FROM DETECTION TO DECISION SUPPORT: EXPANDING THE ROLE OF DOPPLER AVALANCHE RADAR IN HAZARD MANAGEMENT AND PLANNING

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ABSTRACT: Avalanche mitigation infrastructure, including remote avalanche control systems, bridges, snowsheds, and large earthen diversion or arresting structures, requires significant capital investment and ongoing maintenance. Doppler avalanche radar systems can support infrastructure planning by providing high-resolution spatial and temporal data that inform the optimization of infrastructure selection, configuration, and placement.

Event data collected from a steep terrain feature in a high-snowfall region of northwest British Columbia during the 2024-2025 and 2025-2026 winters demonstrate the scale and practical value of these observations. Over this period, the radar system detected more than 8,000 avalanche events within a single monitored area. These observations were collected in conjunction with an operational avalanche forecasting and control program, providing practitioner-based hazard information to support infrastructure planning. In addition to its value as an applied avalanche forecasting tool, this dataset provides planners and asset managers with a quantitative basis for evaluating avalanche frequency and spatial distribution, supporting more informed and defensible infrastructure design decisions. This paper demonstrates how high-resolution radar observations can support both quantitative risk assessment for infrastructure planning and daily hazard forecasting for operational risk management.

KEYWORDS: Doppler Radar, Planning, Operations, Monitoring, Mitigation.

1. INTRODUCTION

Avalanches are a persistent and costly hazard to transportation corridors, industrial operations, and mountain communities and their supporting infrastructure networks (Leone et al., 2014; Eckert et al., 2024). To reduce exposure to avalanche risk, engineers, forecasters, and planners employ a range of active and passive defense measures (Margreth et al., 2010). These measures are often associated with substantial capital investments (Fuchs et al., 2007), complex construction requirements, and long-term maintenance obligations (Margreth et al., 2010). Consequently, infrastructure planning in avalanche terrain requires a robust hazard assessment to ensure that mitigation measures are technically effective and economically defensible (Gauer, 2019). Central to this process is an accurate understanding of event frequency, spatial distribution, magnitude, and event characteristics.

Avalanche hazard assessment typically relies on historical records, field observations, terrain analysis, and practitioner experience (LaChapelle, 1980). While these methods remain fundamental to avalanche forecasting and hazard management, they are often constrained by incomplete event records (Eckert et al., 2024), limited temporal resolution, and observational bias (Statham et al., 2018). Due to operational constraints (e.g., visibility and access) numerous events may go undocumented (van Herwijnen & Schweizer, 2011). As a result, operational and infrastructure design decisions are frequently based on relatively limited datasets or conservative assumptions regarding avalanche occurrence and runout potential and therefore, assume a degree of uncertainty in their application (Barbolini et al, 2001; Jóhannesson et al., 2009; Jamieson et al., 2015; Stritih, 2022).

Avalanche detection has evolved (Rice et al., 2002) into systems including Doppler radar. Doppler avalanche radar allows for spatio-temporal event evaluation (Schreiber et al., 2001; Gauer et

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al., 2007a). These systems have demonstrated considerable value for operational forecasting (Trachsel et al., 2024) and transportation safety programs by improving situational awareness and supporting rapid hazard assessment during storm cycles and operationally challenging periods/locations.

The role of Doppler radar is expanding beyond operational forecasting applications. High-frequency avalanche observations can improve infrastructure planning and quantitative risk assessment. Large observational datasets allow for characterization and evaluation of recurrence intervals, zones of concentrated activity, and avalanche spatial distribution within complex terrain. These factors support optimization of infrastructure type, configuration, and placement, while also providing more information for investment decisions and long-term risk management strategies.

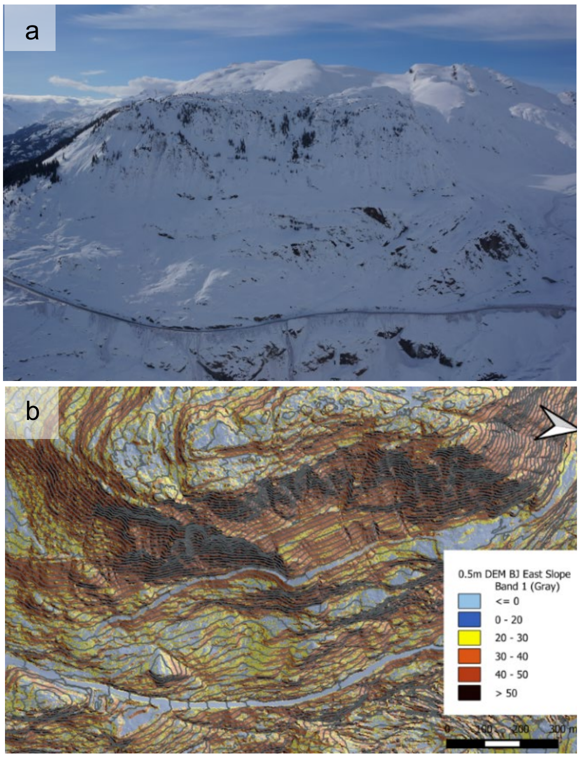

Figure 1 A site overview showing an image of the monitored terrain feature (a) where event data from the 24-25 and 25-26 seasons were collected with a Doppler avalanche radar and a map showing slope in degrees (b) (photo: Geoprevent; data: 6point).

The presented work shows event characteristics collected using a Doppler avalanche radar system installed at a steep terrain feature (Figure 1) in northwest British Columbia, Canada, during the 2024–2025 and 2025–2026 winter seasons. Over this monitoring period, over 8,000 avalanches were detected within the monitored area, representing one of the largest high-resolution avalanche datasets currently available from a single site. Event data in tabular, vector, and raster formats provides information into avalanche frequency, event duration, spatial extent, velocity and trajectory. The monitoring program was conducted in conjunction with an active avalanche forecasting and control program, allowing radar observations to be interpreted alongside practitioner-based hazard assessments and operational mitigation activities.

This paper demonstrates the emerging role of Doppler radar observations in supporting both operational avalanche forecasting and quantitative infrastructure planning through high-resolution characterization of avalanche frequency, spatial distribution, and event characteristics.

2. METHODS

2.1 Winter Summary

The 2024–25 season featured a below-average snowpack shaped by early-season rain events and alternating atmospheric rivers and Arctic Omega block patterns. December saw mild temperatures and rain that densified the base and triggered cycles up to size 2.5. January brought intense atmospheric rivers with high precipitation intensity, producing widespread size 2 to 3 storm slabs. In February, an Omega blocking pattern created outflow wind slabs. March storm cycles reactivated persistent weak layers, triggering slabs up to size 2.5. By April and May, sustained warmth and a 2000 m freezing level triggered extensive wet-loose avalanches, glide cracks, and deep wet slabs up to size 4 failing on the December crust.

The 2025–26 winter delivered above average snowfall driven by frequent Aleutian lows, heavy atmospheric rivers, and an active March storm track. High-intensity loading produced over 7,600 radar-detected avalanche events including 340 explosive-controlled avalanches. December storms repeatedly triggered natural and controlled slabs, culminating in natural size 3 storm slabs releasing from uncommon start zones. January was marked by a massive storm cycle (314 cm snowfall) followed by rain to 1550 m, prompting numerous size 2.5–3.0 avalanches. In early March, a significant storm produced size 3 persistent slabs failing on the February 22 crust, again observing large slabs in uncommon start zones. Spring transitioned into rapid warming by late April and May, driving widespread wet-loose shedding, isothermal snowpack consolidation, and glide crack formation.

2.2 Site Overview

The monitored region is located in a high snowfall area, within the Coast Mountains of northwestern British Columbia. The site is characterized by complex avalanche terrain consisting of very steep slopes above cliffs, relatively small, incised gullies, and planar slopes that form numerous discrete avalanche paths. These terrain features predominantly produce Size 1 and Size 2 avalanches; however, under favorable snowpack and loading conditions, individual paths or connected terrain features can occasionally produce larger Size 3 and Size 4 avalanches. The current avalanche program uses closures and explosive control (case charging, helicopter avalanche control, and twelve RACS) to maintain access through avalanche terrain.

During the monitoring period, the radar was placed in two different locations. For the 2024-2025 season, the radar was located near the roadway in the bottom left of Figure 1. For the 2025-2026 season, the radar was placed on a ridge opposite the monitored region at a distance of approximately 2000 m. In addition to maintaining daily operations, the radar was used to optimize future RACS placements, plan large defense measures, and other road infrastructure.

The deployed radar system (Figure 2) was designed to deal with the challenges of a remote environment. The full system consisted of a pan tilt zoom camera, a DSLR camera, the radar head and antennas, and a broad band satellite communication system which was made redundant by a narrow band iridium satellite link. As power was not available on-site, a combined methanol fuel cell - solar panel array maintained battery capacity ensuring consistent event capture and data transfer.

Figure 2 The radar system used for the 2025-2026 winter season showing solar array, camera systems, and control cabinet with the monitored region in the background.

2.3 Doppler Radar

Utilizing the Doppler effect provides high-resolution spatial and temporal data of avalanche activity under a wide range of weather and visibility conditions. The radar system operates on the principle of frequency-modulated continuous wave (FMCW) (Ulaby & Long, 2014). A frequency modulated radio frequency signal is generated in the 10~GHz (X-band) range, which is amplified to a designated output power, and transmitted through an antenna toward the monitoring area. The signal reflected from the target area is received by multiple dedicated receiver antennae, mixed with the transmit signal such that the resulting low-frequency beat signal can be sampled and further digitally processed. When an object within the monitored area moves with Doppler velocity v_D, the reflected signal undergoes a frequency shift (Δf_{D}) Eq. 1

$$f_{\mathrm{Doppler}} = f_0 - \Delta f_{\mathrm{D}} \quad \text{with } \Delta f_{\mathrm{D}} = f_0 \frac{2v_D}{c} \qquad \text{Eq. 1}$$

Where f_{Doppler} is the frequency of the reflected signal, f_o is the frequency of the emitted wave, v_D the velocity component of v that points towards the radar, and c is the propagation velocity of the radar signal, which approximately equals the speed of light in vacuum.

As seen from Eq. 1, the Doppler frequency shift is directly proportional to the velocity component of the moving object that points towards the radar. The most accurate velocity measurement occurs when the avalanche is moving directly toward or away from the radar, because the radar measures the component of velocity along its line of sight. Positive and negative frequency shifts indicate objects moving toward or away from the radar, respectively. A spectral analysis examines the different frequencies contained in the reflected radar signal to estimate how fast debris is moving and identify the dominant avalanche velocity (Shupe et al., 2004). With additional post-processing methods based on phase differences of the reflected signal as measured with multiple receiver antennas as well as on the frequency of the beat signal induced by the travel time of the propagating wave, the objects position can be determined. Compact targets moving at a uniform velocity produce distinct peaks in the velocity spectrum, while phenomena such as avalanches generate broader spectra due to the simultaneous movement of numerous particles at varying velocities (Koschuch et al., 2015; Schimmel et a., 2017). The Doppler radar utilized in this study had a lateral opening angle of 60° and 20° in vertical direction and a maximum operational distance of 5000 m.

2.4 Data Collection and Event Processing

Radar observations were collected continuously during the 2024–2025 and 2025–2026 winter seasons. The radar system automatically detects and records event information through the integrated processing software. Each detected event generated outputs which included event size, duration, velocity, spatial trajectory and extent, and associated imagery from the integrated camera systems. Events were reviewed through the cloud-based user portal to identify avalanche activity and were exported in tabular, vector, and raster formats for further analysis. The operational avalanche forecasting program provided an independent source of hazard information that was used to contextualize radar observations. Daily forecasting records, avalanche control activities, and practitioner observations were reviewed alongside radar detections to support interpretation of activity patterns.

2.5 Spatial Analysis and Radar Assisted Operational Assessment

The event dataset was used to examine avalanche attributes, recurrence characteristics, and spatial and temporal distributions of avalanche activity within the monitored area. Statistical evaluation was carried out with R-Studio (v. 2026.05.0) while vector and raster datasets derived from radar observations were analyzed within a GIS software (QGIS v.3.44). Spatial analyses and geoprocessing techniques focused on quantifying avalanche frequency, identifying areas of concentrated activity, and evaluating event distribution throughout the monitored terrain feature. The resulting spatial analyses revealed high-impact regions. These outputs were evaluated with respect to existing and proposed transportation corridors, and mitigation and defense infrastructure. Descriptive statistical methods were applied to event data, including frequency, duration, velocity, and size to evaluate data trends and distributions.

For operational applications, event detections were compared with avalanche forecasts and control activities to evaluate situational awareness and support hazard assessment during storm cycles. Additionally, an array of RACS was integrated into the user interface where the triggering of a RACS was indicated on the map, and the resulting success of the mission could be immediately assessed.

3. RESULTS

3.1 Seasonal Event Characteristics

The two seasonal datasets are not directly comparable for overall seasonal avalanche frequency because the monitoring duration, radar location, field of view, detection distance differed between seasons. Seasonal comparisons presented below are therefore primarily used to characterize the datasets and illustrate usefulness.

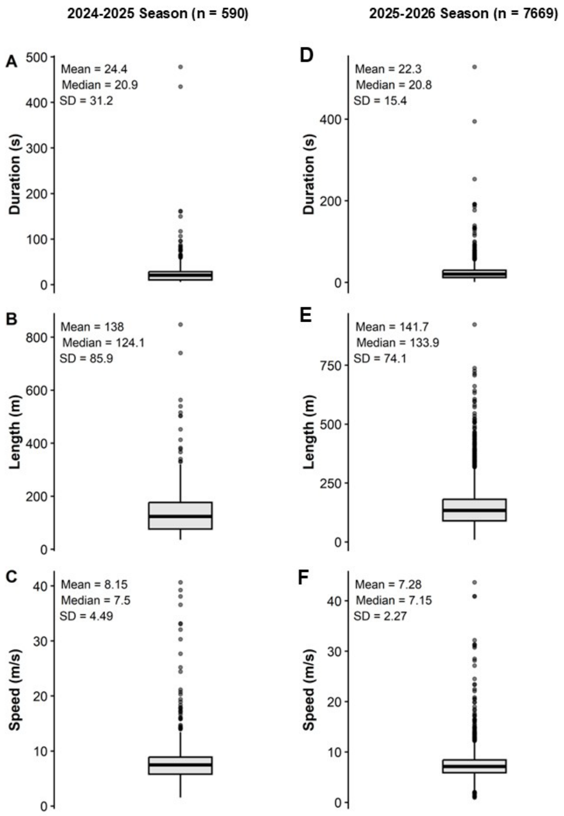

Figure 3 Event data for the 2024-2025 (A-C) and 2025-2026 (E-F) avalanche seasons.

For the 2025-2026 season more emphasis was placed on detecting all events that could potentially impact planned infrastructure, whereas in 2024-2025 the focus was more on daily operations and forecasting and therefore events that could potentially disrupt operational continuity. Descriptive statistics are summarized for 2024-2025 and 2025-2026 avalanche seasons (Figure 3 Figure 4) and indicate significant differences between seasons. The radar was not installed until February 2025; accordingly, the 2024-2025 data set is smaller (n=590) relative to the 2025-2026 season (n=7669). Another contributing factor in the difference in recorded events is that the radar during 2025-2026 had a lower detection threshold, enabling the identification of smaller avalanches (Figure 4), and had a more favorable field of view of the terrain feature, relative to 2024-2025. The radar measured size is evaluated through backend processing and serves as an approximation of EAWS (European Avalanche Warning Service) size classification. In this regard, evaluating radar derived size is done to illustrate the change in the detection threshold, and not as a means to evaluate destructive potential. From an operational perspective, the event length is a better estimation of event size. The Length Based avalanche size was classified following the typical path length, as published in the Canadian Avalanche Association OGRS (2024). The number of size 1 and 1.5 events recorded were relevant for the risk analysis and infrastructure planning described in this paper but were not always important in terms of impacting daily operations and thus could be filtered out. Event filtering is therefore important in managing dual radar applications, where event data requirements significantly differ. Event duration did not significantly change between seasons, which suggests that although the radar configuration influenced the number of detected events, the duration of avalanche movement remained relatively consistent across both seasons.

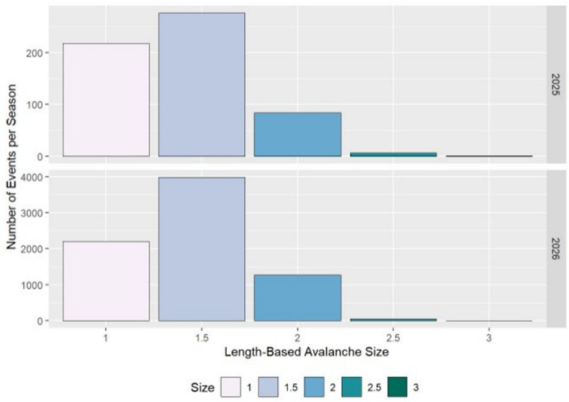

Figure 4 A comparison of radar-detected avalanche sizes from two distinct locations and winters. Despite the differing characteristics of each season, the size distribution illustrates how sensitive data interpretation can be.

3.2 Spatial Analysis – Applications to Infrastructure Planning

Daily event distribution (Figure 5a) allows for identification of avalanche cycles and verification of location specific magnitude-frequency estimates and potential avalanche control effort estimations. Generated map overlays highlight specific areas where spatial analysis quantifies avalanche intersections of proposed infrastructure alignments (Figure 6a Figure 6b). Different locations can be compared to assessing the relative hazard and alignment options (Figure 5b). Spatial querying enables direct comparison of the frequency with which alternative infrastructure alignments intersect with radar-observed avalanche activity. When combined with event frequency and magnitude information, these observations provide a quantitative basis for comparing relative exposure between alignment alternatives and identifying locations where mitigation measures may provide the greatest benefit.

While visualizing total avalanche events by week or month scale provides valuable insight into seasonal cycles and temporal frequency, this aggregate approach presents distinct limitations for infrastructure planning. Evaluating temporal totals across a broad monitoring area fails to isolate the spatial distribution of the hazard, meaning a high overall event count does not necessarily equate to high hazard exposure at a specific location. To make risk-informed decisions, it is helpful to query the event occurrence within the radar viewshed to compare the relative risk across specific infrastructure locations or alignments. Overlaying infrastructure locations on detection locations, engineering and planning decisions can be incorporated into risk assessments

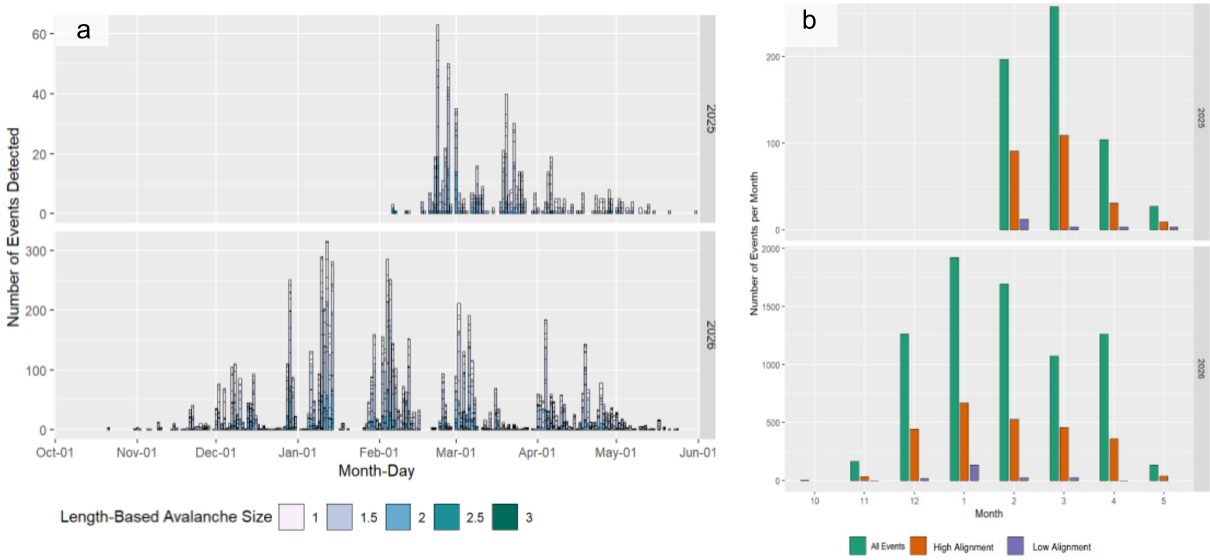

Figure 5 all events shown for both seasons classified by length-based event size (a) and events shown for intersections of two alignment options, green shows all recorded events, orange shows intersection events for an alignment higher up the slope than the lower alignment, purple shows intersections for an alignment lower on the slope (b).

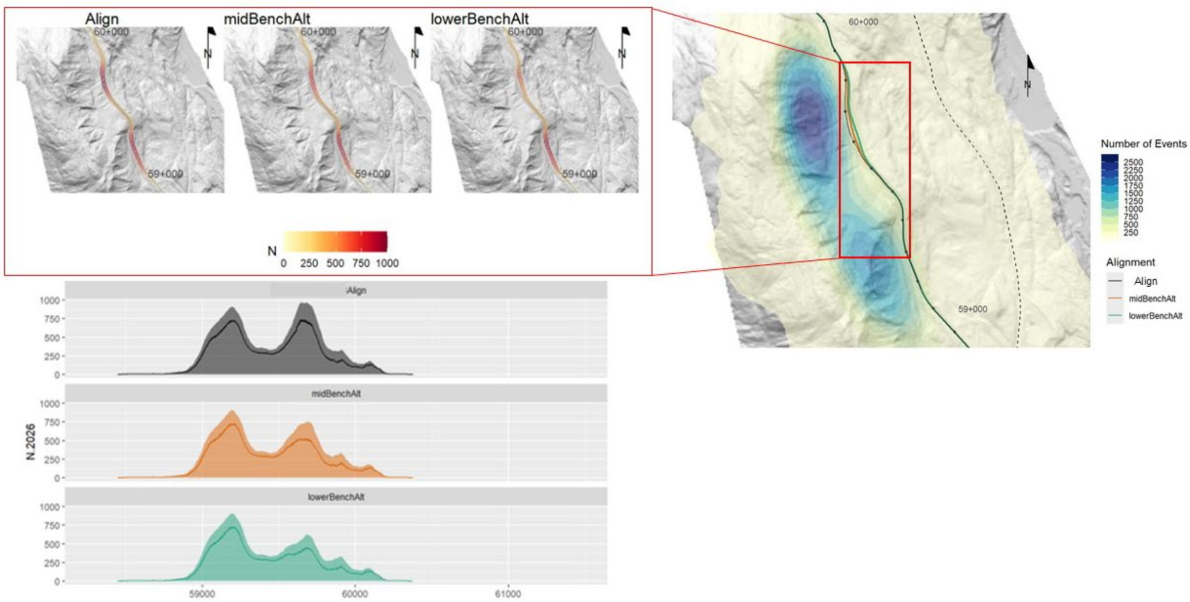

Figure 6 Spatial event distribution illustrated as a heatmap overlaid on a hillshaded DEM and showing a focused look of realignment options and a graphical representation of event observation distribution queried for each alignment alternative.

4. CONCLUSION AND DISCUSSION

Radar monitoring can provide quantitative insight into avalanche frequency in terrain that is difficult, unsafe, or impractical for avalanche technicians to observe consistently from the ground. This is particularly important in steep, complex terrain where visibility, access, overlapping avalanche paths, and frequent small events can substantially limit conventional observations. Continuous radar observations may reveal that avalanche activity in these terrain features occurs at a much higher frequency than is represented in manually compiled datasets, especially for smaller or short duration events that leave limited physical evidence or occur during periods of poor visibility. By resolving the spatial distribution, timing, and relative frequency of this activity, radar datasets can improve understanding of how terrain features—such as cliffs, gullies, convexities, aspect changes, and confined flow paths—influence avalanche initiation and movement. Over time, these observations may improve interpretation of terrain and provide additional information for developing and validating avalanche prediction and hazard assessment methods.

The results demonstrate that continuous radar monitoring can support both operational avalanche management and long-term infrastructure planning. Operationally, improving event detection regardless of visual conditions enhances the documentation of avalanche activity, supports the verification of mitigation measures, and provides objective information on event timing and location that can complement practitioner observations and avalanche forecasts. From an operational perspective, the sheer volume of incoming data during the 2025–2026 season overwhelmed forecasters during intense storm cycles. This highlights the challenges of using the radar system simultaneously for both infrastructure planning and operational forecasting, as planning applications require the detection of all potentially infrastructure-impacting events, whereas forecasting applications are primarily concerned with events likely to cause operational disruptions. Future development should therefore focus on automated event classification, filtering, and prioritization to distinguish operationally relevant detections while retaining the complete dataset required for long-term analysis.

Beyond immediate operational applications, the radar data delivers high value observations for long-term infrastructure planning and risk management. The high-resolution datasets collected by the system inform accurate magnitude and frequency estimations. By leveraging this comprehensive spatial and temporal data, planners and engineers can execute objective, risk-based comparisons when evaluating and selecting the most appropriate and effective mitigation types for avalanche terrain, linking operational avalanche management with long-term infrastructure planning.

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