ACKNOWLEDGMENTS

Thanks are extended to the National Oceanic and Atmospheric Administration scientists who performed early research regarding snow avalanche-generated infrasound. Efforts led by Dr. Alfred Bedard of the Environmental Technology Laboratory showed that avalanches generate sub-audible acoustic signals within the infrasound frequency spectrum. Dr. Bedard recognized that avalanche-generated infrasound signals provide a scientific basis for developing automated avalanche monitoring systems. Since interest in such a system was shown by several transportation entities, Dr. Bedard issued a Department of Commerce (DOC) Small Business Innovative Research (SBIR) Phase I solicitation for investigating the feasibility of utilizing single sensor infrasound monitoring systems for automatic identification avalanche event occurrences.

Conclusion of DOC SBIR Phase I study 50-DKNA-0-90047 was followed by DOC SBIR Phase II study 50-DKNA-90073, with the purpose of developing a prototype single sensor infrasound avalanche monitoring system. Teton Pass was utilized as a research monitoring site during the DOC SBIR Phase II study. Results showed that prototype single sensor monitoring systems could successfully identify avalanche-generated infrasound, but the systems also showed unacceptable rates of false identifications.

Since the Wyoming Department of Transportation (WYDOT) had an interest in the DOC SBIR funded studies, this study was initiated to investigate whether utilizing data from distributed single sensor infrasound monitoring systems on Teton Pass could be utilized for reliable monitoring of avalanche activity. While the DOC SBIR Phase II study had shown that distributed systems could enhance avalanche identification performance, it was questionable as to whether distributed systems could increase performance to a level acceptable for operational use. In an effort to improve upon the performance of distributed single sensor monitoring systems, the National Science Foundation (NSF) SBIR Phase I 0319404 study at the Jackson Hole Mountain Resort was initiated to investigate the feasibility of utilizing sensor array infrasound monitoring systems for automatic identification of avalanche event occurrences.

Results from the concurrent studies showed that sensor array monitoring performance is substantially superior to distributed single sensor monitoring performance. As a result, this WYDOT funded study was granted a no cost extension through June 2005, so that the avalanche identification performance of Teton Pass sensor array monitoring systems could be included in the study findings. Much of the Teton Pass sensor array monitoring efforts discussed in this report have been supported through funding from NSF SBIR Phase II study 0449731, which has the purpose of developing a prototype distributed sensor array infrasound avalanche monitoring system. Further Teton Pass efforts will be funded through the conclusion of the NSF Phase II study.

As is evident from the previous discussions, maturation of infrasound monitoring technology for applying to the identification of avalanche event occurrences in an industrial operational setting has been a timely process requiring multiple funded research studies. Completion of the NSF Phase II study will result in commercial

avalanche-generated infrasound monitoring technology in which the Teton Pass prototype system represent that model for deployment of the technology to other applications.

In addition to the previously mentioned entities, thanks are extended for the support offered from the following entities: Bridger-Teton National Forest, Bridger-Teton Avalanche Information Center, Wyoming SBIR/STTR Initiative, and the University of Wyoming Electrical and Computer Engineering Department. Of special note is that the University of Wyoming Electrical and Computer Engineering Department has recently begun independent funded research geared towards the improvement of current infrasound avalanche monitoring technology. It is certain that results from these efforts will be applied on Teton Pass and benefit WYDOT.

Finally, acknowledgement must be made to the management of Inter-Mountain Laboratories, Inc. whose vision for this project is demonstrated by supporting it through the funding shortfall periods that occurred between grants.

Special thanks is extended to WYDOT snow maintenance personnel Galen Richards and Jamie Yount for providing support that has been instrumental to the project.

EXECUTIVE SUMMARY

Avalanches near Teton Pass that impact Wyoming State Highway 22 have the potential to significantly affect the health and welfare of people in the region and the economics of the region. The identification of natural and control triggered events in near real-time when conditions prevent observation can minimize these impacts. Early detection of natural events minimizes response time. Identification of natural and mitigation activity triggered slides provides valuable information for planning future snow control activities.

The primary objective of this study was to develop, operate, and maintain an easy to use infrasound monitoring system that can reliably and automatically identify Teton Pass avalanche activity in near-real-time (within 2 minutes). A number of specific tasks were necessary to meet this objective and included developing multiple sensor techniques to optimize signal-to-noise ratio and to determine the location of an infrasound source.

The research and development process included the operation of monitoring systems during two winter seasons; 2003/2004 and 2004/2005. These systems consisted of arrays of remotely powered infrasound sensors deployed near known slide paths, a central processing unit (CPU) in the local WYDOT office, custom software, and telecommunications equipment to transfer data from the sensor arrays to the CPU.

Operation of an infrasound monitoring network near the primary slide paths near Teton Pass during the winter of 2004/2005 demonstrated these desired performance characteristics: 1) identification of natural events, 2) identification of control activity triggered events, 3) minimal false identifications, 4) excellent reliability and system availability, 5) time response less than 2 minutes, 6) identification of various magnitude events, and 7) verification of explosive ordinance detonation.

The performance was accomplished by applying unique multiple sensor data processing techniques to reduce the problem of interfering noise and to determine the locations of infrasound sources. The source location information was used to narrow the field of view of the system to known slide paths, eliminating most sources of false positive results. The movement of an infrasound source downward through a known slide path further distinguished slides from interfering signals.

Further development of the CPU user interface is continuing through a National Science Foundation grant. The resulting software will allow for more flexibility in viewing results, investigating events, and system configuration. The systems near Teton Pass will be used for further development in the NSF project and the improved user interface will become part of the WYDOT system.

For continued use of the system after the 2005/2006 winter season, WYDOT will need to upgrade the research configuration to a more permanent operational configuration and plan for annual system maintenance. An additional WYDOT application in Hoback Canyon would require experimental evaluation and development of an infrasound monitoring system operating near the site.

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CHAPTER 1

PROBLEM DESCRIPTION

Snow avalanche activity near Teton Pass frequently impacts Wyoming State Highway 22. The two most active and problematic Teton Pass slide paths are Twin Slides and Glory Bowl. The Wyoming Department of Transportation (WYDOT) performs avalanche hazard mitigation activities for these slide paths to alleviate negative impacts upon the highway. Such snow control activities improve safety for those utilizing the highway and reduce the potential of hard to predict naturally occurring avalanches.

Whether an avalanche occurs naturally or results from an artificial trigger, the consequential closure of highway 22 has a significant impact on the local economy. Highway 22 is one of the most heavily used highways in Wyoming due to several factors: commuter traffic necessary to support service industries in Jackson Hole, tourist traffic, and recreational use traffic. This high usage dictates the necessity to minimize the closure of highway 22.

Information regarding Teton Pass avalanche event occurrences holds operational planning value to WYDOT snow maintenance personnel. It would be beneficial to have systems located near highway 22 that can remotely detect avalanche activity and reliably identify event occurrences in near real-time (within two minutes or less). Such systems would provide early notification of naturally occurring avalanches and initiate quick and appropriate responses (e.g. road closure, clean-up activities, avalanche hazard mitigation activities). An additional benefit from such systems would be the ability to verify results of avalanche hazard mitigation activities when human visual observations are impossible, which would have a direct impact on planning for current and future snow control missions.

Avalanches have been shown to produce airborne acoustic signals in the sub-audible infrasound frequency spectrum (Bedard 1989, Bedard 1994, Chritin, et.al. 1996, Scott and Lance 2002). Avalanche-generated infrasound signals can propagate kilometers from the slide path where the signal originates. Therefore, detection of avalanche-generated infrasound can be accomplished at locations unaffected by avalanche activity and out of harm’s way. The physical characteristics of avalanche-generated infrasound, coupled with modern sensing, data acquisition, and computing technologies hold promise for the implementation of automated detection systems that operate remotely, and identify avalanche activity in near real-time (Bedard, et. al. 1988).

Figure 1 is a conceptual diagram that depicts the problem and an approach to solving the problem. Evident is the utilization of spatially distributed monitoring nodes for recording of infrasound data that is transferred via radio telemetry to a central processing unit that performs data management, data analyses, and appropriate response actions to identified avalanche events. Confounding the reliable identification of desired avalanche signals are the presence of interfering signals and ambient wind noise.

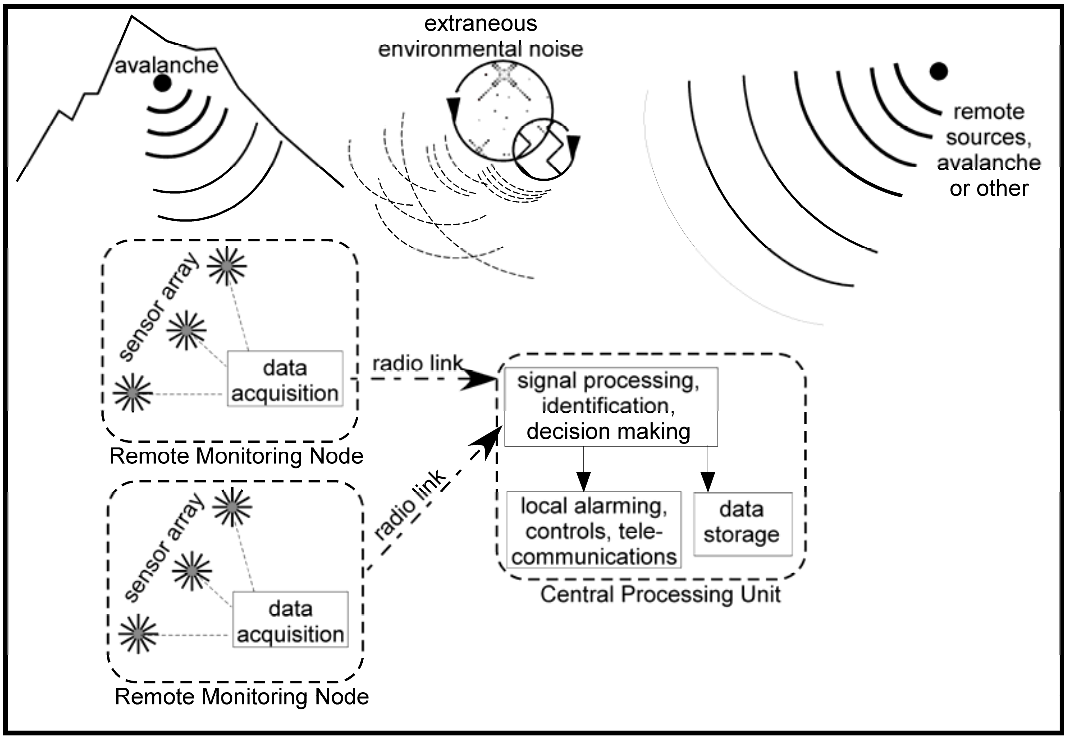


Figure 1. Conceptual Diagram of Avalanche Infrasound Monitoring.

A particularly challenging issue with implementing infrasound monitoring technology for the automated identification of an avalanche signal is the variability in the ratio between avalanche signal and wind induced noise levels inherent to the monitoring environment. This is quite problematic, since high winds are common during periods of high avalanche hazard when naturally occurring avalanches are likely. When the signal-to-noise ratio (SNR) is high due to a large signal and/or low noise, avalanche signal identification can reliably be achieved utilizing a single sensor infrasound monitoring system. However, when the SNR is low due to a small signal and/or high noise, avalanche signal identification cannot reliably be achieved utilizing a single sensor infrasound monitoring system (Scott and Hayward 2003).

A method that improves avalanche signal identification when the SNR is low is to utilize multiple sensor monitoring and data processing techniques (Scott, et. al. 2004). In theory, correlating infrasound data measured at different locations should enhance the detection of a coherent avalanche signal, while mitigating the effects of random wind noise. An additional benefit of multiple sensor monitoring and data processing is that the time delay between propagating infrasound signals impinging upon the spatially separated omni-directional infrasound sensors can be exploited to provide location information regarding the signal source. Knowledge about the physical location of an identified signal source is useful for reducing the possibility of falsely identifying an interfering infrasound signal as an avalanche event. Therefore, this study explored the possibility of utilizing multiple sensor infrasound monitoring to achieve reliable automated near-real time identification of avalanche events occurring near Wyoming State Highway 22 on Teton Pass.

CHAPTER 2

OBJECTIVE

The primary objective of this study was to develop, operate, and maintain an easy to use Teton Pass infrasound monitoring system that can reliably and automatically identify Twin Slides and Glory Bowl avalanche activity in near-real-time.

At the conclusion of this project, the objective has been met. The original project completion date was June 2004. However, a no cost extension was granted through June 2005, so that heuristic responses to problems encountered in the 2003/2004 winter could be implemented and experimentally tested during the 2004/2005 winter and associated results included in this final report. Funding during the no cost extension time period was mostly provided through the National Science Foundation Small Business Innovative Research Phase II award 0449731. This award will also fund monitoring system operation during the 2005/2006 winter and remaining development tasks necessary to make the technology easier to use and maintain for WYDOT snow maintenance personnel.

CHAPTER 3

TASK DESCRIPTION

To meet the project objective, a number of tasks were required. These included:

- Design, build, and install a distributed and integrated Teton Pass infrasound monitoring system.
- Experimentally operate the system throughout winter seasons in both near real-time and post-processing configurations.
- Utilize multiple sensor techniques to optimize SNR levels, so the system performs robustly across the variability in SNR levels that will be encountered.
- Utilize multiple sensor techniques to provide signal source location information, so that false positive identifications of avalanche events are minimized.
- Evaluate system success and failure rates and respond appropriately.
- Determine near-real-time signal processing algorithm configuration that provides for reliable automated early notification and alarms.
- Establish confidence in system prior to implementation of early notification and alarms.
- Optimize WYDOT user interface.
- Enable WYDOT snow maintenance personnel to perform many of the necessary system maintenance tasks required for continual operation.

Experimental evaluation of a Teton Pass infrasound avalanche monitoring system required a seasonally dictated time frame for implementation of the tasks necessary to achieve project objectives. Activities in summer months were focused on designing and configuring remote monitoring node hardware. Activities in fall months were focused on installing the remote monitoring node hardware and developing central processing unit (CPU) software. Activities in winter months were focused on experimental evaluation of the monitoring system and developing CPU software. Activities in spring months were focused on heuristic responses to experimental findings and formulating work plans for the following seasonal cycle of work plan tasks.

Summer 2003 – Spring 2004 Tasks

This project commenced in the summer of 2003. Initial design of the Teton Pass infrasound monitoring system centered about the desire to apply multiple sensor processing techniques on data recorded by spatially distributed single sensor remote monitoring nodes.

Figure 2 is a depiction of the targeted Teton Pass monitoring area. Glory Bowl is the prominent slide path right of center. Twin Slides is apparent as the small sliver along the sky line left of center. Figure 2 includes markers representing landmarks contained in the targeted monitoring region. The summit of Mount Glory is near the blue Avalanche Guard and GazEx markers, which designate snow control mechanisms used by WYDOT to induce avalanches. Yellow markers are included that represent the parking lot at the top of Teton Pass near where Twin Slides crosses Wyoming State Highway 22 and the parking lot where Glory Bowl crosses Wyoming State Highway 22. Wyoming State Highway 22 transverses the yellow parking lot markers.

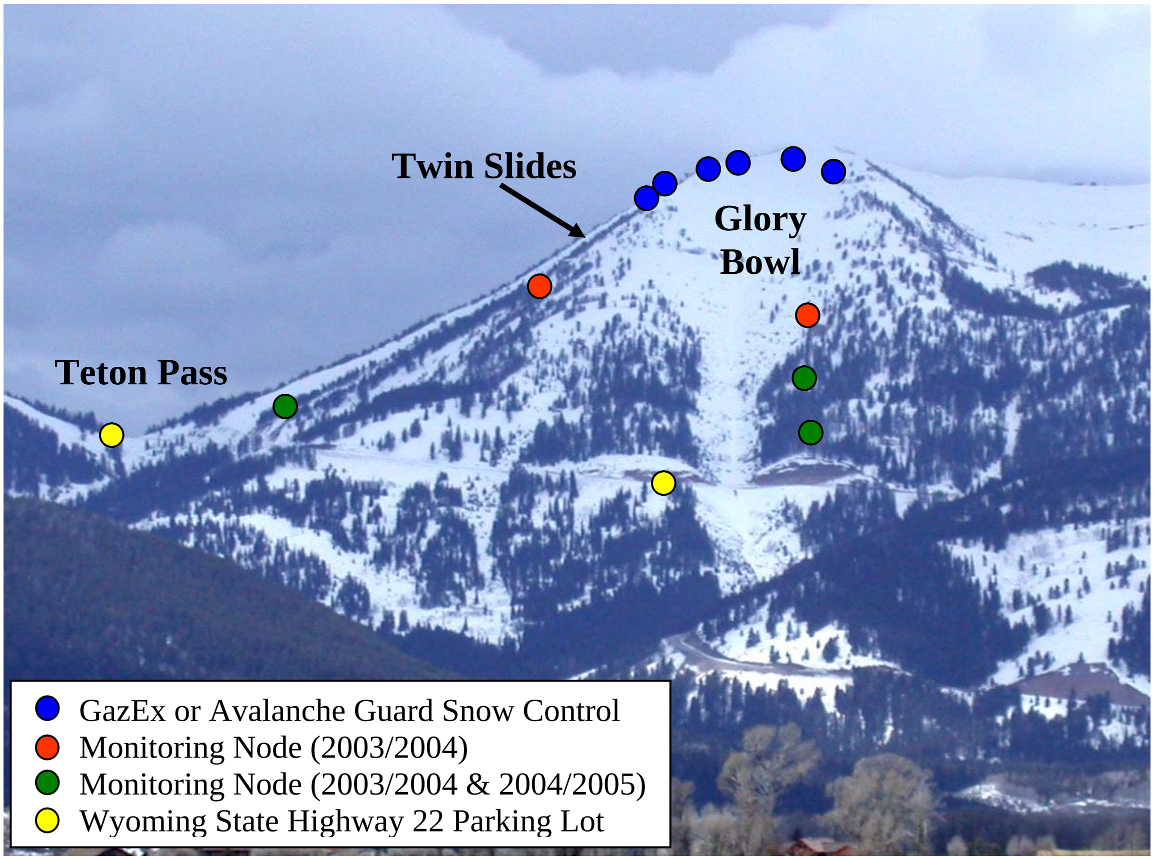


Figure 2. Teton Pass Monitoring Setting.

Upon completing a survey of potential host remote monitoring sites, it was decided to deploy three single sensor distributed monitoring nodes near Glory Bowl to target Glory Bowl. Two additional distributed monitoring nodes (on single sensor and one dual sensor) were selected for deployment near Twin Slides to target Twin Slides. These monitoring locations are shown by the red and green markers in figure 2. While the chosen spatially separated monitoring locations were desired to evaluate the effectiveness of distributed multiple sensor processing techniques, this also allowed for an evaluation of where along the slide paths to locate sensors, so that signal detection and wind noise reduction are optimized. In addition to the desire to maximize monitoring location SNR, other important criterion applied to the selection of the monitoring locations include: solar power potential, telecommunications potential, access, and security.

After the host monitoring locations were selected, remote monitoring node hardware necessary to facilitate infrasound measurement and telecommunications were designed. A remote monitoring node was realized by integrating the following components:

- Chaparral Model II infrasound sensor with 20 meter diameter pneumatic spatial hose array wind noise reducing filter.
- Custom experimental sensor/datalogger signal conditioning interface circuitry.
- Campbell Scientific, Inc. CR5000 datalogger.
- Freewave Technologies, Inc. FGR 900 MHz Spread Spectrum Wireless Data Transceiver with external 10 dB directional antenna.
- Two Kyocera KC80 80 Watt solar panels.
- Morningstar SunSaver 10-12V solar charging regulator.
- Surrette12-CS-11PS deep cycle battery.

The remote monitoring nodes were designed to record infrasound data in the 1 – 8 Hz frequency band at a 30 millisecond sample interval. Since measuring an infrasound sensor every 30 millisecond results in a sizeable amount of data, a high bandwidth radio telemetry network capable of moving data at 115 kbs/sec was utilized. Sensitivity of the Chaparral Model II infrasound sensor was set to 0.02 volts/microbar, which provided a dynamic output pressure range of ±250 ubar. A pneumatic spatial hose array filter coupled the Chaparral sensor to the atmosphere and also provided mitigation of wind induced noise in the 1 – 8 Hz frequency band of interest. The pneumatic spatial hose array was configured in an omni-directional four spoke radial pattern, where three spokes consisted of 4 meters of solid hose followed by 8 meters of porous hose, and one spoke consisted of 8 meters of porous hose. The sensor was interfaced to the datalogger through a custom designed signal conditioning circuit, which ensured that recorded data would not exhibit quantization noise or aliasing errors. Care was also taken when designing the DC solar power supply components to ensure that system operation would continue regardless of short winter days and/or extended winter storms.

Such remote infrasound monitoring nodes were fairly inconspicuous with only the elevated solar panels, radio antenna, various cabling, and a weatherproof outdoor enclosure in visible sight. The outdoor enclosure contained the datalogger, sensor/datalogger interface circuit, radio transceiver, and charging regulator. The infrasound sensor, pneumatic filter, various cabling, and deep cycle battery were placed on the ground and allowed to be covered by snow.

Figure 3 shows examples of the types of instrumentation that were utilized in the distributed infrasound monitoring nodes. While these are not pictures of the Teton Pass monitoring nodes themselves, they effectively illustrate the Teton Pass instrumentation. Two Chaparral sensors and their corresponding pneumatic spatial porous hose arrays are shown in figure 3. Evident in the outdoor enclosure are the solar charging regulator, radio transceiver, datalogger, and a bank of sensor/datalogger interface circuitry.

Figure 3. Remote Monitoring Node Instrumentation.

A Bridger-Teton Forest special use permit authorizing desired experimental field activities was secured in the fall of 2003, and the distributed monitoring nodes were installed and begun operation. Soon after remote monitoring node operation was initiated, project resources were re-focused to development of the CPU that was destined to reside in the Jackson WYDOT office. The CPU was realized by integrating the following components:

- Desktop Windows computer.
- Freewave Technologies, Inc. DGR 900 MHz Spread Spectrum Wireless Data Transceiver with external 10 dB directional antenna.
- Campbell Scientific, Inc. LoggerNet datalogger support software.
- Custom data processing algorithms developed using The MathWorks, Inc. MATLAB technical computing language with Signal Processing Toolbox.
- Custom data management and MATLAB interface software utilities developed using Microsoft Visual Basic .NET.
- An Uninterruptible Power Supply.

Automated near real-time continuous operation of the CPU was achieved during the winter of 2003/2004. LoggerNet datalogger support software was utilized to schedule radio transceiver data transfer between the remote monitoring nodes and the dedicated desktop computer. Upon completion of data transfer, a custom software application developed in Visual Basic .NET performed data archiving operations and forced data processing via the MATLAB signal processing engine execution of an established custom single sensor signal processing algorithm. MATLAB data processing results and any identified avalanche event occurrences were subsequently displayed via a graphical user interface developed in Visual Basic .NET.

This sequence of events was periodically repeated according to the scheduled time interval configured in LoggerNet. Successive data transfer and processing cycles provided updated near real-time every four minutes. While it was desired to have near real-time results updated at a higher rate, this reliable configuration was deemed adequate for experimental research evaluation. It was understood that there are simple design modifications that can be made to the monitoring system to improve this performance in an operational setting.

Experimental evaluation of avalanche monitoring system identification success and failure rates for both multiple and single sensor data processing techniques were performed concurrently with development of the CPU custom software components. WYDOT avalanche hazard mitigation activities were used to produce data during controlled experiments for evaluation. Multiple sensor data processing techniques were investigated through post processing activities.

Upon conclusion of the winter of 2003/2044, project resources were re-focused to heuristically respond to what was learned during the experimental operation and evaluation of the monitoring system. Efforts were applied towards planning and preparation for the next seasonal Teton Pass multiple sensor infrasound avalanche monitoring work plan that was completed during a no cost extension. The spring months of 2004 also included activities necessary to conclude operation of the monitoring system.

Summer 2004 – Spring 2005 Tasks

Corrective actions aimed at fulfilling proposed project objectives began in the summer of 2004. The commercial Chaparral infrasound sensors that were utilized during 2003/2004 monitoring were refurbished prior to re-deployment in a field installation. Replacement of the Chaparral's internal zener diode voltage regulator improved immunity to power supply ripple induced noise that was present in recorded 2003/2004 data. Leaks in the fore volume and backing volume components of the Chaparral sensors were sealed, which ensured that the sensors produced the specified and anticipated broadband frequency response. All sensors were put through thorough quality assurance testing to ensure that the sensor responses were matched, which improved the effectiveness of multiple sensor data processing techniques.

Since prior experimental evaluation efforts showed that the Chaparral sensors are not optimized for avalanche monitoring applications, a custom prototype infrasound sensor optimized for avalanche monitoring was designed and constructed using commercially available electronic components. A primary objective in the development of the prototype sensor was to provide a narrowed frequency response that does not exhibit saturation in high winds or require extraneous filtering. Another objective was to improve upon the operational reliability exhibited by the Chaparral sensors. Figure 4 shows a prototype infrasound sensor that was constructed for experimental Teton Pass evaluation.

Figure 4. Prototype Infrasound Sensor Views with Avalanche Transceiver.

The previous multiple sensor monitoring efforts provided insights into how to best deploy sensors for generating data that best lends itself to successful implementation of multiple sensor data processing techniques. Therefore, the distributed Teton Pass infrasound monitoring nodes were re-designed. A new approach of deploying arrays of spatially separated sensors at each remote monitoring node was adopted. Due to severe ambient wind noise and reduced solar charging, the two higher elevation monitoring sites denoted by the red markers in figure 2 were abandoned. Therefore, infrasound data recording during the winter of 2004/2005 was limited to the three remote monitoring nodes denoted by the green markers in figure 2.

A two-dimensional sensor array of six prototype sensors was deployed near highway 22 for targeting the Twin Slides avalanche path. An additional two-dimensional array of six prototype sensors was deployed near highway 22 for targeting the Glory Bowl avalanche path. The six refurbished Chaparral sensors were deployed in a two-dimensional array configuration at the higher elevation remote monitoring node targeting the Glory Bowl avalanche path. It was desired that the planned operation of the Glory Bowl remote monitoring nodes would provide an experimental performance comparison of the Chaparral sensor and the prototype sensor. Other than the discussed sensor changes, the remaining hardware components of the remote monitoring nodes were integrated in the same manner as was previously accomplished.

After an extension to the Bridger-Teton Forest special use permit was secured, remote monitoring node installation tasks were achieved prior to the fall of 2004. Efforts were then re-focused to development of the CPU that was destined to reside in the Jackson WYDOT office. A primary objective of the CPU development was to submit recorded monitoring node data to sensor array signal processing techniques that were developed via National Science Foundation Small Business Innovative Research Phase I study 0319404. Results from this concurrent study had shown that sensor array processing was superior to the distributed multiple sensor processing that was attempted in the initial experimental evaluation of this study.

A significant amount of effort was applied towards programming the sensor array signal processing algorithm in MATLAB by using a class structure. The class structure that was developed allows for the array processing code to be easily configured and deployed. This ease of use was highly important, since three sensor arrays were operated on Teton Pass. An additional benefit of the array processing class structure is that it allowed for quick alteration of critical array processing parameters. The class structure also provided highly organized code that reduced the effort required to add or change programming features. This well organized code was key, since heuristic improvements to the array processing were required as the winter of 2004/2005 progressed.

Late in fall of 2004 the CPU was deployed to the WYDOT office. With the exception of the newly developed MATLAB array processing algorithm, continuous automated near-real time operation was achieved in the same manner as was previously accomplished. Logging products to the computer hard drive facilitated access to signal processing results. The logged products were designed to automatically create in near real-time a continuous library of results to enabled efficient evaluation of system performance without having to utilize time consuming post processing capabilities. However, post processing capabilities were still utilized to investigate how alterations in the array processing algorithm affected results. Such experimental evaluation led to mid-winter responsive development and implementation of a signal discrimination method that removes the potential of falsely identifying wind or interfering signals as avalanche events. Experimental evaluation and investigative tasks were continued until conclusion of the winter of 2004/2005.

The graphical user display of signal processing results was abandoned, since updating it to allow for the display of the array processing results would have required a delay in deploying the CPU to the WYDOT office. Revisions of the Visual Basic .Net graphical user display occurred concurrently with the experimental evaluation of the continuous automated near-real time monitoring system. Also incorporated in the Visual Basic .Net application was implementation of custom scheduled data collection from the remote monitoring nodes, which allowed for it to be the central graphical interface for the CPU user. In the spring of 2005 the custom Visual Basic .Net software application was incorporated into a monitoring system that is utilized for development rather than operational purposes.

Operation of the Teton Pass infrasound avalanche monitoring system was concluded in the spring of 2005. Project efforts were then re-focused to planning tasks necessary to complete another seasonal cycle of Teton Pass research and development. These tasks will address remaining project objectives regarding the ease of system maintenance and use. The custom infrasound sensor and the custom sensor/datalogger interface circuitry are being upgraded with performance enhancements and to include better connectivity, so that cumbersome wiring will be eliminated from annual system maintenance or troubleshooting efforts conducted by WYDOT personnel. Development of the custom Visual Basic .Net software application continues, and it will be utilized as the WYDOT employee CPU interface for operational evaluations planned during the winter of 2005/2006.

CHAPTER 4

FINDINGS AND CONCLUSIONS

Experimental evaluation of the Teton Pass infrasound monitoring system was accomplished through two seasonal cycles of research and development. After general findings of the two cycles are presented, sensor array processing results and monitoring system operational performance are discussed. Lastly, overall project conclusions are presented.

Summer 2003 – Spring 2004 General Findings

Experimental evaluations of the infrasound monitoring systems ability to successfully identify observed avalanches were limited to a handful of WYDOT snow control missions conducted during the 2003/2004 winter. A historically stable snow pack virtually eliminated natural occurrences of avalanche activity in the targeted Teton Pass monitoring area. On the few occasions that WYDOT avalanche hazard mitigation activities were conducted, the stable snow pack was evident by the lack of resulting avalanches. However, WYDOT snow maintenance personnel did observe a few resultant surface point release events composed of freshly fallen snow.

Data recorded during these events showed that the Chaparral was hardly providing signal detection of the small avalanche-generated infrasound signals. Compounding this problem, the Chaparral data exhibited high noise due to severe winds. As a result, most data recorded during the few observed avalanche events exhibited poor SNR. Performances of single sensor avalanche identification algorithms were found to be deficient. For one of the observed Glory Bowl point slides, multiple sensor data processing techniques applied to data recorded by the three distributed single sensor Glory Bowl systems did show the ability to improve SNR and provide avalanche signal location information.

Contributing to the marginal quality of the infrasound data recorded during the 2003/2004 winter were problems encountered with the remote monitoring node instrumentation. In particular, the high cost commercial Chaparral infrasound sensors were found to be troublesome. Even though the Chaparral sensors were received new from the factory immediately prior to installation, they suffered from operational reliability issues. One of the Chaparral sensors did not operate through the full winter monitoring efforts due to a blown fuse. The Chaparral sensors frequency responses did not meet specifications, which resulted in mismatch between recorded sensor data. After the experimental winter activities concluded, the frequency response problems were found to be due to leaks in the Chaparral sensors acoustic detection components. Several factors (e.g. safety, topography, meteorology) limited the ability to access and perform winter maintenance activities at the remote monitoring nodes. While some corrective field activities were successfully performed, it was clear that deployed remote monitoring node instrumentation needs to operate without problems throughout an entire winter monitoring season.

An additional problem was instrument noise contained in data recorded from the Chaparral sensors. The Chaparral sensors internal voltage regulators did not effectively regulate power supply voltage ripple caused when the remote monitoring radio transceiver transferred data. As a result, recorded data were corrupted when sensor measurement coincided with data transfer. Furthermore, the excessive broadband frequency response of the Chaparral sensors made them susceptible to saturation (i.e. failure) during the extreme winds that often accompany periods of high avalanche hazard.

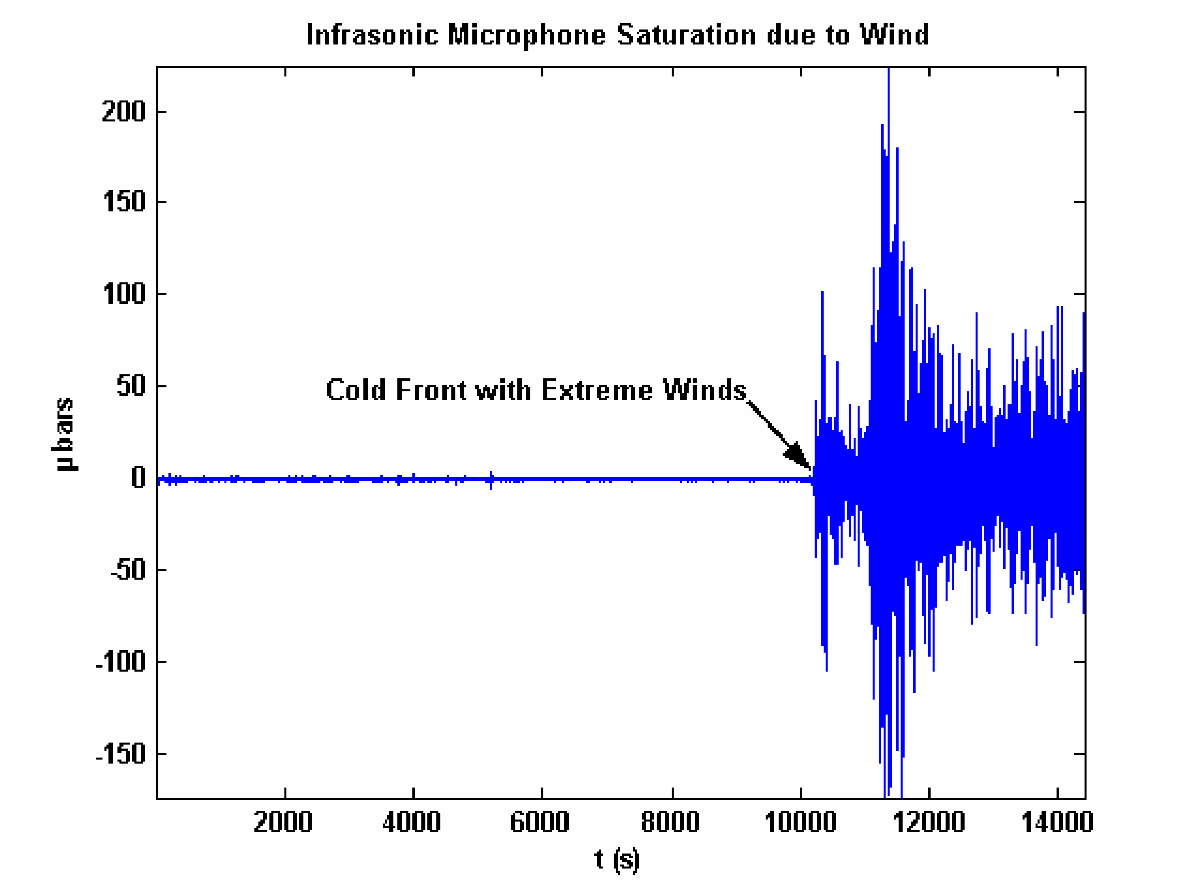


Figure 5. Effects of Extreme Winds upon Chaparral Infrasound Sensor.

Effects of extreme winds upon Chaparral sensor performance are shown in the four hour time period of recorded data illustrated in figure 5. Evident by the sudden increase in measured pressure fluctuations is the arrival of a cold front with extreme winds. Prior to the arrival of the cold front, baseline ambient wind noise levels were low. In addition to the elevated baseline ambient noise levels, the cold front arrival caused the Chaparral infrasound sensor to be randomly driven in and out of saturation. While figure 5 is an extreme example of the effects of high winds on recorded Chaparral infrasound data, it illustrates the challenge of developing infrasound monitoring systems that can reliable identify avalanche signals during periods of high ambient noise. Regardless of the poor data quality issues, data processing results showed that the more exposed host monitoring locations exhibited higher ambient wind noise. However, all host monitoring sites exhibited periods of elevated wind noise.

Also contributing to problems during the 2003/2004 winter experimental evaluations were delays encountered with the CPU development tasks. MATLAB signal processing algorithm development was completed in the early winter, but the Visual Basic .NET data management software utility and the Visual Basic .NET MATLAB interface software utility were not completed until mid winter. Subsequent successful integration of these custom software components into an automated continuous near real-time system was not achieved until late in the winter, when it no longer was needed for experimental avalanche monitoring activities

Upon completion of the 2003/2004 winter, it was obvious that the project objective is lofty; especially considering the resource intensive technical tasks that require completion according to demanding time deadlines inherent to the seasonal aspect of necessary experimental evaluation. Since the project objective was not accomplished, an improved effort was attempted during another seasonal cycle of research and development efforts conducted in a no cost extension.

Summer 2004 – Spring 2005 General Findings

Experimental evaluations of the revised Teton Pass infrasound monitoring systems were initiated in the fall of 2004. Initial evaluations showed that the newly developed prototype infrasound sensor performed according to desired specifications. While the prototype sensor exhibited higher electronic self noise than the Chaparral sensor, the prototype sensor did not exhibit the detrimental saturation and severe wind noise characteristics common with the Chaparral sensor. The prototype infrasound sensor also showed complete noise immunity from the radio induced battery voltage ripple that caused corruptive noise in the Chaparral sensor. Another advantage of the prototype sensor is that it is significantly less expensive than the Chaparral sensor, which makes application of sensor array processing more economically practical.

While there were some operational issues with the prototype sensors during the 2004/2005 winter, those issues were not as severe as the issues that once again were encountered with the Chaparral sensors. By the end of the winter season, four of the six Chaparral sensors in operation had either ceased to operate, or were exhibiting poor frequency responses.

Continuous automated near real- time operation of the monitoring system was remarkably stable during the 2004/20005 winter. There were random instances of failed data transfer due to telecommunication problems, but these instances represent a fraction of a percent of attempted data transfer. There also were instances when the signal processing failed to complete, but these too were negligible in frequency. Even when these failures occurred, the monitoring system continued to operate in an automated near real-time fashion without requiring human intervention.

The CPU at the WYDOT office reliably retrieved data, processed data, and logged processing results from all three distributed sensor array monitoring nodes every three minutes. This near real-time update rate was conservatively set, so there was little chance for the automated continuous near real-time operation to fall behind schedule. It is understood that there are established ways to provide a higher near real-time update rates if required by operational demands.

Since the data transfer via the radio transceivers is the primary bottleneck that limits the maximum operational near real-time update rate, alternative methods of implementing and controlling the radio transceivers have been developed. One simple method is to utilize a dedicated CPU radio transceiver for telecommunications with each of the remote monitoring nodes. This allows for data collection to occur simultaneously from all of the remote monitoring nodes and significantly improves the achievable near real-time update rate. Smaller gains in the near real-time update rate have recently been achieved through improved software task sequencing (i.e. custom programmable controlled multiple threaded data transfer, which eliminated the need for the LoggerNet datalogger support software component in continuous automated near real-time system operation), and advancements of array processing efficiency. Recent experimental evaluation of a developmental infrasound monitoring system composed of only one remote sensor array monitoring node has shown reliable near real-time update rates well within a minute. If current near real-time update rate capabilities are considered inadequate, then there are alternative approaches that can be implemented to make further gains (e.g. utilize higher data throughput instrumentation, implement streaming data capabilities).

Even with the previously discussed advancements achieved in the revised infrasound monitoring system, it was not a total solution for the successful completion of the project objective and goals. The dynamic nature of the atmosphere and the variability of the monitoring environment SNR still represent the major challenge to successfully apply infrasound monitoring for identifying avalanche event occurrences. Critical to combating the remaining and ever present SNR challenges were implementation of the sensor array processing algorithms developed through a concurrently National Science Foundation funded study. Experimental results obtained from the use of the sensor array processing algorithms have shown that full achievement of the overall project objective and goals is likely.

Winter 2004/2005 Sensor Array Processing Results

The Glory Road sensor array composed of prototype sensors was used to demonstrate sensor array signal processing results. A comprehensive set of results for the three sensor array monitoring nodes (Glory Road, Glory Upper, Twin Slides) is included in Appendices A, B, and C.

Figure 6 shows image visualization of sensor array processing results using an Easting and Northing depiction of the targeted Teton Pass monitoring region of figure 2. The start zone of the Glory Bowl avalanche path resides near the GLBAvGuard. GazEx1, GazEx4, and GazEx3 markers that denote the control mechanisms used by WYDOT personnel to perform Glory Bowl avalanche hazard mitigation activities. The track of the Glory Bowl avalanche path extends in a South Easterly direction and crosses Wyoming State Highway 22 at the GLBParking marker that denotes the Glory Bowl parking lot. The start zone of the Twin Slides avalanche path resides near the TSAvGuard and

GazEx2 markers that denote the control mechanisms used by WYDOT personnel to perform Twin Slides avalanche hazard mitigation activities. The track of the Twin Slides avalanche path extends in a Southerly direction and crosses Wyoming State Highway 22 about 400 meters East of the TSParking marker that denotes the parking lot at the top of Teton Pass. The cluster of GRD1, GRD2, GRD3, GRD4, GRD5, and GRD6 markers denote the Glory Road sensor array system. A detailed description of the Glory Road sensor array system is included in Appendix A.

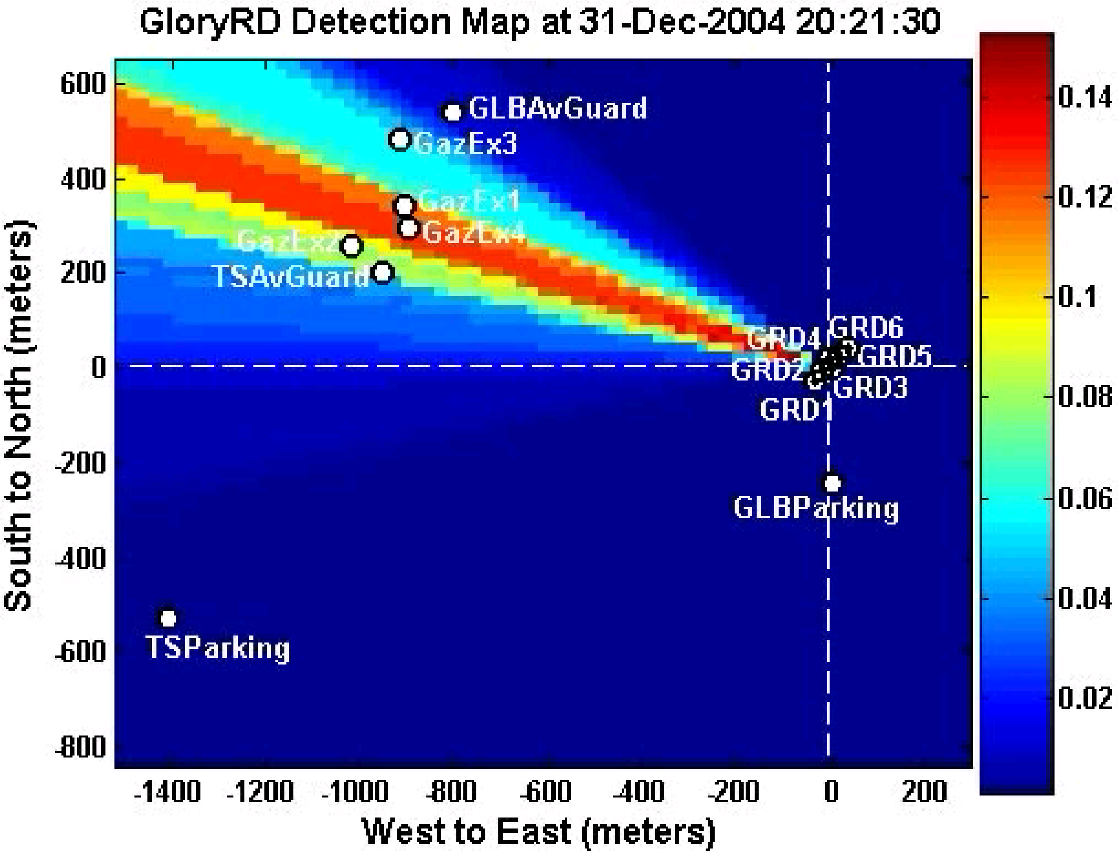


Figure 6. Natural Glory Bowl Avalanche Start Zone Results.

Overlaid on the figure 6 Easting and Northing depiction of the targeted Teton Pass monitoring region are array processing beamforming results obtained from the Glory Road sensor array for an instant in time when a naturally occurring Glory Bowl avalanche was present in the start zone. The presence of an avalanche-generated infrasound signal is shown by applying a linear color scale of arbitrary units to represent beamforming results. Red indicates the presence of a signal while blue represents the absence of a signal. The existence of an avalanche signal emanating from the start zone is clearly evident.

Shown in figure 7 are array processing beamforming results obtained from the Glory Road sensor array after the naturally occurring avalanche impacted Wyoming State Highway 22. For this instant in time it is clearly evident that an avalanche signal is emanating from a lower portion of the Glory Bowl avalanche track that is near the highway.

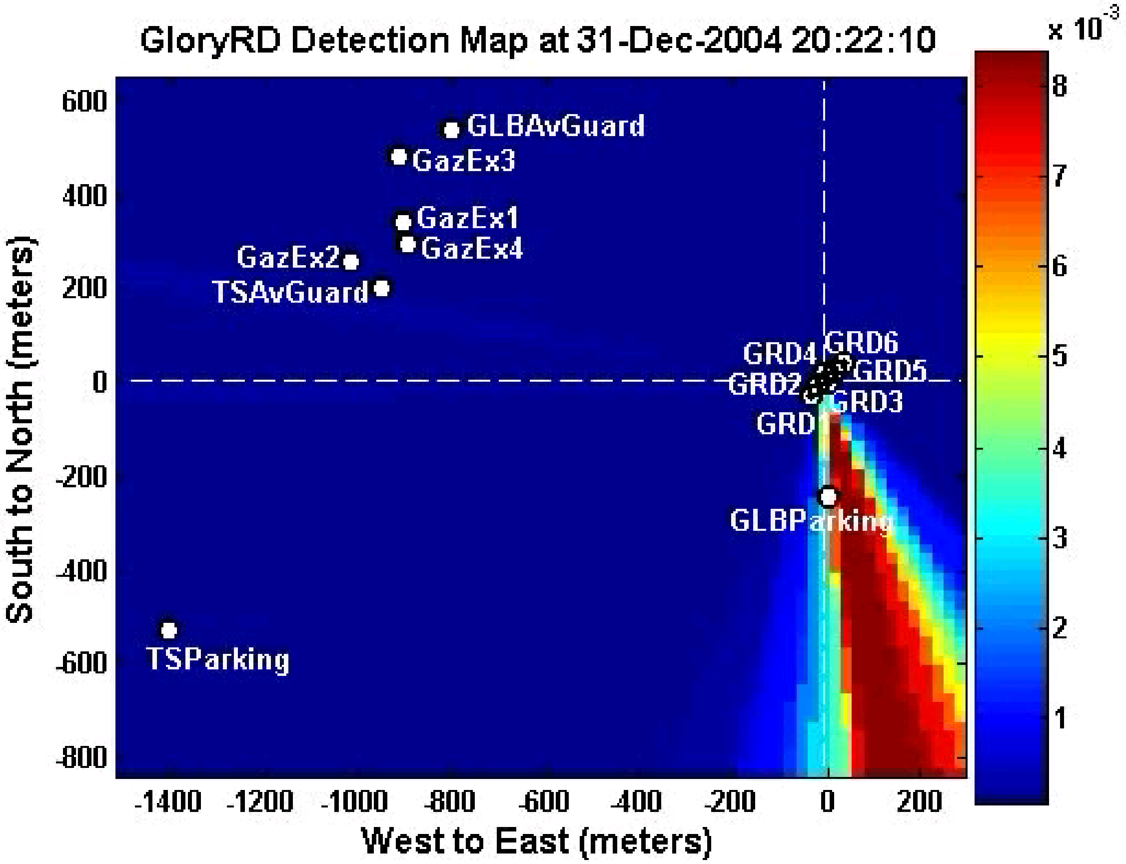


Figure 7. Natural Glory Bowl Avalanche Highway Results.

While figures 6 and 7 are powerful visual displays of the array processing beamforming results, this type of presentation is restricted to only one instant in time, which limits its usefulness. However, the CPU can be utilized to generate an animated sequence of these displays. It is easy to envision how such animation would show the array processing beam sweeping from the start zone to the highway during the forty seconds that the avalanche slides down the track of Glory Bowl. Still, watching an animated sequence of beamforming results requires the user to focus on the images for an extended period of time to interpret the information contained within the beamforming results.

Figure 8 shows a compact presentation across time of the useful information contained in a series of array processing beamforming results. The bottom graph shows signal coherency information that is presented in figures 6 and 7. This coherency information is derived from cross correlation techniques that are applied to the recorded spatial separated sensor array data. Higher correlation values are indicative of a coherent signal impinging upon the sensor array. In this example, the coherent signal is the natural Glory

Bowl avalanche event. The red bracket in the bottom graph demonstrates a threshold applied to the correlation time sequence by the CPU to automate the identification of an avalanche event occurrence. It is obvious in this thirty minute period that the elevated correlation resulting from the avalanche signal provides a reliable way to apply a 0.5 threshold criterion that identifies the avalanche event.

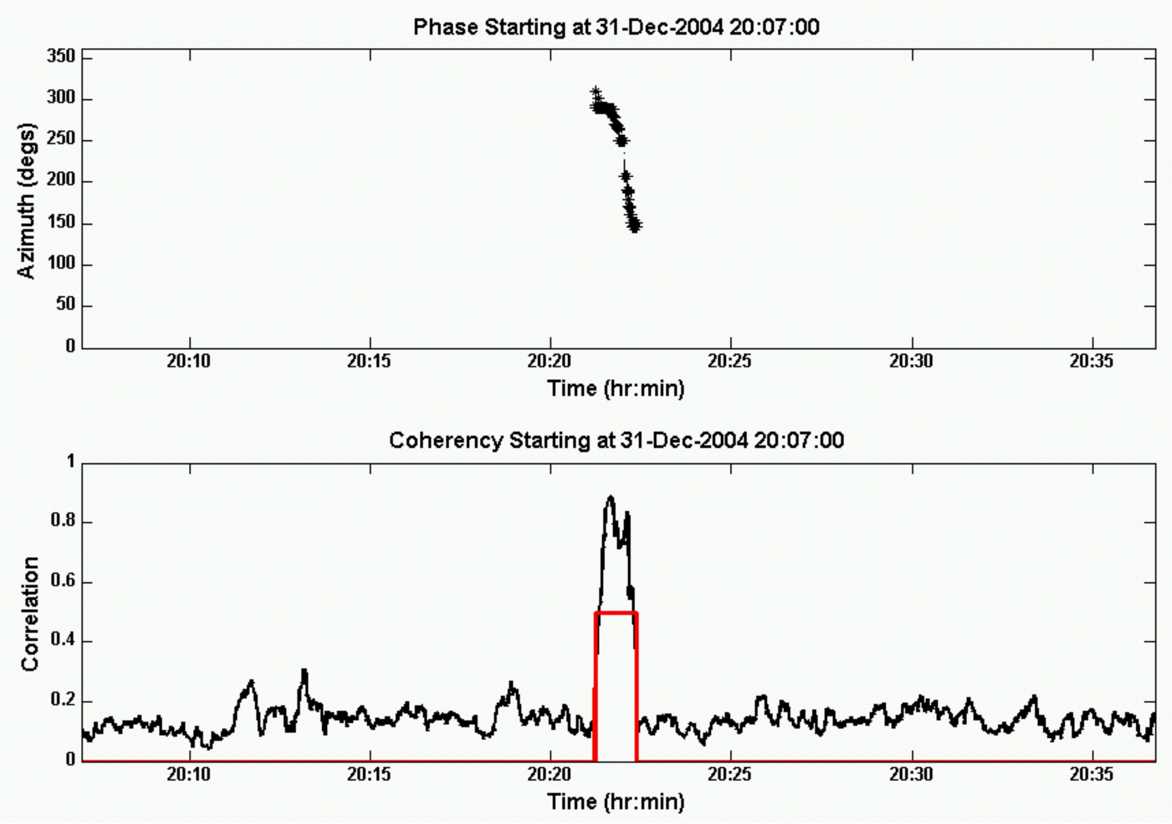


Figure 8. Natural Glory Bowl Avalanche Beamforming Across Time

The top graph in figure 8 shows signal location information that is presented in figures 6 and 7. Evident in the beams of figures 6 and 7 is that the location information only includes the general direction from which the avalanche signal emanates and propagates to the sensor array. Estimates of this azimuth angle across time are contained in the top graph.

The azimuth angle was computed with reference to the sensor array aperture origin shown by the dashed white lines in Figures 6 and 7. The common convention utilized to classify wind direction (i.e. East = 90°, South = 180°, West = 270°, North = 360/0°) was adopted as the convention for defining the azimuth angle. Distance information regarding the depth of the signal source along the azimuth angle is not obtainable from a single sensor array. More accurate avalanche signal source location information could be obtained from utilizing multiple distributed time synchronized sensor arrays. The movement of the natural Glory Bowl avalanche event as it slides is evident in the azimuth angles contained in figure 8.

Figures 6, 7, and 8 demonstrate how a sensor array can be utilized to detect and identify avalanche-generated infrasound signals. This ability also extends to other non-avalanche signals that exist in the infrasound frequency band that avalanche signals occupy. Thus, there is the potential for non-avalanche generated signals to be falsely identified as avalanches by automated array processing algorithms. Explosives and wind are common sources of such infrasound signals. Examples of explosive and wind signals are shown in figures 9 and 10.

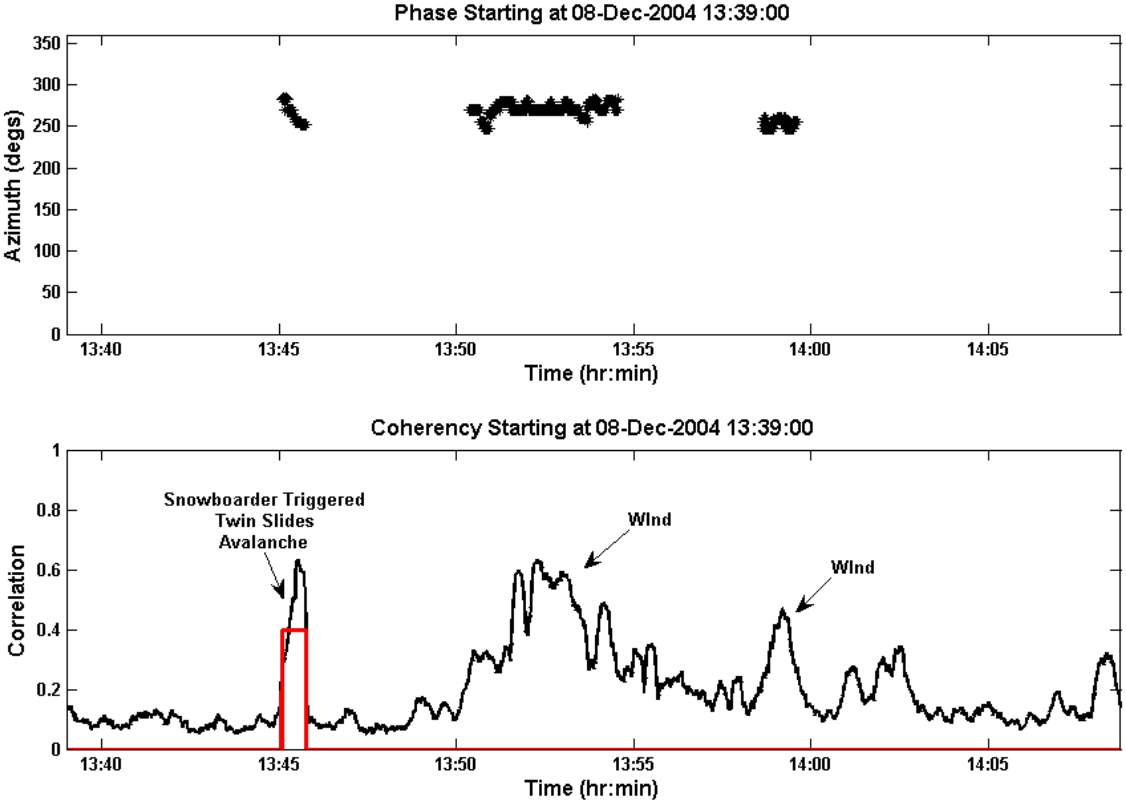


Figure 9. 12/08/04 Snowboarder Triggered Twin Slides Avalanche, and Wind.

Figure 9 shows results for a thirty minute time period that includes avalanche and wind signals. Evident in the time frame is a Twin Slides avalanche signal, which is followed by a series of wind signals. This snowboarder triggered avalanche was the first event of 2004/2005 that reached the highway.

The red bracket in the correlation sequence shows where the signal processing algorithm correctly identifies the avalanche signal. While some of the wind signals also exceed the 0.4 threshold denoted by the bracket value, the signal processing algorithm does not falsely identify these signals as avalanche signals, because the azimuth angle sequence contains features that are used to discriminate between avalanche and wind signals. While the signal processing algorithm is effective at distinguishing between wind and avalanche signals that occur at different times, a wind signal that occurs at the same time as an avalanche signal could mask the avalanche signal and result in the signal processing algorithm failing to identify the avalanche signal. Fortunately, occurrences of interfering wind signals are not common. If interfering wind signals emanate from an area of the targeted monitoring region that is outside of the avalanche paths, then the array processing can be configured to null the interfering wind signals to mitigate their masking capabilities. The continuing National Science Foundation project will provide for developing distributed sensor array processing techniques that will narrow the identified signal location and provide for further mitigation of interfering signals.

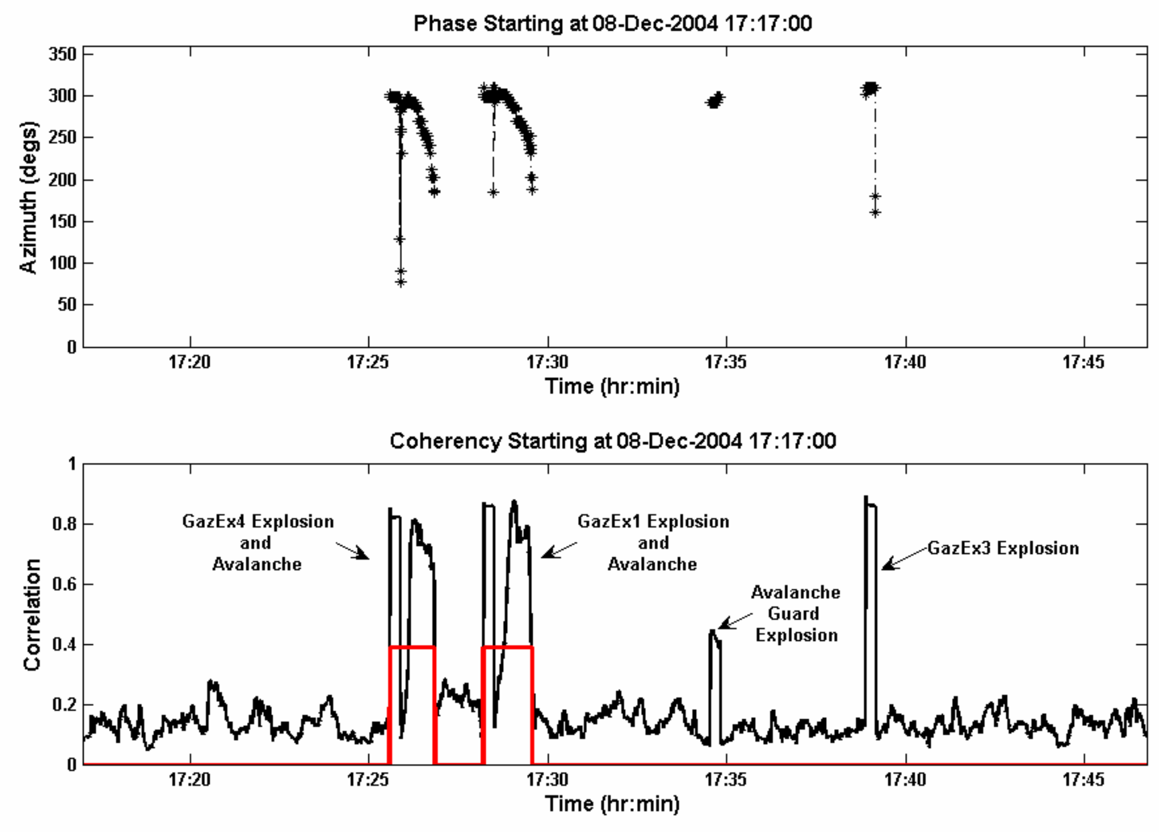


Figure 10. 12/08/04 Glory Bowl Avalanche Hazard Mitigation Activities.

Figure 10 shows results for a thirty minute time period during Glory Bowl avalanche hazard mitigation activities that were conducted shortly after highway 22 was closed due to the snowboarder triggered Twin Slides avalanche. This time period includes avalanche and explosive signals. The impulsive explosive signals create a shape in the correlation sequence that is distinctively different than the shape created by an avalanche signal. While the GazEx4 and GazEx1 triggered avalanches that impacted the highway, the Avalanche Guard and GazEx3 exploder did not produce results.

The red bracket in the correlation sequence shows where the signal processing algorithm correctly identifies the GazEx triggered avalanches. While the Avalanche Guard and GazEx3 signals also exceed the 0.4 threshold denoted by the bracket value, the signal processing algorithm does not falsely identify these signals as avalanche signals. Again, this is because the azimuth angle sequence contains features that are utilized to discriminate between avalanche and explosive signals. Of interest in the azimuth sequence are echos caused by the GazEx exploders.

Winter 2004/2005 Monitoring System Performance Summary

The Teton Pass infrasound monitoring system successfully identified the significant Glory Bowl and Twin Slides avalanche events that impacted Wyoming State Highway 22 during the 2004/2005 winter, as well as avalanches that did not impact the highway. In addition to the avalanche events that were large enough to allow automated identification, there were a few avalanche events that did not allow for reliable automated identification, but were detected and verified by human interpretation of system results. There was one avalanche hazard mitigation mission that resulted in a very small amount of snow reaching the road, which was not detected by the system.

A performance summary of results for all known 2004/2005 winter avalanche events is shown in table 1. An X denotes that a sensor array successfully detected the avalanche event, and a red highlight denotes that it is believed that the recorded sensor array data is sufficient for reliable automated identification by the signal processing algorithm. A detected avalanche signal that did not exhibit an adequate distribution of azimuth angles for reliable wind signal discrimination is designated as non-identifiable due to the potential for wind-induced false alarms. For avalanche signals that are denoted as identifiable in table 1, post-processing analyses have shown that the signal discrimination methods would virtually eliminate false alarms while still identifying the avalanche events. Signal processing results for these events are shown in Appendices A, B, C

Since the signal processing methods that discriminate between avalanche and interfering signals were developed during 2004/2005, the methods were not initially utilized in continuous automated CPU operation at the WYDOT office. Thus, numerous wind caused false alarms were encountered during operation of the continuous automated near real-time system. In early March of 2005, the newly developed signal discrimination methods were incorporated in the continuous automated system. Subsequent operational results prior to the conclusion of the 2004/2005 winter demonstrated that the signal discrimination methods are effective in eliminating false identification of interfering signals.

Table 1. 2004/2005 Performance Summary

Date	Slide Path	System Performance*			Observations
		TS	GRD	GUP	
11/26/2004	Glory		X	X	Very small snowboarder triggered slide in the start zone.
12/8/2004	Twin	🟥 X	🟥 X	🟥 X	Snowboarder triggered slide that reached the highway.
12/8/2004	Glory		🟥 X	🟥 X	GazEx4 triggered slide that reached the highway.
12/8/2004	Glory		🟥 X	🟥 X	GazEx1 triggered slide that reached the highway.
12/9/2004	Twin	🟥 X	🟥 X	🟥 X	GazEx2 triggered slide that reached the highway.
12/9/2004	Glory		🟥 X	🟥 X	GazEx4 triggered slide that did not reach the highway. This event was unknown to WYDOT observers.
12/9/2004	Twin	X			Triggered by a hiker on the boot pack. Did not reach highway.
12/31/2004	Glory	X	🟥 X	🟥 X	Naturally released slide that reached the highway.
12/31/2004	Twin	🟥 X	🟥 X	X	GazEx2 triggered slide that reached the highway.
12/31/2004	Glory		X	X	GazEx1 triggered a very small slide in the start zone. This event was unknown to WYDOT observers.
1/8/2005	Glory		🟥 X	🟥 X	Naturally released slide that did not reach the highway. This unobserved event occurred shortly after WYDOT personnel closed the highway due to road embankment sluffs.
1/8/2005	Twin	🟥 X	X	X	GazEx2 triggered slide that reached the highway.
1/8/2005	Glory	X	🟥 X	🟥 X	GazEx4 triggered slide that did not reach the highway. A powder cloud was observed by WYDOT personnel.
1/14/2005	Twin				GazEx2 resulted in a very small amount of snow reaching highway.
1/14/2005	Glory				GazEx4 resulted in a very small amount of snow reaching highway.
2/20/2005	Glory Road Cut		X		Small, skier-triggered slide originating from the West road cut. Snow was deposited on the highway.

* TS = Twin Slides sensor array, GUP = Glory Upper sensor array, GRD = Glory Road sensor array

X = Signal Detection 🟥 = Automated Identification

Evident in the table 1 performance summary is the ability of the three sensor arrays to successfully detect and identify major avalanche events occurring in their targeted slide path. The three sensor arrays also show the ability to detect and identify major avalanche events that occur in the non-targeted slide path, but this performance is variable. The Glory Bowl sensor arrays exhibited a better ability to detect and identify Twin Slides avalanche events than the ability of Twin Slides sensor array to detect and identify Glory Bowl avalanche events. A reliable Teton Pass avalanche-generated infrasound identification system requires dedicated sensor arrays for Twin Slides and Glory Bowl.

Several of the identifiable avalanche events demonstrated the usefulness and value that an infrasound avalanche monitoring system has for WYDOT snow maintenance personnel. The 12/8/04 Twin Slides snowboarder event was identified in near real-time by the CPU in the WYDOT office. As a result, this event was already being investigated when WYDOT received the phone call that reported it. The phone call provided verification of the avalanche event and WYDOT response activities (i.e. road closure, clearing of highway, and avalanche hazard mitigation activities) immediately commenced.

On 12/9/04 the GazEx4 exploder triggered a Glory Bowl slide that stopped just short of the highway but was not observed by WYDOT personnel. Automated near real-time results provided by the CPU confirmed the avalanche event. Knowledge of this event impacted WYDOT personnel ongoing operational planning of avalanche hazard mitigation activities. The event was an indication of the stability of the snow pack and verified that avalanche hazard mitigation efforts were producing desired results. This influenced decisions regarding whether additional GazEx or Avalanche Guard activities would be conducted during the current snow control mission.

The 12/31/04 GazEx1 exploder avalanche results that were not observed by WYDOT personnel also demonstrate the usefulness and value of the system for verifying results of avalanche hazard mitigation efforts. While this event did not lend itself to reliable automated identification, human interpretation of signal processing results can verify its existence. Verification that avalanche hazard mitigation efforts do not result in avalanche events also has value to WYDOT personnel. Such information on the current status of the potential avalanche hazard to highway 22 impacts WYDOT personnel decision making regarding operational planning of snow maintenance tasks. An additional benefit of the Teton Pass infrasound monitoring system was that it provided verification whether explosive ordinances detonated or not.

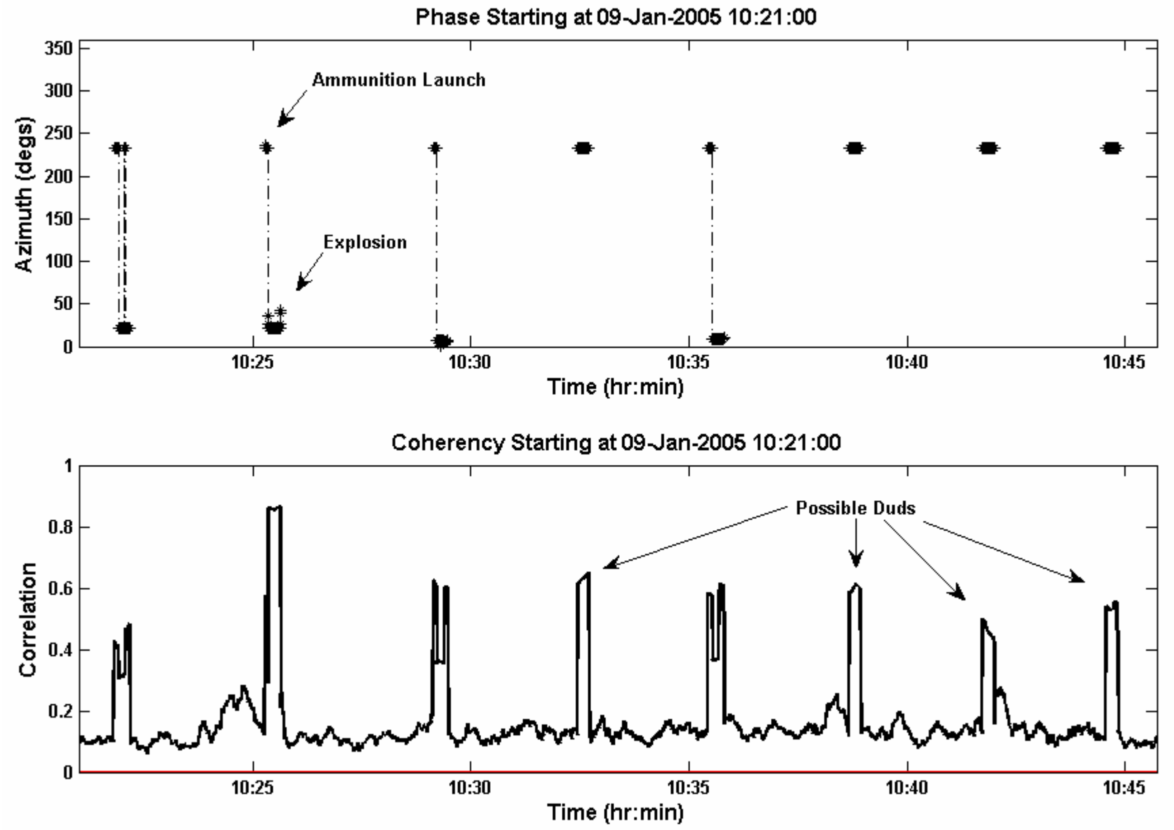


Figure 11. 1/09/05 Twin Slides Artillery Avalanche Hazard Mitigation Activities.

Figure 11 shows signal processing results for a twenty-five minute period of time on 1/9/05 when WYDOT personnel used artillery to perform avalanche hazard mitigation activities near Twin Slides. For detailed information regarding the Twin Slides monitoring setting, see Appendix C. Evident in figure 7 is the launching of eight artillery rounds from an azimuth near 235°, which is from the direction of the gun mount near the top of Teton Pass. The explosion of 4 rounds is verified by the resulting azimuth angles near 0°, which is from the direction of the start zone. WYDOT snow maintenance personnel suspected that failed explosion of several rounds may have occurred during the Twin Slides artillery firing. The infrasound monitoring system confirms the probable occurrence of these failed rounds, which WYDOT personnel attempt to locate for public safety reasons once conditions permit.

Perhaps the most critical events contained in table 1 are the two naturally released Glory Bowl avalanches. The fact that the Glory Bowl sensor arrays and CPU were successful at providing automated near real-time identification of these natural avalanche events shows that a primary goal of this research has been realized. It does appear that reliable automated identification of naturally released avalanches reaching Wyoming State Highway 22 has been accomplished.

While the 12/31/04 natural Glory Bowl avalanche was observed since it reached highway 22, the 1/8/05 natural Glory Bowl avalanche was not observed since it did not reach the highway. Existence of the 1/8/05 would have gone unknown without the infrasound avalanche monitoring system. Knowledge of this event provides some understanding of why subsequent avalanche hazard mitigation activities conducted with GazEx4 on 1/8/05 produced an avalanche event that did not reach the highway. The natural avalanche had already cleared out the slide path, which resulted in a reduction of avalanche potential. Another benefit gained from knowledge of the existence of the 1/8/05 naturally released Glory Bowl avalanche, is that it validated an earlier decision by WYDOT snow maintenance personnel to close the highway. The natural Glory Bowl avalanche occurred approximately one and one half hours after the highway was closed. The identification of such naturally released avalanches that do not impact the highway can be used to improve the safety of WYDOT personnel working on Teton Pass when avalanche hazard is high.

While the value and usefulness of the Teton Pass infrasound monitoring system was demonstrated during 2004/2005, experimental evaluation was limited to a few storm events. After the 1/8/05 storm event and avalanche cycle, there were few winter storms and the snow pack stabilized, which minimized the potential for large powder slab avalanches to occur.

As shown in table 1, on 1/14/05 GazEx2 and GazEx4 resulted in some snow reaching the road. However, the Teton Pass infrasound monitoring system failed to detect these events. WYDOT personnel observations indicate that these were very small events consisting of little snow. It is speculated that these events were surface point releases of fresh light density snow that did not entrain a significant amount of snow. It appears that avalanches of this type have limited potential to generate an infrasound signal. Slides of this type most likely define the detection limit of the Teton Pass infrasound monitoring system.

It is unknown how the Teton Pass infrasound monitoring system would perform during wet slides. It is speculated that wet slides will not generate an infrasound signal that is as robust as the infrasound signals generated by dry powder avalanches.

Overall Project Conclusions

Project activities successfully demonstrated the ability of a Teton Pass infrasound monitoring system to automatically identify snow avalanche events occurring in Twin Slides and Glory Bowl. To achieve this, solutions were implemented to problems associated with the variability of signal-to-noise ratios that is inherent to infrasound monitoring. Development of custom infrasound sensors optimized for avalanche monitoring was facilitated to ensure reliable signal detection; even in high winds conditions that often accompany periods of high avalanche hazard. Development of a novel sensor array processing algorithm was accomplished to provide robust avalanche identification performance.

The array processing algorithms were shown effective, when applied to data recorded by a single remote monitoring node containing multiple spatially separated infrasound sensors. Avalanche event identification was achieved even when the SNR was poor due to small avalanche signals and/or high wind induced noise. While the array processing alleviated challenges associated with SNR, results were still prone to false positive avalanche identifications due to interfering signals. The most common interfering signals were caused by explosions or the flow of winds in the mountainous topography.

A signal discrimination method, that eliminated the false identification of the interfering signals as avalanche events, was developed. Critical to the effectiveness of the signal discrimination method is the signal source location information obtained from the array processing algorithm. The movement of the avalanche event is exploited to reject occurrences of false avalanche event identifications due to the stationary interfering signals. Therefore, reliable automated identification of avalanche events requires the avalanche to travel a significant distance. The distance traveled by Twin Slides and Glory Bowl avalanche events that reach the Wyoming State Highway 22 is adequate for effective implementation of the signal discrimination method.

The snow movement requirement for effective signal discrimination means that small avalanche events of short duration cannot be automatically identified without the risk of false alarms. However, if the interfering signals emanate from a different area of the targeted monitoring region than the avalanche signals, the array processing can be configured to null the interfering signals and improve the confidence level for identification of short duration avalanche events.

Another approach to improving the reliability of automatically identifying small avalanche events is to combine information offered by distributed sensor array monitoring nodes. Combining information from distributed sensor array monitoring nodes through array processing beamforming or triangulation would result in narrowing estimated signal source location, which would provide improved features for use with signal processing methods. Such utilization of distributed sensor array monitoring nodes requires precise time synchronization between the sensor array monitoring nodes, which complicates the design and operation of the monitoring system. Development tasks to overcome these challenging issues are currently being performed.

Even if it is impossible to develop automated methods that provide for reliable identification of small avalanche events, human interpretation of patterns and trends in array processing results can improve confidence in identification of small avalanche events. In addition to improving the understanding of difficult to identify avalanche event occurrences, human interpretation of the results from the infrasound monitoring system contain valuable information that can be disseminated and useful to WYDOT snow maintenance personnel. Confirmation of whether explosive ordinance detonated during avalanche hazard mitigation activities is provided. It also is possible that the systems response to wind could provide an indication of wind loading conditions that are an important factor when attempting to forecast the level of avalanche hazard.

Absolute performance of the monitoring system is difficult to quantify, since its ability to reliably identify avalanche events depends on signal and wind noise levels that are both highly variable. Experimental evaluations have shown that the monitoring system can effectively identify naturally occurring or explosive triggered dry powder slab avalanches in periods of high winds. Monitoring system identification performance was not as robust for explosive triggered shallow surface point slides composed of low density freshly fallen powder snow. It is unknown how the monitoring system would have performed during wet side avalanches.

Results show that a sizeable avalanche event is required for reliable automated monitoring system identification performance. It is estimated that Class 2 Twin Slides and Glory Bowl powder avalanches in the United States classification system (CSAC 2005) contain a sufficient volume and density of snow to produce a detectable signal large enough for identification. However, wind noise levels and interfering wind signals must also be suitable to allow for effective avalanche signal identification performance. Extreme wind noise could mask an avalanche signal and result in a false negative identification (i.e. missed) of the avalanche event.

Another potential identification failure could be caused by interfering wind signals that occur simultaneously with avalanche-generated infrasound signals. While this scenario was not encountered during experimental evaluations, it is believed that the larger of the two simultaneous signals would dictate whether the signal processing algorithm successfully identified the avalanche event. It is anticipated that if the interfering wind signal was of larger amplitude than the concurrent avalanche signal, the signal discrimination method would eliminate successful identification of the avalanche event. It is also anticipated that if the wind signal were of smaller amplitude than the concurrent avalanche signal, that the avalanche signal would successfully be identified.

In summary, operation of the Teton Pass infrasound monitoring system has demonstrated its operational usefulness and value in several ways:

- Early notification of avalanche events that impact the highway.
- Identification of unobserved events.
- Verification of avalanche hazard mitigation results.
- Confirmation of ordinance detonation.

When avalanche hazard is of a concern, availability of this kind of information impacts the operational planning and activities of WYDOT snow maintenance personnel and the resultant safety of those utilizing Wyoming State Highway 22; both the traveling public and the WYDOT employee.

CHAPTER 5

IMPLEMENTATION RECOMMENDATIONS

The demonstrated operational value of avalanche-generated infrasound monitoring systems has led to continued development funding from the National Science Foundation. Many of these research and development activities are planned for the Teton Pass infrasound monitoring system, since it represents a practical application and an operational system. Work completed during these efforts will address the remaining goals of this project and will result in full completion of the project objective; developing an easy to use Teton Pass infrasound monitoring system that can reliably and automatically identify Twin Slides and Glory Bowl avalanche events in near-real-time.

The previous incarnation of the Teton Pass infrasound monitoring system included a minimal CPU software interface for the user to interact with signal processing results. A vastly improved graphical software user interface is currently under development. The graphical software user interface will provide the following functionality:

- Automated near real-time updating of strip chart displays for presenting recent signal processing coherency, azimuth and identification sequences.
- A tabularized summary of recent identifications.
- Alarming capabilities.
- On demand post processing for in depth analyses and visualization of interesting time periods.
- Configuration of important signal processing algorithm parameters.

Information presented in the near real-time strip chart displays will provide an easy and quick method for WYDOT snow maintenance personnel to understand recent monitoring system results. This functionality will be especially useful for WYDOT snow maintenance personnel in the office who initiate GazEx and/or Avalanche Guard snow control mechanisms. These personnel will quickly be able to verify the results of such activities. The near real-time updating strip chart displays will also be useful for viewing results when avalanche hazard is high and there is concern of naturally occurring avalanche events.

The tabularized summary of recent identifications will be useful for accessing results over a longer time period than can be efficiently presented via the strip chart displays. This will ensure recognition of any past identifications that are no longer being displayed by the strip charts. Associated with the summary of recent identifications will be appropriate alarms to provide unattended notification of identified avalanche events.

Post processing capabilities will be provided to the user, so that any interesting attended or unattended time periods can be further investigated. There are a few important signal processing parameters that greatly affect the identification results. Control of these parameters will be offered, so that the user will be able to investigate and fine tune the signal processing algorithm if the need arises.

In addition to improvement of the CPU graphical user software interface, the interconnection of sensor array hardware components at the remote monitoring node will be simplified to allow WYDOT personnel the ability to perform routine system installation and maintenance. Development efforts to address this are currently under way. Additional research is being conducted to investigate the effectiveness of combining data obtained from the distributed remote monitoring sensor array nodes to improve upon results obtained from an independent sensor array monitoring node.

The 2005/2006 winter season will allow for operational evaluation of a fully functional Teton Pass infrasound monitoring by WYDOT personnel. Upon completion of the 2005/2006 winter season, WYDOT will have to make decisions regarding how to proceed with the technology in the future. If monitoring system performance is once again proven to be reliable, useful, and desired for long term use, then there is a need to improve upon the temporary research installations of the sensor array monitoring nodes and transform them into more permanent operational configurations. Issues (e.g. wildlife damage, snow creep, forest service permitting) related to installing the remote monitoring node instrumentation in a permanent fashion will have to be addressed during this process. WYDOT will also have to plan for any upfront costs for upgrading the research components and future ongoing maintenance costs associated with the operation of the system.

A potential second application of the technology for WYDOT exists at the Cow of the Woods slide path that frequently impacts United States Highway 189/191 in Hoback Canyon. For this application, a custom infrasound monitoring system will have to be designed, installed, and operated to investigate whether the technology can provide a solution to the Cow of the Woods problem. If experimental evaluation were to prove the effectiveness and usefulness of a Cow of the Woods near real-time avalanche infrasound monitoring system, then additional steps would be needed to transform the initially deployed research monitoring system into an operational configuration. It is understood that there is a desire for true real-time operation of an avalanche monitoring system at Cow of the Woods, and it is currently believed that this is an achievable goal. However it would require a significant investment to port and embed the signal processing algorithm into custom hardware that could acquire and process data at the remote monitoring node.

APPENDIX A

GLORY ROAD SENSOR ARRAY SIGNAL PROCESSING RESULTS

The Glory Road (GRD) sensor array was located on top of the road cut on the East side of the track of the Glory Bowl avalanche path. Available area to deploy sensors on top of the road cut is limited, so neighboring sensors are staggered with spacing around 25 meters.

GRD examples of select beamforming results were presented in the Winter 2004/2005 Sensor Array Processing Results section of this report. Results presented in this appendix are for avalanches that were designated as reliably identifiable by the signal processing algorithm and are detailed in the table 1 performance summary.

The azimuth angle graphs presented in the following figures include two additional horizontal lines that were not shown in the Winter 2004/2005 Sensor Array Processing Results section of this report. The green line shows the azimuth angle that is near the start zone of the Glory Bowl slide path as defined by the center of the GRD sensor array aperture. The blue line shows the azimuth angle that is near where the Glory Bowl slide path crosses Wyoming State Highway 22 as defined by the center of the GRD sensor array aperture. Glory Bowl avalanche events that run on the West side of the GRD sensor array and reach the highway typically start near an azimuth of 300° and decrease towards an azimuth of 170 °. Twin Slides avalanche events do not display as large of an azimuth range.

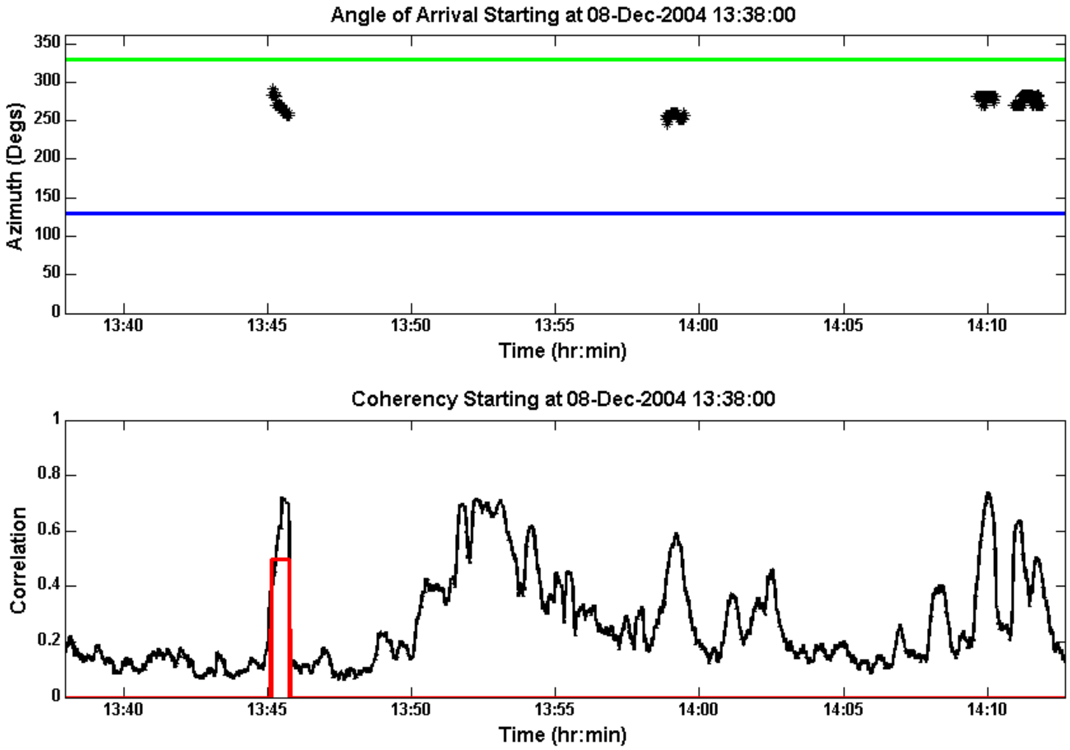
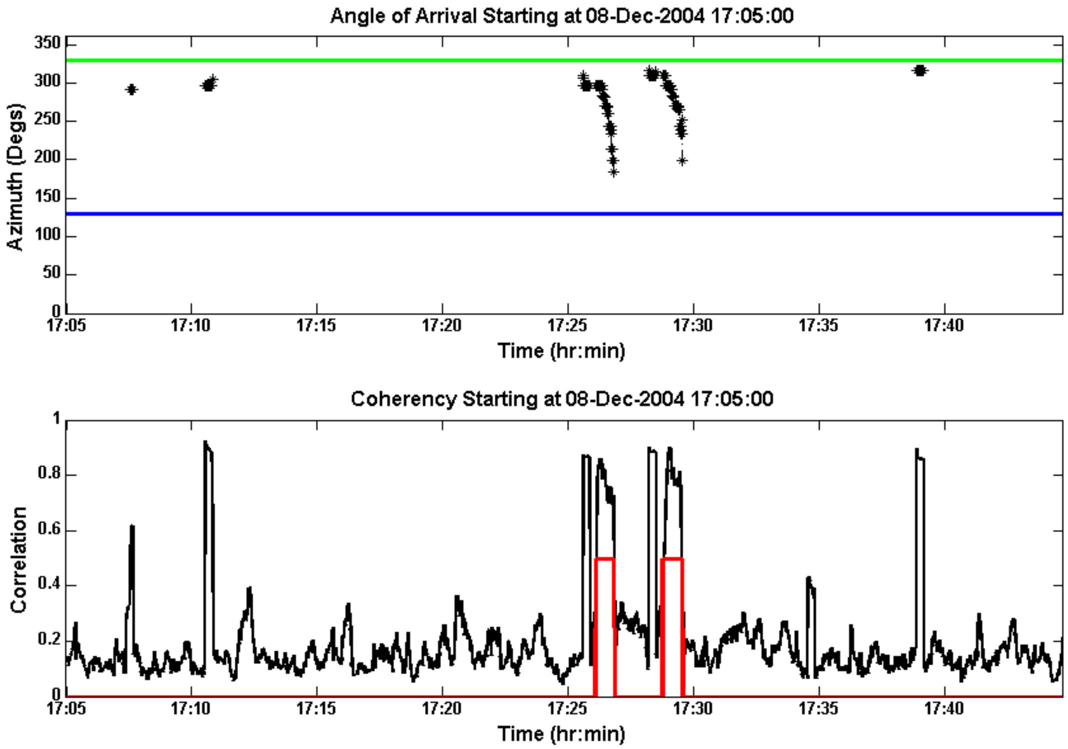
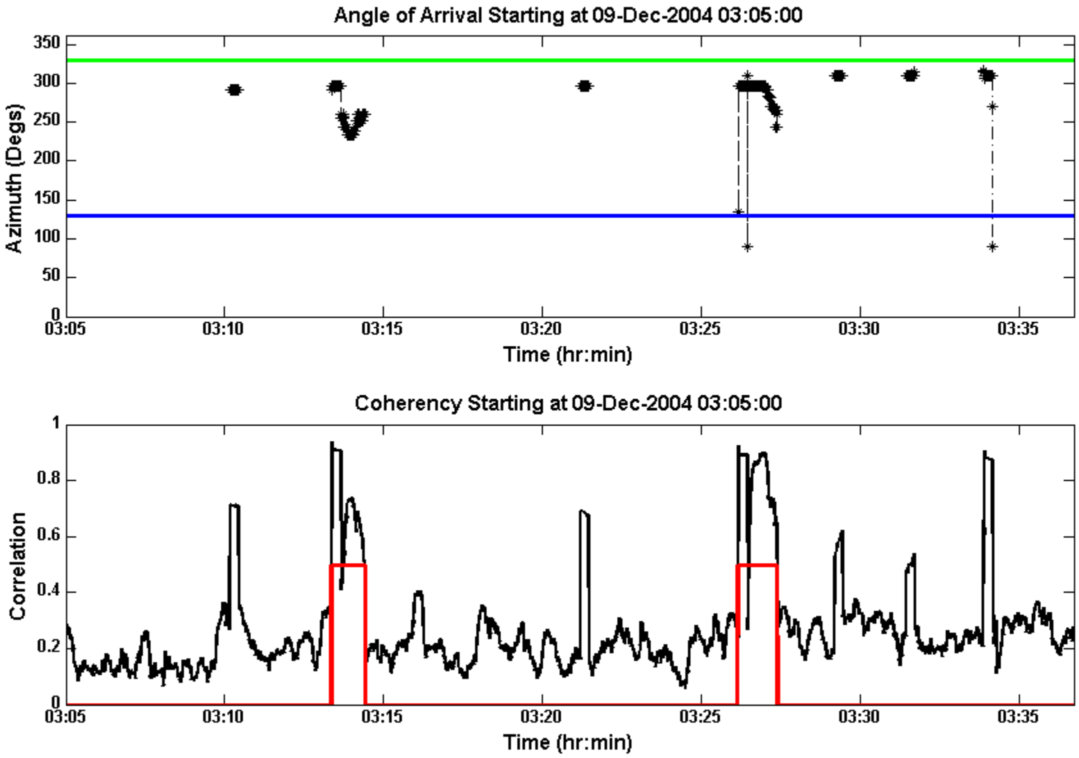


Figure 12. GRD 12/8/04 Twin Slides Snowboarder Avalanche, and Wind.


Angle of Arrival Starting at 08-Dec-2004 17:05:00

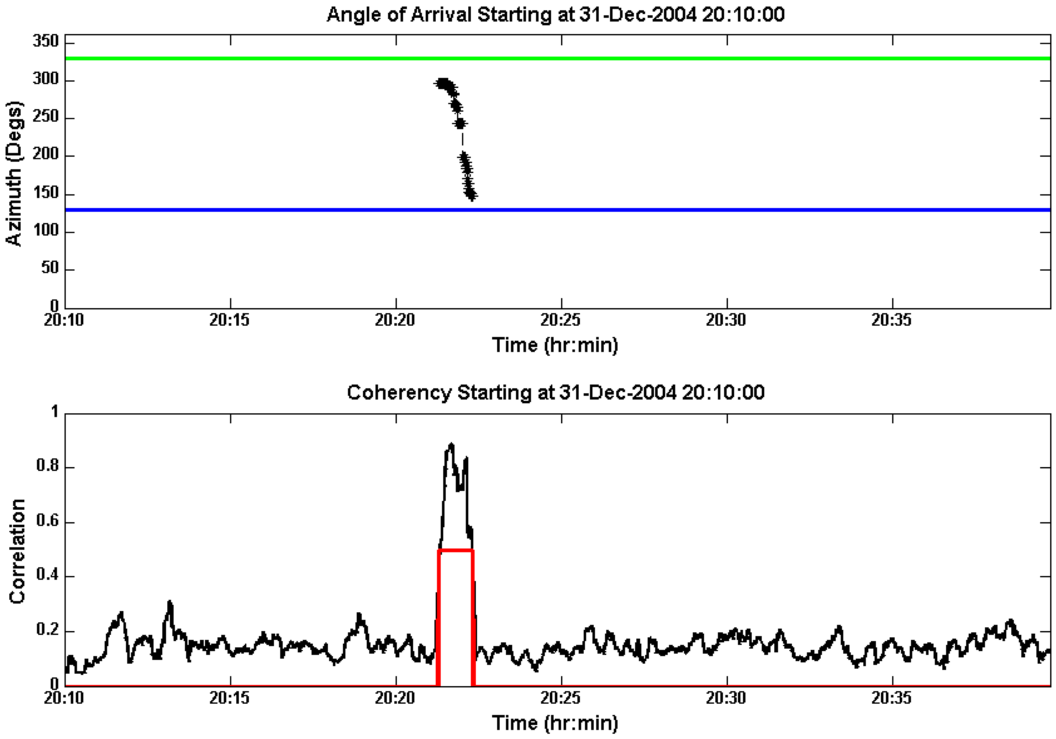
Coherency Starting at 08-Dec-2004 17:05:00

Figure 13. GRD 12/8/04 GazEx4 and GazEx1 Triggered Avalanches.


Angle of Arrival Starting at 09-Dec-2004 03:05:00

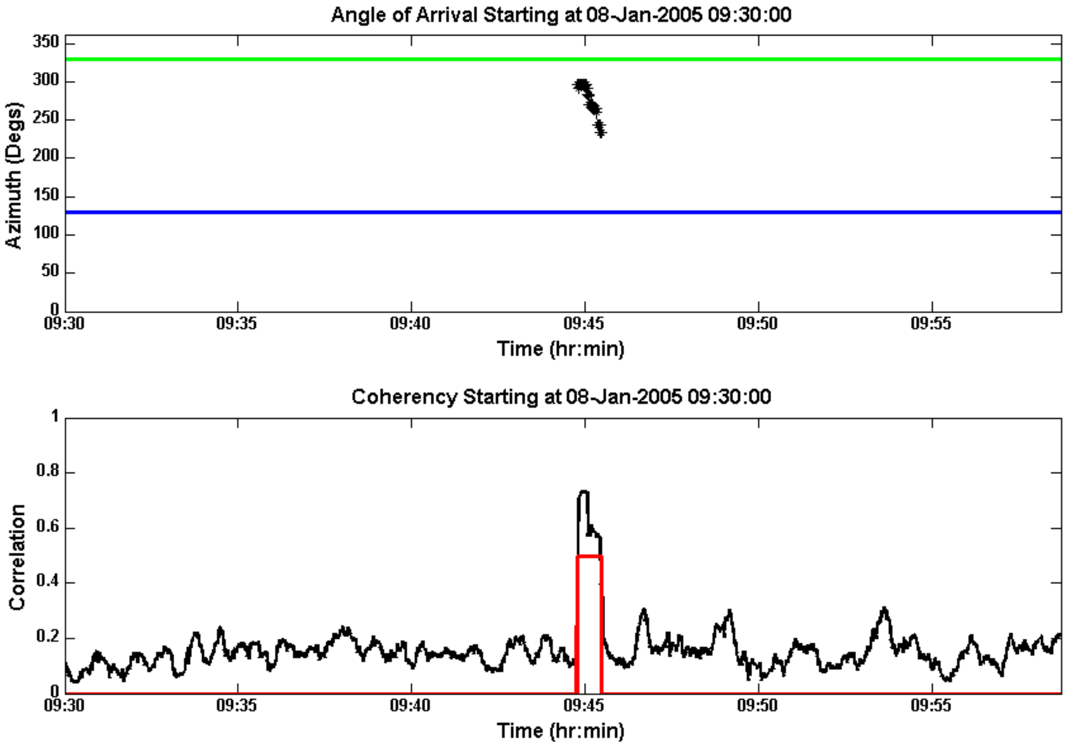
Coherency Starting at 09-Dec-2004 03:05:00

Figure 14. GRD 12/9/04 GazEx2 and GazEx4 Triggered Avalanches.


Angle of Arrival Starting at 31-Dec-2004 20:10:00

Coherency Starting at 31-Dec-2004 20:10:00

Figure 15. GRD 12/31/04 Natural Glory Bowl Avalanche.


Angle of Arrival Starting at 08-Jan-2005 09:30:00

Coherency Starting at 08-Jan-2005 09:30:00

Figure 16. GRD 1/8/05 Natural Glory Bowl Avalanche.

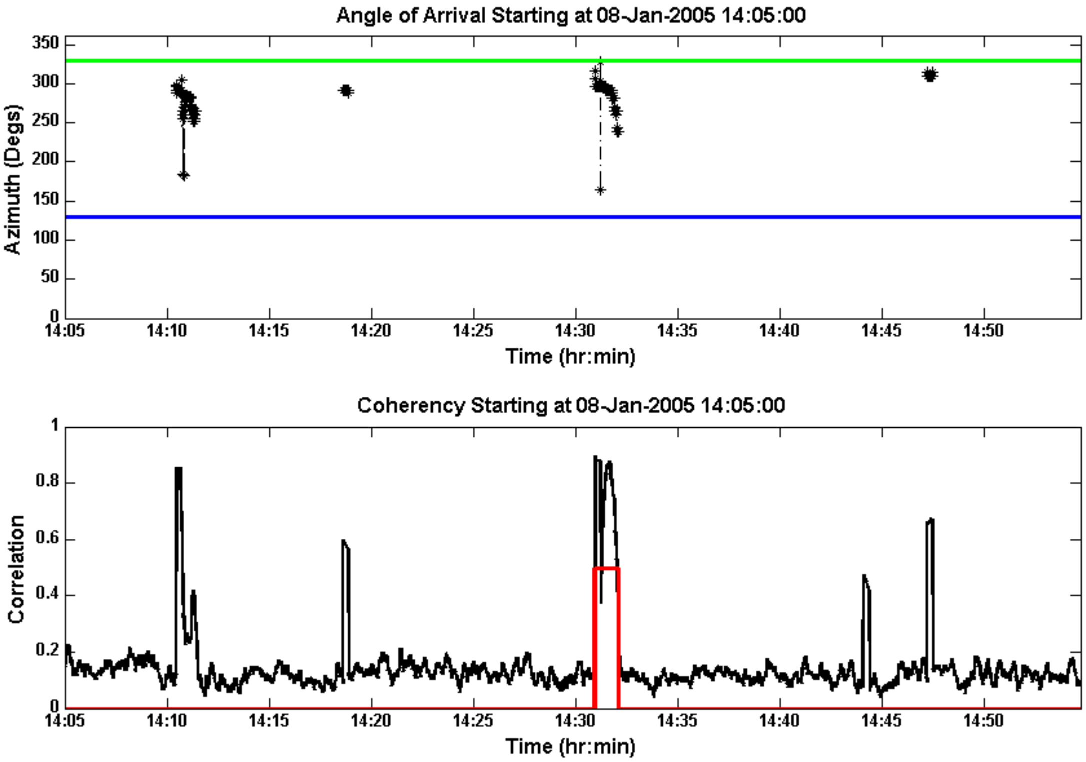


Figure 17. GRD 1/8/05 GazEx4 Avalanche

APPENDIX B

GLORY UPPER SENSOR ARRAY SIGNAL PROCESSING RESULTS

The Glory Upper (GUP) sensor array was located about 200 meters above the road cut on the East side of the track of the Glory Bowl avalanche path. The array was deployed in a rectangular configuration with two sensors near the center of the rectangle. Neighboring sensor spacing averages approximately 40 meters.

Figures 18 and 19 show two instants in time for beamforming results that have been overlaid on the Easting and Northing depiction of the targeted monitoring region. These instants in time show the 12/31/04 naturally released Glory Bowl avalanche when it is both near the start zone and near the road. Only four sensors in the GUP sensor array were utilized for signal processing due to problems encountered with two of the Chaparral sensors. The dashed white lines that mark the center of the sensor array aperture show the reference origin for azimuth angles.

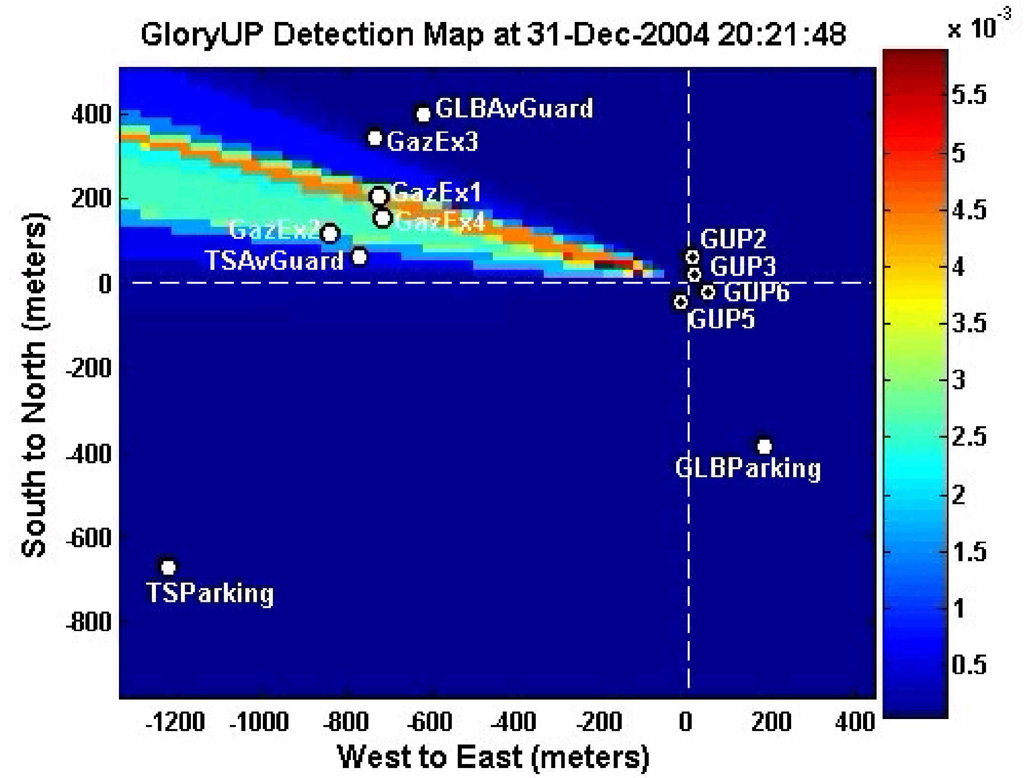


Figure 18. GUP 12/31/04 Natural Glory Bowl Avalanche Start Zone Results.

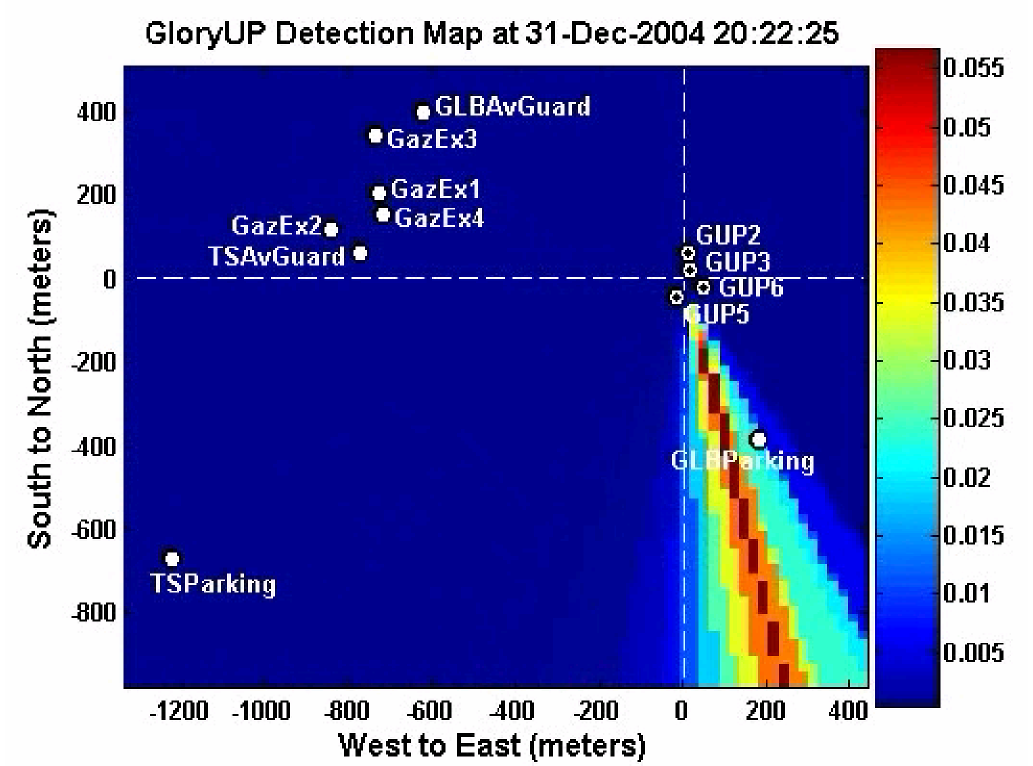


Figure 19. GUP 12/31/04 Natural Glory Bowl Avalanche Highway Results.

Results presented in this appendix are for avalanches that were designated as reliably identifiable by the signal processing algorithm and are detailed in the table 1 performance summary.

The azimuth angle graphs presented in the following figures include two additional horizontal lines that were not shown in the Winter 2004/2005 Sensor Array Processing Results section of this report. The green line shows the azimuth angle that is near the start zone of the Glory Bowl slide path. The blue line shows the azimuth angle that is near where the Glory Bowl slide path crosses Wyoming State Highway 22. Glory Bowl avalanche events that run on the West side of the GUP sensor array and reach the highway typically start near an azimuth of 300° and decrease towards an azimuth of 160°. Twin Slides avalanche events do not display as large of an azimuth range.

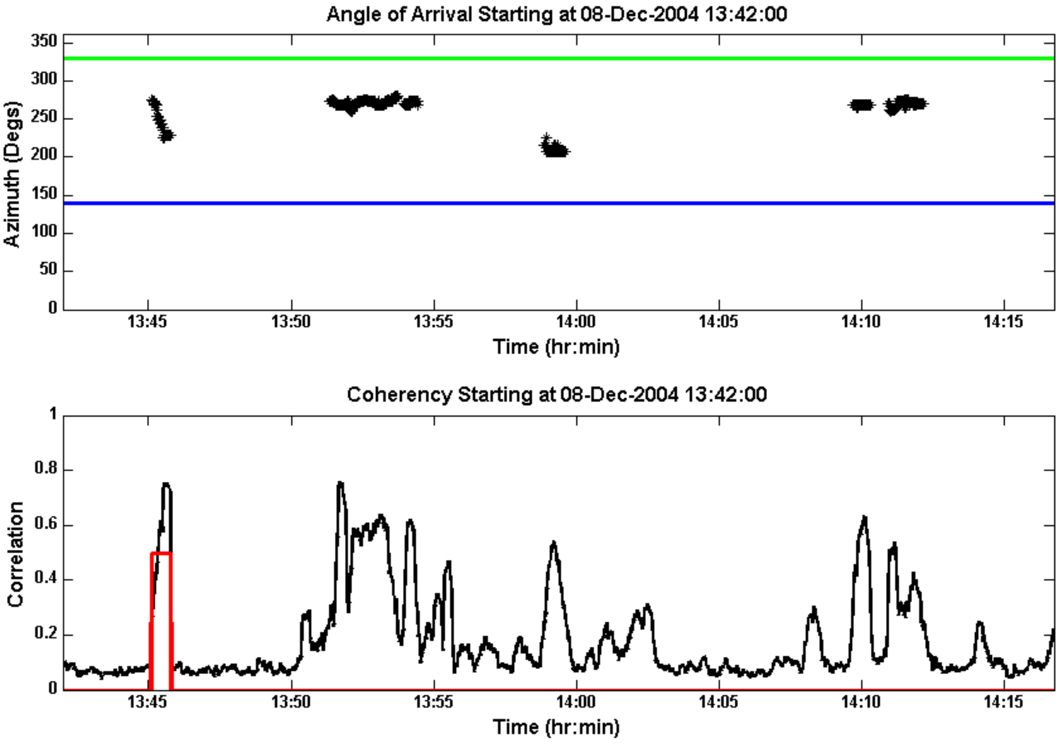


Figure 20. GUP 12/8/04 Twin Slides Snowboarder Avalanche, and Wind.

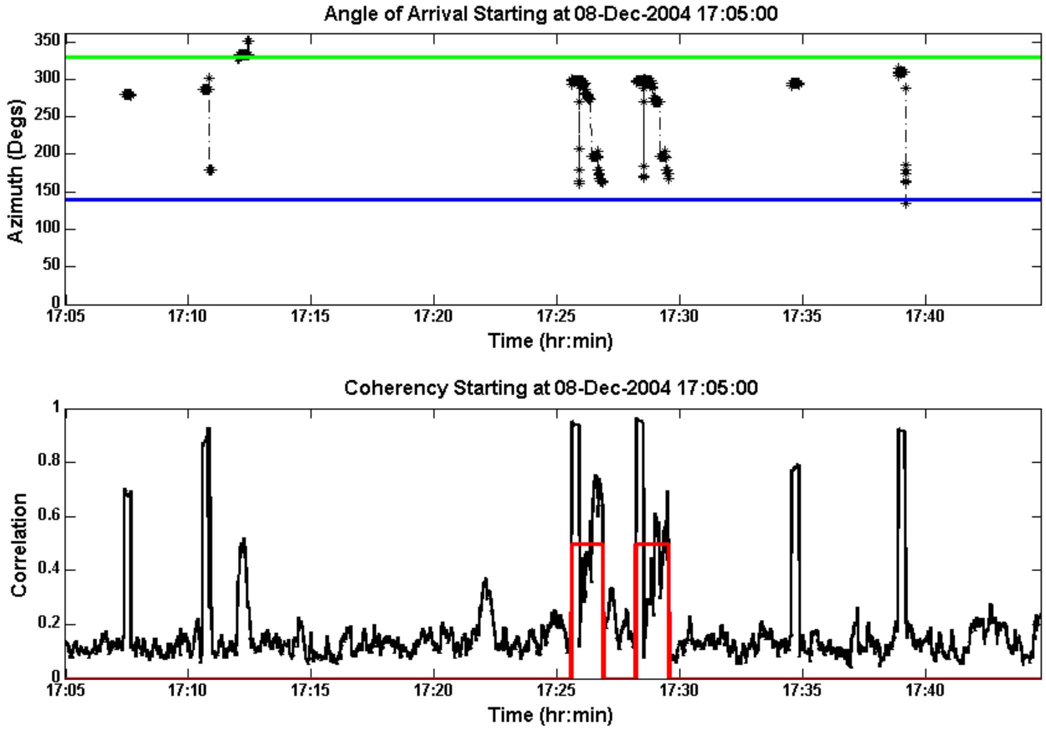


Figure 21. GUP 12/8/04 GazEx4 and GazEx1 Avalanches.

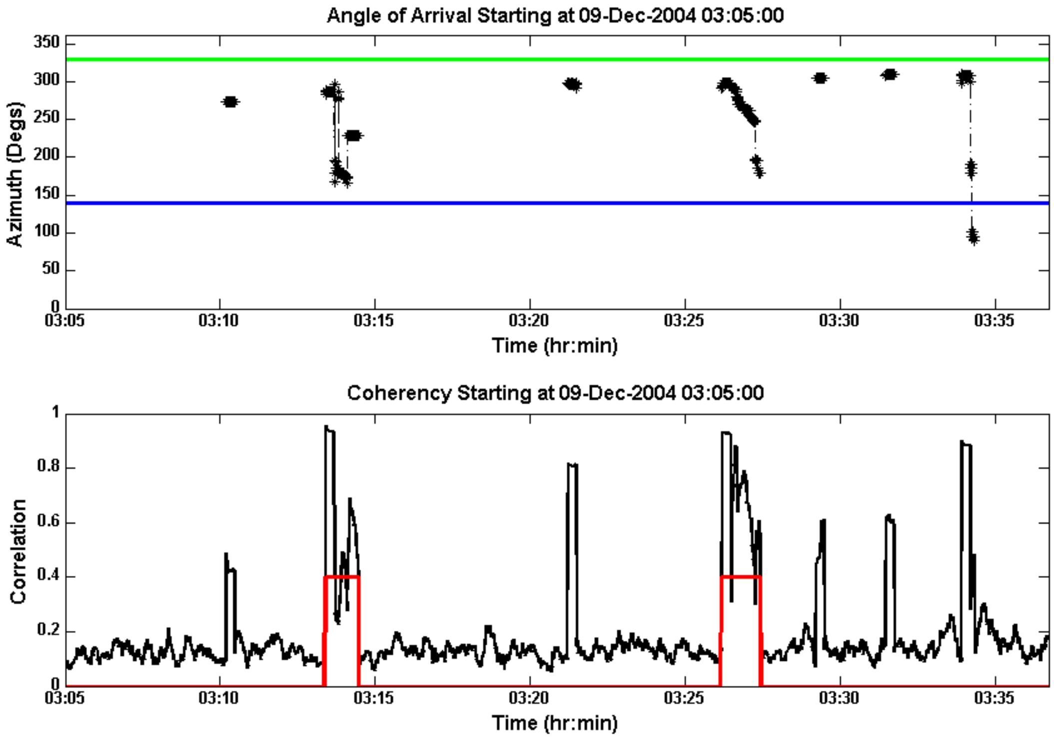


Figure 22. GUP 12/9/04 GazEx2 and GazEx4 Avalanches.

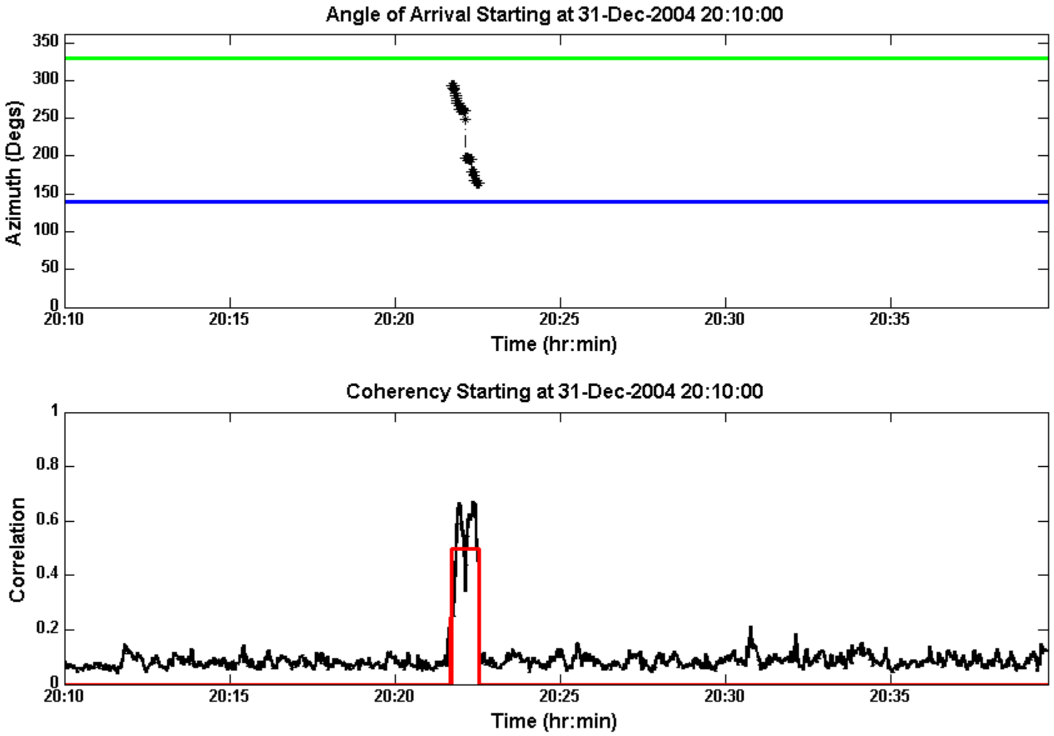


Figure 23. GUP 12/31/04 Natural Glory Bowl Avalanche.

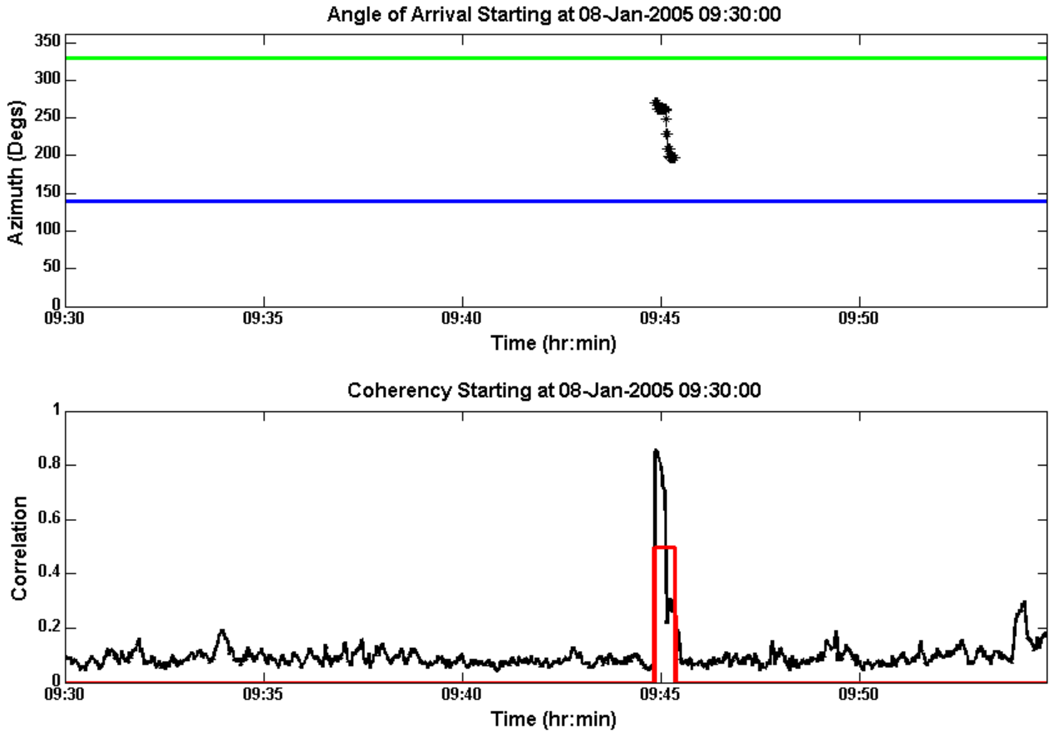


Figure 24. GUP 1/8/05 Natural Glory Bowl Avalanche.

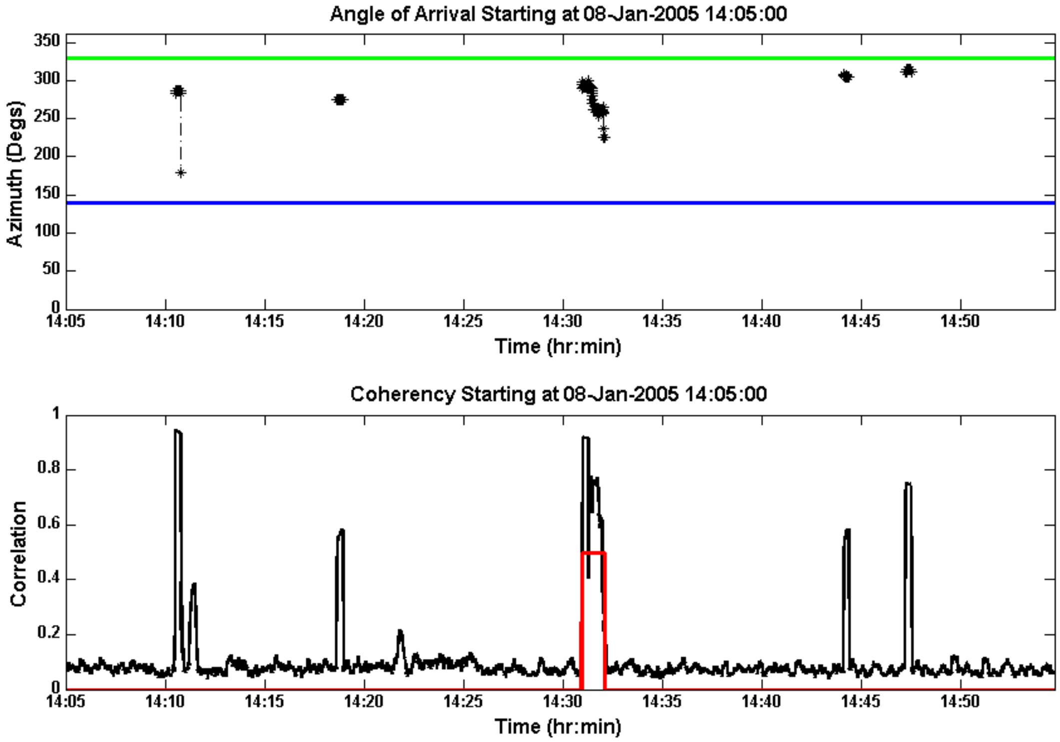


Figure 25. GUP 1/8/05 GazEx4 Glory Bowl Avalanche.

APPENDIX C

TWIN SLIDES SENSOR ARRAY SIGNAL PROCESSING RESULTS

The Twin Slides (TS) sensor array was located on top of the road cut that separates the Upper Twin Slides avalanche path and the Lower Twin Slides avalanche path. The array was deployed in a rectangular configuration with two sensors near the center of the rectangle. Neighboring sensor spacing averages approximately 35 meters.

Figures 26 and 27 show two instants in time for beamforming results that have been overlaid on the Easting and Northing depiction of the targeted monitoring region. These instants in time show the 12/8/04 snowboarder triggered avalanche when it is both near the start zone and near the road. The dashed white lines that mark the center of the sensor array aperture show the reference origin for azimuth angles.

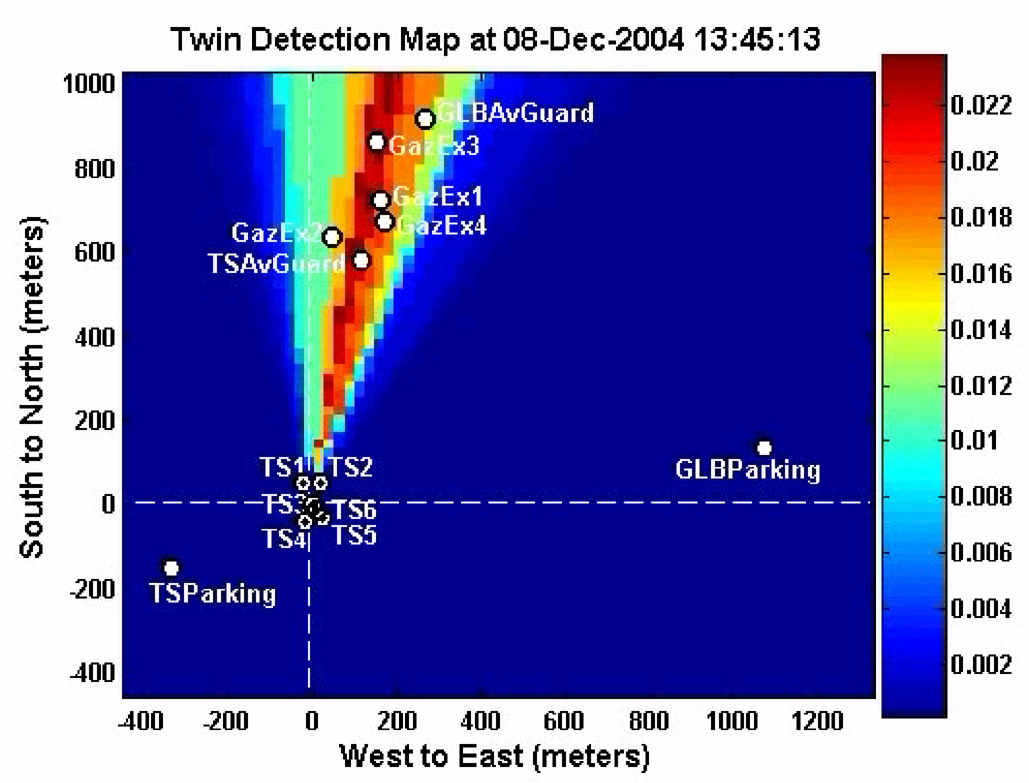


Figure 26. TS 12/8/04 Snowboarder Twin Slides Avalanche Start Zone Results.

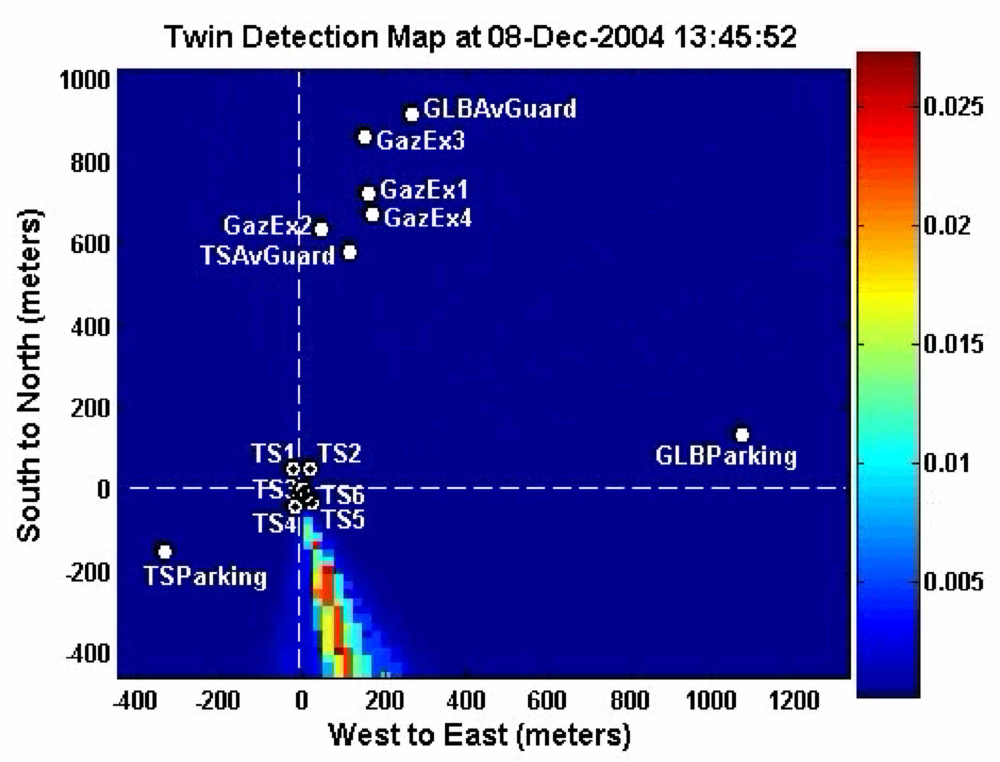


Figure 27. TS 12/8/04 Snowboarder Twin Slides Avalanche Highway Results.

Results presented in this appendix are for avalanches that were designated as reliably identifiable by the signal processing algorithm and are detailed in the table 1 performance summary.

The azimuth angle graphs presented in the following figures include two additional horizontal lines that were not shown in the Winter 2004/2005 Sensor Array Processing Results section of this report. The green line shows the azimuth angle that is near the start zone of Twin Slides. The blue line shows the azimuth angle that is near where Twin Slides crosses Wyoming State Highway 22. Twin Slides avalanche events that run on the East side of the TS sensor array and reach the highway typically start near an azimuth of 0° and increase toward an azimuth of 170°. The TS sensor array azimuth angles occupy a different range of values than the Glory Bowl sensor arrays azimuth angles, because the TS sensor array is located to the West of the avalanche activity, while the Glory Bowl sensor arrays are located to the East of the avalanche activity.

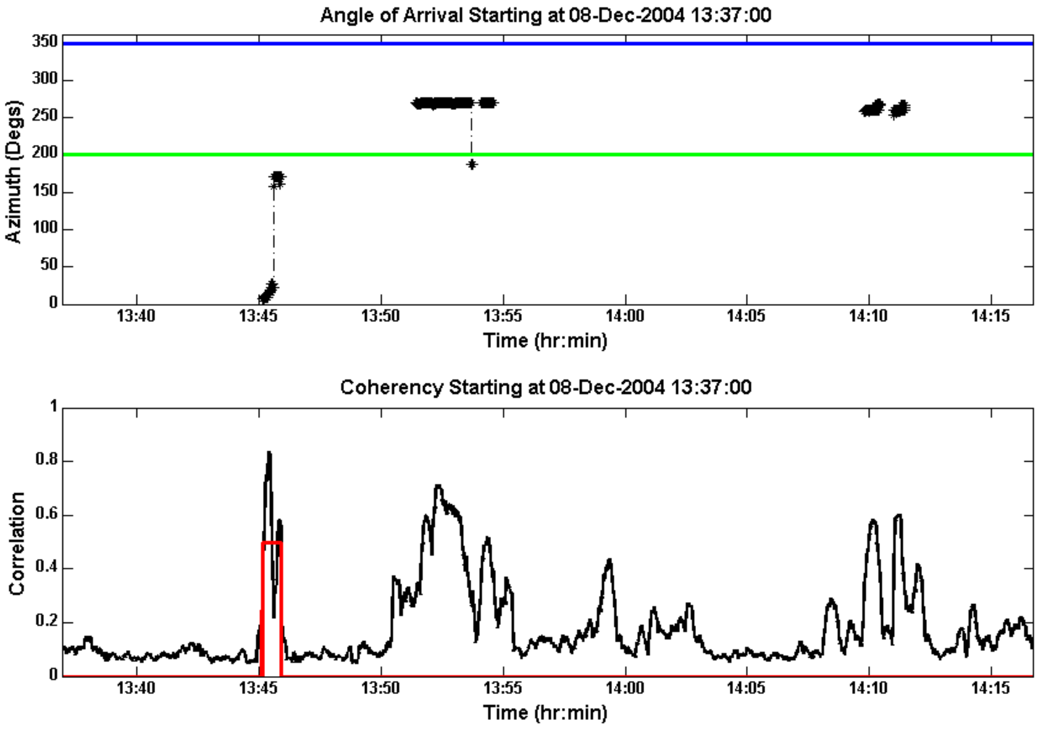


Figure 28. TS 12/8/04 Twin Slides Snowboarder Triggered Avalanche, and Wind.

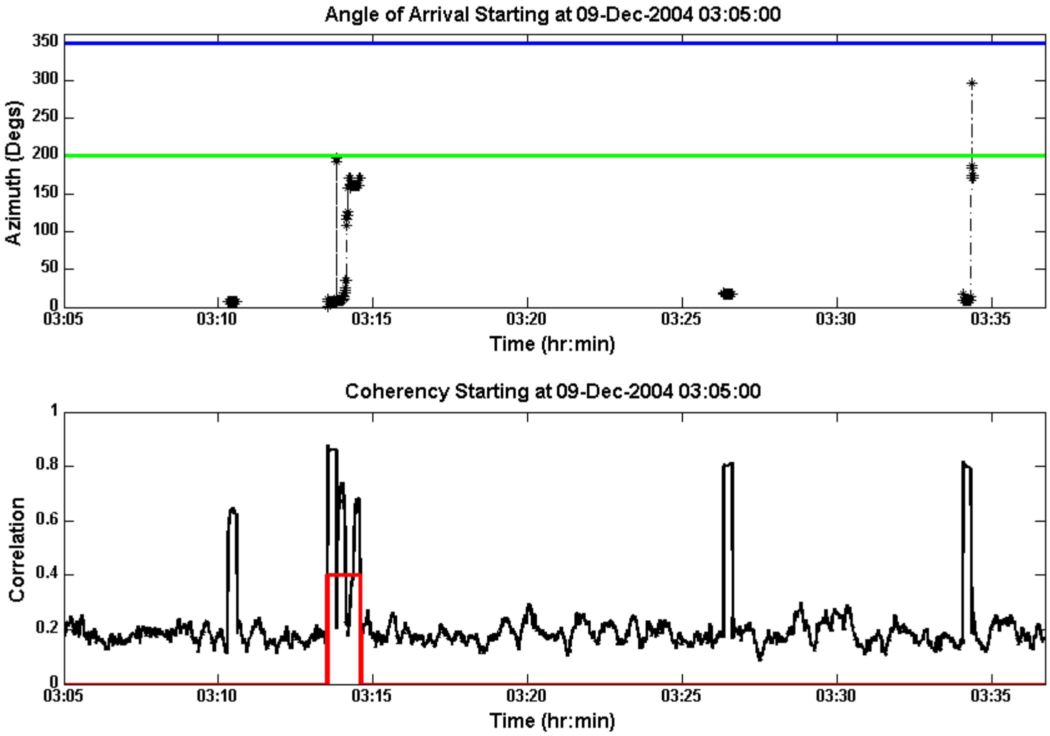


Figure 29. TS 12/9/04 Twin Slides GazEx2 Avalanche.

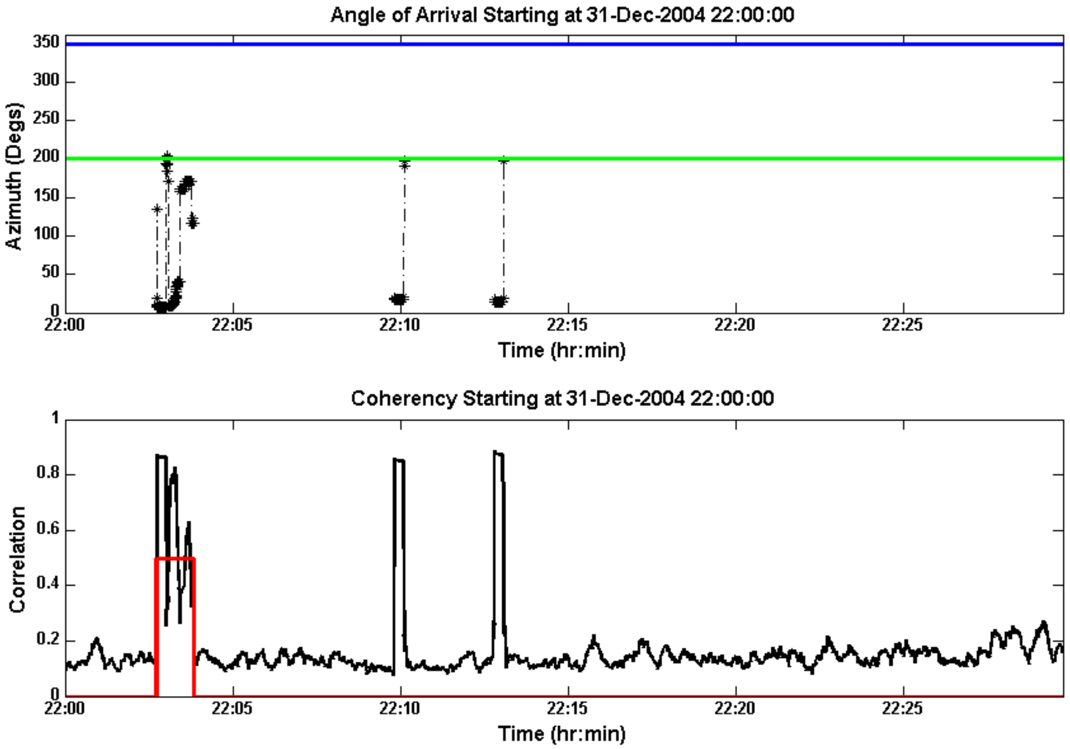


Figure 30. TS 12/31/04 Twin Slides GazEx2 Avalanche.

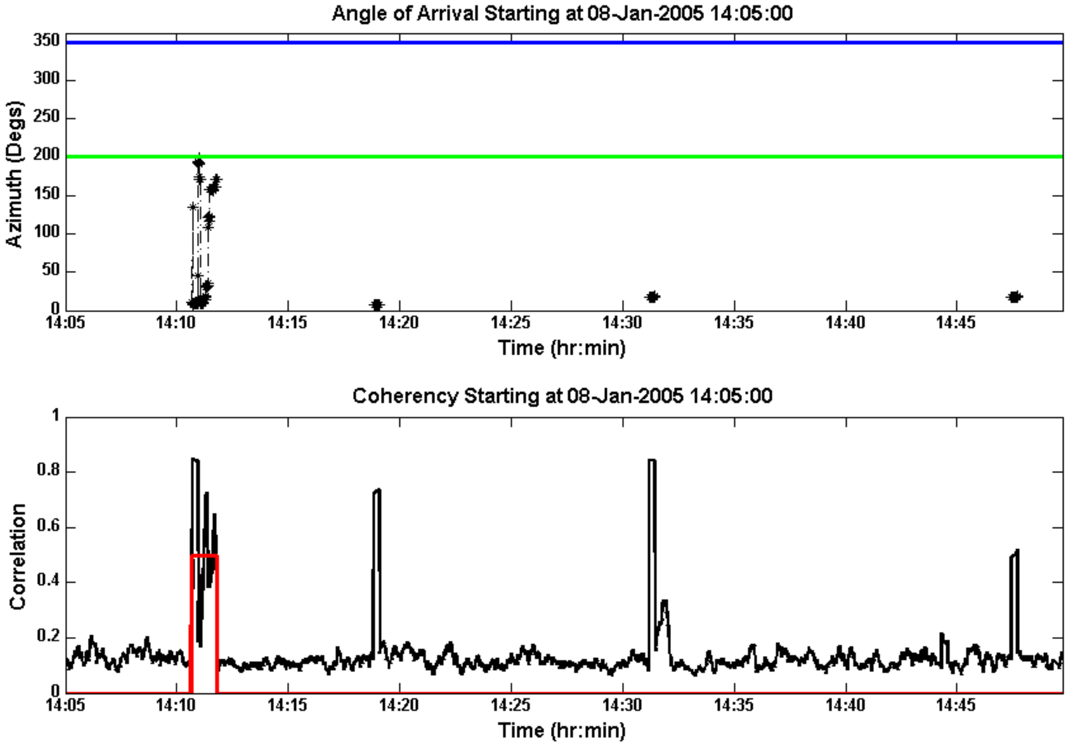


Figure 31. TS 1/8/05 Twin Slides GazEx2 Avalanche.

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