Single and Multiple Sensor Identification of Avalanche-Generated Infrasound

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Abstract: The ability to identify snow avalanches as they occur is essential for aggressive avalanche management in transportation corridors and is a fundamental ingredient of avalanche forecasting. Past studies have shown that moving avalanches emit a detectable sub-audible sound signature in the low frequency infrasonic spectrum. Experimental infrasound avalanche monitoring activities conducted in the United States Rocky Mountain West clarify avalanche event identification capabilities of single sensor and multiple sensor systems. Avalanche identification performance of single sensor monitoring systems vary according to ambient noise and signal levels. While single sensor auto correlation signal processing algorithms identify avalanche activity, uncertainties (i.e. false negative identifications and false positive identifications) increase as wind noise increases, and as signal levels decrease due to increasing distance or smaller sources. Monitoring with multiple sensor systems substantially improves avalanche event identification robustness under windy and noisy conditions, while also allowing location estimates of avalanche events to be made. Avalanche event identification and localization capabilities of cross correlation and semblance multiple sensor signal processing algorithms are demonstrated via a sensor array monitoring system. Also demonstrated are avalanche identification and localization capabilities of distributed networks of infrasound monitoring systems. Garnered knowledge is being ported into near real-time prototype systems that will be operated in the Jackson Hole, Wyoming region. Prototype operation will provide performance evaluations in practical highway and recreational area settings. Reliable implementation of infrasound monitoring technology to automatically identify avalanche events requires further innovative solutions to problematic ambient wind noise and interfering signals.

Keywords: Avalanche monitoring, infrasound, signal, correlation, beamforming, array processing

1. Introduction

Early research performed by the United States National Oceanic and Atmospheric Administration showed that snow avalanches generate acoustic signals within the 1- 5 Hz low noise band of the sub-audible infrasonic frequency spectrum (Bedard 1989, Bedard 1994, Bedard et. al. 1988). Later in Europe, scientists (Chritin et.al. 1996) prototyped an infrasound detection system for operational avalanche forecasting.

Low frequency infrasound signals can propagate kilometers from the avalanche source and provide a basis for developing automated identification and alarm systems that can operate in locations distant and safe from avalanche activity. Such a system provides an opportunity to record avalanche activity or quiescence in a broad area upwards to 4 square kilometers without needing individual path sensors or observations. Knowledge of regional avalanche event activity provides valuable information for those impacted by avalanche activity. Such information is essential for aggressive avalanche management in transportation corridors and is a fundamental ingredient of avalanche forecasting.

Several recent research projects completed in the United States Rocky Mountains investigated the feasibility of utilizing infrasound monitoring for automated identification of avalanche activity (Comey and Mendenhall 2004). A multi-disciplinary team of scientists, engineers, technicians and

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avalanche professionals was assembled to perform these studies. Deployed monitoring systems were designed to record data from commercially available Chaparral Model II infrasound sensors that were coupled to spatial pneumatic porous hose filters, which reduced levels of measured ambient noise. The infrasound sensor and associated spatial pneumatic porous hose filter were placed on the ground and allowed to be covered with snow fall, which provided an additional buffer from ambient noise. Infrasound sensor signals were band limited via analog filtering to be within 0.1 to 8.5 Hz prior to recording at 33.33 Hz by simple Campbell Scientific, Inc. data logging equipment.

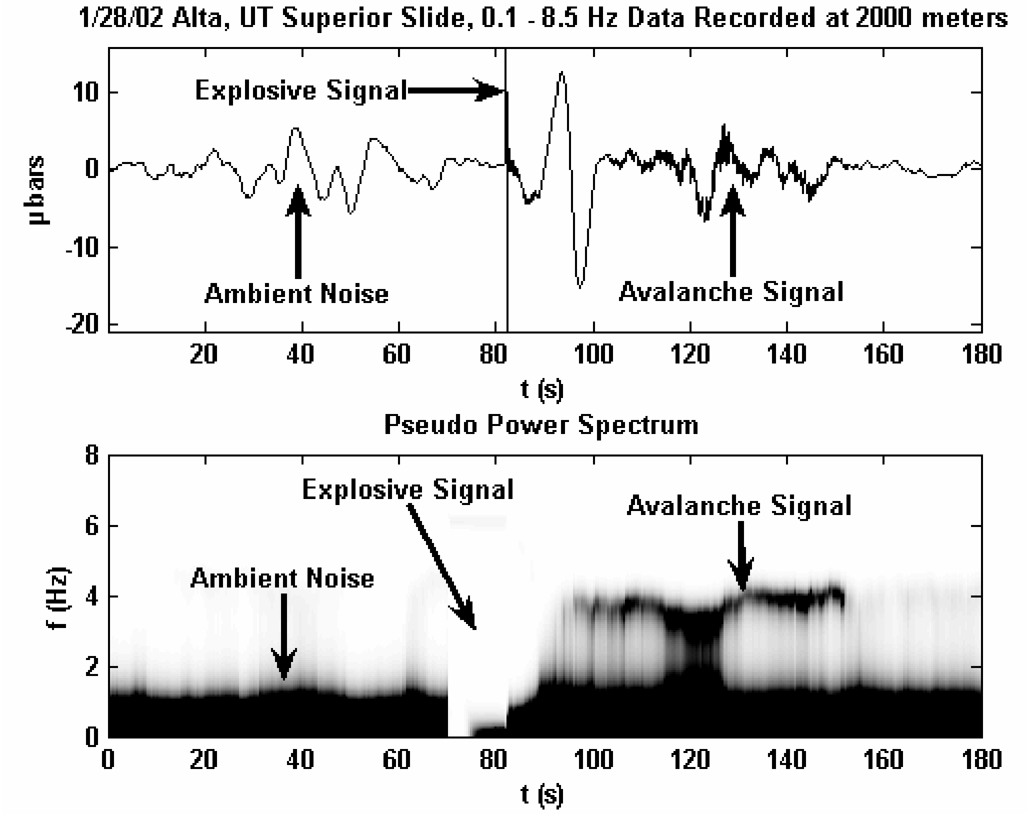

Figure 1. Explosive Signal and Class 3 Avalanche Signal

Signals recorded from avalanche hazard mitigation activities provided a controlled and documented environment to investigate various identification and location schemes using post event processing. Data collected during explosively triggered and observed avalanche events verified the capabilities of sensors to detect both explosive-generated signals and avalanche-generated signals in the 0.1 to 8.5 Hz band of the infrasonic frequency spectrum (Scott and Lance 2002). As shown in Figure 1, recorded data show little overlap of the triggering transient explosive signals and resultant avalanche signals.

Data from a few significant type example events were assembled into a catalog. This was used to develop and test automated avalanche event identification signal processing algorithms. Initial efforts showed that single sensor auto correlation signal processing algorithms could identify recorded avalanche signals and discern them from explosive signals (Scott 2003). Subsequent studies characterized the performance of single sensor signal processing algorithms as ambient noise and signal levels varied (Scott and Hayward 2003). For single sensor algorithms, any combination of increased wind noise levels and decreased signal levels raised the likelihood of false alarms (false positive) or missed (false negative) avalanche event identifications. The potential for ambient wind noise to increase and mask an avalanche signal is evident in the pseudo power spectrum shown in Figure 1. During the middle of the avalanche event at 125 seconds on

Figure 1, a small wind gust similar to that indicated by the ambient noise is added to avalanche signal. Although the wind noise is concentrated at frequencies below 1.5 Hz, some energy does leak into the avalanche band.

The uncertainties of single sensor identifications prompted an investigation of multiple sensors to improve avalanche signal identification robustness. Data were recorded by a sensor array monitoring system and distributed single sensor monitoring systems. It was then post processed to investigate capabilities of multiple sensor avalanche identification signal processing algorithms. Compared to single sensor algorithms, multiple sensor cross correlation and semblance results provided more robust avalanche signal identification in the presence of moderate wind noise. This was found true even for low amplitude avalanche signals. Additionally, multiple sensor signal processing provides location estimates of the avalanche signal source origin, which provides a basis for discrimination of potential interfering signals and further eliminates false alarms.

These promising results lead to current efforts surrounding the development of prototype near real-time avalanche identification systems. Critical to these systems are custom designed software and hardware components that have been optimized for the avalanche infrasound monitoring application. The prototype systems will be utilized in an automated and continuous manner to evaluate avalanche identification performance in practical highway and recreational area settings. Care will be taken to operate the remote sensors at monitoring sites that optimize avalanche signal and ambient noise levels. Problems and associated solutions to the always-present issues of wind noise and interfering signals will be explored through the current studies.

2. Single Sensor Avalanche Identification

An extensive catalog of avalanche-generated infrasound signals was recorded through the various research efforts. This catalogue provided a basis for developing single sensor signal processing algorithms that identify recorded avalanche signals. Auto correlation (power estimation) signal processing techniques form the foundation of the single sensor avalanche identification algorithms. Performance of single sensor avalanche identification algorithms is difficult to quantify, but empirical evidence shows that it depends greatly upon recorded avalanche signal levels and ambient noise levels. Detailed descriptions of the monitoring settings where the following data were recorded are included in Section 3.

2.1 Large Avalanche Signal in Low Wind Noise

Figure 2 shows recorded 0.1 – 8.5 Hz infrasound data and auto correlation coefficients computed through the single sensor signal processing algorithm. These infrasound data were recorded during Wyoming Department of Transportation avalanche hazard mitigation activities on Teton Pass, WY that resulted in a Glory Bowl avalanche estimated as a Class 3 event in the Canadian classification system (CSAC 2004), which uses a scale range of 1 to 5 with 5 being the largest. Infrasound data were recorded by a single sensor monitoring system 1000 meters from the slide path start zone and 200 meters from where the avalanche event stopped. All distances discussed in this report represent straight line point-to-point approximations in all three spatial dimensions. This standardized distance convention is used even if obstructions were present.

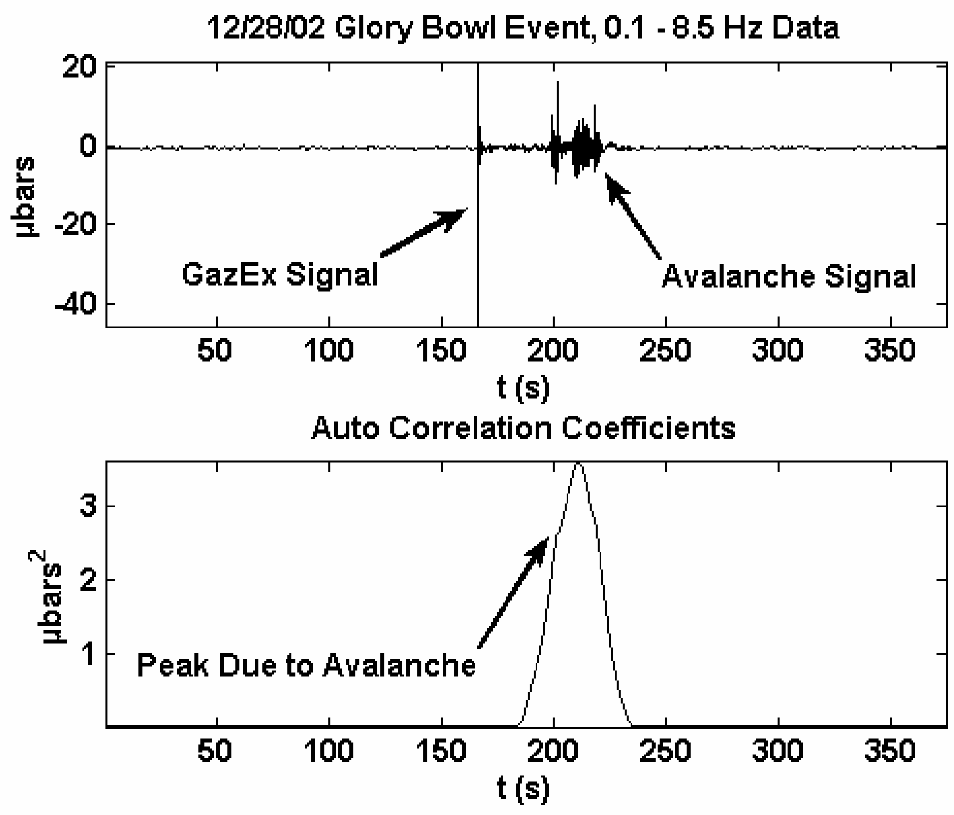

Figure 2. Class 3 Avalanche Signal and Low Wind Noise

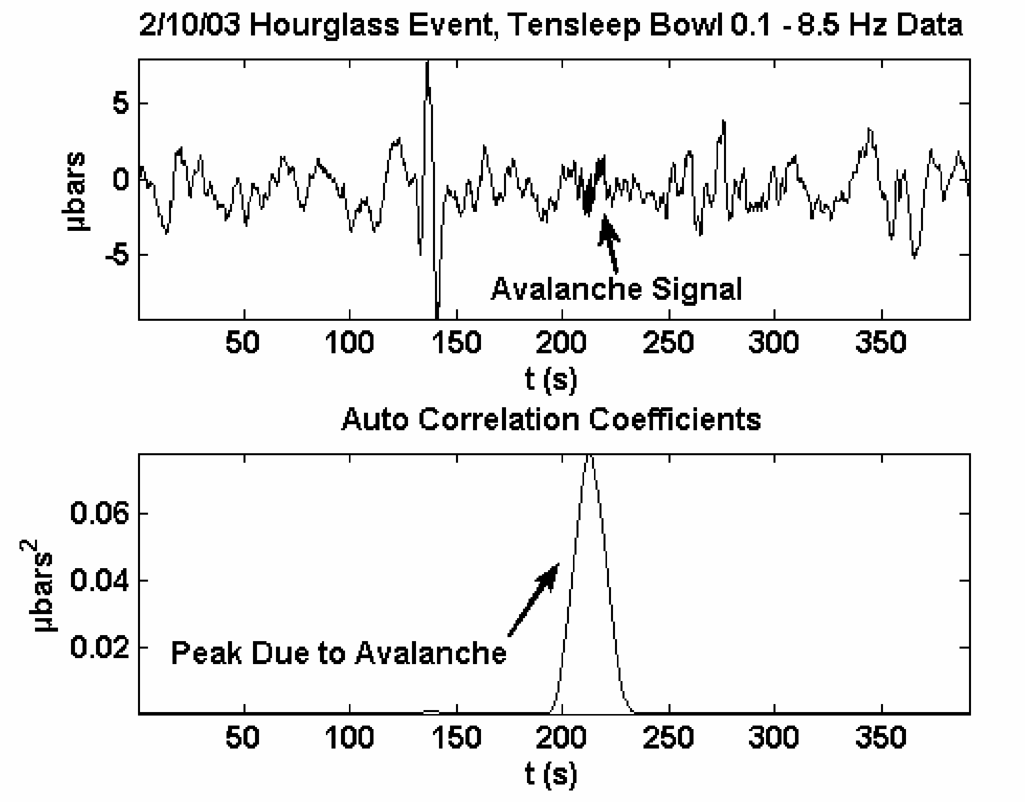

Figure 3. Class 2 Avalanche Signal and Low Wind Noise

Evident in the recorded 0.1 – 8.5 Hz infrasound data time series is the avalanche signal and an additional signal from the GazEx explosion that triggered the avalanche. The time sequence of auto correlation coefficients shows a peak corresponding to the avalanche event, which could easily be used in an automated threshold identification algorithm. The GazEx signal does not exhibit a peak in the time sequence of auto correlation coefficients, because the single sensor signal processing algorithm automatically recognized it as a non-avalanche signal and removed its energy content prior to calculation of the auto correlation coefficients. Automatic removal of explosive energy content was possible, because explosive and avalanche signals exhibit differing signal features that enable discrimination of the two types of signals. The impulsive transient nature of the explosive signal was manipulated through frequency, median, and gradient filtering techniques to discern it from the more Gaussian avalanche signal.

The avalanche signal shown in Figure 2 is over 20 ubars peak-to-peak and is one of the largest amplitude avalanche signals contained in the data catalogue collected during the research studies. Some avalanche signals recorded at Alta, UT, from Baldy and Superior events exhibit similar large magnitude characteristics. The majority of the 50 some catalogued avalanche signals do not exhibit large magnitude characteristics, and peak-to-peak amplitudes were typically an order of magnitude smaller.

For the recorded 0.1 – 8.5 Hz infrasound data shown in Figure 2, the absence of background wind noise is also unusual. This scenario of a large avalanche signal combined with low wind noise demonstrates ideal conditions for reliable avalanche event identification by the single sensor signal processing algorithm. In practical applications this ideal monitoring situation is rarely encountered.

2.2 Small Avalanche Signal in Low Wind Noise

A more common monitoring scenario of a small avalanche signal immersed in low wind noise is depicted in Figure 3. Figure 3 shows recorded 0.1 – 8.5 Hz infrasound data and auto correlation coefficients containing effects of a ski triggered Hourglass avalanche estimated as a Class 2 event, which occurred near Teton Village, WY in a permanently closed area of the Jackson Hole Mountain Resort. Infrasound data were recorded by a single sensor monitoring system that resided 500 meters from the slide path start zone and 200 meters from where the avalanche event stopped.

While the avalanche signal is hardly visible in the raw data time series, the peak in the time sequence of auto correlation coefficients easily identifies sensor detection of the avalanche event. Yet, if ambient wind noise levels were high, this small amplitude signal could be masked, and automation of the single sensor signal processing algorithm would fail to provide reliable identification of the avalanche event.

2.3 Small Avalanche Signal in High Wind Noise

A problematic monitoring scenario of a small avalanche signal immersed in high wind noise is depicted in Figure 4. Figure 4 shows recorded 0.1 – 8.5 Hz infrasound data and auto correlation coefficients from a two-pound explosively triggered Jackson Hole Mountain Resort Cajun avalanche estimated as a Class 2 event. Effects of the small explosion on the auto correlation results are insignificant. Infrasound data were recorded by a single sensor monitoring system 500 meters from the slide path start zone and 200 meters from where the avalanche event stopped.

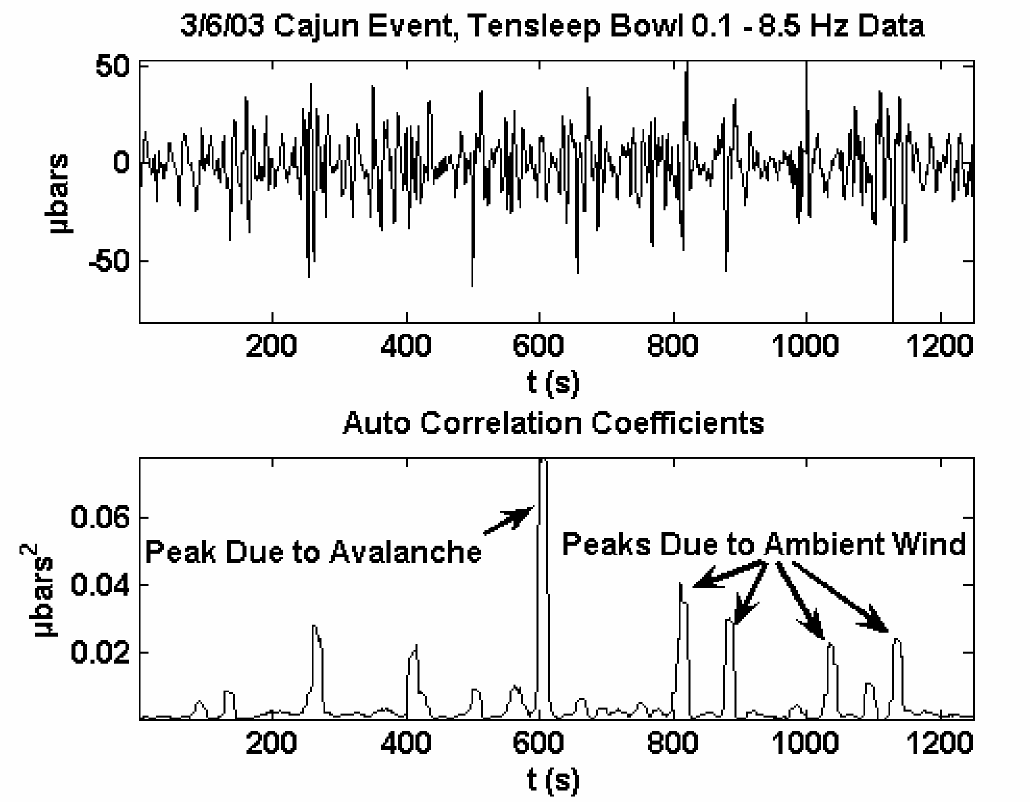

Figure 4. Class 2 Avalanche Signal and High Wind Noise

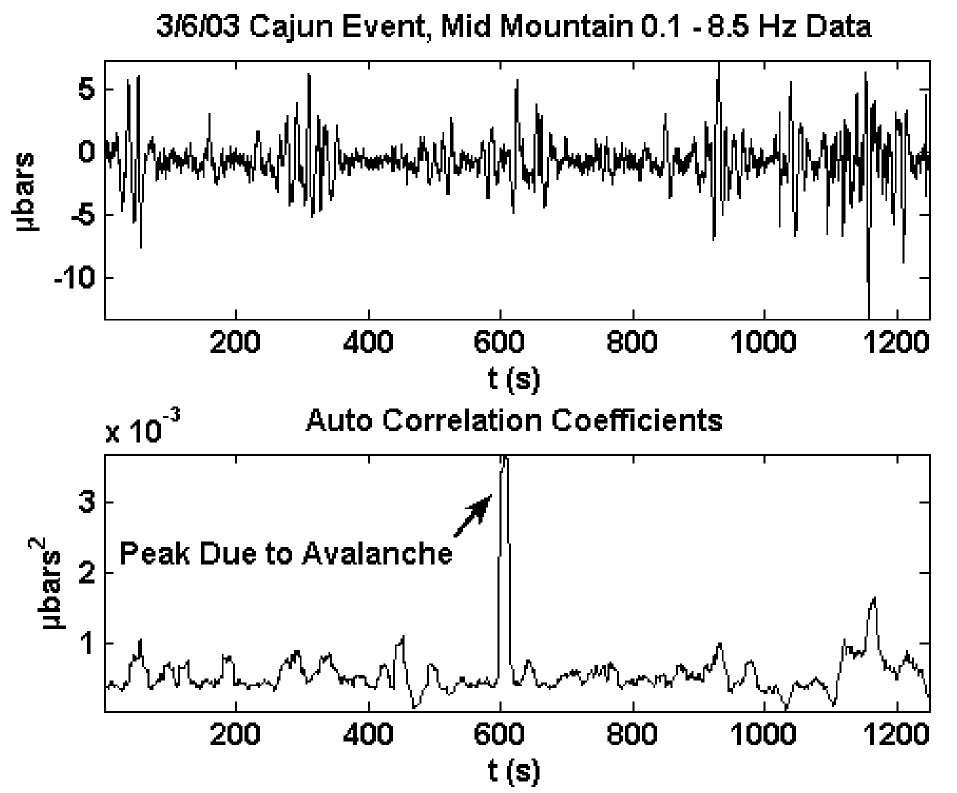

Figure 5. Class 2 Avalanche Signal and High Wind Noise - Second Sensor

Although the avalanche signal is not visible in the raw data time series, it is identifiable in the auto correlation coefficients. This is shown by the peak in the time sequence of auto correlation coefficients that corresponds to the occurrence of the avalanche event. However, this peak does not allow for reliable identification of the avalanche event, since the time series of auto correlation coefficients also exhibits spurious peaks resulting from the high wind noise. Under this scenario, where an automated single sensor monitoring system makes identification on the basis of the auto correlation exceeding some peak threshold (e.g. 0.06 ubars^2), this kind of event may be missed if it were slightly smaller, or it may be included in a sequence of false alarms if the wind noise is slightly larger.

Figure 5 shows recorded 0.1 – 8.5 Hz infrasound data and auto correlation coefficients corresponding to the avalanche event depicted in Figure 4, but these results were obtained from a second infrasound sensor located at a different monitoring site. The second sensor infrasound data were recorded approximately 1500 meters away from the avalanche event.

The small avalanche signal in combination with the more distant monitoring location resulted in the second sensor barely detecting the avalanche signal. While the signal is not visible in the raw data time series, the peak in the sequence of auto correlation coefficients verifies its presence. Also important is that the second sensor exhibits lower and different wind noise effects. Still, the time sequence of auto correlation coefficients is not adequate to provide reliable automated single sensor avalanche event identification, because the auto correlation peak resides very near levels indicative of low wind noise conditions. Any elevation in wind noise would easily rise above the magnitude of the peak and entrain it in a sequence of false alarms.

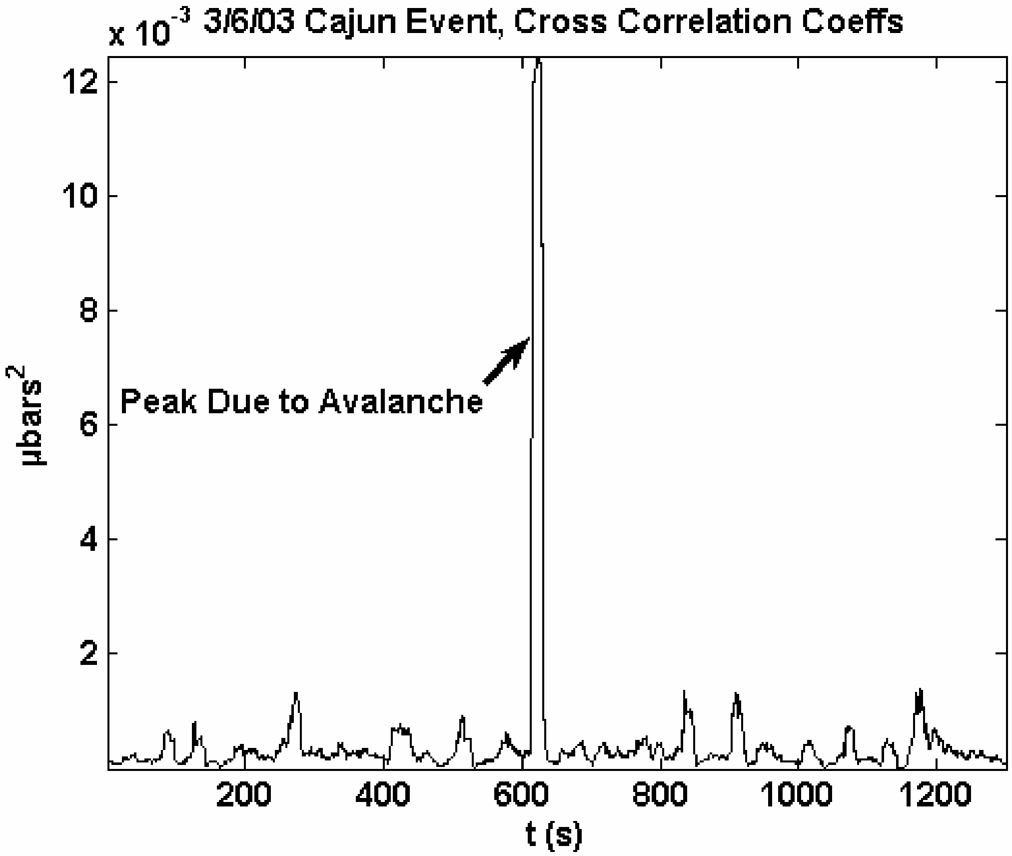

Figure 6. Distributed Sensors Cross Correlation

The coherence of the avalanche signal detection by the two spatially distributed sensors provides a means to mitigate the negative impacts of the ambient wind noise that quickly looses coherency across distances. The time series of cross correlation coefficients shown in Figure 6 demonstrates avalanche identification capabilities obtained through the use of the two distributed sensors. The peak corresponding to the avalanche event is clearly identifiable, while the spurious wind noise peaks are reduced.

3. Multiple Sensor Avalanche Identification and Localization

Experimental evaluation of the single sensor signal processing algorithm showed that reliability of automated avalanche identifications varied according to avalanche signal amplitudes and ambient wind noise levels. Fortunately, multiple sensor signal processing algorithms hold promise for improving robustness of infrasound avalanche monitoring. Spatially separated infrasound sensors produce data that can be utilized to extract and identify coherent avalanche signals immersed in noise through the use of cross correlation and semblance signal processing techniques. These multiple sensor signal processing techniques also allow location estimates of the identified avalanche signals to be made. Recent studies at two independent locations investigated the performance of multiple sensor signal processing algorithms through the use of a sensor array and distributed single sensor monitoring systems.

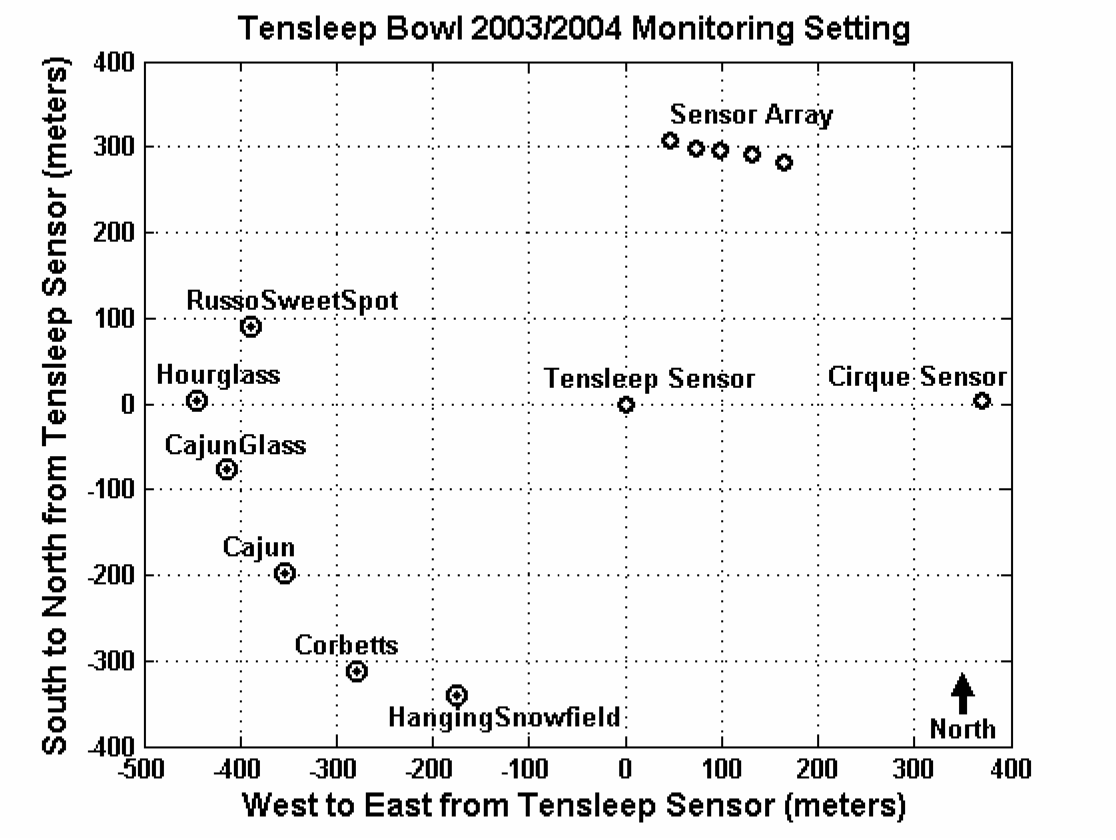

Figure 7. Tensleep Bowl Monitoring Setting

3.1 Jackson Hole Mountain Resort Multiple Sensor Monitoring Setting

Figure 7 shows an Easting and Northing depiction of the monitoring area for a multiple sensor experimental study performed during the 2003/2004 winter at the Jackson Hole Mountain Resort. Data previously presented in Figure 3 and Figure 4 were recorded by the Tensleep Sensor. The Mid Mountain sensor located in an area not covered by Figure 7 recorded data previously presented in Figure 5.

Figure 8. Jackson Hole Mountain Resort Avalanche Paths

Figure 9. Typical Jackson Hole Mountain Resort Class 2 Avalanche

A series of six targeted avalanche start zones at elevations near 3075 meters occupy a ridge in the Southwest portion of the monitoring area. Three infrasound monitoring systems were distributed in North and East directions from the targeted avalanche paths. The Tensleep system at an elevation of 2890 meters consisted of a single infrasound sensor approximately 500 meters from the targeted avalanche start zones. The Sensor Array system at an elevation of 2920 meters was located around 675 meters from the targeted avalanche start zones and consisted of five infrasound sensors deployed in a linear configuration that was broad side to the targets. An approximately 150 meter aperture was obtained from the nearly equally spaced Sensor Array. The Cirque system at an elevation of 2745 meters consisted of a single infrasound sensor that was located approximately 850 meters from the targeted avalanche start zones.

Avalanches originating from the start zones run hundreds of meters down highly vertical terrain towards the Tensleep Sensor. A picture of the targeted avalanche paths viewed from the Sensor Array is shown in Figure 8. Shown in Figure 9 is an explosively triggered Class 2 CajunGlass avalanche event as viewed from near the Tensleep Sensor. This avalanche event is typical of results obtained from the targeted avalanche paths.

3.2 Jackson Hole Mountain Resort Multiple Sensor Signal Identification

It was previously shown that combining a pair of distributed sensors demonstrated an improvement in avalanche identification performance over that offered by each individual sensor on its own. Identification performance continues to improve as more sensors are used in the multiple sensor cross correlation signal processing.

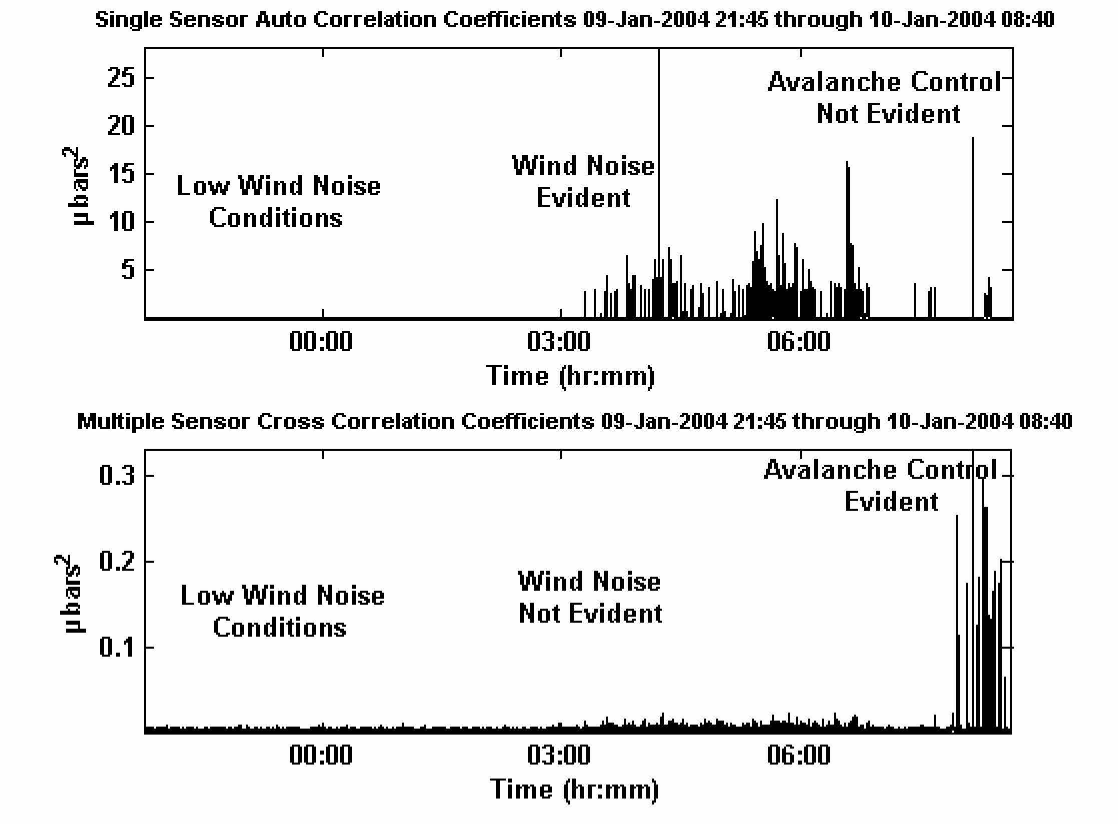

Figure 10. Single vs Six Sensor Signal Identification

Figure 10 demonstrates the ability of multiple spatially separated sensors to drastically improve single sensor signal identification. The data set utilized to obtain these results was selected for presentation, because it covers ten hours of time that contains contrasting monitoring conditions.

The time span starts with a low wind noise monitoring environment. Shortly after the midpoint in the time span, ambient wind noise greatly increases. Near the end of the time span, the ambient wind noise subsides, but remains slightly elevated. Also near the end of the time span, avalanche hazard mitigation activities occur.

The top graph in Figure 10 shows a time sequence of auto correlation coefficients obtained from a single sensor in the Sensor Array. During low wind noise conditions the auto correlation sequence does not exhibit any spurious peaks that could falsely be identified as signals. However, during high wind noise conditions the auto correlation sequence exhibits many peaks that could falsely be identified as signals. These erroneous peaks are exaggerated by the high winds driving the infrasound sensor in and out of saturation. During the avalanche hazard mitigation activities, the auto correlation sequence exhibits several peaks. However, prior results are not robust to the high wind noise, so reliability of identifying peaks as true infrasound signals is poor.

The bottom graph in Figure 10 shows a time sequence of aggregate cross correlation coefficients obtained from arithmetic mean pair-wise cross correlation of the six sensors contained in the combined Tensleep and Sensor Array systems. The Cirque sensor data was unavailable during this time period. During both low and high wind noise conditions the cross correlation sequence exhibits no erroneous peaks that could falsely be identified as signals. During avalanche hazard mitigation activities, the cross correlation sequence exhibits many peaks that correspond to true signals caused by observed events. Since the multiple sensor signal processing algorithm performs robustly during the high wind noise conditions without introducing spurious peaks in the cross correlation sequence, reliability and confidence of automatically identifying the cross correlation peaks during avalanche hazard mitigation activities as true infrasound signals is high.

The signals identified through the cross correlation sequence during avalanche hazard mitigation activities are of both explosive and small Class 2 avalanche origin. Identification of explosive signals was left in the cross correlation sequence to demonstrate the effectiveness of the multiple sensor signal processing algorithms.

Since these true explosive signals are detected as correlated energy, there is a possibility that they could falsely be identified as avalanche events. Positive identification of explosive signals during avalanche hazard mitigation activities could provide beneficial information on whether ordinance detonated. However, false identification of explosive signals is not desired during automated monitoring aimed at providing early notification of unobserved avalanche events. Even though it is highly unlikely that explosions will occur outside of avalanche hazard mitigation activities, methods that discern between explosive and avalanche signals are desired. This desire extends to any other interfering signals that might exist.

Signal discrimination methods developed for the single sensor auto correlation algorithm can be effectively used to remove interfering signals from multiple sensor cross correlations. These signal discrimination methods utilize a variety of filtering techniques that are designed to manipulate unique features of a particular signal signature.   Time domain median filtering techniques can identify the impulsive short duration transient that is characteristic of an explosive signal, but is not characteristic of an avalanche signal. Frequency selective filtering techniques can be used to recognize the higher frequency content of large magnitude explosive signals that is not characteristic of avalanche signals. Time domain difference and gradient filtering techniques can be used to recognize the higher rate of change in magnitude that an explosive or wind induced signal often exhibits over an avalanche signal.   Simple event duration criterion can further assist in alleviating the possibility of false avalanche event identification. Even with the availability of the aforementioned techniques, knowledge regarding the origin of the signal source would provide an additional powerful tool to aid in signal discrimination.

3.3 Jackson Hole Mountain Resort Multiple Sensor Signal Localization

In addition to providing robust signal identification capabilities, monitoring with multiple spatially separated sensors provides the ability to estimate the origin of the signal source. Signal propagation time delays between sensors can be obtained from the lag values of pair-wise cross correlation coefficients to form aggregate beam patterns associated with the geometric configuration of the sensor array. Resultant beams estimate the possible locations in the targeted monitoring area from which the identified signal could have emanated.

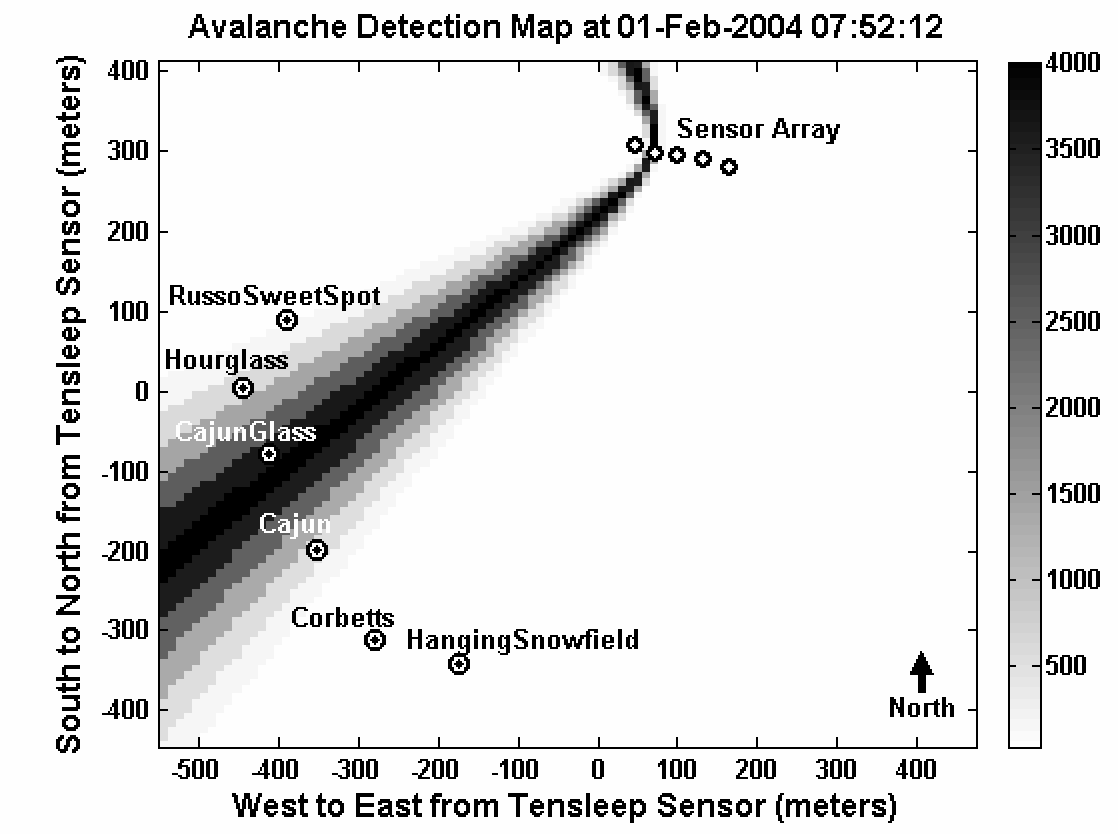

Figure 11. Sensor Array 2/1/04 CajunGlass Identification and Localization

Figure 11 shows an example of cross correlation signal location estimates obtained for a large Class 2 CajunGlass avalanche event that was triggered via a two-pound explosion. Effects of the small explosion on the avalanche signal location estimates are insignificant. Beamforming results presented in Figure 11 were generated using data recorded by the linear five sensor array.

Estimated avalanche signal source locations are presented through the linear gray scale that spans a magnitude range of 0 to 4000 arbitrary units. The use of an arbitrary unit scale is a result of image processing techniques that provide sharper contrast between locations that are and are not indicative of the presence of signals. Black corresponds to a magnitude of 4000 and represents the presence of a strong signal originating from a source location. White corresponds to a magnitude of 0 and represents the absence of a signal emanating from a source location. Intermediate gray tones represent the presence of an intermediary strength signal originating from a source location. The magnitude information represented by the gray scale also provides an alternative presentation for the avalanche signal identification capabilities of the cross correlation multiple sensor processing.

The beam formed by the Sensor Array accurately estimates that the avalanche signal originated from a location indicative of the Cajun Glass slide path. However, the beam does not indicate the distance away from the Sensor Array from which the avalanche signal emanated. The beam also exhibits a false mirror image about the linear array axis. While the beam formed by the Sensor Array exhibits location aliases, it does provide the necessary information to recognize the general location of the avalanche activity.

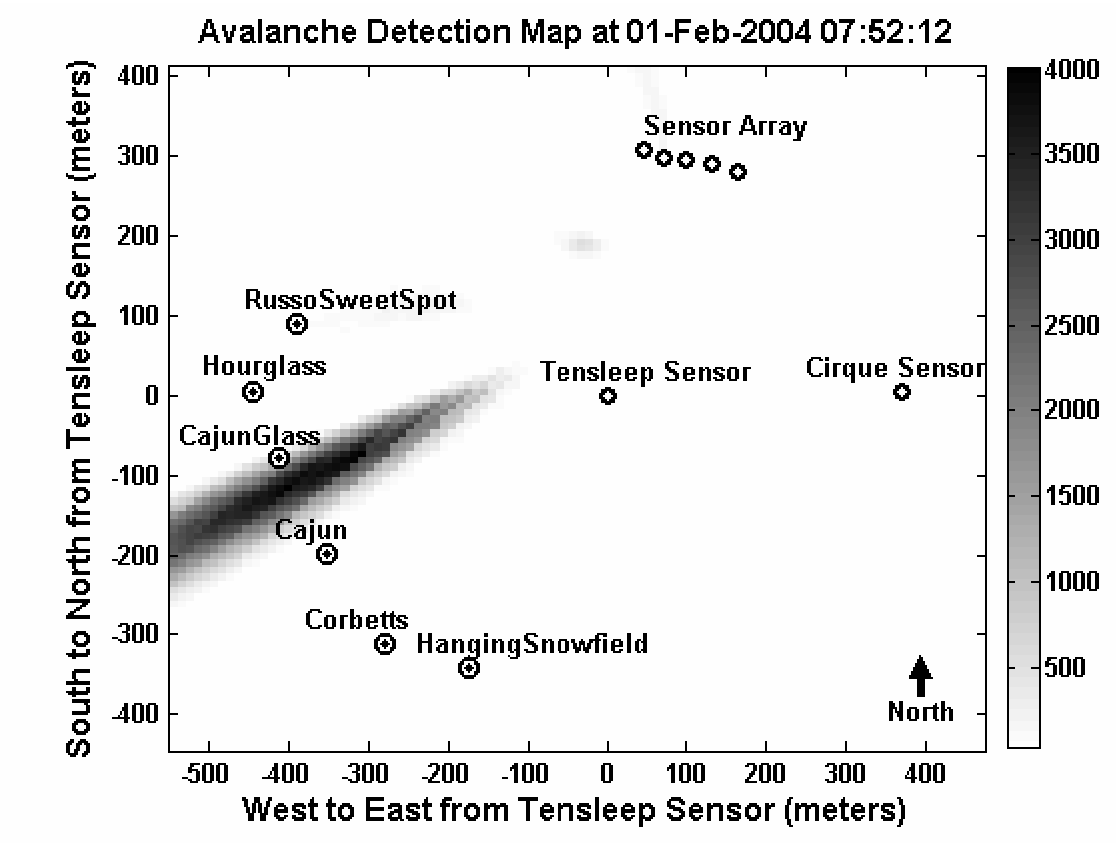

Figure 12. Network Wide 2/1/04 CajunGlass Identification and Localization

Figure 12 shows improved cross correlation beamforming signal source location estimates for the CajunGlass avalanche event. Narrowing of the estimated avalanche signal source locations was accomplished by forming a beam that includes the distributed Tensleep and Cirque sensors with the Sensor Array. The narrowed beam pattern provides an accurate estimate of the avalanche signal source location while minimizing the presence of location aliases.

3.4 Jackson Hole Mountain Resort Semblance Array Processing

Even though the multiple sensor cross correlation signal processing resulted in excellent avalanche identification and localization capabilities, an alternative coherency measure was investigated using experimental Jackson Hole Mountain Resort data. Signal propagation time delays between sensors were exploited through the computation of semblance coefficients (Taner 1996) to form beam patterns associated with the geometric configuration of the sensors. Resultant beams estimate the possible locations in the targeted monitoring area from which the identified signal could have emanated.

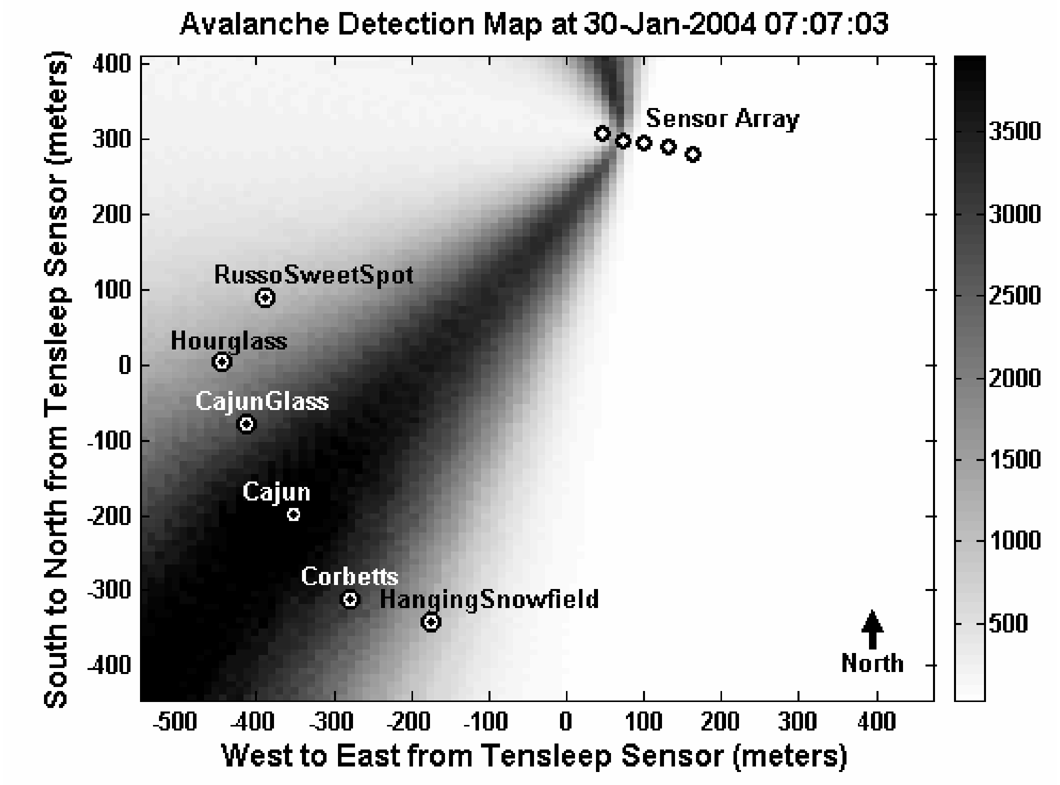

Figure 13. Sensor Array 1/30/04 Cajun Semblance Identification and Localization

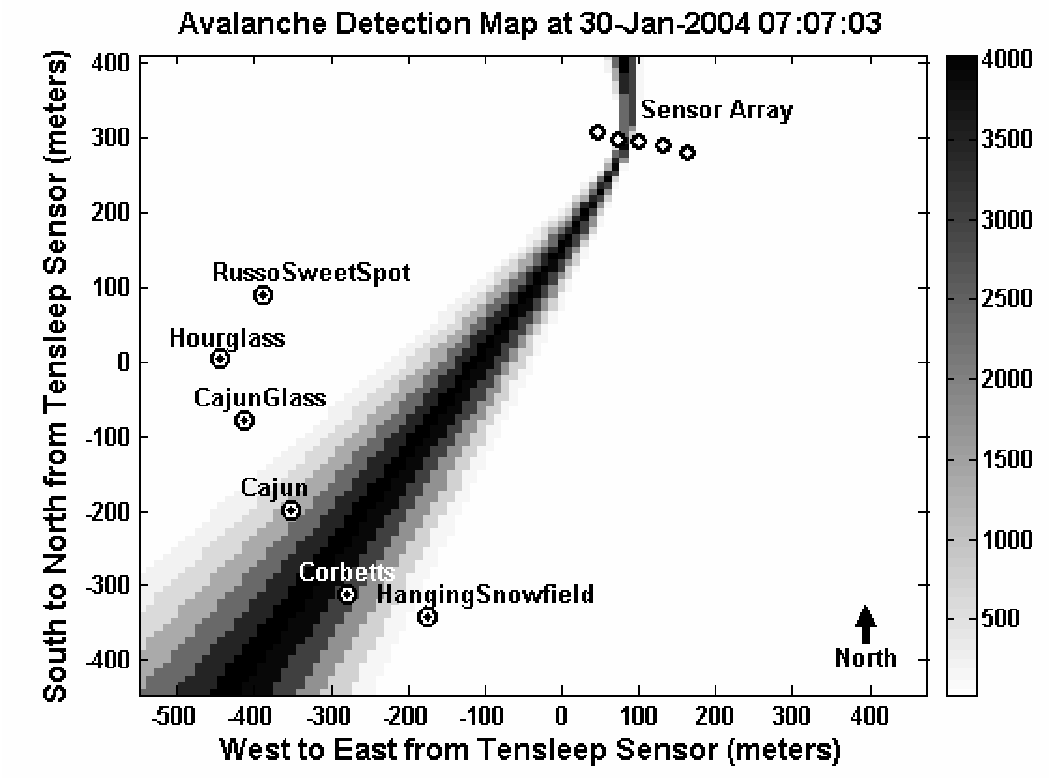

Figure 14. Sensor Array 1/30/04 Cajun Cross Correlation Identification and Localization

Figure 13 shows an example of semblance signal location estimates obtained from the Sensor Array data for a Class 2 Cajun avalanche event that was triggered via a two-pound explosion. Effects of the small explosion on the avalanche signal location estimates are insignificant. The semblance beam accurately estimates that the avalanche signal originated from a location indicative of the Cajun slide path. While the beam exhibits location aliases, it does provide the necessary information to recognize the general location of the avalanche activity.

The semblance beam formed by the Sensor Array manifests itself in a similar manner as the cross correlation beam. Figure 14 shows the cross correlation signal location estimates that correspond to the semblance location estimates shown in Figure 13. Results are very similar, but there are vague differences. The cross correlation beam provides narrowed and slightly different location estimates than the wider semblance beam.

Avalanches were scarce in the targeted Jackson Hole Mountain Resort monitoring area during the 2003/2004 winter season. However, infrasound data recorded during several additional Class 2 avalanches showed that the multiple sensor signal processing algorithms provided consistent and repeatable identification and localization results.

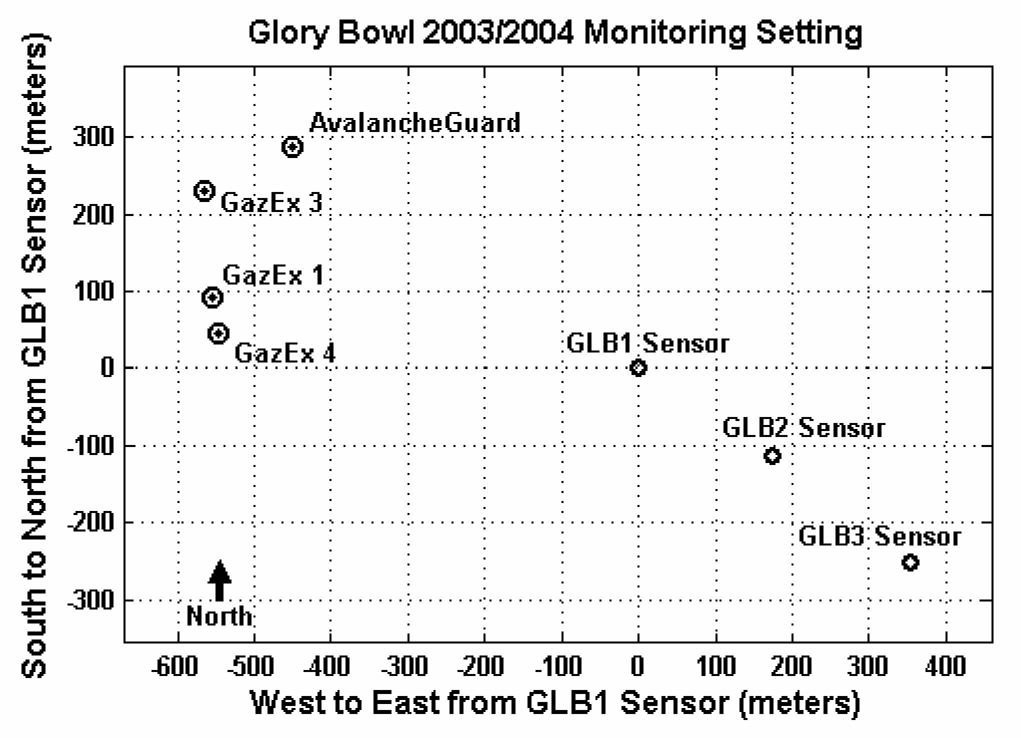

Figure 15. Glory Bowl Monitoring Setting

<u>3.5 Teton Pass Multiple Sensor Results</u>

A multiple sensor monitoring study was also performed in the Teton Pass, WY region. Figure 15 shows an Easting and Northing depiction of the 2003/2004 winter Glory Bowl monitoring setting above Wyoming State Highway 22. Data presented earlier in Figure 2 were recorded by a previously operated single sensor monitoring system that was located within a couple hundred meters of the GLB3 Sensor site.

Three single sensor infrasound monitoring systems were deployed along the Northeast boundary of the large Glory Bowl avalanche path. The three sensors formed a linear spatially distributed array in a parallel orientation with the slide path. The distributed sensors exhibited nearly uniform spacing of around 230 meters. Elevations of the three distributed sensors are as follows: GLB3 at 2480 meters, GLB2 at 2590 meters, and GLB1 at 2715 meters. The Glory Bowl start zone region at an elevation of 3000 meters is shown by the GazEx and Avalanche Guard control mechanisms in the Northwest corner of the targeted monitoring area.

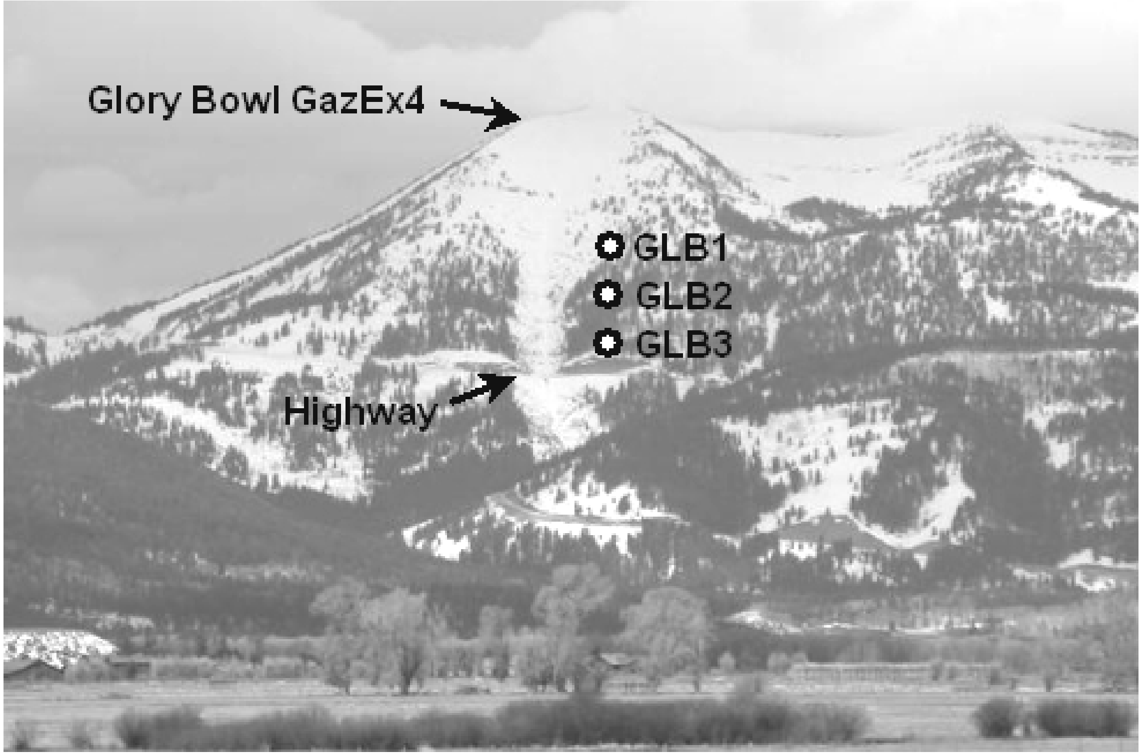

Figure 16. Targeted Glory Bowl Avalanche Path

An avalanche starting hundred of meters above the sensors can approach within 100 meters of the sensors as it passes. An avalanche that makes it past the GLB3 Sensor immediately encounters the highway. The Glory Bowl slide path continues hundreds of meters below the highway to the run out zone. A picture of the Glory Bowl monitoring setting is shown in Figure 16.

Figure 17 shows a cross correlation beam formed through the distributed sensors during a small Class 2 avalanche that was triggered by a GazEx 4 explosion. Beamforming results are presented for an instance in time when effects of the GazEX 4 explosion are not present in recorded data, so results are due to only the avalanche signal. The signal from the observed and documented avalanche event is successfully identified and located. Signal origin location results are highly indicative of the area within Glory Bowl where the avalanche occurred and location aliases are minimized.

A major thrust of the Teton Pass multiple sensor monitoring study was to develop and integrate hardware and software components required to implement distributed infrasound avalanche monitoring in a near real-time manner. Several hardware issues encountered during this process limited the usefulness of recorded data. A highly stable snow pack that minimized avalanche activity also caused difficulties in the Teton Pass study.

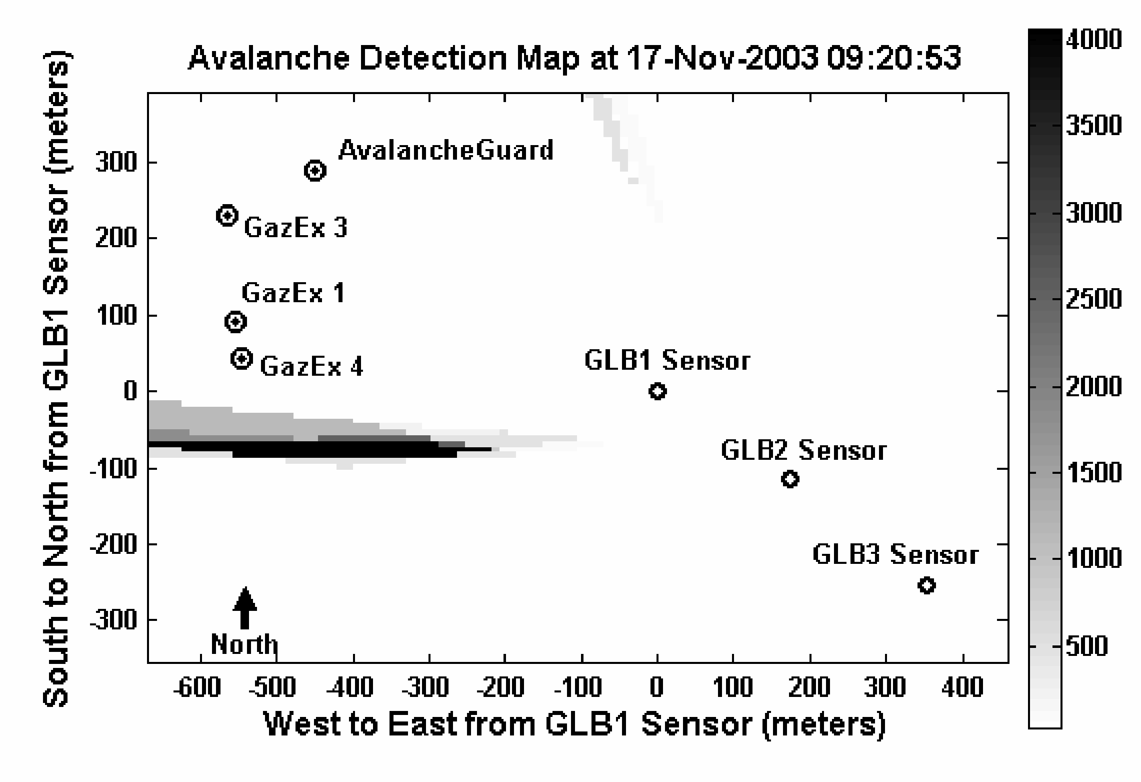

Figure 17. Glory Bowl Avalanche Identification and Localization

4. Current Efforts

Successes obtained in the multiple sensor monitoring studies has brought this project to a point where efforts are largely moving away from scientific discovery and towards applied research. Quickly becoming an artifact of the past is the operation of simple infrasound monitoring systems designed to provide data for post processing analyses purposes. The task at hand is to develop optimized avalanche monitoring system hardware and software components that can be seamlessly operated in a continuous automated near real-time fashion.

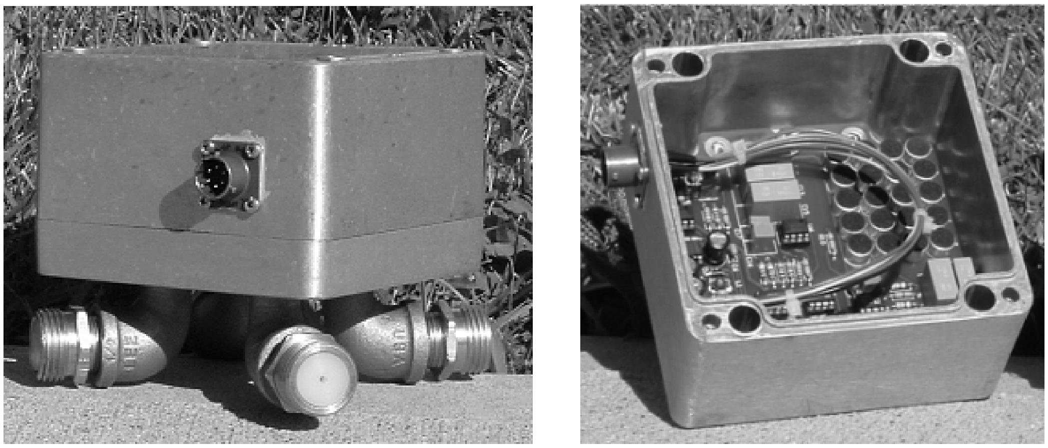

Figure 18. Prototype Infrasound Sensor

Successful attainment of this goal will require overcoming many complex technical challenges. Development of remote hardware optimized for avalanche detection is a high priority technical task. A critical hardware goal is the development of a custom sensor that provides increased reliability and improved immunity to the wind, quantization and radio telemetry noise that has been observed in the commercial infrasound sensors, which were utilized for avalanche monitoring research efforts. Shown in Figure 18 is an unproven first generation prototype sensor constructed of commercially available electronic components that is aimed at meeting this goal. Development of a centralized processing and control unit is also a high priority technical task. A critical software goal is to interface the multiple sensor signal processing with data management and user interface utilities.

Of highest priority is to evaluate the reliability and usefulness of continuous automated near real-time prototype systems in practical applications. Initial prototype operation in a practical application will be performed for the Wyoming Department of Transportation on Teton Pass, WY. Prototype operation will also be implemented at the Jackson Hole Mountain Resort. These two practical experimental settings will be utilized to gain the operational experience necessary for successful deployment of the technology to other practical applications.

Continuous prototype system operational experience will provide much needed improved understanding of the following issues: identification range, identification confidence levels, interfering signals, and incidences of system blinding by wind noise. Apparent from signal processing results is that all of these issues are highly affected by the signal and noise levels of recorded data. An extremely important parameter affecting recorded signal and noise levels is the physical location of the remote infrasound sensors.

While topographical and meteorological characteristics greatly dictate the highest possible infrasound signal levels that can be generated by an avalanche event occurring in a slide path, signal propagation distance between the avalanche signal source and infrasound monitoring site also affect the actual recorded signal level. Meteorological and topographical characteristics of the monitoring site also dictate the statistics that characterize ambient wind noise levels. When selecting monitoring sites for operating the prototype systems, a priority of minimizing ambient wind noise levels will be placed over maximizing avalanche signal levels.

5. Conclusions

Results of recent multiple sensor infrasound monitoring studies have advanced infrasound avalanche monitoring technology capabilities past the limitations of single sensor monitoring systems. Single sensor avalanche identification signal processing algorithms exhibit increasing uncertainties and lower confidence as wind noise increases, and as signal levels decrease. Yet, multiple sensor avalanche identification signal processing algorithms exhibit robustness to the detrimental effects of high noise and small signals. An additional benefit of multiple sensor monitoring is the ability to obtain location estimates of the avalanche signal source origin.

A sensor array monitoring system was used in conjunction with distributed single sensor monitoring systems to experimentally demonstrate multiple sensor avalanche identification and localization potential. Both cross correlation and semblance multiple sensor signal processing algorithms were found effective at identifying and locating avalanche-generated infrasound. Multiple sensor signal processing results were found to be repeatable and consistent at two different monitoring settings.

Whether using single or multiple sensor signal processing algorithms, large avalanche signals and low wind noise conditions are desired for optimal avalanche identification algorithm performance. Small avalanche signals and high wind noise lower confidence in both single and multiple sensor avalanche identification algorithm performance, but the detrimental effects are much less noticeable in multiple sensor avalanche identification algorithms. Still, optimization of the signal and noise levels of recorded data is a critical goal associated with the operation of infrasound avalanche identification systems. Care must be taken to select remote monitoring sites that maximize signal levels while minimizing wind noise levels, but often these desires conflict. In such circumstances, minimizing wind noise levels is currently the higher priority.

Knowledge gained through recent studies is being utilized to develop continuous automated near real-time prototype systems. These prototype systems will be operated and experimentally evaluated in practical highway and recreational settings. Continuous operation is crucial to understanding remaining technical challenges. It is anticipated that innovative solutions to additional wind noise and interfering signal problems is required to make automated avalanche event identification and alarming highly reliable. At the current time it is not understood whether data acquired at a range of greater than 2 kilometers will be of a quality sufficient for a practical application. However, current infrasound monitoring capabilities provide a powerful interactive tool for the avalanche practitioner.

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