategic importance, during those early Cold War years, of nuclear intelligence provided by a worldwide monitoring system that included both remote sensing and a radionuclide sampling program.[2]

Early defense-driven infrasound research had multiple foci,[3] including mathematical models for the intensity and spectrum of sound waves generated by various kinds of explosions, how these waves propagate long distances through the atmosphere, what kinds of sensors would be best suited for detecting their signatures, and how those signatures could be extracted from a bewildering variety of natural and human-made infrasonic noise. The Limited Test Ban Treaty of 1963, which prohibits testing of

ALFRED BEDARD *is a research scientist at the National Oceanic and Atmospheric Administration's Environmental Technology Laboratory, in Boulder, Colorado.* **THOMAS GEORGES** *is a research scientist at the NOAA/Colorado State University Cooperative Institute for Research in the Atmosphere, also in Boulder.*

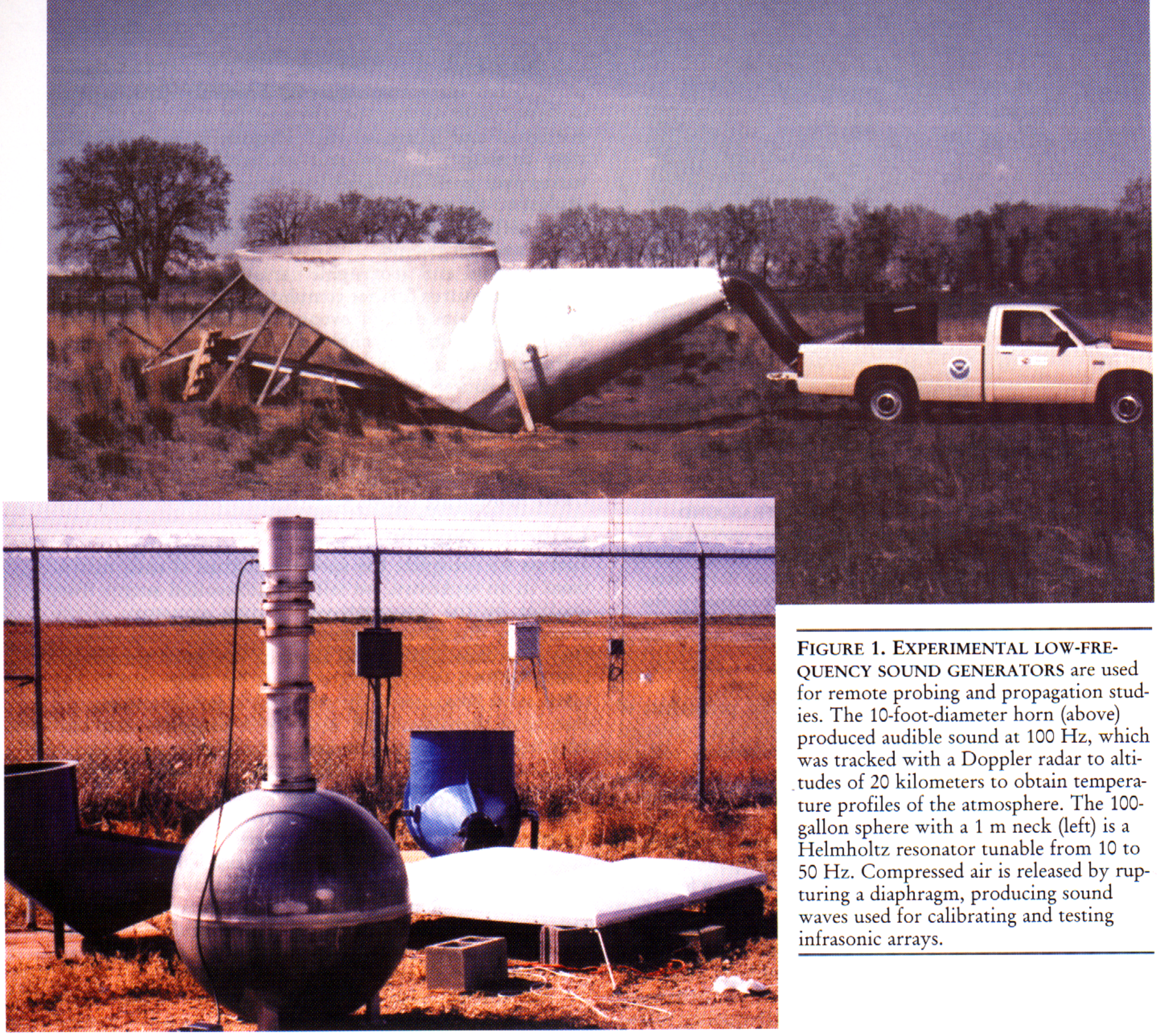

FIGURE 1. EXPERIMENTAL LOW-FREQUENCY SOUND GENERATORS are used for remote probing and propagation studies. The 10-foot-diameter horn (above) produced audible sound at 100 Hz, which was tracked with a Doppler radar to altitudes of 20 kilometers to obtain temperature profiles of the atmosphere. The 100-gallon sphere with a 1 m neck (left) is a Helmholtz resonator tunable from 10 to 50 Hz. Compressed air is released by rupturing a diaphragm, producing sound waves used for calibrating and testing infrasonic arrays.

nuclear weapons in the atmosphere, oceans, and space, resulted in greater emphasis on seismic methods and less on atmospheric acoustic methods. An advanced infrasonic monitoring network was designed but never deployed. With the evolution of a sophisticated satellite-based nuclear detection system, defense funding for "geoacoustics," as it was then called, all but dried up. The end of that era was marked by a 1967 review with the bizarre title, "Exploring the atmosphere with nuclear explosions."[4] By that time, however, the study of Earth's infrasonic environment had expanded beyond its defense boundaries and had grown into a science in its own right.[5]

Noise becomes signal

Uncovering the mysteries of natural phenomena that were formerly someone else's "noise" is a recurring theme in science. Since the 1970s, the science of atmospheric infrasonics has focused on understanding the structure of natural infrasound, where it comes from, and how it travels through the atmosphere. If we listen to these ultra-low frequencies with suitable instruments, we find a virtual symphony of natural and human-made sounds whose intensities are comparable with those of audible sounds and whose signatures often reveal distant geophysical events. What we have learned about this "geophysical noise" may now become an important part of the strategy behind the CTBT monitoring network.

As an example of the richness of the near-infrasound environment, figure 2 is a half-hour spectrogram, or "voice-print" of infrasonic signals between 1 and 20 Hz, recorded during midday near Boulder, Colorado. It shows a variety of inaudible signatures, some with complex frequency variations over time, others with unchanging frequency. This picture is but a small sample of a wealth of infrasonic signals of unknown origin. At other times, signals begin and end abruptly, or recur at certain times of day, suggesting sources in civilization.[6] Even using direction-finding microphones, the sources have proven more difficult to locate than one would expect. Other more complex signatures may have natural origins.

Figure 3 shows the frequency and amplitude ranges of sounds familiar to us. Below the (frequency-dependent) threshold of human hearing lies infrasound. The pressure fluctuations on our eardrums exerted by ordinary conversation are less than one-millionth of normal atmospheric pressure. Roughly the same range of pressure levels

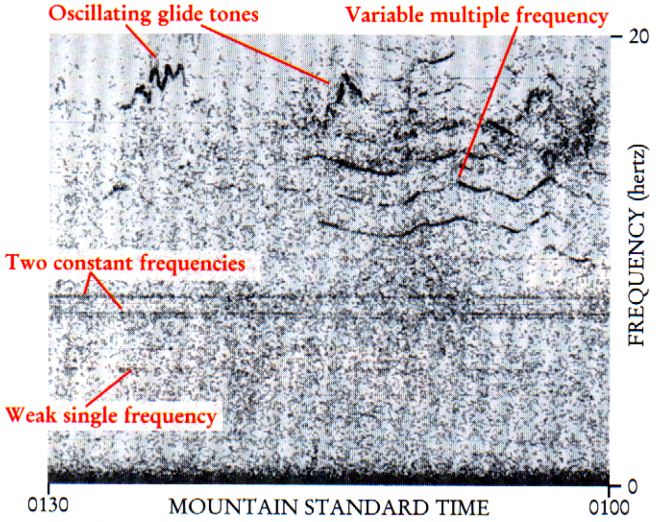

FIGURE 2. SONOGRAM OF ATMOSPHERIC INFRASOUND between 1 and 20 Hz, recorded over a 30 minute interval at Boulder, Colorado. A six-month survey revealed more infrasonic activity and a greater variety of signal types above 10 Hz than below. Although the sources of these signals are unknown, the constant spectral lines probably have artificial origins.

characterize natural and artificial infrasound.

One of the most interesting and useful properties of infrasound is that it travels with relatively undiminished strength over global distances. Even our senses tell us that low frequencies can be heard farther away than high frequencies. When you hear thunder from a nearby storm, its sharp crack is full of high-frequency components. But thunder from distant storms is always characterized as a "deep rumble," devoid of high-frequency components.

So audible sound is rarely heard more than a few tens of kilometers from its source. This is because higher frequencies are more strongly absorbed by atmospheric viscosity and thermal conduction. The air may not seem very viscous, but to an air parcel trying to move back and forth at audible frequencies, it is as sluggish as molasses. Absorption increases as the square of the frequency. Ninety-percent of the energy of a 1000 Hz tone is absorbed (in addition to losses due to spreading) after traveling 7 km at sea level. At 1 Hz, that distance is 3000 km, and at 0.01 Hz, it exceeds the Earth's circumference.

The temperature and wind structure of the atmosphere bends infrasonic waves in the same way that lenses refract light waves. The temperature of the atmosphere decreases and increases with altitude in a complicated way, causing reflection and channeling of infrasound waves over great distances (see figure 4). Waves from an explosion, for example, can arrive at a sensor by way of many different paths that bounce between atmospheric layers and the ground.

Seasonal and geographic variations in global winds and temperatures further complicate the interpretation of infrasound from distant events. The direction of middle atmospheric winds strongly affects the observability of infrasound at ground level, as well as one's ability to locate the source. Waves that propagate "downstream" are more readily detected because they are strongly focused at ground level. Understanding upper-atmosphere climatology and its effects on infrasound propagation would thus be a critical requirement in the design of an infrasonic CTBT monitoring network.

Unheard symphony

Just as we recognize the special qualities of each instrument in an orchestra, we tell one infrasound source from another by the frequency-versus-time signature of the sound, the direction it comes from, and how long it lasts. One difference, however, is that the orchestra we are listening to here contains some unknown instruments. The table below lists some of the geophysical infrasound sources that have been identified, along with potential uses that have been contemplated and areas for further research.

One example is the infrasound from an avalanche, which is identified by its distinct train of nearly monochromatic waves. Experiments have shown that deeper, faster-moving avalanches radiate lower frequencies that can be detected hundreds of miles away. Their frequency content is predicted by a model of roll-wave instabilities that modulate changes of state between ice and liquid. This work has resulted in efforts to create infrasonic monitoring networks for short-term warning, as well as for collecting regional avalanche statistics.

An almost continuous but relatively weak background of atmospheric infrasound lies in the 5-to-7-second range of wave periods. These waves, called "microbaroms" are believed to be generated by nonlinear ocean–wave interactions in ocean storms around the world. While nearly monochromatic in frequency, these infrasonic

Natural Infrasound—Potential Applications and Future Research

Sources	Applications	Areas for research
Avalanches	Determine location, depth, duration, occurrence statistics	Relate signature to avalanche size and type
Meteors	Determine altitude, direction, type of entry (explosive or bow shock); determine size and impact location	Estimate size and type distribution; determine ablation rates, volumetric meteor survey limits
Ocean waves	Locate wave interaction areas; determine wave magnitudes and spectra	Monitor evolution of storms at sea; study wave–wave interactions
Severe-weather systems	Estimate storm location and energy	Study storm microphysical processes; model acoustic radiation
Tornadoes	Detection, location, and warning; estimate core radius; image funnel shape at short ranges	Study tornado formation processes; look for infrasonic precursors
Turbulence	Aircraft avoidance; estimate altitude, strength, and spatial extent	Distinguish among several generative processes; develop practical detection systems
Earthquakes	Measure Rayleigh waves; measure sound from intermediate radiation points; measure sound from the epicenter	Look for infrasonic precursors; understand seismic–acoustic coupling
Volcanoes	Estimate location and energy released	Determine relationships between infrasonic and seismic disturbances

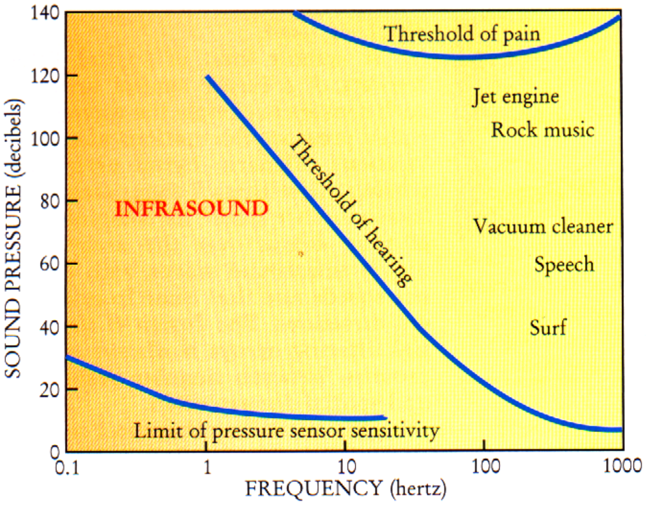

FIGURE 3. THRESHOLD OF HUMAN HEARING at low frequencies. The low-frequency domain of infrasound lies to the left of the nominal threshold of human hearing and feeling on this pressure-versus-frequency diagram. The regions occupied by familiar sounds are at the right. Frequencies below about 1 Hz can travel relatively undiminished for hundreds or thousands of kilometers through the atmosphere. The curve at the lower left roughly indicates the present limit of detectability imposed by atmospheric winds and turbulence.

waves, which have been called "the voice of the sea," are relatively incoherent in space, suggesting a spatially extended source. One model for the sound generation process involves trains of interfering ocean waves producing local regions of vertical motion.

Some infrasounds that last for as long as several days have been triangulated to distant mountain ranges and tend to occur when the winds blowing over them exceed a certain speed. This effect may be the low-frequency version of the aeolian tones produced by the cyclic eddy shedding that occurs when wind flows around obstacles. The reported increase in the incidence of suicides during episodes of warm downslope mountain winds (called Chinooks in the western US and the Föhn in the Alps) may be due to some as yet unknown biological response to these ultra-low-frequency pressure fluctuations with 20-to-70-second periods.

Meteors produce infrasound in the form of impulsive pressure waves resembling sonic booms, as well as continuous, isotropic radiation of unknown origin from the length of the path. Sometimes infrasound records can help locate meteorites.

Auroral activity and magnetic disturbances in the polar upper atmosphere also generate infrasound detected on the ground. Robert Service showed a poet's sensitivity to the natural world in his *Ballad of the Northern Lights*:[7]

> *They rolled around with a soundless sound*
> *like softly bruised silk;*
> *They poured into the bowl of the sky*
> *with the gentle flow of milk.*

Service penned these words more than 50 years before sensitive instruments were developed to record auroral infrasonic waves[8] and the traveling pressure fluctuations associated with geomagnetic activity.[9]

Severe-storm infrasound

In the 1970s, the National Oceanic and Atmospheric Administration began a study of atmospheric infrasound to find out whether it could be used to improve warnings of severe weather events, such as tornadoes.[10] We found that many of the strongest thunderstorms, particularly those powerful enough to reach 15 km altitudes, radiated infrasound with wave periods in the tens of seconds, which could be detected by multiple observatories more than a thousand kilometers away. We found that severe-storm infrasound was not simply a low-frequency kind of thunder. Triangulation shows that it exhibits different spatial and temporal statistics than lightning, and tends to come mainly from the subset of storms that spawn tornadoes. By one estimate, the infrasonic power radiated by the strongest storms is equivalent to the electric power consumed by a city of 100 000.

Further work at NOAA in the 1980s and 1990s monitored severe storms at near-infrasonic frequencies around 1 Hz and found a stronger connection with tornadoes themselves. Coincident Doppler radar measurements of tornadoes have revealed a relationship between funnel diameter and infrasound frequency that suggested an infrasound generation model. Radial modes of vibration in vortices can radiate sound waves whose frequency is inversely proportional to the diameter of the vortex core. For example, radial vibrations of a 400 m diameter core would theoretically radiate at about 1 Hz. Measurements of the sound generated by laboratory vortices and aircraft-wake vortices are consistent with this model. One tornado that passed within 3 km of our Boulder, Colorado, observatory left a signature that permitted us to use this model to "image" the increase in the tornado's diameter with altitude, using the observed decrease in the dominant infrasound frequency at higher elevation angles of

Animal Infrasound

It is well known that bats use ultrasound for echolocation and that dogs and cats hear sounds pitched much too high for humans to hear. But do any animals use infrasound?

The songs of some whales extend into the infrasonic range, apparently for long-distance communication, raising concerns about interference from human activities that have increased the level of background noise in the sea. Human activities have certainly made such communication more difficult. Katy Payne, in her book *Silent Thunder*, describes the discovery that elephants use infrasound to communicate over long distances.[16] Mel Kreithen and others at Cornell University have found that the hearing range of pigeons extends into the infrasonic range. He speculates that this capability might be part of their navigation "tool box" and that perhaps natural sources of infrasound serve as reference beacons. Recent studies of some dinosaur skulls reveal huge nasal cavities whose sole function appears to be to generate and amplify low-frequency sound.

For what purpose? Generally, animals create and detect sounds for mating, locating prey, navigating, keeping track of their young, or warning others of danger. By generating infrasound, large animals would greatly extend the range of these signals. Some predators may even have evolved infrasound-sensing systems to detect the breathing or heartbeats of prey, but more research is needed to find out whether this is possible against the background of natural infrasonic noise.

In addition, there are many anecdotal reports of unusual animal responses preceding earthquakes. The warning potential of these responses has been the subject of intense research in China. Infrasound is one of many candidate mechanisms, all of which require more rigorous study.[17]

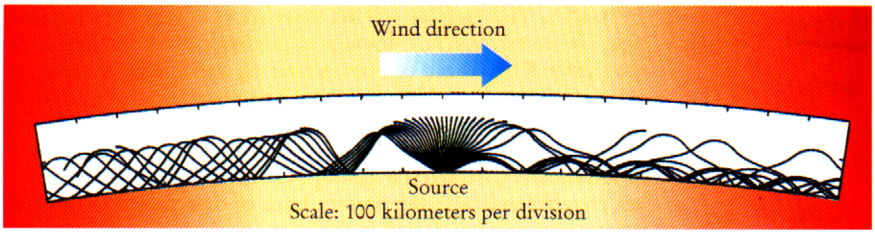

FIGURE 4. COMPUTER RAY TRACE models how infrasound at a frequency of 1 Hz is refracted and channeled over long distances by the temperature and wind structure of the atmosphere. A 60 m/s jet of wind blowing to the right at 60 km altitude is simulated to show the difference between upstream and downstream propagation. Rays that end abruptly are absorbed by atmospheric viscosity and thermal conduction.

arrival. This work shows promise for infrasonic tornado detection systems that could complement the existing Doppler radar network.[11]

Measuring infrasound

Sound (and infrasound) waves are longitudinal air waves of compression and expansion. Modern low-frequency pressure sensors, called microbarographs or low-frequency microphones, can record pressure changes of less than 10^{-3} pascals, or 10^{-8} atmospheres. This is still 45 times less sensitive than the human ear is at audio frequencies! (The SI unit of pressure is the newton per square meter, or pascal. One standard atmosphere is about 100 000 Pa. The threshold of human hearing, which acousticians call 0 decibels, is about 20 micropascals.) One type of far-infrasound sensor uses a sensitive diaphragm open to the air on one side and backed by a large, thermally insulated reference volume on the other. A calibrated flow resistor, or leak, across the diaphragm filters out very-low-frequency barometric pressure changes.

The ability of pressure sensors to detect infrasonic waves is usually limited not by their sensitivity, but by local pressure fluctuations in the atmosphere that have nothing to do with sound waves. These may be caused by winds and turbulence near the sensor, or by weather-related changes in barometric pressure. (The pressure amplitude of a typical infrasound signal from a distant source is 0.1 Pa, which is equivalent to the barometric pressure change due to a one-centimeter change in altitude.)

A single pressure sensor often cannot tell the difference between the pressure fluctuations caused by a passing wave of infrasound and the non-acoustic pressure changes. One way to weed out unwanted pressure fluctuations is to apply filters that take advantage of the known spatial and temporal characteristics of the infrasound, as well as those of the unwanted "noise." One property of sound waves is that they travel at about 344 m/s, or roughly 758 miles per hour. Another is that they possess a certain amount of coherence in space and time; that is, they maintain a similar wave-form when sampled by sensors spaced a few wavelengths apart. A known property of the nonacoustic pressure fluctuations is that they are less coherent in space and increase in intensity at lower frequencies. So it makes sense to design sensors that average incoherent pressure fluctuations over space and have a high-pass frequency response.[12]

Attached to the pressure sensor shown in figure 5 are 12 radial arms with ports at one-foot intervals, covering an area 50 feet in diameter. Waves of near-infrasound (with wavelengths much larger than the array) produce a coherent response over all the ports, while smaller-scale pressure fluctuations are partially averaged out. Noise reducers with dimensions greater than 1000 feet have also been used.

A similar kind of spatial filter consists of a larger spatial array of such sensors to sample the wave-associated pressure fluctuations at spaced locations. Modern digital array-processing algorithms[13] then search in "wavenumber space" for combinations of time delays over the array that match infrasound waves with different speeds and that come from different directions. The design of the spatial filtering arrays is always a compromise between angular resolution and spatial decorrelation.

Infrasound wavelengths are so long that most sensors are deployed at ground level in two-dimensional arrays. (The wavelength at a frequency of 1 Hz is 340 m; at 0.1 Hz, it is 3.4 km.) When only two-dimensional array processing is practical, the elevation angle of arrival of a wave must be inferred from the speed that it travels across the array. For example, a wave traversing the array at 340 m/s is arriving essentially along the ground; a wave traversing the array at 480 m/s is interpreted as arriving from about 45° above horizontal.

Generating infrasound

Historically, low-frequency sound propagation has been studied using explosive sources,[4] but this is practical only in remote areas. To study infrasound and its propagation through the atmosphere in a controlled and unobtrusive way, or to measure the directional response of receiving sensors, it would be useful to be able to generate coherent, narrowband infrasound at will. Practical uses for such sources would include inaudible probing of propagation paths where noise pollution is a concern and assessing atmospheric conditions (like temperature inversions) where audible sound could be harmfully trapped or ducted. But infrasound is difficult to generate artificially, because sources of manageable size are small compared to a wavelength and are thus very inefficient.

In 1988, we designed a 100 Hz audible sound source for use with a radio acoustic sounding system in which atmospheric temperature profiles are measured by tracking vertically traveling sound waves with radar. This audio source required a 10-foot-diameter horn driven by four 18-inch speakers using several thousand watts of electrical power. Figure 1 shows the acoustic horn and speakers mounted on a pickup truck. Sound waves from this system reached a 20 km altitude, but infrasonic versions could approach ionospheric heights.

To generate still lower frequencies, we experimented with a spherical Helmholtz resonator that was tunable from 10 to 50 Hz and sealed with a rupture disk. When pressurized to 1 atmosphere and ruptured, it emitted a consistent pulse waveform that could be recognized more than a kilometer away and detected at 30 kilometers. Figure 1 shows this resonator. The design of a practical coherent source of infrasound remains elusive, but devices such as very large organ pipes, strings, and drums have been suggested. Such an "orchestra" would have dimensions of hundreds of feet and require a huge amount of huffing and puffing to produce a useful infrasound level, which nevertheless would go unheard.

Acoustic-gravity waves

Far-infrasound behaves physically just like ordinary sound until its wave period exceeds about 1 minute (0.017

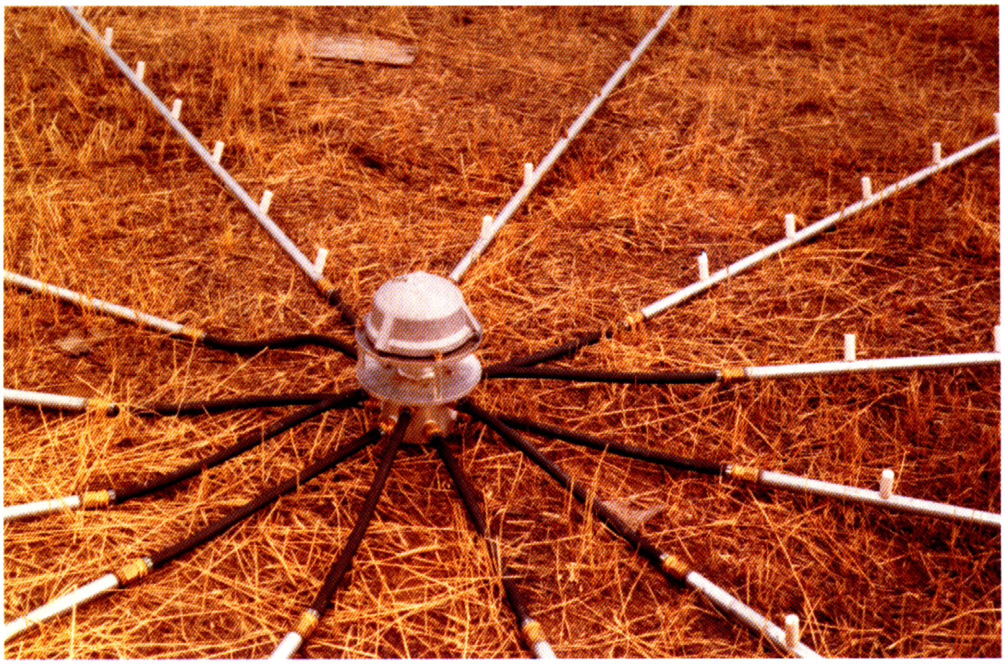

FIGURE 5. NOISE-REDUCING MICROPHONE. The large device uses spatial averaging to smooth out small-scale pressure changes caused by winds and turbulence, thus enhancing its response to longer waves of infrasound. The small white cylinders are porous filters protecting calibrated flow resistors inserted at 1-foot intervals along twelve 20-ft lengths of pipe that radiate from the central sensor.

Hz frequency). In a density-stratified atmosphere, the buoyancy forces on a parcel of air become comparable to pressure-gradient forces, and the wave-associated air motion is no longer exactly longitudinal. As frequency decreases, propagation of these "acoustic-gravity waves" becomes more dispersive (frequency dependent) and anisotropic (direction dependent).[14] At wave periods longer than about 4 minutes, the waves are transformed into the almost pure internal atmospheric-gravity waves whose oceanic counterpart is well known. (Lucid treatments of the theory of acoustic-gravity waves are given in reference 15.) These long-period waves are an important component of the signature of distant explosions, even underground ones. Another kind of long-period infrasound radiated by distant explosions is guided along the Earth's surface and is called a Lamb wave.[3] The CTBT monitoring network will have to be "smart" enough to distinguish the long-period signatures of nuclear tests from many natural sources of acoustic-gravity waves. Among those that have been studied are earthquakes, weather fronts, jet streams, and clear-air turbulence in the upper atmosphere.

What next?

Our present understanding of Earth's natural infrasonic environment is largely phenomenological and lacks quantitative, testable physical models for how the various observed infrasound sources actually radiate. The wave theorists have their work cut out for them and should be able to find support in the context of CTBT false-alarm requirements.

The CTBT observing network will be far larger, more sensitive, and more integrated than any previous infrasound/hydroacoustic/seismic network. (See figure 1 in Sullivan's article, PHYSICS TODAY, March 1998, page 24.) Even if the network becomes bored by the absence of any nuclear tests to monitor, it will offer an abundance of high-quality data for global geophysical research. As these data are made available to the scientific community, the monitoring system would become a focal point of international scientific cooperation on topics such as those listed in the table on page 34.

Sonic and infrasonic monitoring systems have a role to play in the exploration of other planetary atmospheres. Indeed, the ill-fated Mars Polar Lander carried a tiny microphone to sample that planet's acoustic environment. No one knows what the Mars microphone would have discovered, although the Planetary Society sponsored a K–12 essay contest to predict what might be heard. Some day we will find out what Mars and other worlds have to say.

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