SITE SUITABILITY, PERFORMANCE, AND OPERATIONAL LESSONS FROM SIX YEARS OF INFRASOUND AVALANCHE MONITORING

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ABSTRACT: Infrasound monitoring uses low-frequency acoustic signals, typically below 20 Hz, to detect and characterize avalanche activity over operationally useful distances. This makes it useful in remote terrain and during periods when direct observation is limited by weather, darkness, distance, or exposure. Infrasound carries great distances due to its low frequency, so arrays can often be placed in locations which are close, but less likely to be destructively hit by an avalanche. As infrasound monitoring becomes more common in operational avalanche programs, clearer guidance is needed on where the method is well suited and where limitations should be expected. Infrasound is generally best suited for detecting larger, energetic avalanches, typically D2 or greater, and for supporting explosive mitigation work with howitzers, hand charges, and similar tools. It can be especially useful in poor visibility, remote terrain without available power, highway corridors, and settings where multiple avalanche paths need to be monitored. Current challenges in signal analysis are focused on detections of small events, slow wet avalanches, and locations with significant cultural noise. Successful operational use depends on careful system design and implementation. Detection confidence is influenced by distance to the avalanche path, terrain geometry, terrain shielding, path orientation, and array placement. Because infrasound sensors record low-frequency sound from all nearby sources, background noise from wind, traffic, aircraft, artillery, construction, and ski area operations can affect both detection confidence and interpretation. Drawing on six years of operational experience and 24 deployed arrays, we address practical considerations including power, telemetry, maintenance, site access, data health, and user expectations. We focus on two questions: what makes a site suitable for infrasound monitoring, and what strengths and limitations should be expected for a given application? By describing what has worked, what has not, and what conditions affect performance, we aim to support more informed use of infrasound in avalanche programs.

KEYWORDS: infrasound, avalanche detection, remote monitoring, site suitability, avalanche mitigation

1. INTRODUCTION

Knowing whether avalanches are running, where, and how large, is fundamental to avalanche forecasting and mitigation. Yet the conditions that produce avalanche cycles are often the same conditions that prevent observing them. Storms obscure visibility, cycles peak at night, and many paths of operational concern are remote or unsafe to approach. Forecasters are routinely asked to make closure, reopening, and mitigation decisions with incomplete knowledge of what has already occurred, including whether an explosive charge detonated as intended, or whether a round remains unaccounted for.

Avalanches radiate low-frequency sound, below 20 Hz, which propagates with very little attenuation through the atmosphere and can be detected by specialized microphones at operationally useful distances. The same detection principle extends to confirming whether explosive mitigation shots have fired as intended, discussed further in Section 5. Sound radiates independently of conditions, allowing detections during storm cycles, night or low visibility conditions. The low attenuation also gives more latitude in where arrays can be placed: ideally outside harm's way, but near enough to the path to gather as much local data as possible. Since the microphones are not directional, sound is recorded

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in all directions, leading to possible detections in complex topography like valleys. But this also introduces other sounds that occur close to the sensors, or half way around the world.

Infrasound monitoring of avalanches has moved from research demonstration to routine operational use. State DOTs and ski areas are increasingly utilizing infrasound arrays (Johnson et al., 2021b). Existing work has established the physical basis for infrasound detection and demonstrated its feasibility; it offers less direction for programs deciding whether infrasound is a good fit for a given path, and what performance to expect once it is installed. This paper addresses two questions: what makes a site suitable for infrasound monitoring, and what strengths and limitations should be expected for a given application.

2. BACKGROUND

Following early characterization of avalanches with infrasound by NOAA in the 1980s (Bedard, 1989, 1994; Bedard et al., 1988), infrasound moved from a research tool toward operational application for real time alerting of avalanche activity (Fig. 1). Chritin et al. (1996) prototyped one of the first systems intended for operational avalanche forecasting in Europe, and subsequent work has extended this toward networked arrays capable of localizing the source region within a flow and characterizing how acoustic output changes over its duration (Johnson et al., 2021a). More recent work has extended infrasound detection to avalanche types and climates outside the original research settings, including large plunging avalanches in the maritime climate of Fiordland, New Zealand (Watson et al., 2022).

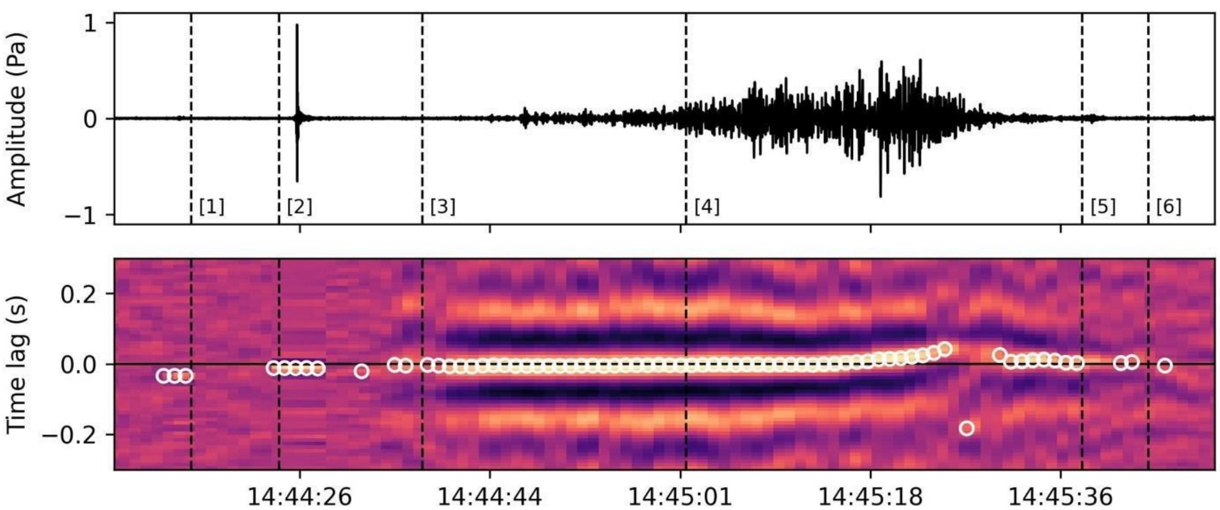

Fig. 1: Example of a mitigation explosion followed by the resulting avalanche. The top panel is the filtered infrasound signal and the bottom is a correlogram of the signal. The sequence is as follows [1] 14:44:17: Shot fired, [2] 14:44:25: Shot detonation, [3] 14:44:38: First avalanche detection, [4] 14:45:02: System starts event tracking, [5] 14:45:38: System classifies event as avalanche, [6] 14:45:44: System stops event.

Performance data from operational deployments has begun to quantify these patterns. Studies at sites in the Swiss Alps and at Little Cottonwood Canyon, Utah, have examined detection probability as a function of avalanche size, snow condition, and distance from the array (Mayer et al., 2020; Johnson et al., 2024). These findings, and how they relate to our own operational experience, are discussed further in the Performance Characteristics and Limitations section. Infrasound is one of several remote sensing tools used to fill observational gaps in avalanche programs, alongside seismic sensors, radar, and camera systems, each suited to different terrain, budget, and operational constraints.

3. DEPLOYMENT CHARACTERISTICS

Infrasound deployments consist of 3 infrasound sensors connected to a seismic data logger. Telemetry is through an internet connection that can come from cell modem, radio or direct connection. While the data loggers and sensors are low power, telemetry adds additional power draw. Power needs are easily met with solar power or AC power.

Each array contains 3 sensors in a triangle pattern (Fig 2). The distance between the sensor and the middle of the array is between 15 and 20 meters, making it roughly 30-40 meter footprint for the entire array. The sensors can be centered around the tower (typical of solar applications) or connected via a junction box, allowing the electronics enclosure to be mounted where it’s convenient but ensuring that the array is in its most suitable location. The sensors are allowed to be buried by the snowpack which helps reduce interference from wind. Based on site survey data collected by Snowbound, it appears that around 30 cm of snow on top of the sensor reduces wind noise considerably.

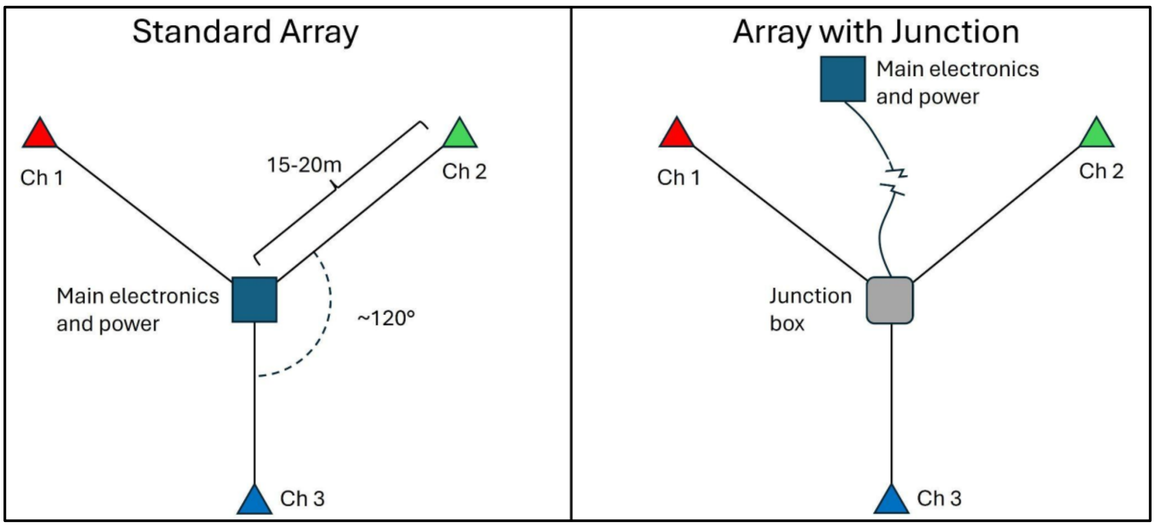

Fig. 2: Typical array configurations, with and without a junction box.

4. SITE SUITABILITY

Detection confidence at a given site depends on several factors: distance from the array to the avalanche path, terrain geometry, terrain shadowing, path orientation relative to the array, and the specific placement of individual sensors. None of these can be fully assessed from a desk review and each has produced surprises across our deployments that only became apparent after installation or, in some cases, after a full season of operation. Terrain shadowing is among the least predictable factors before installation where ridgelines, valley walls, and other small topographic features between an array and an avalanche can attenuate or redirect the low-frequency signal in ways that are difficult to anticipate from maps or short site visits alone.

Table. 1: Site suitability decision factors for infrasound monitoring.

Factor	Consideration
Avalanche size	Best suited to D2 and larger; smaller events reduce detection confidence
Distance & placement	1.2 to 1.6km range observed in current use, further may be possible
Array spacing	Roughly 500-1,000 m between arrays, depending on topography
Terrain shadowing	Sound can bend around terrain and direct line of sight is not required
Power	~5-8 W, either solar or AC
Telemetry	Cell modem; radio
Cultural noise	May require site-specific tuning (wind, traffic, aircraft, construction, ski operations)

Because infrasound propagates with low attenuation, arrays do not need to sit within or immediately adjacent to a path to detect it. Array placement requires judgment as an array too far from a path, or poorly oriented relative to it, will produce weaker or more ambiguous detections, particularly for smaller events. In our experience, current systems are in the 1.2 to 1.6 km range from an array to the upper start zones. Larger avalanches can be heard from farther away with some detected up to 4 km away. Since arrays are placed near the bottom of the avalanche paths, avalanche events get louder as they move downhill towards the arrays, reducing the location uncertainty

Spacing between arrays within a network is a related but distinct placement consideration. Operational experience across our deployments suggests a sweet spot of roughly 500 to 1,000 meters between arrays, with the ideal spacing within that range depending on topographic features, line-of-sight obstructions between arrays and constraints on access. Array placement is critical for high quality detections and locations. Arrays too far from each other, poorly spaced or shadowed with terrain can reduce the effectiveness of the system.

Beyond acoustic and geometric considerations, power and telemetry availability are practical constraints on where an array can go. Arrays can be powered by either solar or AC, depending on what is available at a site. At a draw of roughly 5-8 W, power supply has rarely been the limiting factor in site selection. Telemetry is often more site-limiting and if has access to the internet. While band width to stream infrasound data is relatively small (<2GB per month per array), interruptions in communications can affect data processing. Spotty internet can cause significant issues due to data gaps at inconvenient times. Therefore, ensuring reliable internet connection is a key factor in an array's overall success.

5. PERFORMANCE CHARACTERISTICS AND LIMITATIONS

Infrasound is generally best suited to larger, more energetic avalanches. Data from a network in Little Cottonwood Canyon, Utah, has shown that a properly tuned array can reliably identify avalanches as small as D2 at distances greater than 1 km (Johnson et al., 2024), and our own operational experience across sites of varying size and terrain is broadly consistent with this threshold as a practical planning guidance.

Infrasound also supports explosive mitigation work. Detonations produce a distinct, easily recognizable signal in the infrasound range, allowing the same arrays used for avalanche detection to confirm whether a control shot, from a howitzer, hand charge, or other explosive, fired as intended. This is valuable in terrain where a misfire or dud cannot be safely or immediately verified by direct observation.

Multi-path monitoring is another area of strength. A single array can record events from a zone containing multiple avalanche paths and multiple arrays can be spaced to cover an extended area. For example, infrasound can be recorded from all directions and with the correct array placement, can monitor both sides of a valley with a single installation. These strengths come with corresponding limitations, concentrated in three areas: small events, wet avalanches, and cultural noise. Small avalanches, generally below D2, produce weaker signals that are harder to distinguish from background noise and have a reduced likelihood of being picked up on multiple arrays, needed for robust locations. Wet, slow-moving avalanches are also harder to detect than dry avalanches of comparable size. An operational study in the Swiss Alps found consistently lower detection rates for wet-snow avalanches than for dry-snow avalanches (Mayer et al., 2020), a pattern consistent with our own operational experience.

Cultural noise is background sound from sources unrelated to avalanche activity and presents a further limitation. Because infrasound sensors record sound from all nearby sources, wind, vehicle traffic, aircraft, artillery, construction, and ski area operations can all affect detection confidence and interpretation. These signals can either mask a genuine event or by producing a signal that must be filtered. Addressing this may require site-specific tuning where each new site could required a particular sources of cultural noise present in that setting rather than relying on a single, general-purpose solution (Fig. 3).

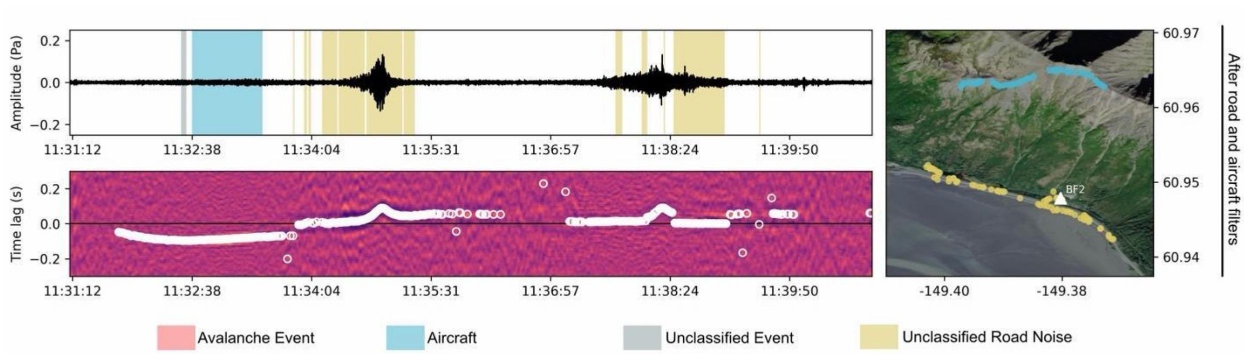

Fig. 3: Example of cultural noise interference.

Programs new to infrasound monitoring are learning to interpret a new kind of data alongside Snowbound's own ongoing refinement of detection accuracy and noise filtering. Early performance at a new or recently tuned site should be communicated as part of an active calibration process rather than a finished product, so that forecasters and program staff can build appropriate trust in the system as its site-specific tuning matures.

6. CONCLUSION

Returning to the two questions posed at the outset, years of operational experience show that infrasound is best suited to larger avalanches, generally D2 and above, in terrain where direct observation is limited and where an array can be placed at a safe but effective distance from the path. It performs a valuable secondary role confirming explosive mitigation shots, and its low power requirements and tolerance for placement outside line of sight give it flexibility. Its principal limitations are smaller avalanches, wet and slow-moving avalanches, and cultural noise, each of which requires ongoing attention rather than a one-time fix.

For programs considering infrasound monitoring, site suitability and expected performance are closely linked. We hope the factors described here help programs set realistic expectations and make more informed decisions about where and how infrasound monitoring can support their operations.

CONFLICT OF INTEREST

The authors are employees of Snowbound, the company that designs, deploys, and operates the infrasound systems described in this paper. This study draws on Snowbound's own commercial deployments and operational data.

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