

INVESTIGATION OF AN AUTONOMOUS ULTRA-LONG-DISTANCE TERRESTRIAL LASER SCANNER TO MONITOR THE SEASONAL SNOWPACK & AVALANCHE CONDITIONS ABOVE THE MILFORD ROAD, NEW ZEALAND

Simon Morris^{1*} and Kevin Thompson¹

¹ *Milford Road Alliance, New Zealand.*

ABSTRACT: The Milford Road Alliance (MRA) avalanche programme represents a collaborative effort between the Waka Kotahi New Zealand Transport Agency and Downer New Zealand, focused on leveraging the capabilities of a Riegl VZ®-6000 ultra-long-distance terrestrial light detection and ranging (LiDAR) laser scanner to monitor the seasonal snowpack along the Milford Road (State Highway 94). The project objectives include exploring the potential of autonomous scanning, establishing a permanent alpine scanning structure, and optimizing communication and post-data processing workflows. The key focus is on achieving high spatial and temporal resolution, enabling the provision of near real-time information on snow accretion and ablation. The project seeks to enhance the MRA understanding of the spatial distribution of snow depth, detect glide slab deformities, while also providing data for RAMMS (Rapid Mass Movement Simulation) to determine avalanche impact pressures on vehicles on the highway. The project will allow for safe, temporal independence, coverage of inaccessible terrain, unbiased, non-destructive continuous monitoring of the seasonal snowpack and avalanche paths. By advancing the MRA knowledge of the spatial distribution of snow depth and variations within the seasonal snowpack, this project contributes to a deeper understanding of avalanche formation and characteristics along the Milford Road.

KEYWORDS: LiDAR, Milford Road, autonomous, ultra-long-distance terrestrial LiDAR.

1. INTRODUCTION

State Highway 94, also known as the Milford Road, extends 120 km from Te Anau to Milford Sound/Piopiotahi on the southwest coast of New Zealand's and through the Fiordland National Park. Milford Road stands out as New Zealand only public highway facing significant avalanche challenges.

The highway traverses a distance of 29 km, following a path along the valley floor below the avalanche mitigation area that covers an approximate 60 km². Situated centrally within this area, the highway passes through the Homer Tunnel (-44.76° S, 167.98° E). Pre-pandemic, this route witnessed nearly a million visitors annually. The traffic flow along the Milford Road follows a strong tidal pattern, resulting in periods of intense morning and afternoon traffic concentration.

Within the avalanche mitigation area, the landscape underwent extensive sculpting following the recession of glaciers from Fiordland, resulting in the formation of nearly vertical walls, large hummocky basins, and large cirques.

The avalanche mitigation area climate exhibits a pronounced maritime influence, resulting in significant annual precipitation. On the valley floor, precipitation levels surpass 8000 mm annually, while within the release zones, they escalate to more than 13,000 mm annually. Of this, half the annual precipitation amount can fall as snow during the winter months. Throughout winter, individual storms frequently deposit 200 to 300 cm of snow in the release zones. The area experiences high precipitation rates, often exceeding 20 mm/hr, and it is common to have significant winter rain-on-snow events, with 300 mm or more of rain falling on the existing snowpack. Such occurrences are a regular part of the winter climate.

The avalanche paths along the highway are defined by significant hummocky release zones, some of which maintain permanent snow cover and exhibit an average slope angle of 30-35° (Fig. 1). The avalanche tracks, on the other hand, feature large cliffs with inclinations exceeding 75°. Particularly, the avalanche tracks near the cirques having a vertical drop up to 300 m. Both

* *Corresponding author address:*

Simon J Morris, Milford Road Alliance,
29 Caswell Road, PO Box 12, Te Anau 9640;
tel: +64 03 249-7004. fax: +64 03 249-7979.
email: simon.morris@downer.co.nz

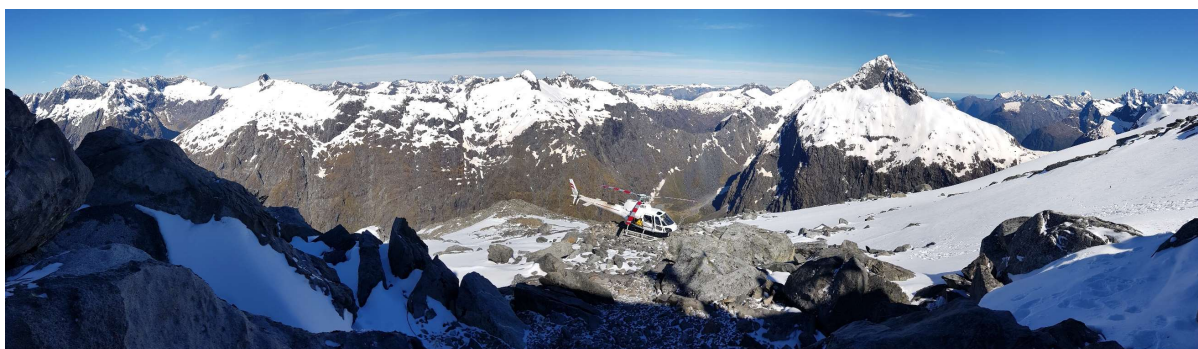


Figure 1: Captured perspective from Mount Crosscut scanning position for the Riegl VZ®-6000 overlooking the Milford Road. This vantage encompasses an expansive 23 km² of scannable topography, encompassing a stretch of 6.5 km along the primary ridgeline (visible in the middle background), or an area of 9.45 km², which strategically covers five important release zones situated above the highway. Additionally, the scanning capacity extends to cover 13.72 km² of secondary avalanche release zones above the highway, along with significant indicator slopes.

Both the release zones and tracks exhibit surface topography with minimal soil or vegetation, predominantly exposed bedrock. As for the runout zones, they are characterized by wide, flat valley floors, which are covered with dense Southern beech rainforest (*Nothofagus*) or large avalanche impact zones.

The avalanche paths adjacent to the cirques often generate large plunging avalanches due to the steep terrain, where the core detaches from the slope and is propelled over a cliff. Once the core becomes airborne, it typically impacts the valley floor. Research by Miller et al. (2022), Watson et al. (2021), Hendrikx (2005), Fitzharris and Owens (1980) have explored these phenomena. The presence of significant precipitation and the avalanche path morphology contribute to the occurrence of these events, which can transport masses of up to 300,000 tons, generating high impact pressures of approximately 5040 kPa, attaining velocities of 81 m/s, and displaying snow debris densities of up to 775 kg/m³ (McLauchlan, 1995).

The impact of these avalanche events on the local landforms is notable and diverse. Avalanche tarns, characterized by plunge pools, are formed. In addition, there are ejected debris fields, avalanche terminus boulder fields, and vegetation scarring that clearly show the effects of the extensive wind and water blasting resulting from the avalanche impacts. These observations have been documented in studies conducted by Fitzharris and Owens (1984) and Owen et al. (2004).

Throughout its existence, the Milford Road avalanche program has been subject to continuous assessment and improvement. It has undergone rigorous evaluation through international peer reviews, as exemplified by the works of Föhn

(1999), Hamre and Hendrikx (2018), Hamre (2019) and Greene (2022).

Numerous researchers have contributed to the program's development and enhancement through their research and studies. Notable researchers include Fitzharris and Owens (1984), Carran et al. (2000, 2009), Conway et al. (2000, 2002), Hendrikx et al. (2004, 2005, 2006), Weir (1998), Miller et al (2022) and Watson (2022). Their contributions have played a crucial role in shaping the program and ensuring its effectiveness over time.

To effectively manage the Milford Road avalanche program, reduce occurrences of highway closure, and ensure the safety of program personnel and road users, the program is dedicated to ongoing monitoring of the seasonal snowpack along the highway. Additionally, the program aims to develop tools that expedite the prompt and efficient reopening of the highway. In situations of increased avalanche hazard, the highway is closed until the slopes reestablish stability, achieved either through natural processes or via deploying explosives via helicopters to mitigate potential hazards.

The spatial distribution of snow depth within the release zones plays a crucial role in shaping the formation and characteristics of avalanches along the Milford Road (Fig. 3). The release zones often experience significant variations in snow depth over short distances, particularly in areas influenced by wind. The thickness of the snow slab and the depth to the weak layer are critical factors that must be carefully assessed before implementing avalanche mitigation measures. These variables play a crucial role in determining the effectiveness of the explosives, in transmitting its energy to the buried weak layer. By understanding these variables, the avalanche mitigation

team can make informed decisions about the appropriate methods and timing for avalanche control measures.

Collecting snowpack data within the release zones is exclusively accomplished through helicopter operations. This access is further constrained by the necessity to fly exclusively during favorable weather periods due to rapid weather changes in the area. Additionally, finding safe landing areas for the helicopters adds to the limitations. Consequently, due to these logistical challenges and limited field observations, the avalanche program heavily relies on remote data collection.

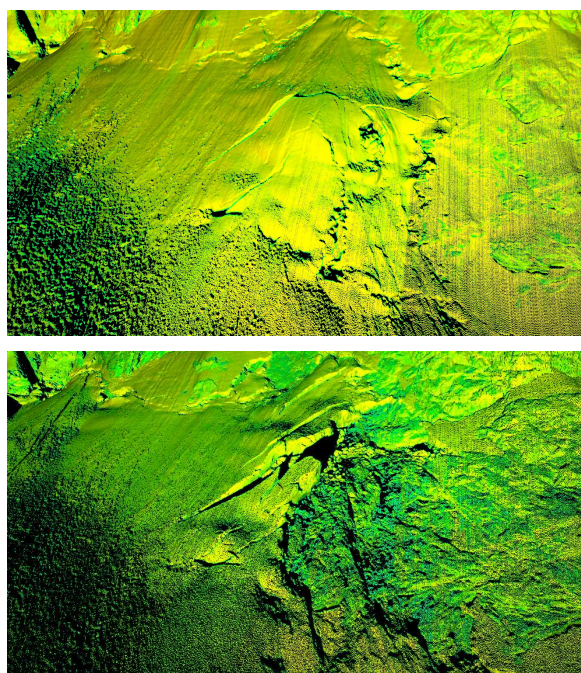


Figure 2: Two successive scans conducted with a two-day interval, focusing on a Glide Crack on Mount Crosscut (-44.77, 168.04). The initial scan (upper) unveiled a crack stretching 61 meters in length and reaching widths of up to 4.3 meters. Subsequently, over the following 30-hour period, a total of 170 mm of rainfall, with rates peaking at 13 mm/hr was recorded. In the subsequent scan, it is evident that the entire right side of the Glide Crack gave way, resulting in an exposed crown face measuring up to 10.3 meters in height.

By integrating LiDAR technology into the MRA, the organization gained the capability to remotely gather high-resolution maps of snow depth, revealing intricate patterns of snow accumulation and melting. This incorporation also enables the formulation of effective mitigation strategies and the evaluation of control measure outcomes.

After a thorough investigation, examining both the positive and negative aspects, MRA chose terrestrial laser scanning (TLS) over other methods like unmanned aerial vehicles (UAV) or vehicle-

mounted LiDAR. The TLS system offered two main advantages for the MRA: firstly, it can collect data without exposing observers to the risks linked with collecting snowpack data; secondly, it reduced reliance on helicopters to access the alpine areas.

MRA held doubts regarding the effectiveness of UAVs within its operations. Among these concerns were the significant reduction in flight time due to battery performance in the cold alpine environment, limitations imposed by the Civil Aviation Authority of New Zealand, and the necessity of relying on helicopters for transportation to the scanning sites.

The TLS system also encounters a notable limitation due to the unfavorable angle of incidence in flat terrain, resulting in measurement shadows obscured by obstacles. To tackle this issue, the MRA adopted a proactive strategy that entails carefully selecting optimal scanning positions. This approach involves prioritizing higher altitude sites that offer improved scanning angles. Moreover, the incorporation of multiple scans and point cloud registration techniques plays a crucial role in mitigating the adverse effects of measurement shadows.

Another advantage of the TLS system for the MRA was its ability to accurately resolve intricate terrain shapes, especially steep and overhanging features that are not easily visible from aerial perspectives. These characteristics are commonly encountered in the avalanche mitigation area.

2. METHODS

2.1 *Laser Scanner*

To fulfill the needs of the TLS, the acquisition of the Riegl VZ@-6000 ultra-long-distance ground-based laser scanner was driven by the unique and specific requirements of the MRA avalanche programme. By incorporating this cutting-edge laser scanning system, the MRA avalanche program strives to enhance its effectiveness and safety protocols along the highway. This ensures consistent monitoring of snow conditions and mitigates potential hazards highway users and infrastructure resulting from avalanches.

The Riegl VZ@-6000 scanner was selected due to its ability to accurately cover extensive distances, making it an ideal choice for monitoring the seasonal snowpack along the highway. This capability will provide valuable information for avalanche forecasting and mitigation efforts.

TLS systems commonly operate at a wavelength of approximately 1500 nm. These scanners exhibit low reflectance and high absorption when

used over snow and ice, resulting in limited scanning distance. Consequently, their utility for applications related to snow and ice monitoring is constrained.

In contrast the Riegl VZ®-6000 employs a Class 3B laser and operates at a wavelength of 1064 nm, which makes it highly suitable for accurately measuring terrain covered in snow and ice. The Riegl VZ®-6000 allows for swift surveying with rate of up to 222,000 measurements per second. This high data acquisition speed is achieved even at considerable distances, reaching up to 1500 m. Additionally, this scanner offers an alternative mode in which it can still capture 30,000 measurements per second at even greater distances of up to 6500 m. Despite its rapid data collection capabilities, the Riegl VZ®-6000 does not compromise on accuracy and precision. It maintains a remarkably low error margin of just 15 mm, ensuring reliable and precise results.

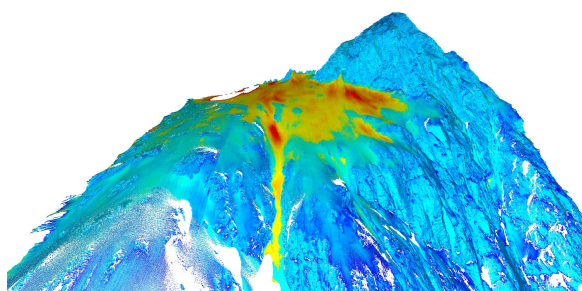


Figure 3: A detailed scan was conducted, capturing 0.87 km² of the topography of West Peak. This visualization reveals the temporal variability in snow depth during the springtime. Turquoise shading denotes a state of equilibrium, where snow depth remains unaltered, while the utilization of dark blue hues signifies a reduction of up to 0.5 m in the snowpack. Conversely, the adoption of red hues highlights an increase of up to 2 m in the snowpack depth.

2.2 Scanning Sites

A permanent alpine scanning site has been chosen to cover a substantial portion of avalanche-prone terrain, situated east of the Homer Tunnel (Fig. 1). This site is conveniently situated adjacent to an MRA alpine research hut, positioned at an elevation of 1895 m on West Peak (-44.76° S, 168.02° E). It provides approximately 10 km² of scannable topography that includes five significant release zones situated above the highway. Furthermore, the scanning capacity extends to encompass an additional 14 km² of secondary avalanche release zones above the highway, in conjunction with noteworthy indicator slopes.

To facilitate a more streamlined evaluation and development process for the housing, a decision

was made to first conduct testing at an alternate site near Consolation Peak (-44.84° S, 168.07° E) situated at the outer eastern end of the avalanche area. This site offers several advantages for evaluation over the permanent scanning location. These advantages include greater accessibility via helicopters, a preinstalled 9 kW generator, a communication hut, and a 1 Gbps Radio network. The scannable topography at this site encompasses approximately 5.5 km², spanning an altitude range from 660 m to 2474 m. It includes three significant avalanche paths.

2.3 Scanner Evaluation

The Riegl VZ®-6000 underwent testing in various meteorological conditions to assess its performance at ranges of up to 3000 m. The objective was to evaluate how effectively the unit would operate under different weather scenarios.

Under conditions of light rainfall intensity, defined as rainfall less than 4 mm/h, the unit demonstrated satisfactory performance. However, there was incidental rain scattering interference detected before the detection surface, which could be easily filtered out.

In scenarios with moderate rainfall intensity, ranging from 4 to 12 mm/h, there was uniform rain scattering interference. Nevertheless, a clear detection surface was observed, and the interference could be filtered out successfully.

The most challenging conditions were observed during very heavy rainfall intensities, between 13 and 20 mm/h. Here, the detection surface became difficult to discern due to significant interference caused by the raindrops. Filtering out this interference was very problematic.

The Riegl VZ®-6000 was subjected to rigorous testing under varying snowfall intensities, encompassing light snowfall rates ranging from 1 to 4 cm/h to moderate snowfall rates of 4 to 10 cm/h.

In the presence of light snow conditions, the LiDAR beam encountered some reflection caused by the presence of snowflakes. However, this interference was easily manageable through effective filtering techniques, allowing for clear observation of a distinct detection surface.

Under moderate snowfall intensity, significant interference was experienced, resulting in a limited detection range of approximately 300 m. In these meteorological conditions, filtering out the interference proved to be exceptionally challenging.

The performance of the Riegl VZ®-6000 was also assessed under cloudy conditions. Under such circumstances, irrespective of the distance of the cloud, almost 100% of the emitted light from the LiDAR scanner was reflected. The presence of

the cloud acted as a formidable obstacle, essentially functioning as a solid barrier to the LiDAR beam. Consequently, the performance of the LiDAR system was substantially impacted in these conditions.

Under typical meteorological conditions, the Riegl VZ@-6000 showcases remarkable capabilities by effortlessly detecting surfaces at distances of up to 6.5 km. Under favorable conditions, the device can even detect returns from snow and ice at distances exceeding 10 km. However, when the unit is configured for maximum range, the spatial resolution of the LiDAR returns is reduced to approximately 0.3 m at a distance of 6.5 km.

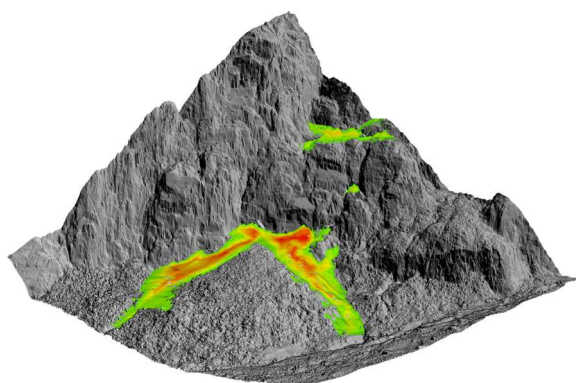


Figure 4: A scan capturing the avalanche deposit on the valley floor from the Sink avalanche path provides a visualization that highlights the dynamic fluctuations in snow depth caused by the avalanche. The color spectrum transitions from green to red, representing snow depths reaching up to 6 meters.

2.4 Snow-free Digital Surface Model

The Riegl VZ@-6000 was employed to perform high-resolution scans of the snow-free topography encompassing both the intended monitoring areas.

In the permanent scanning area, a comprehensive composite point cloud was created by amalgamating 39 individual scans acquired over the period from 2019 to 2023. The utilization of multiple scans was essential to achieve exhaustive coverage of all avalanche paths and the surrounding terrain along the highway. The resulting composite point cloud is composed of nearly five billion points, with varying point densities across the dataset but with an average of 7016 pts/m². This high-resolution composite point cloud enables detailed and accurate representation of the landscape and facilitates precise analysis and monitoring of the avalanche paths.

At the second site, a single summer scan acquired in 2023 is utilized to generate a snow-free

Digital Surface Model from a point cloud containing over 213 million points, with an average point cloud density of 18 pts/m².

2.5 Housing

The Riegl VZ@-6000 will be housed within a UniStar* Enclosure cabinet (600 mm x 600 mm x 1000 mm). The cabinet is constructed with a steel skeleton and features outer skin panels made of aluminium. It incorporates a double French-style doors design on two sides, providing optimal viewing angles for the scanner inside. When a single door is opened, it offers a scanner viewer angle of approximately 105°, and with both doors opened, this angle increases to 210°.

To prevent the accumulation of ice and rime on the external surface of the housing, the aluminium panels are designed without any protrusions or rough edges. This smooth design minimizes areas where ice and rime could build up. The cabinet will also be painted black intended to facilitate the removal of snow, ice, or frost from the surface, enhancing the overall ice and snow management on the housing surface and improving system effectiveness.

The housing doors will be operated using two HIWIN linear actuators. This configuration allows for smooth and precise linear motion, enabling the actuators to extend or retract as needed to open and close the housing doors.

Inside the cabinet, a 16RU Stackable AV Rack system is implemented to store the internal electronic components. This setup ensures convenient access to the components and elevates them above the scanner, optimizing the available space and keeping them out of the scanner's way.

A Campbell Scientific CR1000X datalogger will provide a robust and familiar solution for controlling the doors, power control, sensor feedback and heating, as well as recording internal environmental conditions completes the setup.

2.6 Network

The Riegl VZ@-6000 is connected to the private MRA network using an Ethernet Network Cable. Communication over the network occurs through a 1 Gbps Ubiquiti AirFiber 5XHD 5GHz Radio, combined with Ubiquiti Radome dish antennas. Within MRA network, various components are interconnected, including Network-attached storage (NAS), a post-data processing computer, and the MRA Data Visualization Platform (DVP). The DVP serves as the MRA platform for displaying the data collected within the avalanche programme.

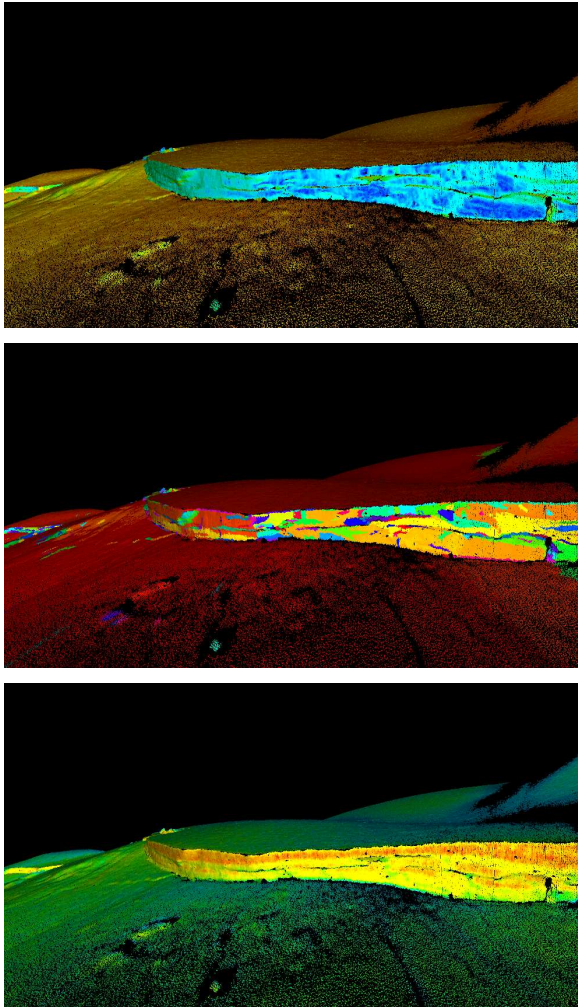


Figure 5: Depicts a detailed, high-resolution scan that captures of the facial structure of the crownwall that ranges in height between 2.2 m and 3.5 m, that resulted from the avalanche event on Mount McPherson Miller et al. (2022). The scan was conducted at a distance of 1900 m, with an average point cloud density of 2,281 pts/m². The upper visualization displays the angle of incidence relative to the normal vector of each point. The middle visualization highlights the crownwall fracture facial origination. The lower visualization showcases the reflective properties of the snow surface of the crownwall.

2.7 *Post-data Processing*

During the evaluation stage, all the LiDAR data is being processed using RiSCAN PRO, which is Riegl's proprietary processing software. This manual processing is being employed as the personnel involved are familiar with the software and well-versed in post-data processing techniques.

3. CONCLUSION

In summary, the performance of the Riegl VZ@-6000 was influenced in distinct ways by different

meteorological conditions. Filtering out interference was manageable during instances of light and moderate snowfall. However, under cloudy conditions, the penetration of the LiDAR beam was significantly hindered.

Rainfall adversely impacted the performance of the Riegl VZ@-6000. Despite this, the unit was able to collect valuable data from the detection surface by implementing effective interference filtering, particularly in rainfall intensities below 12 mm/h.

The current approach to data processing has demonstrate inefficiencies and has time-consuming attributes, requiring specialized software expertise for operation. In the upcoming development phase, the main objective is to automate and enhance these processing procedures. As part of this initiative, several fundamental processing tasks have already been shifted from the RiSCAN PRO software to the Python programming language. Additionally, there are plans to migrate these core processing tasks to the Graphics Processing Unit (GPU) using CUDA@ Python. By harnessing the power of the GPU for mathematical and geographic computations, this approach is anticipated to yield notably enhanced efficiency and performance.

The Riegl VZ@-6000's is providing a comprehensive high-resolution dataset of the avalanche paths and has become an invaluable tool for avalanche monitoring and mitigation efforts along the highway (Fig. 5). It enables better understanding and analysis of the avalanche path morphology, snowpack evolution and aids in the design and implementation of more effective avalanche control measures to ensure the safety of the highway and its users, and MRA staff.

4. OUTLOOK

The MRA remains dedicated to enhancing its post-data processing protocols and advancing the ongoing development of the permanent alpine scanning infrastructure along with autonomous scanning capabilities. Additionally, the MRA will initiate research and development efforts focused on automating systems for avalanche detection (Fig. 4) and the identification of glide slab deformities (Fig. 2). An investigative endeavor into analyzing the LiDAR Return Signal to gather snow surface properties is also on the horizon. Furthermore, the organization is actively exploring the integration of snow depth data derived from LiDAR technology into its proprietary Android Helicopter Avalanche Control application.

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