Advancements In Avalanche Mitigation and Monitoring – Mt. Superior, Utah

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ABSTRACT: Mt. Superior, situated within the Uinta-Wasatch-Cache National Forest in Utah, United States, generates avalanches that pose a significant hazard to sections of State Route 210 through Little Cottonwood Canyon. The proximity of Little Cottonwood Canyon to Salt Lake City facilitates extensive ski area and backcountry access, resulting in substantial vehicle traffic passing under Mt. Superior. Historically, Mt. Superior has posed operational challenges as significant seasonal snowfall combined with paths that reach the road each winter makes hazard management and mitigation a dynamic process. These combined factors have influenced the progression of the Utah Department of Transportation (UDOT) avalanche mitigation and monitoring plan, which incorporates a range of advanced technologies and systems. The primary focus of Mt. Superior mitigation measures is on destructive avalanches that may impact the roadway and infrastructure. However, these efforts do not address the full local avalanche hazard, and risk remains for backcountry users. The mitigation strategy has transitioned from using long-range artillery to Remote Avalanche Control Systems (RACS), which are supported by a comprehensive monitoring system. This transition has significantly reduced the exposure of inhabited buildings to overhead artillery shells while also supporting centralized management of event data and mitigation management. This monitoring system includes the automatic detection of avalanches and people using Doppler radar, which allows for detection and monitoring to occur independent of weather and time of day. Event and person detection work by analyzing waves that are reflected by an object and received by the radar at a different frequency than the original signal. The frequency shift allows the radar to measure the avalanche's velocity and, with additional processing techniques based on the travel time, determine its position. Event detection facilitates RACS verification and supports forecasting efforts. The people detection component supports verifying that areas subject to active mitigation measures are clear of human presence. This combined approach of mitigation, forecasting, and monitoring exemplifies an integrated, state-of-the-art method to manage complex avalanche hazards in heavily trafficked corridors.

KEYWORDS: Avalanche radar, Mitigation, Monitoring

1. INTRODUCTION

State Route 210 (SR-210) traverses Little Cottonwood Canyon in the central Wasatch Range of northern Utah and is one of the most avalanche-exposed transportation corridors in North America, with the highest Avalanche Hazard Index (AHI) on the continent (Nalli and McKee, 2018). SR-210 provides access to ski resorts while supporting heavily used backcountry recreation areas near the Salt Lake City metropolitan region. Consequently, thousands of vehicles and recreationists are exposed to avalanche hazards. Among the numerous avalanche-producing terrain features affecting this corridor is Mt. Superior. Mt. Superior (3,367 m) rises more than 600 m above the canyon floor, with its south-facing aspects consisting of numerous start zones. Orographic lifting coupled to Pacific storm systems regularly produces annual snowfall exceeding 12–15 m at upper elevations. Frequent storm cycles, combined with steep terrain and persistent wind loading along the ridge, generate numerous natural and explosive-triggered avalanches throughout the winter. This presents a significant operational challenge, as large, destructive avalanches frequently reach the highway, causing considerable operational and economic consequences through infrastructure disruptions and damage, and posing risks to public safety. Complicating these factors, Mt. Superior is a popular backcountry destination; accordingly, users are frequently staged in parking areas below or are pursuing winter recreation on the mountain.

To improve mitigation efficacy, operational safety, and efficiency at Mt. Superior, the Utah Department of Transportation (UDOT) has transitioned from long-range artillery to Remote Avalanche Control Systems (RACS) (Nalli, 2016). The previous artillery-based system required firing explosive projectiles over State Route 210 and the Town of Alta to initiate avalanches, whereas the RACS deliver explosive charges directly into avalanche starting zones. This transition eliminates the risks associated with long-range artillery while enabling rapid, repeatable

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https://doi.org/10.15788/1790099061

avalanche mitigation under a broader range of operational and weather conditions. Supporting RACS mitigation efforts is a reliable monitoring system capable of confirming avalanche initiation, velocity, extent, and duration as well as detecting human movement in runout and initiation areas, ensuring that mitigation missions occur without people in exposed areas. The full monitoring system consists of a Doppler avalanche radar, a people detection radar, and camera systems. The monitoring system has been in place since January 2024.

The integration of Remote Avalanche Control Systems (RACS) with Doppler avalanche radar, people detection radar, and camera systems provides a comprehensive framework for a modernized avalanche hazard system at Mt. Superior. Continuous monitoring enables natural avalanche detection, verification of explosive results, characterization of avalanche activity, and confirmation that exposed terrain is clear of people prior to control work. Together, these technologies enhance situational awareness and support avalanche forecasting, mitigation planning, and operational decision-making, demonstrating how integrated monitoring and remote mitigation can improve safety and operational efficiency along heavily trafficked transportation corridors that also experience high levels of winter recreation.

2. METHODS

2.1 Doppler Avalanche Radar

Doppler avalanche radar provides continuous, high-resolution monitoring of avalanche activity under virtually all weather and visibility conditions by exploiting the Doppler effect (Figure 1). The system operates as a frequency-modulated continuous wave (FMCW) radar, transmitting an X-band (~10 GHz) radio frequency signal into the monitored terrain (Ulaby & Long, 2014). Signals reflected from moving targets are received by multiple antennas and digitally processed to determine both the velocity and position of the target.

Motion within the radar field produces a Doppler frequency shift proportional to the target's radial velocity relative to the radar, where positive and negative shifts indicate movement toward and away from the radar, respectively. Spectral analysis of the returned signal is used to estimate the velocity distribution of the moving target (Shupe et al., 2004). Additional processing of the reflected signal, including wave differences between multiple receiving antennas and travel-time measurements, enables the spatial location of the target to be determined. Compact objects moving at a constant velocity produce narrow spectral peaks, whereas avalanches generate broader velocity spectra because they comprise large numbers of snow particles moving simultaneously at varying speeds (Koschuch et al., 2015; Schimmel et al., 2017). These factors support an accurate and robust evaluation of temporal aspects of event behavior, while a general limitation is assessing spatial components. In this regard event size is derived from a post processing sequence, is based on multiple factors, and serves as good approximation, but results should be interpreted and referenced to local conditions and event behavior. The Doppler radar used in this application had a horizontal field of view of 60°, a vertical field of view of 20°, and an operational range of up to 5 km, allowing continuous monitoring of the Mt. Superior avalanche paths.

2.2 Site Overview

The monitored region is the south face of Mt. Superior (Figure 2), including its lower flanks where recreation activities are concentrated. The people detection radar was implemented as a part of the radar monitoring program, so while not directly related to the RACS systems that were implemented, it has shown to be a proven as a resource utilized by UDOT. Clear signage indicates that the area is subject to mitigation work, however, these warnings can be ignored, and the people detection radar provides an additional layer to ensure people are clear from hazardous areas. The location of the Doppler avalanche radar is below the heliport used by Powderbird Heli-skiing, which has posed challenges. The flight path for take-off and landing is through the field of view of the radar system, which in the past, had triggered events. These false positives were tuned out of the system through refining the detection algorithms. The unique situation of the heliport being proximal to the radar provided a beneficial opportunity to refine algorithms to identify and remove aircraft from the event criteria.

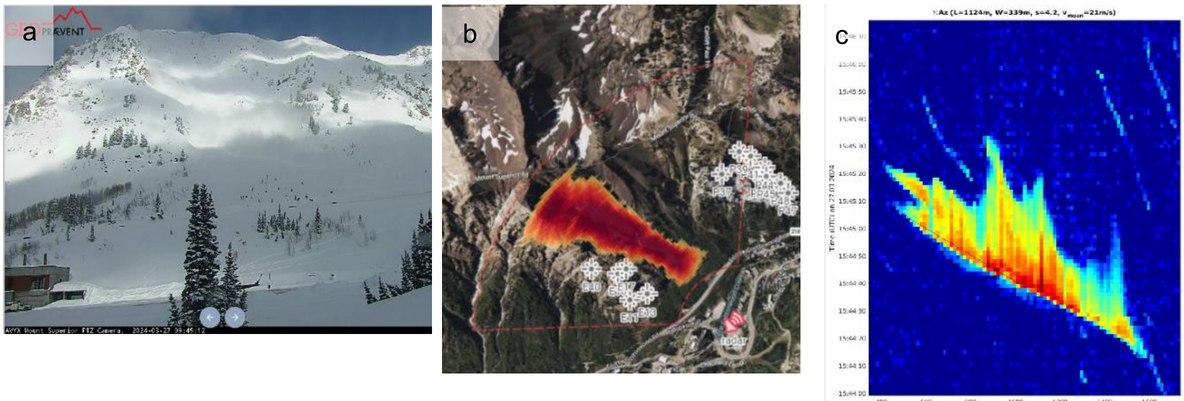

Figure 1 Detected on March 27, 2024. Panel a is an avalanche near its terminus. Panel (b) shows the location of the avalanche. Panel (c) is the radar detection plot, showing of a typical avalanche. The vertical axis is time, and the horizontal axis is range (distance) from the radar. The additional lines in the panel c identify skiers on the slope at the same time as the avalanche.

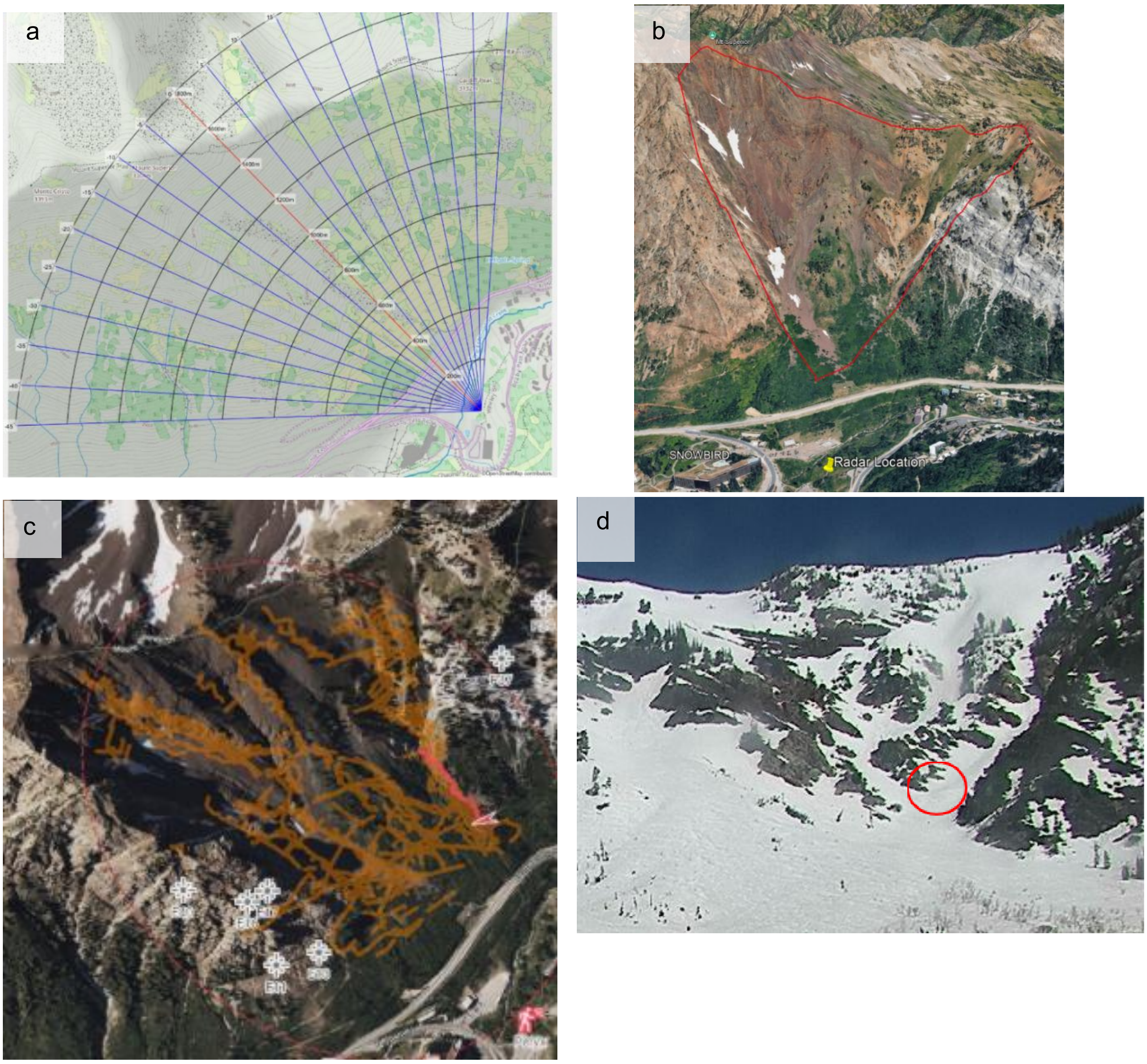

Figure 2 Mt. Superior and Radar location (a, b) the red polygon in panel (b) indicates the monitored region. Distances and angles are displayed showing the radar field of view (a). Identified people movement is displayed (c) where the highlighted track in red is a skier that is displayed and circled (d).

3. RESULTS

3.1 *Avalanche Characteristics*

The Doppler radar has operated continuously since January 2024, capturing three winter seasons that exhibited markedly different avalanche activity. During the partial 2023–2024 season, 552 avalanche events were detected following system installation. The 2024–2025 season recorded the greatest activity (n = 768), whereas the 2025–2026 season, characterized by below-average snowfall, produced only 229 detected events. Despite differences in event frequency, avalanche characteristics were consistently evaluated, specifically event duration, size, velocity, and travel length (Figure 3 - Figure 5 and Table 1- Table 3). The 2023–2024 season was characterized by longer-duration events (mean = 68.5 s) than either subsequent season, while the 2024–2025 season exhibited the greatest average travel length (545.8 m) and the highest average velocity (10.9 km h⁻¹). Conversely, avalanches during the low-snow 2025–2026 season were generally shorter (274.6 m), slower (9.0 km h⁻¹), and shorter in duration (33.6 s), although the average radar-derived avalanche size remained comparable among seasons (2.7–2.9). The boxplots demonstrate substantial variability within each season, particularly for duration, velocity, and travel length, reflecting the broad spectrum of avalanche behavior observed on Mt. Superior. Numerous high-value outliers correspond to infrequent but operationally significant events. These larger events represent avalanches that are most likely to reach SR-210 and therefore have the greatest implications for highway operations and hazard exposure.

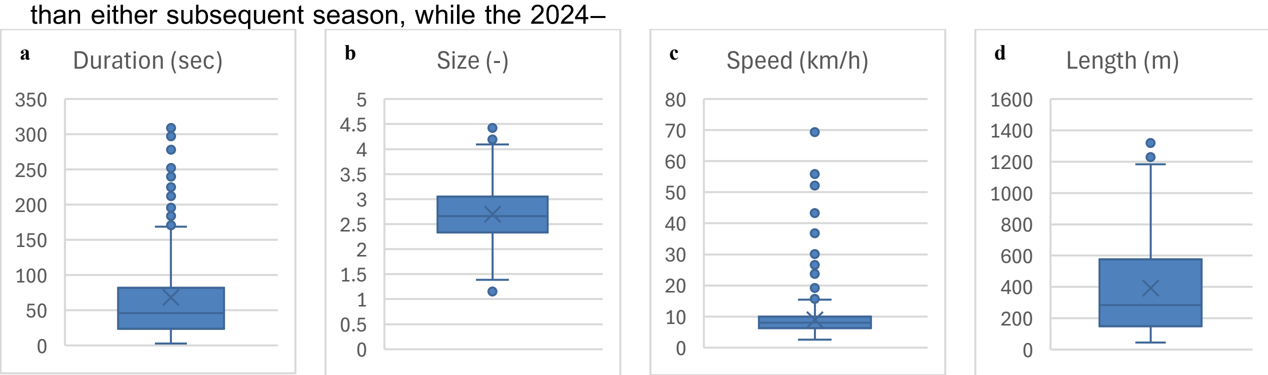

Figure 3 Boxplots of measured event characteristics for the 2023-2024 season showing event duration (a), size (b), velocity (d) and length (e). n = 552.

Table 1 Descriptive statistics for the 2023-2024 season. n = 552.

	Avg	Max	Min	Std.
Duration (sec)	68.5	317.0	3.0	67.6
Size	2.7	4.4	1.2	0.5
Speed (km h⁻¹).)	8.9	69.4	2.5	5.8
Length (m)	392.4	1364.1	45.0	301.6

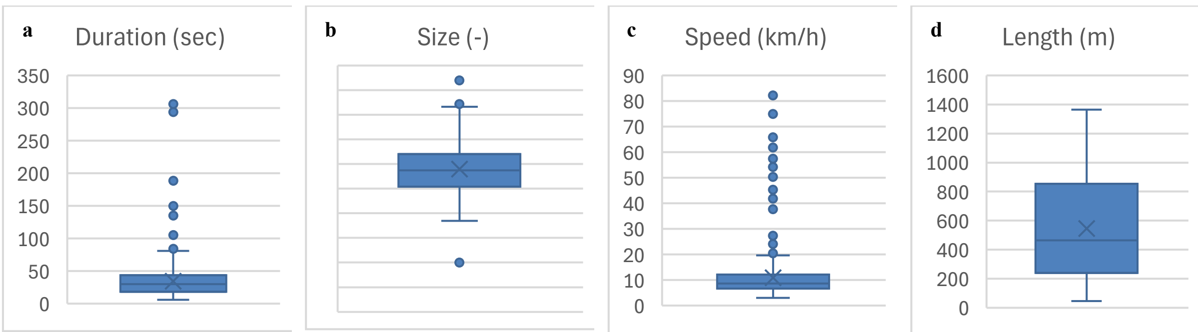

Figure 4 Boxplots of measured event characteristics for the 2024-2025 season showing event duration (a), size (b), velocity (d) and length (e). n = 768.

Table 2 Descriptive statistics for the 2024-2025 season. n = 768.

	Avg	Max	Min	Std.
Duration (sec)	34.5	312.0	5.8	26.7
Size	2.9	4.7	1.0	0.5
Speed (km h⁻¹).)	10.9	83.7	3.1	9.1
Length (m)	545.8	1364.1	45.0	356.4

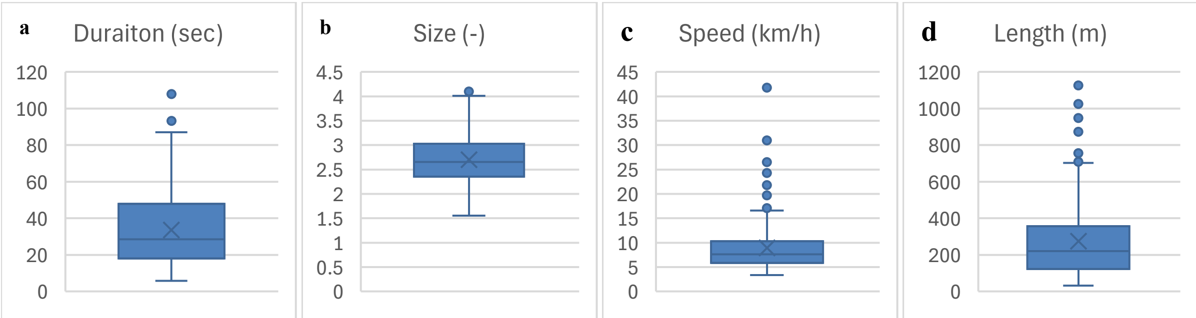

Figure 5 Boxplots of measured event characteristics for the 2025-2026 season showing event duration (a), size (b), velocity (d) and length (e). n = 229

Table 3 Descriptive statistics for the 2025-2026 season. n = 229.

	Avg	Max	Min	Std.
Duration (sec)	33.6	109.3	5.8	20.1
Size	2.7	4.2	1.6	0.5
Speed (km h⁻¹).	9.0	41.8	3.4	5.0
Length (m)	274.6	1127.0	32.0	205.7

3.2 *People Detection Characteristics*

Figure 6 illustrates the number of people detections recorded every 15 minutes throughout the full operational period. Several short-lived peaks in detections coincide with periods of increased backcountry use, particularly during favorable snow/weather conditions.

Figure 7 illustrates the operational value of the people detection radar during, for example, an active storm cycle from 26–28 March 2024. During this period, Mt. Superior experienced cold winter conditions, with temperatures ranging from −8.3 to −2.8°C and approximately 7 cm of new snowfall on 27 March as part of a prolonged late-March storm cycle that deposited nearly 1 m of snow over five days (NOAA.gov). These conditions were conducive to widespread avalanche activity and intensive mitigation operations; however, repeated skier movements were detected within the monitored area throughout the storm. The persistence of backcountry recreation during periods of elevated avalanche hazard highlights the operational challenges of conducting avalanche control in heavily trafficked recreation areas. Continuous people detection, independent of weather and visibility conditions, provides critical situational awareness by verifying that exposed terrain is clear before mitigation, thereby supporting safer and more efficient avalanche control operations.

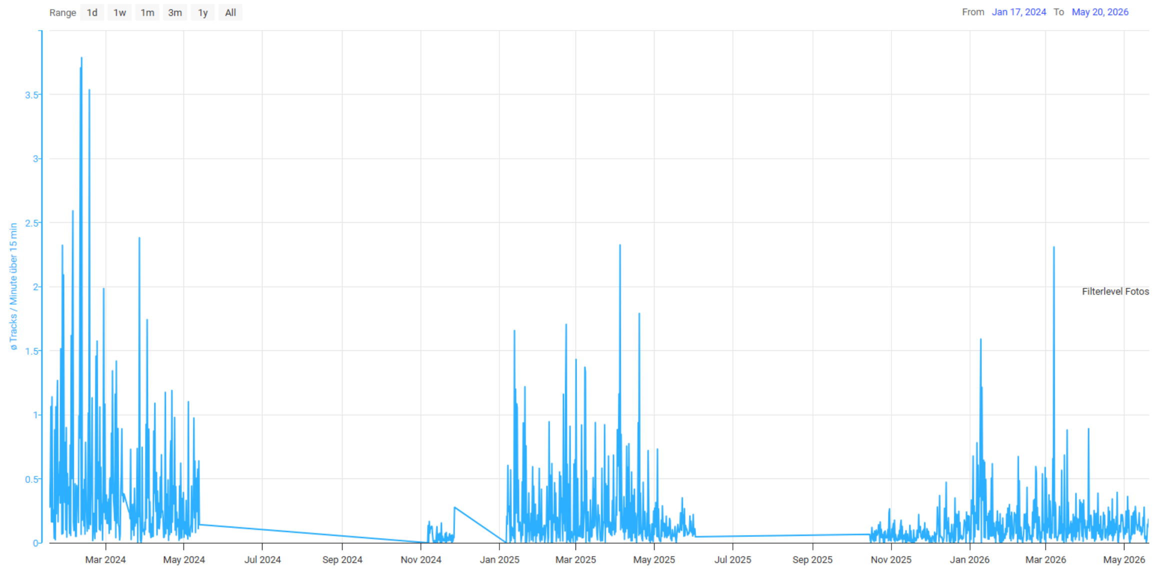

Figure 6 Plot showing the Number of people detections occurring every 15 minutes (y-axis) showing the full operational duration (x-axis)

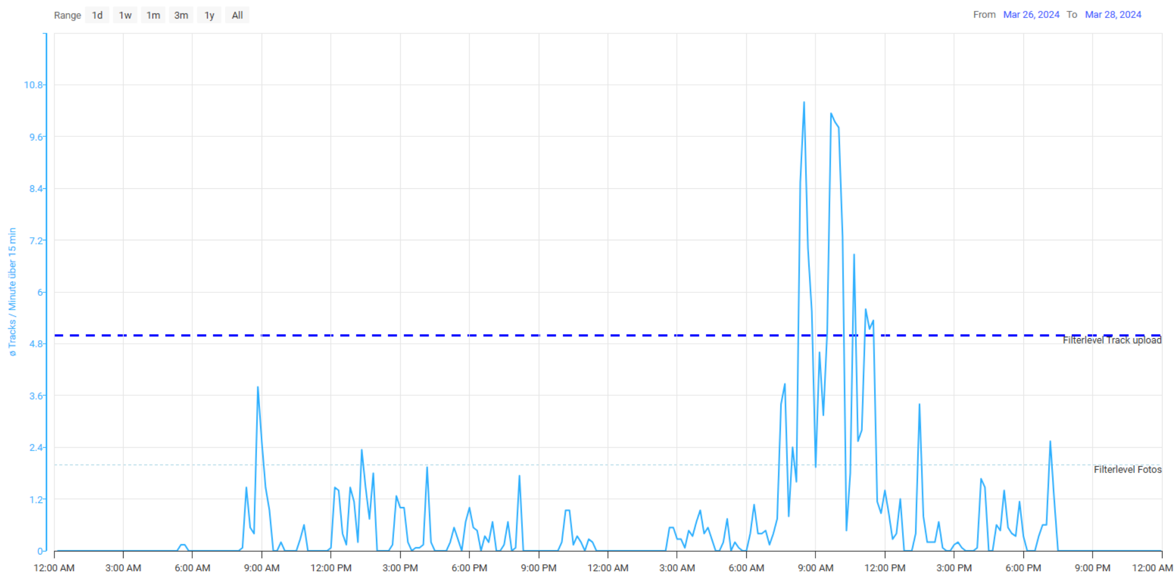

Figure 7 A focused showing hour intervals on 26-28 March 2024 where people detections correlate with people leaving the Mt. Superior base area during an active storm cycle.

4. CONCLUSION AND OUTLOOK

The deployment of an integrated monitoring system consisting of a Doppler avalanche radar, people detection radar, and camera systems has enhanced avalanche hazard management at Mt. Superior. Continuous monitoring over three winter seasons demonstrated the system's ability to reliably detect and characterize avalanche activity across a wide range of environmental conditions while simultaneously monitoring backcountry recreation within the mitigation area. People detection provided an additional operational capability by identifying recreationists within exposed terrain during active storm and avalanche cycles. Real-time situational awareness ensuring that mitigation areas are clear prior to initiating RACS missions, improves operational safety for both avalanche control personnel and backcountry users.

The transition from long-range artillery to RACS, supported by integrated monitoring technologies, represents a substantial advancement in avalanche risk management along the SR-210 transportation corridor. Beyond reducing the hazards associated with artillery-based control, the system provides objective documentation of avalanche occurrence and mitigation outcomes while supporting centralized operational decision-making.

Future work will focus on further refinement of the detection algorithms, to reduce false positives, improve event classification, and spatial definition of avalanche boundaries. As additional seasons of data become available, the long-term record will provide valuable insight into avalanche frequency, magnitude, and backcountry use, supporting continued improvements in avalanche forecasting, mitigation, and public safety in one of North America's most avalanche-exposed transportation corridors.

ACKNOWLEDGEMENTS

The authors thank the Utah Department of Transportation for their ongoing efforts in managing avalanche hazards and for their support of this paper.

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