State of Wyoming
Department of Transportation

U.S. Department of Transportation
Federal Highway Administration

FINAL REPORT

FHWA-WY-09/02F

PRACTICAL OPERATIONAL IMPLEMENTATION OF TETON PASS AVALANCHE MONITORING INFRASOUND SYSTEM

By:

Inter-Mountain Laboratories, Inc.
555 Absaraka Street
Sheridan, WY 82801

December 2008

Notice

This document is disseminated under the sponsorship of the U.S. Department of Transportation in the interest of information exchange. The U.S. Government assumes no liability for the use of the information contained in this document.

The contents of this report reflect the views of the author(s) who are responsible for the facts and accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the Wyoming Department of Transportation or the Federal Highway Administration. This report does not constitute a standard, specification, or regulation.

The United States Government and the State of Wyoming do not endorse products or manufacturers. Trademarks or manufacturers' names appear in this report only because they are considered essential to the objectives of the document.

Quality Assurance Statement

The Federal Highway Administration (FHWA) provides high-quality information to serve Government, industry, and the public in a manner that promotes public understanding. Standards and policies are used to ensure and maximize the quality, objectivity, utility, and integrity of its information. FHWA periodically reviews quality issues and adjusts its programs and processes to ensure continuous quality improvement.

Report No. FHWA-WY-09/02F	Government Accession No.	Recipients Catalog No.
Title and Subtitle Practical Operational Implementation and Evaluation of Teton Pass Avalanche Monitoring Infrasound System		Report Date December 2008 Performing Organization Code
Author(s) Ernie Scott		Performing Organization Report No.
Performing Organization Name and Address Inter-Mountain Laboratories, Inc. 555 Absaraka Street PO Box 4006 Sheridan, WY 82801		Work Unit No. RS06(206) Job No. B53E Contact or Grant No.
Sponsoring Agency Name and Address Wyoming Department of Transportation 5300 Bishop Blvd. Cheyenne, WY 82009-3340 WYDOT Research Center (307) 777-4182		Type of Report and Period Covered Final May 2006 – December 2008 Sponsoring Agency Code
Supplementary Notes WYDOT Technical Contact: James Montuoro, P.E.; Jamie Yount		

Abstract

Highway snow avalanche forecasting programs typically rely on weather and field observations to make road closure and hazard evaluations. Recently, infrasonic avalanche monitoring technology has been developed for practical use near Teton Pass, WY to provide another tool for Wyoming State Highway 22 technicians in their operational forecasting and decision making. The technology detects low frequency sound waves produced by avalanches with automated near real-time processing provided to facilitate an alarm. Monitoring system operation provides information to confirm results from avalanche control work, notification of 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 WYDOT operates in its mission to provide a safe and efficient transportation route.

Key Words: Wyoming, Teton Pass, infrasound, infrasound monitoring, avalanche, avalanche monitoring, sensor, sensor array, acoustic energy, Jackson, infrasonic		Distribution Statement Unlimited	
Security Classif. (Of this report) Unclassified	Security Clasif. (Of this page) Unclassified	No. of Pages 33	Price

Form DOT F 1700.7 (8-72) Reproduction of form and completed page is authorized.

S1* (Modern Metric) Conversion Factors

Approximate Conversions from S1 Units

Symbol	When You Know	Multiply By	To Find	Symbol
Length				
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
Area				
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
Volume				
ml	milliliters	0.034	fluid ounces	fl oz
1	liters	0.264	gallons	gal
m^3	cubic meters	35.71	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
Mass				
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg	megagrams	1.103	short tons (2000 lbs)	T
Temperature (exact)				
°C	Centigrade temperature	1.8 C + 32	Fahrenheit temperature	°F
Illumination				
lx	lux	0.0929	foot-candles	fc
cd/m^2	$candela/m^2$	0.2919	foot-Lamberts	fl
Force and Pressure or Stress				
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	pound-force per square inch	psi

Approximate Conversions to SI Units

Symbol	When You Know	Multiply By	To Find	Symbol
Length				
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
Area				
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yards	0.836	square meters	m^2
ac	acres	0,405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
Volume				
fl oz	fluid ounces	29.57	milliliters	ml
gal	gallons	3.785	liters	1
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
Mass				
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lbs)	0.907	megagrams	Mg
Temperature (exact)				
°F	Fahrenheit temperature	5(F-32)/9 or (F-32)/1.8	Celsius temperature	°C
Illumination				
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	$candela/m^2$	cd/m^2
Force and Pressure or Stress				
lbf	pound-force	4.45	newtons	N
psi	pound-force per square inch	6.89	kilopascals	kPa

ACKNOWLEDGMENTS

Thanks are extended to the United States National Science Foundation (NSF) for providing concurrent and matching Small Business Innovative Research Phase II\IIb funds (award 0449731) to complete significant technical development tasks, which refined and greatly improved practical operation of the Teton Pass avalanche infrasound monitoring system. An added Utah Department of Transportation (UDOT) funded practical application of the infrasound monitoring technology in Little Cottonwood Canyon near Salt Lake City has also provided a stimulus for further critical technological advancements that have benefited Teton Pass efforts. The symbiotic relationship between the NSF, UDOT, and Wyoming Department of Transportation (WYDOT) funded projects has had an immensely positive overall impact.

Additional gratitude is extended for the support offered from the Bridger-Teton National Forest, Bridger-Teton Avalanche Information Center, and the University of Wyoming Electrical and Computer Engineering Department. Of particular note is that Timothy J. Colgan received a Master of Science degree from the University of Wyoming Electrical and Computer Engineering Department via using project efforts to facilitate completion of required thesis research. Results from these academic efforts are actively being applied to the benefit of WYDOT and UDOT infrasound monitoring operations.

Finally, special thanks are extended to WYDOT employees Ted Wells, Jim Montuoro, Michael Patritch, Tim McDowell, Galen Richards, Mike Lance, and Jamie Yount for providing support that has been instrumental to the project.

EXECUTIVE SUMMARY

Teton Pass snow avalanche occurrences impact Wyoming State Highway 22 (WY-22), which can detrimentally affect local economics and the welfare of the traveling public. Highway snow avalanche mitigation programs typically rely on weather and field observations to make road closure and hazard evaluations. During conditions that prevent visual observation, reliable automated early notification of natural and control triggered avalanche events would minimize necessary response time and assist with operational planning, supporting WYDOT's mission to provide a safe and efficient Teton Pass transportation route.

Spurred by promising results from National Oceanic and Atmospheric Administration research studies, WYDOT research project RS07(203) began in 2003 with a goal of developing a practical infrasound monitoring system to target Teton Pass avalanche activity that threatens WY-22. The technology is based on the fact that avalanches produce sub audible acoustic energy in a relatively noise free band of the infrasound spectrum. Such low frequency infrasound signals propagate away from the avalanche source, which allows for continuously operating monitoring equipment to be placed at locations that are not harmed by avalanches.

During the initial WYDOT research project, difficulties were encountered establishing a Teton Pass infrasound monitoring solution that did not suffer excessive false positive avalanche identifications associated with interfering signal sources and ambient noise. A concurrent NSF funded research project resulted in sensor array technical advancements, which were applied at Teton Pass to show the feasibility of deploying a practical tool that provides information to confirm results from avalanche control work, alarming from natural avalanche events, and verification of explosive detonations. At the conclusion of the initial WYDOT research project, a working methodology had been demonstrated via a basic near real-time infrasound monitoring system prototype. However, the novel prototype monitoring system required further refinements to enable transferring the technology to the authority of WYDOT personnel.

The primary objective of this project, which commenced in 2006, was to refine the prototype Teton Pass infrasound monitoring system to create a reliable final form that is easily operated and maintained by WYDOT personnel, while minimizing annual budget expenditures. A critical project task was finalizing the location, configuration, and installation of remote sensor array monitoring nodes that target avalanche activity occurring in the Twin Slides and Glory Bowl slide paths. Also critical was the development of thorough monitoring system documentation and associated training of WYDOT personnel. The project also provided a bridge for incorporating the technology into practical WYDOT operations by facilitating operation of the Teton Pass monitoring system for the winters of 2006/2007 and 2007/2008.

In addition to the specific achievements of this WYDOT Project, the continuing concurrent NSF project enabled significant development of the monitoring system capabilities, and an additional UDOT practical application showed that utilization of the technology could successfully be transferred to new locations. Thus, success has been achieved in deploying infrasound monitoring technology in a manner that provides a practical tool for assessing highway avalanche hazard, changing the way WYDOT and UDOT operate in their mission to provide safe and efficient transportation routes.

TABLE OF CONTENTS

Chapter **Page Number**

LIST OF FIGURES

CHAPTER 1

PROBLEM DESCRIPTION

Wyoming State Highway 22 (WY-22) is one of the most heavily used highways in Wyoming due to such devise factors as:

- Commuter traffic necessary to support service industries in Jackson Hole.
- Tourism.
- Recreational use.

Snow avalanche activity near Teton Pass frequently impacts WY-22 with the two most active and problematic slide paths being 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 WY-22. Such snow control activities reduces the frequency and size of hard to predict naturally occurring avalanches, which improves the safety of those utilizing the highway, while also minimizing costly WY-22 closures that have a significant impact on the local economy.

The WYDOT Teton Pass avalanche mitigation program has traditionally relied on weather and field observations to make avalanche hazard evaluations for incorporating into WY-22 closure decisions. However, visual observations are not always possible, so avalanche hazard evaluations would benefit from an automated continuously operating monitoring system, which can detect and identify Teton Pass avalanche activity that threatens WY-22. Such a system would provide early notification of naturally occurring avalanches and verification of explosive avalanche hazard mitigation activities, which would assist decision making and accelerate appropriate responses (e.g. WY-22 closure, clean-up activities, avalanche hazard mitigation activities, emergency search and rescue efforts, etc.).

Preliminary research conducted by National Oceanic and Atmospheric Administration (NOAA) scientists showed that avalanches release acoustic energy in a relatively noise free band of the sub-audible infrasound frequency spectrum (Bedard, Greene, Intrieri, & Rodriguez 1988). Such, avalanche-generated infrasound signals propagate away from the slide path of origin, which allows for infrasound signal detection to be performed at locations unaffected by the source avalanche activity (Bedard, 1989). Therefore, modern sensing, data acquisition and computing technologies hold promise for the development of continuously operating monitoring systems that automatically identify avalanche activity without the need to be manually reset (Bedard, 1994).

As a result of these early studies, NOAA spurred subsequent research efforts focused on a general goal of developing infrasound monitoring technology for use by professionals charged with maintaining transportation avenues that are affected by avalanche activity (Comey, & Mendenhall, 2004). Initial monitoring system development efforts focused on sensing methodology that utilized a single remote monitoring node comprised of a single infrasound sensor. Data acquired from the single sensor remote monitoring node was then transferred to a central processing unit (CPU) where the capability to positively identify avalanche activity was demonstrated (Scott, & Lance, 2002).

Such positive results in part lead to WYDOT research project RS07(203) “Infrasonic Monitoring of Avalanche Activity on Teton Pass”, which investigated the practical operational value and use of an automated near real-time infrasound monitoring system to target Teton Pass avalanche activity that threatens WY-22. The initial Teton Pass infrasound monitoring system was comprised of a CPU at the local WYDOT office, wireless data communications, and a distributed network of single sensor monitoring nodes. However, it was discovered that this system configuration suffered excessive occurrences of false positive and false negative avalanche identifications due to the variability of encountered infrasound signals (e.g. signal amplitude, interfering sources) and the variability of ambient noise levels (Scott, Hayward, Kubicheck, Hamann, & Pierre, 2004).

Fortunately, concurrent project support from the National Science Foundation (NSF) allowed for investigations into whether theoretical data processing advantages offered by the use of arrays of infrasound sensors could resolve encountered problems. It was indeed found that the use of sensor arrays improved the ability to detect infrasound signals in poor signal/noise environments, while also providing improved reliability in identifying targeted avalanches due to being able to exploit additional inherent information regarding the source location of detected infrasound signals (Scott, Hayward, Kubicheck, Hamann, Pierre, Comey, & et al., 2007). Application of these sensor array technological advancements were implemented and extensively tested through operation of the Teton Pass infrasound monitoring system. By deploying sensor arrays at properly located remote monitoring nodes, it was shown (Scott, Colgan, Hayward, Kubicheck, Hamann, Pierre, & et al., 2006) that it is feasibly to set up a practical infrasound monitoring system, which provides valuable information regarding the following:

- Natural avalanche activity.
- Verification of avalanche hazard mitigation results (i.e. whether desired avalanches are or are not released).
- Verification of avalanche hazard mitigation explosive detonations (i.e. whether explosive ordinance does or does not detonate).

At the conclusion of the initial WYDOT research project, an advanced prototype version of an automated near real-time infrasound monitoring system, which targeted Teton Pass avalanche activity that threatens WY-22, was nearly complete (Scott, 2005). However, there were still several issues that needed to be addressed in order to fully meet the overall project objective of deploying a practical system for operational use by WYDOT personnel. These issues were successfully resolved with the efforts of the present project and the NSF investigations.

Appendix A provides a theoretical discussion of the concept that was followed to fulfill implementation of the infrasound monitoring system.

CHAPTER 2

OBJECTIVES

The primary objective of this project was to refine the previously developed prototype Teton Pass infrasound monitoring system and turn it into a reliable system that is easily operated and maintained by WYDOT personnel, while minimizing required annual budget expenditures. A group of subset objectives was devised in order to facilitate meeting this overall project objective.

Finalize system configuration

Past Teton Pass activities included the deployment of infrasound sensors in a variety of differing configurations at a variety of monitoring sites. It was no longer necessary to experiment with these system parameters, and appropriate permanent remote sensor array monitoring node (RSAMN) locations and refined configurations could be recommended.

Improve remote sensor array monitoring node installations and maintenance

Previous experimental Teton Pass efforts had utilized temporary RSAMN installations to facilitate investigations. These RSAMN installations lacked equipment mounting structures necessary to provide permanence and ease of maintenance. Since finalized RSAMN sites and configurations were being recommended, permanent equipment mounting structures and standardized maintenance procedures could be implemented.

Mitigate infrasound signal degradation issue

Prior operation of the prototype system had shown that the utilization of sensor arrays could provide a reliable method for identifying targeted avalanche activity that impacts WY-22. However, these efforts also exposed a potential failure scenario related to degradation of recorded infrasound signal quality as a winter season progresses. As is common in infrasound monitoring, pneumatic spatial wind noise reducing filters constructed of solid and porous hose have been used as a wave guide between the infrasound sensor and the atmosphere. Icing and crushing of the porous hose sections and crushing of the solid hose sections were observed as potential causes of the experienced infrasound signal degradation. Such problems effectively impede infrasound signal propagation through the wave guide and result in a degradation of detected signal quality and associated signal analyses results. It was hypothesized that deep snow pack, which is allowed to cover the infrasound sensor, is at the root of this problem. Thus, these issues had to be mitigated to provide a stable infrasound monitoring solution that could last through an entire winter season.

Provide system documentation and training to WYDOT personnel

Throughout the project's history, there were continual research and development activities that resulted in frequent heuristic changes to the technology as it matured into the prototype system. Such ever changing experimental progression created a problematic situation for developing system documentation and associated training of WYDOT personnel on operation and usage. Since the technological development tasks were being concluded and the permanent installation of a refined system was being facilitated, dedication of significant resources to documentation and training efforts was warranted.

Provide two seasons of operational support
Even though technological research and development efforts were being concluded, it was understood that the existing prototype system was going to undergo significant changes during the process of establishing a permanent refined system configuration. During this transitional period, it was not realistic to expect that WYDOT personnel could provide all necessary maintenance for continued system operation; especially since thorough documentation and personnel training had yet to be completed. While many complex technical components were contained in the prototype system, a goal was set to have the refined system deployed in a stable easy to use and maintain final form upon successful facilitation of two winter seasons of operation. After which, continued system operation would only require minor annual maintenance by properly trained WYDOT personnel.

Minimize required annual maintenance costs
In order to successfully transfer the deployed refined system into practical WYDOT operations, it was clearly understood that requisite annual maintenance costs could not be excessive. Meeting this goal would require minimizing system complexity, while empowering WYDOT personnel to facilitate routine system maintenance that had previously been performed by the skilled technicians and engineers that were responsible for project research and development efforts.

CHAPTER 3

TASK DESCRIPTION

Facilitating the deployment of a refined Teton Pass infrasound monitoring system required following a seasonally dictated time frame to implement the tasks necessary to achieve project objectives. Activities in the spring included evaluating the previous winter's operational results, while also decommissioning the system for non-operational storage across the summer. The summer was occupied by activities required to prepare for the fall activities, which ensured that the system was operational for the ensuing winter season. Winter months were focused on operation and evaluation of the system. Regardless of the season, numerous associated NSF supported development tasks were completed and integrated into it. While efforts to train WYDOT personnel on system use and maintenance occurred throughout the project, critical system documentation efforts were not achieved until the end of the project after two years of operational support was completed.

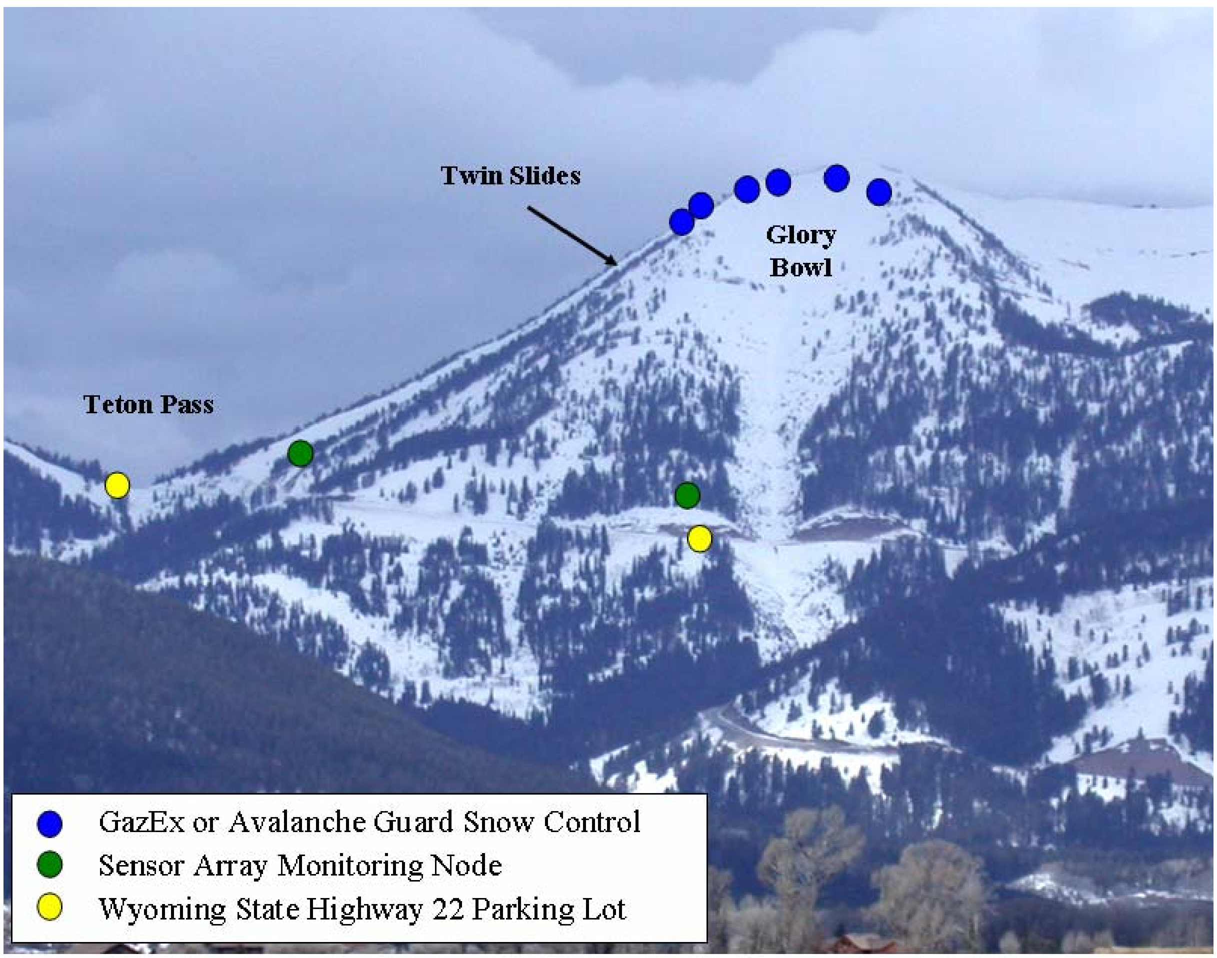

Figure 1. Teton Pass Monitoring Setting

Prepare to finalize remote sensor array monitoring nodes

Preparations necessary to deploy the required RSAMN sites in a permanent refined configuration began in June 2006. The previously deployed temporary experimental RSAMN's utilized to implement the prototype system were removed to prepare for the refinement. Decisions regarding the ultimate configuration of the refined system had to be made prior to making the RSAMN's operational for the 2006/2007 winter season.

Preceding research and development activities had clearly shown that results obtained from the processing of data recorded at multiple distributed RSAMN sites are superior to results obtained from the processing of data recorded at only a single RSAMN site (Yount, Naisbitt, Scott. 2008). Experimental results also repeatedly showed that avalanche-generated infrasound signals originating from Glory Bowl could not be consistently detected at a RSAMN located next to Twin Slides, and likewise; avalanche-generated infrasound signals originating from Twin Slides could not be consistently detected at a RSAMN located next to Glory Bowl (Scott, 2005). As a consequence of these facts, an additional RSAMN site would have to be deployed near each of the two targeted slide paths to be able to implement effective processing of data recorded at distributed RSAMN sites. Considering this, a decision was made to design a refined system configuration that forgoes an attempt to facilitate processing of data recorded at distributed RSAMN sites, which effectively minimized complexity and associated annual maintenance costs.

Shown in Figure 1 is the targeted Teton Pass monitoring region and the locations that were selected to deploy the permanent refined RSAMN sites. A six sensor RSAMN targeting avalanche activity in Twin Slides was installed at the consistently used site that resides on the road cut between Upper Twin and Lower Twin. A six sensor array monitoring node targeting avalanche activity in Glory Bowl was installed at a recently used site that resides on the road cut to the west of Glory Bowl

Each RSAMN site was placed at an easy to access location near the mid track area on the up-wind lateral side of its targeted slide path (Twin Slides or Glory Bowl). These mid track sites provide an ideal scenario for maximizing the likelihood that the processing using data recorded at a single RSAMN will properly classify detected infrasound signals as either a positively identified targeted avalanche event or a discriminated interfering event. This is because the signal classification methodology is based upon the deterministic movement of a targeted avalanche event, which can be recognized through the acute variance in the distribution of azimuth angles of arriving infrasound signals that will be encountered during a targeted avalanche event, which is unlikely to be mimicked by interfering infrasound signal sources (Scott, 2005).

According to practical and necessary requirements, appropriate installation plans were designed and specified to deploy 20 ft (6.1 m) tall mounting towers at the RSAMN sites. The ability for the towers to withstand snow glide, snow creep, and solar panel wind loading were critical design parameters. Since it is desirable to prevent tower failure for a worst case scenario, hefty steel towers with sturdy bases were specified. A new tower was purchased for the Twin Slides RSAMN site, and an existing Teton Pass WYDOT tower was salvaged for the Glory Bowl RSAMN site.

While the two towers had slightly different design specifications, both towers required a short tower section to be set in a plumb concrete footer base with two 10 ft (3.05 m) tower sections attached in sequence. Each tower base footer section was specified to be set in an approximately 4 ft (1.22 m) deep by 4 ft (1.22 m) square hole. Construction of the tower base was specified to require around 3 yd^3 (2.25 m^3) of concrete along with rebar spaced at 1 ft (0.305 m) intervals in each direction.

Prior Teton Pass monitoring efforts were completed under the authority of a Bridger-Teton Forest special use permit that allowed temporary establishment of RSAMN sites, which expired at the beginning of this project. With the assistance of WYDOT personnel, a United States Forest Service (USFS) permit was pursued to establish permanent RSAMN sites. Also undertaken was required logistical planning and supplies procurement (e.g. towers, annual consumables, upgrades) to realize the RSAMN sites, which included the service of a helicopter for tower construction.

Install mounting structures at remote sensor array monitoring nodes

Efforts to complete this task were delayed due the amount of time that it took to obtain the required USFS permit. Unfortunately, the USFS permit was not issued until the end of September, 2006. As a result, serious set backs were incurred in the planned timing for RSAMN installation and associated subsequent tasks (e.g. central processing unit deployment, training, seasonal system operation).

After the required USFS permit was obtained, the holes required to facilitate the concrete tower footer bases were manually dug. Per a requirement of the USFS permit, the towers and associated mounting brackets were painted green. A locally stationed helicopter facilitated transportation of the tower sections and necessary construction materials. After framing of the footers was completed, the concrete tower bases were poured. Again helicopter services were utilized to transport the concrete to the RSAMN sites. Due to a valiant effort from the construction crew, cured bases were ready to stand the mounting towers upon the last week of October, 2006.

It was planned to utilize helicopter services to assist in standing of the towers. However, the pilot of the locally stationed helicopter was fired shortly after the concrete pour was completed, so helicopter services were no longer a viable option. Since inclement winter weather was pending, completion of the tower installations and all other subsequent associated work plan tasks were in serous jeopardy. Fortunately, WYDOT personnel assisted in devising and facilitating an alternative method to erect the towers.

For each tower, the bottom tower section was manually stood on the tower base. A gin pole borrowed from the Casper WYDOT office was then used to manually hoist and place the upper section of each tower. While this was a difficult and dangerous process to perform in steep mountainous terrain during stormy weather, construction of the towers was completed the first week of November, 2006.

Install remote sensor array monitoring node instrumentation

Even though installation of RSAMN instrumentation was delayed due to the tower construction set backs, preparatory activities for this task began in August, 2006. RSAMN instrumentation that was retrieved in June, 2006 was put through quality control checks and refurbishment to ensure proper operation upon subsequent re-deployment. In an effort to prevent animal damage and unintentional installation caused damage, previously utilized infrasound sensor cables were replaced using a type of signal cable that provides a more durable outer casing and less memory.

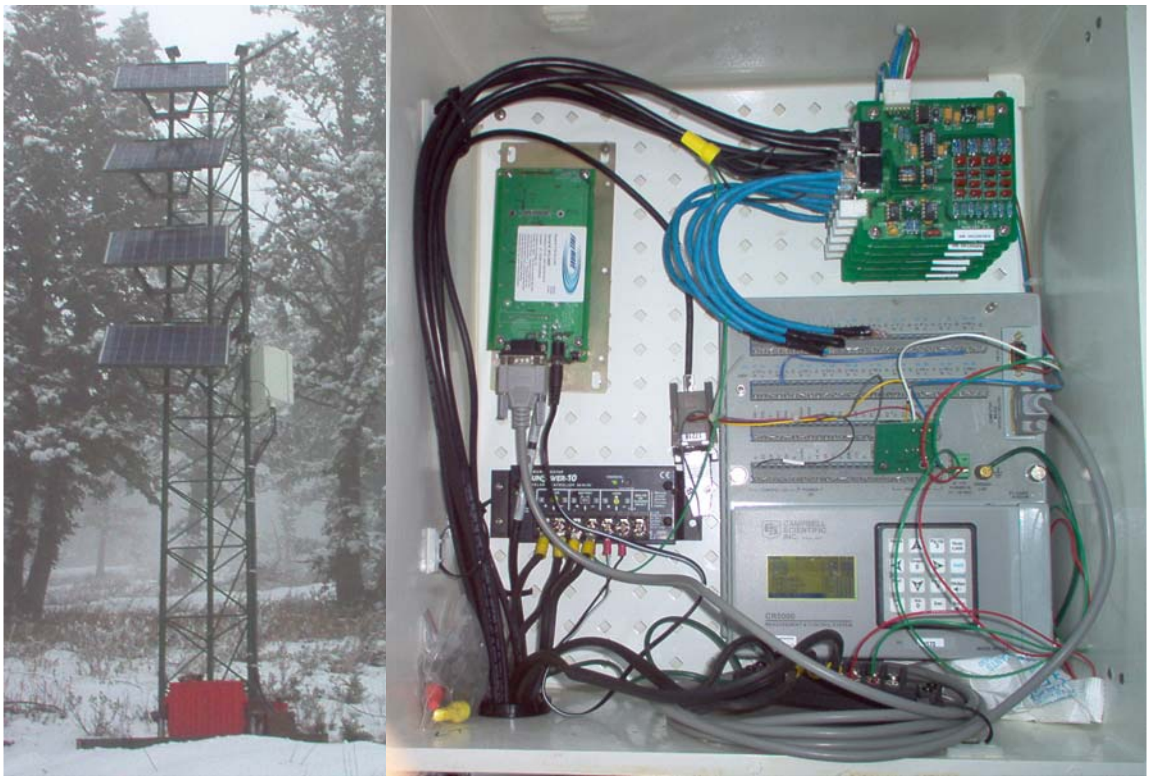

Figure 2. Twin Slide RSAMN Tower and Outdoor Instrument Enclosure

After the tower installations were completed, necessary instrumentation was installed in a similar manner at each RSAMN and made operational during the inclement winter weather conditions of the first week of November, 2006. Figure 2 shows critical components of the fully installed and operational Twin Slides RSAMN, which is analogous to the Glory Bowl RSAMN.

Many items were mounted at the tower with the intent that they would permanently reside at the RSAMN site without the need for annual retrieval and re-deployment, which had been a time consuming and costly endeavor during previous project efforts. These RSAMN items include:

- Solar panels with cabling.
- 12 Volt deep cycle battery bank.
- Wireless data communications antenna with cable.
- Global positioning receiver with cable.
- Outdoor instrument enclosure.
- Conduit to protect infrasound sensor cables and battery cables.

The outdoor instrument itself protects several sensitive electronic components in a weather proof manner. These RSAMN items include:

- Solar charging regulators.
- Wireless data transceiver.
- Datalogger.
- Infrasound sensor interface circuit cards (bank of 6).
- Efficient precision five volt regulator circuit.
- Instrument interconnection cabling.

The section of infrasound sensor cables and battery cables that were run between the outdoor instrument enclosure and the ground were enclosed in conduit to alleviate potential strain caused by the snow settlement that is encountered throughout a winter season. The remaining length of each infrasound sensor cable was laid on the ground as it was stretched out to the appropriate location of the infrasound sensor that was placed near ground level and allowed to be covered by snow.

Each infrasound sensor was placed on an elevated platform to protect electronics from potential water intrusion damage. Electronic infrasound sensor gain settings were increased in an effort to mitigate the infrasound signal degradation issues that were previously encountered during operation of the prototype system. Also attempted as mitigation to the infrasound signal degradation issues was altering how the solid and porous hose sections of the infrasound sensors pneumatic spatial wind noise reducing filters were deployed

As is shown in Figure 3, the configuration of the hoses connected to each of the four infrasound sensor ports differs. The infrasound sensor port connected directly to the single section of coiled porous hose was done as an attempt to provide a failsafe infrasound signal path, since it was speculated that the extra rigidity provided by stacking coils of the porous hose could mitigate the potential of the porous hose being crushed or flattened. It is suspected that the porous hose material itself encourages the formation of ice, which impedes the infrasound signal. In an effort to prevent ice from forming, various sections of the porous hoses were wrapped in poly tubing with the idea that the infrasound signal would penetrate the poly tubing while the poly tubing itself will provide a barrier for the bonding of ice to the porous hose material. Another alteration was the use of durable, light weight, and flexible PVC conduit material to facilitate crush and kink proof solid hose sections.

At the conclusion of the prior WYDOT research project, there were many implementation recommendations related to desired improvements in the manner of deploying the RSAMN hardware (Scott, 2005), which would greatly advance maintenance ease, while reducing the time spent on such activities. The concurrent NSF funded project efforts had facilitated these development desires, so that their benefits were incorporated into the refined RSAMN installations.

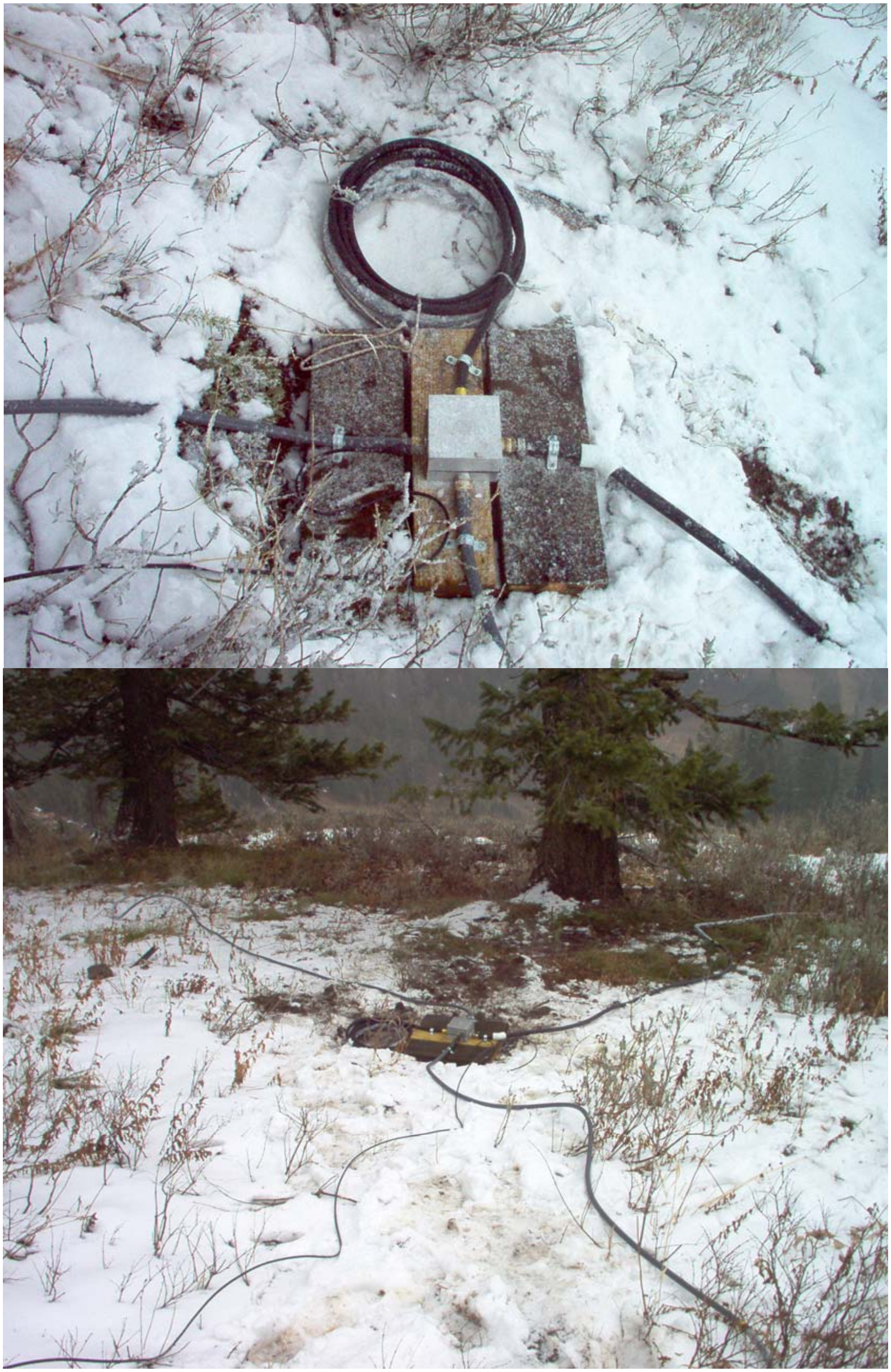

Figure 3. Deployed Infrasound Sensors

Install central processing unit at WYDOT office

Installation of the refined CPU at the local WYDOT office near Hoback Junction was initiated in conjunction with the October/November, 2006 RSAMN installations. Most core CPU components from the prototype system were again utilized to implement the CPU for the refined system. These components include the following:

- Computing hardware and operating system.
- Wireless data transceiver with communications antenna and cabling.
- Uninterruptible power supply.
- Datalogger utility software.

In addition to facilitating routine computer operating system updates, upgraded versions of the CPU's graphical user interface (GUI) software package and the signal processing software package were installed at this time. At the conclusion of the prior WYDOT research project, there were many implementation recommendations related to wanted improvements of the GUI software and signal processing functionality (Scott, 2005). The concurrent NSF funded project efforts was largely focused on facilitation these development desires, and the achieved progress toward these goals was incorporated into the refined CPU via the software upgrade efforts.

In conjunction with these software upgrade tasks, the GUI software package and associated signal analyses were configured to provide operation that would be consistent with the refinements that had been made to the RSAMN's. Configuration of the signal analyses that targeted identifying avalanche activity occurring in Twin Slides and Glory Bowl required a decision to be made regarding the tolerance of acceptable false positive and false negative avalanche identification rates. At the time of CPU installation, the signal analyses event classification properties were configured in a manner that was expected to eliminate nearly all false positive avalanche identifications caused by interfering signal sources. A consequence of this was that it was expected that some small avalanche events, which do not come close to reaching WY-22, would result in false negative avalanche identifications, so an attempt was made during the signal analyses configuration process to minimize this possibility without jeopardizing the desire to eliminate all false positive identifications of targeted avalanche events.

Another assignment that was successfully accomplished during the CPU installation was to network the computing platform with the internet, so that remote system access could be implemented to facilitate support of project activities. Achieving this was critical, because project development members were no longer going to be stationed in the Jackson Hole area, and the remote CPU internet access provided an adequate means to utilize, upgrade software components, troubleshoot, and maintain the refined system from afar.

Proposed software help documentation and WYDOT personnel training associated with this task were not addressed until December, 2006. Upon commencing GUI software help documentation efforts, it became apparent that some of the GUI software features exhibited poor organization and reliability. At that time, a decision was made to thoroughly address the major problems with the GUI software prior to completing software help documentation. Thus, initial CPU training efforts were delayed until the end of January, 2007. While this delay was regrettable, it resulted in upgraded GUI software containing expanded functionality that was significantly more user friendly and bug free. Also, comprehensive help documentation was incorporated into the GUI software. In addition to providing a general overview into the application of infrasound monitoring for avalanche identification, this help documentation completely details all features and functionality of the GUI software. Initial training of pertinent WYDOT personnel on the use of the CPU GUI software was completed at the local WYDOT office during the second week of February, 2007.

Provide seasonal support services

Turnkey support services were provided for the maintenance and operation of the refined system across the 2006/2007 and 2007/2008 winter seasons. In order to facilitate practical hands-on training, WYDOT personnel were included in pertinent activities that were completed in this time frame. Facilitating these seasonal support services also provided a means to evaluate and quantify the annual maintenance and cost requirements that will be required for continued future WYDOT operation of the refined system. Routine seasonal support activities that were provided included the following:

- Decommissioning of system for non-operational summer storage.
- Quality control checks of infrasound sensors prior to fall re-installation.
- Annual consumables procurement and subsequent fall installation.
- Installation of available CPU software upgrades.
- Practical utilization of the system during WYDOT Teton Pass winter operations.

Shortly after the CPU was installed for the 2006/2007 winter season, the computing hardware failed due to a hard drive failure that was caused by a graphics card overheating when its cooling fan quit working. To correct this problem, a new and superior computer was procured and installed at the CPU. This required all pertinent software packages to be installed on the new computing platform.

The project delays encountered going into the 2006/2007 winter season contributed to a need to provide frequent support services to ensure proper utilization and interpretation of system results for inclusion into WYDOT operations. While more autonomous WYDOT system usage was desired, this goal continued to be strived for through the continued concurrent NSF development efforts that provided regular GUI software improvements and signal processing improvements that were routinely incorporated into the CPU during the 2006/2007 winter season.

Also periodically facilitated was altering of CPU software signal analyses configuration parameters to respond to occurrences of false positive avalanche identifications caused by interfering infrasound signal sources. These false positive avalanche identifications, which were anticipated due to the refinements that had been made to the prototype system, were few in number and mainly occurred at the beginning of the 2006/2007 winter season.

Throughout the course of the 2006/2007 winter season, the system results were carefully watched for indications of any infrasound signal degradation issues. No signs of quality deterioration were observed in recorded explosive signals and avalanche signals. However, the 2006/2007 winter season exhibited a much lower than average snow fall, which resulted in few avalanche-generated infrasound signals being encountered and the likely possibility that the snow pack never became deep enough to facilitate a valid test of the attempts at mitigating the signal degradation issues.

In the spring of 2007, the system was decommissioned for the ensuing summer. Outside of suspending software operation at the CPU, this undertaking was mostly comprised of analogous efforts that were performed at each RSAMN site. The infrasound sensors were retrieved, while the associated sensor cables were inspected for damage and coiled for storage at the base of the mounting tower. Also inspected for damage and stored on site were the infrasound sensors pneumatic wind noise reducing hose array filters. Monitoring equipment mounted at the tower was allowed to be stored in that permanent manner. The sensitive electronic equipment contained in the outdoor instrument enclosure was disconnected from any conductive paths (e.g. power, cabling) that could potentially facilitate damage due to lighting strikes.

During the summer of 2007, the infrasound sensors were submitted to quality control checks. Required annual consumables were procured in addition to the supplies required to replace items that were found damaged during the spring decommissioning efforts. In the fall of 2007, the system was made operational for the 2007/2008 winter season by facilitating efforts that were similar to those previously discussed regarding the installation of the refined system.

Over the course of the 2007/2008 winter season, WYDOT personnel assumed operational responsibilities for the routine utilization and interpretation of the refined system results without the need for extensive and frequent project support services. A few encountered false positive avalanche event identifications did spur corrective changes to the CPU signal analyses configuration parameters. Feedback obtained from WYDOT personnel indicated that the system performed well and provided the desired valuable information to assist with Teton Pass avalanche hazard mitigation activities (Yount, et al., 2008).

The 2007/2008 winter season exhibited a much higher than average snow fall, which provided a practical test of the attempts that were made to mitigate the signal degradation issues. Observations indicated the there was some loss in the quality of recorded infrasound signals as the season progressed, but not to the extent that was seen during previous project efforts that discovered this problem. The performed spring, 2008 decommissioning of the RSAMN sites offered an opportunity to inspect the state of the infrasound sensors pneumatic wind noise reducing hose array filters. Where there were still hose sections encased in remaining snow banks, it was observed that some of the porous hose sections, which were not covered in poly tubing, were indeed flattened. However, it was also observed that the porous hose sections, which were covered in poly tubing, were not flatted within the snow banks.

Project conclusion

As has been mentioned, a complimentary concurrent NSF project provided the means to conclude remaining technical development tasks that were also considered essential to meeting this projects primary objective. While all of the NSF technical development objectives were indeed met, the necessary tasks were not completed until the summer of 2008. Unfortunately, this had the detrimental consequence of delaying the daunting duty of developing detailed and thorough system documentation, which was critical to empowering WYDOT personnel to utilize and maintain the system with autonomy. An additional conflicting issue was an immediate need to complete the preparatory tasks required to enable necessary fall RSAMN field work to make the system operational for the 2008/2009 winter season. Necessary summer and fall support services were thus provided to WYDOT personnel to resolve the fact that the system documentation had yet to be completed. Thus, completion of the detailed and thorough system documentation was delayed until after the system was made operational for the 2008/2009 winter season.

While support services were provided to assist WYDOT personnel in making the system operational for the 2008/2009 winter season, these services did not include any physical assistance with the required RSAMN fall field work. Rather, it was decided that WYDOT personnel would independently perform the required RSAMN fall field work for the first time in project history. To support these WYDOT field work efforts, the infrasound sensors were submitted to quality control checks, necessary annual consumables were provided, and documented suggested standard procedures were provided. WYDOT personnel did indeed succeed in making the RSAMN's operational through their independent field work activities!

Unfortunately, problems with the wireless data communications between the CPU and the RSAMN sites was discovered after the RSAMN's were made operation in the fall. Support was remotely provided to WYDOT personnel during efforts to troubleshoot, diagnose, and fix the problem. The problem was eventually resolved via replacement of the CPU's wireless data communications antenna and cable in conjunction with alteration of the CPU's wireless data transceivers configuration settings.

Efforts to complete the detailed and thorough monitoring system documentation commenced after it was determined that the refined Teton Pass infrasound monitoring system was indeed ready for WYDOT 2008/2009 winter season operations. A detailed system user manual and datasheets for custom developed RSAMN hardware components was finished in the fall of 2008, which brought this project to a successful conclusion. The documentation was developed with a focus of providing all required system information to empower independent WYDOT employee maintenance without the need for any project development team input or outside consultation.

CHAPTER 4

FINDINGS AND CONCLUSIONS

The conclusion of this project offers the successful culmination of research and development efforts that were long ago initiated by NOAA, which envisioned the possibility of developing automated infrasound monitoring technology for practical operational use by professionals charged with maintaining transportation avenues that are affected by snow avalanche activity. In addition to critical project funding sources (i.e. NOAA, NSF, WYDOT), meeting this lofty goal required innovative ideas and the completion of resource intensive technical tasks within demanding time deadlines dictated by the seasonal aspect of necessary experimental evaluation. The final required step in this process was to mature the prototype incarnation of the technology, which had established an infrasound monitoring methodology offering a proven avalanche identification solution, into a practical cost effective version that could easily be utilized and maintained in an independent manner by avalanche practitioners.

Facilitating this were efforts to refine the previously developed prototype Teton Pass infrasound monitoring system, which targeted Twin Slides and Glory Bowl avalanche activity that threatens WY-22. Success was achieved in upgrading the system to a reliable permanent final form that requires minimal annual budget expenditures and is easily operated and maintained by WYDOT personnel for assisting with Teton Pass avalanche hazard mitigation activities. Thus this project has provided the ability for WYDOT to independently continue future operation the refined Teton Pass infrasound monitoring system to provide valuable information regarding the following:

- Early notification of natural Teton Pass avalanche events.
- Verification of avalanche hazard mitigation results.
- Confirmation of avalanche hazard mitigation explosive ordinance detonation.

When avalanche hazard is of a concern, availability of this kind of information can significantly impact the operational planning and activities of WYDOT personnel and the resultant safety of those utilizing WY-22; both the traveling public and the WYDOT employee.

System performance

While the prototype system was refined to an easy to use and maintain final form, it was important to ensure that these achievements did not cause any serious performance degradation. Excluding typical on-going development caused problems, the system hardware and software performed reliably in a continuous automated manner. By the end of the 2007/2008 winter season, continuous automated near real- time operation of the system was remarkably stable.

There were random instances of failed wireless communication transfer of RSAMN data to the CPU, but these instances represent a fraction of a percent of the attempted data transfers. There also were instances when a CPU signal analyses failed to complete, but these too were negligible in frequency. Even when these failures occurred, the system continued to operate in an automated near real-time fashion without requiring human intervention. One area of CPU use that was wrought with problems was the simultaneous use of the GUI software post processing functionality while near real time-monitoring was actively operating. GUI software post processing use is considered highly important, because presented results offer a totality of system information as opposed to the condensed information presented during near real-time monitoring. Fortunately, the challenges related to the conflicts between implementing post processing GUI software activities during near real-time monitoring operation were resolved through extensive NSF project development efforts.

Absolute performance of automated system results is difficult to quantify, since the ability to reliably identify targeted avalanche activity in near real-time depends on easily altered signal analyses configuration settings, which dictate whether detected signals are classified as identified avalanche events or discriminated as interfering events. The classification methodologies are mostly based upon exploiting the deterministic movement of a targeted avalanche event to reject occurrences of false positive avalanche event identifications due to commonly encountered stationary interfering signals. Prior to 2006.2007 season winter operational use, the signal analyses classification configurations were set to balance the desire to automatically identify all targeted avalanche events, even small short traveling avalanches, with the desire to not incur any false positive avalanche event identifications.

Early in the 2006/2007 winter season the CPU GUI software signal analysis targeting Twin Slides produced eight false positive avalanche event identifications, and the signal analysis targeting Glory Bowl produced one false positive avalanche event identification. It is believed that more problematic meteorological and topographical challenges at the Twin Slides RSAMN are the source of the higher false positive Twin Slides avalanche identification rate. As a response to these false positive avalanche event identifications, the signal analyses classification configuration setting were altered to require that detected infrasound signals exhibit further deterministic movement down the targeted slide paths to provide for avalanche event identification. This did indeed nearly eliminate all occurrences of false positive avalanche event identifications during remainder of the 2006/2007 winter season. During the 2007/2008 winter season operations, there were a total of four false positive identifications of Twin Slides avalanche events and one false positive identification of a Glory Bowl avalanche event.

The distance traveled by Twin Slides and Glory Bowl avalanche events that reach the WY-22 is adequate for reliable avalanche identification utilizing the altered signal analyses classification configuration settings, and even Glory Bowl avalanches that stop well short of WY-22 are reliably identifiable. Since the currently settled upon signal analyses classification settings requires that targeted avalanche events travel a significant distance for reliable true positive identification, this means that small targeted avalanche events of short duration will not be automatically identified as avalanche events and instead classified as interfering infrasound signal events. However, human utilization of the CPU GUI software post processing capabilities can easily allow for proper interpretation of such false negative avalanche event identifications. Likewise, the rarely encountered false positive avalanche identification can easily be recognized through further the further in depth signal analyses capabilities offered by the post processing functionality of the CPU GUI software.

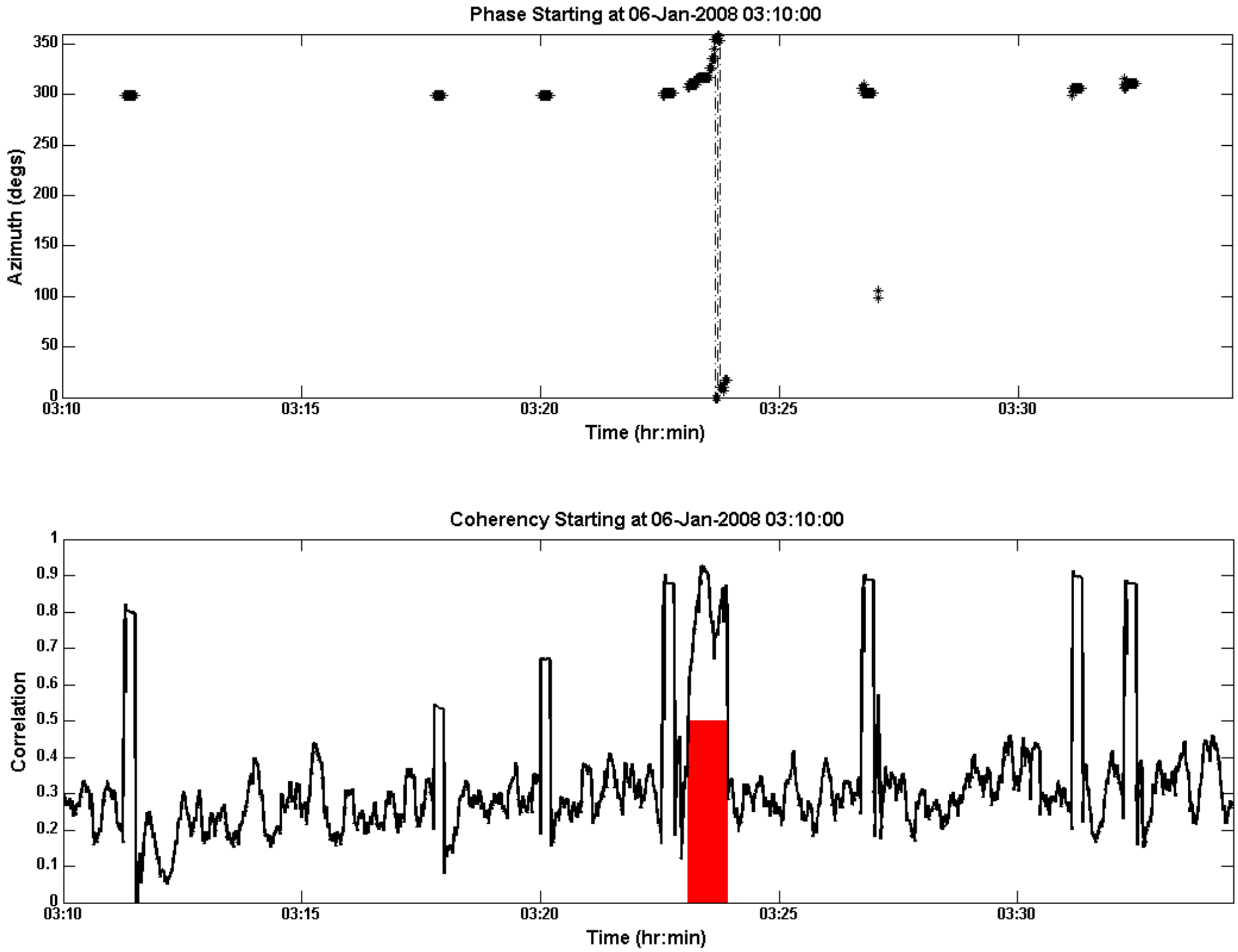

Figure 4. Teton Pass Avalanche Mitigation Glory Bowl RSAMN Results

The executed CPU GUI software signal analyses were shown effective, even though data recorded at only a single RSAMN sited near the targeted slide path (Twin Slides or Glory Bowl) is utilized by each signal analyses. Shown in Figure 4 are Glory Bowl RSAMN signal analysis results obtained during a WYDOT Teton Pass avalanche hazard mitigation mission. Evident via the elevated correlation levels are a series of stationary interfering explosive infrasound signal events with the positive identification (designated by the red bar) of one released moving Glory Bowl avalanche event that stopped well short of WY-22, which was valuable information to have in near real-time as these operations were carried out by WYDOT personnel.

Figure 5 shows a complimentary geographic detection image of a time instance during the identified Glory Bowl avalanche event. Blue to red colors indication the intensity of the infrasound signals detected at the RSAMN. Evident is that the only reliable signal source location information is the azimuth angle of arrival for the detected infrasound signal. This location information could be extended to be reliable in three dimensions, if data recorded at distributed RSAMN sites were utilized by the signal analysis (Yount, et al., 2008).

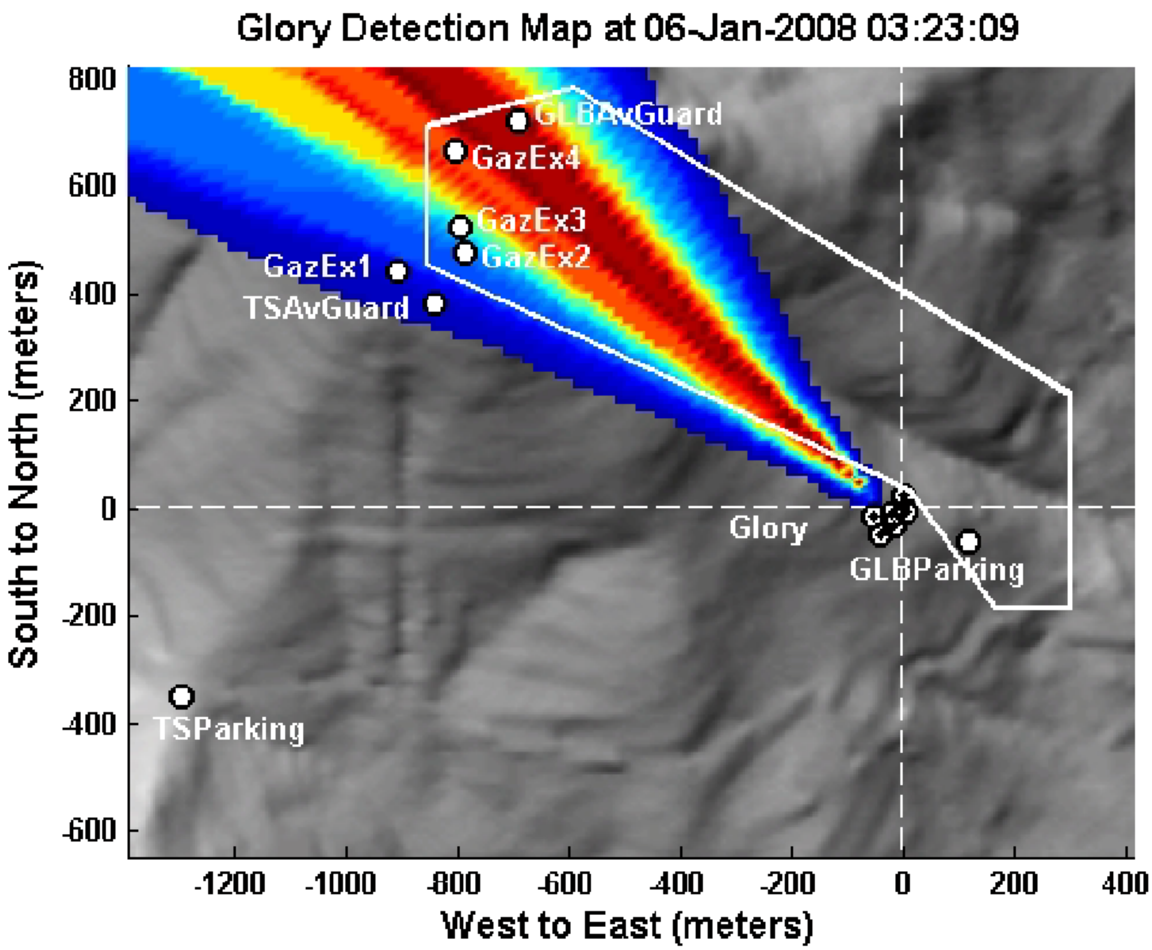

Figure 4. Teton Pass Geographic Glory Bowl Avalanche Detection

There is no doubt that the reliability and performance of each signal analysis would be improved if data recorded at distributed RSAMN's sited near each targeted slide path were utilized within each signal analysis. This is especially true, if the additional RSAMN node sites were located directly across from the current RSAMN sites and on the opposite side of each targeted slide path. For this ideal case where the targeted slide paths would be bracketed by RSAMN sites at mid track, it is expected that virtually all occurrences of the false positive avalanche event identifications would be eliminated due to the targeted avalanche events moving between infrasound sensors, which would be very difficult for an interfering infrasound signal source to mimic. In such an operational deployment scenario, it is quite likely that the near real-time operation of the monitoring system could provide performance worthy of allowing it to provide decision making for the automated closures of WY-22 gates when a positive avalanche identification occurred. However, this type of operational performance would come at an increased cost and budget impact in order to maintain the additional required RSAMN sites.

Previous experimental operation of the prototype system showed that deep snow pack covering of the infrasound sensors pneumatic wind noise reducing hose array filters can cause icing, crushing, and flattening of hose sections, which degrades the quality of the detected signal. This problem was successfully mitigated by altering how the porous hose sections are deployed (e.g.

wrapping in poly tubing, coiling) and using sturdy flexible PVC electrical conduit to facilitate the solid hose sections. Over all system results did not indicate that there were severe signal degradation issues, but it was observed that some sections of porous hose that were not covered in poly tubing were once again flattened, which certainly impeded infrasound signal propagation and resulted in deterioration of measured infrasound signals. However, it was also observed that sections of the porous hose, which were covered with poly tubing, did not flatten and that the poly tubing does indeed prevent bonding of ice to the porous hose section. Since the flexible PVC electrical conduit did prevent infrasound signal impeding problems, it is speculated that covering the entire lengths of porous hose sections in poly tubing might complete the resolution of the infrasound signal degradation problem. However, it is not understood whether the poly tubing detrimentally impedes infrasound signal propagation itself, so more seasonal experimental evaluation would be needed to verify that this is indeed a viable solution. Another possible fix to issues encountered with the porous hose sections would be to protect the porous hose with rigid structures (e.g. perforated drill pipe casing) that could prevent detrimental damage.

An additional experimental insight from current project efforts is that the signal analyses results appear to be much more sensitive than in past efforts. It is speculated that the reason for this is partially due to the improved waveguides that have been implemented at the infrasound sensor. It is also speculated that the a newly implemented custom precision five volt regulator reduced the baseline electronic system noise and resulted in more sensitivity.

WYDOT Autonomy

Entering the 2008/2009 winter season, there is a high amount of confidence in the ability of WYDOT personnel to independently and efficiently utilize the CPU GUI software to obtain the desired valuable information. Finalizing the configuration of the RSAMN sites greatly helped facilitate this, since this brought stability and familiarity to the performed GUI signal analyses, which had continually changed during earlier project efforts where experimentation with proper RSAMN siting was performed. This permanence provided the ability to complete detailed GUI software help documentation that explains the use and functionality of all software features. Also critical were NSF funded efforts to improve GUI software and signal analyses functionality, which provided full featured and crash free operation in a distribution worthy version.

In addition to independent CPU operation, there is a high amount of confidence in the ability of WYDOT personnel to independently service and maintain the RSAMN sites. Greatly helping to facilitate this is the establishment of stability and familiarity with RSAMN configurations. Also assisting this were NSF funded efforts to simplify the wiring and cable connections required to implement a RSAMN site. The finalization of the RSAMN configurations enabled the completion of detailed and thorough system documentation, which provided a system user manual and appropriate custom instrumentation datasheets. This documentation provides all required system information to empower independent WYDOT personnel maintenance without the need for any project development team input or outside consultation.

Outside of possible infrasound sensor quality control efforts, it is believed that system can be maintained by currently trained WYDOT employees. Not only was this evident through the conducted project training efforts, but this was demonstrated via the independent WYDOT personnel efforts that were responsible for making the system operational for the 2008/2009 season. It also is believed that operation and maintenance of the system could be assumed by skilled individuals without prior project experience who are willing to read the system documentation and learn the necessary details.

Annual maintenance requirements

Throughout the course of this projects activities, effort was consistently applied to the desire to minimize the annual maintenance that would be required to provide for continued future system operation, because it was clearly understood that practical use and operation of the system could not necessitate significant monetary expenditures. In order too achieve this goal, there was a focus to empower WYDOT personnel to be able independently facilitate annual maintenance in a timely manner without the need for external consultation.

The RSAMN sites are where the most annual service attention is required, so this is where the majority of improvements were made to streamline tasks. Installing permanent mounting towers at the RSAMN's produced a reduction in the amount of RSAMN equipment that must be retrieved and re-deployed on an annual basis. These mounting towers also have provided a work environment where maintenance tasks are easier, safer, and quicker to perform. The decision to only establish two RSAMN sites at the sacrifice of improved system signal analyses performance also greatly helped to reduce annual maintenance requirements.

As is detailed in the system user manual, routine annual maintenance efforts will be required in the spring to decommission the system for storage across the summer and also in the fall to make the system operational for winter season use. A summary of the estimated routine annual maintenance tasks follows:

Spring Decommission (Estimated Person Hours: 12, Estimated Supplies Monetary Cost: < $50)

- Retrieve infrasound sensors from RSAMN.
- Coil and store infrasound sensor cables at RSAMN.
- Store pneumatic wind noise reducing hose array filters at RSAMN.
- Isolate sensitive RSAMN electronics from possible lightning damage.
- Fill RSAMN batteries with distilled water.
- Inspect for any RSAMN damage.
- Remove worn-out RSAMN consumables (e.g. porous hose).
- CPU GUI software seasonal configuration and event log management.

Fall Re-installation (Estimated Person Hours: 24, Estimated Supplies Monetary Cost: $300)

- Prepare to replace RSAMN consumable supplies.
- Re-install infrasound sensors at RSAMN.
- Replace RSAMN consumables.
- Reconnect RSAMN outdoor instrument enclosure electronics.
- Fill RSAMN batteries with distilled water.
- Facilitate any CPU software upgrades.
- Test system operation.

These conservatively estimated annual maintenance requirements represent anticipated current costs for the work to be performed by a single WYDOT employee that has the pertinent knowledge regarding the required tasks. Project training efforts have indeed provided WYDOT with a current employee capable of facilitating these requirements, and it is expected that other WYDOT employees could also be similarly trained if the need arises. The estimated routine annual consumable supplies cost is mainly to cover replacement of damaged hose sections of the infrasound sensors pneumatic wind noise reducing hose array filters.

Not estimated in the annual maintenance time and cost requirements are non-routine needs that might arise due to damaged or malfunctioning equipment. Actually encountered examples of such non-routine system needs that were dealt with during the course of this project include the CPU computer failure during the 2007/2008 winter season and the encountered wireless data communications problems prior to the current 2008/2009 winter season. Other non-routine maintenance needs that will likely be encountered in future system operations include:

- Replacement of worn out RSAMN 12 Volt deep cycle batteries.
- CPU computer hard drive management.
- Replacement of damaged RSAMN infrasound sensor cables.
- Replacement of damaged RSAMN infrasound sensors.

While incurred infrasound sensor damage is not expected to be common, there have been a few cases in prior project efforts where infrasound sensors were damaged due to water intrusion into the sensor enclosure. The potential for this type of damage can be mitigated by taking care to lay out the pneumatic wind noise reducing hose array filters so that they do not provide a drainage path for water to enter the infrasound sensor enclosure. Even when there is moisture damage to an infrasound sensor, it can be difficult to recognize at the CPU, since the infrasound sensor typically will continue to produce data that appears reasonable to the human eye. Even though infrasound sensor moisture damage will certainly result in subtle deterioration of CPU GUI signal analyses results and can usually be verified through visual inspections of the internal infrasound sensor circuitry that reveals corrosion, mildew, or mold, it is recommended that all system infrasound sensors be submitted to annual quality control checks to ensure that they exhibit a well matched phase response, which is critical for producing quality system results. Such infrasound sensor quality control could be done by a skilled WYDOT technician through the use of a spectrum analyzer. Otherwise, it is anticipated that annual externally contracted infrasound sensor quality control service would currently cost around $500 for the system.

Another optional system service possibility is to purchase annual software license maintenance agreements that provide for upgrades of critical CPU software packages, which currently would cost around $700. These annual license agreements have been maintained throughout project efforts, but will expire after the current 2008/2009 winter season. Certainly a turnkey service contract that covers all system annual maintenance needs could be entered into with an external consultant, but it is not anticipated that WYDOT desires to incur the monetary costs (~$17,500 estimated) that would be required of such an agreement.

National Science Foundation supplemental project
It cannot be emphasized enough how important the concurrent NSF project was to achieving the primary objective of this project. In addition to providing independent funding to complete critical complimentary technical development efforts, NSF also provided a 50 percent funding match of this projects budget.

Development efforts and activities that were covered through NSF funds and applied to the refined system include the following:

- Spring 2006 decommission/removal of the prototype system.
- Development of an improved infrasound sensor enclosure.
- Development of an improved infrasound sensor signal cable.
- Investigations into improving infrasound sensor pneumatic wind noise reducing hose array filters.
- Development of GPS based distributed RSAMN time synchronization scheme.
- Development of the highly efficient precision five volt regulator circuit.
- CPU computer replacement at the beginning of the 2006/2007 winter season.
- Extensive development of the GUI software.
- Extensive improvement to signal analyses capabilities.

Utah Department of Transportation application
While not part of this project, it is worth noting that the Utah Department of Transportation (UDOT) provided partial funding (matched 50 percent by NSF) for this researcher to deploy an infrasound monitoring system in Little Cottonwood Canyon near Salt Lake City to target avalanche activity they impacts Utah State Route 210. The UDOT system is a more sophisticated configuration of the technology, since the signal analyses process data that is recorded at distributed RSAMN sites. In part due to this fact, results obtained from the UDOT system represent unprecedented project achievements, which have provided tremendous practical operational value (Yount, et al., 2008).

It is very exciting and rewarding for project participants to have achieved this successful transfer of technology from practical WYDOT avalanche hazard mitigation operations to practical UDOT avalanche hazard mitigation operations. Even more exciting is that the deployed WYDOT and UDOT systems have had such a positive impact that they have changed the way these two programs facilitate their missions to provide safe and efficient public transportation routes (Yount, et al., 2008).

CHAPTER 5

IMPLEMENTATION RECOMMENDATIONS

The refined Teton Pass infrasound monitoring system is currently being independently operated by WYDOT personnel to assist with 2008/2009 winter season avalanche mitigation activities. Successful conclusion of this project has facilitated the ability for the system to be fully transferred to the authority of WYDOT personnel for future long term use without the need for extensive external support services or excessive monetary impact upon the operational budget. However, there are still costs associated with the annual maintenance of the system and WYDOT will have to decide whether incurred costs justify continued operation and whether optional external support services (e.g. infrasound sensor quality control, software license maintenance) are desired.

If WYDOT deems continued long term future operation of the system appropriate, then it is suggested that responsible WYDOT personnel examine the extensive user manual and adopt the recommended standard operating procedures, so that the system can be utilized to its full potential. The mature CPU GUI software package version is very full featured, which is detailed in the software help, and all of its functionality should be understood and exploited.

While the automated near real-time monitoring capability of the system has operated in a practical reliable fashion, the system also offers powerful manual post processing capabilities that can provide a wealth of information when properly utilized by a human operator. This is especially true for recognizing any false positive or false negative identifications of targeted Twin Slides or Glory Bowl avalanche activity. Additionally, the manual use of CPU GUI post processing capabilities can be exploited to investigate the affect of altering critical signal analyses configuration settings, which can facilitate adopting an altered CPU GUI automated near real-time monitoring configuration that better matches the performance tolerance of the WYDOT user.

If WYDOT were to eventually desire elimination of virtually all near real-time monitoring positive avalanche event identifications to provide absolute faith in automated results, then additional RSAMN sites could be deployed on the opposite side of the targeted slide paths from where the current RSAMN sites are located. This would allow for the use of data measured at distributed RSAMN sites to be used within the signal analyses, which certainly would provide the desired performance increase and offer a realistic potential for the automated closure of WY-22 gates when the system identifies naturally occurring avalanche activity. Currently, system results are reviewed by WYDOT personnel to assist with decision making regarding WY-22 gate closure.

If infrasound signal degradation issues are again encountered in future use of the system, then it is encouraged that WYDOT personnel experiment with new ways to protect the porous hose sections of the infrasound sensor pneumatic wind noise reducing hose arrays. This could be as simply as covering the entire length of porous hose sections in poly tubing, or enclosing the first few feet of porous hose at a solid hose to porous hose junction with perforated drill pipe casing.

As was mentioned in the prior WYDOT final report, another potential WYDOT application for deployment of an avalanche infrasound monitoring system is in Hoback Canyon where the Cow of the Woods and the Calf of the Woods slide paths threaten United States Highway 189/191 (Scott, 2005). Another potential application within Wyoming where interest has been shown in the technology is to assist the National Park Service with Yellowstone's Sylvan Pass avalanche program that is critical to maintaining an open East entrance avenue for winter use. Other applications where recent interest in the technology has been expressed include the following:

- Snoqualmie Pass on Interstate 90 in Washington.
- Along Idaho State Route 21 between Stanley and Lowman.
- Along the Canadian Pacific Railway.

APPENDIX A

CONCEPTUAL INFRASOUND MONITORING SUMMARY

Snow avalanches generate low frequency acoustic energy as they occur. The resultant airborne signals propagate away from their source and occupy a relatively low noise band of the sub-audible infrasonic frequency spectrum, which provides a functional basis for avalanche event detection by sensing equipment that is not placed in the slide path. Since avalanche infrasound signal detection does not require the sensing equipment to be physically harmed, monitoring can occur in a continuous automated fashion without the need to reset measurement components. However, 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. For the often encountered non-ideal signal and noise environment, utilization of multiple, spatially separated infrasound sensors allows for beamforming signal processing that effectively confirms detection of coherent signals and estimates their geographic source location.

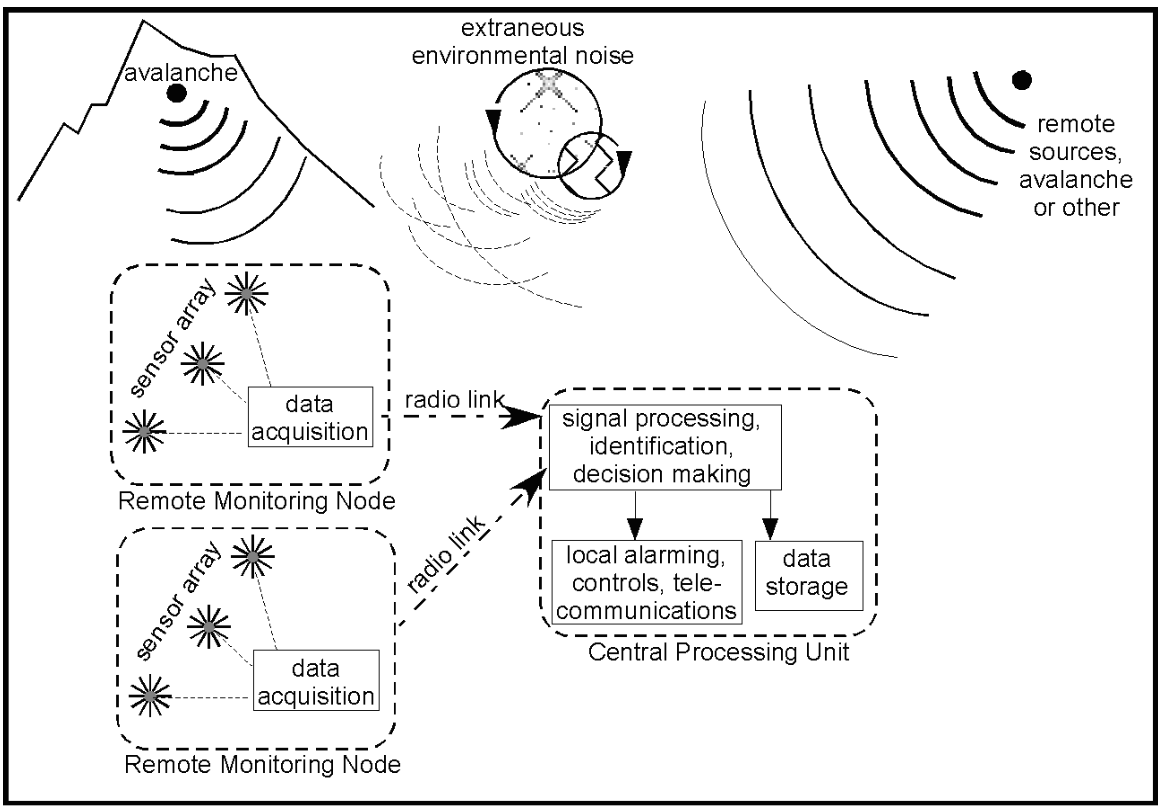

Figure 6. Avalanche Infrasound Monitoring Concept

As is conceptually depicted in Figure 6, infrasound measurements are facilitated via remote sensor array monitoring nodes, which are deployed in mountainous environments that contain avalanche-generated infrasound signals in addition to problematic interfering infrasound signals and ambient noise. On a continuous near real-time interval (e.g. every 1 minute), measurement data are automatically transferred via wireless communications to a centrally located processing facility to perform multiple sensor correlation beamforming. 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 the multiple sensors. Subsequent time duration criterion and signal source movement based pattern recognition techniques are then applied to any detected signals to classify the signals as either targeted avalanche events or discriminated interference events, which provides reliable automated positive avalanche event identification and alarm notification. At the same time, a graphical software interface presents results in dynamic interactive visual displays for human interpretation, while post processing software utilities allow for further in depth manual investigation of time periods of interest. Additional configuration functionality exists to allow for alteration of all critical signal processing parameters.

REFERENCES

Bedard, A. J. Jr. (1989). *Detection of avalanches using atmospheric infrasound.* Proceedings; Western Snow Conference, Fort Collins, CO.

Bedard, A. J. Jr. (1994). *An evaluation of atmospheric infrasound for monitoring avalanches.* Proceedings; 7th International Symposium on Acoustic Sensing and Associated Techniques of the Atmosphere and Oceans, Boulder, CO.

Bedard, A. J. Jr., Greene, G. E., Intrieri, J., & Rodriguez, R. (1988). *On the feasibility and value of detecting and characterizing avalanches remotely by monitoring radiated sub-audible atmospheric sound at long distances.* Proceedings; A Multidisciplinary Approach to Snow Engineering, Santa Barbara, CA.

Comey, R. H., & Mendenhall, T. (2004, September). *Recent studies using infrasound sensors to remotely monitor avalanche activity.* Proceedings; International Snow Science Workshop, Jackson Hole, WY.

Scott, E. D. (2005), *Infrasonic monitoring of avalanche activity on Teton Pass.* (Report No. FHWA-WY-05/08F), WYDOT research project RS07(203), Cheyenne, WY.

Scott, E. D., Colgan, T.J., Hayward, C. T., Kubicheck, R. F., Hamann, J. C., Pierre, J. W., & et al. (2006, October). *Practical implementation of avalanche infrasound monitoring technology for operational utilization near Teton Pass Wyoming*. Proceedings; International Snow Science Workshop; Telluride, CO.

Scott, E. D., & Lance, C. (2002, October). *Infrasonic monitoring of avalanche activity*.” Proceedings; International Snow Science Workshop, Penticton, British Columbia.

Scott E. D., Hayward, C. T., Kubicheck, R. F., Hamann, J. C., & Pierre, J. W. (2004, September). *Results of recent infrasound avalanche monitoring studies.* Proceedings; International Snow Science Workshop, Jackson Hole, WY.

Scott E. D., Hayward, C. T., Kubicheck, R. F., Hamann, J. C., Pierre, J. W., Comey, B., & et al. (2007, January). “Single and multiple sensor identification of avalanche-generated infrasound”, *Cold Regions of Science and Technology, Special Issue ISSW 2004*, *49:1-2*:159-170.

Yount, J., Naisbitt, A., & Scott, E.D. (2008, September). “*Operational highway avalanche forecasting using the infrasonic avalanche detection system.*” Proceedings; International Snow Science Workshop, Whistler, BC.