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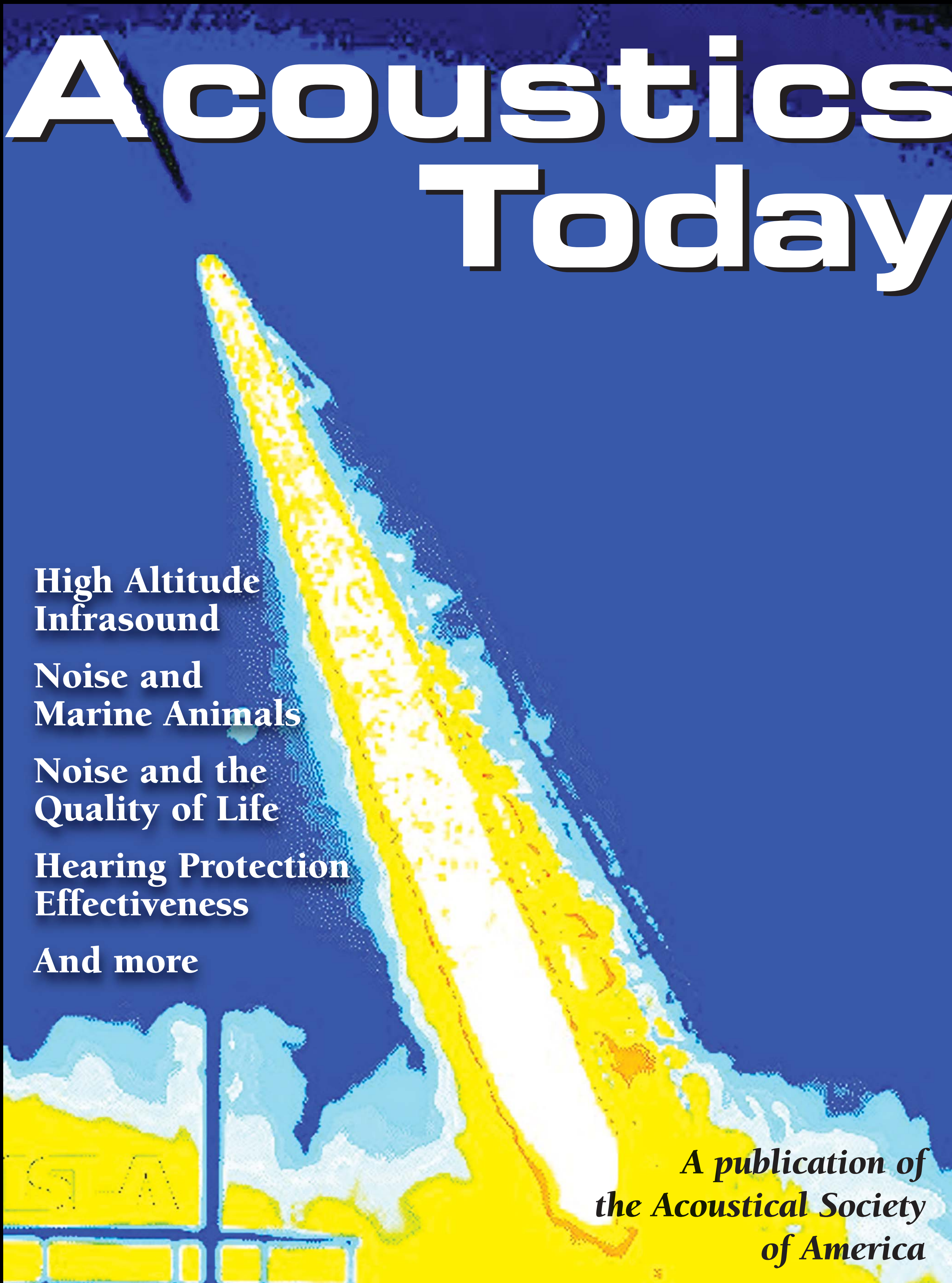
Acoustics Today



High Altitude Infrasound

Noise and Marine Animals

Noise and the Quality of Life

Hearing Protection Effectiveness

And more

A publication of the Acoustical Society of America

Infrasound Sources Reach High Altitudes Using Rockets

HIGH-ALTITUDE INFRASOUND CALIBRATION EXPERIMENTS

Eugene T. Herrin
Department of Geological Sciences, Southern Methodist University
Dallas, Texas 75275

Henry E. Bass
Jamie Whitten National Center for Physical Acoustics,
University of Mississippi
University, Mississippi 38677

Bill Andre
Radiance Technologies
Huntsville, Alabama 35805

Robert L. Woodward
Incorporated Research Institutions for Seismology
Washington, D.C. 20005

Douglas P. Drob
Space Science Division, Naval Research Laboratory
Washington, D.C. 20375

Michael A. H. Hedlin
Institute of Geophysics and Planetary Physics,
University of California, San Diego
La Jolla, California 92093

Milton A. Garcés
Infrasound Laboratory of the University of Hawaii Kailua-Kona
Kailua-Kona, Hawaii 96740

Paul W. Golden
Department of Geological Sciences, Southern Methodist University
Dallas, Texas 75275

David E. Norris
BBN Technologies
Arlington, Virginia 22209

Catherine de Groot-Hedlin
Institute of Geophysics and Planetary Physics,
University of California, San Diego
La Jolla, California 92093

Kristoffer T. Walker
Institute of Geophysics and Planetary Physics,
University of California, San Diego
La Jolla, California 92093

Curt A. L. Szuberla
Geophysical Institute, University of Alaska Fairbanks
Fairbanks, Alaska 99775

Rodney W. Whitaker
Los Alamos National Laboratory
Los Alamos, New Mexico 87545

F. Douglas Shields
Jamie Whitten National Center for Physical Acoustics,
University of Mississippi
University, Mississippi 38677

Introduction

Infrasound (acoustic signals below the 20 Hz limit of human hearing) has been known since the eruption of Krakatoa in 1883. This event registered on barometers around the world. In 1909, barometers also registered a strong signal from the now-famous Tunguska event. As illustrated by these two cataclysmic events, infrasound energy can travel reasonably unattenuated for thousands of kilometers through refractive ducts in the atmosphere. Recognizing the utility of this energy as a tool for the remote study of atmospheric sources, and as a probe of the atmosphere, infrasound was commonly used to monitor atmospheric nuclear tests starting in the 1940's. With the Limited Test-Ban Treaty that eliminated atmospheric nuclear testing and with the advent of satellite technology, infrasound research had declined dramatically by the early 1970's. The recent Comprehensive Nuclear Test-Ban Treaty (CTBT) that banned nuclear tests of all yields, in all environments, included the use of a worldwide network of infrasound receiving arrays. This has led to a re-birth of infrasound as a technology for monitoring the Earth's atmosphere and shallow crust for nuclear tests as well as other natural phenomena.

"An obstacle to refining our knowledge of infrasound propagation and improving source location techniques has been the lack of sources with known yield, location, and time."

The re-birth and study of infrasound has led to improvements in instrumentation such as microbarometers and has benefited from advances in digital signal processing and recent improvements in knowledge of the middle- and upper-atmosphere. New infrasound stations, such as those deployed as part of the CTBT, have led to dramatic increases in the quality and quantity of data available. However, the physics of global infrasound propagation is not fully understood and significant challenges remain before better advantage of this wealth of new data can be taken. This has led to dynamic research programs in areas such as evaluation of signal propagation codes, atmospheric models, development of infrasound as a remote sensing tool (e.g., earthquakes, volcanoes), and operational infrasound source location and characterization. An obstacle to refining our knowledge of infrasound propagation and improving source location techniques has been the lack of sources with known yield, location, and time.

To improve understanding of the most pressing research issues, a calibration experiment was organized involving six rockets, each carrying a small payload of chemical explosives. The rockets were launched from White Sands Missile Range (WSMR) in southern New Mexico during 2005-2006.[1,2,3] Two rockets were launched during each of three WSMR experiments. The carefully tracked rockets flew a northward trajectory tens of kilometers into the stratosphere, where the explosives were detonated. The resulting infrasonic signals were recorded at sites throughout the southwestern US to distances of nearly 1000 km.

The WSMR tests have provided a high-quality set of measurements of travel-time, signal amplitude and frequency to help address specific challenges in infrasound propagation modeling and source location. First, as increased numbers of infrasound events have been analyzed during the past decade, a systematic tendency to overestimate observed travel times has been clearly identified.[4] Data from the WSMR tests will provide precise travel time data to address this issue. Second, the significance of internal wave scattering of acoustic energy in the stratospheric and thermospheric ducts has also been identified but is not completely understood.[5,6,7] Scattering is often invoked to explain observations of energy leakage from elevated ducts and possibly signals in some classic zones of silence.[8] The spatial coverage of the WSMR data provide a means for direct observation of scattered acoustic energy. Another challenge addressed through analysis of the WSMR data includes a better understanding of thermospheric attenuation.[9] Finally, the WSMR experiments also provided an opportunity to validate the scaling relationships between yield and dominant frequency as well as between yield and pressure amplitude for elevated sources. This article describes the general characteristics and preliminary results of the experiments. Experiment participants are preparing more detailed analyses of the large quantity of data collected.

Experiment design considerations

The scheduling of the experiments, as well as the geographic distribution of the stations, was intended to maximize the probability of observing signals under differing atmospheric conditions. Long-range infrasound propagation is primarily controlled by high-altitude winds and by the static sound speed that depends on the air temperature. Vertical gradients in the static sound speed and high-altitude wind profiles enhance or diminish atmospheric ducting between the ground and the lower, middle, and upper atmosphere, allowing infrasound waves to propagate to distances of hundreds to thousands of kilometers.

Tropospheric infrasound arrivals result from acoustic energy propagating in lower-atmosphere ducts. These ducts are a transient phenomenon involving temperature inversions in the lower atmosphere that may arise early in the day due to cool ground-level air temperatures or the tropospheric jet stream. Stratospheric arrivals, caused by ducting between the ground and stratopause, are significantly impacted by seasonal variations in the zonal (east-west) stratospheric winds. In the northern hemisphere, these winds flow to the east in the winter and the west in the summer. Spring and fall are transition periods. This feature results in directional ducting of the sound. For example, summertime conditions favor long-range

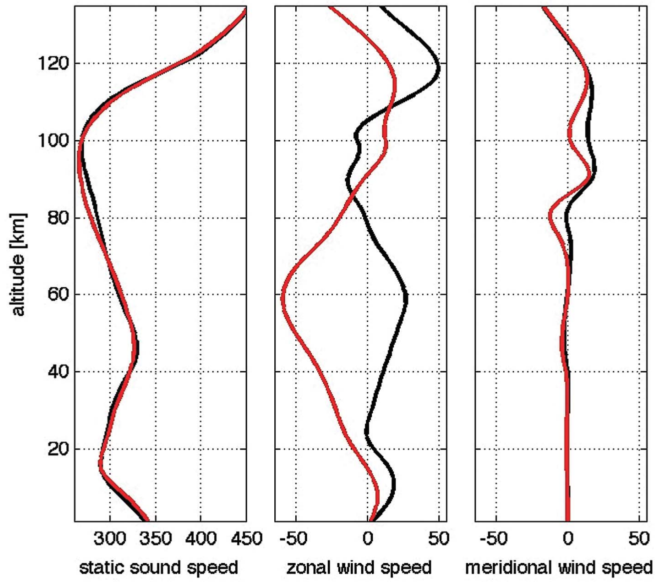


Fig. 1. Static sound speed profiles for WSMR2 (black line) and WSMR3 (red line) at 33.2°N, 106.5°W, near the center of the region in which the detonations took place (left). Zonal winds (positive from west to east) for WSMR2 (black) and WSMR3 (red) (middle). Right panel is same as for middle, but for the mean meridional wind speed profile (positive northward).

acoustic observations to the west of a source, but not to the east. Thermospheric arrivals, resulting from downward refraction of acoustic energy by the steep sound speed gradients of the upper atmosphere, are more rarely observed due to high acoustic absorption within the thin upper atmosphere.[9] More generally, the significance of natural atmospheric variability on infrasound propagation characteristics has been investigated and presented by several authors.[10,11,12]

To evaluate the likely existence of stratospheric ducting for the WSMR experiments a series of computations was performed. In Fig. 1, profiles of static sound speed as well as zonal and meridional (north-south) wind components are shown as a function of altitude for dates and locations corresponding to the second and third WSMR experiments (WSMR2 and WSMR3, respectively). These profiles are based on the Naval Research Laboratory Mass Spectrometer and Incoherent Scatter Radar Model-00/Horizontal Wind Model-93 (NRLMSISE-00/HWM-93) upper atmospheric empirical models.[13,14] As shown, static sound speeds at the ground were predicted to be greater than those within the stratosphere for these dates, and one would not predict stratospheric ducting. However, the stratospheric winds must also be considered, and this was done via ray tracing computations using the atmospheric profiles illustrated in Fig. 1.

To highlight the direct arrivals and stratospherically ducted arrivals, only the lower 60 km of the atmospheric profiles (Fig. 1) were used in the computations. Ray tracing for acoustic sound transmission in a windy environment relied on the physics governing acoustic refraction of rays in an advected media.[15] Rays were launched over a series of azimuths and declination angles from the source point and the locations at which the rays intersect with the ground surface are marked by dots in Fig. 2, color-coded by time of arrival after the detonation. As shown, enhanced propagation

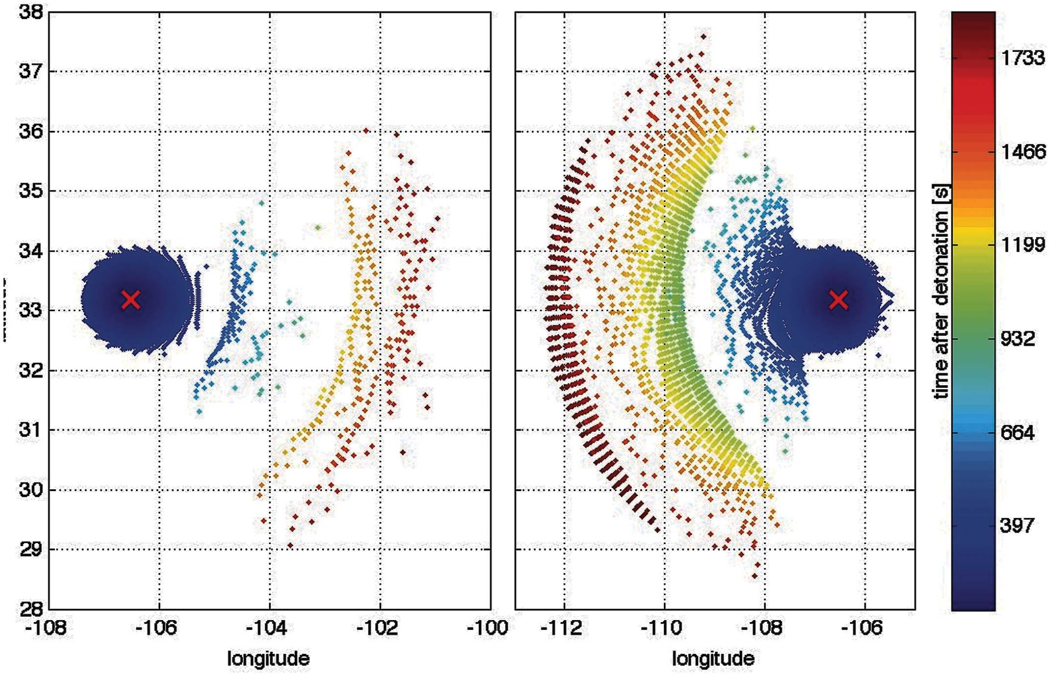


Fig. 2. Maps of ray endpoints that reach the ground for WSMR2 (left) and WSMR3 (right). The rays were propagated through atmospheric profiles shown in Fig. 1, starting at 33.175° N, and 106.515° W, altitude 40 km, the center of the region in which the detonations took place (marked on each map by a red X). For illustration, we have not considered rays that turn in the thermosphere; these would arrive significantly later. The ray endpoints are color coded according to the predicted arrival time in seconds after detonation.

to the east is predicted for WSMR2 and to the west for WSMR3.

Atmospheric and signal propagation modeling guided the general station distribution, though specific station sites were chosen based on land access, local winds and terrain, and logistical considerations. The maps in Figs. 3-5 show the relative locations of explosions and recording stations in each of the three experiments, and also indicate whether signals were observed. The dates of the WSMR experiments were selected to sample three different characteristic high-altitude wind patterns (fall, spring, and summer). Figures 4 and 5 illustrate the different deployments designed to take advantage of the predominantly westerly winds of spring (WSMR2) versus the predominantly easterly winds of summer (WSMR3).

Each of the three WSMR experiments consisted of two explosions separated by 4 to 6 hours, to understand the influence of atmospheric variability on this time scale better. Surface wind conditions and station operator logistics were also a consideration in determining the event timing.

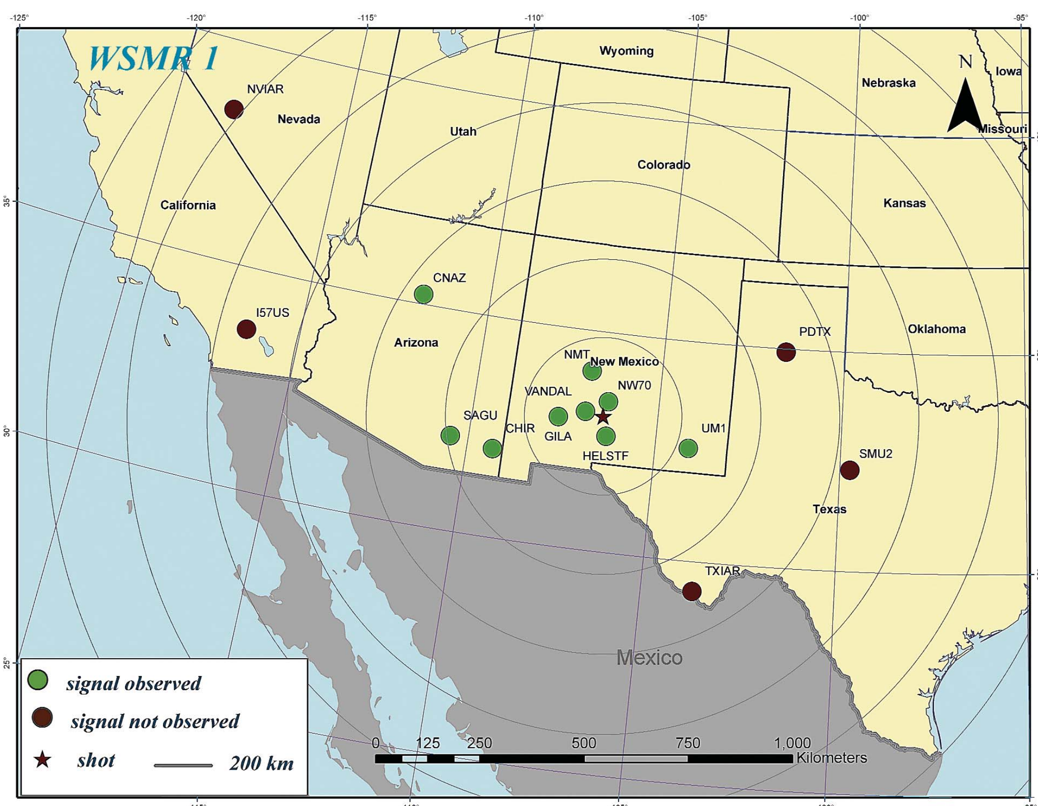


Fig. 3. Infrasound stations participating in the WSMR experiment on Septemper 9, 2005 (WSMR1). The explosion site is marked with a red star. Epicentral distance circles every 200 km from the explosion site are also indicated. The station symbols indicate whether signals were observed or not.

Infrasound stations

A total of 30 infrasound stations participated in the three experiments (Table 1). The stations were located in the southern and western US at distances between 35 and 1213 km from the explosions.[16] All but three of the stations used infrasound arrays. In addition to acoustic measurements, some stations also recorded meteorological data (surface wind speed, wind direction, and temperature). One station (HELSTF, at a distance of 60 km) also recorded seismic data. Six optical fiber infrasound sensors (OFIS)[17,18] were co-located with a 4-element infrasound array at station BACA. At another set of stations (NMT, NMT2, NMT3) a dense array of microphones was used to create a "distributed sensor."[19] Five of the thirty stations are permanent, while the others were deployed temporarily for these experiments. Of the five permanent stations, four are operated for research (DLIAR, NVIAR, SGAR, and TXIAR), and one (I57US) is operated as part of the Comprehensive Nuclear-Test-Ban Treaty Organization's International Monitoring System.[20]

The temporary stations typically consisted of arrays of three to five elements, with a spatial separation of roughly 100 to 300 m (Fig. 6). Teams were deployed to these recording sites one or two days before each experiment to set up equipment and record the stable, pre-event noise levels. A variety of acoustic transducers were used. These ranged from commercially available infrasound sensors, traditional laboratory grade microphones, and experimental transducers. While the detailed instrument responses varied somewhat between stations, all sites were capable of recording frequencies ranging from audible to sub-audible (infrasonic).

Arrays provide significant advantages over single sensors. The multiple time-synchronized recordings from sensors distributed across an area can be processed to estimate the azimuth of incident signals as well as their speed across the ground—parameters essential for evaluating atmospheric models. Combining multiple recordings also increases the ratio of coherent signal to incoherent noise due to wind and thus can be essential for extracting weak signals from noise at the more distant stations or improving understanding of the signal structure at all distances. Wind speeds generally increase after sunrise, due to solar heating of the surface, and thus each of the six explosions were set-off before dawn.

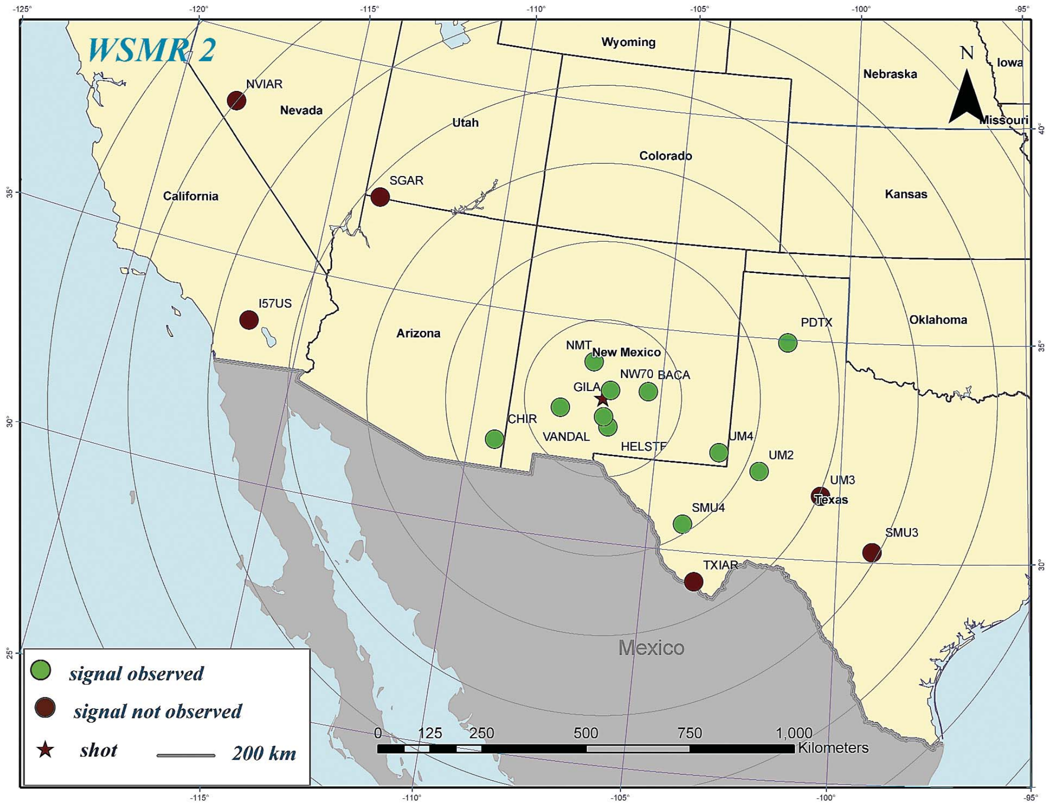


Fig. 4. As for Figure 3, but for the experiment of March 25, 2006 (WSMR2).

Nearly all of the sites used some type of noise reduction mechanism (i.e., windscreens) attached directly to the transducers. One of the simpler schemes is the use of porous hose (i.e., garden "soaker" hose) to provide a means for filtering out short wavelength pressure fluctuations (Fig. 7). However, multiple noise-reduction systems were employed. For the Optical Fiber Infrasound Sensors (OFIS) and dense microphone arrays, the increased spatial extent of the sensors themselves provides noise reduction as an integral element of the instrument design. In general, the diverse suite of stations operated well, with few recording failures.

The explosions

Three experiments were carried out, in the fall of 2005 and in the spring and summer of 2006. Two explosive charges, of approximately 30 kg TNT equivalent, were launched and detonated during each experiment, with launches roughly

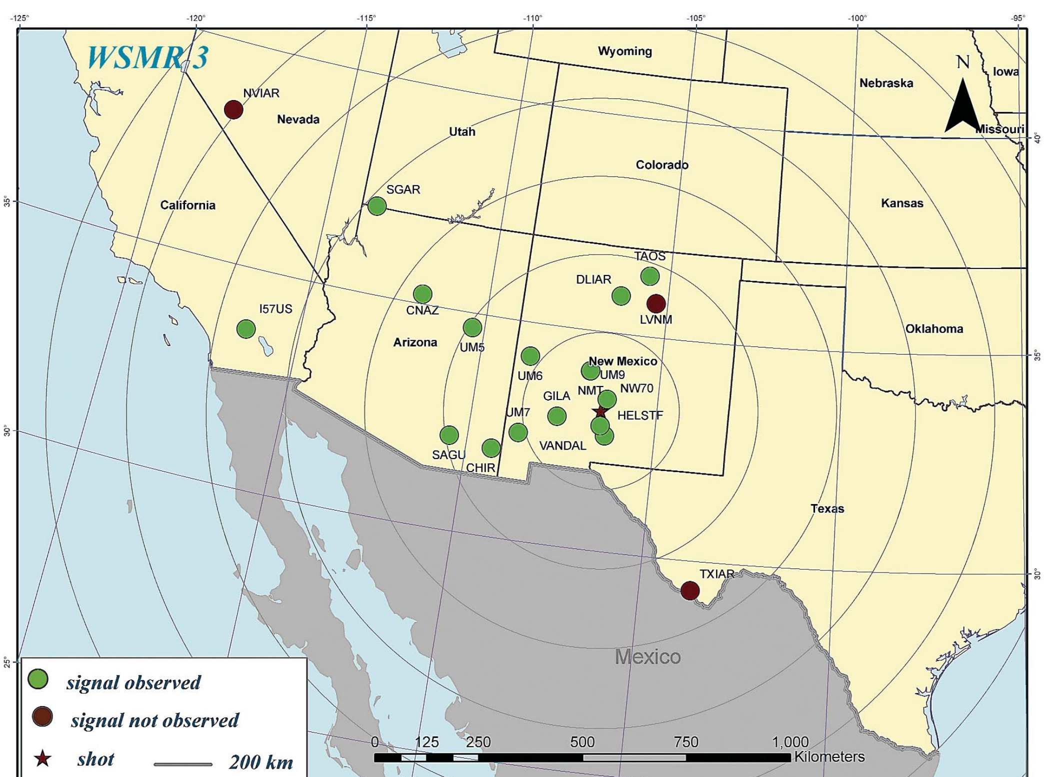


Fig. 5. As for Figure 4, but for the experiment of July 21, 2006 (WSMR3).

Table 1. Stations which participated in the WSMR infrasound calibration experiments.

Station	Operator	Distance (km)	Station Characteristics		
			Elements	Aperture (m)	Sampling (sps)
BACA	UCSD / UH	114.5	10	122	200
CHIR	UCSD / UH	292.2	4	110	100
CNAZ	SMU	548.3	4	203	40
DLIAR	LANL	300.2	5	1,340	10
GILA	UCSD / UH	113.0	4	100	100
HELSTF	ARL	60.3	4	38	50.1
I57US	UCSD/IMS	925.5	8	1,452	20
LVNM	Miltec	308.0	25	22	300
NMT	Miltec	116.8	25	7.6	80
NMT2	Miltec	95.1	93	30	200
NMT3	Miltec	109.8	93	30	200
NVIAR	LANL	1213.1	4	1,576	40
NW70	LANL	33.0	3	35	200
PDTX	UA	489.8	6	255	200
SAGU	UCSD / UH	389.7	4	91	100
SGAR	LANL	772.9	4	173	20
SMU2	SMU	638.3	4	151	40
SMU3	SMU	782.8	4	155	40
SMU4	SMU	376.4	4	160	40
TAOS	SMU	355.3	4	572	40
TXIAR	SMU	505.0	4	1,428	40
UM1	UM	230.2	9	0	42.8
UM2	UM	437.0	4	175	100
UM3	UM	603.2	4	242	100
UM4	UM	323.6	4	271	100
UM5	UM	381.4	4	295	5000
UM6	UM	229.4	4	289	200
UM7	UM	216.8	4	239	500
UM9	UM	109.0	4	240	500
VANDAL	ARDEC/ARL	36.5	4	38	50.1

ARDEC=Army Research, Development and Engineering Center, ARL=Army Research Laboratory, LANL=Los Alamos National Laboratory, Miltec=Miltec Corporation, SMU=Southern Methodist University, UA=University of Alaska, UCSD=University of California, San Diego, UH=University of Hawaii, UM=University of Mississippi

four hours apart. The Naval Surface Warfare Center group at WSMR was contracted to prepare and launch the rockets. The original intent was to detonate the charges at an altitude of approximately 50 km to maximize the long distance propagation of energy. The rocket design called for the explosive payload to detonate within the rocket, rather than being ejected prior to detonation. Thus, the explosion would result in the breakup of the rocket—the dimensions of the resultant debris pattern on the ground being a function of explosion altitude. Based on model results predicting the dimensions of the debris field, the initial WSMR explosions took place at roughly 30 km altitude. Empirical evidence gathered through the experiment permitted a gradual increase in the altitude of subsequent explosions. The final explosion of the six shots took place at about 49 km altitude.

The experiment utilized single-stage, rail-launched Orion rockets (Fig. 8). The rockets passed through a launch and a ballistic phase, with the explosive charges detonated during the ballistic phase after the missile passed apogee (Fig. 9). All six of the detonations took place within a virtual "box" 20 km high, 9 km wide (east-west) and 24 km long (north-south), centered at 40 km altitude at 33.175° N, and 106.515° W.

Preliminary estimates of the explosion parameters (time and altitude) were provided by WSMR staff to infrasound team members who were present at the launch, and these estimates were relayed to participants in the field. After each experiment, WSMR personnel provided detailed radar data that gave three-component rocket position (latitude, longitude and altitude), velocity, and acceleration as a function of time. The radar data were analyzed to pinpoint the detonation coordinates. After analysis of the radar data, the remaining uncertainties in the explosion location and time were on the order of several kilometers and several seconds, respectively. In addition, infrared cameras operated by M. Garcés (U. Hawaii) and by WSMR were used for two of the experiments to provide additional corroboration of launch and detonation times.

Observations

In the exploratory study of the data, basic observations about the spatial distribution of the recorded signals, and various parameters of the signals were made. It is these preliminary findings that will form the basis of more in-depth analyses.

Fig. 6. Site view of station BACA, showing 60-m long optical fiber array elements.

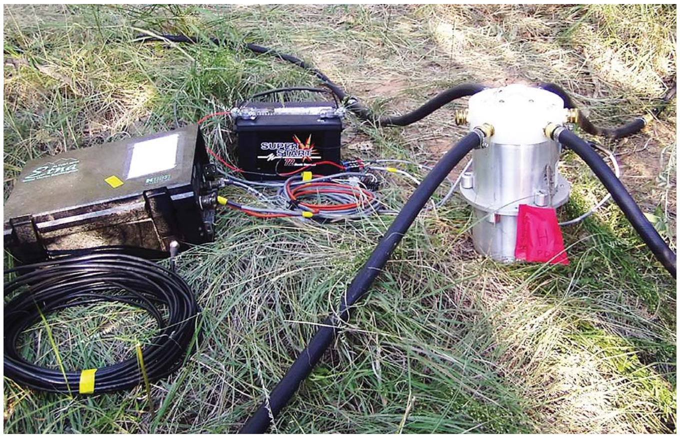


Fig. 7. Close up of infrasound sensor connected to four porous hoses. The porous hoses act as a windscreen for the sensor and are connected to a central manifold (the white segment) at the top of the sensor.

Fig. 8. Orion rocket attached to launch rail.

The distribution of recorded signals

Signals from the explosions of the three experiments were recorded at array stations to a range of approximately 900 km. Twenty four of the thirty stations recorded signals from at least one of the explosions.

The spatial distribution of the observations, as seen in Figs. 3 to 5, provides insight into the dominant propagation mode of the sound. For the September 2005 test (Fig. 3), the predicted zonal wind direction was to the west. Therefore, the station distribution favored this direction, where most of the acoustic energy would be expected to return back to the ground. The observations (green dots) confirm this ducting of acoustic energy—long range observations (greater than 400 km) were only observed in the westward direction.

The March 2006 test (Fig. 4) is a good example of observations driven by stratospheric winds to the east. In the July 2006 test (Fig. 5), the winds transitioned back to the west and the resulting observations fell in that direction. Further study of these acoustic “footprints” will provide an opportunity to refine understanding of the atmosphere and its effect on acoustic propagation.

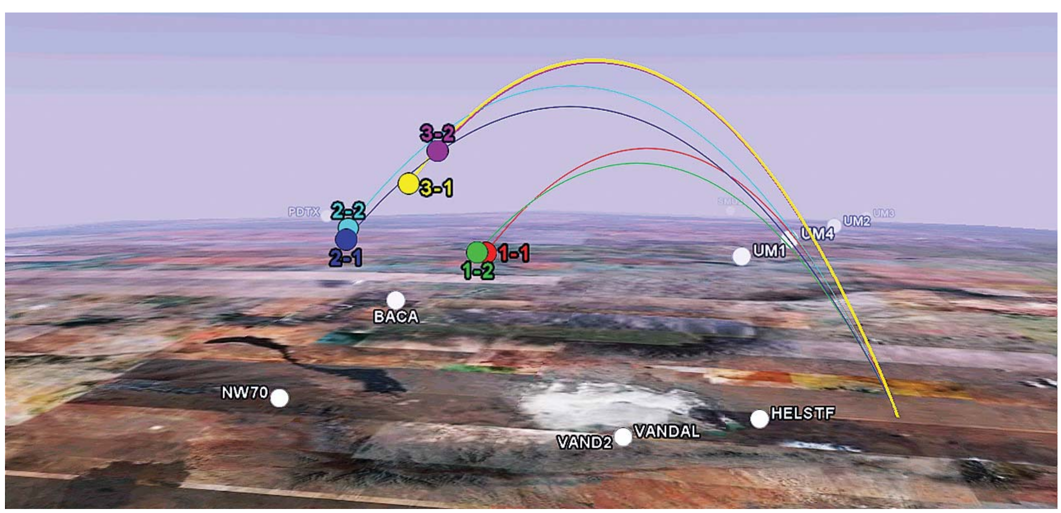


Fig. 9. Rocket trajectories and explosion locations (colored circles) for the WSMR infrasound experiments (view looking to east). White circles indicate the sites of some of the closer recording stations.

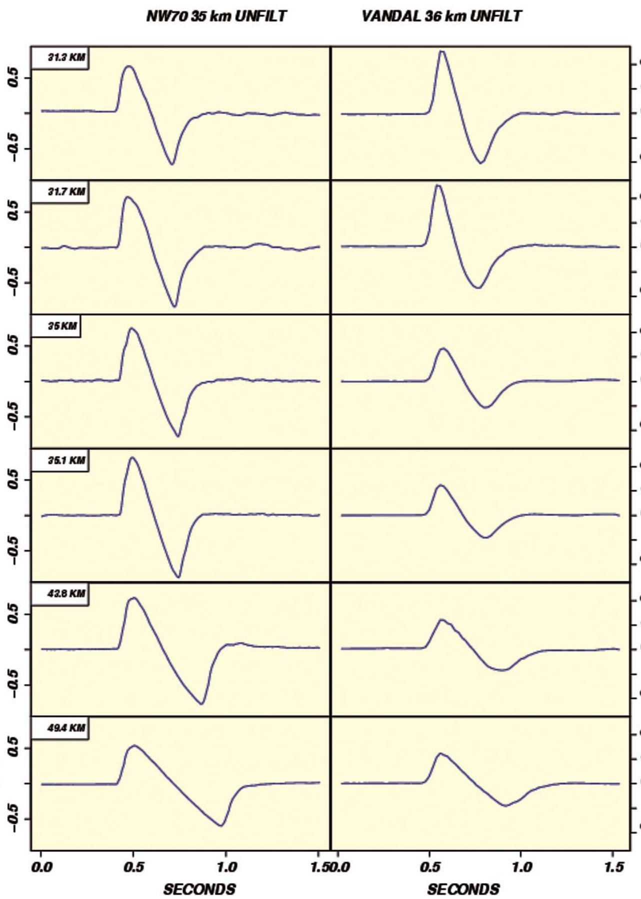
Waveforms

Figures 10 and 11 show examples of signals recorded at the two closest arrays, NW70 and VANDAL (less than 100 km), as well as at two arrays further away, GILA and CHIR (100–300 km). The time series in these figures are aligned to the approximate signal onset. The simple pulse-like signals (N-waves) recorded at the two stations at close range (Fig. 10) contrast with the increasing complexity and reduced signal-to-noise ratio (SNR) of the multi-pathed waveforms at the more distant stations (Fig. 11). The two CHIR waveforms for the WSMR3 explosions were separated by only four hours in time, yet the waveforms are quite different—a dramatic illustration of the effects of atmospheric variability on long-range infrasound propagation.

At many stations there were several distinct signal arrivals from each explosion. Signals associated with the explosions were identified based on the expected arrival time, as well as on the stability of azimuth and phase velocity estimates and the value of the F-statistic during the time windows of stable azimuth and phase velocity. The beginning and end of such stable data windows were picked manually. Arrival times for stations at close distances (less than 100 km) were also measured manually. Signal parameters were calculated for each apparent discrete arrival in the selected data windows. In addition, root-mean-square (RMS) noise values were measured, both for time windows prior to the first signal arrival as well as in a time window spanning the expected arrival time (for those cases where no signal was observed). Average and RMS wind speed was also calculated from the time windows of received or expected arrivals.

Signal group velocity

The observed group velocity of all signals, defined as the (distance)/(arrival time–explosion time), is plotted in Fig. 12 (where the distance has been corrected for the altitude of the source). For the WSMR2 experiment the signals propagating eastward (with the wind) show increased velocities, whereas in WSMR3 it is just the opposite. These observations are consistent with the distribution of observations noted in Figs. 3-5, as well as with the modeling presented in Fig. 2.



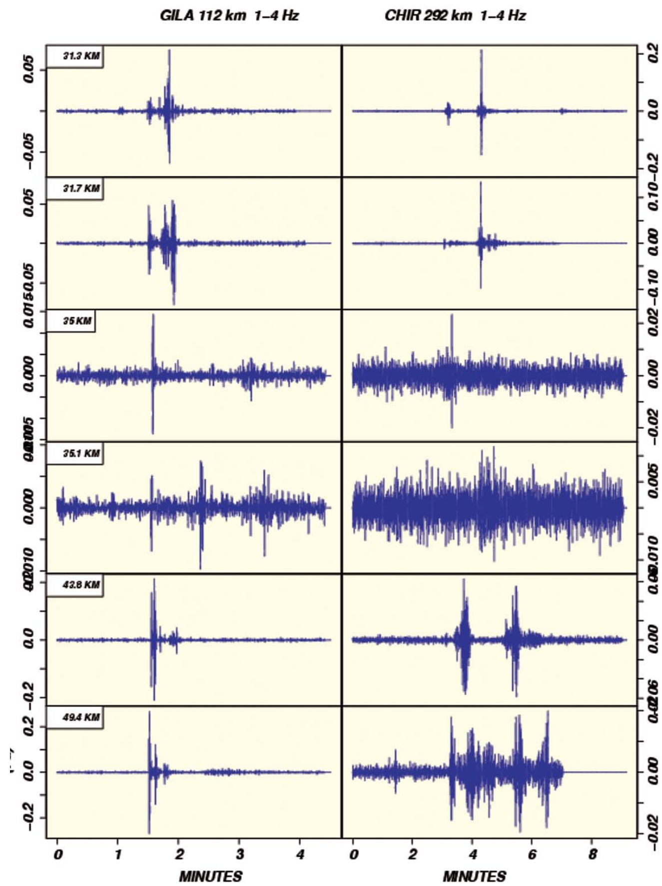


Fig. 10. Signals at the two closest stations, NW70 (left) and VANDAL (right), from the six explosions. The amplitude scale is the same for every explosion for each station. The signals represent the beam of the unfiltered array elements steered towards the explosions. With higher altitude (later shots, towards bottom of figure) the pulse-like shapes of the signals are broadened, with some variation in amplitude.

Fig. 11. Signals at the stations GILA (left) and CHIR (right), from the six explosions. The amplitude scale is normalized for each trace. The signals represent weighted beams (bandpass filtered between 1-4 Hz) of the array elements steered towards the explosions.

Signal amplitude

The maximum observed amplitudes are plotted in Fig. 13 that shows attenuation with distance. This decrease can be related to enhanced sound absorption at high altitudes. Atmospheric density falls off exponentially with altitude, so the mean free path between molecular collisions increases accordingly. This results in greater attenuation of sound energy at high frequencies (short wavelengths) than at low frequencies. The attenuation is proportional to the square of the frequency, thus sound energy undergoes greater attenuation for sources at high altitudes than at low altitudes, especially at high frequencies.

Noise amplitudes were measured at all stations, including those for which no signal was detected. The noise levels were then compared to observed signal amplitudes across the experiments. These comparisons clearly indicate that some stations "missed" observations due to periods of increased local noise levels—during which times the noise levels exceeded the expected signal levels.

Signal duration

Signal duration varied from a few seconds for the closest stations up to about a minute for the more distant stations. With a few exceptions, azimuth residuals (observed–true azimuths) are fairly consistent with no obvious bias and have standard errors around five degrees with no striking dependence on array distance.

Signal period vs. explosion yield and altitude

The dominant period of each recorded signal was calculated using an autoregressive (AR) process of order 16 with Burg's method.[21] The AR method is a parametric method, widely used in statistics and has direct applications in many areas of interest. The method provides an estimate of the spectrum and the fundamental (or system) frequencies of the time series.

Table 2 gives the altitude of the sources, the dominant periods and calculated yields for each of the signals. The periods given in the table were derived by calculating the mean dominant period for each array of sensors (at least four) and then the mean of all arrays. Arrays that were close to the source that recorded N-waves or decaying N-waves and the arrays with very low signal-to-noise ratio were excluded from the analysis.

Previous empirical formulas for estimating yields of explosions were derived from a historic dataset of nuclear explosions conducted above ground at the Nevada Test Site (NTS). The dominant period of the recorded infrasound signal from the explosions was used to calculate the yield.[22] The formula is given as:

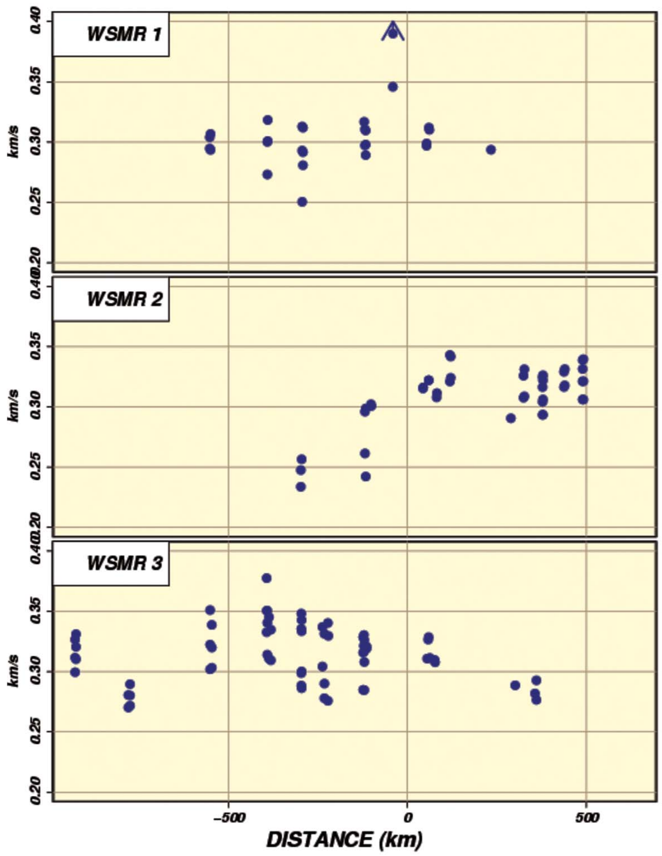


Fig. 12. Group velocity, distance/(observed arrival time – explosion time), plotted as a function of distance (range) for identified arrivals. The top, middle, and bottom panels correspond to the first, second, and third WSMR experiments, respectively. Stations to the west and to the east of the explosion locations are plotted with negative and positive distances, respectively. Data falling outside the ranges of the plots are indicated with arrowheads.

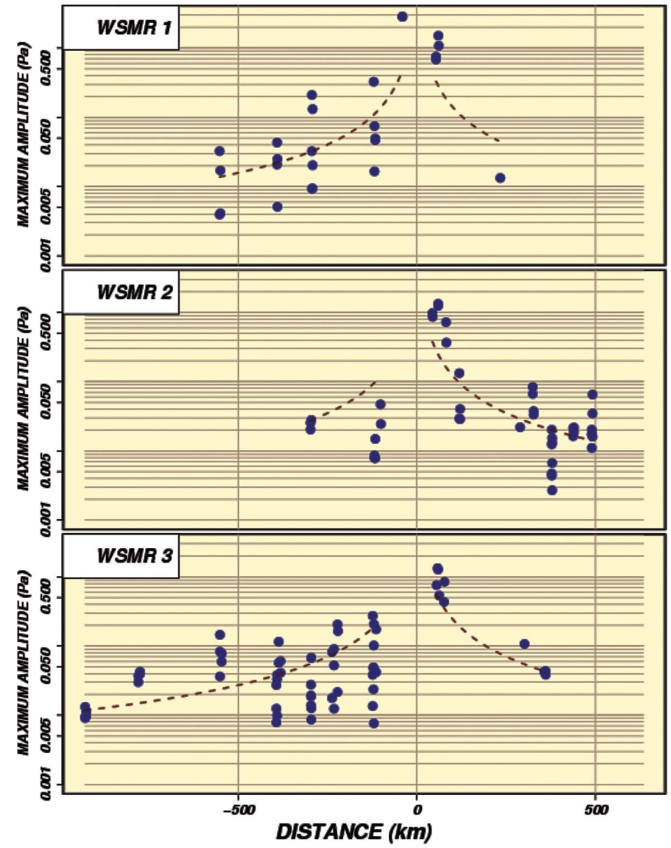


Fig. 13. Maximum pressure amplitude as a function of distance. Dashed lines correspond to amplitude attenuation as distance-1.36. See caption to Fig. 12 for an explanation of figure conventions.

$$Y_0 = (2)\times 2.38\times T^{3.34} \quad (1)$$

where Y_0 is the yield in tons of the explosion at the Earth's surface and T is the dominant period of the signal. The physical basis for this relationship is found in an increased acoustic transit time of the explosion blast radius with increased explosive yield. The constant (2.38) was derived empirically. The doubling factor in brackets compensates for the non-nuclear nature of the explosions.

Because the explosions were not at the surface a further altitude correction is necessary. With constant period, the blast energy, or yield, Y, will scale with the ambient pressure, which falls off exponentially with increasing altitude. Once a yield (or energy) is calculated from the formula given above, it is scaled using the following formula:

$$Y(z) = Y_0 \exp^{-Z/H} \quad (2)$$

where Z is the altitude of the explosion and H is the pressure scale of the atmosphere (about 7 km).

There is definitely an increase in the dominant periods with altitude,[16] as shown in Fig. 14, but if we apply the same formula for all explosions the yields computed for the WSMR3 experiments were a factor of 2–4 smaller than the lower altitude experiments. To our knowledge this effect is reported for the first time, and the members of the team were not able to explain this difference. At higher altitudes the yield/dominant period relationship appears to fail. Future work on the yield/period relationship will attempt to add confidence intervals on the yield estimates.

Table 2. Altitude of the sources, the observed dominant frequencies/periods, and calculated yields for each of the explosions.

Event	Frequency (Hz)	Period (sec)	Altitude (km)	Yield (lb)
WSMR1-1	2.21	0.452	31.3	9.39
WSMR1-2	2.16	0.463	31.7	9.57
WSMR2-1	2.04	0.490	35	7.23
WSMR2-2	1.91	0.524	35.1	9.01
WSMR3-1	1.64	0.609	43.8	4.26
WSMR3-2	1.50	0.666	49.6	2.51

Concluding comments

Infrasound signals from the WSMR experiments were recorded at 24 out of 30 temporary and permanent stations at distances ranging up to 900 km. The recorded signals span a range of signal to noise ratios, and measurements of basic signal characteristics are consistent

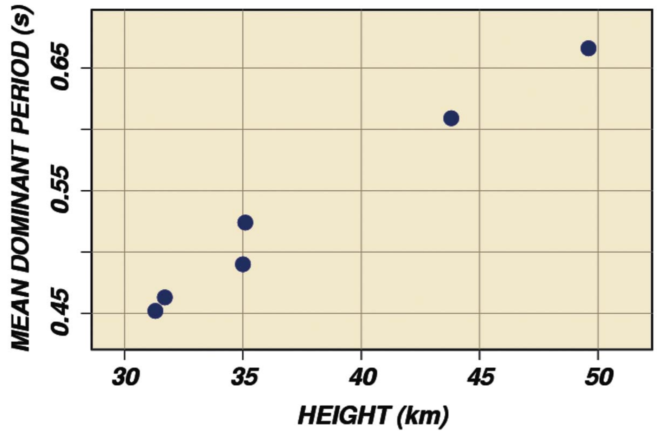


Fig. 14. Mean dominant period as a function of explosion height. This shows increasing period with height, as pointed out earlier by Herrin et al.[16]

across the multiple explosions. Beginning at about 100 km distance, the waveforms for explosions separated by only four hours in time showed significant variations due to atmospheric effects.

The data collected during the WSMR experiments, combined with the precise data on the six explosions, are proving to be of significant value across the entire spectrum of infrasound research, including source studies, propagation, instrumentation and data processing. Focused analyses using the WSMR data to answer questions both fundamental and practical are underway. For example, the WSMR data will fuel studies of a broad suite of processing algorithms to gauge the relative utility of each approach for detecting and characterizing signals. Furthermore, there are a number of important questions in propagation modeling to be investigated: Can accurate model attenuation and accurate absolute, or at least relative, signal amplitudes be predicted? In doing so, can it be predicted which stations should be able to record signals above the noise? How accurately can the timing of the arrivals at each station be predicted? Is the azimuth bias due to crosswinds accurately predicted? Can multipathing be predicted, or the overall waveform structure at each station? Do predictions improve noticeably with up-to-date atmospheric specifications? Comparisons between the predictions and the observations will provide a means to quantify the performance of the existing models, identify deficiencies in the models where physical processes may not be accounted for, and ultimately expand understanding of the interaction between propagating sound waves and atmospheric dynamics. The data are also being used to test advanced instrumentation concepts, including optical fiber infrasound sensors and the distributed sensor.

Progress in these areas, however, should also improve the ability to use infrasound data to monitor the atmosphere and the shallow earth for nuclear explosions. In this arena, event detection, location and identification are key issues. The WSMR data will be used to determine if waveform recordings can be used to identify unambiguously the source as an explosion, and to determine accurately both the geographic position of the source and its altitude. The experiments used an unusually high density of infrasound sensors, and thus there is a rare opportunity to assess the station density required to obtain sufficiently accurate location estimates and learn more about the range from which useful information about the source can be extracted.

In summary, the WSMR experiments will foster basic research as well as provide further insights relevant to nuclear monitoring in addition to proving useful in testing the use of infrasound data for monitoring natural hazards.

Participants

In addition to the authors of this article, the following people participated in various aspects of the WSMR experiments:

C. Talmadge, C. Hetzer, S. Breeding, R. Stribling, S. Dravida, V. Male, The University of Mississippi;
D. Fee, W. Bortz, The University of Hawaii;
J. Heberly, Army Research, Development and Engineering Center;
C. Coon, E. Blum, M. Zumberge, R. Matoza, P. Walsh, P. Durdevic, J. Berger, S. De Wolf, The University of California, San Diego;
P. Negraru, Southern Methodist University;
H. Israelsson, M. Bahavar, B. North, Science Applications International Corporation;
S. Mangino, Department of Defense Nuclear Treaty Managers Office;
J. Noble, Army Research Laboratory;
R. Gibson, J. Bhattacharyya, BBN Technologies;
D. Osborne, J. Olson, J. Helmericks, The University of Alaska Fairbanks;
K. Dillion, J. Williams, A. Kent, T. Turner, Miltec Corporation;
M. McKenna, U.S. Army Engineering Research and Development Center;
K. Veith, ITT Corporation;
J. Behrens, R. Wright, BAI, Inc.

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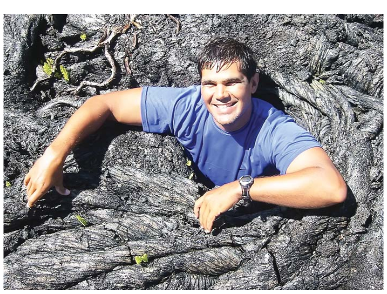
Bill Andre served as Chief of the SMDC DARPA Office within the Space and Missile Defense Center of the US Army Space and Missile Defense Command (SMDC), and retired from government service in June 2007 after 40 years of service. He was the Command Agent to the Defense Advanced Research Project Agency (DARPA), and Executive Agent for the Deputy Assistant to the Office of Secretary of Defense for Chemical Demilitarization and Threat Reduction. His responsibilities as manager of research programs also included Monitoring Systems Research for seismic, acoustic and radionuclide sensor networks over a period of ten years. A special interest was in the area of acoustic sensors and working with the U.S. Infrasound team. He received engineering degrees in Mechanical Engineering from Louisiana State University, and in Systems Engineering from Texas A&M University.

Henry E. Bass joined the Physics faculty of the University of Mississippi in 1970, and was appointed Frederick A. P. Barnard Distinguished Professor in 1988. He served as Acting Chairman, Department of Physics and Astronomy, Acting Director of the Acoustics Research and Development Division of the Institute for Technology Development, Director of the University of Mississippi Physical Acoustics Research Center, and Director of the National Center for Physical Acoustics since 1992. He was a visiting Distinguished Professor of Physics at the Naval Postgraduate School, 1989-1990, and is an adjunct member of the Graduate Faculty in the Department of Earth Sciences at The University of Memphis. He holds B.S. and Ph.D. degrees from Oklahoma State University. Dr. Bass is a Fellow of the Acoustical Society of America (ASA) and the Military Sensing Symposium. In 1978, he was awarded the ASA

Biennial Award (now the R. Bruce Lindsay Award) and in 2006 received the ASA Silver Medal in Physical Acoustics. He was Director of the 1994, 1996, 1998, 2000, 2002, 2004, and 2006 Physical Acoustics Summer Schools. Dr. Bass has served in an advisory capacity for a number of organizations including the Physics Division, National Research Council of Canada, U.S. Army Atmospheric Sciences Laboratory, Northrop Corporation, Textron Defense Systems, General Dynamics, University of Tulsa, NASA Langley Research Center and the U.S. Army Research Laboratory.

Catherine de Groot-Hedlin received a Ph.D. in Earth Sciences in 1991 from the University of California, San Diego, and is currently a project scientist at the Scripps Institution of Oceanography. Her research interests include the propagation of acoustic energy in the ocean and the atmosphere, with application to verification of the nuclear test-ban treaty, and the analysis of hydroacoustic signals from underwater earthquakes. She is a member of the American Geophysical Union and the Acoustical Society of America.

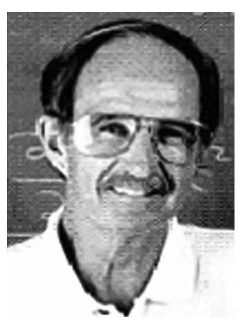
Douglas P. Drob received a Bachelor's degree in Engineering Physics from Embry-Riddle Aeronautical University in Daytona Beach, FL in 1991 and a Ph.D. in Atmospheric and Space Science in 1996 from the University of Michigan, Ann Arbor. Since then he has worked as a Research Physicist at the Space Science Division of the Naval Research Laboratory, Washington, DC. His research involves the statistical analysis and interpretation of satellite- and ground-based measurements that improve the fundamental understanding of the Earth's upper atmosphere. These activities provide physical knowledge and meteorological information to improve infrasound propagation models in support of international nuclear treaty monitoring efforts.



Milton Garcés is the Director of the Infrasound Laboratory (ISLA) of the University of Hawaii at Manoa. The ISLA is involved in multidisciplinary applied research projects in volcanology, oceanography, meteorology, and just about anything big that blows up.

Paul Golden is the Director of the Geophysics Laboratory at Southern Methodist University and is responsible for planning and implementation of the technical, financial, and scientific efforts of the Laboratory. In this role he oversees daily operations and adherence to schedules and budgets. His scientific interests include seismic data acquisition and analysis, basic research in infrasound phenomenology and seismo-acoustic studies. He has been involved in high-profile national and international programs over his 20+ year career.

Michael Hedlin received his Ph.D. in Earth Sciences in 1991 from the University of California, San Diego. He is currently a research geophysicist and senior lecturer at the Scripps Institution of Oceanography at UCSD. His research interests include the use of seismic and acoustic energy for nuclear test-ban verification, the analysis of acoustic signals from large-scale atmospheric phenomena and other sources such as volcanoes. One of his main activities over the past several years has been the design, construction and operation of infrasound monitoring arrays in the United States and the Atlantic Ocean. He founded the Laboratory for Atmospheric Acoustics at UCSD in 2002 and currently serves as the chief editor of InfraMatics (see www.inframatics.org). He has been nominated three times as the outstanding undergraduate lecturer at the Scripps Institution of Oceanography. He is a member of the American Geophysical Union and the Acoustical Society of America.



Gene Herrin is the Shuler-Foscue Professor at Southern Methodist University whose research interests encompass infrasound, seismology, and other topics. His primary research interests in seismology include: (1) extension of seismological observations to high frequencies, (2) seismic observations in deep boreholes, (3) processing of high frequency seismic data, (4) design of advanced seismic instruments and observatories, and (5) research in the seismic verification of nuclear arms-control treaties.

David Norris is a Senior Scientist at BBN Technologies. He has over 15 years of experience in propagation modeling, atmospheric characterizations, and signal processing. Dr. Norris received a Ph.D. in Acoustics in the Graduate Program in Acoustics at Pennsylvania State University, and M.S. and B.S. degrees in Electrical Engineering at Arizona State University. At BBN, he has worked extensively in the creation of the infrasound propagation tool kit InfraMAP, developing and applying propagation and atmospheric models to the study of events of interest to the infrasound monitoring community. Dr. Norris' research interests include outdoor sound propagation experimentation and modeling, surface-layer atmospheric dynamics, and mathematical control theory.

Doug Shields received a Ph.D. from Vanderbilt University in 1956. He brought acoustics research to the University of Mississippi in 1959. At Ole Miss he has served as Professor of Physics and Associate Dean of Liberal Arts. Since 1988 he has worked as a senior research scientist at the National Center for Physical Acoustics. Dr. Shields's early work was in the use of acoustics to study vibrational relaxation processes in gases. More recently he has been involved in building distributed arrays of infrasound sensors to filter wind noise from infrasound signals.

Curt Szuberla is Assistant Professor of Physics at the Geophysical Institute and University of Alaska Fairbanks (UAF). Before joining the Geophysical Institute as a Ph.D. student in 1992, Szuberla served as an Airborne and Ranger-qualified infantry officer in the U.S. Army and is a graduate of the U.S. Military Academy. Following graduate school, he taught high school physics and mathematics at North Pole High School for eight years. Since 2000, as a consultant and now a faculty member, he has helped to build an internationally recognized infrasound research program at UAF, known as the Wilson Infrasound Observatories.

Kris Walker is currently a postdoctoral researcher at the University of California, San Diego. During the last 11 years, he has been working on problems in solid earth and atmospheric geophysics involving active- and passive-source seismic imaging, seismic velocity anisotropy characterization, potential field modeling, array-analysis techniques, and acoustic sensor development.

Rodney Whitaker graduated from Indiana University, Bloomington, Indiana, with a Ph.D. in Astronomy in November, 1976. His work at Los Alamos National Laboratory began with a post-doctoral position in late 1976, and about one year later he became a technical staff member. For several years he worked on finite difference simulations of atmospheric nuclear explosions and their effects. These numerical calculations included radiation transport and hydrodynamics. This work also led to interesting calculations related to star formation in inter-stellar molecular clouds. In the early 1980s, Dr. Whittaker began work on low frequency atmospheric acoustics or infrasound, and this work has continued to the present. During this period, he gained experience in all aspects of the program at Los Alamos: field deployment and operations, data collection, signal processing, source modeling, wave propagation, and interpretation. In addition to underground tests, the program collected data on earthquakes, large conventional surface explosions, microbaroms, and a few other man made sources. The large surface explosions were in the range of a few kilotons of explosive.

Bob Woodward is the Director of the EarthScope USArray project for the Incorporated Research Institutions for Seismology (IRIS). Prior to joining IRIS he worked for Science Applications International Corporation (SAIC), where he managed a variety of geophysical research and development projects, advanced technology research and development activities, and large-scale systems integration efforts. Prior to his work with SAIC, Bob managed the Data Collection Center at the USGS Albuquerque Seismological Laboratory, collecting and managing data from the Global Seismographic Network. Bob earned a B.A. in Geophysics and Applied Mathematics from the University of California, Berkeley and a Ph.D. at Scripps Institution of Oceanography, University of California, San Diego,