BINARY AVALANCHE DETECTION SYSTEM (BADS)

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ABSTRACT:

Detecting avalanche events in real-time remains a challenge for ski resorts, transportation agencies, railways, and avalanche mitigation professionals. Existing solutions are often cost prohibitive, labor intensive, or limited in coverage. This paper presents the Binary Avalanche Detection System (BADS): a low-cost, scalable sensor network designed to provide binary (yes/no) real-time detection of avalanche and shock events, i.e. explosive detonations from avalanche mitigation work. The core innovation and design elements of BADS is a bespoke enclosure, a pressure sensor and amplifier, and algorithm chain for detection. The enclosure features an acoustic ear with a custom membrane and orifice to modulate air flow. The customized pneumatic filter integrated into the housing rejects ambient pressure changes while capturing pressure transients characteristic of avalanches and shocks (Marcillo et al. 2012; Anderson et al. 2018). Field deployments during the 2025-2026 season at Kirkwood Mountain Resort (CA), Powder Mountain (UT), and Jackson Hole Mountain Resort (WY) yielded 132 corroborated events: 33 confirmed avalanches and 99 confirmed shocks. Avalanche events produced characteristic pressure signatures within a 30 second window, while shocks produced much shorter, higher frequency signatures. Wind noise, the primary interference source, has proven distinguishable in most scenarios. A machine learning (ML) algorithm trained on the confirmed events is in active development and has demonstrated promising early detection performance. Two deployment architectures have been tested and validated: 1) a wired Power-over-Ethernet (PoE) network with nodes spaced up to 600 meters apart, and: 2) a wireless system capable of transmitting over/around ridgelines and from under 3+ meters of snowpack at distances exceeding one mile. The wireless architecture utilizes standalone nodes running local inference and transmitting alerts to a solar-powered base station with cellular uplink. For the 2026-2027 season, a 75 node deployment is planned across the northwestern US and Alaska with nodes installed beneath remote avalanche control systems (RACS) and in well-documented natural slide paths. This expanded dataset will be used to refine the detection algorithm and explore correlation between pressure spike duration and avalanche runout distance and footprint. BADS represents a practical, affordable path toward widespread automated avalanche detection for operational safety applications.

KEYWORDS: avalanche detection, differential pressure sensor, remote sensing, avalanche mitigation, machine learning

1. INTRODUCTION

Avalanche mitigation programs work by preemptively triggering avalanches before they can release naturally onto a road, rail line, or during resort operations. Ski areas, transportation agencies, and railways in avalanche terrain rely on a mix of explosive charges, RACS, and forecasting to manage avalanche risk. Even when the mitigation work goes as planned, confirming the outcome is often the more difficult issue, i.e. did a given shot actually release the target slope, did it simply detonate in place, did it detonate at all, and/or did any natural avalanche activity occur elsewhere on the intended route during a storm cycle?

Alpine Infrastructure manufactures and installs gas-based RACS, e.g. the Boom Whoosh (BW), across a number of ski areas and is moving into other areas of slope-side infrastructure in the near future. A large gap in avalanche mitigation programs is not RACS themselves, but the accurate and timely detection of avalanches and explosive detonations. Historically, avalanche and shot confirmation has depended on ski patrol or highway crews being in position to see or hear the result, which is not always possible at night, in poor visibility, or in complex terrain that is hard to directly observe. The BADS addresses this gap: a low-cost, binary sensor network that automatically detects, logs, and alerts if avalanche or detonation occurred within its purview. This paper describes the BADS system design (see Figure 1), its field deployment across three ski areas in the winter of 2025-2026, and the operational results and lessons learned from said deployment.

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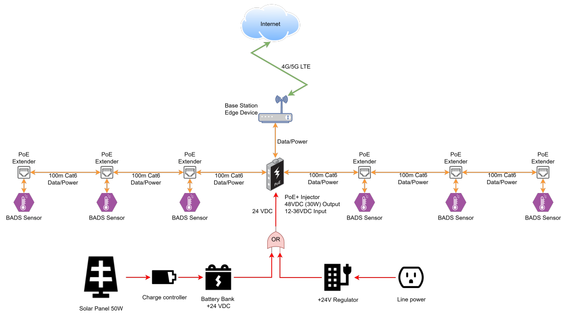

Figure 1: BADS PoE System Network Diagram

2. BACKGROUND

Several detection technologies are already used operationally to monitor avalanche activity. Doppler radar systems, such as the Gravimon Avymonster, scan avalanche terrain continuously and can track an avalanche's location, extent, and speed in real-time, day or night and in poor weather. Infrasound-based systems, including the sensor arrays developed by Snowbound Solutions, detect low-frequency pressure waves (roughly 0.1–20 Hz) that avalanches generate and concurrently monitor multiple avalanche paths using arrays of appropriately spaced sensors. Both approaches are well proven and provide rich operational detail, but are cost prohibitive for many entities and programs.

BADS is designed and built on detecting the same underlying signal properties as these infrasound-based systems — the low-frequency pressure waves produced by an avalanche or an explosive detonation — yet trades the spatial detail of radar and multi-sensor arrays for a single pressure sensor and binary output: did an avalanche or detonation occur? The core innovation of BADS is a custom pneumatic enclosure paired with a differential pressure sensor and signal conditioning circuit and its corresponding detection algorithm. This mechanical filter rejects ambient pressure changes — persistent wind gusts, weather fronts — while capturing the rapid pressure spikes characteristic of avalanches and explosive events. The measured differential pressure across the ear can be expressed as:

$$\Delta P = P_{ear} - P_{ambient} \quad (1)$$

Avalanche events produce characteristic sub-hertz to 20Hz pressure signatures that can last for 30+ seconds while the flowing snow front passes over the sensor, yet explosive detonations produce short, higher frequency spikes (Figure 1). This spectral and temporal separation is what allows a single, low-cost sensor body to distinguish between these events without relying on cameras, seismic arrays, manual confirmation, or the high cost of a radar or multi-sensor infrasound installation.

3. METHODS

3.1. Development and Field Progression

BADS development consisted of numerous iterate-test-iterate cycles, bench-testing the sensor, filters, amplifier, enclosure, membrane configuration, and orifice geometry. When the sensor node performed reliably on the bench, field testing commenced by pairing the unit with a repeatable shock-wave inducing BW device. Once the node reliably distinguished between avalanche events and detonation shots over a complete storm cycle, small pilot networks were stood up at three cooperating ski areas: Kirkwood Mountain Resort (CA), Powder Mountain (UT), and Jackson Hole Mountain Resort (WY). Then three field arrays with centralized base station were deployed during the 2025-2026 winter season, one at each of the three sites listed above, see Figure 2. The raw data collected from these arrays provides the training foundation for the machine learning algorithm described below.

Figure 2: BADS PoE Field Deployment with Base Station

3.2. Constraints

It is important to highlight the constraints of the BADS node, see Figure 3, as this is partially what makes the sensor novel in its design an application. Regarding avalanche event detection, the node must be directly impacted by the avalanche debris in some way: in the start zone, within the slide path, or in the runout zone at the toe. This constraint dictates the binary yes/no sensor design, but also keeps it simple, low-cost, and easy to install. The sensor node is deployed on the ground in the slide path of interest before the snow accumulates. It can be anchored to the ground or not. The sensor node can "hear" the avalanche through the snowpack yet this snow barrier also helps attenuate potential noise sources that may cause false positives in the algorithm chain. The shock detection range is less sensitive and has yet to be precisely quantified but detonations of at least 1 km away were detected in the current 2025-2026 dataset.

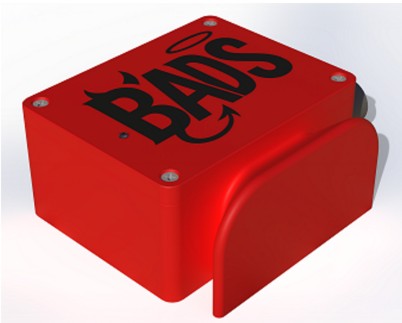

Figure 3: BADS Standalone Node

3.3. *Two Deployment Architectures*

BADS nodes report events over one of two links, PoE-Wired or Wireless, chosen per site based on existing infrastructure and terrain. PoE connected nodes stream raw sensor data continuously over a wired Ethernet cable (nodes cascaded every 300–600 meters, with individual runs up to 1 km) to a centralized base station for logging and evaluation. Specifically, this configuration has been critical to train and validate the machine learning algorithms. Wireless nodes are fully self-contained and standalone, where local battery power and hardware intelligently apply digital signal processing (DSP) and inference algorithms in real-time. Essentially, the wireless node becomes the edge test bed for ML evaluation. To conserve power, the node only transmits event features upon event detection with via a long range radio link to a base station, which immediately alerts the cloud platform. Each wireless node also logs raw sensor data associated with said event to an onboard SD card; this locally stored data is periodically retrieved and added to the ML training set. Table 1 compares these two BADS deployment architectures.

Table 1: Deployment Architecture Comparison

Attribute	***Wired***	***Wireless***
Power	PoE	Battery
Node Range	1 km	1.5 km
Snow Depth	DC	3+m
Processing	Centralized/ Cloud	Local/ Edge
Lifespan	~2 yrs	~6 mos

3.4. *Identifying Wind Noise*

One of the primary hurdles in developing the detection algorithm was identifying and isolating wind noise from true events. Sustained wind gusting was the major anticipated nuisance-alarm source since gusts can produce infrasound pressure transients superficially similar to the flow of an avalanche event. Wind resilience design was twofold for the BADS sensor: 1) deploying the sensor before snowfall guarantees ample snow coverage providing a natural wind baffle and 2) using unique ML feature extraction techniques, wind noise exhibits certain features that don't present in true avalanche and explosive signatures. Continued training of the ML classifier on the confirmed field events, especially with more expected activity this upcoming season, will only sharpen the model distinction as the network scales.

4. RESULTS

4.1. *Isolating Avalanche and Shock Events*

The two most interesting event types are isolated primarily by their temporal duration and frequency content. Figure 4 and Figure 5 below represent differential pressure traces from confirmed field shock and avalanche events, respectively.

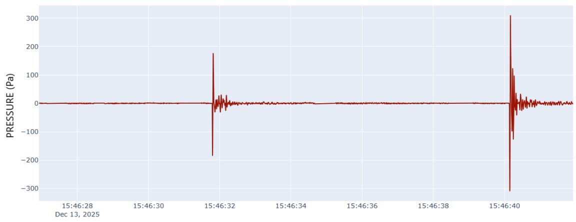

Figure 4: Confirmed Shock Event: dual hand charge

Avalanche flow events produce a broad pressure rise and fall lasting roughly 3–30 seconds as the moving snow front passes over the sensor, while explosive detonations produce a short, typically less than 1 second, higher frequency spike resembling a classic overpressure blast wave (Kinney and Graham 1985). This difference in duration

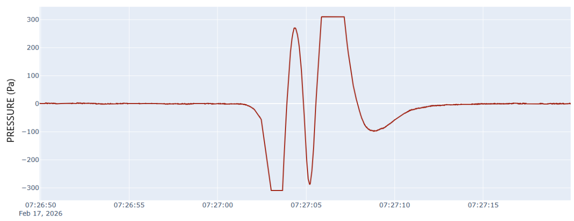

Figure 5: Confirmed Avalanche Event

and spectral content is what allows a single differential pressure sensor to provide the foundation to automatically distinguish the two event types without cameras, seismic arrays, or manual confirmation. Various signal processing techniques running in parallel coupled with ML inference at the centralized/cloud level or the local/edge level, depending on deployment architecture, facilitate isolating and identifying these events from other noncritical or spurious event types.

4.2. ML Algorithm Development

Using the confirmed avalanche and explosive events recorded across the three field arrays, a machine learning classifier was developed and trained to automatically distinguish between avalanches and shocks, as well as high-energy noise events, e.g. prolonged wind gusts. This classifier is under active development and has demonstrated promising early detection performance. The classifier provides a confidence probability supporting a binary avalanche decision versus shock and noise events. Generalizing the model over the entire season of pressure data yields the following confusion matrix when prioritizing the 33 true positive avalanche events, see Figure 6. Most events being wind noise or other pressure anomalies were rejected correctly as true negatives.

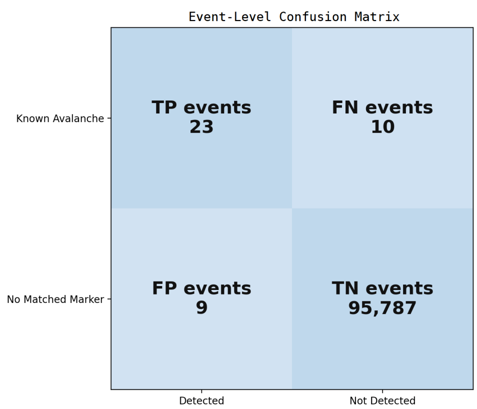

Figure 6: BADS Event Confusion Matrix

More specifically, to rigorously test model iterations and provide practical validation, the computationally-expensive ML model(s) were translated to an embedded model version and evaluated across all 1289 sensor-hours of acquired data to yield the true positive and true negative results. One example of the sliding window model output is shown below in Figure 7, evaluated on the avalanche event from Figure 5.

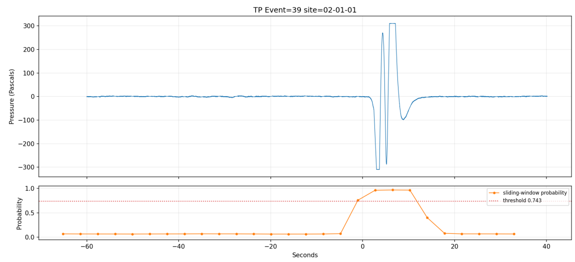

Figure 7: True Positive Probability Marker

4.3. Field Detection

Over the 2025-2026 season, BADS logged 33 confirmed avalanche detections and 99 confirmed explosive responses across the three field arrays at Kirkwood, Powder Mountain, and Jackson Hole, giving patrol staff a record of shot outcomes they previously did not have. The immense practical benefit has been fewer ambiguous shots — cases where a crew was not sure whether a target was released — and a clearer basis for deciding whether a slope needs to be re-shot.

4.4. Wireless Range

Getting a reliable wireless link over/around ridgelines and through multiple meters of snowpack requires repeated antenna tuning and radio configuration. Using 3D electromagnetic simulation and firmware tweaks, nodes achieve reliable transmission at distances exceeding one mile through snowpack of at least 3 meters. Furthermore, this was verified by field testing at Jackson Hole Mountain Resort before it became repeatable.

5. CONCLUSIONS

Running BADS as an operational program, rather than a lab prototype, has proven feasible by accelerating field development in real avalanche terrain. Deploying at three ski areas with differing terrain and existing infrastructure highlights that a single, low-cost differential pressure-based sensor body can provide value tantamount to more expensive radar and infrasound instrumentation for shot and avalanche confirmation, provided that results are framed simply as a binary yes/no rather than full spatial tracking. The 33 confirmed avalanche detections and 99 confirmed explosive detections recorded during the 2025-2026 season provides confidence that this simplification does not come at the cost of reliability. For the ski industry, that translates into a determination — did a slope release? — that patrol and mitigation teams could previously only make by direct observation, at a fraction of the cost and installation labor of existing detection systems. Moreover, this means fewer ambiguous shots, less time spent verifying uncertain terrain, and an improved documented basis for reopening runs and roads after mitigation work.

6. FUTURE WORK

For the 2026-2027 season, a 75 node deployment is planned across sites in the northwestern US and Alaska with nodes installed beneath Alpine Infrastructure RACS and in well-documented natural slide paths. This expanded dataset will be used to further inform and refine the detection algorithms and explore whether pressure spike duration correlates with avalanche runout distance and footprint. Furthermore, plans exist to integrate BADS alerts into the Colorado Department of Transportation (CDOT) intelligent transportation system (ITS) and test the automation of traffic control using BADS data.

ACKNOWLEDGEMENTS

The authors emphatically thank the avalanche safety teams at Kirkwood Mountain Resort, Powder Mountain, and Jackson Hole Mountain Resort for facilitating BADS field deployments. Furthermore, this work was partially supported through funding from a Colorado Department of Transportation (CDOT) grant.

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