RESULTS OF RECENT INFRASOUND AVALANCHE MONITORING STUDIES

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ABSTRACT: Results of recent infrasound avalanche monitoring studies have advanced technological capabilities and provided further understanding of technological challenges. Avalanche identification performance of single sensor monitoring systems varies according to ambient noise and signal levels. While single sensor signal processing algorithms can identify avalanche activity, uncertainties (missed detections and false alarms) increase with increasing wind noise, and as signal levels decrease due to increasing distance or smaller sources. Multiple sensor signal processing algorithms substantially improves avalanche event identification robustness under windy and noisy conditions. Multiple sensor signal processing algorithms also allow location estimates of avalanche events to be made. An infrasound sensor array monitoring system has successfully demonstrated avalanche identification and localization capabilities. Also demonstrated were 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 during the 2004/2005 winter in the Jackson Hole, Wyoming region. Prototype operation will provide performance evaluations in highway and recreational area settings, while facilitating development of a commercial form factor.

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 a low noise band of the sub-audible infrasonic frequency spectrum (Bedard and Greene 1988, Bedard 1989, Bedard 1994). Research performed by European scientists has also documented the existence of avalanche-generated infrasound signals (Chritin, et al. 1996).

These low frequency infrasound signals have the ability to propagate kilometers from the avalanche source and provide a basis for developing automated monitoring systems that can operate in locations unaffected by avalanche activity. Reliable implementation of infrasound avalanche monitoring technology requires innovative solutions to problematic ambient wind noise and interfering signals.

Several research projects were completed in recent years that investigated the feasibility of monitoring for avalanche-generated infrasound. Initial studies showed that single sensor monitoring systems can detect and identify avalanche-generated infrasound (Scott and Lance 2002). Subsequent studies characterized the variability of single sensor infrasound avalanche monitoring performance (Scott and Hayward 2003) and resulted in studies aimed at improving monitoring robustness by utilizing multiple sensors (Comey and Mendenhall, 2004).

Multiple sensor results were found to be extremely promising for providing reliable avalanche monitoring and have resulted in current efforts surrounding the development of near real-time prototype monitoring systems. The prototype systems will be utilized to prove the technology and provide a basis for commercial infrasound avalanche monitoring systems.

2. SINGLE SENSOR RESULTS

An extensive catalog of avalanche-generated infrasound signals was recorded through the various research efforts. This catalogue provided a basis for developing single

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sensor signal processing algorithms that can identify recorded avalanche signals.

2.1 Large Avalanche Signal in Low Wind Noise

Figure 1 shows raw infrasound data and auto correlation coefficients computed through the single sensor signal processing algorithm. These infrasound data were recorded during 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. Raw data were recorded approximately 200 meters from where the avalanche stopped.
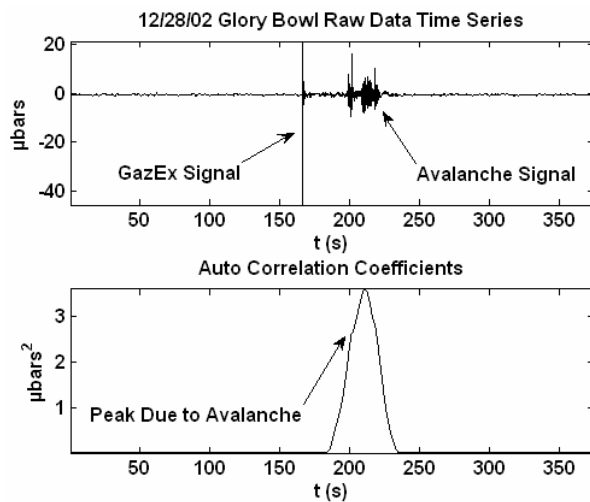
Figure 1. Class 3 Avalanche and Low Wind Noise

Evident in the infrasound raw data time series is the avalanche signal and an additional signal from the GazEx control mechanism that was utilized to trigger the avalanche. The time sequence of auto correlation coefficients shows a peak corresponding to the avalanche event from which automated avalanche identification can easily be accomplished. The GazEx signal does not exhibit a peak in the time sequence of auto correlation coefficients, because the single sensor signal processing algorithm automatically filtered it as a non-avalanche signal.

The avalanche signal shown in Figure 1 is one of the largest magnitude avalanche signals contained in the catalogue of avalanche signals 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 catalogued avalanche signals do not exhibit large magnitude characteristics.

Also of importance exhibited by the infrasound raw data time series shown in Figure 1 is the non-existence of ambient wind noise. This scenario of a large avalanche signal combined with low wind noise demonstrates ideal conditions for reliable avalanche 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 amongst low wind noise is depicted in Figure 2. Figure 2 shows raw infrasound data and auto correlation coefficients containing effects of a ski triggered avalanche estimated as a Class 2 event. The data were recorded approximately 250 meters from the Jackson Hole Mountain Resort Hourglass avalanche event.

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 magnitude signal could be masked, and the single sensor signal processing algorithm would fail to provide reliable identification of the avalanche event.
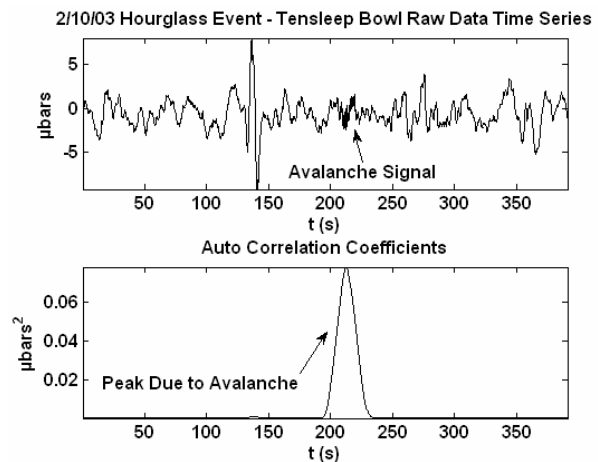

Figure 2. Class 2 Avalanche and Low Wind Noise

2.3 Small Avalanche Signal in High Wind Noise

A problematic monitoring scenario of a small avalanche signal immersed amongst high wind noise is depicted in Figure 3. Figure 3 shows raw infrasound data and auto correlation

coefficients containing effects of a two-pound explosive triggered avalanche estimated as a Class 2 event. Effects of the small explosion on the auto correlation results are insignificant. The raw data were recorded approximately 250 meters from the Jackson Hole Mountain Resort Cajun avalanche event.
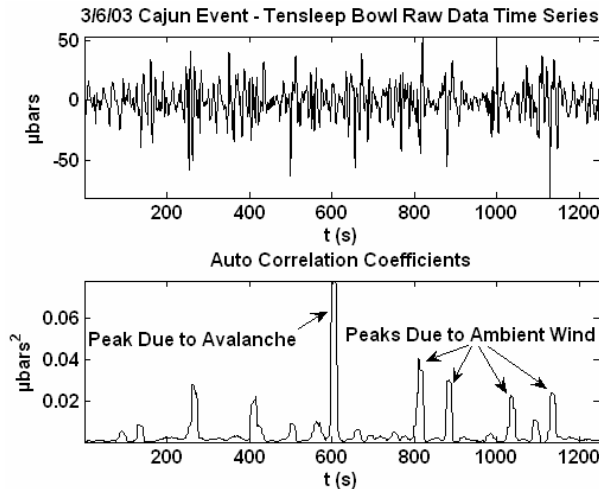

Figure 3. Class 2 Avalanche and High Wind Noise

The avalanche signal is not visible in the raw data time series, but the infrasound sensor detected it. 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, automation of the single sensor signal processing algorithm could result in wind induced false positive identifications or missed avalanche identification.

Figure 4 shows raw infrasound data and auto correlation coefficients corresponding to the avalanche event depicted in Figure 3, but these results were obtained from a second infrasound sensor located at a different monitoring site. The second sensor raw data were recorded approximately 1000 meters 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 avalanche event identification.
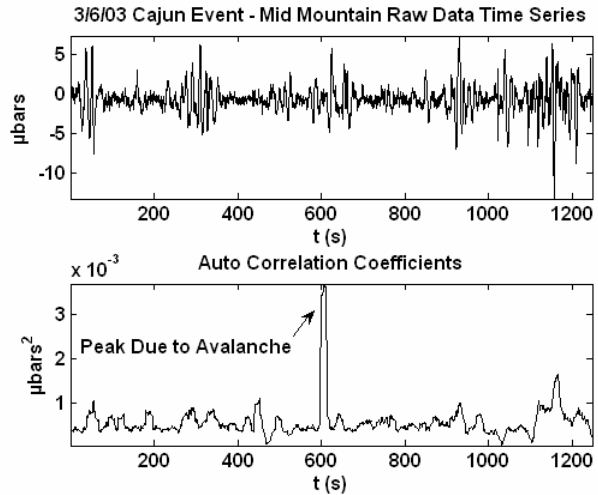

Figure 4. Second Sensor Analyses

The coherence of the avalanche signal detection by the two 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 5 demonstrates avalanche identification capabilities obtained from 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.
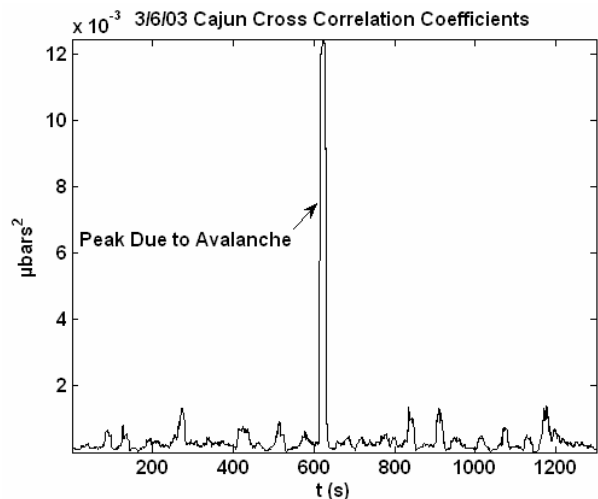

Figure 5. Combined Distributed Sensor Analyses

3. MULTIPLE SENSOR RESULTS

Experimental evaluation of the single sensor signal processing algorithm showed that reliability of 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. Recent studies investigated the performance of multiple sensor signal processing algorithms through the use of sensor array and distributed monitoring systems.

3.1 Multiple Sensor Monitoring Setting

Figure 6 shows an Easting and Northing depiction of the monitoring area for a multiple sensor experimental study performed at the Jackson Hole Mountain Resort recreational area. A series of six targeted avalanche start zones 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 consisted of a single infrasound sensor located approximately 300 meters from the targeted avalanche start zones. The Sensor Array system was located around 600 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 consisted of a single infrasound sensor that was located nearly 750 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 7.
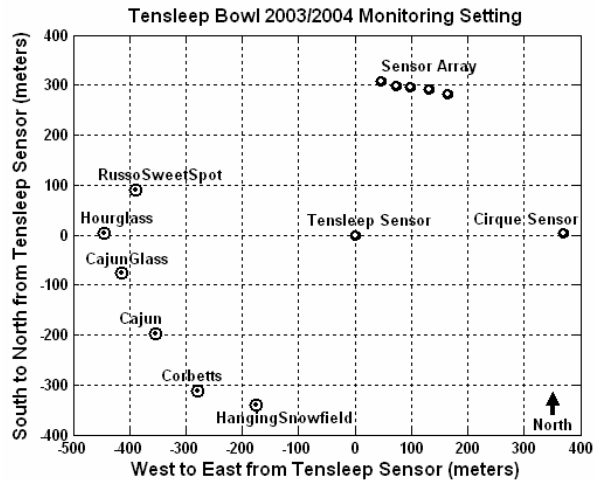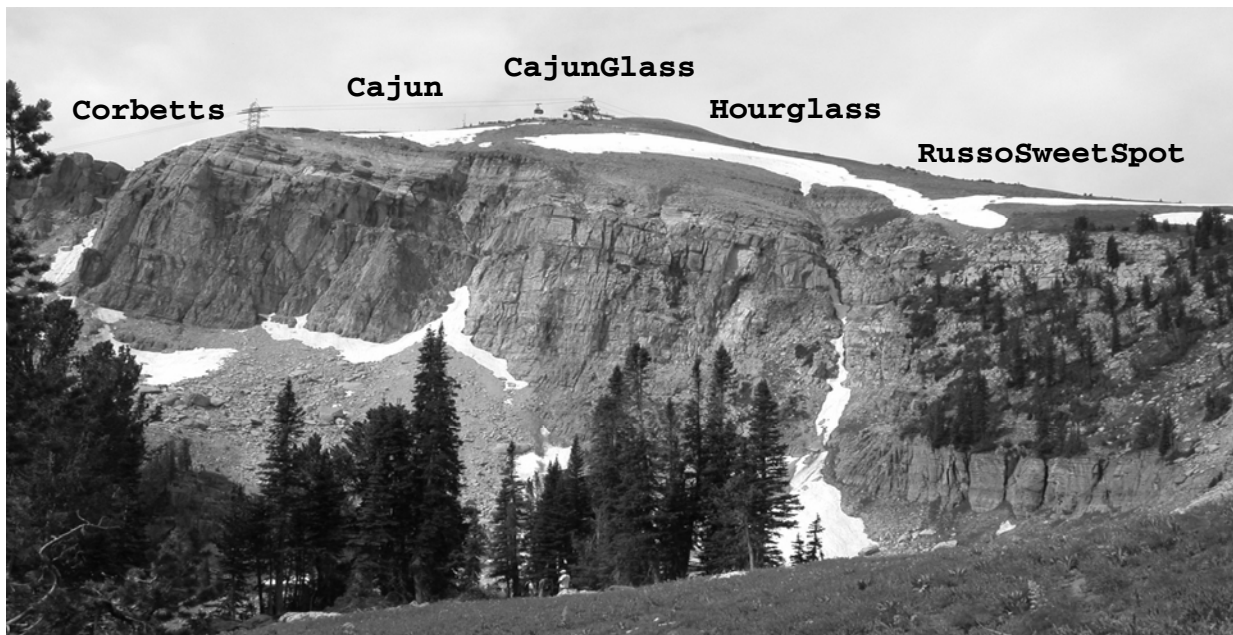

Figure 6. Tensleep Bowl Monitoring Setting

Figure 7. Targeted Jackson Hole Mountain Resort Avalanche Paths Viewed from Sensor Array

3.2 Multiple Sensor Signal Identification

Combining the pair of distributed sensors demonstrated an improvement in avalanche identification performance over that offered by each individual sensor on its own. Performance continues to improve as more sensors are used in the multiple sensor signal processing.

Figure 8 demonstrates the ability of multiple spatially separated sensors to drastically improve upon 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 elevates. Near the end of the time span, the ambient wind noise subsides some, but remains elevated. Also near the end of the time span, avalanche hazard mitigation activities occur.
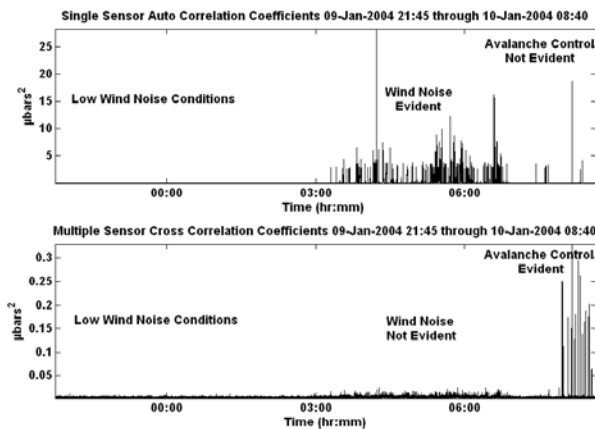

Figure 8. Single vs. Six Sensor Signal Identification

The top graph in Figure 8 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 would 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, 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 8 shows a time sequence of aggregate cross correlation coefficients obtained from the six sensors contained in the Tensleep and Sensor Array systems. The Cirque sensor data was not utilized in the analyses due to its unavailability. During both low and high wind noise conditions the cross correlation sequence does not exhibit any 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. Reliability of identifying the cross correlation peaks as true infrasound signals is high due the robust performance of the multiple sensor signal processing algorithm during high wind noise conditions.

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 ability to reliably identify true signals. Since these true explosive signals are identified, there is a possibility that they could falsely be attributed as avalanche events.

Identification of explosive signals during avalanche hazard mitigation activities could provide beneficial information on whether ordinance detonated. However, 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 interfering signals that might exist.

Signal discrimination filters developed for the single sensor auto correlation algorithm can also be effectively used to remove interfering signals on multiple sensor cross correlations. These signal discrimination filters are based on unique features of a signal signature. Knowledge regarding the origin of the signal source would provide an additional powerful tool to aid in signal discrimination.

3.3 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 utilized 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 9 shows an example of signal location estimates obtained for a large Class 2 Cajun Glass 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 8 were generated using data recorded by the linear five sensor array.
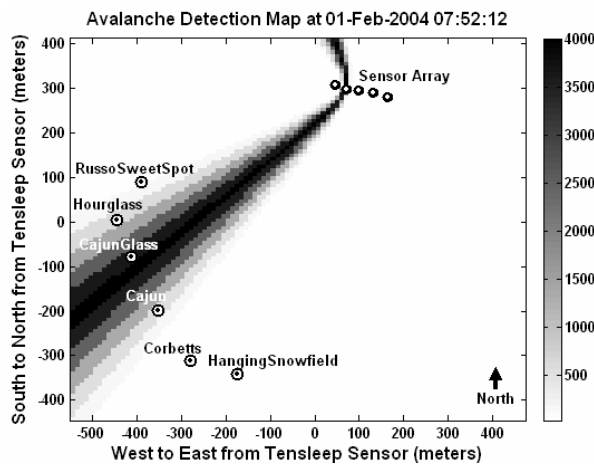

Figure 9. Sensor Array Avalanche Localization

Estimated avalanche signal source locations are presented through the linear grey scale that spans a magnitude range of 0 to 4000. 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. A gray tone represents the presence of an intermediate 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 multiple sensor processing.

The beam formed by the Sensor Array accurately estimates that the avalanche signal originated along an azimuth angle aligned with the Cajun Glass slide path. However, the beam does not indicate the depth along the azimuth angle 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 for recognition of the general location of the avalanche activity.

Figure 10 shows improved beamforming signal source location estimates for the Cajun Glass 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.
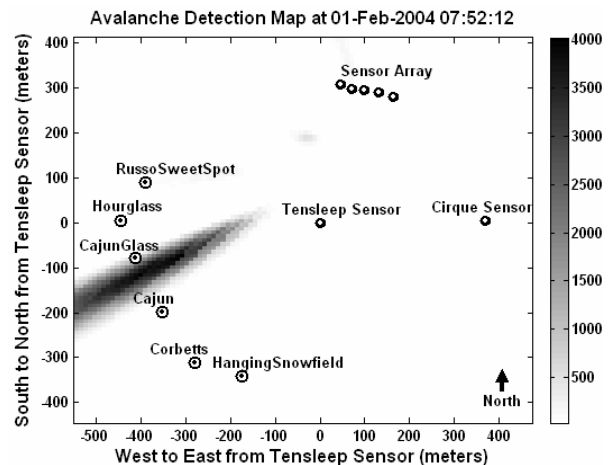

Figure 10. Network Wide Avalanche Localization

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

3.4 Teton Pass Multiple Sensor Monitoring

A multiple sensor monitoring study was also performed in the Teton Pass, WY region. Figure 11 shows an Easting and Northing depiction of the Glory Bowl monitoring area above Wyoming State Highway 22.
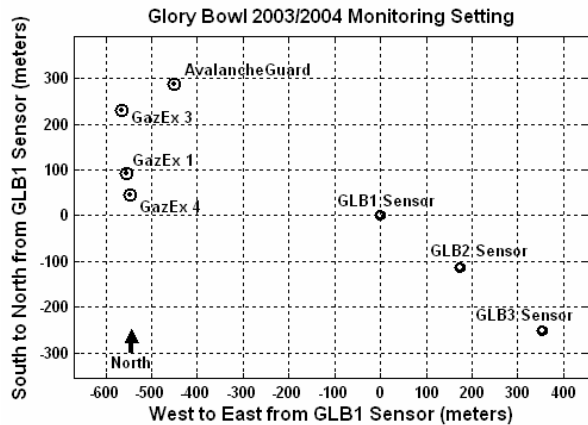

Figure 11. Glory Bowl Monitoring Setting

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 distributed array in a parallel orientation with the slide path. The distributed sensors exhibited nearly uniform spacing of around 100 meters.
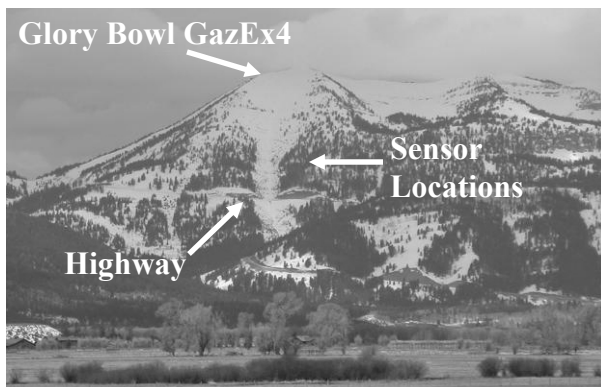
Figure 12. Glory Bowl

The Glory Bowl start zone region is shown by the GazEx and Avalanche Guard control mechanisms in the Northwest corner of the targeted monitoring area. 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 run out zone is around 500 meters below the highway. A picture of the Glory Bowl monitoring setting is shown in Figure 12.

Figure 13 shows a beam formed through the distributed sensors during a small Class 2 avalanche that was triggered by the GazEx 4 control mechanism. Beamforming results are presented for an instance in time when effects of GazEx 4 are not present in recorded data, so results are due to only the avalanche signal. The avalanche signal is successfully identified and located. Signal origin location results are indicative of the area within Glory Bowl where the avalanche occurred and location aliases are minimized.
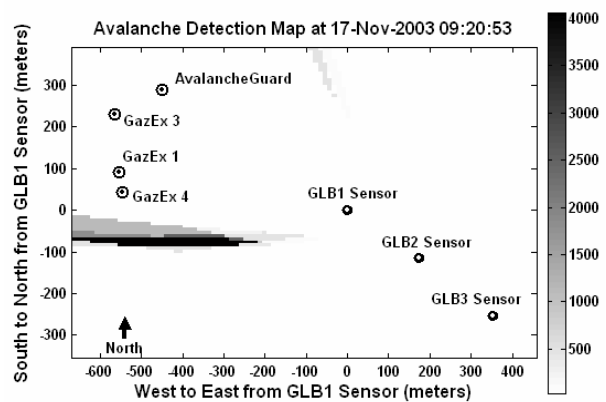

Figure 13. Glory Bowl Avalanche Localization

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 study.

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 current task at hand is developing optimized avalanche monitoring system hardware and software components that

can be seamlessly operated in a continuous automated near real-time fashion.

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 (shown in Figure 14) that shows improved immunity to wind, quantization and radio telemetry noise. 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.

Figure 14. Prototype Avalanche Infrasound Sensor

Of highest priority is to prove 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 recreational area. These two practical experimental settings will be utilized to gain the operational experience necessary for successful deployment of the technology to the commercial marketplace.

5. CONCLUSIONS

Results of recent multiple sensor infrasound monitoring studies have advanced infrasound avalanche monitoring technology capabilities past the limitations of single sensor signal processing algorithms. Single sensor avalanche signal identification algorithms exhibit increasing uncertainties (missed detections and false alarms) as wind noise increases, and as signal levels decrease due to increasing distance or smaller sources. Multiple sensor avalanche signal identification 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 demonstrate multiple sensor avalanche monitoring potential. Consistent results were shown for two different monitoring settings. Knowledge gained through recent studies is being utilized to develop continuous automated near real-time prototype systems. These prototype systems will be tested and proven experimentally in practical highway and recreational settings. Upon achievement of reliable and beneficial operation, the technology will be made available to the commercial marketplace.

6. ACKNOWLEDGEMENTS

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