OPERATIONAL HIGHWAY AVALANCHE FORECASTING USING THE INFRASONIC AVALANCHE DETECTION SYSTEM

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ABSTRACT: Highway avalanche forecasting programs typically rely on weather and field observations to make road closure and hazard evaluations. Recently, infrasonic avalanche monitoring technology has provided another tool for highway technicians in their operational forecasting and decision making. The technology detects low frequency sound waves produced by avalanches with near real-time processing providing alarming. Such technology has been deployed on Teton Pass near Jackson Wyoming for the Wyoming Department of Transportation since 2002; and for the Utah Department of Transportation in Little Cottonwood Canyon near Salt Lake City Utah since 2006. Uniqueness in deployed sensor configurations in addition to local terrain and meteorology provide differing results from the two monitoring systems with results obtained in Little Cottonwood Canyon being superior to those obtained on Teton Pass. The systems provide information to confirm results from avalanche control work, alarming from natural avalanche events, and verification of explosive detonations. The ability to monitor avalanche activity in poor visibility and confirm avalanche control work results are powerful tools for assessing highway avalanche hazard and has changed the way these two programs operate in their mission to provide safe and efficient transportation routes.

KEYWORDS: Avalanche Monitoring, Infrasound, Avalanche Forecasting

1. INTRODUCTION

Several research studies conducted in recent years have investigated the development of an automated near real-time monitoring system to detect and identify acoustic signals generated by snow avalanche activity (Comey and Mendenhall 2004). Encouraging results from these studies resulted in deployment of an operational grade monitoring system for the Wyoming Department of Transportation (WYDOT) to utilize within its Teton Pass avalanche safety program (Scott 2005). The practical value demonstrated by the prototype Teton Pass monitoring system led to the deployment of a second, refined, system in Little Cottonwood Canyon (LCC), UT, for use by the Utah Department of Transportation (UDOT) avalanche safety program. While differences exist in the configuration of the two deployed monitoring systems, both WYDOT and UDOT utilize the technology as a tool for making operational decisions concerning snowpack stability, effectiveness of active control measures, and artillery ordinance detonation confirmation.

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2. TECHNOLOGY OVERVIEW

Snow avalanche-generated, airborne acoustic signals occupy a relatively low noise band of the sub-audible infrasonic frequency spectrum and provide a functional basis for developing automated avalanche monitoring systems. In addition to problematic ambient noise and interfering signals, both the atmosphere and snow are inherently variable media, which complicates the ability to deploy a reliable and stable infrasound monitoring solution targeting avalanche activity.

Critical to the success of both WYDOT and UDOT monitoring systems was the custom development of a precise infrasound sensor that does not saturate during periods of high wind. Also vital, was the advancement of the monitoring technology from a single sensor form, to a single array of multiple spatially separated sensors, or Single Sensor Array Monitoring (SSAM) node. The SSAM node has now evolved to a distributed set of arrays of multiple spatially separated sensors, or Distributed Sensor Array Monitoring (DSAM) nodes.

For the often encountered non-ideal signal and noise environment, utilization of multiple spatially separated sensors allows for use of a custom beam forming signal processing algorithm that effectively confirms detection of signals and estimates their geographic source location. Detection of infrasound signals is facilitated via spatial geographic filtering of unwanted noise and applying a threshold criterion to a correlation measure that estimates the coherency of data recorded between sensors. Subsequent time duration criterion and signal source movement based pattern recognition techniques are then used for reliable classification of detected signals as either an avalanche or interference.

Beams formed with a SSAM node contain imperfect signal source location information. Existence of aliased location information limits the usefulness of extracted location features from the beams to be only the signal's azimuth angle of arrival relative to the sensor array. Utilizing DSAM nodes to form beams mitigates the existence of aliased location information. This narrowing of formed beams provides the ability to estimate the three dimensional location of signals detected within the targeted monitoring region.

In addition to the signal processing algorithm development, Graphical User Interface (GUI) software was developed to control system operation and efficiently present results in an easy to use manner. On a preset near real-time interval (e.g. one minute), recorded infrasound data is transferred via spread spectrum radio transceivers from the sensor array(s) to an office residing Central Processing Unit (CPU). The GUI then invokes the series of data processing steps that verifies detection of infrasound signals and classifies any detected signals as either targeted avalanche events or interference. Data, correlation estimates, and geographic location estimates are presented via interactive time graphs that typically display the most recent thirty minutes of results and behave as strip charts.

Images that show the geographic location time progression of all detected signals, whether classified as targeted avalanches or interference, are available for viewing. Accompanying the images are statistical summaries of the parameters utilized by the time duration and signal source movement based pattern recognition classification techniques. If desired, email and\or text message notifications are sent for detected signals that are classified as targeted avalanche events.

Access to further in depth manual investigation of detected signals or interesting time periods is facilitated via post processing capabilities. Additional configuration functionality exists to allow for alteration of all critical signal processing algorithm parameters.

3. WYDOT APPLICATION

Infrasound monitoring for avalanche activity has been researched on Teton Pass since the 2002/03 season when a single sensor system was initially deployed. A variety of configurations were tested, which resulted in viable multiple sensor monitoring methodology by the end of the 2005/06 season. The myriad of Teton Pass research efforts are well documented via past publications (Scott et al. 2004, 2006, 2007), which show examples of the sensor array monitoring hardware, signal processing results derived from a SSAM node, and the GUI. Not previously published are impressive signal processing results obtained from DSAM nodes that are worthy of presentation and discussion.

Signal processing features obtained during explosive avalanche control efforts during the 2005/06 Teton Pass research season are shown in Figure 1. A complimentary geographic detection image corresponding to the Figure 1 avalanche time period is shown in Figure 2, which

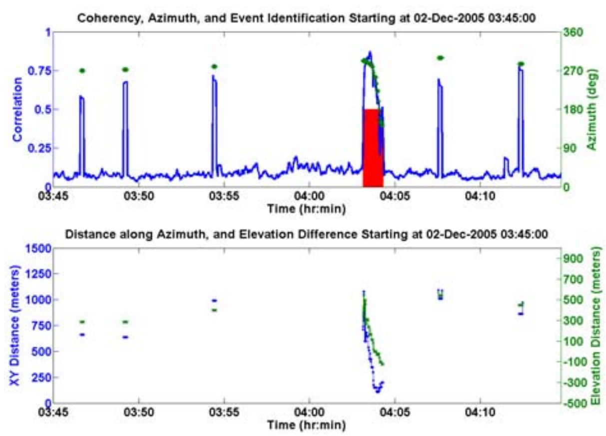

Figure 1: 12/02/05 Glory Bowl feature set.

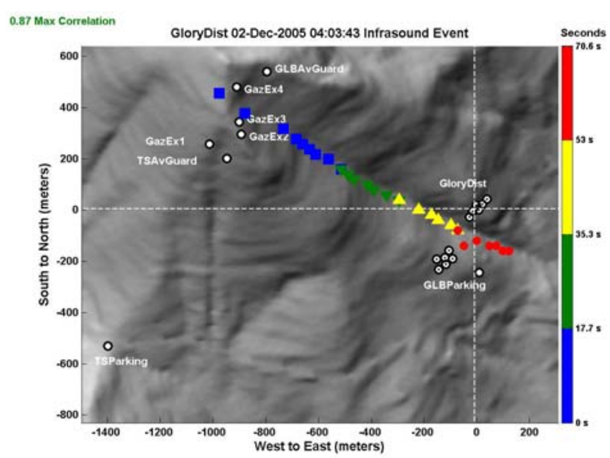

Figure 2: 12/02/05 Glory Bowl avalanche event.

depicts the time progression of the Glory Bowl avalanche infrasound signals location estimates on an Easting and Northing (i.e. XY) geographic view of the Teton Pass monitoring region. Included in Figure 2 are markers that correspond to the GazExs, Avalanche Guards, and Highway 22 parking lot markers depicted later in Figure 3. Also shown are sensor markers depicting the utilized DSAM nodes. The estimated signal source location features in Figure 1 were computed relative to the origin defined by the intersection of the dashed white lines in Figure 2. A standard wind direction convention for defining azimuth angles relative to the XY origin is utilized (i.e. 0/360º = North, 90º = East, 180º = South, 270º = West).

Evident in the thirty minute period of Figure 1 are five stationary explosive signals and one moving avalanche signal. In addition to infrasound signal classification, the top time graph shows the correlation and azimuth angle features that can be reliably estimated from a SSAM node, while the bottom graph shows the additional features (XY distance along the azimuth angle, and a Z elevation component) that can be reliably estimated from DSAM nodes. These results clearly show the detection of a Glory Bowl avalanche event and the ability to exploit signal source movement to properly classify a detected signal as either a targeted avalanche event or interference.

Since the end of the 2005/06 season, Teton Pass efforts have largely focused upon the desire to transition the monitoring system from an ever evolving heuristic research entity to a steadfast and practical utility for on-going WYDOT operational use. Upon entering the 2006/07 season, a finalized design and configuration of the Teton Pass infrasound monitoring system was settled upon. While processing from DSAM nodes had demonstrated clear advantages over SSAM node processing, a decision to forgo designing a system capable of effective DSAM node processing was made in order to minimize on-going operational maintenance costs.

Two arrays of six spatially separated sensors are now deployed with the aide of permanent towers at the host monitoring sites depicted in Figure 3. Each monitoring site is located in the mid track area on the up-wind lateral side of its targeted avalanche path (Twin Slides or Glory Bowl). Recorded data is transferred via spread spectrum radio transceivers every 45 seconds to the CPU located at the WYDOT office facility, which is approximately 16 miles away. Upon reception of data, the CPU performs sequential signal analyses, which are each designed to process data recorded at a SSAM node to target the desired slide paths.

WYDOT has made large investments in GazEx and Avalanche Guard avalanche control infrastructure with a decreased artillery presence on Teton Pass. This permits for control work to be conducted remotely and in the very early morning hours with minimum manpower. In place control infrastructure allows for more frequent missions to reduce avalanche size, decrease cleanup operations, and minimize road closure times. Typically, avalanche control missions are conducted at 0300 with extremely poor visibility and no confirmation of control work results unless avalanche debris is observed at the highway. With increased frequency in control missions, avalanche size has been greatly reduced with most missions resulting in avalanche debris stopping short of the highway. With infrasonic technology, avalanche reduction results are available in near real time at the WYDOT office and post control highway avalanche hazard can be evaluated immediately.

Similar to all forecasting and control programs, WYDOT relies on timely weather forecasting for avalanche hazard decision making. The variable mountain climate of Western Wyoming can produce unpredictable weather and avalanche conditions that force WYDOT crews into poorly planned situations. In these scenarios, infrasonic avalanche detection and alarming provides valuable information on a rapidly changing avalanche hazard. Alarming of larger natural or skier triggered slides helps facilitate a rapid response of clean up operations and highway closures.

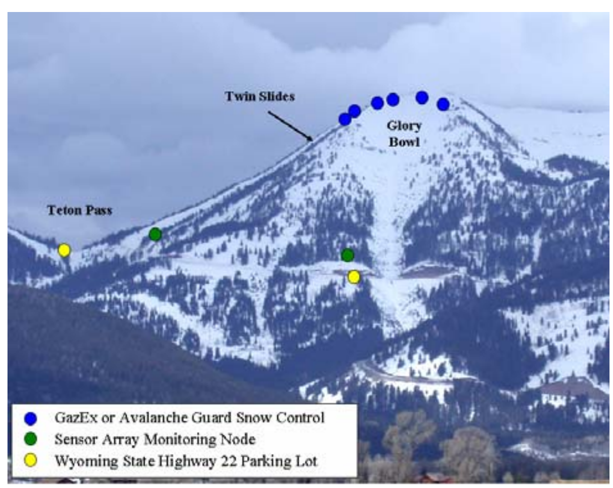

Figure 3: Finalized Teton Pass monitoring.

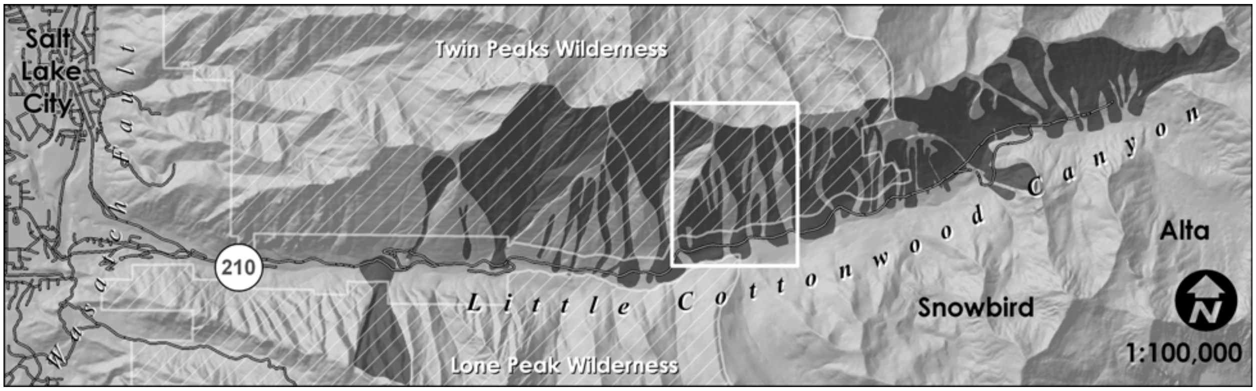

Figure 4: Infrasonic study area located in Little Cottonwood Canyon, UT.

The current Teton Pass SSAM node processing does produce occasional false avalanche classifications from various interfering signals or ambient noise. During the 2007\08 winter season, there were a total of four false classifications of Twin Slides avalanche events and one false classification of a Glory Bowl avalanche event. These erroneous results are typically interpreted correctly by avalanche technicians and adjustments investigated via post processing functionality can help to reduce future false avalanche classifications. Unfortunately, the Teton Pass meteorology (i.e. common high wind) and topography (i.e., differing aspects of Twin Slides and Glory Bowl) does not provide an adequate acoustic environment to facilitate reliable simultaneous detection of all desired avalanche-generated signals by both the monitoring nodes. Thus, processing via the DSAM nodes cannot effectively be used to improve signal classification.

4. UDOT APPLICATION

The LCC highway avalanche corridor is known to be one of the most hazardous highways in North America with just under 50 active avalanche paths in a nine mile stretch of road (Figure 4). Proximity to Salt Lake City, as well as the popularity of Alta Ski Area and Snowbird Ski Resort produces a large number of tourists and recreational users during the winter months. Access to these areas from the Salt Lake Valley is along dead end State Road 210 (SR-210), which is maintained by UDOT. Given the daily volume of traffic, steep terrain, density of avalanche paths, and abundance of snowfall, active snow avalanche paths, and abundance of snowfall, active snow avalanche control measures are common during winter months. These measures reduce the risk of natural avalanches crossing the road while open, as well as provide protection for structures at the head of the canyon during periods of instability. Management of such activities is provided by the UDOT Avalanche Safety Office and is implemented through the Town of Alta and a co-operative agreement with both ski areas. Control measures are carried out with the use of three primary artillery weapons, hand charge routes, and two GazEx exploders when deemed necessary. Travel along the canyon road, as well as travel outside of inhabited buildings, is prohibited during avalanche control work and during periods of high avalanche hazard.

The infrasonic study site lies adjacent to the highway, on a southern exposure in the LCC mid-canyon area (Figure 4). This site encompasses the run out zones of six major avalanche paths known to overrun SR-210: the White Pine Chutes (1-4), White Pine, and Little Pine (Figure 5). The study area was carefully chosen for several reasons: the density of paths, frequency of events inherent to each path, difficulty of artillery accuracy, and to achieve optimal acoustics and accessibility to the site.

Unlike the Teton Pass system, the LCC infrasound monitoring system was designed and deployed to effectively utilize processing via DSAM nodes to localize infrasound signals originating within the targeted geographic region. GPS sensors are utilized at the monitoring nodes to facilitate the precise time synchronization necessary for accurate DSAM processing. Infrasound data measured at each of the three sensor array monitoring nodes of LC-1, LC-2, and LC-3 (Figure 5) are transferred up-canyon via spread spectrum radio transceivers every 90 seconds to a CPU located at the UDOT Alta Guard Station office facility for immediate processing.

Three instances of DSAM processing provide targeting of three defined zones within the study site: Zone 1 encompasses the White Pine

Chutes using LC-3 and LC-2, Zone 2 encompasses White Pine and Little Pine using LC-2 and LC-1, and Zone 3 includes all paths using LC-3, LC-2 and LC-1 (Figure 5). Given the close proximity to the highway and amount of noise generated as such, exclusion of such information is desirable as not to confuse the system. Effective three dimensional signal source movement based pattern recognition parameters were tuned to properly classify detected signals by using data recorded and verified by forecasters during the 2006/07 season.

The initial 2006/07 season of LCC system operation was unusually void of significant snow fall and few avalanches occurred in the targeted mid-canyon region. However, a significant storm cycle in February 2007 provided the first experimental test of the deployed LCC system. Figures 6 through 11 show examples of unprecedented DSAM processing results obtained during an UDOT avalanche control mission that targeted Zone 1. For the forty minute period shown in the Figure 6 feature set, the highly correlated stationary explosive signals were classified as interference based on failure to satisfy the three- dimensional signal movement pattern recognition criterion, while five avalanche signals were successfully classified as avalanche events occurring in the targeted White Pine Chutes. Figures 7 thru 11 show the geographic

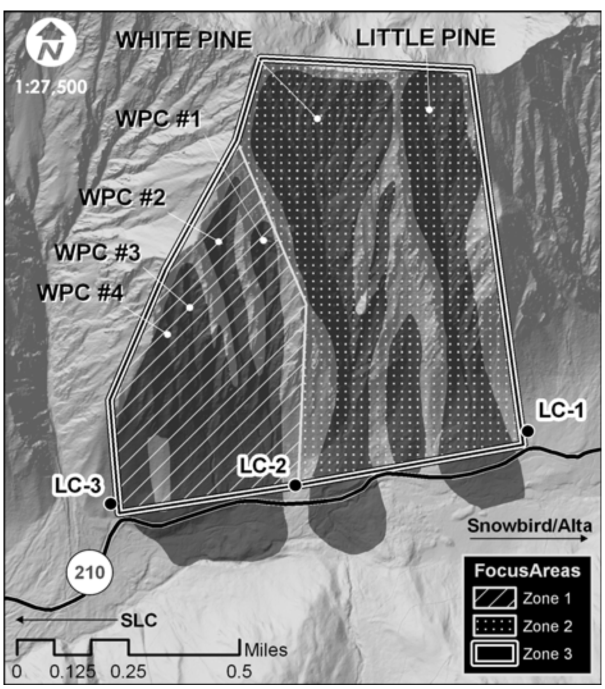

Figure 5: LCC infrasonic study site.

detection images for the five avalanche events depicted in Figure 6. Even though the events occurred in close spatial proximity, the DSAM processing provided signal source location information with enough accuracy and resolution to enable recognition of infrasound signals originating in the adjacent slide paths.

During the recent 2007/08 season, the LCC system provided many exemplary cases that stressed its significance. In the early morning hours of 1/9/2008 at the onset of a significant natural avalanche cycle, the monitoring system properly classified several detected signals as targeted avalanche events and provided early alarm notification. Previous to these observations, closure of the highway was deemed unnecessary given several factors involving the storm, previous snowfall, and snowpack stability. Shortly after this decision was made, a density inversion occurred within the new snow as a result of increased winds and precipitation intensity. Subsequently, the earlier decision to not close the highway and conduct control work was reversed and as procedures for closing the highway were being implemented, a natural avalanche from Little Pine crossed the highway. While no notable harm was done by this event, trust in the system was strengthened substantially. On several occasions the monitoring system provided critical evidence of avalanche activity occurring during control work conducted in poor visibility. Without this information, the highway may have remained closed until either substantial activity or stability was observed by forecasters and/or weather permitted visual evidence. Such prolonged closures can result in significant economic loss to ski areas and businesses in the canyon, but are necessary if snowpack instability is in question.

False classifications of detected signals as avalanche events were virtually non-existence in system results during the 2007/08 season. The DSAM processing targeting Zone 1 produced one false avalanche classification from what is suspected to be a flying object, and the DSAM processing targeting Zone 2 produced one false avalanche classification from two successive explosive signals. Also encountered were several instances where the DSAM processing targeting Zone 1 would classify avalanche signals emanating from Zone 2 as a Zone 1 avalanche event. Table 1 provides a summary of the 2007/08 season avalanches that occurred in Zones 1 and 2 and whether the detected signals were properly classified as a targeted avalanche event or erroneously classified as interference.

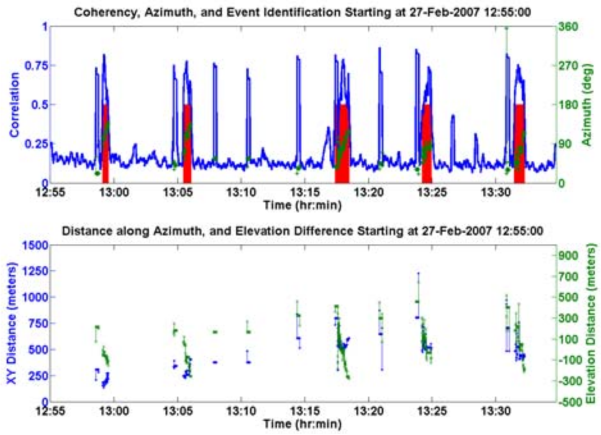

Figure 6: 2/27/07 UDOT active control feature set.

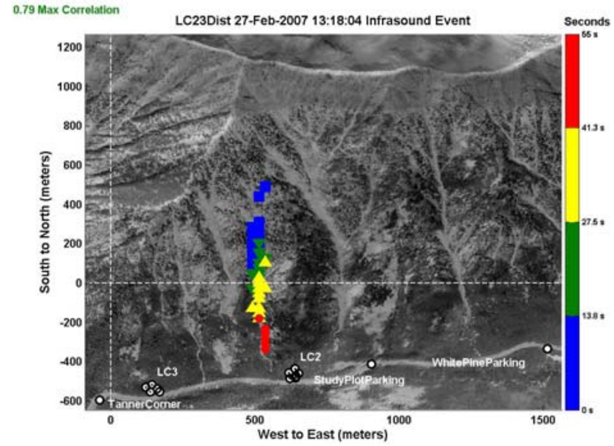

Figure 9: 2/27/07 White Pine Chute #1 event.

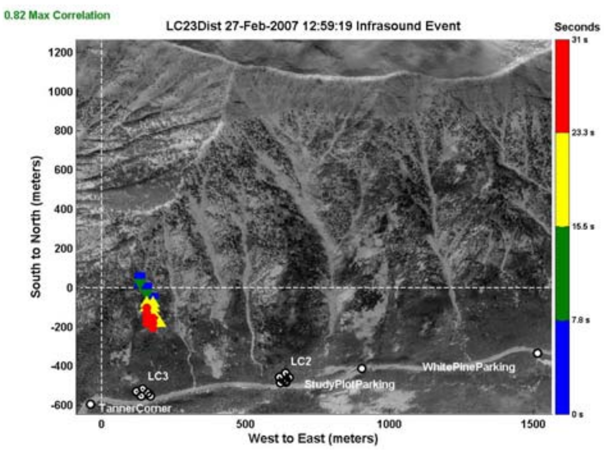

Figure 7: 2/27/07 White Pine Chute #4 event.

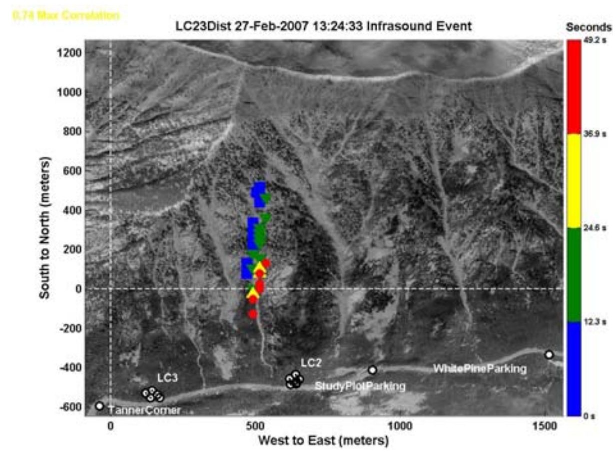

Figure 10: 2/27/07 White Pine Chute #1 event.

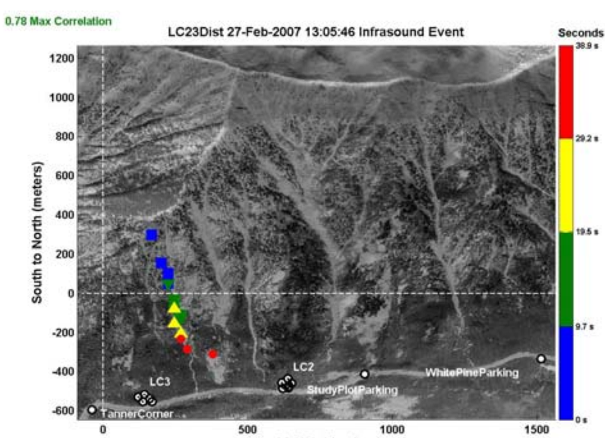

Figure 8: 2/27/07 White Pine Chute #3 event.

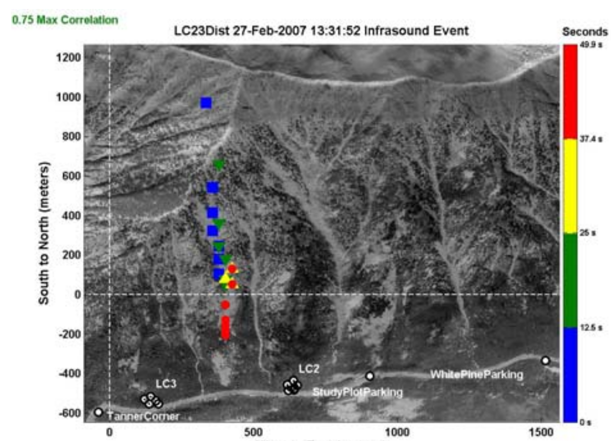

Figure 11: 2/27/07 White Pine Chute #2 event.

Table 1: Zones 1, 2 avalanche summary, 2007/08.

Processing Target	Avalanche Detections	Resultant Classification	
		Avalanche	Interference
Zone 1	49	31	18
Zone 2	51	29	22

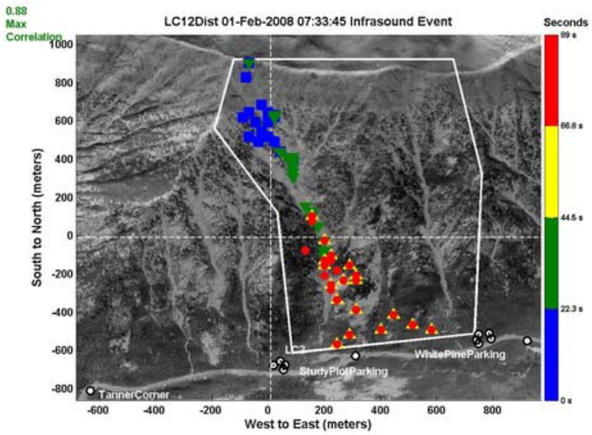

Figure 12: 2/1/08 Zone 2 White Pine event

An example of a successful avalanche classification by the DSAM processing targeting Zone 2 is shown in Figure 12. This artillery controlled class 3 White Pine avalanche exhibited a large dust cloud and deposited debris on the highway. The avalanches that were erroneously classified as interference were typically small events that did not travel far enough to meet the signal source movement pattern recognition criteria. Such avalanche events were manually recognized through user inspection and interpretation of the infrasound signals assigned to the interference classification.

While false classification of any detected avalanche signals as interference is not ideal, the signal source movement pattern recognition criteria was purposely configured to be more likely to error in this manner instead of a manner that falsely classifies detected interfering signals as avalanches. As was previously discussed, there were a total of two false avalanche classifications of detected Zone 1 and Zone 2 interfering signals. At the same time over 1100 other detected Zone 1 and Zone 2 interfering signals were properly classified as interference! Considering these facts, the performance of the two DSAM processing instances targeting Zone 1 and Zone 2 was considered adequate and as anticipated.

Not yet discussed is the performance of the DSAM processing instance that targeted Zone 3. It was found that simultaneous signal detection of small targeted avalanches by all three monitoring nodes was marginal. However, larger avalanche events did indeed result in robust signal detection and resultant reliable Zone 3 avalanche classification. As the 2007/08 progressed, the Zone 3 DSAM processing instance was more commonly used to verify that explosive ordinance both detonated and hit the desired target, while the Zones 1 and 2 DSAM processing instances were utilized for recognizing targeted mid-canyon avalanche events. Occasionally, the monitoring system was also utilized to investigate avalanche events occurring outside of the targeted mid-canyon region.

Thus far, the infrasound avalanche monitoring system has been implemented with great success in LCC and is seen as a valued utility for the applied avalanche forecasting toolbox. Given the success of this system in detecting and identifying natural and artificial avalanches as well confirmatory artillery reports, further installation in other areas along the LCC highway corridor are seen as desirable.

5. TECHNOLOGY ISSUES

Although there has been considerable success demonstrated via the WYDOT and UDOT applications, the deployed infrasound monitoring technology still has limitations and desired improvements. As in typical infrasound applications, the monitoring methodology uses ground placed porous soaker hoses in sensor waveguides that help limit the detrimental effects of localized wind. Deployment of the porous hose is problematic as the hose can be crushed in heavy or dense snow conditions, which limits the sensors ability to gather infrasound signals. Various hose configurations have been tested in the winter environment with a successful arrangement of rigid and porous hose shown in Figure 13. Providing future structural protection for critical sections of porous hose is being considered.

Even with the use of noise reducing porous hose waveguides and the correlation based beamforming algorithm that is robust to high noise environments, extreme wind noise can effectively mask sensor detection of infrasound signals; especially small signals. This is a constant challenge at the WYDOT application where the high elevation (2570 meters) of Teton Pass exposes the sensor array monitoring nodes to strong and variable mountain winds. In comparison, the UDOT sensor array monitoring nodes are located near the floor of LCC, which provides more forgiving calm winds.

Figure 13: Typical sensor waveguide of hoses.

While large avalanches do generate infrasound signals that propagate vast distances, it is believed that sensor array monitoring nodes must be place in close proximity to the targeted slide paths for effective use in practical applications where information regarding small avalanche events is desired. The sensor array monitoring nodes must also be situated with a proper relative orientation to the targeted slide paths to ensure adequate location estimates for the signal source movement based pattern recognition technique to work effectively. Thus, the technology must be deployed in a custom fashion as allowed and dictated by each particular application. This can be cost prohibitive depending on terrain and size of the avalanche monitoring area.

Another newly encountered problematic situation exposed by the UDOT application is the existence of simultaneous infrasound signals emanating from differing locations. Such multi-path signal scenarios are common in LCC when various entities are performing snow control measures at the same time, and it is common for nearly simultaneous explosive and or avalanche signals to originate within the targeted monitoring region. Even during natural avalanche cycles there were often sympathetic events resulting in simultaneous avalanche signals. Not surprisingly, the largest signal encountered in such multi-path scenarios dominates processing and can confuse signal classification techniques.

Information of avalanche run out distance and precise location of avalanche debris is valuable in highway applications and for estimating avalanche size and classification, but such information has not always been readily available in near real-time monitoring results and can be difficult to ascertain from manual driven post processing results. It is hypothesized that the elongated nature of an avalanche creates a multi-path signal scenario for which larger signals originating higher in the avalanche track supersede smaller signals originating near the debris pile and hence locations estimates are assigned away from the where the avalanche eventually terminates. Complicating this is that certain parts of an avalanche track appear to be more or less conducive to generating infrasound signals due to physical differences of the track.

6. CONCLUSIONS

In addition to the ability to identify naturally occurring avalanche activity, both the UDOT and WYDOT monitoring systems have demonstrated the capability to provide verification of explosive avalanche hazard mitigation activities. It is clear that the systems ability to provide confident knowledge of both whether explosive control work *does* or *does not* create avalanches is highly valued. Similarly, the ability of the systems to confirm the detonation of explosives and whether launched ordinance actually hits the desired target was repeatable proven valuable. As such the WYDOT and UDOT infrasound monitoring systems are now considered viable operational tools that are relied upon.

Since the WYDOT Teton Pass system uses SSAM node processing to target a desired slide path, the signal source movement based pattern recognition is limited to the estimated azimuth angle of the infrasound signals. This produces inferior results to the UDOT LCC situation where DSAM node processing is utilized, which allows the signal source movement based pattern recognition classification technique to be applied to three-dimensional location estimates of detected infrasound signals.

It is now easy to conclude in a defensible manner what has long been suspected; Utilization of signal source movement based pattern recognition on location estimates derived from properly sited and time synchronized DSAM nodes virtually eliminates all occurrences of falsely classifying detected interfering signals as targeted avalanche events! However, this capability is balanced by the fact that there certainly will be some false classifications of short traveling avalanche events as interference. Still, the longer traveling avalanche events will likely be properly classified. This type of cumulative system performance does indeed provide high confidence in the reliability of detected signals that are classified as targeted avalanche events.

7. ACKNOWLEDGEMENTS

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