RECENT STUDIES USING INFRASOUND SENSORS TO REMOTELY MONITOR AVALANCHE ACTIVITY

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ABSTRACT: The ability to detect avalanches as they occur is essential for aggressive avalanche management in transportation corridors and is a fundamental ingredient of avalanche forecasting. Past studies have shown that moving avalanches emit a detectable sub-audible sound signature in the low frequency infrasonic spectrum. Experimental activities conducted in the Rocky Mountain West during the winter of 2002/2003 clarified the capabilities of single sensor infrasound avalanche monitoring systems. During the winter of 2003/2004 two projects were conducted in the Teton Range of Wyoming to research the use of multiple infrasound sensors to monitor avalanche activity. A distributed network of monitoring systems were deployed along the Twin Slides and Glory Bowl slide paths on Teton Pass to evaluate technology applicability in a highway setting. At the Jackson Hole Mountain Resort a distributed network of monitoring systems were deployed to research the potential for sensor array processing to improve upon single sensor processing capabilities. Research efforts related to these studies were funded through the following: National Oceanic and Atmospheric Administration Small Business Innovative Research Award, National Science Foundation Small Business Innovative Research Award, and a Wyoming Department of Transportation Research Award.

Keywords: avalanche monitoring, avalanche detection, infrasound, sensor

1. INTRODUCTION

Many natural and manmade processes are sources of sub-audible sounds in the low frequency infrasonic spectrum. In the 1950's infrasonic sensing technology was developed to monitor for nuclear explosions. Once the United States developed satellite technology to monitor for nuclear explosions, infrasound research efforts declined. International adoption of the Comprehensive Test Ban Treaty in the 1990's has sparked renewed research in infrasound monitoring. Prior to this renewed interest, scientists familiar with this technology at the National Oceanic and Atmospheric Administration (NOAA) in Boulder, Colorado determined that avalanches emit a unique infrasonic sound signature that could lead to the development of an automated detection system (Bedard 1989, Bedard 1994, Bedard et al. 1988).

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In September of 2000, NOAA scientists awarded the air science section of Inter-Mountain Laboratories, Inc. (IML) in Sheridan, WY a six-month Small Business Innovative Research (SBIR) Phase I contract to study the feasibility single sensor monitoring systems to detect avalanche-generated infrasound. After successfully demonstrating the ability of infrasound sensors to detect avalanche-generated infrasound (Scott 2000), IML was awarded a two-year SBIR Phase II contract to characterize avalanche-generated infrasound signals and develop a single sensor prototype avalanche identification system. Experimental studies conducted in the western Unites States during the 2001-02 and 2002-03 winter seasons characterized avalanche-generated infrasound signals and resulted in a single sensor signal processing algorithm that can identify avalanche activity (Scott and Lance 2002, Scott and Hayward 2003).

While single sensor signal processing algorithms were proven to identify infrasound avalanche signals, it was also apparent that the techniques would fail when recorded data exhibits high ambient noise. A six-month National Science Foundation (NSF) SBIR award during the 2003-04 winter enabled IML to investigate using multiple sensors to improve upon single sensor avalanche identification techniques. Also during 2003-04, an eighteen-month Wyoming Department of Transportation (WYDOT) Research Project was conducted by IML to investigate the performance of a distributed near real-time infrasound monitoring network in a highway setting.

This paper provides an overview of the studies conducted since 2000. The focus is on the research conducted during the 2003-04 season and a discussion of the work proposed for the upcoming 2004-05 winter.

2. NOAA RESEARCH (2000-2003)

The NOAA SBIR research contracts were limited to single sensor studies with the goal of developing technology for a highway avalanche warning system.

The initial six-month Phase I efforts targeted the Revolving Door research slide path operated by Montana State University Civil Engineering at the Bridger Bowl Ski Area in Bozeman, Montana. In January 2001, an infrasound sensor deployed at the lower Alpine Lift shack (1000 meters from the Revolving Door) detected the signal emanating from the one Revolving Door avalanche that was explosively triggered during the contract period. This event provided the data and results depicted in Figure 1, which justified the two-year NOAA Phase II SBIR funding for this project.

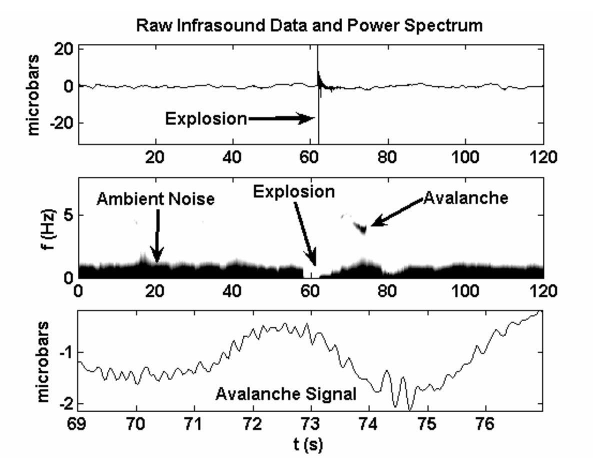

Figure 1. NOAA Phase I Results

The top graph in Figure 1 shows the raw infrasound data that were recorded during this experiment. An air blast shortly past 60 seconds results in an avalanche signal around 70 seconds. The avalanche is difficult to see in the top graph, but the power spectrum of the middle graph clear shows the avalanche event and its unique frequency. Also seen in the power spectrum is background low frequency ambient noise. The bottom graph presents a zoomed view of the raw avalanche signal, since it is not visible in the top graph.

For the 2001-02 winter of NOAA Phase II efforts, single sensor systems were deployed at several locations for the purpose of building a catalogue of avalanche-generated infrasound signals. Monitoring locations in the following areas were used:

- Alta, UT
- Bridger Bowl Ski Area. MT
- Jackson Hole Mountain Resort, WY
- Provo Canyon, UT
- Red Mountain Pass, CO
- Thompson Pass, AK

During the 2001-02 winter, six documented avalanche-generated infrasound signals were recorded at and the Jackson Hole Mountain Resort (JHMR), and seven documented avalanche-generated signals were recorded at Alta. Avalanche-generated infrasound signals were not recorded at the other sites, which can be attributed to many factors including: sensor location, snow fall amounts, snow stability, and avalanche hazard mitigation efforts that reduce the occurrence of large magnitude events. These efforts enabled the research team to begin a catalog of avalanche-generated infrasound signals, which enabled characterization of an avalanche signal signature signal. This led to the development of a single sensor avalanche signal identification algorithm.

During the 2002-03 winter research efforts were concentrated at Alta, UT and in the Teton Range of western Wyoming due to the close proximity to members of the research team, and because of the positive results produced during the previous winter season. Single sensor monitoring stations were deployed near Alta at the Guard Station and Harold's Cabin. Single sensor systems were deployed at two Jackson Hole Mountain Resort locations (Mid Mountain and Tensleep Bowl) and along the Teton Pass Glory Bowl slide path on Highway 22.

Twenty-four (JHMR – 15, Alta – 5, and Teton Pass – 4) documented infrasound signals generated from both natural and explosive triggered avalanches were recorded during the 2002-2003 winter. Several avalanche signals recorded at the Alta and Glory Bowl monitoring locations are uniquely large in amplitude when compared to other signals recorded during the project. Figure 2 shows recorded raw infrasound data for three of the large signal events.

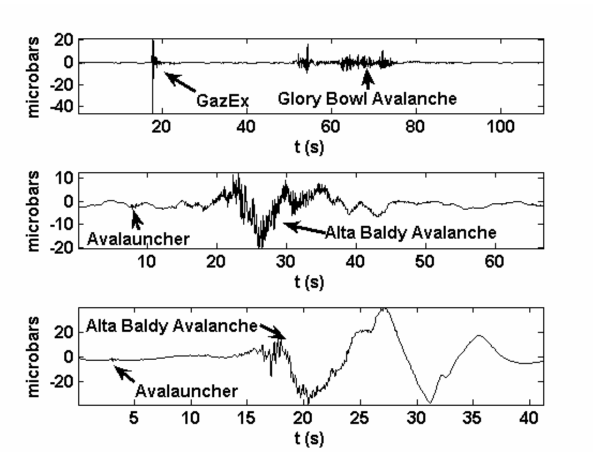

Figure 2. Large Avalanche Signals

The signals shown in Figure 2 exhibit peak-to-peak pressure fluctuations approaching twenty microbars with sustained levels above five microbars. For these data the single sensor signal processing algorithm was able to successfully identify the avalanche events without the risk of false alarms. Yet, this reliability did not always hold true for the smaller signals contained in the catalogue. Data analyses showed that high wind noise easily masked the smaller signals.

By the end of the 2002-03 season, the limitations of a single sensor avalanche identification system were realized. A single sensor system could successfully detect a large event in low wind noise conditions with confidence, but it would not be able to detect a small event in high noise conditions with the same confidence. As the baseline noise on the sensor increases, so does the chance of false detects, or missed detections.

The distributed systems operated at Alta and JHMR provided insight into the possibility of using multiple sensors to improve upon single sensor avalanche monitoring. Results from the 2002-03 season showed that multiple sensors would likely mitigate the effects of the wind and provide improved avalanche identification. These efforts concluded the NOAA funded research.

3. NSF & WYDOT RESEARCH (2003-04)

The experience gained from the NOAA SBIR studies was used to obtain a six-month NSF SBIR award to investigate the potential of multiple sensors to mitigate small signal levels and high wind noise levels. NSF efforts in 2003-04 also studied the potential of multiple sensors to provide location information regarding avalanche signal origin. JHMR provided a controlled research environment to conduct the NSF study.

Funding for an eighteen-month study was also obtained from WYDOT to research the feasibility of operating a network of distributed single sensor monitoring systems along Highway 22 on Teton Pass. A primary objective of the WYDOT study was to develop and evaluate near real-time infrasound avalanche monitoring infrastructure in respect to a practical highway application.

An additional aspect of the WYDOT study was the collection of baseline data from a single sensor monitoring system located along Highway 191 near the active Cow of the Woods slide path in Hoback Canyon. Collection of baseline data was performed to evaluate avalanche signal amplitude levels of typical Cow of the Woods avalanche events.

3.1 NSF JHMR Study Area

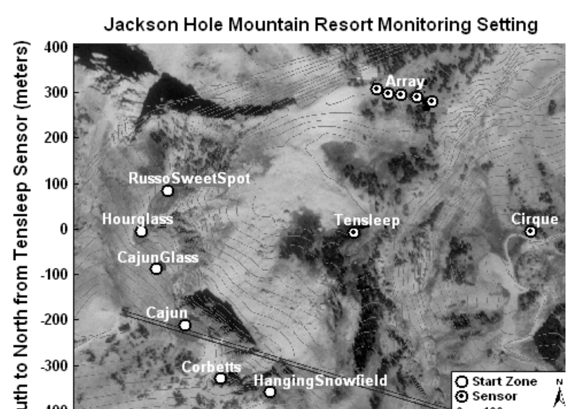

Figure 3. JHMR Monitoring Setting

An aerial view of the JHMR monitoring setting is shown in Figure 3. Two sensor sites were selected at the in the Tensleep Bowl area of the JHMR. Tensleep Bowl is a north and east facing glacial cirque with multiple avalanche paths. Most of the paths have starting zones at an elevation of about 3,400 meters and drop 300 meters to the floor of this cirque. It is the location of numerous natural and explosive triggered slides.

An array of five sensors (Array) was deployed on the floor of this cirque approximately 400 to 600 meters from the avalanche starting zones. A single sensor monitoring system (Tensleep) closer to the slide paths was also operational in the same location from which it obtained data during the 2001-02 and 2002-03 seasons.

Two additional single sensor monitoring systems (Cirque and Mid Mountain) located approximately 0.5 and 1.5 kilometers downhill at elevations of 2,900 and 2,600 meters respectively supplemented the data collected from the Array and Tensleep sites.

Show in Figure 4 is an explosively triggered Cajun Glass avalanche event as viewed from near the Tensleep Sensor. This avalanche event is typical of results obtained from the targeted avalanche paths.

Figure 4. Typical JHMR Avalanche

<u>3.2 WYDOT Study Areas</u>

Distributed single sensor monitoring systems were placed along Wyoming State Highway 22 near the Glory Bowl and Twin Slides avalanche paths on Teton Pass. Highway 22 climbs to an elevation of nearly 2,800 meters as it crosses over the low point between the Snake River Range and the southern terminus of the Teton Range. It is a vital transportation link between the resort communities of Jackson Hole, Wyoming and Teton Valley, Idaho. Numerous large avalanche paths cross the highway. Large storm cycles can result in extensive avalanche activity that can close this highway for extended periods.

The east facing Glory Bowl avalanche path runs from the top of Mt. Glory at 3,300 meters to Crater Lake at an elevation of 2,200 meters. Highway 22 crosses this path at an elevation of 2,700 meters. It is one of the most active paths crossed by the highway. Slides in this path have killed three people and nearly killed a WYDOT plow driver who was swept off of the highway. Three sensors were deployed along this avalanche path. A photograph of Glory Bowl is shown in Figure 5.

Figure 5. Glory Bowl on Teton Pass

The Twin Slides avalanche path also frequently impacts the highway. This path releases avalanches from a starting zone on a southerly aspect near the summit of Mt. Glory. Like the Glory Bowl path the highway crosses the Twin Slides avalanche footprint at mid path. Three sensors were deployed along this avalanche path. A photograph of Twin Slides is shown in Figure 6.

In addition to the Teton Pass infrasound monitoring systems a single sensor monitoring system was operated near the run-out zone of the Cow of the Woods avalanche path near Highway 191 in Hoback Canyon. The Cow of the Woods slide path is a lower elevation path that frequently impacts the road. A natural event was recorded during a period of high winds. The documented event is visible to the human eye, but it would not be easily identifiable in an automated system as there would be a high risk of false detects during that time period as well. Such data reinforces the necessity of using multiple sensor monitoring systems.

Figure 6. Twin Slides on Teton Pass

4. METHEDOLOGY SUMMARY

A multi-disciplinary team of scientists, engineers, and avalanche professionals was assembled by IML to perform the 2003-04 studies. A variety of avalanche practitioners provided snow expertise and field support services. University professors of Electrical Engineering and Geological Sciences provided highly specific technical guidance. IML employees provided hardware, software, and project management services.

In the early stages of this research explosives were exclusively used to trigger avalanches near operating sensors. Explosives create their own unique infrasonic signatures that were very easily identified in the data. During field operations avalanche specialist noted the time and results from a sequence of explosive hand charges while data loggers recorded and stored detected sensor signals. Post processing of the data collected during these events characterized a unique avalanche signal after the explosive triggers.

These results were used to develop a single sensor signal processing algorithm that allowed researchers to instruct computers to automatically identify the unique avalanche signature from recorded data. Further analyses showed that the single sensor processing algorithm could identify avalanche signals from naturally occurring and skier triggered events.

An extensive distributed network composed of single sensor monitoring systems and a sensor array was then deployed. Data from these monitoring systems was transmitted from the site by spread spectrum radio modems. The simultaneous collection and transmission of huge volumes of data is a challenging aspect of operating the infrasound monitoring systems.

Data recorded by the distributed network of monitoring systems was utilized to develop robust multiple sensor signal processing algorithms. The multiple sensor techniques have shown improved avalanche event identification capabilities over single sensor techniques. Multiple sensor methods also provide estimates of the avalanches physical location and size.

A detailed discussion of the methods and results of these studies is provided by Scott, et.al 2004.

5. FINDINGS

Avalanches were found to emit significant infrasound noise approximately 10 seconds after slope failure occurs provided the path is large enough to enable debris to flow downhill at a significant rate. This noise has been found to continue until the slide stops.

This finding leads to the speculation that the actual process within the avalanche that generates this infrasound signal may be related to an increase in the velocity of the slide, a transformation from laminar to turbulent flow and/or the entrainment of air and additional snow into the flow. The source of the sound in the avalanche is likely a moving non-point source that provides a challenge for data processing.

Unique signals from avalanches were detected at Alta and JHMR at distances of up to two kilometers from relatively small avalanches (Class 2 & 3 events). The distance from which larger events can be detected has not been determined.

Multiple sensors were found to greatly increase the ability of a monitoring system to suppress wind noise and other interfering noise sources. Results obtained from multiple sensors were able to estimate the location and magnitude of detected and identified avalanche events.

6. FUTURE EFFORTS

The studies conducted for the NSF SBIR Phase I conducted during the 2003-04 season have been reported and two-year Phase II proposal to obtain follow-up funding has been submitted. A funding decision is expected in fall 2004.

Since the multiple sensor results have proved extremely promising, IML has proceeded with the proposed Phase II work plan. Based on the experience gained from four years of research, new infrasound sensors have been developed and optimized for avalanche detection. These are being deployed in anticipation of being granted the Phase II award.

Regardless of whether the Phase II proposal is approved, arrays of new and traditional infrasound sensors will be operational during the 2004-05 season at JHMR and on Teton Pass. IML will continue to monitor avalanche events and expand its catalogue of avalanche events. This data will be used to further refine signal processing algorithms and monitoring techniques.

Further development of the ability to process the data in a continuous automated near real-time manner is a primary goal of the 2004-05 efforts. These efforts will build on large advancements gained through the WYDOT project. Another primary goal of the 2004-05 efforts is to evaluate the performance of the systems with a continuous data set as opposed to the fragmented data that has been obtained in previous studies.

As is the directive of SBIR funding sources, these efforts are intended to result in the development of prototype for a commercially available product and spurn economic growth. If the NSF Phase II is awarded, then development efforts will continue on the proposed work plan until the spring of 2006.

7. CONCLUSIONS

Four years of research have verified that moving avalanches emit a detectable and uniquely identifiable infrasound signal. A network of multiple sensors was found to greatly increase the reliability of monitoring for avalanche activity as it occurs. These networks have shown the capability to estimate the physical location and magnitude of avalanches.

8. APPLICATIONS

Based on the work conducted, infrasound technology has the potential to remotely detect avalanches in near real time. One limitation is the minimal 30-second delay between the initiation of an avalanche event and the resultant issuance of an alert/warning.

This delay originates from the finding that avalanches are not detectable during the first 10 seconds of an event. A second period of at least 20 seconds is necessary for remote data acquisition, data transmission, data processing, confirmation and alerting tasks. It follows that an avalanche monitoring system using infrasound technology does not allow for instant notification of an event occurrence. Instead, identification and alarming will most likely occur after the avalanche event is over. Knowledge will not be provided of an impending avalanche event.

Still, infrasound avalanche monitoring systems would be useful in most applications to alert practitioners to the immediate need to initiate mitigation efforts at facilities and transportation corridors as avalanches are occurring. Knowledge regarding the time, size and location of avalanche events would also be a valuable tool for avalanche forecasters.

Networks of monitoring systems are likely to be useful on paths that directly impact facilities and on “indicator paths” which typically fail frequently or early in a storm cycle and are a potential prelude to activity on other paths.

This technology also promises to be an excellent method to confirm the remote detonation of explosives, artillery or other high-energy triggering methods of avalanche initiation such as GAZ-EX.

A practical application of this system became apparent at JHMR on February 10, 2003 when local skier Steve Haas entered Hourglass Couloir, a permanently closed slide path in the Tensleep Bowl study area of JHMR. Steve and a partner triggered an avalanche that swept them down a steep couloir. Steve was buried and died.

This skier triggered event was detected by a single sensor monitoring system operating in Tensleep Bowl, and a single sensor monitoring system operating at the Mid Mountain Study Plot.

However, the monitoring systems in 2003 were not configured to operate in near real-time.

Forty-five minutes lapsed from the time of the initiation of this avalanche to the time a call for assistance was received by the resort patrol. Response time for the patrol was in the order of five minutes. Had the monitoring systems been far enough along to immediately alert the patrol, this in-area avalanche rescue could have been initiated 35 minutes earlier.

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