A COMPREHENSIVE AVALANCHE MITIGATION AND MONITORING FRAMEWORK FOR ARCTIC COASTAL INFRASTRUCTURE PROTECTION ON ARNØYA, NORWAY

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ABSTRACT: Arnøya, a remote island in Troms County, Northern Norway, saw the installation of a comprehensive avalanche mitigation and monitoring system in 2024, focused on two major high-risk zones along county road 9740: Singla and Oterelvene. The primary objective was to protect critical road infrastructure, ensuring reliable year-round access for the local population while supporting regional economic activity. The system consists of 24 remotely operated O'Bellx avalanche gas control systems supported by two Doppler avalanche radars, camera networks and two weather stations. This integrated monitoring framework provides both quantitative and qualitative data in a region where operational assessments are frequently constrained by limited daylight and Arctic coastal weather conditions, making direct visual evaluation of mitigation outcomes and natural avalanche cycles difficult. In addition to supporting avalanche hazard assessment and control operations, the radar system is used to track and count boats and vehicles and to provide warnings in situations where natural avalanche activity may have exposed road users or marine traffic. This capability is particularly important because many avalanche paths terminate abruptly near the shoreline, placing transportation infrastructure and marine traffic routes at direct risk. The combined mitigation–monitoring system provides two primary operational benefits. First, centralized control and event management reduce exposure of practitioners to hazardous avalanche terrain and make post-control verification easier and more precise. Second, real-time data from cameras, weather stations and radars provide precise tools for forecasters and operators to plan and time avalanche mitigation to support effective operations. In this study, we demonstrate how advanced mitigation and monitoring technologies can be deployed in parallel to enhance avalanche hazard management in remote and operationally challenging environments, where infrastructure disruptions can have immediate and significant consequences for local communities.

KEYWORDS: Avalanche Monitoring, Norway, RACS, Mitigation, Forecasting

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1. INTRODUCTION

Transportation corridors in northern Norway are frequently exposed to avalanche hazards that disrupt critical infrastructure, threaten public safety, and require extensive winter maintenance (Eiselt & Graversen, 2025). Effective hazard management relies on avalanche activity observations to support forecasting, mitigation, and infrastructure operations. However, in remote Arctic environments, these observations are often difficult to obtain because of severe weather, prolonged periods of darkness, and limited accessibility restrict direct observation (Eckerstorfer et al., 2017). As a result, operational decisions frequently rely on incomplete information during periods of greatest avalanche hazard (Jóhannesson et al., 2009; Jamieson et al., 2015).

Artificial avalanche initiation and field-based observations remain the foundation of operational avalanche risk management. While these approaches have proven effective, they require personnel to work in hazardous terrain and often provide limited capability for immediate verification of avalanche release timing, extent, and runout (van Herwijnen & Schweizer, 2011). Consequently, there is increasing interest in technologies that can reduce operator exposure while providing continuous, objective observations of avalanche activity. The recent development of remote avalanche control systems (RACS), combined with Doppler radar and complementary monitoring technologies, offers the potential to improve operational safety, provide real-time verification of mitigation missions, and generate long-term datasets that support quantitative hazard assessment and infrastructure planning.

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Arnøya, located in Troms County, Norway, represents a particularly challenging operational environment where, at the Singla and Oterelvene areas, both land- and sea-based traffic are exposed to avalanche hazards. To improve year-round transportation reliability and reduce operational risk, Troms County implemented, based on a cost benefit analysis of active vs passive measures, an integrated, active, avalanche mitigation and monitoring system in 2024 consisting of 24 O'Bellx,2 Geoprevent Doppler avalanche radars and 2 Automatic-Weather Stations (AWS) (Table 1). The project provides a unique opportunity to evaluate how continuous radar observations and remote avalanche control can be integrated into daily avalanche operations while simultaneously generating high-resolution datasets for long-term infrastructure risk management. This paper describes the system architecture, summarizes the commissioning process and discusses the operational advantages and lessons learned during the first winter of operations. The combined monitoring system was required to evaluate the following selected event characteristics:

- Total event duration
- Maximum velocity of the avalanche along the line of sight of the radar system
- Maximum signal strength, e.g. maximum intensity [db]
- Distances from radar to detected avalanche movements, max. and min. [m]
- Outer horizontal (azimuth angle) and vertical (elevation angle) boundary for detected avalanche movements, max. and min. [°]
- Estimated avalanche size according to EAWS standards
- Heat map of the spatial extent of the avalanche
- Display of all O'Bellx, avalanche paths, and avalanche detections on the same map.
- Video footage and still images (visual and thermal) of the event
- Verification tool, the ability to confirm and refute a detected event according to
    - Confirmed avalanche
    - Confirmed weather event
    - Other (e.g. plane or helicopter)

Table 1 Overview of deployed systems and their operational role

Component	Function
O'Bellx systems	Remote mitigation of selected avalanche paths
Doppler avalanche radars	Continuous avalanche detection, documentation, vehicle/vessel tracking and warning support
Camera networks	Visual and thermal context for event interpretation and snow-cover assessment
Weather stations	Local wind and temperature information for timing and hazard assessment
Event management / notification	Communication, logging, verification and post-event review

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2. METHODS

2.1 Site and System Overview

The Arnøya monitoring concept covers two avalanche-prone areas, Singla and Oterelvene, where avalanche paths create a combined road and maritime hazard (Figure 1). The maritime climate, with intense snowfall in situations with an onshore wind direction and occasional polar low, yields swiftly changing avalanche conditions. The climate is mild and often the freezing-altitude in the avalanche paths create a challenging forecasting environment with both dry and wet avalanche problems present in these paths. The location of the O'Bellx gas exploder systems, and Doppler radars are shown in Figure 1. Supporting the radar system are Pan Tilt Zoom and thermal cameras, and weather stations to provide continuous operational awareness. Weather stations supply local meteorological data for hazard forecasting, while cameras provide visual confirmation of environmental conditions, avalanche activity, and depositional extent. observations, including radar detections, imagery, weather data, and system status, are transmitted to relevant databases (e.g., Figure 3). Automated detections provide rapid SMS and email notifications, while manual verification by avalanche forecasters and operators confirms events, filters false detections, and supports ongoing system calibration. Together, these components provide a continuously updated decision-support framework for avalanche mitigation and road and maritime safety. The first season (Nov. 15, 2024, to May 15, 2025) was used as a calibration and optimization phase of the radar system where thresholds and radar calibration were adapted to local conditions. During this phase the radar system was installed November 15, 2025, which required additional calibration and tuning.

2.2 *Doppler Radar*

The Arnøya monitoring concept includes two Doppler avalanche radars, one focused on the Singla area and one focused on the Oterelvene area (Figure 2). The radars support mitigation missions by detecting and documenting avalanche initiation in the monitored region. Radar observations provide quantitative event information which is captured independent of weather and time of day and can therefore provide valuable data when visual observation is limited (Malnes et al., 2013). Motion within the radar field produces a Doppler frequency shift proportional to the target's velocity relative to the position of the radar. Positive and negative shifts indicate movement toward and away from the radar, respectively. 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 antennae and travel time measurements, supports determining the spatial location of the event. Radar detections are interpreted in relation to predefined monitoring areas and operationally relevant zones. The system supports classification of detected events in relation to whether they affect a road or vessel hazard zone. In addition to avalanche detection, the radar systems track vehicle and vessel movements within predefined danger zone monitoring areas, supporting situational awareness during natural avalanche cycles or artificially released events. Hazard zones describe regions where an avalanche could potentially impact the road or the fjord. The hazard zone for vehicles extends across the road and about 30 m towards the mountainside, measured from the road. The hazard danger zone for ships extends from the road to about 300 m in the fjord for and about 600 m for the Oterelvene and Singla areas, respectively. The key requirements of the deployed radar system include detecting:

1) Avalanche or suspected avalanches of relevant magnitude imitates in the area of interest

2) Avalanche runout in the area of interest (before the hazard zone)

3) Avalanches in the hazard zone (vehicles and ships)

4) False positive detection caused by a weather event with similar characteristics to avalanches (e.g. rain or snow showers within the measurement range) are automatically reclassified as such.

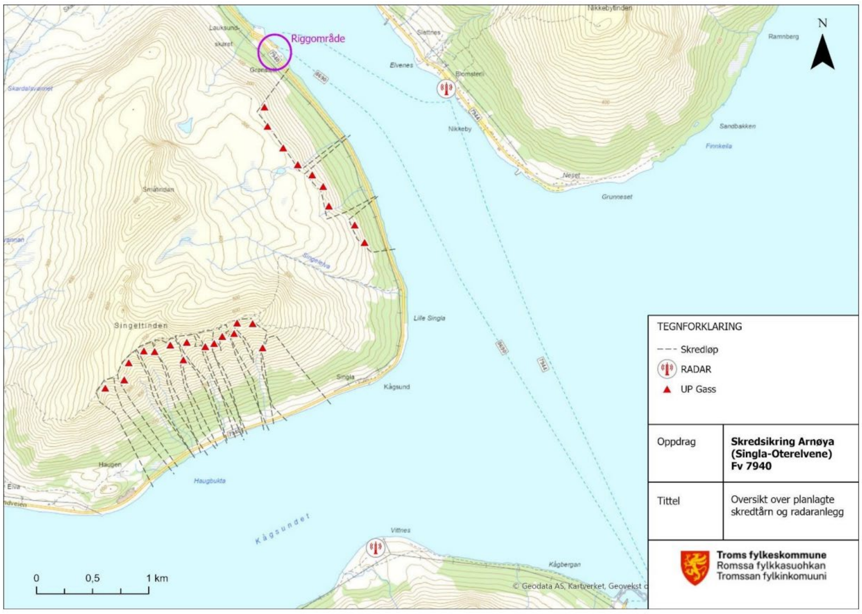

Figure 1 Site overview showing radar locations, O'Bellx locations and avalanche paths Source: Troms County.

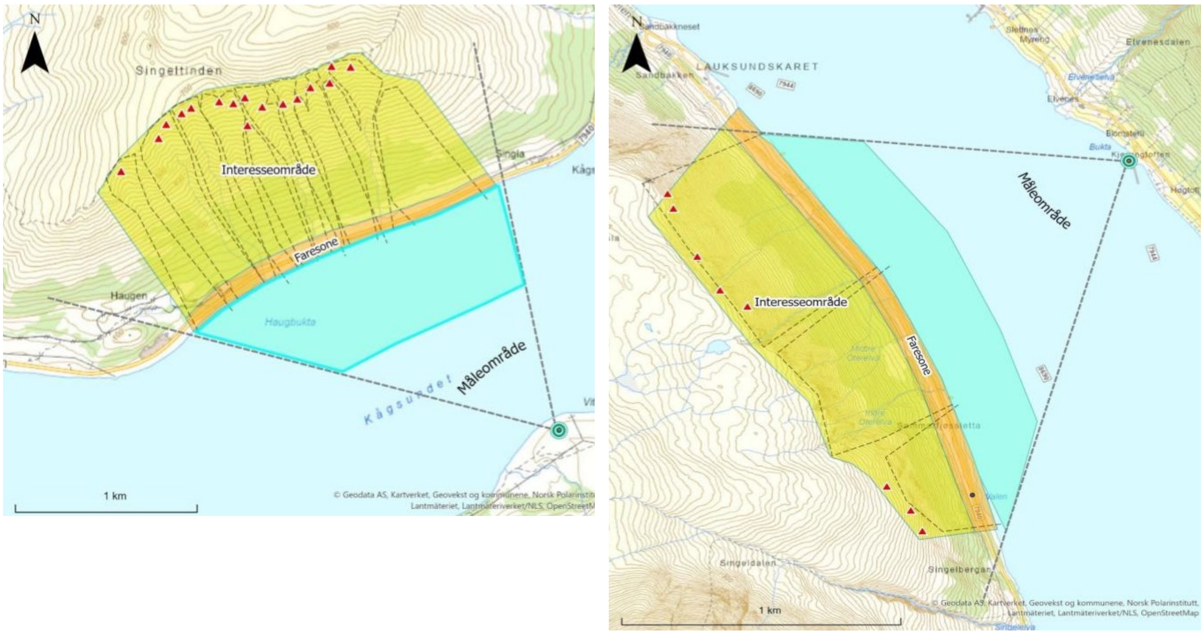

Figure 2 Maps showing Singla (left) and Oterelvene (right) areas. The blue polygon shows the ship tracking extent, the red triangles indicate RACS, and the orange polygon shows the vehicle tracking zone (Source: Troms County).

3. RESULTS

The first winter of the combined system served as a commissioning and optimization phase. During this period, radar monitoring areas, detection thresholds, notification logic, camera views, and event interpretation procedures were refined to reflect local avalanche behavior, coastal exposure, and operational requirements. This iterative calibration is typical for complex sites where mitigation, monitoring, and decision support must function as a unified operational workflow. Installation in the exposed Arctic coastal environment highlighted the importance of robust mechanical design and site-specific design. Storms and prolonged darkness, for example, can reduce camera performance, even when radar detection remains unaffected. This emphasizes the need to consider radar, cameras, power supply, communications, mounting infrastructure, and operational software as an integrated system rather than independent components. Radar detections, including during the polar night, documented avalanche activity, cameras provided visual confirmation of releases and deposits, and weather stations supported interpretation of wind loading and temperature-related changes. Together, these data enabled more reliable verification of mitigation results and natural avalanche activity than visual observations alone. Furthermore, observations from the first winter illustrated the speed at which start zones were loaded as maritime conditions supported rapid accumulation rates. Radar-based tracking of vehicles and vessels further enhanced situational awareness where avalanche paths intersected road and coastal traffic corridors (Figure 3).

The commissioning phase also identified opportunities for continued refinement, including optimization of radar regions of interest, improved classification of weather-related signatures, integration of avalanche control actions into operational displays, enhanced reporting workflows, and refinement of detection algorithms as operational experience increases. These developments are an expected part of commissioning and demonstrate that successful implementation of an integrated avalanche monitoring system requires continuous calibration against real avalanche events, local environmental conditions, and operational practices. The operational experience in the forecasting team also gives better insights and more effective use of the system with time and increases operational precision

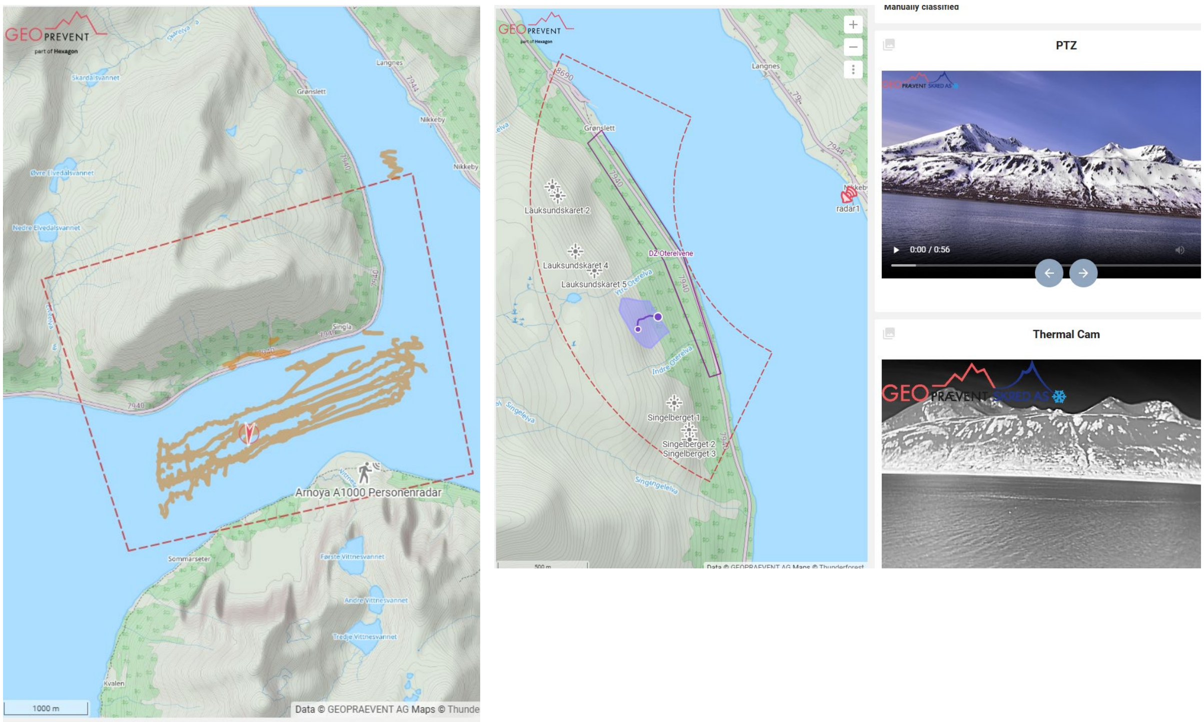

Figure 3 An example of ship detection at Singla (left) and avalanche detection showing trajectory, PTZ and thermal images (right).

4. CONCLUSION AND OUTLOOK

The Arnøya project demonstrates how remote avalanche control systems and continuous hazard monitoring can be integrated into a single operational framework to improve avalanche risk management in remote Arctic environments. By combining Doppler radar, weather stations, camera networks, and centralized event management, the system provides continuous quantitative and qualitative observations that support the complete operational workflow, from mitigation to post-event verification. The ability to objectively document avalanche occurrence independent of daylight and visibility represents a significant advancement over conventional field observations alone, while radar-based tracking of vehicles and vessels extends situational awareness to all transportation users exposed to the hazard. This capability is particularly valuable at the described sites, where avalanche paths terminate near the shoreline and infrastructure disruptions can immediately affect both road and marine transportation, causing hardships for local communities

Beyond demonstrating the operational feasibility of the system, the first winter of deployment highlighted that successful implementation depends on site-specific commissioning and continuous refinement of detection algorithms, monitoring zones, and operational workflows. Rather than a one-time installation, integrated monitoring systems should be viewed as evolving decision-support tools whose performance improves as additional operational data and user experience are incorporated. This iterative process is essential for maximizing detection reliability, minimizing false alarms, and ensuring that monitoring output remains directly relevant to operational decision making.

While this contribution focuses on system design, implementation, and initial operational phase, the collected datasets provide a valuable resource for future research and planning. Long-term radar observations, integrated with mitigation records and meteorological data, offer opportunities to quantify avalanche characteristics and infrastructure exposure at an unprecedented temporal resolution. These datasets can support forecasting efforts, validation of numerical avalanche models, evidence-based infrastructure planning, and efficacy of remote avalanche control systems. As transportation agencies increasingly seek resilient, data-driven approaches to natural hazard management, integrated mitigation and monitoring systems such as the one implemented at Arnøya have the potential to become the operational standard for protecting critical infrastructure in avalanche-prone regions

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