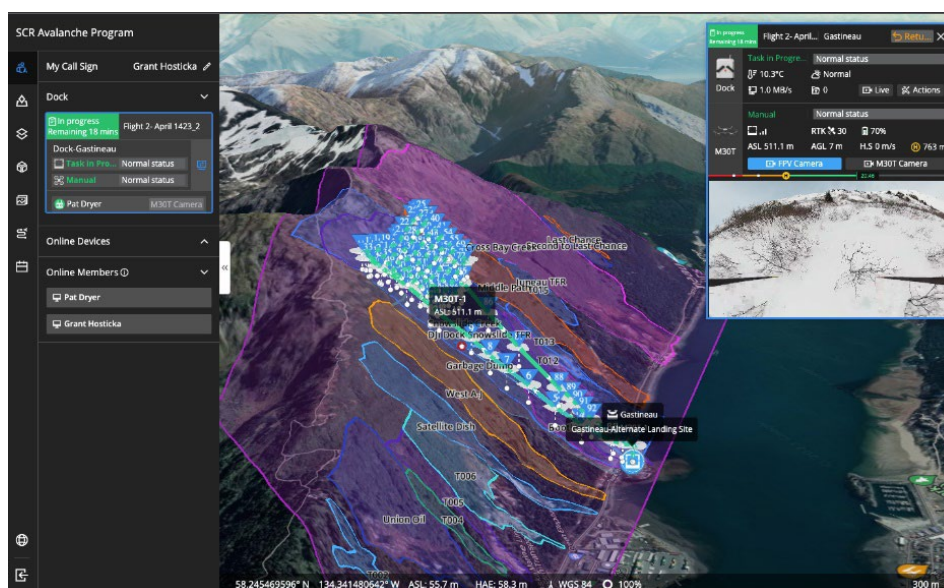




Integrated Avalanche Detection, Warning, and Snow Distribution Mapping

Thane Road, Juneau, Alaska

FINAL REPORT



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METRIC (SI*) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol SI
<u>LENGTH</u>				
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km

AREA

in ²	square inches	645.2	square millimeters	mm ²
ft ²	square feet	0.093	square meters	m ²
yd ²	square yard	0.836	square meters	m ²
ac	acres	0.405	hectares	ha
mi ²	square miles	2.59	square kilometers	km ²

VOLUME

fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft ³	cubic feet	0.028	cubic meters	m ³
yd ³	cubic yards	0.765	cubic meters	m ³

NOTE: volumes greater than 1000 L shall be shown in m³

MASS (WEIGHT)

oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")

TEMPERATURE

°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C
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ILLUMINATION

fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m ²	cd/cm ²

FORCE and PRESSURE or STRESS

lbf	poundforce	4.45	newtons	N
lbf/in ²	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol SI	When You Know	Multiply By	To Find	Symbol
<u>LENGTH</u>				
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi

AREA

mm ²	square millimeters	0.0016	square inches	in ²
m ²	square meters	10.764	square feet	ft ²
m ²	square meters	1.195	square yards	yd ²
ha	hectares	2.47	acres	ac
km ²	square kilometers	0.386	square miles	mi ²

VOLUME

mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m ³	cubic meters	35.314	cubic feet	ft ³
m ³	cubic meters	1.307	cubic yards	yd ³

MASS (WEIGHT)

g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T

TEMPERATURE

°C	Celsius	1.8C+32	Fahrenheit	°F
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ILLUMINATION

lx	lux	0.0929	foot-candles	fc
cd/cm ²	candela/m ²	0.2919	foot-Lamberts	fl

FORCE and PRESSURE or STRESS

N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in ²

These factors conform to the requirement of FHWA Order 5190.1A

*SI is the symbol for the International System of Measurements

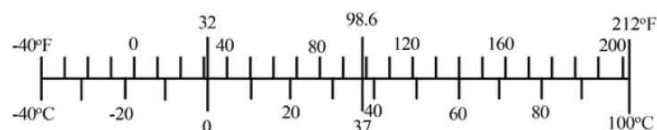


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The Department acknowledges the contributions of Snowbound Solutions LLC for their technical expertise in the design, deployment, and refinement of the infrasound monitoring system. Their work was instrumental in addressing system performance challenges, including electromagnetic interference (EMI), and contributed to improvements in hardware configuration and installation practices.

The Department also recognizes the cooperation of Alaska Electric Light & Power (AEL&P), whose infrastructure context was integral to the deployment of the system within the Thane Road corridor. Appreciation is extended to DOT&PF field personnel who supported installation, data collection, and operational integration under challenging environmental conditions.

Executive Summary

This report documents the successful deployment and operational evaluation of an integrated avalanche detection system along the Thane Road corridor in Juneau, Alaska. This project represents the first use of infrasound technology by Alaska DOT&PF for real-time avalanche detection and hazard assessment. Avalanche hazard management along Thane Road has historically been constrained by limited visibility, severe weather, and reduced mitigation capabilities. These constraints have resulted in increased uncertainty in hazard assessment and operational decision-making.

To address these challenges, DOT&PF deployed an infrasound monitoring system capable of detecting avalanche activity in real time under all environmental conditions. The system successfully identified avalanche events, including those not observable through traditional methods, significantly improving situational awareness.

In parallel, unmanned aircraft systems (UAS) equipped with LiDAR and photogrammetry were used to map snow distribution and characterize avalanche activity. These technologies enabled high-resolution assessment of snowpack conditions and avalanche extent.

The integration of infrasound detection and UAS-based mapping resulted in a substantial improvement in avalanche forecasting capabilities. Real-time detection provided direct confirmation of snowpack instability, allowing DOT&PF to better anticipate hazard conditions and make more informed decisions regarding roadway operations. These advancements directly increased safety for DOT&PF personnel and the traveling public while improving efficiency in road closure management.

Lessons learned during deployment—particularly related to electromagnetic interference—led to improvements in system design and installation practices that have been adopted beyond this project, demonstrating broader industry impact.

CHAPTER 1 – INTRODUCTION AND RESEARCH APPROACH

1.1 Problem Statement and Research Objective

Avalanche hazard along the Thane Road corridor in Juneau, Alaska presents a significant and persistent risk to public safety, transportation reliability, and critical infrastructure access. The corridor is exposed to multiple avalanche paths originating from steep alpine terrain, with frequent snowfall and storm cycles producing conditions conducive to avalanche activity. These avalanche hazards directly impact roadway operations, requiring preventative closures, avalanche debris removal, and ongoing avalanche hazard assessment by Alaska DOT&PF personnel.

Historically, avalanche hazard management along Thane Road has relied on a combination of weather observations, snowpack assessments, historical knowledge of avalanche behavior, and limited visual confirmation of avalanche occurrence. These methods are inherently constrained by environmental conditions, including persistent cloud cover, heavy precipitation, limited daylight during winter months, and complex terrain that restricts visibility of start zones and runout paths.

In addition, reductions in traditional avalanche mitigation capabilities have increased reliance on reactive hazard management approaches. As a result, DOT&PF personnel often face uncertainty when assessing hazard conditions, determining when it is safe to conduct maintenance operations, and making decisions regarding roadway closures and reopening.

The objective of this research was to evaluate the effectiveness of an integrated system combining infrasound-based avalanche detection and unmanned aircraft system (UAS) remote sensing to improve avalanche hazard assessment and operational decision-making. Specifically, the project aimed to:

- Provide real-time detection of avalanche activity independent of visibility and weather conditions
- Improve understanding of avalanche occurrence, timing, and spatial distribution
- Enhance avalanche forecasting through direct observation of avalanche events
- Reduce uncertainty in operational decision-making
- Increase safety for DOT&PF personnel and the traveling public

1.2 Scope of Study

This study focused on the deployment, evaluation, and operational integration of an avalanche detection system as well as snowpack distribution characterization using UAS systems within the Thane Road corridor.

The scope of work included:

- Installation and evaluation of infrasound monitoring arrays for real-time avalanche detection
- Deployment of UAS platforms equipped with LiDAR and photogrammetry for snow distribution mapping and avalanche characterization
- Integration of detection and mapping systems into operational workflows
- Evaluation of system performance under real-world environmental and operational conditions
- Identification of limitations, challenges, and lessons learned

In addition to evaluation within the Thane Road corridor, this study was intended to inform broader application of integrated avalanche detection and remote sensing technologies across Alaska's transportation network. The scope includes consideration of scalability to other avalanche-prone corridors, integration with existing DOT&PF operational systems, and applicability to infrastructure impacted by natural hazards, including transportation and energy systems.

The study also incorporates lessons learned related to system design, installation practices, and environmental constraints, with the intent of improving deployment reliability in complex operational environments. These findings support technology transfer and provide a foundation for future implementation of similar systems in other regions with comparable terrain, climate, and infrastructure challenges.

1.3 Research Approach

A phased, field-based research approach was implemented to evaluate system performance under real-world operational conditions. The project emphasized iterative deployment, testing, and refinement to ensure that the technologies were assessed within the context of actual DOT&PF operations.

The research approach consisted of the following phases:

1. **Initial Site Assessment and Temporary Deployment** Selection of monitoring locations and installation of temporary infrasound arrays to evaluate baseline performance and environmental conditions.
2. **System Evaluation and Data Collection** Collection of infrasound detection data and preliminary UAS datasets to assess system capability and identify performance limitations.
3. **System Refinement and Sensor Deployment** Implementation of design improvements, including mitigation of electromagnetic interference and optimization of system components.
4. **UAS Integration and Operational Testing** Deployment of UAS platforms to collect snow distribution and avalanche data for integration with detection systems.

5. **Operational Evaluation and Workflow Development** Assessment of system performance within operational decision-making processes and development of recommended practices.

The research approach also accounted for Alaska's uniquely challenging environmental conditions, including complex terrain, persistent cloud cover, high precipitation, extreme cold, and proximity to critical infrastructure such as high-voltage power transmission lines. Installation and deployment strategies were adapted to address these constraints, with particular emphasis on system reliability in remote and electrically complex environments.

This included iterative refinement of sensor placement, power and telemetry configurations, and system shielding to mitigate environmental and electromagnetic interference effects. Field deployments were conducted under real-world operational conditions to ensure that system performance reflected actual use scenarios encountered by DOT&PF personnel.

1.4 Methodology

The evaluation was conducted over two winter seasons, allowing for assessment of system performance across a range of snowpack conditions, storm cycles, and operational scenarios. This extended duration provided the opportunity to observe variability in avalanche activity, environmental conditions, and system reliability, ensuring that findings reflect both typical and extreme conditions encountered in Southeast Alaska.

Data collection efforts included:

- **Infrasound Detection Data:** Continuous monitoring of low-frequency acoustic signals to detect and characterize avalanche events, including timing and relative magnitude.
- **UAS Data Collection:** Acquisition of aerial imagery and LiDAR datasets to map snow distribution, avalanche extent, and terrain features influencing hazard conditions.
- **Field Observations:** Ground-based observations of snowpack conditions, avalanche activity, and operational impacts to validate and contextualize remote sensing data.
- **Environmental Data:** Collection of weather and environmental conditions, including precipitation, temperature, and storm characteristics, to support interpretation of avalanche activity.

The methodology emphasized operational relevance by prioritizing data collection and analysis under conditions representative of actual DOT&PF decision-making environments. Integration of multiple data sources enabled cross-validation of findings and supported development of a comprehensive understanding of avalanche behavior

within the corridor.

All infrasound, environmental data, and field observations collected were input into Snowbound Solutions web database for visualization and analysis. UAS data collected was processed using several different software packages and then input into ArcGIS for analysis and distribution.

CHAPTER 2 – FINDINGS

2.1 Avalanche Detection Capability

Infrasound monitoring systems were deployed to provide continuous, real-time detection of avalanche activity along the Thane Road corridor. These systems were designed to detect low-frequency acoustic signals generated by avalanche events, enabling identification of avalanche occurrence independent of visibility, lighting conditions, or weather.

During the first winter season, the system was not fully operational due to significant electromagnetic interference (EMI) associated with nearby high-voltage power transmission infrastructure. Persistent electrical noise was observed across all sensor arrays, degrading signal quality and limiting the ability to distinguish acoustic signals associated with avalanche activity. In some instances, one or more arrays were rendered unusable, while others provided only partially reliable data.

The initial deployment demonstrated that standard installation practices were insufficient for operation in electrically complex environments. EMI was introduced through multiple pathways, including cable shielding gaps, connector interfaces, and inconsistencies in system grounding. As a result, acoustic signals were masked by electrical noise, limiting the system's effectiveness during the first winter season.



Small avalanche detected via infrasound along Thane Road (left) and view from webcam (right).

Resolution of these issues required a comprehensive, system-level redesign rather than isolated corrective actions. Key improvements included implementation of continuous shielding across all signal paths, elimination of exposed cable segments, use of dual-shielded twisted-pair cabling with an overall external shield, and improved grounding consistency throughout the system. In addition, custom electronics were developed to enhance resistance to electrical noise, including improved filtering of power inputs and signal processing within the sensor hardware.

Following these modifications, the system transitioned from degraded performance to fully operational status. During the second winter season, the infrasound monitoring system reliably detected avalanche activity across a range of environmental conditions. Detection capability was maintained during periods of poor visibility, heavy precipitation, and darkness, demonstrating the system's effectiveness as an all-weather monitoring tool.

2.2 Situational Awareness Improvements

The integration of infrasound detection data with UAS-based mapping significantly improved situational awareness of avalanche activity within the Thane Road corridor. Real-time detection provided immediate identification of avalanche occurrence, while UAS platforms enabled visualization and spatial characterization of avalanche events.

UAS platforms were deployed to collect aerial imagery and terrain data during periods when weather and visibility conditions allowed for safe flight operations. These flights provided high-resolution datasets that were used to assess avalanche debris distribution,

snowpack conditions, and terrain influences on avalanche behavior.

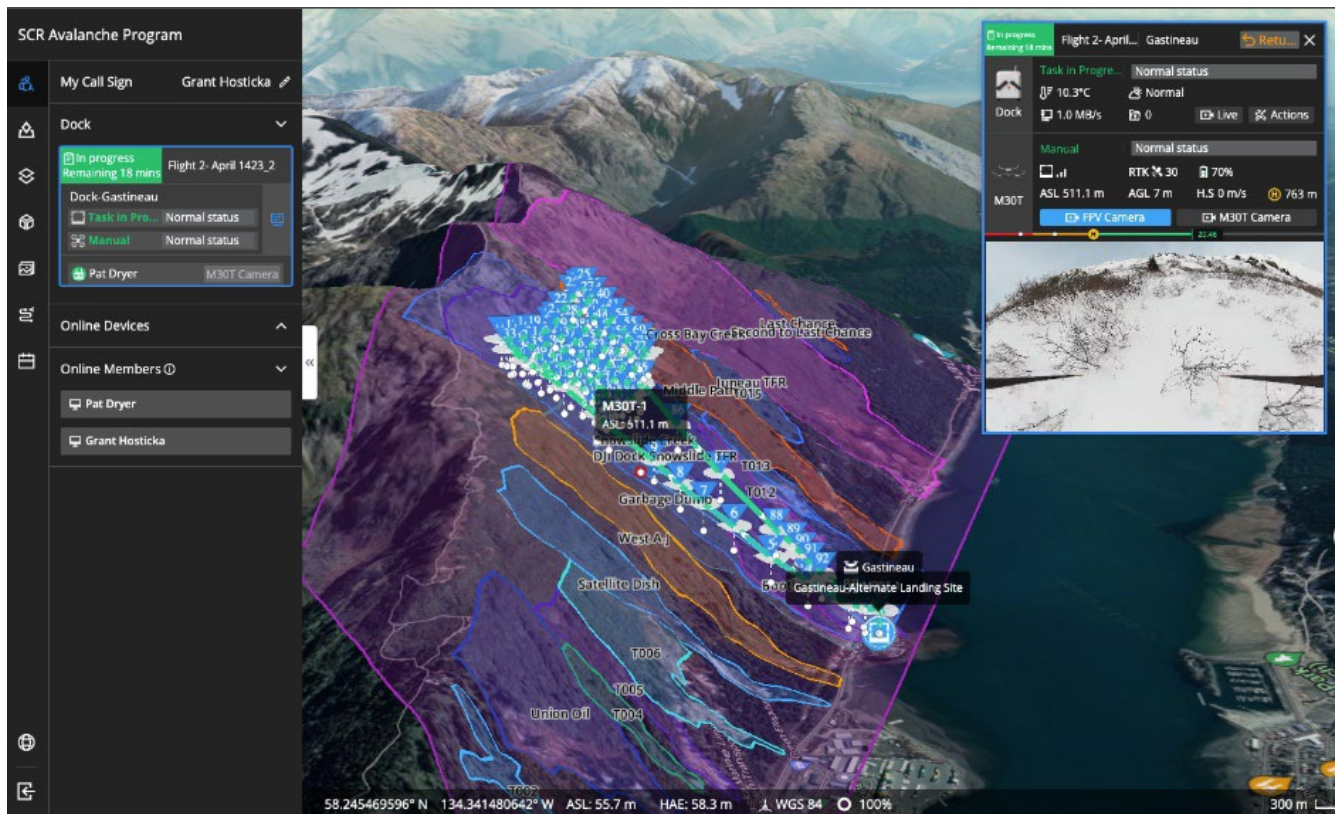
However, while imagery collection was effective, processing timelines for photogrammetry and LiDAR datasets limited the ability to utilize these products in near real-time operational decision-making. Data processing often required significant time to generate usable outputs, resulting in delays between data acquisition and actionable insights.

Despite these limitations, the combined use of detection and mapping technologies provided a more comprehensive understanding of avalanche conditions than traditional methods alone. The system enabled DOT&PF personnel to observe both the occurrence and spatial extent of avalanche activity, improving confidence in hazard assessments and operational decisions.

2.3 Snow Distribution Mapping

Unmanned aircraft systems equipped with LiDAR and photogrammetry were used to generate high-resolution snow distribution maps and characterize avalanche extent within the study area. These mapping efforts provided insight into spatial variability of snow accumulation, terrain influences on loading patterns, and avalanche debris distribution.

Snow distribution maps were successfully produced during the study; however, data collection during the first winter season was limited by below-average snowfall conditions. Reduced snow accumulation constrained the ability to fully evaluate snow distribution patterns and limited the range of conditions under which mapping techniques could be assessed.



View of UAS based snow distribution mapping mission planning and flight operations above Thane Road.

Despite these limitations, the project yielded important lessons related to data collection techniques, flight planning, sensor configuration, and environmental considerations. These lessons informed improvements in UAS deployment strategies, including optimizing flight timing relative to storm cycles, refining data acquisition parameters, and enhancing consistency in repeat surveys.

These advancements will be applied in future projects to improve the accuracy, efficiency, and completeness of snow distribution mapping efforts and to better support operational decision-making.

2.4 Operational Decision Support

The integration of infrasound detection and UAS-based mapping significantly enhanced operational decision support by providing timely, objective data on avalanche activity within the Thane Road corridor. Prior to this deployment, avalanche forecasting relied heavily on indirect indicators such as weather observations, snowpack assessments, and limited visual confirmation of avalanche occurrence.

The ability to detect avalanche occurrence in real time represents a fundamental improvement in avalanche forecasting capability. Confirmed avalanche activity provides direct evidence of snowpack instability, allowing forecasters to validate or adjust hazard assessments based on observed conditions rather than inferred risk.

Knowledge of when and where avalanches have occurred allows DOT&PF personnel to better interpret snowpack conditions, assess the progression of avalanche cycles, and identify periods of increasing or decreasing hazard. Detection of multiple avalanche events during a storm cycle confirms widespread instability, while reduced activity following a storm may indicate a transition toward more stable conditions.

When combined with snow distribution mapping and environmental data, real-time detection supports a more dynamic and data-driven forecasting framework. This integrated approach improves both the accuracy and confidence of operational decision-making and reduces reliance on subjective judgment alone.

2.5 Safety Improvements

The integration of real-time infrasound detection and UAS-based mapping significantly improved safety for DOT&PF personnel and the traveling public by reducing uncertainty in avalanche hazard assessment and limiting exposure to hazardous conditions.

The addition of real-time avalanche detection provided a direct and objective measure of snowpack instability, fundamentally improving avalanche forecasting within the corridor. Knowledge of when and where avalanches occurred allowed DOT&PF personnel to validate hazard assessments and better understand the progression of avalanche cycles.

This feedback loop significantly increased confidence in operational decision-making. Detection of active avalanche cycles supported more conservative safety measures during periods of elevated hazard, while reductions in detected activity provided greater assurance when transitioning to lower hazard conditions.

In addition to improved forecasting, remote monitoring reduced the need for personnel to enter hazardous terrain to confirm avalanche activity, thereby limiting direct exposure to risk.

Overall, the system resulted in a substantial increase in safety by improving forecasting accuracy, reducing uncertainty, and enabling more controlled and informed operational responses.

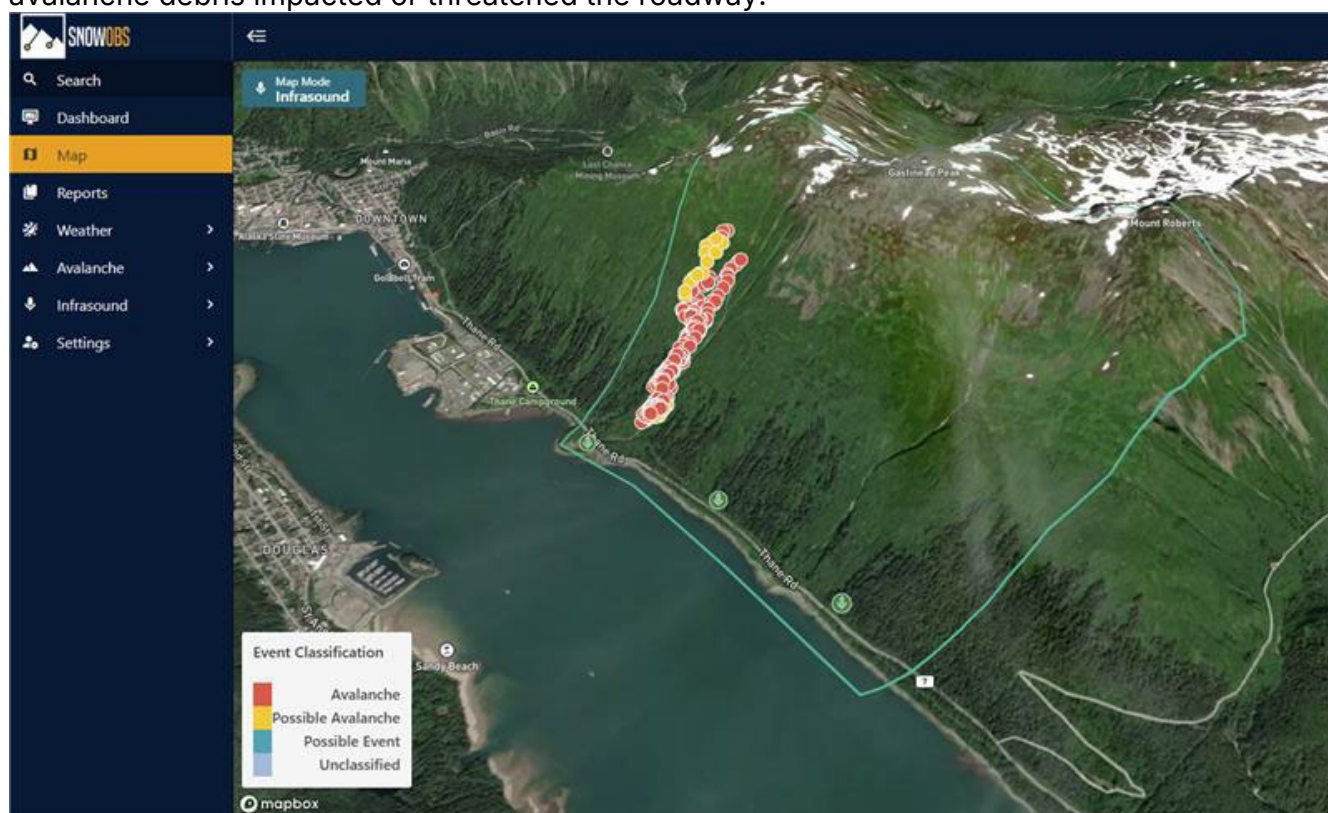
2.6 Road Closure Management

The integration of infrasound detection and UAS-based snow distribution mapping significantly improved road closure management along the Thane Road corridor by providing a more accurate, timely, and objective assessment of avalanche hazard conditions.

Prior to implementation, closure decisions were based primarily on weather forecasts, historical patterns, and limited visual observations, often introducing uncertainty. The addition of real-time avalanche detection provided direct confirmation of avalanche occurrence, allowing decisions to be based on observed conditions rather than inferred risk.

The enhanced forecasting capability enabled a more dynamic approach to closure management. Detection of multiple avalanche events during storm cycles supported maintaining closures and implementing conservative safety measures. Conversely, a reduction or cessation of detected activity provided critical information indicating a transition toward more stable conditions, allowing DOT&PF to more confidently initiate roadway reopening procedures.

UAS-based mapping further supported closure decisions by providing spatial context to detected events, including avalanche extent, runout zones, and proximity to the roadway. This information was critical for assessing residual hazard and determining whether avalanche debris impacted or threatened the roadway.



Multiple avalanches detected during a road closure that might not have been otherwise observed during periods of reduced visibility or daylight.

Together, these technologies enabled a more precise and data-driven approach to managing closures, reducing the likelihood of prolonged or unnecessary roadway restrictions while maintaining appropriate safety margins. This improved alignment between hazard conditions and closure duration enhanced operational efficiency and reduced impacts to corridor users.

2.7 System Performance and Lessons Learned

The deployment of the infrasound monitoring system along Thane Road identified significant challenges associated with electromagnetic interference due to proximity to

high-voltage power infrastructure. Initial system performance was degraded by persistent electrical noise, highlighting the need for improved system design and installation practices.

Resolution of these challenges required a comprehensive system-level approach, including continuous shielding, improved grounding, and redesign of electronic components. These modifications resulted in substantial improvements in system performance and reliability.

The revised system design was validated in subsequent deployments and is now incorporated into standard practices for infrasound monitoring systems. These lessons learned demonstrate the importance of considering environmental and infrastructure-related factors in system design and highlight the value of iterative field-based testing.

CHAPTER 3 – INTERPRETATION, APPRAISAL, AND APPLICATIONS

3.1 Interpretation of Findings

The results of this study demonstrate that the integration of infrasound detection and UAS-based snow distribution mapping represents a significant advancement in avalanche hazard monitoring and management for transportation corridors. Individually, each technology provides valuable information; however, when combined, they create a more comprehensive and reliable framework for understanding avalanche activity and associated hazards.

Infrasound monitoring provides continuous, real-time detection of avalanche events independent of visibility or weather conditions, addressing a critical limitation of traditional observation-based methods. This capability enables DOT&PF personnel to detect avalanche activity during periods when visual confirmation is not possible, including during storms, at night, or under persistent cloud cover.

UAS-based mapping complements this capability by providing spatial context to detected avalanche events. High-resolution imagery and LiDAR datasets allow for detailed visualization of avalanche release zones, runout extent, and snow distribution patterns. This spatial information enhances interpretation of avalanche behavior and provides critical insight into terrain influences and residual hazard conditions.

A key finding of this study is that direct knowledge of avalanche occurrence fundamentally improves avalanche forecasting capability. Real-time detection provides confirmation of snowpack instability, allowing forecasters to validate hazard assessments and better understand the progression of avalanche cycles. This represents a shift from reliance on inferred conditions based on weather and snowpack observations to a more data-driven approach grounded in observed avalanche activity.

The combined use of detection and mapping technologies enables a transition from reactive hazard management to a more proactive and adaptive operational framework, improving both the accuracy and reliability of avalanche hazard assessments.

3.2 Operational and Economic Impact

The implementation of this integrated system has a direct impact on operational effectiveness, safety, and resource efficiency. The ability to detect avalanche activity in real time and correlate it with environmental conditions significantly enhances avalanche forecasting within the corridor.

Improved forecasting capability allows DOT&PF personnel to better anticipate periods of elevated hazard, refine operational decision-making, and more accurately determine when it is safe to conduct maintenance activities or reopen the roadway. This reduces uncertainty and improves consistency in operational decisions.

From an operational standpoint, improved hazard assessment supports more efficient road closure management by better aligning closure duration with actual hazard conditions. The ability to confirm avalanche occurrence and monitor the progression of avalanche cycles reduces reliance on conservative assumptions, helping to avoid unnecessarily prolonged closures while maintaining appropriate safety margins.

These improvements also reduce exposure of personnel to hazardous conditions by minimizing the need for direct field observation and allowing decisions to be made based on remotely collected data. This contributes to increased worker safety and more efficient use of resources.

Although direct cost savings were not quantified within this study, the system demonstrates clear potential to reduce operational costs through improved efficiency, reduced exposure to risk, and more effective allocation of personnel and equipment. Improved timing of maintenance activities and more precise closure management represent meaningful economic benefits.

In addition to DOT&PF-specific benefits, this project contributed to advancements in industry practices for infrasound monitoring systems. Lessons learned during deployment—particularly related to electromagnetic interference and system design—resulted in improvements to hardware configuration, shielding, and installation techniques. These improvements have been incorporated into subsequent deployments, demonstrating broader economic and operational value beyond this project.

3.3 Applications to Practice

The findings of this study support immediate application of integrated avalanche detection and snow distribution mapping systems within DOT&PF operations. The system can be implemented as:

- A real-time avalanche detection and warning network
- A decision support tool for avalanche hazard management
- A framework for integrating remote sensing technologies into operational workflows

In practice, the integration of these technologies enables field personnel and decision-makers to operate with improved situational awareness and increased confidence in hazard assessments. The ability to detect avalanche events in real time and validate conditions through remote sensing allows for more consistent, defensible, and informed decision-making.

This approach is particularly valuable in high-risk corridors where environmental conditions frequently limit traditional observation methods. The system is well-suited for application across other avalanche-prone transportation corridors in Alaska, where similar challenges related to visibility, terrain, and weather are present.

3.4 Integration into Standards and Policies

The results of this study support the incorporation of infrasound monitoring and UAS-based mapping into DOT&PF standards, specifications, and operational procedures. To ensure consistent and reliable deployment, these technologies should be integrated into established workflows and supported by standardized practices.

Recommended actions include:

- Development of standard operating procedures (SOPs) for system deployment, operation, and maintenance
- Integration of infrasound detection data into existing avalanche hazard assessment frameworks
- Establishment of best practices for UAS data collection, processing, and interpretation
- Incorporation of electromagnetic interference (EMI) mitigation strategies into installation guidelines
- Development of training programs for personnel to effectively utilize these technologies

Formalizing these practices will improve consistency, reliability, and scalability of system deployment across multiple corridors.

3.5 General Recommendations

Based on the findings of this study, the following recommendations are provided:

- Expand deployment of infrasound monitoring systems to other high-risk avalanche corridors in Alaska
- Continue development and operational integration of UAS-based snow distribution mapping

- Invest in rapid data processing capabilities to support near real-time decision-making
- Integrate detection and mapping data into avalanche forecasting workflows
- Develop standardized deployment and operational procedures to support statewide implementation

These actions will support broader adoption of these technologies and enhance their effectiveness as operational tools.

3.6 Limitations and Considerations

While the system demonstrated significant benefits, several limitations were identified during the study. Infrasound monitoring systems are sensitive to environmental and infrastructure-related factors, particularly electromagnetic interference. Reliable operation in complex environments requires careful attention to system design, installation practices, and shielding.

UAS operations are inherently weather-dependent and may be limited by visibility, precipitation, and wind conditions. Additionally, processing timelines for photogrammetry and LiDAR datasets currently limit the ability to fully integrate these products into real-time operational decision-making.

Snow distribution mapping efforts were also limited during the first winter season due to below-average snowfall, which constrained the ability to fully evaluate variability in snowpack conditions.

These limitations highlight the need for continued refinement of system design, deployment strategies, and data processing workflows to maximize operational effectiveness.

3.7 Broader Implications

The findings of this research extend beyond DOT&PF and demonstrate broader applicability to other agencies, industries, and environments where natural hazard monitoring is critical.

The Thane Road deployment identified previously unaddressed challenges associated with electromagnetic interference in infrastructure corridors and required advancements in system design, electronics, and installation practices. These improvements have been validated in subsequent deployments and are now incorporated into standard industry practices, demonstrating meaningful technology transfer.

The ability to deploy reliable infrasound monitoring systems in complex environments expands the applicability of this technology to transportation corridors, energy infrastructure, and remote sensing applications. As a result, this project represents not only an operational improvement for DOT&PF, but also a contribution to the advancement of avalanche monitoring technology at a broader scale.

CHAPTER 4 – CONCLUSIONS AND SUGGESTED RESEARCH

4.1 Conclusions

This research demonstrates that the integration of infrasound detection and UAS-based snow distribution mapping provides a viable, effective, and scalable approach to avalanche hazard assessment for transportation corridors. The successful deployment along the Thane Road corridor represents the first operational use of infrasound technology by Alaska DOT&PF and confirms its value as a reliable, all-weather detection system capable of overcoming limitations associated with visibility, weather, and terrain.

The primary outcome of this project is the significant improvement in avalanche forecasting capability within the corridor. The ability to detect avalanche occurrence in real time provides direct confirmation of snowpack instability, allowing DOT&PF personnel to validate hazard assessments and better understand the progression of avalanche cycles. This represents a fundamental shift from reliance on inferred conditions based on weather and snowpack observations to a more data-driven approach grounded in observed avalanche activity.

The integration of real-time detection with UAS-based snow distribution mapping further enhanced situational awareness by providing spatial context for avalanche activity, including release zones, runout extent, and residual hazard conditions. Together, these technologies support a more dynamic and responsive forecasting framework, improving both the accuracy and confidence of operational decision-making.

These advancements directly contributed to increased safety for DOT&PF personnel and the traveling public. Improved forecasting capability reduced uncertainty in hazard assessments and enabled more informed decisions regarding maintenance operations, debris removal, and roadway access. In addition, remote monitoring reduced the need for personnel to enter hazardous terrain to confirm avalanche activity, further limiting exposure to risk.

The project also identified critical challenges associated with deployment in electrically complex environments. Electromagnetic interference (EMI) initially limited system performance; however, resolution of these issues through system-level design improvements—including continuous shielding, improved grounding, and custom electronics—resulted in a robust and reliable monitoring system. These lessons learned have been validated in subsequent deployments and have contributed to improved industry practices, demonstrating the broader impact of this research beyond DOT&PF. Overall, this project represents a significant advancement in the application of emerging technologies for avalanche hazard management. It establishes a scalable framework for implementation across other high-risk transportation corridors in Alaska and demonstrates the value of integrating real-time detection with remote sensing to support data-driven operational decision-making.

4.2 Suggested Research

While this study demonstrates the effectiveness of integrated avalanche detection and snow distribution mapping systems, several areas for further research have been identified to support continued development, operational integration, and statewide application.

Additional research is recommended to further advance UAS-based snow distribution mapping capabilities, with a particular focus on improving data collection under a broader range of snowpack conditions. The first winter season of this study was characterized by below-average snowfall, which limited the ability to fully evaluate snow distribution variability and its relationship to avalanche activity. Future efforts should prioritize data collection during periods of typical and above-average snowfall to better capture representative snowpack conditions and improve understanding of spatial variability in snow loading.

Building on lessons learned from this project, further work should focus on refining UAS data acquisition techniques. This includes optimizing flight planning relative to storm cycles, improving repeat survey consistency, and refining sensor configuration to enhance data quality and comparability across time. These improvements will strengthen the reliability of snow distribution datasets and support more robust analysis of avalanche-prone terrain.

In addition, development of rapid data processing workflows is critical to enable near real-time use of UAS-derived data in operational decision-making. Current processing timelines for photogrammetry and LiDAR datasets limit the ability to fully integrate these products into time-sensitive hazard assessments. Future research should explore cloud-based processing, automated workflows, and streamlined data pipelines to reduce latency between data collection and actionable insights.

Further research is also recommended to enhance infrasound detection capabilities. This includes refinement of signal processing algorithms, improved localization of avalanche events, and integration of infrasound data with other environmental datasets such as weather observations and snowpack modeling outputs. Expanding system deployment across additional corridors will provide opportunities to validate system performance under a wider range of environmental and terrain conditions.

Finally, future efforts should focus on the development of integrated decision support systems that combine real-time detection, snow distribution mapping, and environmental data into a unified operational framework. Such systems would enable fully data-driven avalanche forecasting and support consistent, scalable application across Alaska's transportation network.