ENHANCING OPERATIONAL AVALANCHE RISK ASSESSMENT WITH RPAS LIDAR SNOW DEPTH MAPS AND AVALANCHE SIMULATIONS: A CASE STUDY IN WESTERN CANADA.

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In this study, we present a novel approach to operational avalanche risk assessment using numerical avalanche models initialized with snow depth maps to simulate the maximum possible avalanche for a given snowpack depth distribution. We demonstrate an application of this approach as part of an operational risk assessment at a mine in British Columbia, Canada, where it was used to determine whether specific snowpack conditions could generate avalanches large enough to affect worksites and infrastructure. This study also demonstrates the advantages of using Remote Piloted Aircraft Systems (RPAS, colloquially, drones) as a platform for capturing LiDAR data for path-scale snow depth mapping, highlighting their ability to provide high accuracy and repeatable measurements.

Assessing potential avalanche magnitudes is critical to operational risk management. Uncertainty in these assessments can lead to overly conservative risk treatments. Our study, which integrates RAMMS (Rapid Mass Movement Simulation) with high-resolution snow depth data from RPAS LiDAR, demonstrates a practical and objective risk assessment tool to support these evaluations. While this approach does not predict avalanche size, it offers valuable information on the upper bounds of potential avalanche runout under specific snowpack conditions. This is particularly useful for assessing the exposure of elements at risk, especially for infrequent avalanches or early and late-season conditions, thereby enabling better-informed risk management decisions.

KEYWORDS: RPAS, UAV, drone, LiDAR, RAMMS, forecasting.

1. INTRODUCTION

In this study, we present a novel approach to operational avalanche risk assessment. This method uses Light Detection and Ranging (LiDAR) equipped Remote Piloted Aircraft Systems (RPAS, colloquially, drones) to map snow depth at a path scale. Numerical avalanche simulations initialized with these maps are used to model the maximum avalanche runout possible for a given snowpack distribution. We present a case study where this approach was used to assess whether a specific snow depth distribution was capable of producing avalanches large enough to impact worksites and infrastructure at a mine in British Columbia, Canada,

Effective workplace avalanche risk management is a regulatory requirement in British Columbia and a critical consideration in ensuring worker safety and operational efficiency. Operational avalanche risk management depends on the ability of avalanche forecasters to assess whether avalanches can impact specific elements at risk, such as fixed infrastructure or worksites, given specific snowpack and weather conditions (CAA., 2016). Traditionally, these assessments have been subjective, relying heavily on the forecaster's experience and familiarity with avalanche terrain and snowpack. However, complex or unusual conditions or limited familiarity with specific avalanche release and flow characteristics for a path can diminish confidence in these assessments and lead to more conservative risk treatments. Although a conservative approach biases safety, it can significantly impact operational efficiency and costs. Integrating numerical avalanche simulations such as the Voellmy-Salm-based Rapid Mass Movement Simulation (RAMMS) (Christen et al., 2011) into operational risk assessments could support evaluations of the potential for avalanches to reach a particular element at risk under specific conditions, and lead to more targeted risk management strategies.

Several studies (Dillon and Hammonds, 2021; Glaus et al., 2024; Stoffel et al., 2018; Valero et al., 2016) have explored the potential for RAMMS simulations, initialized with measured or modelled snowpack and weather data, to forecast avalanche runout distances. While these approaches are promising, further research is required into the appropriate model parametrization needed to accurately simulate non-extreme events before they can be broadly implemented as a predictive tool (Campbell et al., 2024). In this study, we propose a reframed operational application of RAMMS simulations. Instead of aiming t

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predict whether an avalanche will reach elements at risk under specific snowpack conditions, our objective is to identify whether these elements lie within the maximum runout extent for those given conditions. To do so we propose initializing RAMMS simulations using high-resolution snowpack depth and distribution data captured using RPAS LiDAR with friction parameters calibrated to simulate extreme events. Although this approach does not offer the broad utility of a predictive tool, it can provide critical information to inform the avalanche risk assessment for infrequent avalanche paths or early or late-season conditions.

2. BACKGROUND

Numerical avalanche simulations such as RAMMS are commonly used in planning stage risk assessments to model extreme magnitudes for long return-period avalanches (CAA, 2016) but have had limited application in operational risk assessments. This limitation arises partly due to several factors:

- The sensitivity of model results to input variations, which have historically been calibrated against extreme avalanche events (Buser and Frutiger, 1980).
- Inaccuracies cause by modelling the sliding surface using snow-free topography (Bühler et al., 2011)
- Challenges in accurately initializing simulations, as release volume, entrainment, and snow temperature all affect runout length (Valero et al., 2015).

However, advances in remote sensing and snowpack modelling are changing this paradigm. In particular, integrating measured or modelled snowpack data with high-resolution interface topography can lead to more accurate and reliable simulations of avalanche behaviour (Miller et al., 2022).

The distribution of snow depth plays a crucial role in determining the magnitude of avalanches, influencing both the release volume and the snow available for entrainment. (Schweizer et al., 2003). Snowfall and wind interact with terrain and vegetation to create highly variable snow accumulation patterns, which has proved to be challenging to sample manually or model (Winstral et al., 2002). However, terrestrial LiDAR scanners have been effectively employed for laser altimetric mapping of snow depth and distribution in avalanche start zones (Deems et al., 2015; Prokop et al., 2015; Ruttner-Jansen et al., 2024). LiDAR uses reflected laser pulses to create a detailed three-dimensional representation of topography as a point cloud. Point clouds consist of millions of data points, each containing X, Y, and Z coordinates representing the precise location and elevation of objects and surfaces in the scanned area. Terrestrial LiDAR can provide repeatable and high-resolution measurements of the snow surface. By comparing elevation data collected under bare earth and snow-covered conditions, snow depth maps can be generated. However, the fixed nature of these sensor installations limits the scale over which data can be captured. LiDAR sensors, mounted to a fixed-wing aircraft or helicopter, henceforth referred to as airborne LiDAR, can capture data over much larger areas but at slightly lower accuracy and significantly high cost.

RPAS LiDAR is an emerging alternative to terrestrial and airborne platforms that offers several advantages. RPAS units provide a mobile and highly flexible platform, allowing repeatable data capture over much larger areas than terrestrial systems at comparable resolutions. Their ability to capture data from multiple angles and perspectives can provide significantly higher point cloud densities and greater accuracy than airborne platforms, especially in steep and complex terrain (Jacobs et al., 2021). Furthermore, RPAS units and compatible LiDAR systems are becoming increasingly cost-effective. Notably, King et al. (King et al., 2023) successfully captured laser altimetry from snow using a LiDAR-equipped smartphone mounted to a consumer-grade drone.

Snow depth maps can be generated either by comparing bare earth and snow surface point clouds or by differencing bare earth and snow cover elevation rasters. While the Cloud-to-Cloud (C2C) method generally provides higher precision results, steep terrain or complex topography can lead to inaccuracies due to errors in point-to-point calculations (Koutantou et al., 2021). The DEM of Difference (DoD) approach reduces the impact of anomalies and outliers on snow depth maps by averaging the snow depth over each raster grid. When the bare earth and snow surface DEMs are generated from high-density LiDAR point clouds (i.e., point densities of greater than 25 points/m^2), DoD can provide precise estimates of snow depth at scales finer than 1 m (Jacobs et al., 2021), sufficient for most avalanche modelling applications.

The intersection of accessible remote sensing technologies and ever-improving numerical avalanche models presents exciting opportunities. RPAS LiDAR enables repeatable, high-accuracy snow depth mapping at path scales. Integrating this data into RAMMS simulations enhances spatial resolution, provides more accurate representations of release volume and entrainment, and offers more realistic top graphic models of the snow-on-snow sliding interface.

3. CASE STUDY

3.1 Study Site

We present an example of this approach applied at a mine in British Columbia, Canada where worksites and an access road, are within the runout of a 1000 m-long channelized avalanche path capable of producing Size 4 avalanches (Figure 1). Although there has been no recorded activity on this path since the mine's avalanche safety program began in 2016, vegetative indicators along the path and trim lines in the runout zone suggest that these sites are within the maximum runout extent of an avalanche with a 3.3% annual occurrence probability (i.e., 30 year return period) as shown in Figure 2. The region has a continental snow climate (Haegeli and McClung, 2007) and the path can be characterized as having a thin and generally faceted snowpack. The path's starting zone is often both ridge or cross-loaded, leading to highly variable and often discontinuous snow accumulation patterns.

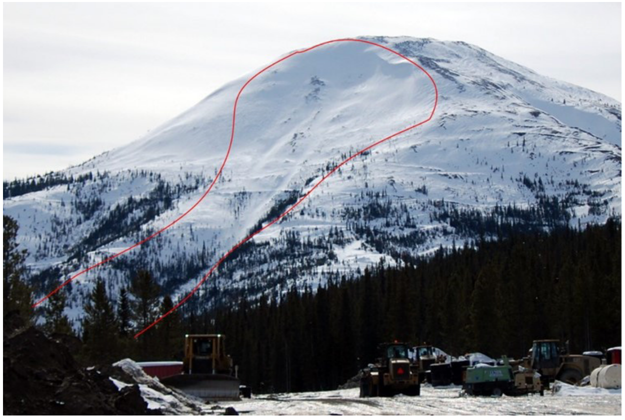

Figure 1: The study path, British Columbia, Canada

Given the lack of path history, the complex snowpack structure, and the nature of the exposure, the mine's avalanche program typically adopts a cautious approach to risk assessment. Historically, worksite mitigations for areas within the 30-year runout extent of the path have remained in place until ground roughness is sufficient to arrest any avalanche high in the runout or track. In March 2024, several Size 3 deep persistent slab avalanches occurred in neighboring paths, which all terminated in their respective upper runouts. The forecast team looked to RAMMS simulations, initialized with a current, high-resolution snow depth map, to support their assessment that the remaining seasonal snowpack at the start of the study path was insufficient to produce an avalanche large enough to reach the exposed worksites and roads and that avalanche mitigations were no longer required.

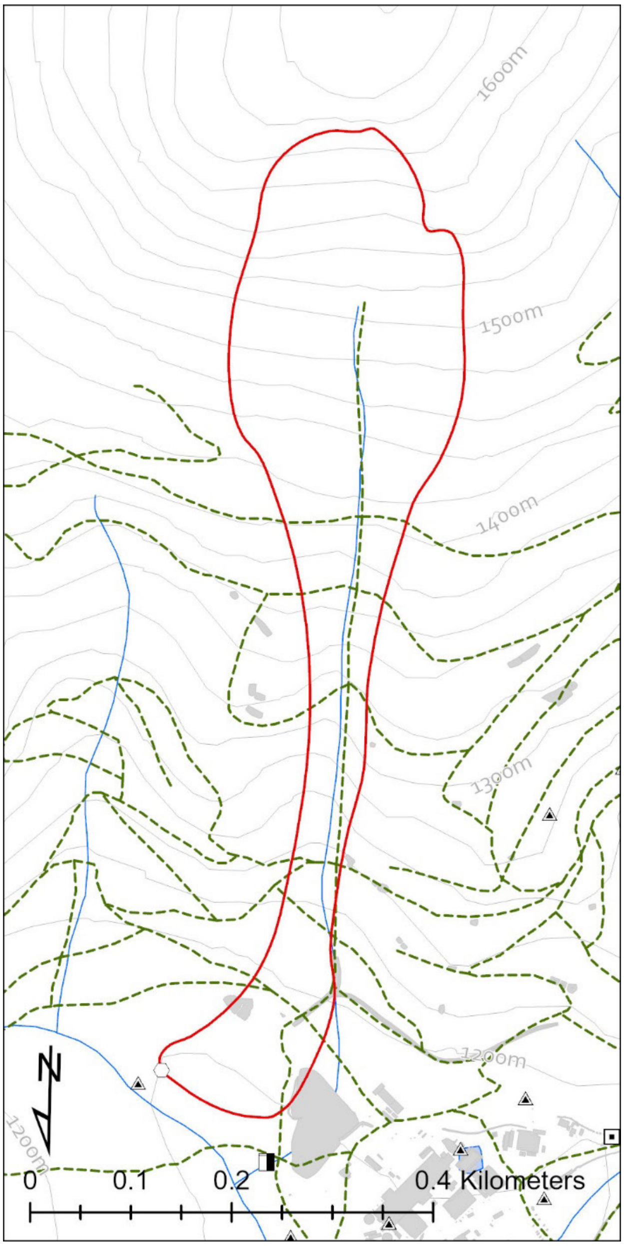

Figure 2: 1:7,500 scale map depicting the study avalanche path boundary in red, roads in green, and an environmental monitoring site represented by a hexagon.

3.2 Snow Depth Mapping

RPAS LiDAR snow surface data was acquired on Mach 25, 2024. A Zenmuse L2 LiDAR mapping payload mounted to a DJI M350 RPAS airframe was used. The L2 employs a frame-based LiDAR sensor with an integrated Inertial Measurement Unit (IMU) paired with dual quad-band Global Navigation Satellite System (GNSS) receivers. The LiDAR sensor operates at the 905nm wavelength, providing a sufficiently high spectral albedo from snow to be applicable for snow surface mapping (Deems et al., 2013). The sensor has a 70° field of view and can receive up to 1,200,000 point-returns per second. According to manufacturer specifications, the L2 can achieve a point cloud vertical accuracy of ±0.05 m root mean squared error (RMSE).

The UgCS flight control software developed by SPH Engineering was used to generate terrain-following flight paths referencing a 1 arc-second resolution DEM. Flight parameters were established to prioritize mapping efficiency over maximizing point cloud accuracy. LiDAR capture was flown at an altitude of 122 m AGL, the maximum allowable under general RPAS flight rules in Canada, with a constant flight speed of 12 m/s to minimize the necessary flight time. Mapping sweeps were aligned perpendicular to the avalanche path and spaced to ensure a sensor swath overlap of 50% (Figure 2). LiDAR data was captured using a repetitive scan pattern registering only the first pulse return. These flight parameters resulted in a nominal pulse density of 119 points/m^2. Given the negative effect of cold temperatures on battery life, the maximum flight time per battery set was conservatively limited to 30 minutes. This required the flight plan to include three return flights for battery exchanges. The study also employed an existing airborne LiDAR point cloud captured in snow-free conditions in the summer of 2018.

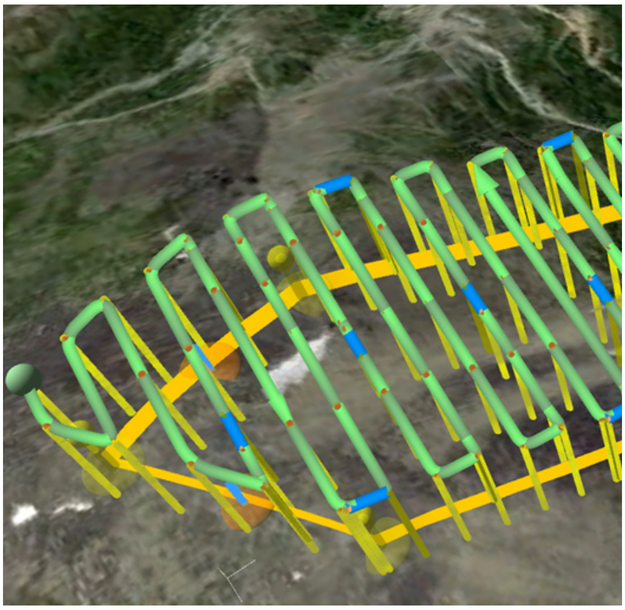

Figure 3: Sample terrain following flight path for the study path produced by UGCS flight control software.

Due to the unavailability of geodetic markers near the study area, a site control point was established using the Canadian Spatial Reference System (CSRS) Precise Point Positioning (PPP) system. An Emlid R3+ GNSS receiver (base station unit) occupied the control point, and dual-frequency (GPS and GLONASS) GNSS logs were collected for 12 hours concurrent with the mapping work. The base station log was submitted to the CSRS-PPP online service to generate reference coordinates with a 95 % confidence interval of ±0.006 m latitude, ±0.005 m longitude, and ±0.022 m elevation.

Ground control points (GCPs) were collected on the same day as the RPAS LiDAR survey using an Emlid R3+ receiver (rover unit) at 17 locations to assess the accuracy of the LiDAR point cloud and snow depth map (Figure 4). GCPs were collected in both bare earth and snow-covered areas. Targets were marked with florescent spray paint so as to be visible in the colourized LiDAR point cloud and surveyed at 10Hz for 2 minutes, resulting in lateral and vertical RMSEs of 0.004 m and 0.015 m, respectively. Manual snow depth measurements were taken at 11 of the GCPs using an avalanche probe.

Figure 4: Collecting GSPs and snow depth measurements

For increased accuracy, a post-processing kinematics (PPK) workflow, referencing the base station log, was used to correct positional errors in the LiDAR point cloud and GCPs. Emlid Flow GNSS processing software was used for the PPK processing of the GCPs. DJI Terra LiDAR data processing software handled the point cloud PPK correction as part of the integration of the L2's LiDAR returns with its GNSS and IMU records into a georeferenced point cloud and smooth best-estimated trajectory (SBET) log.

The snow surface point cloud and SBET log were imported into Terrasolid's TerraScan point cloud processing software for post-processing. A swath alignment procedure was employed to correct misalignment between overlapping scan swaths and ensure consistency and accuracy across the data by addressing any misalignments due to positional errors or flight dynamics. Noise and outlier removal filters were applied to eliminate extraneous data points and anomalies caused by signal reflections or sensor errors. Finally, a point-thinning filter was used to reduce the size of the dataset and achieve a more uniform point density.

An Adaptive Triangulated Irregular Network (ATIN) ground classification algorithm was used to identify ground points in the point cloud. Given the study path's open and relatively smooth terrain, no additional manual classification ground classification was required. The resulting ground-classified point cloud had a final density of 51 points/m² and a vertical RMSE of 0.148 m compared to the GCPs. Comparatively, the bare earth ground-classified point cloud had a density of 4.7 points/m² and a vertical RMSE of 0.432 m. Applying a uniform vertical correction to the bare earth surface reduced this RMSE to 0.243 m.

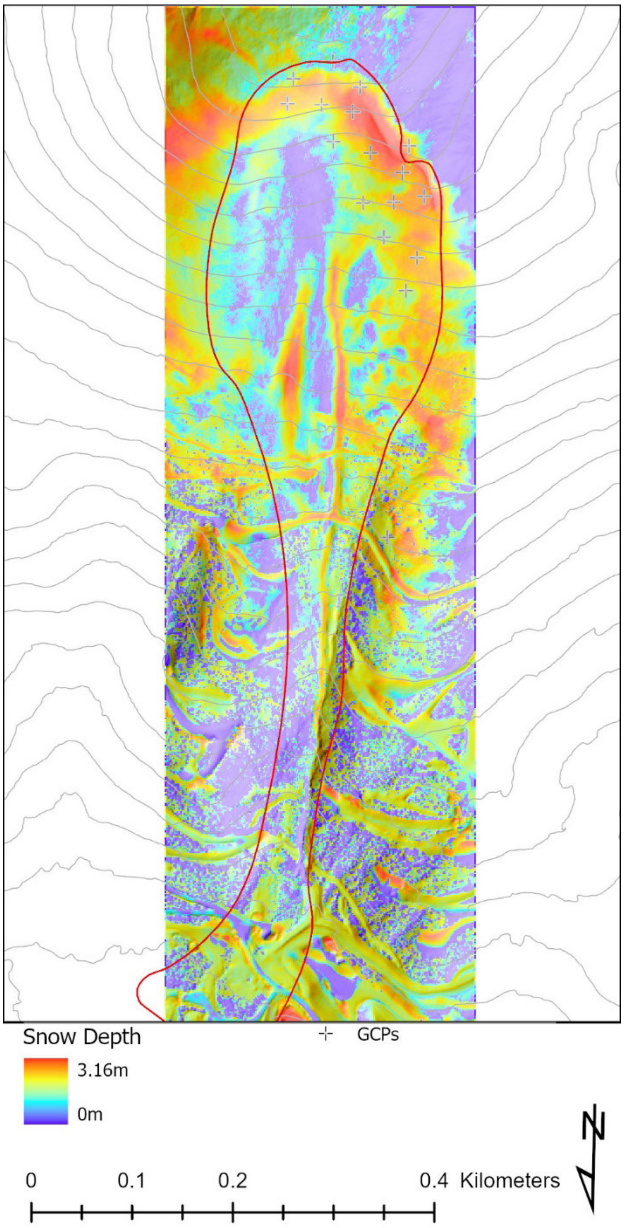

Figure 5: Snowpack depth map for the study path, collected March 24, 2004

Given the steepness of the terrain and the point densities achieved, a snow depth model was generated using the DoD approach. The snow-covered and bare-earth ground-classified point clouds were imported into ESRI ArcGIS Pro GIS software and converted into two aligned raster surfaces via an Inverse Distance Weighted (IDW) interpolation algorithm. A raster resolution of 1m was used for both DEMs to ensure convergence and minimize the effect of data gaps in the bare-earth model. Raster algebra was then used to subtract the bare-earth elevations from the snow surface elevations to calculate snow depth for each raster cell. Cells with negative snow depth values were reclassified to 0 as a manual error correction. The resulting snow depth model (Figure 5) had an RMSE of 0.251 m compared to manual snow depth measurements.

3.3 RAMMS simulation

A RAMMS model run was initiated to simulate the maximum avalanche given the specific snow depth and distribution. A maximum release area was identified using a fuzzy logic potential release area (PRA) mapping algorithm (Veitinger et al., 2016). This area was then refined by excluding cells with a snow depth of less than 0.3 m to account for anchoring effects due to ground roughness (Figure 6). A mean snowpack depth for the refined release area of 1.6m was calculated using zonal statistics. To simulate the maximum possible avalanche (i.e., a deep, persistent slab), a RAMMS simulation was initialized using a vector representation of the refined release area and release depth equal to the mean snowpack depth. Default values for Coulomb friction (μ) and viscous resistance (ξ) coefficients were used to simulate a 30-year avalanche. The simulation was then run using the topography of the 1 m resolution snow-surface DEM.

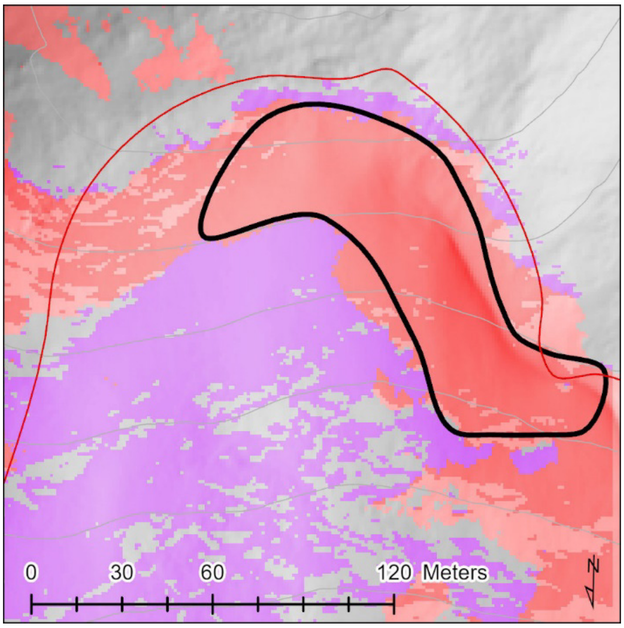

Figure 6: Avalanche release area outlined in black refined from PRA analysis in purple and threshold snowpack depth in red.

4. RESULTS

The resulting simulation provided realistic upper bounds of the maximum avalanche runout for the current snowpack distribution and depth. The simulation terminated well above the maximum 30-year runout established by previous studies and 200m short of the mine's active roads and worksites (Figure 7). These results aligned with the recent avalanches in neighbouring paths. As a result, worksite avalanche mitigation requirements were rescinded for sites within the avalanche path, allowing regular operations to commence almost two months earlier than in previous seasons.

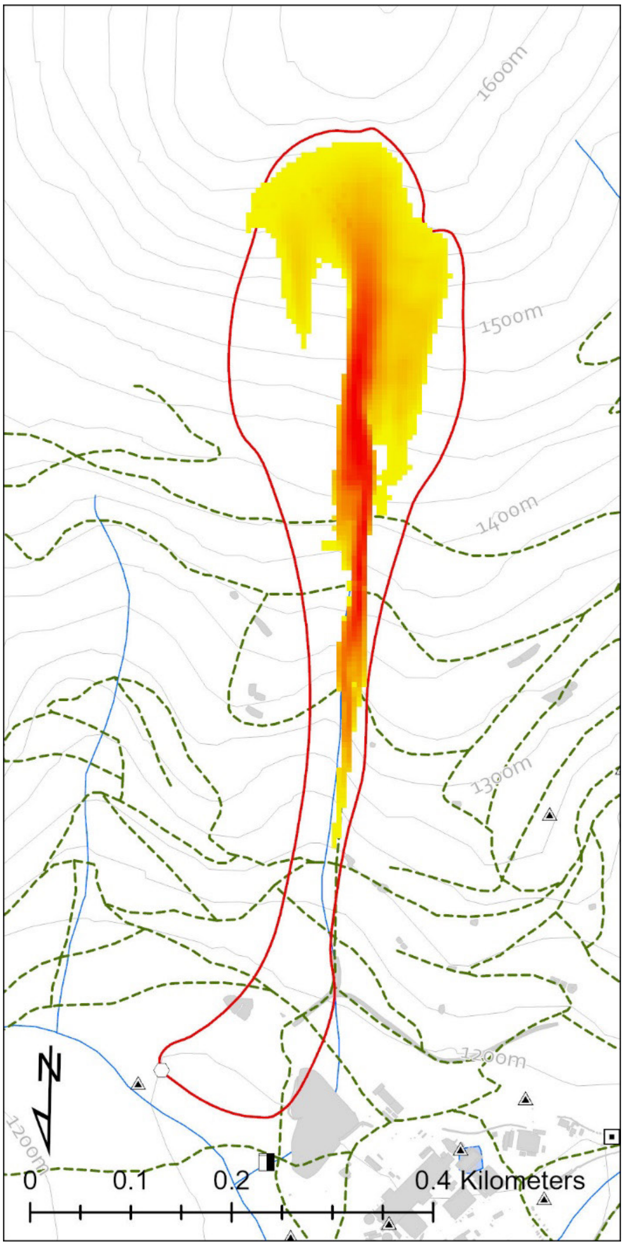

Figure 7: RAMMS simulation of maximum core pressure.

5. DISCUSSION AND CONCLUSIONS

In our experience, RPAS LiDAR proved an efficient technology for measuring snow depths in avalanche terrain. It strikes a balance between terrestrial and airborne platforms in its ability to repeatably capture high-density point clouds of path-scale terrain features and provide accurate laser altimetry of snow surfaces. Establishing optimal flight parameters, however, remains an open question. Higher point cloud densities result in more accurate DEMs (Bater and Coops, 2009) but at the cost of reduced mission efficiency, requiring slower and lower flights. Flight planning can be further complicated by regulatory restrictions such as limited maximum flight altitudes and prohibited beyond the visual line of site operations. Another consideration for winter operations is the adverse effects cold temperatures have on battery life. However, even with conservative flight planning and mission parameters that prioritize efficiency, RPAS LiDAR can achieve much higher point densities than airborne platforms. In this study, our choice of a 1-m resolution snow depth raster was driven by the data density of the bare earth point cloud. A finer-resolution snow depth model would have been possible with higher point density bare earth data. Future work is needed to identify the optimal model resolution for this application and establish the necessary flight parameters.

The results of this study illustrate the significant impact of model inputs on RAMMS simulations and highlight the value of LiDAR data in providing a more realistic simulation of specific conditions. High-resolution DEMs offer significantly better PRA segregation than is achieved with coarser terrain models, and refining PRA boundaries based on snow cover yields a more precise representation of conditions. Although using a variable snow depth distribution in the release area has little effect on simulation output compared to using a uniform mean depth (Dillon and Hammonds, 2021), using measured rather than modelled release depths to define the release volume results in a more accurate simulation of specific avalanche characteristics, such as a deep persistent slab avalanche. Furthermore, high-resolution bare earth DEMs are commonly down-sampled to represent the smoothing effect of snow cover on terrain, which can drastically impact simulation results (Bühler et al., 2011). Using a snow-covered DEM provides a more accurate topography for the simulation while maintaining the resolution necessary to model realistic terrain effects.

As previous studies have suggested, the operational implementation of RAMMS requires further research and potential modifications before it can be broadly used as an avalanche forecasting tool. However, our approach, which simulates the maximum avalanche runout under specific conditions, can provide valuable guidance on whether avalanches are capable of reaching elements at risk. Furthermore, repeated

RPAS LiDAR snow depth measurements offer an opportunity to expand the application of this methodology. Collecting LiDAR data regularly throughout the winter would allow for the creation of LiDAR-derived DEMs corresponding to potential weak layers and allow simulations of maximum avalanche runout for specific failure interfaces. Additionally, RPAS LiDAR promises to be a valuable tool in moving towards predictive avalanche simulations. Snow depth mapping at a path scale could support the back-calculation of avalanche events, providing accurate measurements of release volumes, entrainment depths, and runout deposits necessary to fine-tune model parameterization for non-extreme events.

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