

## Evaluation of an infrasound detection system for avalanches, Rogers Pass, Canada; Winter 2016-17



***Recent avalanche debris on MacDonald West Shoulder following the large 11-19 March avalanche cycle. (Photo: Lisa Dreier, 20 March, 2017.)***

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## Executive summary:

Infrasound technology for the detection of snow avalanches was tested at Rogers Pass, BC, Canada over the 2016-17 winter season (24 December 2016 to 11 May 2017). Wyssen Avalanche Control provided a single IDA® infrasound array for this study. The summit area of Rogers Pass, Glacier National Park was selected as the test location for a single infrasound array due to its proximal location to avalanches from different aspects on several paths combined with a robust manual observational record.

Infrasound waves are low frequency sound waves that travel through the air at the speed of sound. Infrasound is widely used for the detection of natural hazards, including avalanches, and there have been significant improvements in this technology in recent years. Infrasound is used operationally on a number of highway avalanche programs in the USA, Norway and Switzerland and has provided valuable real-time information on avalanche occurrences and success with active control for these operations. Obtaining the precise timing of avalanche activity and the extent and confirmation of avalanche control, at night or during periods of poor visibility and in remote areas significantly improves operational avalanche forecasting, reduces closure time, and increases worker and public safety.

An analysis of the 2016-17 season was undertaken using detailed avalanche observations, as collected by Parks Canada Agency's Avalanche Control Section (ACS) and supplemented with additional manual observations, and compared with infrasound detected avalanche activity. Using both quantitative statistical and qualitative case-study approach methods, the performance of single infrasound array was evaluated for one season. This analysis clearly shows the ability of an infrasound system to automatically detect avalanche events, ranging from Size 1.5 to 3.5 at distances up to 4 km, and with consistently reliable detections up to 2.5 km. Furthermore, detailed case-study analysis shows the ability of the infrasound system to provide path specific location, point of initiation, run-out distance, and avalanche velocity estimates.

Statistical analysis of the results from this one season shows relatively poorer results than similar studies in other locations using infrasound (e.g. Norway<sup>1</sup> and Switzerland<sup>2</sup>) with a lower probability of detection of events (POD) of 0.41, or 41%. This difference is attributed to a combination of factors, including: the difference in avalanche control (i.e. artillery at Rogers Pass versus air-blast from Wyssen tower), number of avalanches and lack of full documentation (i.e. natural backcountry activity), the duration of the trial (i.e. one season only), and the number of sensors installed (i.e. a single array). Based on this analysis and other similar studies, significantly improved results are anticipated with the use of multiple arrays, and with more local calibration of the algorithm. Limitations to any infrasound system include topographic sheltering that results in channeling or blocking of the infrasound signal, incomplete observational record from areas within the detectable range and view-shed, and background noise.

Recommendations from this analysis for operational deployment include: installing multiple infrasound arrays with overlapping view-sheds 2.5 to 3.5 km apart to allow for more accurate detection and triangulation of avalanche events, ongoing local calibration of the algorithm, and further detailed analysis to quantify system functionality and performance over a number of years.

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<sup>1</sup> Humstad, T., Söderblom, Ø, Olivieri, G., Langeland, S., Dahle, H., 2016. Infrasound Detection of Avalanches in Grasdalen and Indreidsdalen, Norway. Proceedings of the International Snow Science Workshop 2016 Proceedings, Breckenridge, CO, USA

<sup>2</sup> Thüring, M. S., van Herwijnen, A., and Schweizer, J., 2015. Robust snow avalanche detection using supervised machine learning with infrasonic sensor arrays, Cold Reg. Sci. Technol., 111, 60-66, doi:10.1016/j.coldregions.2014.12.014

## 1.0 Introduction

This report has been prepared for McElhanney Consulting Services Ltd. (McElhanney), to document the evaluation of an infrasound detection system for avalanches in Glacier National Park (Rogers Pass), British Columbia (BC), over the winter season of 2016-17.

Dynamic Avalanche Consulting (DAC) coordinated the avalanche observation, evaluation and reporting for the infrasound system that was supplied and installed by Wyssen Avalanche Control (Wyssen) and DAC at the Rogers Pass Summit in December 2016. The installed system is identified by Wyssen as the IDA® infrasound detection system. Details of the system installation (e.g. location and equipment) were provided by DAC in a report to McElhanney titled “Wyssen Avalanche Control IDA – Rogers Pass Summit Research Concept V1” (Dynamic Avalanche Consulting, 2016). The IDA® system was active from December 24, 2016 to May 11, 2017.

### 1.1 Objectives

The objectives of the system installation at Rogers Pass Summit were to:

- Evaluate the infrasound system performance at Rogers Pass Summit during a trial period during winter 2016-17;
- Evaluate the limitations and performance characteristics of the system at this location, including the range of detection and size and type (wet, dry, powder) of avalanches that can be detected, and any system customizations needed for operation in Rogers Pass;
- Utilize the information obtained during this installation for the development of system specifications for tendering purposes on behalf of Parks Canada Agency (PCA) Highway Engineering Services (HES).

### 1.2 Tasks and coordination

DAC provided services to coordinate the efforts of the various parties involved in implementing this project, including:

- Equipment supply, software, system calibration (Wyssen);
- Avalanche occurrences and control result observations and verification (Parks Canada Agency’s Avalanche Control Section (ACS));
- Avalanche observers and data preparation and analysis (DAC and Lisa Dreier);
- IDA® signal processing and analysis (Giacomo Olivieri at iTem s.r.l and Department of Earth Science, University of Florence (iTem)); and
- Independent data analysis, interpretation of results and report preparation (Jordy Hendrikx at Montana State University (MSU)).

This report was prepared by Jordy Hendrikx, PhD., (MSU) with contributions from Lisa Dreier, Dipl. Ing., MSc (DAC sub-contractor) and Giacomo Olivieri, PhD (iTem). Data was primarily collected, organized and initially analyzed by Lisa Dreier. The infrasound analysis and updating of the algorithm for automatic detection was under taken by Giacomo Olivieri, PhD (iTem). Final data analysis and report preparation was completed by Jordy Hendrikx.

## 2.0 Background

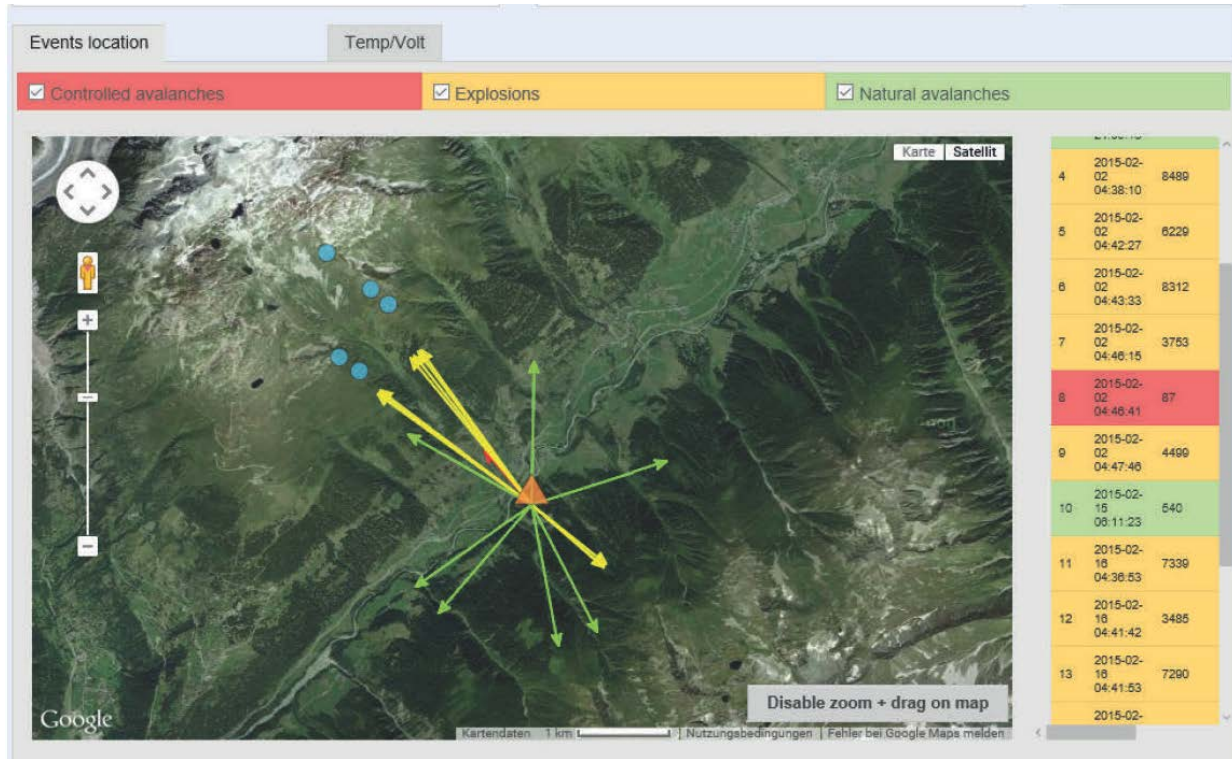
Operational avalanche forecasting is based on the combination of observations and models of the snowpack and weather (e.g. physical, empirical, and conceptual), which are validated by on-site observation of avalanche occurrence (McClung and Schaerer, 2006). Natural avalanche activity is a very clear sign of instability and is therefore often considered as the best warning for further events. This fact is often used operationally with the utilization of a test slope that shows avalanche activity, but which may not affect the highway or rail corridor. However, natural avalanche activity and verification of avalanche control work estimated by visual observations is limited by inclement weather and is difficult at night. This often prevents an operation from knowing the exact time of the occurrence of the event, or the level of success with avalanche control, thus resulting in a poor correlation with forecast models and a poor estimate of the danger (Schweizer et al., 2003). For this reason, obtaining the precise timing of avalanche activity and the extent and success of avalanche control, under all conditions, including at night or during periods of poor visibility and in remote areas, would significantly improve operational avalanche forecasting. This would both improve worker and public safety, as well as reducing closure times for the highway and railway.

A range of different approaches have been used to improve the observation of avalanches, including radar (e.g. Rammer et al., 2007; Vriend et al., 2013), seismic sensors (e.g. Van Herwijnen and Schweizer, 2011; Vilajosana et al., 2007), videogrammetry (e.g. Vallet et al., 2004) and infrasound (e.g. Scott et al., 2007; Ulivieri et al., 2011; Havens et al., 2014a; 2014b; Thüring et al., 2015; Steinkogler et al., 2016). In particular, the use of infrasound for operational avalanche monitoring has been increasing in the recent decade with significant improvements in sensors and automatic avalanche detection (Marchetti et al., 2015).

Infrasound waves are low frequency (<20 Hz) sound waves that travel through the air at the speed of sound (~340 m/s). Infrasound is widely used for the detection of natural (e.g. volcanic eruptions) and artificial phenomenon (e.g. nuclear explosions). Infrasound detection has made significant improvements in system design in recent years. After the initial work with single infrasound sensors (e.g., Bedard, 1989), the use of infrasound arrays has significantly improved the signal-to-noise ratio (e.g., Scott et al. 2007; Ulivieri et al., 2011; Havens et al., 2014a), thus resulting in a larger efficiency of infrasound in detecting snow avalanches even at larger (i.e. a few km) distances. Array processing techniques showed that back azimuth and apparent velocity of infrasound generated by snow avalanches can be traced at a source-to-receiver distance of 2 km (Ulivieri et al., 2011) and can be used to evaluate avalanche front velocity (Havens et al., 2014). Recently, a network of three infrasound arrays deployed in three different valleys in Valle d'Aosta, Italy, permitted detection and location of a Size 3 avalanche at a source-to-receiver distance of ~ 20 km (Ulivieri et al., 2012).

A typical infrasound system consists of a 4 to 6 element array with an aperture (maximum distance between sensors) of approximately 150 m. Sensors and housing can lie on the surface, be buried in the ground or possibly mounted on towers, depending on site conditions. Partial burial in the ground and under snow cover has the benefit of reducing background noise (Ulivieri pers. comm., 2016). The typical range of detection is commonly stated as 3 - 5 km, but large avalanches have been detected at a range of 10 - 20 km, albeit inconsistently. Infrasound systems can resolve the signal's azimuth angle of arrival

relative to the sensor, which can then be used to indicate an avalanche occurrence in a particular path (Figure 1).



**Figure 1:** Online map visualization of the IDA® system showing explosively triggered avalanches (red arrows), explosions (yellow arrows) and natural avalanche activity (green arrows). Blue circles indicate positions of Remote Avalanche Control Systems (RACS) (from Steinkogler et al., 2016).

Currently, in North America there are several infrasound installations used for avalanche detection, including several operational systems. These systems include the Wyoming Department of Transportation (WYDOT) on Teton Pass (Scott et al., 2007; Scott, 2008), the Utah Department of Transportation (UDOT) in Little Cottonwood Canyon Road (Vyas, 2009), and research focused systems by Boise State University and Idaho Transportation Department on Highway 21 (Havens et al., 2014b).

There are also several infrasound installations in Europe, including: one in Ischgl, Austria (Marchetti et al., 2015), four in Switzerland (Steinkogler et al., 2016), and two in Norway (Indreidsdalen and Grasdalen) (Humstad et al., 2016). In all of these locations, infrasound systems are used to confirm avalanche control blasts and their resulting avalanches, as well as to detect and provide warning of natural avalanche occurrences. Operations that currently use detection systems note the effectiveness of their systems in improving the program, with demonstrable qualitative and quantitative benefits to program performance, improved safety and reduced closure times.

## 3.0 Methods

### 3.1 Equipment supply and installation

In late November, 2016 multiple potential sites near to the Rogers Pass Summit area were selected for this evaluation of the infrasound system (DAC, 2016). While the IDA<sup>®</sup> system can be operated autonomously with fuel cells / batteries, locating this trial unit in close proximity to existing buildings permitted a permanent power supply to be used, thereby reducing set-up costs and increasing the efficiency of deployment. Based on an evaluation of three proposed sites, a final location east of the existing ACS weather study plot near Rogers Pass was selected.

Giacomo Ulivieri with the assistance of Chris Argue (DAC) and Alan Jones (DAC) and installed the IDA<sup>®</sup> array on Monday – Wednesday, 12-14 December 2016. The IDA<sup>®</sup> infrasound system was operational and providing real-time automatic detections via an online platform with cellular text message alerts on 24 December, 2016.

The infrasound monitoring system deployed at Rogers Pass Summit consisted of a 4-element array, with a triangular geometry and an aperture (maximum distance between two elements) of approximately 100 m. Three sensors were placed on the ground, and the fourth sensor was housed in the central unit (Figure 2), which consisted of a small wooden hut with power supply from a Parks Canada building nearby, data storage, and data transmission using the mobile phone network. The infrasound array was installed in the forest on the valley bottom with views towards multiple different avalanche paths nearby (Figure 3). Shortly after installation, the three infrasound sensors distant from the central unit were covered with snow, which further dampened ambient background noise and reduced the impact of wind and other noise disturbance. The fourth sensor, located in the central unit was not covered in snow, and hence had a higher level of background noise throughout the winter, which was most noticeable during valley bottom wind events.

Similar to the recent installations in Norway (Humstad et al., 2016), the four elements of the infrasound system were equipped with a differential pressure transducer (iTem-prs0025f) with high sensitivity (200 mV/Pa), broad-band frequency range (0.01-50 Hz) and low noise level (<0.01 Pa). Analog to digital conversion of pressure, temperature and battery voltage is performed at each array element, and digital data are transmitted using fiber optic cables to a central data collector, and are stored at 50 Hz sampling rate and 24 bit of resolution. The system was equipped with a GPS receiver, which ensured the absolute time synchronization. The raw infrasonic record was then transmitted real-time using a cellular data modem, and analysis was done from an off-site server. The data are processed and then presented online, with multiple data visualizations options and real-time cellular text messaging and email messaging alert systems.

While this study used and evaluated an IDA<sup>®</sup> infrasound system provided by Wyssen, our analysis should be considered more generic in context, as all infrasound systems are fundamentally designed in a similar way to record and then interpret infrasound waves. A different supplier's system would have somewhat different hardware, software, and presentation of results, but the fundamental method and interpretation of data is common to all infrasound systems.



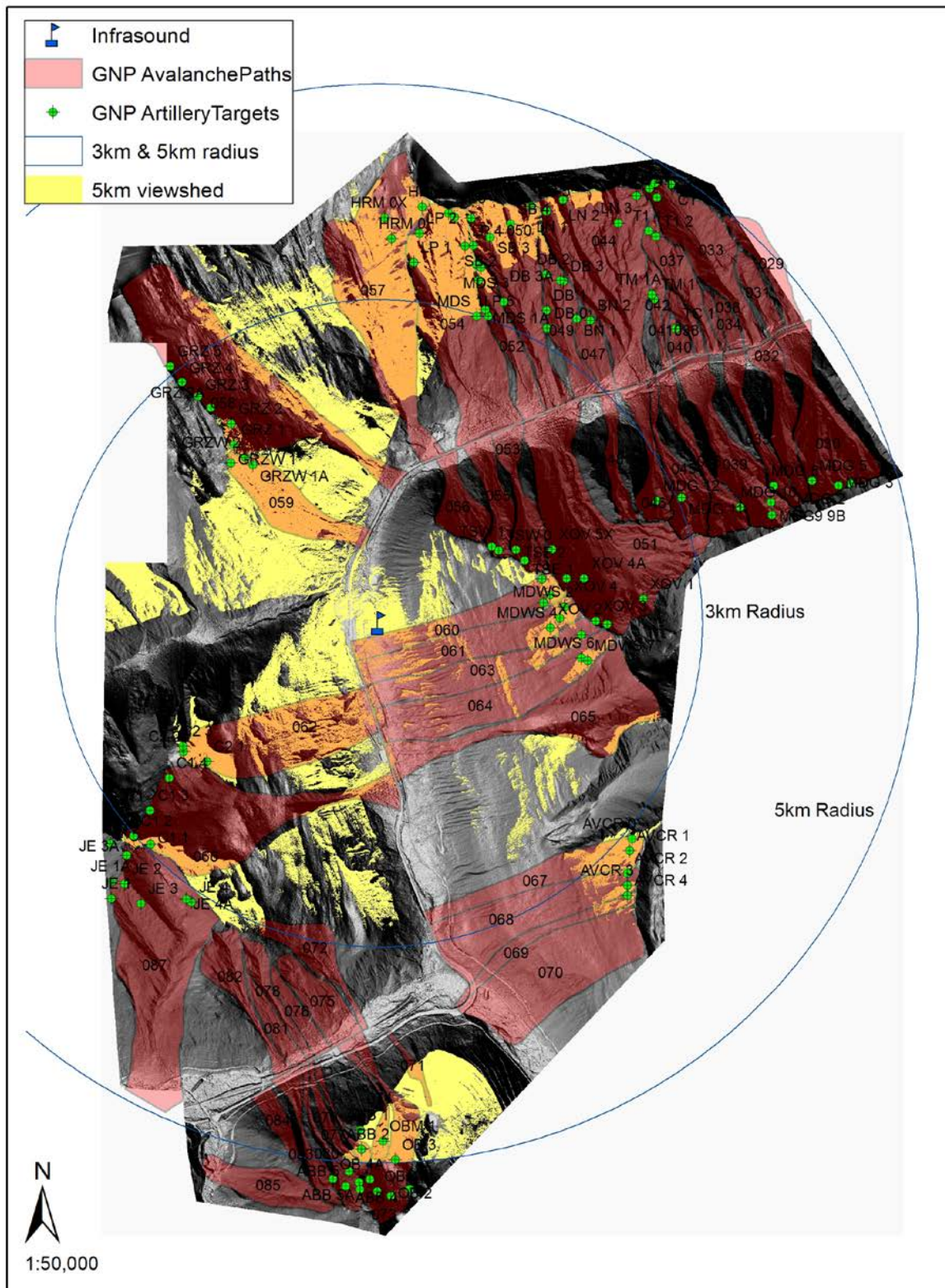
**Figure 2:** **Left and Center:** Central element of the infrasound station enclosed within the wooden structure with power supply, data storage and data transmission units as well as one infrasound sensor. **Right:** One of the outer sensors being installed, showing the transducer inside a partially buried plastic housing. Left and center photos by Lisa Dreier (May 11, 2017 and March 17, 2017). Right by Chris Argue, DAC (12 December, 2016).

### 3.2 Avalanche control and observations

Observation of both natural and controlled avalanches were made by ACS for the entire road corridor, as a routine component of their avalanche forecasting and management program for the highway. The records of avalanches observed and avalanche control undertaken within a 5 km radius of the infrasound system were provided weekly to DAC by ACS. During this winter season ACS increased their efforts to record smaller avalanches ( $\geq 1.5$ ) in this area to support this study.

These records were reviewed by Lisa Dreier and verified both by review of the database and field observations. Additional backcountry activity was also sporadically added to this database, as time and resources permitted. The quality and quantity of these backcountry avalanche records is variable, but improves the information obtained during critical avalanche cycles. The result of this effort ensured a robust set of avalanche and avalanche control records for all avalanche paths that directly affect the road, and a less robust, but still valuable record of backcountry avalanche activity.

Following major avalanche cycles, photos of the avalanches were taken by Lisa Dreier from the highway corridor with support of the ACS forecasting team. Furthermore, ACS also provided photos of specific events that were along the highway corridor. Some photos were also taken of backcountry avalanches.



**Figure 3:** View-shed analysis (in yellow), where overlapped with avalanche paths (in orange) from the infrasound location, showing all avalanche paths (light red) and artillery targets (green) within a 5 km radius of the infrasound. Data is presented overlain on a hill-shade raster.



### 3.3 Signal processing

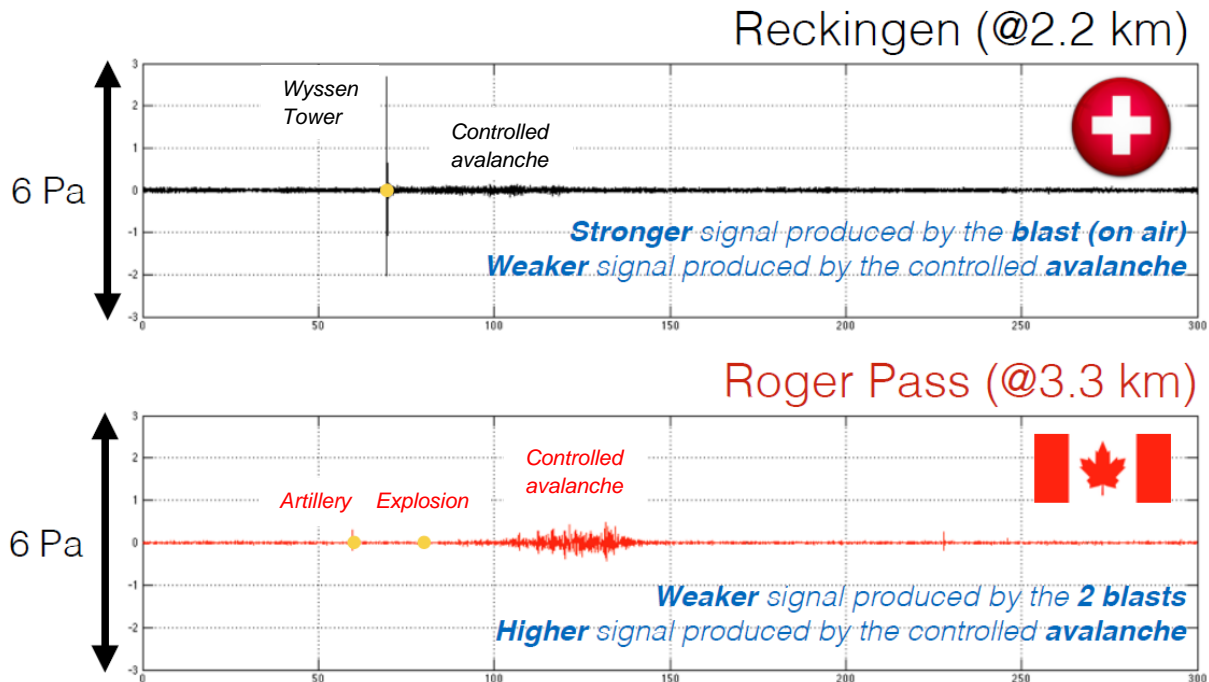
The array signal processing is based on the assumption that an infrasound signal is coherent (i.e. as defined by the Fisher statistic) at the different sensors, while noise does not show any correlation. The detection algorithm is based on a multichannel correlation method using different parameters. To identify signals from noise, time correlation, amplitude, wave propagation, back-azimuth, apparent velocity and dominant frequency are calculated. For more details about the specifics of the signal processing for the infrasound system the reader is referred to Ulivieri et al. (2011, 2012).

In this evaluation, two versions of the automatic detection algorithm were employed. Version 1 (v1) of the algorithm has been previously used in Europe with the IDA<sup>®</sup> system (e.g. Ulivieri et al., 2012). This algorithm has been specifically designed to detect the explosion from a Wyssen tower (i.e. 5 kg explosive air-blast) or a Gazex (i.e. gas explosion in the air) followed by an avalanche. It should be noted that this produces a very different signal to an artillery round (i.e. 2.5 kg on-snow detonation) which detonates on impact with the snow surface. The v1 algorithm specifically checks for the air-blast, and then increases its sampling rate to observe subsequent avalanche activity. Given that both natural and artillery triggered avalanches occur frequently in the Rogers Pass corridor, we anticipate that this v1 algorithm will not fully demonstrate the potential of infrasound in this setting.

Version 2 (v2) of the algorithm is an updated version of the above described algorithm, but rather than specifically using the air-blast to help with avalanche detection, it was designed to detect the firing of the artillery from the highway level, the detonation of the artillery in an avalanche starting zone, and then the subsequent avalanche activity. Due to the low ambient noise setting of the installed infrasound, this algorithm was also able to effectively detect natural avalanche activity. This v2 of the algorithm was prepared at the end of the season (May – July, 2017) and then used to retroactively detect avalanches for the full winter season. Despite this post-season (i.e. non real-time) deployment of this algorithm, the results in real-time usage would be the same, so comparison of the algorithm performance can still be undertaken.

Figure 4 presents an example of the differences in the signal, where the top graph represents data from the Reckingen site in Switzerland with a Wyssen tower air-blast, followed by an avalanche (v1 algorithm scenario), and the bottom graph represents data from Rogers Pass site, with artillery use, followed by an avalanche (v2 algorithm scenario).

When using these algorithms, automatic detection of avalanches results in automatic alerts, via email and/or text message service, and reporting of the Peak Pressure (mPa), Back Azimuth (° from North), Azimuth migration (°), duration (seconds) and likely path attribution is provided.



**Figure 4:** Differences in the infrasound signal, where the top graph represents data from the Reckingen site in Switzerland: Wyszen tower air-blast, followed by an avalanche (v1 algorithm scenario); and the bottom graph represents data from Rogers Pass site: artillery use, followed by the explosion, followed by an avalanche (v2 algorithm scenario).

### 3.4. Data preparation

Before an analysis of the effectiveness of the infrasound system can be undertaken, the avalanche observation and avalanche control records, and infrasound records need to be connected. To facilitate this, the avalanche paths that the infrasound can accurately detect must be determined. We elected to only use those avalanche paths that are both within the 5 km radius from the Rogers Pass Summit infrasound location, and were also within direct line-of-sight (i.e. within the GIS estimated view-shed). Expert judgement was used to refine this list where there was uncertainty. This is shown graphically in Figure 3. This selection resulted in ten (10) paths for the subsequent analysis (Table 1).

Manual matching of infrasound automatic detections and manual avalanche observations was then undertaken for these paths. This used a multi-parameter approach which included the date and time of the detection, the back azimuth of the detection, and cross referencing these to manually observed avalanche events. A multi-sensor system with overlapping view-sheds would permit improved automatic attribution of infrasound detections to specific paths, which has clearly been demonstrated operationally in Little Cottonwood Canyon, Utah (e.g. Scott, 2008, Vyas, 2009).

In addition to tracking all avalanche events within 5 km and within line-of-sight of the infrasound, an Avalanche-Activity Index (AAI) was also calculated. The AAI is the sum of avalanche sizes observed (McClung and Tweedy, 1993) and provides a numerical expression for the scale and intensity of avalanche activity for a given day.

**Table 1** Avalanche paths within 5 km and within the infrasound view-shed. Paths are shown in Figure 3, and labelled according to their Path ID#

Avalanche Path	Path #	Targets within view-shed	Targets out of view-shed
Lone Pine	054	LP1, LP2, LP3, LP3A, LP4	LP5*
Hermit Slide	057	HRM0, HRMOX, HRM1	
Grizzly West	059	GRZW1, GRZW1A, GRZW2	
MacDonald West Shoulder #1	060	MDWS0, MDWS1, MDWS1A	
MacDonald West Shoulder #2	061	MDWS2, MDWS3, MDWS4	
MacDonald West Shoulder #3	063		MDWS5*
MacDonald West Shoulder #4	064	MDWS6, MDWS7	
Cheops #1	066	C1 1	C1 2*, C1 3, C1 4
Cheops #2	062	C2 1, C2 2, C2 3	
Shoulder Valley	065		

\* Targets outside of the GIS estimated view-shed, but likely still within the infrasound “view” of the infrasound since line-of-site is not necessarily needed for sound waves.

### 3.5 Independent data analysis

To document and describe the performance of the two automatic detection algorithms for the trial period we used standard model assessment metrics, including: the unweighted average accuracy (RPC); the true skill score (TSS); the false alarm ratio (FAR); the probability of detection of events (POD); and non-events (PON). We used the same definitions as documented by Wilks (1995) and Doswell et al. (1990), and as used by Hendrikx et al. (2014) for avalanche-days (Equations 1-5):

$$\text{Unweighted average accuracy: } RPC = 0.5 \left( \frac{a}{a+c} + \frac{d}{b+d} \right) \quad (1)$$

$$\text{True skill score: } TSS = \frac{d}{b+d} - \frac{c}{a+c} \quad (2)$$

$$\text{False alarm ratio: } FAR = \frac{c}{c+d} \quad (3)$$

$$\text{Probability of detection } POD = \frac{d}{b+d} \quad (4)$$

$$\text{Probability of non-events } PON = \frac{a}{a+c} \quad (5)$$

The definitions are shown in the contingency table (Table 2). An ideal model should have a high POD, while maintaining a high PON, thereby predicting events and non-events equally well. This would also reduce the FAR (where 0 is a perfect score) and show in the TSS and RPC (values between 0 and 1) where values approaching 1 are desirable.

**Table 2** Contingency table for our model performance equations (1-5).

		Manual Observations	
		Non-Avalanche Event	Avalanche Event
Infrasound Detection	Non-Avalanche Event	a: Correct non event	b: Misses
	Avalanche Event	c: False alarm	d: Hits

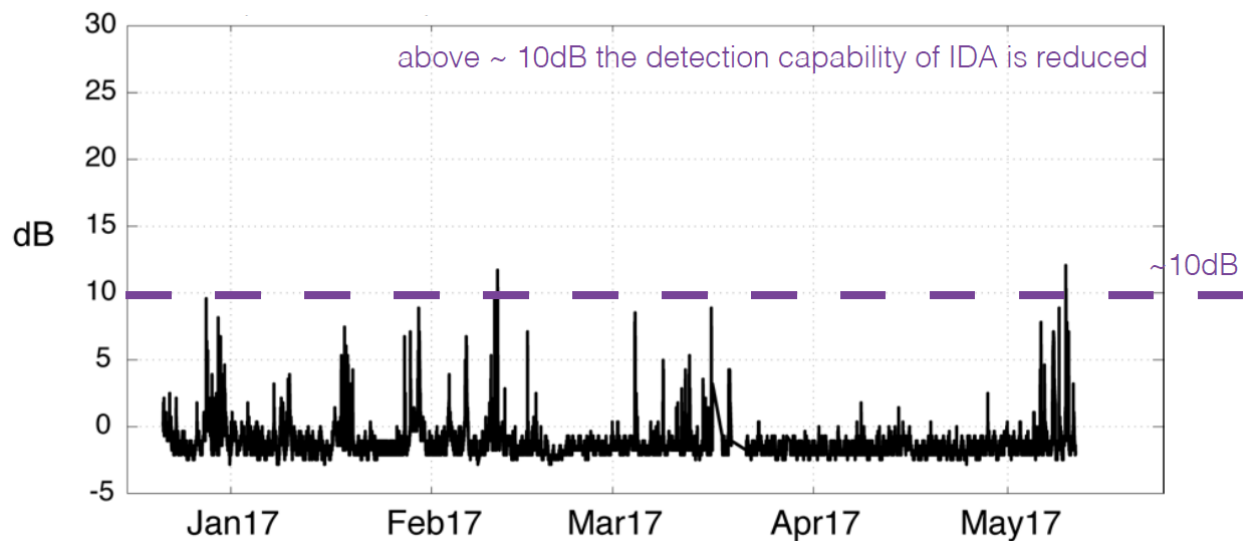
In addition to these quantitative measures of the infrasound system performance, a series of case-studies of specific avalanche cycles were selected for qualitative analysis. These avalanche cycles were representative of almost the entire continuum of avalanche activity expected at Rogers Pass, from cold and dry powder avalanches in January, February and March, to warm and wet flowing avalanches in May. The intent of this analysis was to evaluate the potential of an infrasound system to detect the full spectrum of avalanche events, and also more closely examine the limitations of the system.

## 4.0 Results and Discussion

### 4.1 Sensor performance

The infrasound system provided 59 automatic detections using the version 1 algorithm, and 149 automatic detections using the version 2 algorithm over the duration of the test season (December 24, 2016 – May 11, 2017).

The test site was ideally suited with respect to background noise (e.g. wind or anthropogenic), with the mean infrasonic background noise level exceeding 10 dB only 1% of time (equivalent to approximately 1 day over 4.7 months). Background noise exceeding 10 dB is considered to be the level at which the infrasound system performance is reduced (Ulivieri, et al., 2011) (Figure 5). This mean noise from the 4 sensors was likely higher due to increased noise levels from the fourth sensor inside the central enclosure, which was not covered in snow. Had this sensor also been covered in snow, the mean background noise would likely have been even lower.



**Figure 5:** Mean infrasonic noise level for the four (4) sensors from the Rogers Pass infrasound system. Note that 10 dB is the background noise level at which infrasound performance is reduced.

The sensors were subjected to several months of burial under snow with no impact on the sensor performance. The burial under the snowpack of the three outermost sensors provided additional filtering of the background noise. On removal of the system in May, local surface flooding near the sensors was observed, and this should be considered for future sensor deployment. Elevating sensors above the local flooding height, but still below the mean winter snowpack height would be ideal.

## 4.2 Seasonal summary

A seasonal overview is presented in Figure 6. This seasonal overview includes:

- The Glacier National Park Hazard form levels from 1 to 4, where: None (1) = Green; Alert (2) = Yellow; Hazard (3) = Orange; and Control (4) = Red;
- Glacier National Park Avalanche danger levels as documented in the afternoon (PM) report in InfoEx for the Alpine (ALP) and Treeline (TL), where: Low = Green; Moderate = Yellow; Considerable = Orange; and High and Extreme = Red;
- 24h Precipitation (in mm) [blue bars]; and minimum and maximum temperatures (in °C) [black bars] at the Rogers Pass weather station;
- Observed avalanches (natural and controlled) within 5 km and in-sight of the infrasound (as per the avalanche paths shown in Table 1);

- Avalanche-activity index (AAI) is the sum of avalanche sizes observed (McClung and Tweedy, 1993);
- Automatic infrasound detections (only version 1 of the algorithm shown):
- Significant avalanche cycles (highlighted in gray)

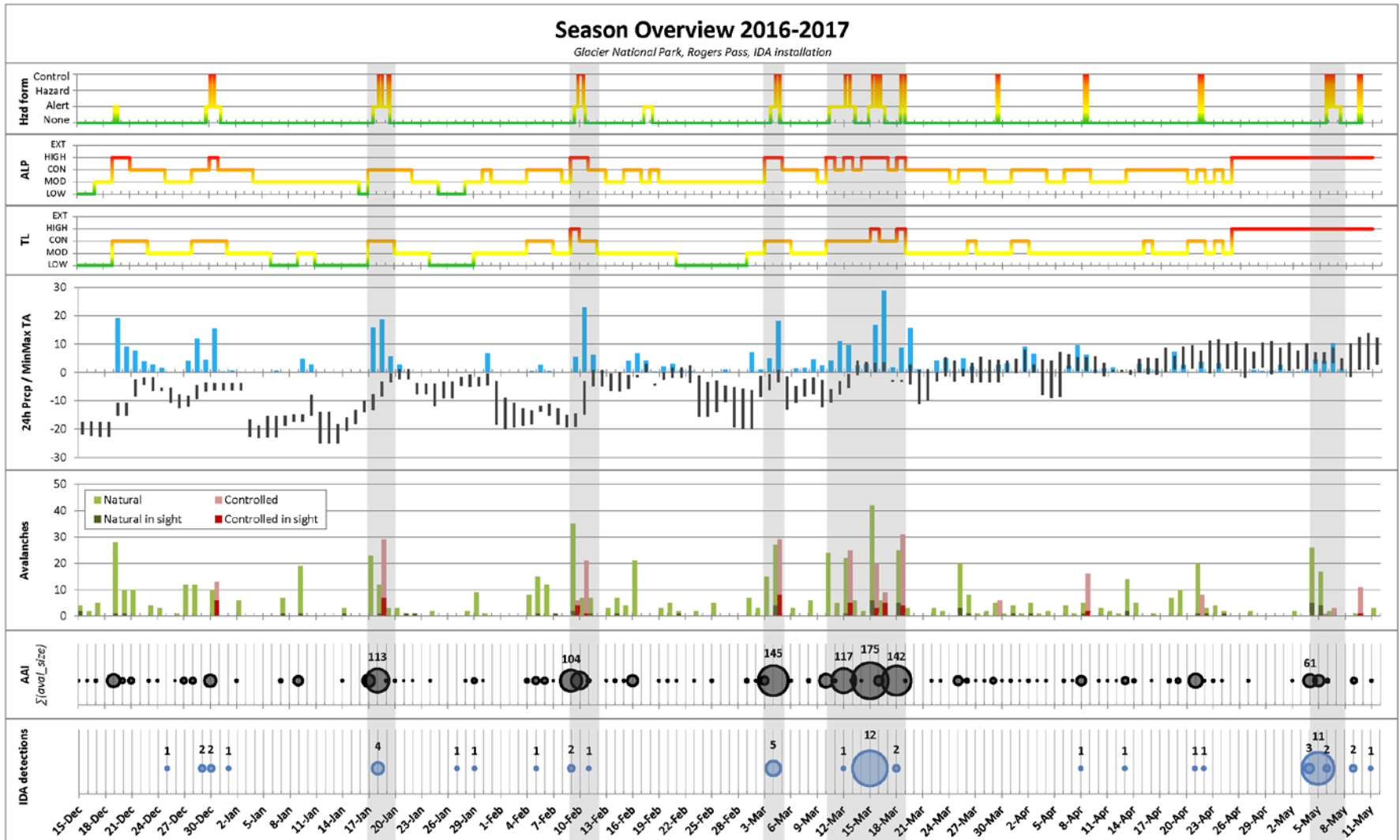
The overview provides a quick summary of the season, and clearly shows that the infrasound, even using the v1 algorithm, was able to automatically detect avalanche activity during each of the significant avalanche cycles. It is worth noting that these avalanche cycles are representative of the range of avalanche conditions expected at Rogers Pass, from cold and dry powder avalanches, to warm and wet flowing avalanches. Furthermore, the infrasound system provided automatic detections for both naturally triggered avalanches as well as artillery controlled avalanches.

### 4.3 Automatic detections seasonal summary

Our first analysis of the infrasound performance is considered in aggregate, where all avalanche observations within the ten paths of the infrasound view-shed (as specified in Table 1) are directly compared to all automatic infrasound detections in this same view-shed. This first analysis considers the version 1 (v1) of the infrasound algorithm only. Note, as mentioned in the methods section above, this algorithm was specifically designed for locations in Europe where Wyssen towers with a 5 kg air-blast and Gazex installations with gas explosions in the air were used, opposed to artillery with a 2.5 kg on-snow detonation for avalanche control. We acknowledge that this difference makes the automatic detection of avalanches with infrasound using this algorithm more challenging. Our second analysis using this data set uses an updated v2 of the automatic detection algorithm, which is specifically designed to detect the firing of artillery from the highway, and the subsequent explosion, and where present triggered avalanches.

For this analysis we consider all avalanche occurrences on these ten paths over the period December 24, 2016 to May 11, 2017. This resulted in a sub-set of 97 avalanche observations (from a total of 125 avalanche and avalanche control observations). The remaining 28 records were avalanche control work which did not result in an avalanche, with 26 from artillery control (Xa) and 2 from helicopter bombing (Xh) which is used by ACS periodically in the springtime.

Of the 97 avalanche observations, 51 were natural (N), 45 were from artillery control (Xa) and one was from helicopter bombing control (Xh). These avalanches ranged in Size from 1.5 to 3.5 according to the standard Canadian destructive size scale for avalanches. This represents a sub-set from a larger data set of 977 avalanches and avalanche control observations, recorded within a 5 km radius of the infrasound over this period. Neither this larger database (N = 977), nor the smaller subset (N = 97), included all avalanches that occurred within the backcountry area, but that which do not affect the road way (e.g. in the Connaught Creek area).



**Figure 6:** Seasonal summary for the 2016-17 avalanche season at Rogers Pass, Glacier National Park. See Section 4.2 for full description of the data presented.

#### 4.3.1 Version 1 algorithm

Using the v1 algorithm over this same period of time there were 59 automatic detections by the infrasound, with 47 being automatically defined as “LOW” reliability detections, and 12 as “HIGH” reliability detections. From these 59 automatic detections, 20 detections could be conclusively linked to the manual avalanche observation records, and a further 10 detections could be linked with less confidence to this record, for a total of 30. These 30 avalanches ranged in Size from 1.5 to 3.

The remaining 29 infrasound detections were attributed to avalanche occurrences in the backcountry, which were not documented in the avalanche records. This lack of verification data for backcountry avalanche activity presents a challenge for quantitative assessment of the infrasound performance according to the performance metrics (Equations 1-5). However, based on previous infrasound system analysis, the type of signal, and the low noise environment that this equipment was set up in, we consider it highly likely that these 29 automatic detections are real avalanche observations that went unrecorded in the backcountry. In 21 of these 29 events, independent manual observations (i.e. by Lisa Dreier), or proxy data (e.g. related activity elsewhere) provided a high degree of confidence that these infrasound detections were backcountry avalanche events; however, specific avalanche occurrences could not be linked due to a lack of observations. For the analysis of infrasound performance metrics (as per Equations 1-5), these backcountry events cannot be considered, but will be discussed in a later section of this report.

In summary, over the period of record there were 97 recorded avalanche observations in these 10 paths, of which 30 were correctly identified by the infrasound automatically using v1 of the algorithm (Table 3). A further 17 signals were manually connected to signals in the infrasound record, but were not automatically detected as avalanches. In this analysis these manual assessments are considered separately in the performance metrics (as per Equations 1-5), and show potential for improvement in an enhanced algorithm (Table 4).

While the correct detection of avalanches is important for an operational avalanche program, this should not come at the cost of detecting avalanches when they are not occurring (i.e. false alarms). To assess this component of the performance of the infrasound, we randomly selected 100, 1-hour periods with no observed avalanche occurrences. These were selected from the whole season with infrasound observations (24 December, 2016 to 11 May, 2017) using a random number generator from periods of avalanche activity. Where the random number selected a one hour period that coincided with documented avalanche activity, the next random number was selected. This resulted in a set of one-hour periods of non-avalanche events during periods of potential instability, which was then compared to the infrasound detections. No infrasound detections were present during any of these times (Table 3 and 4), suggesting no false alarm signals (i.e. avalanche detection when no avalanche occurred) were generated from the infrasound system. These summary metrics are presented in Table 6.



**Table 3:** Contingency table algorithm v1

		Manual Observations	
		Non-Avalanche Event	Avalanche Event
Infrasound Detection	Non-Avalanche Event	a: 100	b: 67
	Avalanche Event	c: 0	d: 30

\*Note: An additional 29 avalanches were detected by IDA, but were from areas outside of where these 97 events were observed, so have not been included here.

**Table 4:** Contingency table algorithm v1 plus manual

		Manual Observations	
		Non-Avalanche Event	Avalanche Event
Infrasound Detection	Non-Avalanche Event	a: 100	b: 50
	Avalanche Event	c: 0	d: 47

\*Note: An additional 29 avalanches were detected by IDA, but were from areas outside of where these 97 events were observed, so have not been included here.

### 4.3.2 Version 2 algorithm

Using the v2 algorithm over this same period, but run in a hind-cast mode for the season, there were a total of 149 automatic detections. These did not have a specific reliability measure included. From these 149 automatic detections, 40 detections could be conclusively linked to the manual avalanche observation records (i.e. the 97 events discussed above) within these 10 selected paths. These 40 avalanches ranged in Size from 1.5 to 3.5 at distances up to 4 km, but more typically less than 3 km. The remaining 109 infrasound detections could not be linked to avalanche observations from these 10 paths, and are very likely to either represent natural backcountry activity (e.g. in the Connaught Creek area), natural or controlled avalanches on paths outside of these 10 paths selected for this analysis. A manual review of the infrasound signals strongly supports this idea as an avalanche provides a distinctive signal which is clearly different to background noise. For the analysis of infrasound performance metrics (as per Equations 1-5), these events cannot be considered, but will be discussed in a later section of this report.

When we consider the record of observed natural avalanches, 26 of the 51 natural events were successfully detected by the infrasound system, while 25 of the 51 natural events were not. When examining the 26 naturals that were detected in more detail; 2 were Size 1.5 (Lone Pine and Grizzly West); 5 were Size 2; 4 were Size 2.5; 12 were Size 3 and 3 were Size 3.5. This compares to the 25 undetected natural events; where 4 were Size 1.5; 15 were Size 2; 2 were Size 2.5; 2 were Size 3 (MacDonald West Shoulder #1 and Cheops #2) and 1 was Size 3.5 (Hermit slide). Clearly the infrasound system is better at detecting natural avalanches larger than Size 2.5 with 19 of 25 natural events above this size accurately detected. Of concern are the 2 Size 3 and 1 Size 3.5 that were not successfully detected. The largest of these was the Size 3.5 on Hermit slide, and could possibly be explained by the lower sections of the run-out zone being outside of the infrasound view-shed due to a significant terrain feature.

When we consider the record of observed controlled avalanches, 14 of the 46 controlled events (Size greater than zero), were successfully detected by the infrasound system, while 32 of the 46 controlled events were not. When examining the 14 controlled events that were detected; 2 were Size 2; 7 were Size 2.5; and 5 were Size 3.

This compares to the 32 undetected events; where 2 were Size 1.5; 8 were Size 2; 11 were Size 2.5; 9 were Size 3; and 2 were Size 3.5 (both on Lone Pine). The infrasound system struggled to detect controlled avalanches, but did manage to detect those larger than Size 2.5 with 12 of 34 controlled events above this size accurately detected. Of particular concern are the large number of Size 3 and 3.5 that were not successfully detected. Interestingly, specific paths including Lone Pine and Cheops #1 represent 16 of the 32 events that were not detected by the infrasound. An examination of the GIS view-shed analysis shows that the entire runout zone for Lone Pine is not visible, whereas the majority of the Cheops #1 path is deeply incised into the slope, with only the lower most sections of the run-out zone within the GIS estimated view-shed. It is possible that view-shed limitations resulted in these non-detections, which would likely be resolved with a multi-array system.

In summary, over the period of record we have 97 avalanche recorded observations in these 10 paths, of which 40 were correctly identified by the infrasound automatically using v2 of the algorithm (Table 5). Of these 40 correctly identified events, 14 were for controlled avalanches, and 26 were for natural avalanche activity. We used the same 100, 1-hour periods for our non-avalanche events during periods of potential instability, which was then compared to the infrasound detections. As for the above analysis, no infrasound detections were present during any of these times (Table 5). Summary metrics from Equations 1 to 5 are presented in Table 6.

**Table 5:** Contingency table algorithm v2

		Manual Observations	
		Non-Avalanche Event	Avalanche Event
Infrasound Detection	Non-Avalanche Event	a: 100	b: 57
	Avalanche Event	c: 0	d: 40

\*Note: An additional 109 avalanches were detected by IDA, but were from areas outside of where these 97 events were observed, so have not been included here.

**Table 6:** Performance metrics for the automatic detection algorithm.

Performance Metric	v1 algorithm	v1 algorithm & Manual	v2 algorithm
RPC (Unweighted average accuracy):	0.65	0.74	0.71
TSS (True skill score):	0.31	0.48	0.41
FAR (False alarm ratio):	0.00	0.00	0.00
POD (Probability of detection)	0.31	0.48	0.41
PON (Probability of non-events)	1.00	1.00	1.00

An ideal model should have a high probability of detection (POD), while maintaining a high probability of non-events (PON), thereby predicting events and non-events equally well. This would also reduce the false alarm ratio (FAR), where 0 is perfect, and increase the true skill score (TSS) and unweighted average accuracy (RPC) scores (values between 0 and 1).

With the assumptions made, regarding avalanche detections that were not connected to documented events in one of the ten paths, there is greater uncertainty in the non-avalanche detection periods, which clearly results in greater uncertainty in some of the performance metrics presented here. Specifically, the unweighted average accuracy (RPC); the true skill score (TSS); the false alarm ratio (FAR); the probability of detection of non-events (PON) have higher levels of uncertainty. The probability of detection of events (POD) can be considered with the greatest confidence, but even this metric is challenged by the fact that we have excluded the infrasound detections of avalanche events from paths outside the 10 selected paths.

Despite this, comparison of these results to other examples of the infrasound systems used in Europe highlights the relatively poor performance in this trial at Rogers Pass using the version 1 and 2 algorithms. Humstad et al., (2016) documented much higher success rates with POD of 0.84 to 1.0 and FAR of 0.08 and 0.00 for Gransdalen and Indreidsdalen Norway respectively. The results from this study show much lower POD, likely attributed to the exclusion of infrasound observations outside of these 10 paths, but with a comparable FAR.

Given the nature of these data, the nuances of these metrics when dealing with missing and or extra observations that are poorly classified into the contingency table, it is also helpful to assess the infrasound system performance in a more qualitative manner.

#### 4.4. Major avalanche cycles

In addition to the examination of the infrasound detections for the whole season for two algorithms, we also examined in detail three key avalanche cycles in the 2016-17 winter at Rogers Pass (grey bars in Figure 6). These were:

- Avalanche Cycle 1: 9 – 13 February, 2017
- Avalanche Cycle 2: 11 – 18 March, 2017
- Avalanche Cycle 3: 4 – 9 May, 2017

These avalanche cycles are representative of almost the entire continuum of avalanche activity expected at Rogers Pass, from cold and dry powder avalanches in January, February and March, to warm and wet flowing avalanches in May.

The following section provides a qualitative assessment of the infrasound system performance with respect to these cycles. The intent of this section is to explore the potential of an infrasound system, and also more closely examine the limitations. These case-studies will not document every infrasound

detection and avalanche event during these periods, but rather focus on notable events that show the utility, potential and limitations of the system.

#### 4.4.1 Avalanche Cycle 1: 9 – 13 February, 2017

Snow started falling on the evening of Wednesday 8 February, with increasing intensity on Thursday 9 February. The snow buried a slab which in turn was formed on top of a variety of surfaces 40-50 cm below the new snow surface; sun crust on steep solar slopes, wind-slabs in the alpine and gully features, small surface hoar and facets. The storm snow added up to 55 cm on the morning of Saturday 11 February and fell with moderate to strong winds from NE to S. Avalanche debris was heavily blown over and often barely or not visible at all anymore the next day. The blown in snow made it hard distinguish the age of existing debris. Over this period, maximum temperatures increased from -15°C on Wednesday 8 February to 1 °C on Friday 10 February.

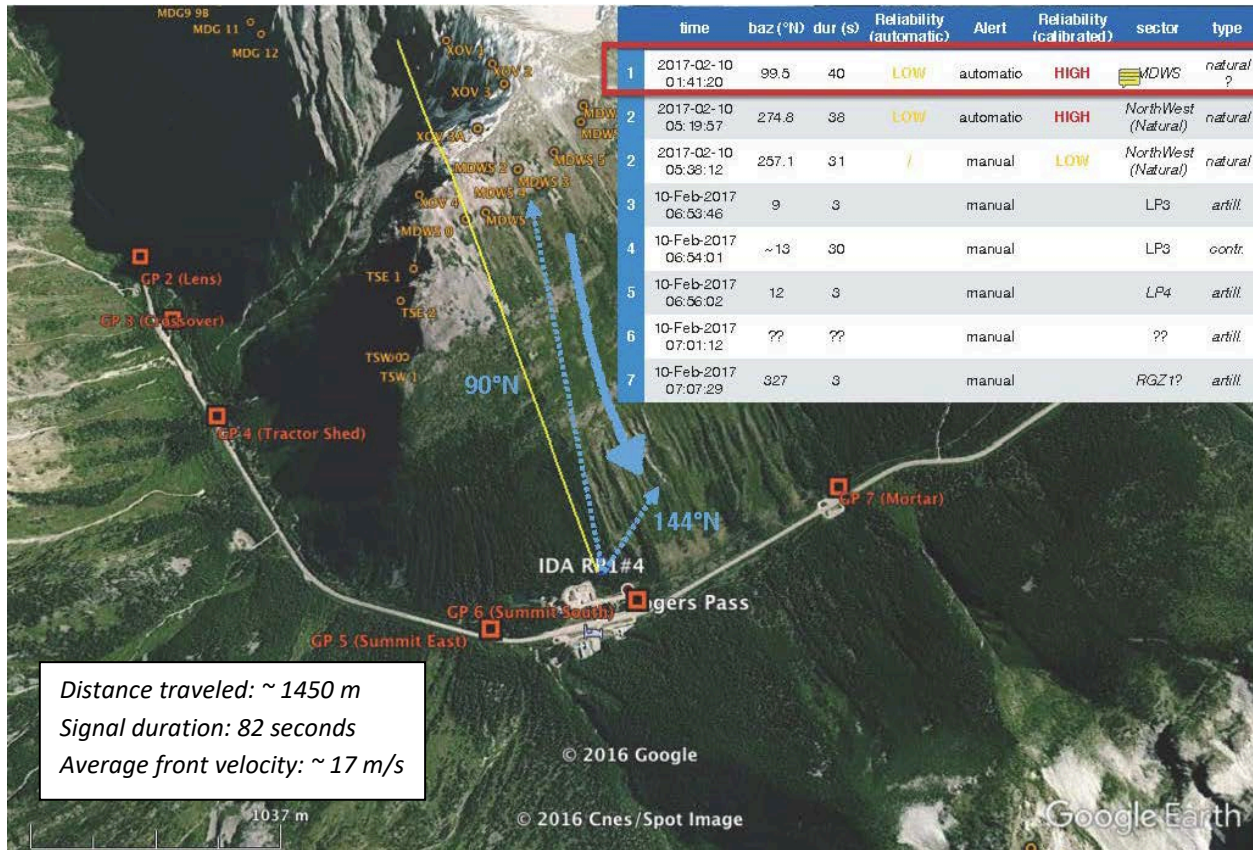
During this avalanche cycle, 5 controlled and 3 natural avalanches were observed in the ten avalanche paths in sight of the infrasound system. This number was out of 27 controlled and 52 natural avalanches observed within the 5 km radius.

Natural avalanche activity started on the afternoon of Thursday, 9 February. Avalanches were reported in Connaught Creek (Cheops North and Frequent Flyer) in the afternoon. One of these is likely the second automatic detection by the infrasound in this period. The first infrasound detection in this period was a natural Size 2.5 avalanche in the evening (1741 PST on Thursday 9 February) at MacDonald West Shoulder Path #2. The infrasound detection assisted in the documentation of the time of occurrence by ACS. Furthermore, due to the heavy snowfall, the debris was almost undetectable by ACS observers the next morning, and may have been missed if the infrasound detection had not alerted them to this event. A summary of this event, showing the distance traveled, signal duration, back-azimuth and migration, and estimated velocity, is shown in Figure 7.

Artillery control started on Thursday 9 February shortly before 2300 PST, and ended the next morning on Friday 10 February around 0930 PST. Good artillery results were obtained at the east side of the pass, with fewer results obtained on the west side of the pass. No results were obtained at MacDonald West Shoulder, despite only being a few of hours after the natural avalanche occurred. The widespread natural avalanche cycle tapered during the day of Friday 10 February, with only a couple new avalanches observed on Saturday 11 February.

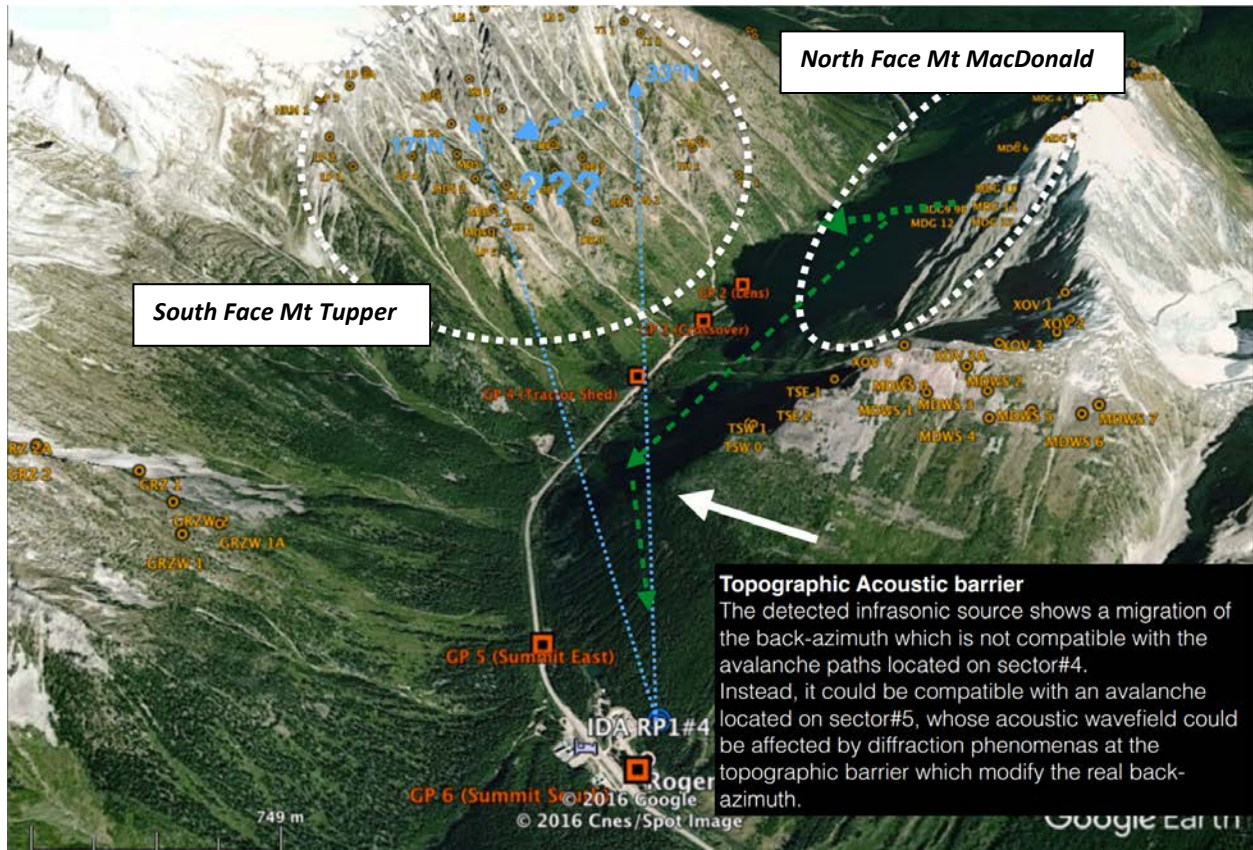
A manual analysis undertaken by Giacomo Ulivieri showed the detection of a natural avalanche in the night of Thursday 9 February, which was most likely a Size 2 avalanche that occurred in Cheops North #2 (backcountry terrain in Connaught Creek). With respect to the artillery control work, the analysis revealed the detection of the gun shot and resulting avalanche in the Lone Pine Target 3, as well as a subsequent artillery control of Target 4 with no resulting avalanche. The fact that no signal of a controlled avalanche was received after this shot helped the forecasters to finally record this artillery shot with 'no result' as they were not completely sure at the time of control, due to poor visibility at night and potentially blown-over debris the next morning when conditions finally allowed for visual

observations. Two more shots were detected during the control work (Hermit Slide target 1 and Grizzly West target 2), however the resulting avalanches were not detected.



**Figure 7:** Example output from the infrasound system showing the back-azimuth (upper dashed blue arrow), the signal migration (lower dashed blue arrow) and inferred flow direction of the detected avalanche (dark solid blue line). The inset shows the details for the automatic detection.

The third automatic detection by infrasound in this period on Saturday 11 February could be matched with a natural avalanche observed in MacDonald Gully #6 after further manual analysis by Giacomo Ulivieri. The signal of this avalanche was likely reflected off the opposite side of the valley as it had to have traveled around a ridge, a topographic and acoustic barrier, to be detected since this avalanche path is not in sight of the infrasound system, and not within the GIS view-shed (see Figure 8).



**Figure 8:** Example output of the manual analysis of the infrasound signal. The arrow of the automatic detection was pointed towards the south face of Mt. Tupper, whereas the manual analysis revealed a migration of the back-azimuth off the North Face of Mt MacDonald (MacDonald Gully #6 Path), which was most likely due to the reflection of the signal around the ridge which presented a topographic barrier to the signal.

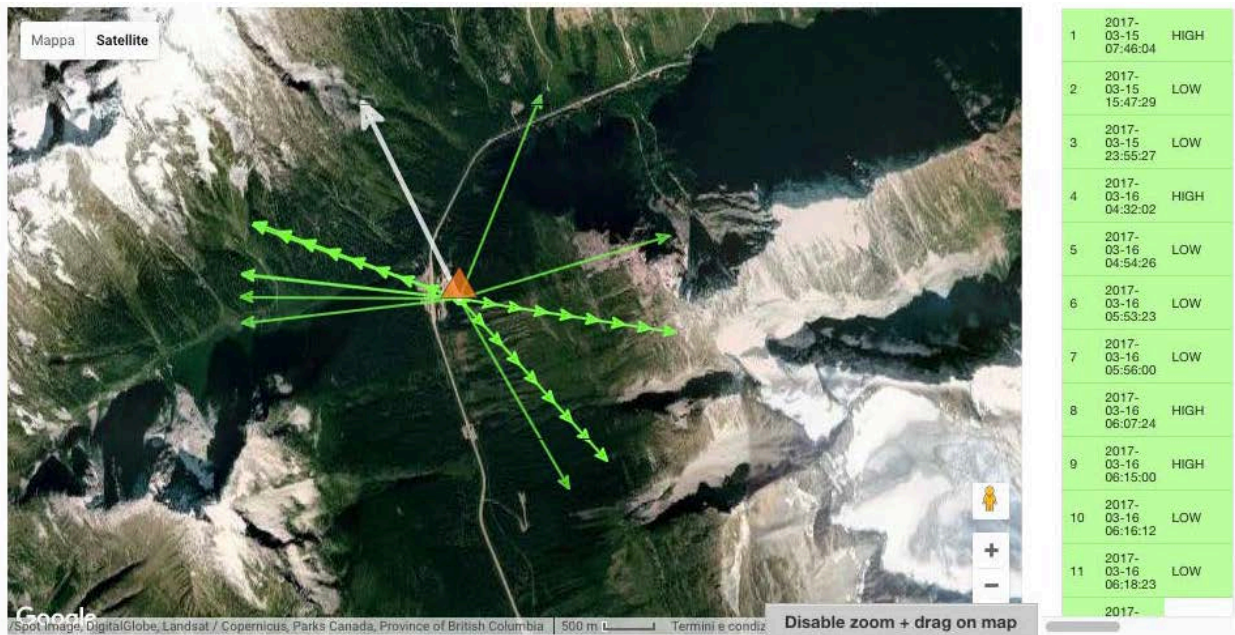
This case study provides a robust example of the infrasound system providing accurate timing information for a natural avalanche event (MacDonald West Shoulder), which may have been missed by avalanche forecasters given the storm conditions. It also provided clear evidence of instability, which assisted with the decision to proceed with avalanche control. Furthermore, it demonstrates both the capability and challenge of locating avalanches where signals have been reflected around topographic (and therefore acoustic) barriers. The installation of multiple infrasound arrays (i.e. a network) with overlapping view-sheds along the highway corridor would likely resolve this challenge and also aid in more robust attribution of signals to specific avalanche paths.

#### 4.4.2 Avalanche Cycle 2: 10-18 March, 2017

In the first 10 days of March, more than 100 cm of snow fell at 1900 m with strong to extreme southerly winds. It continued snowing continuously over the entire avalanche cycle period with moderate to strong southerly winds which created reactive storm slabs. Increasing temperatures led to a rapid

settlement of the snowpack and a moist surface up to 2100 m by Tuesday, 14 March. Rain below tree line, and heavy snow above created additional load on the snowpack. Towards the end of this cycle the freezing level came down below tree line forming a rain crust below tree line.

Avalanche activity started on Friday 10 March, with avalanches running full path almost every day until Saturday 18 March. On Friday and Saturday (10-11 March) several Size 4 avalanches were observed along the highway corridor. Avalanche control work was carried out on Sunday, 12 March triggering avalanches up to Size 4. The infrasound system showed 12 detections over this period, with many from the backcountry areas in Connaught Creek (Figure 9). From Friday 10 March until Sunday 12 March, 25 controlled and 61 natural avalanches were observed in the 5 km radius of the infrasound system. Of these observed avalanches, 5 controlled and 1 natural avalanche occurred in one of the ten paths in the view-shed of the infrasound system.



**Figure 9:** Example output from the infrasound system showing the direction of the 12 signals.

A few loose snow avalanches entraining snow to the ground were observed on Wednesday 15 March. The avalanche activity peaked on Wednesday 15 March, and into the night on Thursday 16 March, with significant precipitation amounts, strong winds and warm temperatures. Control work was carried out on Wednesday 15 March and in the night to Thursday, triggering numerous avalanches to Size 4. From Wednesday 15 until Saturday 18 March, 12 controlled and 11 natural avalanches were observed in the ten avalanche paths in the view-shed of the infrasound system, out of 60 controlled and 73 natural avalanches within the 5 km radius.

Figure 10 presents the example of the infrasound detection from an artillery shot placed in Target #2 on the Lens avalanche path (0848 PDT on Wednesday 15 March). The artillery control released a Size 3

avalanche which ran approximately half-way down the track (as shown in yellow in Figure 10). The incorrect attribution of this event to the adjacent path is likely due to topographic shielding resulting in channeling of the signal in the valley.

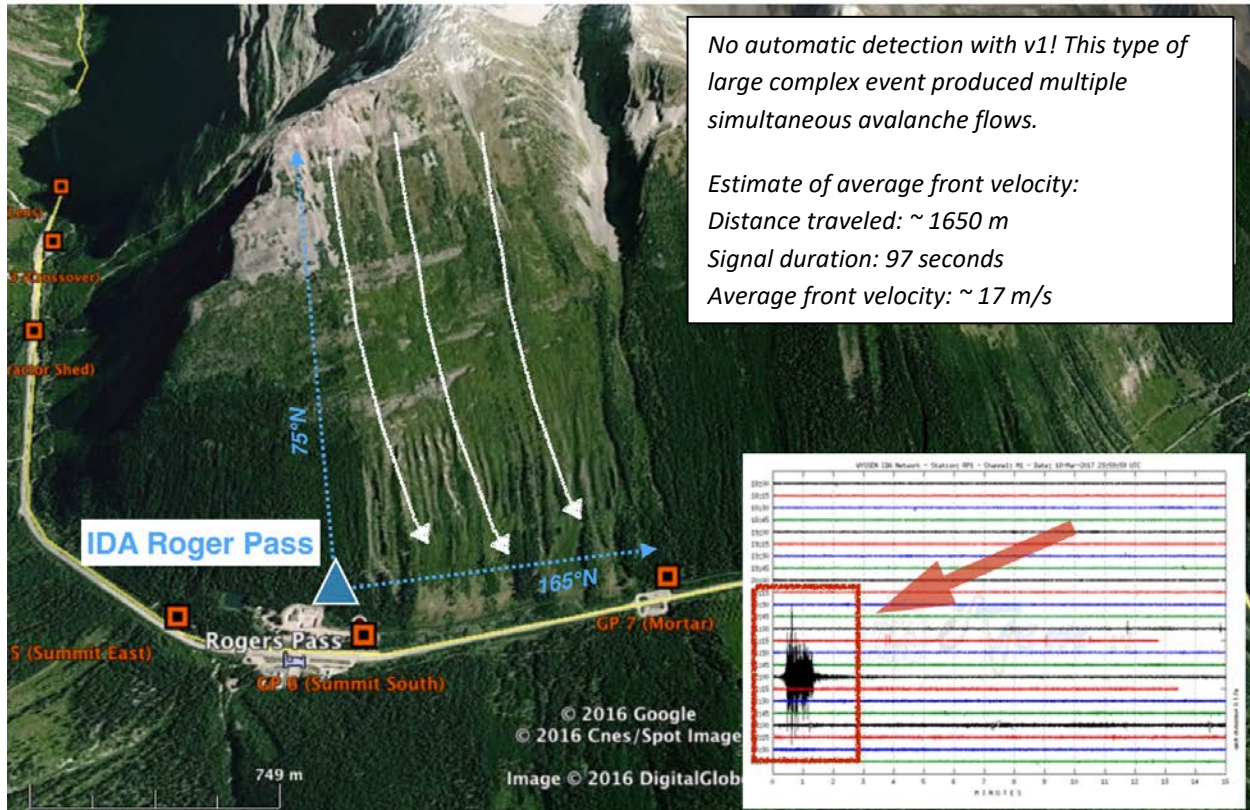


**Figure 10:** Example output from the infrasound system showing the back-azimuth (upper dashed blue arrow), the signal migration (lower dashed blue arrow) and inferred flow of the detected avalanche (red arrow). The observed event is shown with the yellow line. The incorrect attribution is likely due to topographic shielding.

While the control work was being undertaken, numerous natural avalanches to Size 3.0 were also observed. Avalanche activity subsided during the day on Thursday and picked up again on Friday 17 March and Saturday 18 March with several natural and controlled Size 4 avalanches on Saturday along the highway corridor. The biggest observed avalanche on Saturday was MacDonald West Shoulder which occurred simultaneously in four start zones, removing some mature timber and running to the valley floor. This event was not detected automatically by the infrasound system (using v1 algorithm) as the signal amplitude was much larger than of all previously detected avalanches due to the size of the avalanche and the proximity to the infrasound sensors (Figure 11). However, the improved v2 algorithm did detect this event, but recorded it as a single large event, rather than attributing it to the 4 individual paths. Given simultaneous timing and proximity of these paths to one another, this outcome is not unexpected, and demonstrates some of the complexities involved for automatic avalanche detection



and attribution. Multiple, overlapping infrasound arrays might help resolve this type of event into individual paths.



**Figure 11:** Output of the manual analysis of the natural avalanche which occurred at MacDonald West Shoulder using the v1 algorithm. All four paths failed simultaneously with a crown of approx. 1 km length. The updated v2 algorithm was able to detect this event.

#### 4.4.3 Avalanche Cycle 3: 4 – 9 May, 2017

Precipitation and continuing high temperatures triggered the onset of a widespread natural wet snow avalanche cycle on Thursday 4 May, which lasted until Saturday 6 May with a couple of natural avalanches Size 3 to 4.

Avalanche control work was carried out with a helicopter on Friday 5 May at Avalanche Crest, resulting in a Size 4 avalanche which ran across the highway. Helicopter control work on 6 May east of the pass resulted in several Size 3.5 to 4 avalanches. Further control work on Tuesday 9 May resulted in several Size 2 and a few Size 3 avalanches.

During this avalanche cycle, 15 controlled and 46 natural avalanches were observed of which 1 controlled and 9 natural avalanches occurred in the ten avalanche paths in the view-shed of the infrasound system. The connection to observed avalanche events over this period is challenging due to reduced ACS observers and high avalanche activity which required staff to concentrate on the more

significant avalanche events. A further 18 avalanches were automatically detected by the infrasound system, but these were not conclusively matched due to the lack of thorough manual observations over this period combined with the infrasound system providing detections which suggested that they occurred in the backcountry setting of Connaught Creek. Despite this limitation, the amount of automatically detected avalanches is impressive considering the fact that all these avalanches were wet avalanches, which are more challenging to detect by the infrasound system (due to their typical slower velocity and therefore lower levels of infrasound). This case study provides an example of the infrasound system providing automatic detections for wet avalanche activity situations, which are outside the scope of the current algorithm and usually not expected to be detectable. These results hold promise for future improvements of the system to be able to detect wet avalanches at Rogers Pass, perhaps in a consistent, reliable manner.

## 5.0 Challenges

This analysis identified a number of challenges with the trial and verification of an infrasound system and also with the eventual operational deployment. Some of the key challenges are presented below:

**Avalanche observations:** The large number and detailed observation of avalanches in the Rogers Pass avalanche paths by ACS provides an impressive and unique data set. However, full and complete verification of the trial system is problematic as a full and complete record of avalanche activity is not available for the entire detection area of the infrasound system, in particular backcountry areas such as Connaught Creek. This means that using the standard performance metrics has a degree of uncertainty as not all detections can be included. Therefore, consideration should be given to additional monitoring of avalanche activity (e.g. time-lapse camera (Hendrikx et al., 2012), or radar from satellite (Vickers et al., 2016)) if a complete record of avalanche activity and therefore statistically robust verification is desired. Alternatively, future assessments of an operational infrasound system should be limited to only the paths that impact the highway, which was the approach taken in this report.

**Attribution of detections:** A single array as used in this trial has limitations with respect to signal attribution to specific paths, especially when very oblique to the avalanche event, or when topographic / acoustic shielding is present. This results in a high degree of manual intervention needed for attribution of the infrasound signal to specific paths. This is not a desirable result for an operational system, as avalanche forecasters do not have sufficient time or expertise to perform this type of analysis throughout the winter.

A multi-sensor array with overlapping view-sheds, so that intersection of signals can be determined will likely decrease the level of manual intervention needed to attribute a signal to a specific path and increase overall detection rates and performance. Based on the data examined here, and previous work by Ulivieri et al., (2012) these could either be located at distance of 2.5 km to 3.5 km with overlapping view-shed, and no topographic shielding, or with two arrays within 500 m then separated by another two arrays within 4 km (Ulivieri, pers. comm., 2017).

Furthermore the calibration of the software and algorithm to Rogers Pass will likely improve the attribution of an avalanche to a specific avalanche path. As such, specific path attribution and overall performance of an operational infrasound system should be evaluated after one year, and then again after 2 and ideally 3 years of operation. A marked improvement of system performance should be anticipated after 2-3 winters of operation.

**Calibration of the signal:** Software must be programmed and calibrated to the site (noise, direction of avalanche paths, type of avalanche control, etc.). Hence, the full benefits may not occur in the first season of operation. The v2 algorithm compared to the v1 algorithm demonstrates this difference to some extent, but multiple arrays, and multiple years of data and algorithm improvement should show further improvement in automatic detections. The UDOT Little Cottonwood Canyon infrasound system went through this level of development, and as a result now provides very reliable avalanche detection using multiple arrays (Vyas, 2009).

Furthermore, wet avalanches are shown in the signal, but current algorithms tend to not interpret them as avalanches. Improvements in algorithms are currently in progress to address these shortcomings (Steinkogler, pers. comm., 2016).

**Noise in the signal:** Transportation corridor noise (e.g. highway traffic, trains, aircraft) should not be an issue once the system is fully calibrated, since the signal is always on a consistent linear route. Programming can therefore correctly rule out signals from transportation corridors. Testing the infrasound in the 2016-17 season also showed that low noise sites can be found, particularly in forested areas which are ideal. Furthermore, wind can create noise in the signal, resulting in false detection. Improvements in algorithms are reducing this issue (Steinkogler, pers. comm., 2016), as does burial of the sensors in snow.

**Cyber-attacks:** As experienced in the 2016-17 trial, the infrasound system was inundated with SPAM requests, thereby using all the data as per the contracted data limits on the cellular modem. This can likely be addressed by converting to a dynamic, rather than static IP address. This will need to be checked with any cellular data coverage provider.

**Site specific environmental conditions:** As the sensors might not be manufactured entirely waterproof the selection of the site should be done with an awareness towards environmental condition such as flooding in spring.

## 6.0 Conclusions

An analysis of the 2016-17 season using detailed avalanche observations supplemented with additional manual observations and compared with infrasound detected avalanche activity was undertaken. Using both quantitative statistical and qualitative case-study approach methods we have evaluated the performance of a single infrasound array for one season at Rogers Pass, Canada.

This analysis clearly shows the potential of an infrasound system to automatically detect avalanche events, ranging from Size 1.5 to 3.5 at distances up to 4 km, and more reliability at distances less than 3 km. Detailed case-study analyses show the ability of the infrasound system to provide path specific location, point of initiation, run-out distance, and avalanche velocity estimates. The system can also indicate the onset of avalanche activity before an avalanche cycle, as seen in the avalanche cycle of 9-13 February where the first infrasound detection was a natural avalanche at MacDonald West Shoulder, which provided valuable information to ACS forecasters to initiate avalanche control a few hours later

Statistical analysis of the results from this one season shows relatively poorer results than similar studies in other locations using infrasound. This difference is attributed to a combination of factors, including the difference in avalanche control, lack of a full record of every avalanche occurrence within the infrasound range, the topographic complexity of Rogers Pass, the duration of the trial, and the number of sensors installed.

As demonstrated with the improved results from v1 to v2 of the algorithm, and a review of similar studies, we anticipate improved results with more local calibration and use over multiple seasons and multiple arrays. Limitations to any infrasound system include topographic sheltering resulting in channeling or blocking of the infrasound signal, incomplete observational record from areas within the detectable range and view-shed, and background noise.

Despite these shortcomings, the data collected and presented here represents a unique and valuable data set to robustly evaluate an infrasound system. If an infrasound system is deployed for operational use, then there should be an expectation of achieving similar results in the first year (using the v2 algorithm), with marked improvement over subsequent seasons as improvements to the algorithm are completed using observed avalanches.

While this study used and evaluated an IDA<sup>®</sup> infrasound system provided by Wyssen, our analysis should be considered more generic in context, as all infrasound systems are fundamentally designed in a similar way. A different supplier's system would likely have different hardware, software, and presentation of results, but should be able to provide similar results.

Ultimately, this infrasound system shows the potential for obtaining the timing of avalanche activity and the extent and success of avalanche control, at night, during periods of poor visibility and in remote areas, which has the potential to significantly improve operational avalanche forecasting, increase public and worker safety, and reduce highway closure hours. However, as no infrasound system is currently sold as a complete "off the shelf" product, operational deployment will come with challenges that will take several years to overcome, but also likely lead to substantial improvements and a reliable forecasting tool over time.

## 7.0 Recommendations

Based on the analysis undertaken for this report, the following recommendations and suggested performance criteria for an operational infrasound system are presented:

- Multiple sensors with overlapping view-sheds should be installed along the length of the road corridor impacted by avalanches. These sensors should be spaced at distance of 2.5 km to 3.5 km with overlapping view-sheds, and no (or limited) topographic shielding, or with two arrays within 500 m then separated by another two arrays within 4 km. This would permit more accurate detection and attribution of avalanche events through triangulation of signals. Careful placement of the arrays will need to be considered, with the need to elevate some sensors above the local flooding height, but still below the mean winter snowpack height.
- A detailed analysis should be undertaken to examine potential locations that meet these criteria, which results in the greatest benefit to the avalanche forecasting and control program, with specific focus given to avalanche paths with the greatest risk to the highway.
- An operational infrasound array with multiple sensors should be able to achieve performance metrics not less than a PON of 0.90 and a POD greater than 0.50 in first season, increasing to a POD of at least 0.80 by the end of the third operational season. These metrics are consistent with reported performance at other locations around the world.
- An operational infrasound array with multiple sensors should be able to detect dry flowing avalanches of Size 1.5 to 2 within 1.5 km and Size 2.5 and larger avalanches within 3 km with the above POD suggestions. These metrics are consistent with reported performance at other locations around the world.
- An operational infrasound array with multiple sensors should also be able to detect larger wet avalanches of Size 3 and larger within 3 km. While these are not explicitly calibrated for, based on observations from this season, a network with good overlap should be expected to capture the larger wet avalanches. No specific POD performance metrics are recommended for these events.
- Avalanche run-out distance down the path should be attainable within gross delineations (e.g. track, runout, over-road) for the majority of paths, and could be expected to be more refined (i.e. 100 m above road), with a high density of sensors and calibration of the software to the site specific paths. Other avalanche programs have been able to achieve this level of accuracy with multiple arrays (e.g. UDOT), and this should also be achievable at Rogers Pass.

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