Infrasonic Monitoring of Avalanche Activity

Ernest D. Scott* and Craig Lance
Inter-Mountain Laboratories, Inc., Sheridan, Wyoming

Abstract: Avalanches have been shown to produce sub-audible acoustic pressure fluctuations in the low frequency infrasonic spectrum, but limited information that specifically details avalanche-generated infrasound exists in open literature. During the winters of 2000/2001 and 2001/2002, single sensor infrasonic monitoring systems were deployed at several locations to collect data aimed at characterizing infrasonic signals produced by avalanche activity. Results obtained from these efforts verify the existence of avalanche-generated infrasound. While the frequency content of the recorded avalanche-generated infrasonic signals is consistent with previous research findings, the near source amplitudes of the infrasonic pressure fluctuations were found to be an order of magnitude lower than previous research findings. Collected data also contains information regarding potential interfering noise sources. The obtained catalog of data is being analyzed to investigate the variability in the statistical characteristics of infrasound produced by avalanches. These findings are being utilized to develop signal processing algorithms to employ in automated avalanche detection systems. Research efforts related to the development of automated avalanche detection systems will continue through August 2003.

Keywords: avalanche monitoring, avalanche detection, infrasound

1. Introduction

Avalanches are powerful and unpredictable natural phenomena that claim lives, destroy property, and disrupt transportation each winter season. With increasing settlement and winter travel in mountainous country, it is expected that injuries, deaths, and property loss will increase until more effective avalanche warning systems are developed. It would be beneficial to have automated systems to detect avalanches in real time. Automated detection could expedite emergency and rescue responses, effect audio/visual warnings to control traffic, notify road maintenance personnel, and provide information for avalanche forecasters.

1.1 Background Information

Avalanches have been shown to produce 1 – 5 Hz acoustic signals within the sub-audible infrasonic frequency spectrum (Bedard, et.al. 1994). Previous research indicates that avalanche-generated infrasound is of significant amplitude and occupies a relatively noise free band of the infrasonic spectrum (Bedard, et.al. 1989). These properties lend themselves to the development of automated avalanche detection systems. Low frequency avalanche-generated infrasound has the ability to propagate many miles from the slide path in which the signal is generated. Thus, an infrasonic avalanche detection system has the potential to operate away from the slide path in a location unaffected by the avalanche activity.

Wind noise is recognized as one of the major obstacles to the development of an infrasonic avalanche detection system. Wind creates pressure perturbations that affect infrasonic sensors and introduce noise in acquired data, which confounds identification of an avalanche-generated signal. Effective pneumatic filtering methods that minimize the potential infrasonic sensor response to wind noise are essential to the successful collection and identification of avalanche-generated infrasound. However, pneumatic filtering techniques cannot eliminate all of the sensor responses to wind, and additional methods of utilizing the information in the acquired data to reduce the detrimental effects of wind are necessary.

Other naturally occurring phenomena (e.g. severe weather, volcanic activity, and earthquakes) can produce interference present in data acquired from infrasonic monitoring systems (Bedard, et.al. 1988). Additionally, interference from man-made sources (e.g. avalanche control release mechanisms, vehicle traffic, and mining activity) can be found in infrasonic data. Monitoring system design can eliminate some potential interference from acquired data; however, interfering signals that have similar frequency content to avalanche-generated infrasound may be present in the data. Sophisticated signal processing methods are required to reject this interference.

*Ernie Scott, Inter-Mountain Labs, Inc., Sheridan, WY 82801; tel: 307-674-7506; e-mail: scotte@imlinc.com

2. Monitoring Systems

While previous research findings support the idea of automated infrasonic avalanche detection systems, detailed information characterizing avalanche-generated infrasonic signals and potential interfering noise sources is not readily available. Such information is critical to the development of appropriate monitoring systems and the associated avalanche detection signal processing algorithms. In order to provide a basis for this development, infrasonic monitoring systems were designed, deployed and operated at several locations to collect infrasonic data during periods of observed avalanche activity.

2.1 Monitoring System Specifics

The primary purpose of the infrasonic monitoring systems was to provide high quality data for post processing analyses. This goal, coupled with knowledge gained from previous research findings, formed the basis for the monitoring system design specifications. Major components of a monitoring system include: a pneumatic wind noise reducing filter, a single infrasonic sensor, signal conditioning circuitry, and a data acquisition system. All system components were designed to operate reliably at a remote site during winter weather conditions. A primary consideration in the monitoring system design was the desire to maximize the signal-to-noise ratio of the acquired data.

Critical in producing a desirable signal-to-noise ratio is the coupling of a pneumatic wind noise reducing filter to the infrasonic sensing element of the monitoring system. Through a spatial acquisition of atmospheric pressure fluctuations, the signal-to-noise ratio is increased because the desired avalanche-generated signal content is coherent at the various pickups while the interfering wind noise is less coherent because of its random nature. Due to the long wavelengths associated with infrasound, the pneumatic filter array requires a large physical area for deployment.

The performance of many pneumatic filter configurations has been investigated in dedicated studies (Hedlin, et.al. 2001, Noel, et.al. 1991). The pneumatic filter configurations deployed in the avalanche monitoring systems consisted of a central manifold attached to a star configuration of 25-foot solid radial plumbing arms that were each connected to a 25 or 50 foot porous garden hose infrasound pickup. The pneumatic filters were placed on the ground and covered by snowfall, which provided some additional damping of wind noise. When feasible, the hose arrays were placed within tree cover to allow for further damping of wind noise. While a general pneumatic filter scheme was adopted, the exact configurations were dependent on the physical nature of each monitoring site.

The infrasonic sensor was configured for acquiring pressure signals through a $\pm$ 250 μbar dynamic range. Previous research indicates that avalanche-generated infrasound has pressure levels reaching hundreds of μbars (Bedard, et.al. 1994). Since the infrasonic sensor responds to frequency content of up to 100 Hz, an analog signal conditioning circuit was designed to interface the sensor to the data acquisition system.

The primary purpose of the signal conditioning circuit is to limit the frequency content contained in the data acquired from the infrasonic sensor to below 10 Hz. Information in the avalanche-generated infrasonic frequency band is provided to the data acquisition system while ensuring that available data acquisition sampling rates do not introduce aliasing errors into acquired data. The circuit also slightly attenuates frequencies lower than 0.1 Hz, so that acquired data is further limited to the frequency band that avalanche-generated signals occupy. The physical construction and realization of the signal conditioning circuit was implemented in a manner that reduces electronic noise.

Budget constraints and the planned number of monitoring systems dictated the data acquisition systems used. Campbell Scientific, Inc. datalogging equipment was used for the data acquisition systems. This equipment was desirable for several reasons: the 15 bit analog-to-digital converter provides sufficient quantization levels, data acquisition rates are sufficient to eliminate aliasing errors, and the equipment is field proven to operate in harsh weather environments while requiring low power. A drawback to the Campbell Scientific, Inc. datalogging equipment is that memory for storing acquired data is limited.

2.2 Monitoring Systems Sites

Selections of the monitoring sites were influenced according to the following desired criteria: close proximity to documented avalanche activity, easy wintertime accessibility, a large installation area for the pneumatic hose array, and the availability of support personnel. In order to mitigate the possibility of poor snowfall in a given region, systems were deployed at several sites in different regions of the United States. This scattering of monitoring systems ensured that a low snowfall year in a particular region would not eliminate the possibility of recording observed avalanche-generated infrasound. Host sites were installed in the following regions: Alta UT, Bozeman MT, Jackson WY, Silverton CO, and Valdez AK. All monitoring systems were installed within two miles of slide paths.

2.3 Monitoring Systems Data Catalogue

A large catalogue of infrasonic data was collected. The majority of the data are representative of ambient conditions without avalanche activity. This data contains typical background ambient noise levels and other interfering noise sources. The two most prevalent noise events present in the data were caused by wind and artificial avalanche control release mechanisms.

Many data sets were collected during avalanche control activities that include observed and documented avalanche activity. Tens of observed avalanche-generated infrasonic events are evident in the recorded data. Class two and three avalanches comprise the majority of these events, but a few class four events from large slide paths were recorded. These recorded events provide the basis for the development of signal processing algorithms designed for the automated identification of avalanche activity.

3. Results

Sufficient quantities of data were collected to characterize the infrasonic properties of both avalanches and interference signals that are prevalent in wintertime mountainous conditions. Inherent in all data collected is a dominant sinusoidal low frequency wave (~ 0.1 Hz).

3.1 Interfering Noise Signals

When wind effects are prevalent in the data, the underlying waveform contains periods of irregular large amplitude pressure fluctuations. The underlying waveform during wind noise events moves away from a sinusoidal form to become more representative of a triangle wave. The fundamental frequency of the resultant waveform is lower than the avalanche-generated frequency band, but the waveform contains harmonic frequency content that lies within the avalanche-generated frequency band.

In addition to wind, the data contains other significant interference signals. Figure 1 illustrates the large amplitude pressure fluctuations associated with wind in addition to four explosions from avalanche control activities, which released no snow. Large explosive mechanisms produce higher amplitude pressure fluctuations that are longer in duration than those produced by smaller explosive mechanisms.

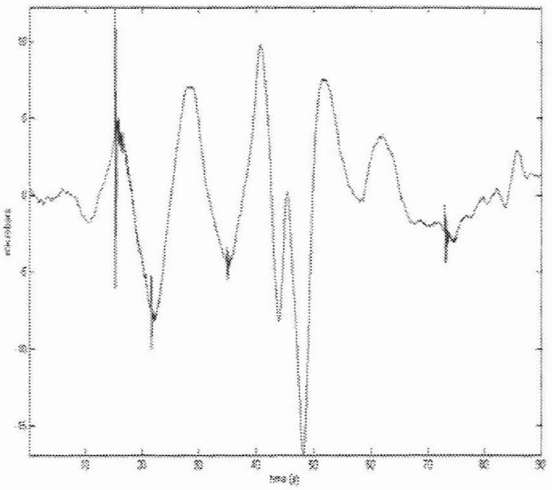

Figure 1: Wind and Explosive Noise

Aside from these differences, the sensor response due to explosive mechanisms is very consistent. The explosives used in avalanche control activity cause a damped sinusoidal signal waveform with fundamental frequency content higher than 4 Hz. This damped sinusoidal sensor response is partially attributable to the transient impulse response of sensor and signal conditioning electronics.

Figure 2 illustrates a series of interfering signals that are not attributable to avalanche control activity. While observations are unavailable to identify this interference, it is hypothesized that the source is man made because of the higher frequency impulse response of the monitoring system.

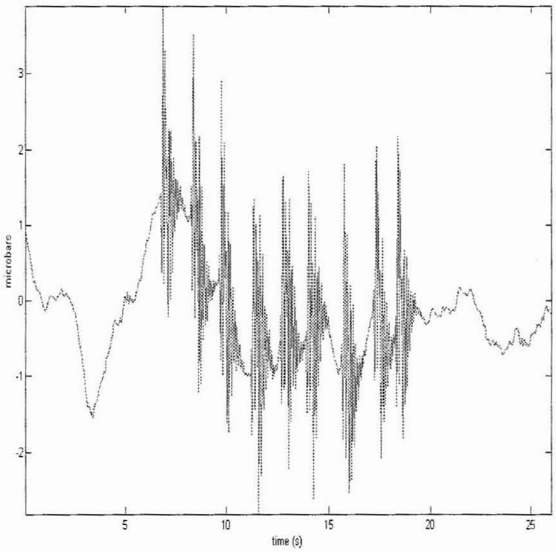

Figure 2: Unidentified Artificial Interference

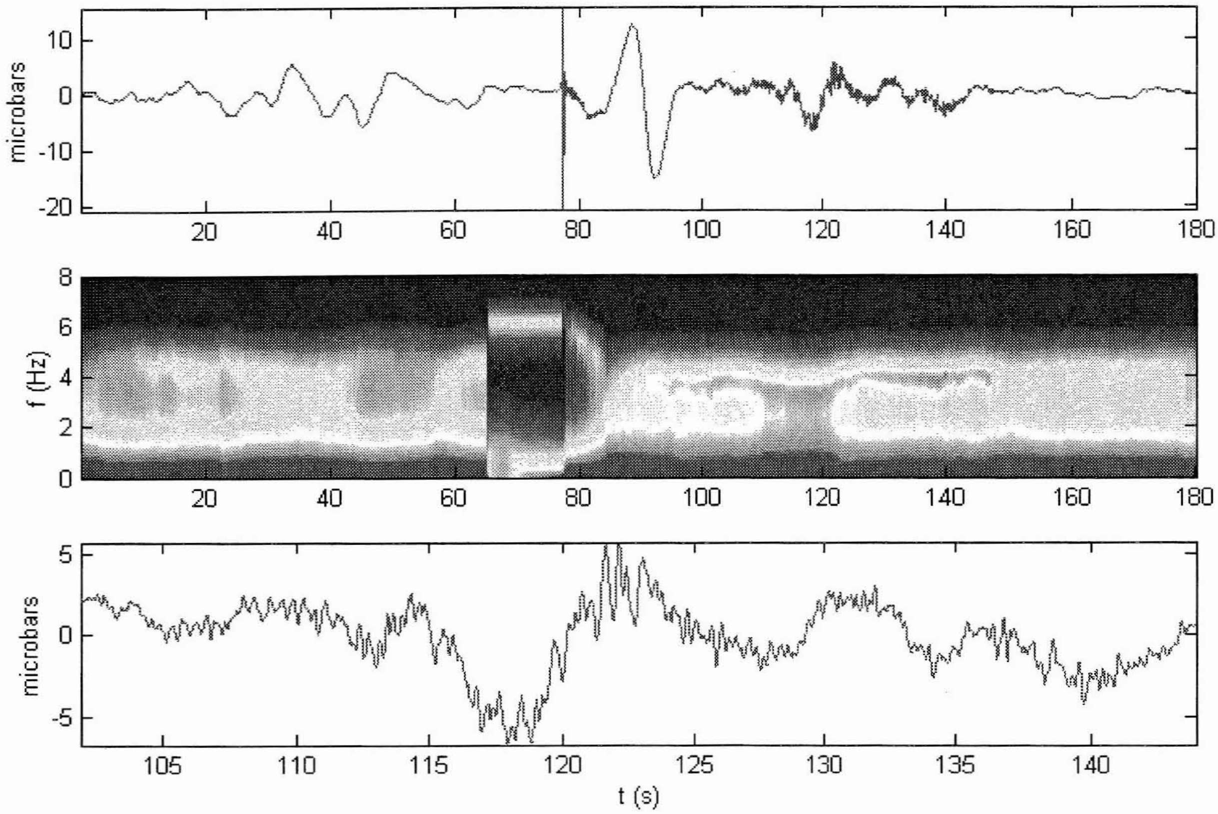

Figure 3: Powder avalanche-generated time series, power spectrum, and magnified time series

3.2 Avalanche-Generated Signals

Data collected during a controlled avalanche release are presented in Figure 3. Approximately 50 seconds of a class 4 powder avalanche from a large slide path are prevalent in the data around 20 seconds after the artificial control mechanism explodes. Exhibited in time series is the relatively small avalanche signal amplitude as compared to the explosive release mechanism and background ambient noise. Maximum signal pressure fluctuations attributable to the avalanche are less than 5 μbars peak-to-peak. The avalanche-generated data contains broad frequency content in a 1 to 8 Hz bandwidth, but the dominant energy is centered around 4 Hz as depicted in the power spectrum. Of importance to notice in Figure 3 are the effects on the power spectrum of the explosive release mechanism and the wind noise present during the avalanche.

Data recorded during an unclassified but observed naturally triggered wet avalanche are presented in Figure 4. Of interest with the wet slide event is that the dominant energy content is at higher power spectrum frequency than powder slide events. Pressure fluctuations associated with the wet slide event are only tenths of a μBar in magnitude.

3.3 Avalanche Detection Algorithm

The large data catalogue has been utilized to develop an avalanche detection algorithm. Through the use of digital filtering, statistics, and weighted threshold decision-making, potential avalanche signals can be quickly found with a high degree of reliability. Artificial events are easily rejected as interference. However, if an avalanche occurs at the same time as a man made event, then the avalanche is masked by the interference and not detected. Currently, the principal shortcoming in the algorithm is that it also detects certain interfering wind events and other interfering sensor responses that are not well characterized. While these false detections are not large in quantity, they must be removed to produce results that absolutely identify avalanche activity. Current efforts using complex signal processing techniques to remove the false detections are showing promise. Testing of the algorithm has shown that it is fairly stable across differing data sets and detection sites. Tuning algorithm parameters to fit specific monitoring site locations does improve algorithm performance.

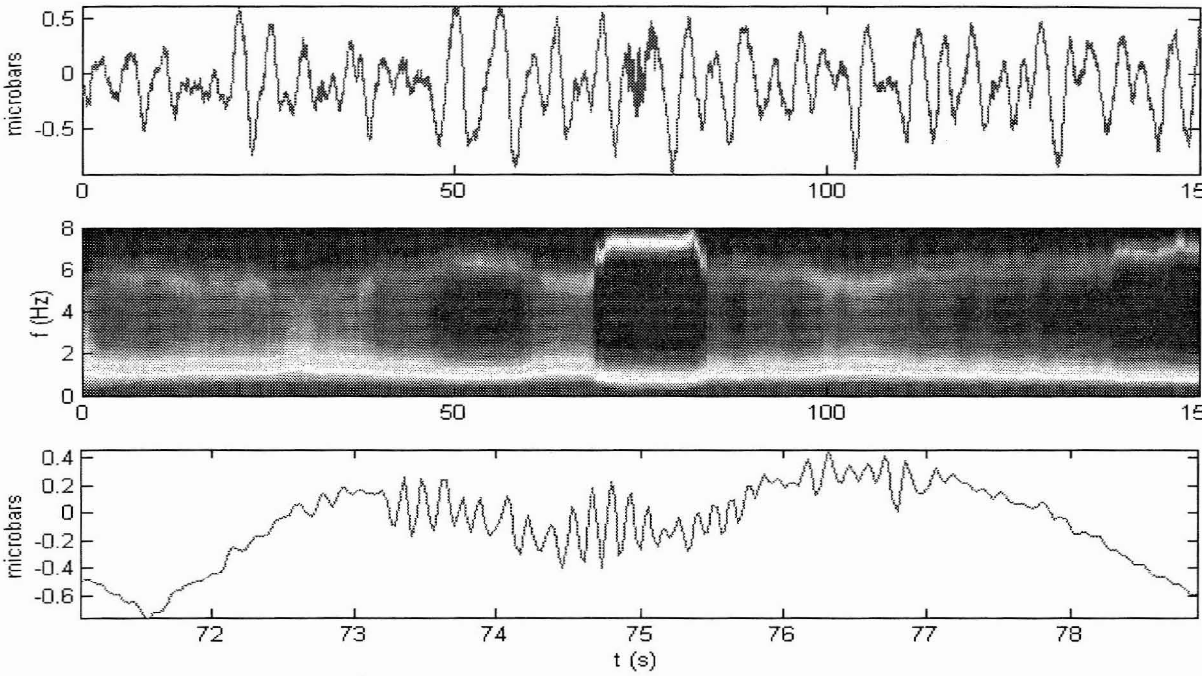

Figure 4: Wet avalanche-generated time series, power spectrum, and magnified time series

Illustrated in Figure 5 are two common detections obtained from the avalanche detection algorithm. Approximately 10 seconds into the data the algorithm creates a false detection attributable to high winds. The time period of this false detection is identified by the first bracketed square pulse, which has been superimposed on the raw sensor data. Around the mid point in the data set, an avalanche release mechanism is exploded that is rejected by the algorithm as an avalanche. A class 2 avalanche that is difficult to visualize in the raw data is detected by the algorithm about 20 seconds after the explosive release mechanism.

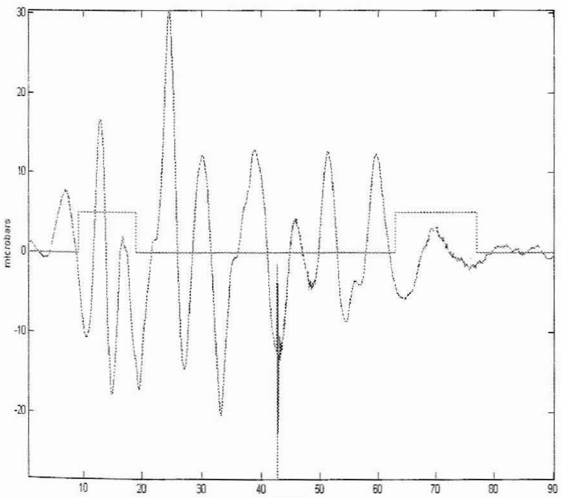

Figure 5: Examples of Algorithm Detections

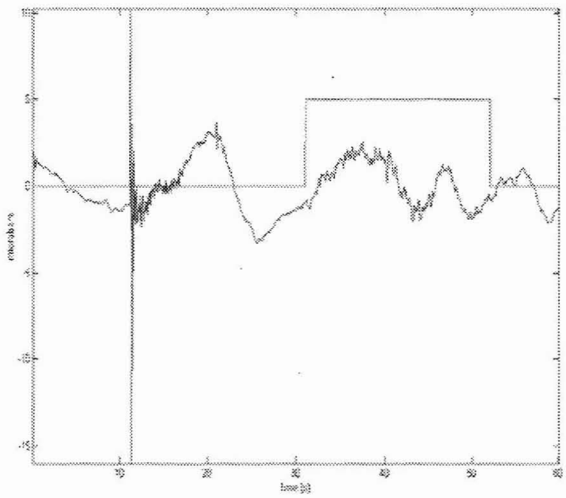

Figure 6 : Class 2 Avalanche and Detection

Figure 6 is presented to show a typical example of results obtained from the avalanche monitoring systems and detection algorithm. This result is indicative of a typical avalanche that can be identified due to an adequate signal-to-noise ratio. A potential method to raise the signal-to-noise ratio is to simply place the sensor closer to the slide path.

4. Future Work

Current research activities are focusing on removing false detections produced by the single sensor automated avalanche detection algorithm. Additional activities involve preparations for field monitoring that will take place during the winter of 2002/2003. During monitoring activities, it will be a priority to collect avalanche-generated infrasonic data simultaneously from very near an observed slide path and from much further away. This data will provide insight into how avalanche-generated infrasonic pressure amplitudes relate to the proximity of the monitoring system to the slide path. Additionally, it is anticipated that false detections from the automated avalanche detection algorithm will be reduced by using information obtained from monitoring systems operated at different locations. Concurrent efforts will be applied to operate the automated avalanche detection algorithm in a real-time fashion.

A long-term goal not included in the efforts currently funded is to develop an infrasonic sensor array monitoring system that can provide signal phase data for spatial filtering and source localization algorithms.

5. Conclusions

An extensive catalogue of infrasonic data aimed at the development of automated avalanche detection systems was collected during the winters of 2000/2001 and 2001/2002. Many data sets collected during observed avalanche activity verify previous research findings that avalanches produce infrasound in the 1 – 8 Hz frequency band. Amplitudes of the avalanche-generated infrasonic pressure fluctuations were found to be on the order of μbars.

The infrasonic data catalogue also provides information characterizing potential interfering infrasonic sources. The major interfering sources identified in the data are electronic transient impulse responses stimulated by artificial sources, and random wind noise. The data have been utilized to develop a signal processing algorithm that identifies infrasound attributable to avalanche activity. At the current time, the automated detection algorithm suffers from false avalanche detections when the signal-to-noise ratio is low. Future algorithm development work utilizing complex signal processing techniques to remove false detections is planned during the remaining year of funding

6. Acknowledgements

This paper is funded in part by a contract from the Department of Commerce, National Oceanic and Atmospheric Administration. The views expressed herein are those of the authors and do not necessarily reflect the views of the Department of Commerce/NOAA or any of it sub-agencies.

The authors would like to thank the following organizations and their people for providing support services that have been integral to the successes of this project; Alaska Department of Transportation, Bridger Bowl Ski Area, Bridger Teton National Forest Avalanche Center, Colorado Avalanche Information Center - Silverton Office, Jackson Hole Mountain Resort, Montana State University Civil Engineering Department, Southern Methodist University Department of Geological Sciences, University of Wyoming Electrical & Computer Engineering Department, and the Utah Department of Transportation.

7. References

Bedard, A. J. Jr., "An Evaluation of Atmospheric Infrasound for Monitoring Avalanches", Proceedings; 7th International Symposium on Acoustic Sensing and Associated Techniques of the Atmosphere and Oceans, Boulder, CO, 1994.

Bedard, A. J. Jr., "Detection of Avalanches Using Atmospheric Infrasound", Proceedings; Western Snow Conference, Fort Collins, CO, 1989.

Bedard, A. J. Jr., G. E. Greene, J. Intrieri and R. Rodriguez, "On the Feasibility and Value of Detecting and Characterizing Avalanches Remotely by Monitoring Radiated Sub-Audible Atmospheric Sound at Long Distances" Proceedings; A Multidisciplinary Approach to Snow Engineering, Santa Barbara, CA, 1988.

Hedlin, Michael A. H., J. Berger, "Evaluation of Infrasonic Noise Reduction Filters", 23rd Seismic Research Review: Worlwide Monitoring of Nuclear Explosions, Jackson, WY, October 2-5, 2001

Noel, S. D., and R. W. Whitaker, "Comparison of Noise Reduction Systems", Los Alamos National Laboratory, LA-12003-MS, 1991.