Applied Research and Innovation Branch

Assessing Gazex Avalanche Control Effectiveness with Terrestrial Laser Scanning

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16. Abstract
This 2-year project used a ground-based laser scanner to map avalanche path snow depths to support an effectiveness assessment of recently-installed Gazex avalanche control systems in the Loveland Pass (Seven Sisters) and Berthoud Pass (Stanley) highway corridors. Scans were collected during snow-free conditions for a baseline, and then prior to and post-storm event and post control operations, as weather and logistics allowed. Snow depth and snow depth change maps were derived from the laser scans, informing an assessment of specific controlled avalanche events and the general performance of the Gazex exploders in the individual starting zones. Good results were obtained from 27 scans at the Seven Sisters site. While a good snow-free data set was collected at the Stanley site, conditions and site geometry prohibited snow-on collection at Stanley with the laser instrument available. Results indicate that the exploders in Sisters 3 and 4 reliably remove snow accumulations from their starting zones, likely due to the focusing effect of the concave starting zone geometries. The 1Low exploder was buried in both seasons of the study, and cross-sections indicate that this exploder location is likely suboptimal. Some evidence of work-hardening exists near the 2Low and 5.5 exploders, warranting future observation and perhaps modification of explorer use timing. The snow depth maps generated in this project provide an unprecedented look at snow accumulation and avalanche dynamics at this site. This rich data set will continue to support future investigations when combined with observations of weather and control activity.
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TARP Research Project Final Report

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Project:

Assessing Gazex Avalanche Control Effectiveness with Terrestrial Laser Scanning

Executive Summary:

This 2-year project used a ground-based laser scanner to map avalanche path snow depths to support an effectiveness assessment of recently-installed Gazex avalanche control systems in the Loveland Pass (Seven Sisters) and Berthoud Pass (Stanley) highway corridors. Scans were collected during snow-free conditions for a baseline, and then prior to and post-storm event and post control operations, as weather and logistics allowed. Snow depth and snow depth change maps were derived from the laser scans, informing an assessment of specific controlled avalanche events and the general performance of the Gazex exploders in the individual starting zones. Good results were obtained from 27 scans at the Seven Sisters site. While a good snow-free data set was collected at the Stanley site, conditions and site geometry prohibited snow-on collection at Stanley with the laser instrument available.

Results indicate that the exploders in Sisters 3 and 4 reliably remove snow accumulations from their starting zones, likely due to the focusing effect of the concave starting zone geometries. The 1Low exploder was buried in both seasons of the study, and cross-sections indicate that this exploder location is likely suboptimal. Some evidence of work-hardening exists near the 2Low and 5.5 exploders, warranting future observation and perhaps modification of explorer use timing.

The snow depth maps generated in this project provide an unprecedented look at snow accumulation and avalanche dynamics at this site. This rich data set will continue to support future investigations when combined with observations of weather and control activity.

Project Objective:

This project used terrestrial laser scanning (TLS) technology to create snow depth maps in avalanche starting zones for an effectiveness assessment of the new Gazex systems in reducing avalanche hazard in the Loveland Pass (Seven Sisters) and Berthoud Pass (Stanley) highway corridors (Figure 1). Snow depth maps created prior and post Gazex firing allow assessment of avalanche control results and Gazex exploder placement, as well as identification of snow accumulation features.

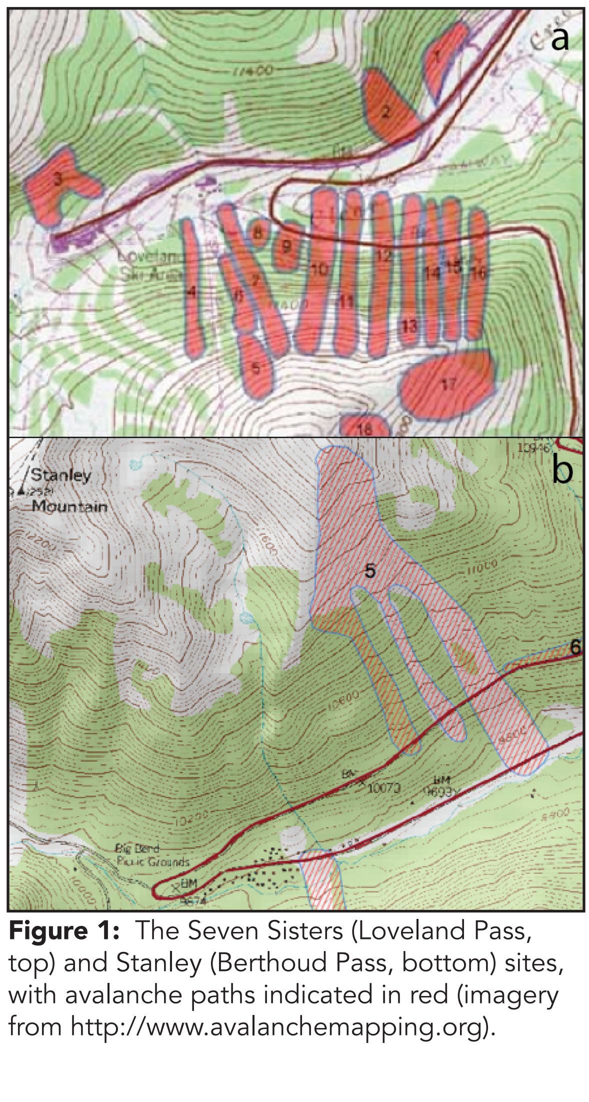

Figure 1: The Seven Sisters (Loveland Pass, top) and Stanley (Berthoud Pass, bottom) sites, with avalanche paths indicated in red (imagery from http://www.avalanchemapping.org).

Background and Methodology:

Background

The spatial distribution of snow depth exerts a strong influence on avalanche occurrence, triggering, character, and potential size. Snow depth also affects snow density, hardness, and weak layer failure. Extreme snow depth heterogeneity is common, especially in wind-affected environments. Avalanche control efforts are often more successful when shallow trigger point areas next to deeper slabs can be targeted with explosives or ski cutting. Control results from permanent installations such as Gazex are optimized when sufficient snow slab has accumulated to create a sizeable release, but before extensive accumulations threaten infrastructure. High resolution snow depth and snow depth change maps from repeat TLS scans can provide quantitative information on snow accumulation patterns for use in avalanche control planning, targeting of explosives, and especially post-control results assessment, and could be used to assess optimal control timing for new operations or installations.

TLS Measurement of Snow Depth

Snow depth is commonly measured by insertion of a ruler into the snowpack, or at in-situ stations via a sonic ranging instrument. Neither method allows safe, repeat, non-destructive, spatially complete sampling in avalanche starting zones where data are most relevant.

In recent years TLS systems have been applied for mapping of snow-free and snow-covered surface elevations. Subtraction of snow-free from snow-covered elevation models provides high-resolution (decimeter resolution) maps of snow depth or depth change, data products which hold tremendous potential for evaluation of snow accumulation patterns and operational assessment and planning of avalanche control efforts.

Until recently, TLS surveys have either been limited to short ranges (< 150m range from scanner) due to system wavelength and power or have required long-duration nighttime scans due to the slow acquisition rate of the scanner and limited detection capabilities at longer ranges. A new TLS system owned by collaborator Finnegan allows unprecedented range and resolution for mapping surface elevation of snow-free or snow-covered terrain. We have employed the Riegl VZ-4000 TLS in snow-covered mountain environments and reliably retrieved decimeter-resolution measurements at ranges over 1 km, with 180° x 60° (horizontal x vertical) field-of-view scans, with durations under 30 minutes. Further, the VZ-4000 uses an eye-safe 1550nm wavelength laser source which can be safely operated in populated areas. This technology is a potentially revolutionary development for remote measurement of snow depth at high resolutions in complex and hazardous terrain.

Specific Methods and Limitations

Storm/accumulation events and avalanche control missions were targeted in this project, with the aim of collecting data pre-storm (for accumulation baseline), post-storm (to map storm accumulation), and post-control (to map avalanche activity). Operational and logistical constraints, as well as weather conditions, precluded TLS mapping of every snow accumulation event and Gazex control mission. As such, the data sets and avalanche events captured as a part of this project represent a sample of the conditions experienced during the two-year project, and thus also a sample of the potential range of conditions that could be encountered at the 7 Sisters site.

On a given scan day, the TLS system was set up on a tripod in the CDOT lot at the base of Loveland Pass. A typical scan of the 7 Sisters area would take on the order of 25 minutes, though in poor-visibility conditions, supplemental, high-resolution scans of specific starting zones were often collected, adding 10-15 minutes total to the scan time.

Raw data were georeferenced and registered to prior scans and GNSS survey control, then the elevation point clouds were exported to laz (compressed las) format. In-air points (e.g. from snowfall or blowing snow) were filtered out, and vegetation points were classified using a terrain curvature filter to produce 'bare-earth' data sets.

Each pre- and post-storm bare-earth (or bare-snow) data set was then converted to a 0.5m gridded surface model, to allow differencing from subsequent data sets. Calculation of the vertical difference between a snow-on point cloud and a bare-earth surface model produces a snow depth (HS; relative to snow-free) or change in snow depth (dHS; relative to a prior snow-on scan) value for each point in the particular point cloud data set. These values can then be mapped and analyzed for snow accumulation properties, avalanche occurrence, and avalanche metrics. A more detailed methodology description is included in Appendix B.

Research Plan, Tasks, and Deliverables:

<u>Task 1:</u> Conduct site assessments, study feasibility, coordinate workflow and site access details with CDOT/CAIC collaborators

Deliverable 1: Initial scan data images

Progress on Task 1: All Task 1 elements were completed at the Loveland Pass/7 Sisters site in January 2016.

Loveland Pass initial scan images (Deliverable 1) are included in Appendix A in this report. Three scan locations were initially examined and used for snow-free scan acquisition, with the resulting scan data merged into a single dataset. It was determined that a single scan location would suffice for the great majority of snow-on situations. Several communication and coordination challenges were identified and addressed – individual storm and road closure events often do not follow a predictable evolution, and weather and access are not always conducive to scan acquisition.

Task 1 is complete at the Berthoud Pass/Stanley Path site. Initial scan images (Deliverable 1) are included in Appendix A in this report. A single scan location at the gun pad along Highway 40 provided the best view of the Stanley starting zones. Several attempts at snow-on data collection were made at the Stanley Path site. Terrain geometry severely limits the look angles and range to target at this site, the combination of which (long range and high incidence angles) along with the low reflectivity and forward scattering properties of snow test the limits of the VZ-4000 TLS system. The Riegl VZ-6000 TLS system would be more appropriate for use at Stanley, but this system was unavailable during the duration of the project, and furthermore eye safety concerns require many precautions and coordination to occur. These two constraints prevented use of the longer-range VZ-6000 system for this effort, and therefore Task 1 results indicate that project goals are not achievable at the Berthoud Pass/Stanley site given the currently available equipment.

<u>Task 2:</u> Collect snow-free TLS scans of both sites after construction of Gazex systems.

Deliverable 2: Snow-free elevation point cloud

Deliverable 3: Snow-free bare-earth digital elevation model

Progress on Task 2:

Snow-free scans were conducted in September 2015 at the Loveland Pass/7 Sisters site, and in August 2016 at the Berthoud Pass/Stanley Path site. Elevation point clouds (Deliverable 2) were cropped to the area of interest to reduce data volume. Snow-free digital elevation models (Deliverable 3) were generated at 0.5 m resolution from the point cloud data. The data products for Deliverables 2 and 3 will be delivered to CDOT and CAIC in parallel with this report.

<u>Task 3:</u> Conduct snow-on scans prior to storm events, and pre- and post-Gazex avalanche control operations

Deliverable 4: Pre-control snow depth and storm slab thickness maps

Deliverable 5: Post-control snow depth maps

Deliverable 6: Avalanche area and volume measurements

Progress on Task 3:

A total of 27 scans were collected under Task 3 efforts at the 7 Sisters site, including 11 pre-storm scans, 9 post-storm scans, and 6 post-control scans (Table 1).

A number of pre-control scans were followed by control missions with negative results, and on other occasions atmospheric conditions – fog or snow in the air – precluded or severely limited data collection. However, several efforts produced excellent results, details of which are explored below.

Data products for Deliverables 4, 5, and 6 will be delivered to CDOT and CAIC in parallel with this report. See *Data Products and Delivery* section below for format details.

Analysis and Effectiveness Assessment:

Overview

Measuring the effectiveness of the new Gazex system relative to the preceding Avalauncher-based control program is difficult to achieve on a short time scale – storm dynamics and sequences, changes in personnel and control procedures, and trends in traffic volumes and patterns all conspire to challenge a direct comparison. In lieu of such a comprehensive assessment, the ability to evaluate the performance of each individual Gazex exploder over several storm or loading events can support the development of a holistic effectiveness assessment.

In that context, the mapping project detailed in this report serves to supplement a more conventional effectiveness assessment of the Gazex system, which could include such metrics as road closure time, explosives/gas expenditure, and other measures. The TLS tool can aid a broader assessment by documenting and quantifying the spatial properties of individual storm/accumulation and control event results. The following analysis and assessment is organized by slide path.

Table 1: Listing of 7 Sisters scan days with storm and control mission timing indication.

Date	Pre-Storm	Post-Storm	Post-Control	Comment
9/2/15	-	-	-	Snow-Free
1/13/16	X			
1/21/16	X			
1/31/16		X	X	Pre control: lots of blowing snow
3/11/16	X			
3/15/16		X	X	Lots of blowing snow for both scans
4/14/16	X			
4/17/16		X	X	Upslope storm
12/23/16	X			
1/2/17	X			
1/7/17	X			
1/10/17		X		1A; 1Hi;4; 5.5; 6Hi; 7
1/18/17	X			
1/25/17		X	X	no results
2/5/17		X		1Hi; 3; 4; 5.5; 6
3/1/17		X	X	1Hi; 2Hi; 3; 4; 6Hi; 7
3/24/17	X			
3/27/17	X			
3/29/17		X	X	1Hi; 2Hi; 4; 5.5
4/24/17	X			
4/28/17		X		1Hi; 4

Individual Avalanche Path Assessments

1A Sisters

These two adjacent small paths are to the west of 1st Sister, with their exploders programmed to fire simultaneously. The starting zones are small and planar, with trees within the starting zones and around the margins. Depth maps indicate that these paths receive lower total snow accumulations than in adjacent start zones. The 1A exploders are less frequently used than those in most of the other Sisters (15 firings in 2017), and usually produce small slides that do not reach the highway, likely due to the relatively low snow accumulations mentioned above.

From the TLS maps it appears that the 1A exploders are usually quite effective at clearing accumulated snow from the starting zones. One episode in particular helps inform the range of impact of the 1A exploders. On 1 March 2017, a small release was observed on the bank low in the track of 1st Sister (Figure 2). Due to delays that morning, the pre-control scan was not completed before control operations began, and an avalanche produced by Exploder 1 High was captured by the pre-control scan – this avalanche therefore shows no change in the post-control scan. However, the small bank release does show change between the pre- and post-control scans, indicating that it was most likely induced by the 1A exploders, which were fired between the scans. This unplanned timing suggests that the concussion from the 1A exploders can impact terrain well outside the 1A starting zones, and that therefore they provide sufficient blast intensity to affect the full 1A starting zones.

1st Sister

The 1st Sister path is equipped with two exploders, 1 High at the top of the starting zone, and 1 Low, on a cross-loading drift located mid-track.

1 High

The 1 High exploder regularly produces results, with release areas observed ranging from ~1/3 to full start zone extent. Crown heights Events produced by 1 High often remove snow under the 1 Low exploder. The start zone around 1 High is moderately confined, with a shallow dish shape that tends to collect drifting snow across its full lateral extent. Figure 3 illustrates a common result from 1 High, with a wide-propagating thin slab and scouring in the track.

1 Low

The 1 Low exploder ceased operating during the 2016 snow season due to snow overburden compressing and occluding one of the gas supply lines. The exploder was subsequently completely buried by drifting snow (Figure 4).

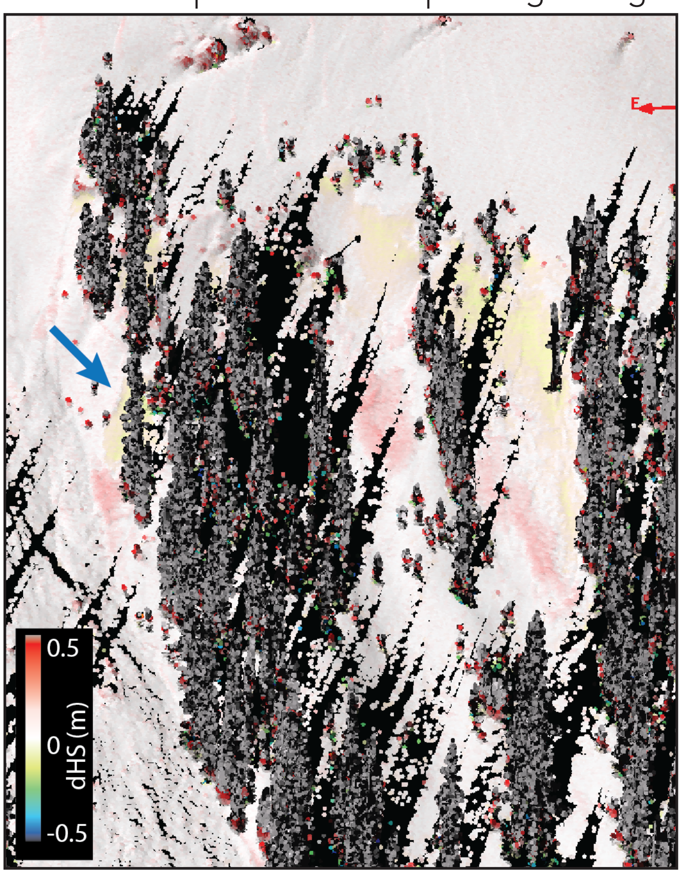

Figure 2: Post-control scan of 1A/B and lower 1st Sister track on 1 March 2017, showing releases below 1A/B exploders as well as a sympathetic release from a bank low in the 1st Sister track (blue arrow).

The 1 Low exploder was buried again in 2017 despite remaining functional. It appears that either the snow drift accumulation rate was too rapid for control efforts to keep pace

(Case A), or that multiple drifting/accumulation events occurred with no instability present, and the accumulation eventually overwhelmed the exploder (Case B). A combination of Cases A and B is also possible. Either case presents the possibility that the exploder was located too low in the drift/start zone, leaving only a narrow set of conditions under which the exploder effectively mitigates snow accumulation in the cross-loading starting zone. Case A would suggest that more frequent use or more targeted timing of 1 Low activation might prevent drift build-up and maintain exploder functionality.

2nd Sister

The 2nd Sister path is equipped with two exploders: 2 High, located in a lower-angle portion of the starting zone, above a sharp break in slope, and 2 Low, located on the East edge of the steeper portion of the starting zone.

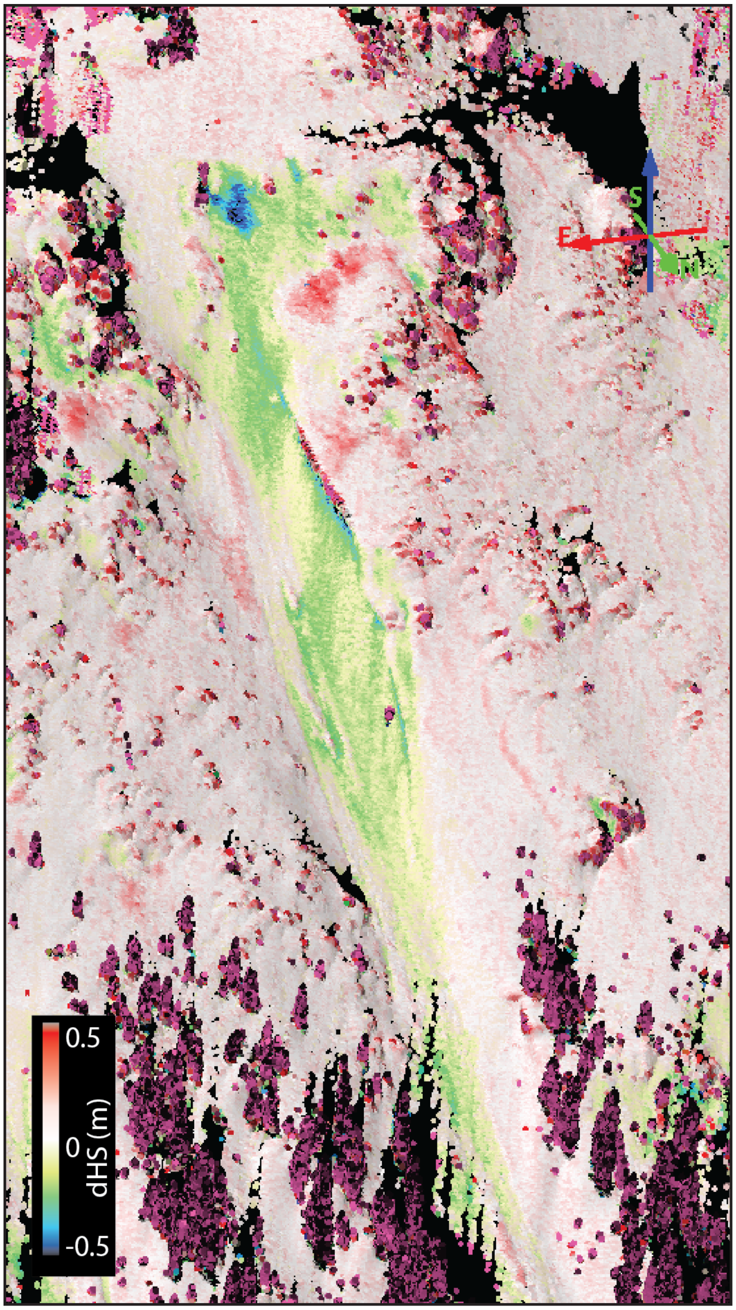

Figure 3: Result from 1 High exploder on 31 Jan 2016, showing lateral extent of thin slab release.

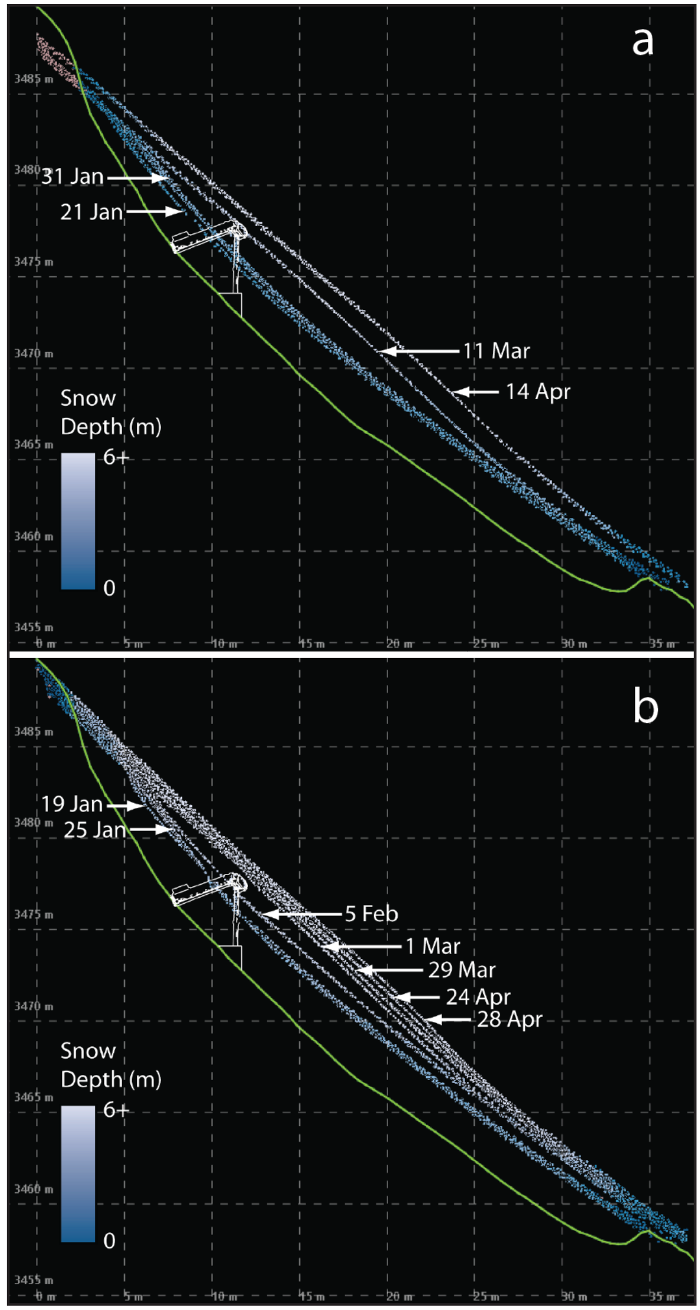

Figure 4: Time series cross-section through the wind drift at exploder 1 Low, 2016 (top) and 2017 (bottom). Green line represents snow-free terrain, and lidar point elevations are colored by snow depth.

2 High

No use of the 2 High exploder occurred in conjunction with any scan efforts.

2 Low

The 2 Low exploder produces regular results in its mildly concave start zone. This exploder tends to produce shallow slides, frequently releasing only a portion of the start zone. This can be partly attributed to variable accumulation patterns in the start zone. Additionally, substantial drifting can occur well below exploder, in which case successful triggering relies on propagation through connected snow slab, undercutting by moving debris, or sufficient blast pressure on far side of the start zone.

Results from 1 March 2017 exemplify the potential for variable loading patterns in the 2 Low start zone and suggest that repeated exploder-induced compression is potentially work-hardening the snow in this area, which would make older snow more less susceptible to triggering. The post-control results illustrate that the accumulated snow directly below the 2 Low exploder did not release, but that a drift low in the start zone did fail (Figure 5a). It is possible that this result, rather than exemplifying work-hardening, simply is an effect of variable new snow load with the critical instability confined to lower in the start zone – further observation of this path is warranted. In contrast, a storm in April 2016 loaded the area around the exploder, and the majority of the starting zone was released (Figure 5b).

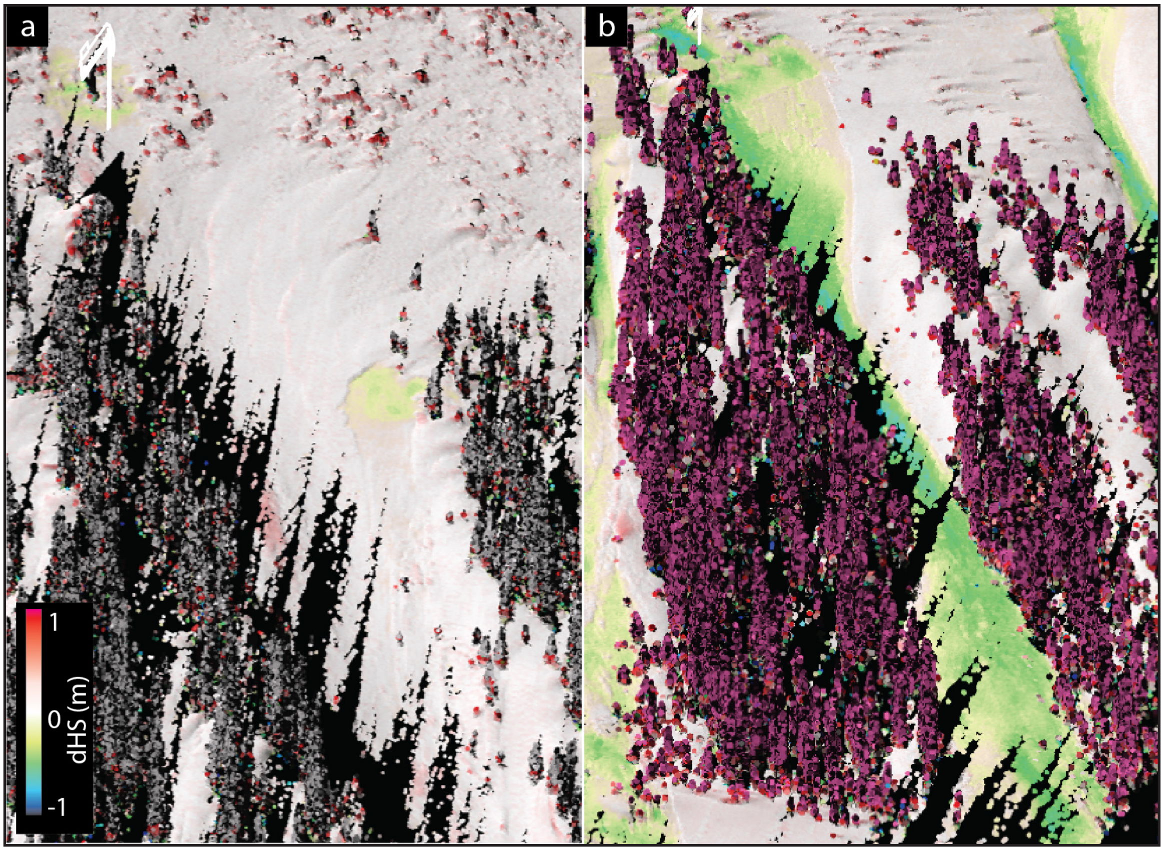

Figure 5: A) Control work on 1 March 2017 released the bottom portion of the starting zone, leaving the snow directly under the exploder intact. B) On 17 April 2017, the majority of the starting zone released. (Note the different zooms in each panel – white Gazex cartoon for scale).

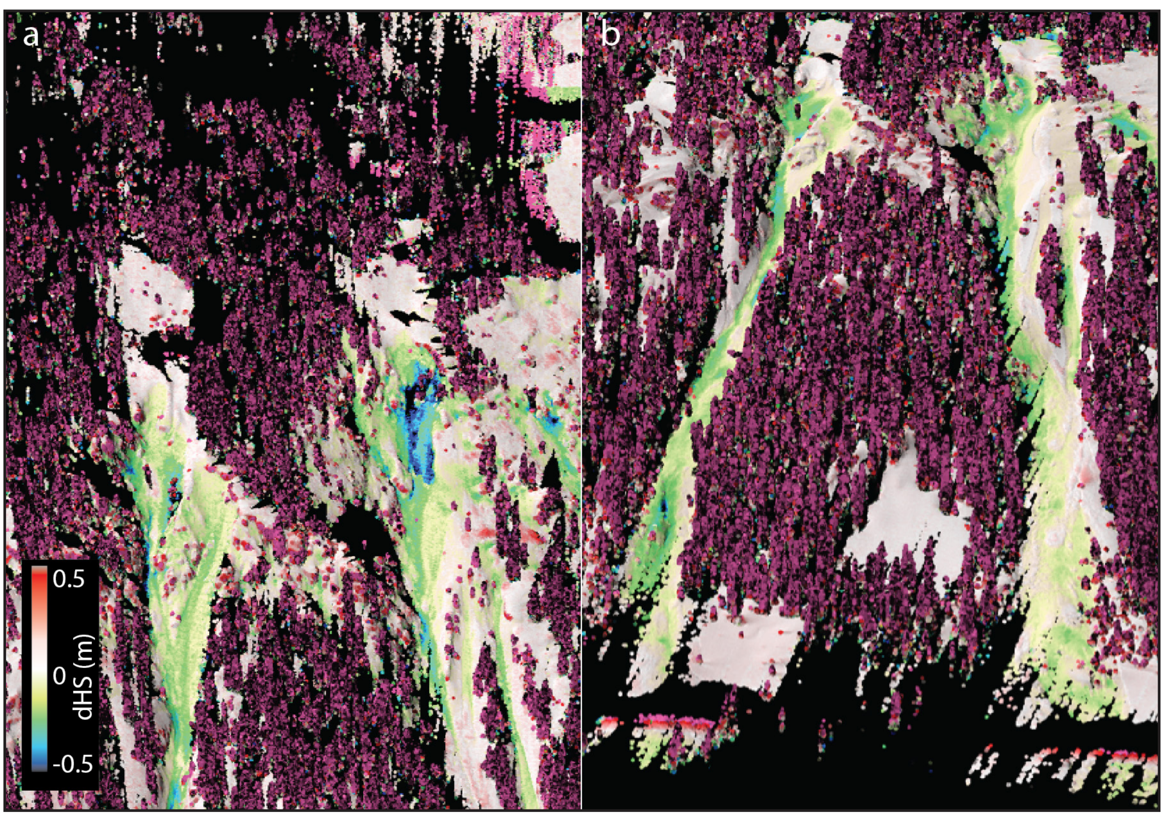

Figure 6: The confined starting zones of Sisters 3 and 4 appear to concentrate the exploder air blasts, producing regular and reliable control results. A) 31 Jan 2016, and B) 17 April 2016.

3rd and 4th Sister

The 3rd and 4th Sister paths are adjacent, similar in morphology, and behave similarly in regards to snow accumulation patterns and avalanche activity – hence they are treated together here.

The start zones of these paths are concave and appear to concentrate or contain the air blast from the Gazex exploders, as most events release a large fraction of the start zone area (e.g. Figure 6). Use of these exploders reliably produce results, suggesting that the concave start zones concentrate the air blast sufficiently to release snow even at times when a critical instability is not present. The wind loading direction seems less important in these paths, as in addition to their concave shape, the start zones are confined and somewhat symmetrical in the cross-slope direction, allowing them to accumulate drifting snow efficiently from either side.

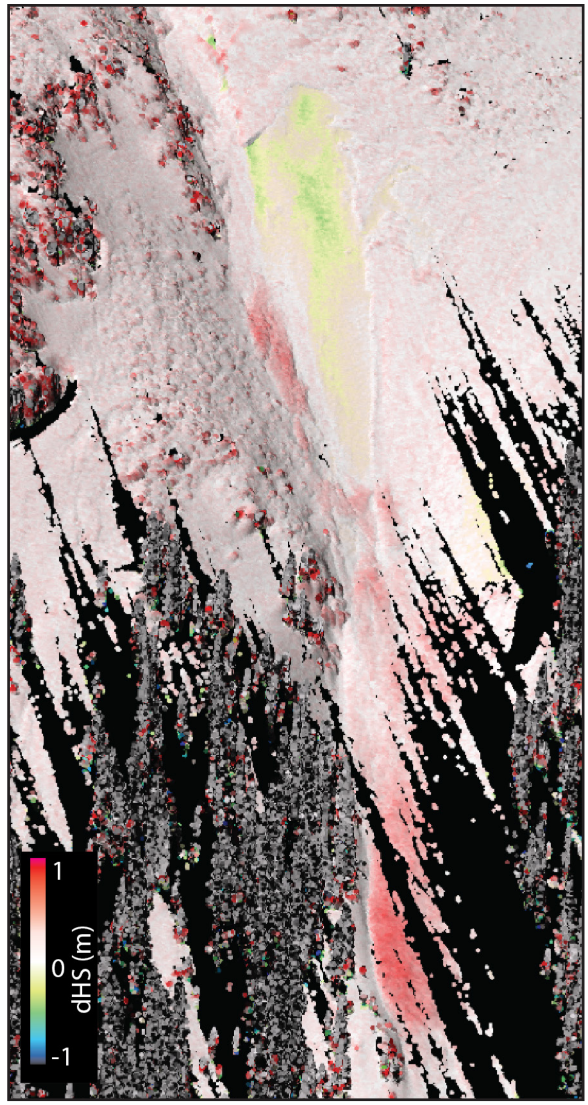

Figure 7: the 6 High exploder on 1 March 2017 released a small sluff which stopped high in the track. Movement of this sluff appeared to release a small slab from below exploder 5.5, which ran to mid-track.

6th Sister (including 5.5)

The 6th Sister path consists of a relatively well-defined and slightly concave start zone near the top of the ridge, and a secondary, cross-loading start zone mid-track that accumulates snow scoured from the large, planar slope to the west (above Sisters 2-4). One exploder is located in each of these starting zones, referred to as 6 High and 5.5, respectively.

6 High

The 6 High exploder is located in a moderately confined, slightly concave start zone near the ridgeline, which can experience cross-loading (more from easterlies than from the west), but primarily seems to receive drifting snow from the south side of the ridge. Several small slides were captured during the study, and though no event appeared to clean out the entire start zone, most slides observed tended to deposit debris low in the track or near/on the highway (e.g. Figure 7). There is a small bench or concavity low in the track (above the highway) that often slows or stops debris from small slides, especially early in the accumulation season.

This exploder was partially buried part of 2017, and the accumulating drift buried all but its top 1.5 m (Figure 8). It is possible that more frequent or more optimally-timed use of the exploder could have prevented this burial – analysis of shot logs and storm timing could provide guidance.

5.5

Exploder 5.5 is aimed at controlling cross-loading drifts in the middle of the 6th Sister path, the locations of which appear to be sensitive to wind dynamics and perhaps loading patterns in the fetch area to the west. These drifts exhibited only a small number of controlled releases during the study. It is of interest to know if this low number of results is due to non-critical accumulation amounts, suboptimal exploder siting, suboptimal timing of control efforts, or perhaps work-hardening of the snow under the exploder. The results from 2016 lend support to the work-hardening hypothesis: the exploder was used frequently, producing a small result early in the season (13 Jan 2016) but a stubborn accumulation feature formed directly below the exploder, with a shape that qualitatively resembles the "footprint" of the air blast from 5.5 (Figure 9), or potentially a drift shaped by wind interaction with the exploder itself. There is little direct examination of Gazex-induced work-hardening in the relevant literature, though studies by Elder and Newcomb (1994; 1996) indicate that the area of influence of Gazex exploders is anisotropic, with greater extent in the downslope direction (~40m) than across-slope (~10m). This general shape corresponds well with the shape of the accumulation feature below exploder 5.5, which measures roughly 7x30m.

In the 2016/17 season, Exploder 5.5 was fired less frequently. On March 1, 2017, moving debris produced by firing Exploder 6 appears to have triggered the drift below Exploder 5.5 (which was not fired), running to mid-track (see Figure 7). This mid-season result is consistent with the hypothesis that a lesser degree of work hardening occurred with reduced use of exploder 5.5 in 2017, however with only two seasons of lidar mapping observations, this result is not conclusive.

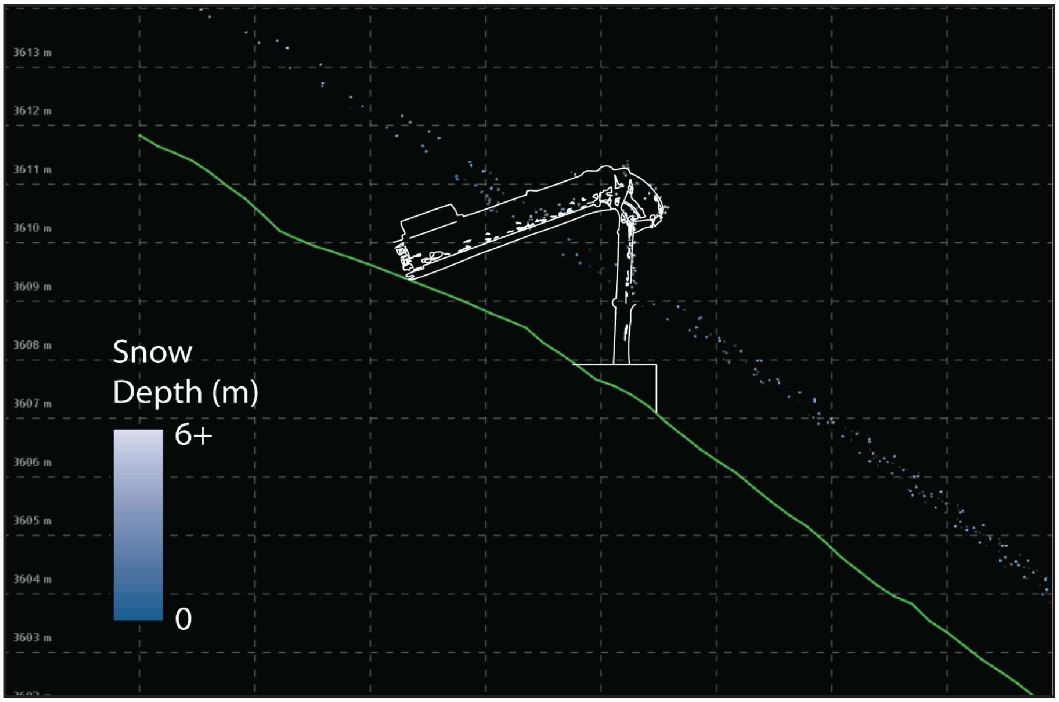

Figure 8: Cross section through the 6 High exploder on 29 March 2017, showing that only the top 1.5 m of the exploder is above the snow surface.

<u>7th Sister</u>

Few results from the 7th Sister path were captured during this project. On 17 April 2016 an upslope (easterly) storm loaded the eastern side of the starting zone, and a small slab was triggered by exploder 7 (Figure 10).

On 1 March 2017 a small loose snow avalanche was recorded, though it exists in the pre-control scan data, indicating that the sluff occurred prior to control efforts.

It is difficult to draw any substantive conclusions from this limited number of events, though the first event noted suggests that the exploder in the 7th Sister is reasonably well-positioned to affect

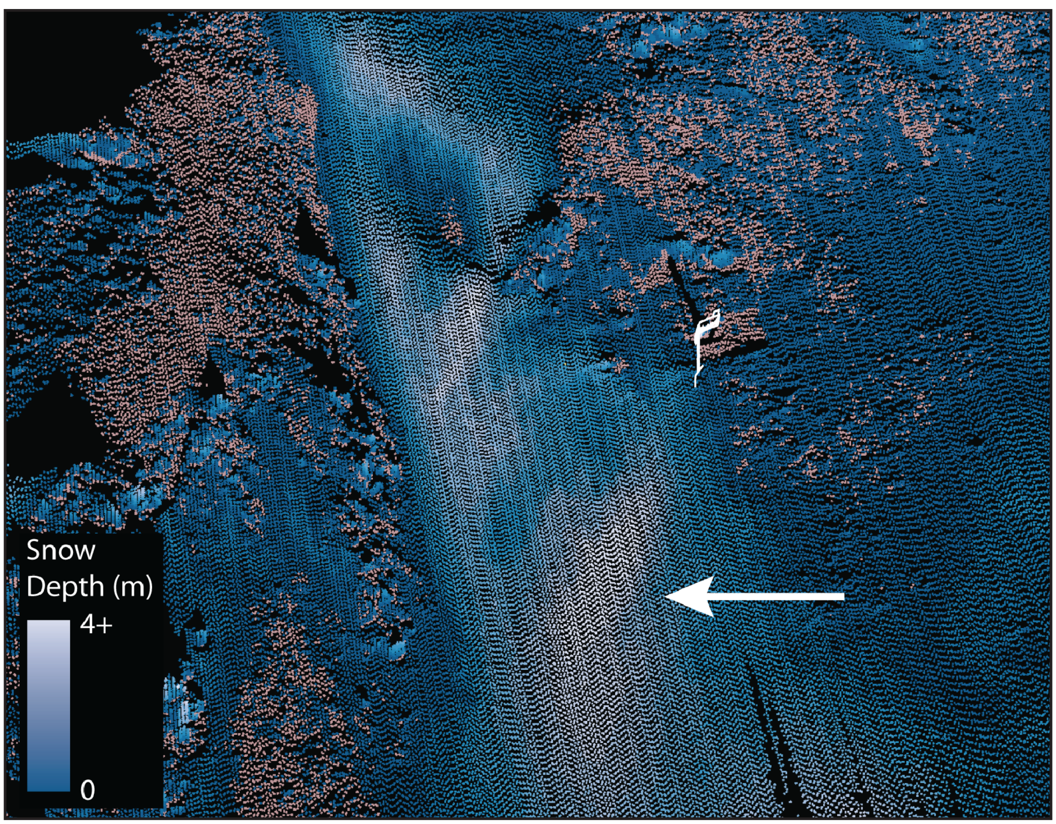

Figure 9: Oblique view of the 5.5 exploder on 14 April 2016. White arrow indicates a persistent accumulation feature. The location of the feature directly downslope of the exploder along with its oblong shape, in contrast to other visible wind drift features in the vicinity, suggest that effects from the exploder create this feature.

snow accumulations in the eastern portion of the start zone.

<u>General Observations and Discussion</u>

The storm and control events observed during this study represent a subset of the event sequences during the two years of observation, and further, serve to characterize a portion of the total accumulation and avalanche dynamics that are possible in the 7 Sisters domain. As such, a complete and robust effectiveness assessment of the new Gazex system remains a challenge. However, the unprecedented spatial resolution and coverage provided by the lidar snow depth mapping provides some novel insights into the performance of the exploder network.

The operational paradigm in the 7 Sisters changed from the prior avalauncher approach – where specific locations in each path were routinely targeted but launcher inaccuracy, wind, and the ability to add or move targets as needed allowed variation in actual explosives placement – to the static Gazex emplacements where changes to the target location are not possible, nor is the addition of extra shot placements. Therefore, it is possible (or even likely in the case of 1 Low and 5.5 exploders) that the static exploder locations provide a reduced operational flexibility in handling variation in loading patterns. This is likely offset by increased flexibility in control mission timing. Additional influences of blast directionality and start zone geometry contribute other, unquantified differences in mitigation reliability or effectiveness.

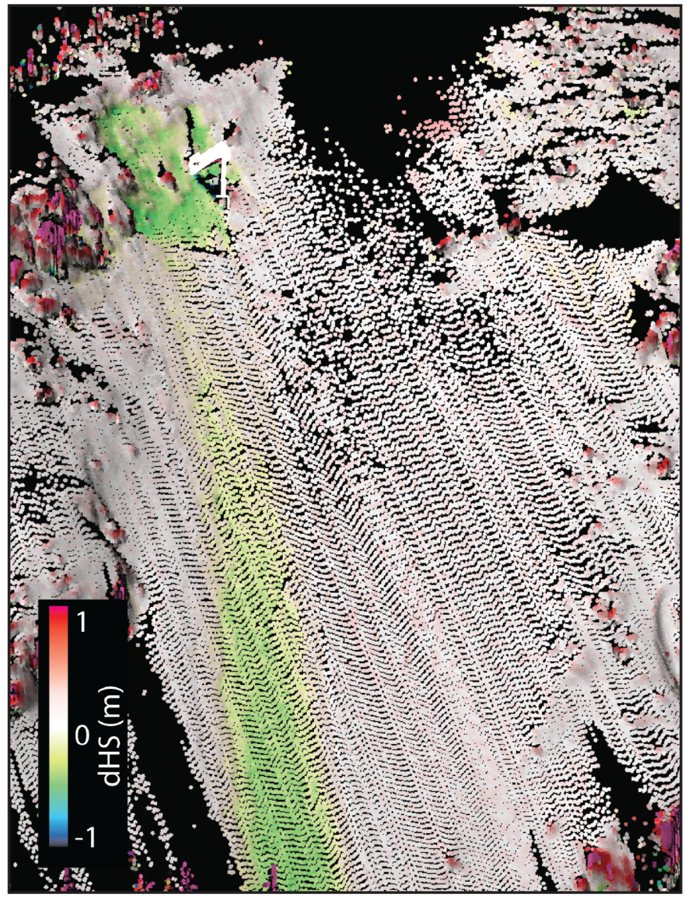

Figure 10: Small slab release from exploder 7 on 17 April, 2017.

General assessment of effectiveness

Based on the TLS mapping effort and recognizing that the events captured by this study represent only a sample of the potential conditions at the 7 Sisters site, the placement of the Gazex exploders and their operation seems generally effective at producing small avalanches that clear the new snow load from the majority of the starting zone areas and depositing debris low in the track. The activity observed in Sisters 3 and 4 in particular indicates a reliable reduction of the hazard from those paths.

The 1st Sister offers an interesting contrast in exploder effectiveness. The 1 High exploder appears to be well-positioned and operated given the starting zone morphology and the typical loading pattern there, with the results observed commonly releasing a large portion of the starting zone. The 1 Low exploder, on the other hand, was completely buried in both years of the study, rendering it inoperable (and ineffective). It seems clear, both from this fact and from examining the time series of snow drift formation detailed in Figure 3, that this exploder is not properly sited and will not be effective in affecting avalanche formation in the future, regardless of operation.

Exploder 5.5 appears to be well-positioned to directly affect the mid-track accumulation feature in the 6th Sister (Figure 9), however as noted above, it is difficult to assess whether that feature would form in the same configuration or at all were the exploder not present. Regardless, the feature appears to be stubborn and not frequently responsive to triggering, which is suggestive of work-hardening of the snow below the exploder. It is possible that adjustments to the timing of use of the exploder (either less frequent application or usage earlier in an accumulation event sequence) could produce different, more reliable results.

As discussed above, it could be fruitful to integrate the results of this study with other effectiveness measures as the operational record and personnel experience with the system grows. For example, statistics integrating frequency of activation and triggering alongside storm accumulation and timing data could be paired with these spatial observations to explore optimal timing and sequencing of Gazex control missions.

Discussion

A persistent challenge in avalanche management is how to account for negative results – where for example an explosive is applied to the starting zone but no avalanche is produced. This situation generates considerable uncertainty for operational managers – is the snowpack stable? Did we miss the trigger point? Did we miss the optimal timing? Some of these questions can be addressed with the laser-mapped snow depth data. A study (beyond the current scope) evaluating the spatial distribution of storm snow thickness (from the post=storm/pre-control scans) for new snow load, connectivity of slab thickness, and (in conjunction with in-situ meteorological data or models) the distribution of loading rates could provide important insights into both operational timing and location as well as physical process understanding.

In addition to the limited range of storm and avalanche event characteristics sampled, several other limitations of this study serve to highlight opportunities for future development. First, the challenges of timely site access and rapid data product generation would be assisted by a fixed laser system installation. Such an installation would allow for remote operation at more optimal times and would simplify the relative registration of snow-off and snow-on data sets in the postprocessing steps, allowing faster and more robust data product generation. Second, whether portable or installed in a fixed location, the ground-based laser system by its nature suffers from shadows areas generated by terrain or dense forest. New unmanned aerial systems (UAS) with laser scanner or photogrammetric mapping capabilities can provide an optimal viewing geometry to minimize shadowing. Using this type of technology, especially for the snow-free data sets, would serve to minimize the impacts of data gaps. Third, the cost of the laser sensor and processing software are prohibitive for small-scale deployment, and therefore point to either continued applied science research projects, or a larger-scale effort potentially involving multiple partners or cross-departmental benefits.

Data Products and Delivery

Data products include geolocated elevation point clouds and gridded elevation surfaces. Following the methodology described in Appendix B, two versions of the point cloud data are produced, one containing snow depth values, and the other containing snow depth change values relative to the prior scan (either pre-storm or pre-control). The point cloud data are provided in Las 1.2 format, compressed using the Laszip utility (*.laz; free unzipping utility is available at http://www.laszip.org/).

Ground-classified (or snow-surface classified) points are subsequently interpolated to a 0.5m resolution grid to serve as reference surfaces from which to calculate snow depth or change in snow depth. These gridded surfaces are provided in GeoTiff format.

Conclusions and Recommendations for Future Work:

This project, building on prior efforts, demonstrates the unique capabilities of long-range TLS systems to map snow depth and snow depth changes at very high resolutions in avalanche paths. In this particular application the time series of snow depth maps collected over two snow seasons supports an evaluation of the effectiveness of the newly installed Gazex exploder array at US6/Loveland Pass.

The results illustrate a range of effectiveness in the various starting zones and exploder placements in the 7 Sisters paths. The 3rd and 4th Sister paths, with their confined starting zones, demonstrated reliable results during the project, with control work usually clearing out the entire starting zone areas. The 1 High and 2 Low exploders also produced control results regularly, though with more variation in the release area.

In contrast, the 1 Low exploder was buried by a cross-loaded drift in both years, and depth profiles through the exploder and drift indicate that this exploder was poorly-sited and burial can be expected even in low snow years. Results also suggest that the placement and/or usage of exploder 5.5 is less than optimal, with some evidence for work-hardening of snow in the exploder footprint. Further observation is warranted in that case.

The TLS system and procedures used for this project offer a number of distinct benefits for measurement and tracking of snow properties in inaccessible avalanche starting zones. The high spatial resolution of the snow depth measurements vastly exceeds conventional approaches to measurement or estimation of depth distributions in starting zones. This high resolution captures the fine-scale variability in snow depth or slab thickness that can be critical to avalanche triggering but is very difficult to capture by conventional means. The three-dimensional nature of the data sets can support quantification of avalanche properties such as average and variation of slab thickness, crown heights, and runout length or alpha angle. The relatively fast acquisition time is compatible with operational needs, and further effort establishing reference targets or using fixed stations would allow for rapid generation of data products to support on-site decision-making. The TLS system is an active sensor and does not depend on ambient light for measurement (unlike camera/photogrammetric mapping methods). Further, the system's ability to log multiple targets per laser pulse allows some degree of snow mapping below or behind trees (an airborne or UAV system with its downlooking geometry would produce even more reliable results in forest areas).

The TLS avalanche application is not without its challenges. First, while the system is not limited by daylight, it is affected by visibility, with low clouds or snowfall inhibiting the laser pulses – reducing range, increasing noise, or even preventing survey altogether. This limitation particularly affects the potential to track deposition patterns and rates during a snowfall or wind loading event. Second, currently-applied processing methods require several hours to produce data products. However, a specific effort to produce actionable data on-site, involving identification or installation of reference targets and a specific operational goal, could reliably reduce processing time to a fraction of an hour. Third, the laser system used in this project operates at an inherently eye-safe wavelength, which, though maximizing opportunities for data collection in populated areas, is far from ideal for snow mapping. This wavelength is especially limiting in conditions with wet or coarse-grained snow, these properties absorbing more laser energy than fine-grained, dry conditions. A shorter-wavelength system exists (and is owned by the CRREL partners who enabled this project), would provide increased range in all conditions including spring/wet snow, and would allow mapping at the Berthoud Pass/Stanley path site. However, its non-eye safe nature limits the operational environment in which it can be used – protection of survey and control teams is straightforward, but limiting general public exposure is more challenging in a highway corridor.

As alluded to above, the Stanley path at Berthoud Pass was initially a target of this project, and snow-free scans of the area were collected. However, the range to the starting zone from the only reliable scan position is at the limit of the TLS sensor available for this project, and any deterioration in snow or atmospheric conditions effectively prohibits data collection at this site. The longer-range scanner, combined with well-coordinated timing with highway closures, would be an effective solution at this location.

Future Applications

Future work building on this project could range from targeting of specific avalanche problem evolution to site characterization and planning. Additional seasons of mapping the 7 Sisters paths, for example, would add to the library of events captured with the laser mapping technology, and help build the detailed spatial understanding of how the avalanche paths behave under varying conditions. Targeted TLS acquisitions could be designed to characterize avalanche debris deposition in tracks or around diversion structures. High resolution terrain models from laser scans could be used in conjunction with shock propagation models to simulate various control methods in specific paths or could feed into fine-scale wind and snow drift simulations to anticipate loading event magnitude and extent.

Planning of new exploder installations would greatly benefit from a laser mapping effort, regardless of the specific exploder technology. The snow-free data sets would enable site assessment, engineering, and construction planning. Mapping of snow distributions, either a peak accumulation map or a series of maps capturing specific loading events, would inform exploder placement to optimize explosives impact as well as avoid selection of locations where equipment burial is likely. Subsequent (post-installation) mapping efforts would aid validation of the placement decisions.

In an operational support setting, installation of a permanently-installed scanning system would allow remote assessment, minimize logistical constraints, and speed processing to generate timely data products to support control missions. Such a system would also allow much more detailed evaluation of the time evolution of snow distributions in starting zones, including drift evolution, snow settlement rate, and mapping of prior avalanche activity to assess re-loading or potential areas of differing snow metamorphism (e.g. enhanced depth hoar development in the shallower release areas). The spatially-extensive, quantitative statistics on avalanche properties derived from such a monitoring system would enable new science and applied science questions.

Additionally, there is great potential for integration of laser scanning systems with other survey tools. Photogrammetric surface models, built from drone-based or handheld cameras, can be a cost-effective means for generating additional snow depth maps, despite greater environmental constraints on data collection. Emerging radar technologies, when combined with the high-resolution TLS snow depth maps, could map snow density/SWE and perhaps stratigraphy, thus allowing assessment of mass loading and variation of internal snowpack structures.

As in the snow water resources world, the 'spatial revolution' is ongoing – new technologies such as the TLS system used in this project are providing unprecedented information about the spatial variation of snow properties and how they change over time. This information is critical for reliable avalanche prediction and control efforts and represents a paradigm shift in how we address snow and avalanche dynamics from both scientific and operational perspectives. This work, its future iterations, and parallel efforts to bring spatially extensive, high resolution, high accuracy data sets into regular and operational use represent the vanguard of a new era in snow science and snow safety applications.

Acknowledgements

This project was enabled by the efforts and support of many individuals and groups. Thanks are due to the Transportation Avalanche Research Pool (TARP) for funding support and regular feedback. The CRREL RS/GIS team (Dave Finnegan, Adam LeWinter, Pete Gadomski) provided the equipment and deep expertise to help develop this new application of laser survey technology. Ethan Greene at the Colorado Avalanche Information Center (CAIC) was instrumental in fine-tuning the project idea and laying the groundwork for its implementation. Stu Schaefer and Ron Simenhois at CAIC coordinated scan opportunities with control operations at the 7 Sisters site.

Appendix A

Initial scan data images from Loveland Pass/7 Sisters site

The images in this Appendix result from the Task 1 activities and demonstrate the capabilities of the sensor and approach to map the areas of interest at appropriate levels of detail. The multiple views of the elevation "point cloud" (colored by height above ground level – AGL) illustrate the data resolution, its three dimensional nature, and some of the limitations induced by vegetation or terrain shadowing and sensor field-of-view.

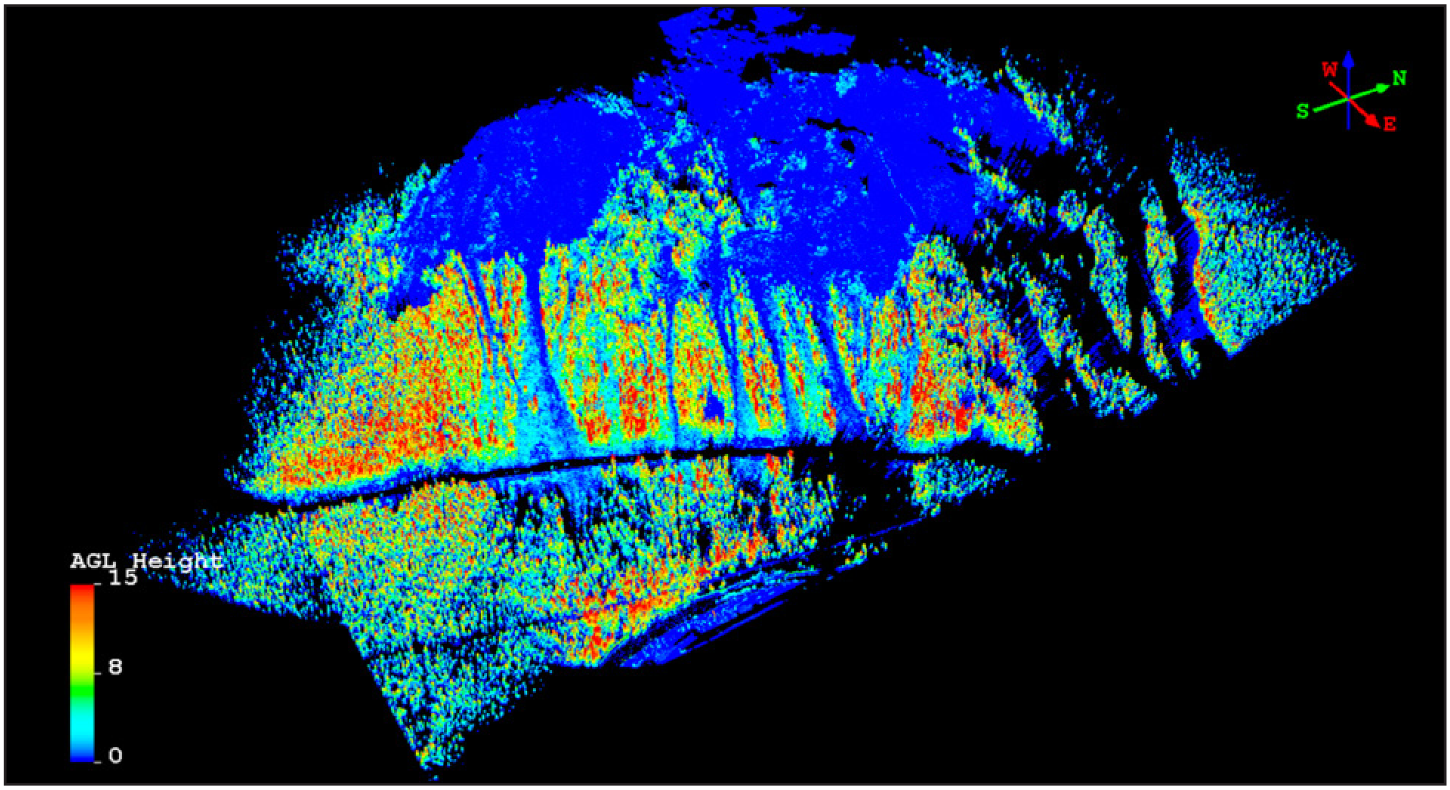

Figure A1: Image from snow-free scan of 7 Sisters paths, 2015. Points are colored by height above ground surface.

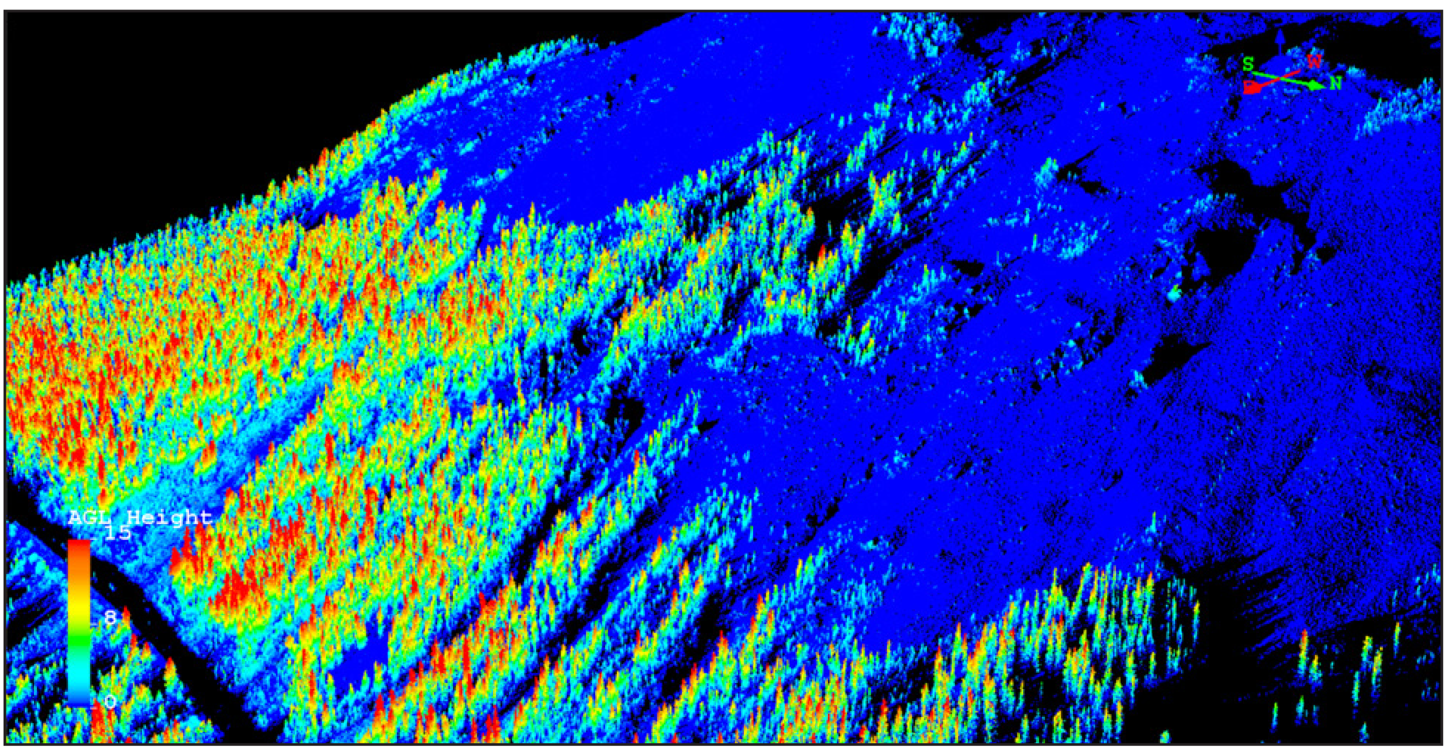

Figure A2: Oblique view of 7 Sisters snow-free scan. Point colors as in Figure A1.

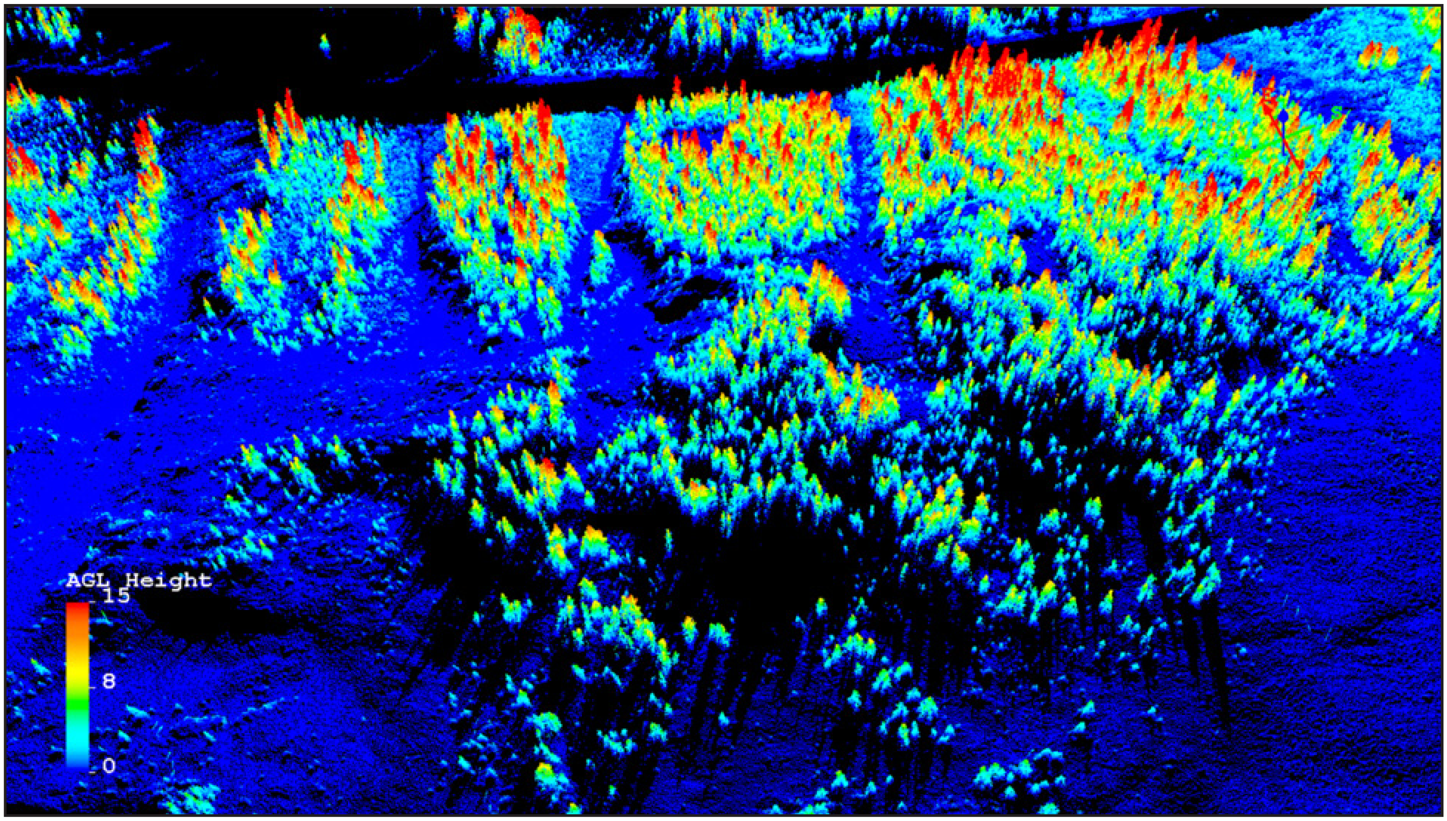

Figure A3: View of snow-free scan looking down 7 Sisters 1-4. Point colors as in Figure A1.

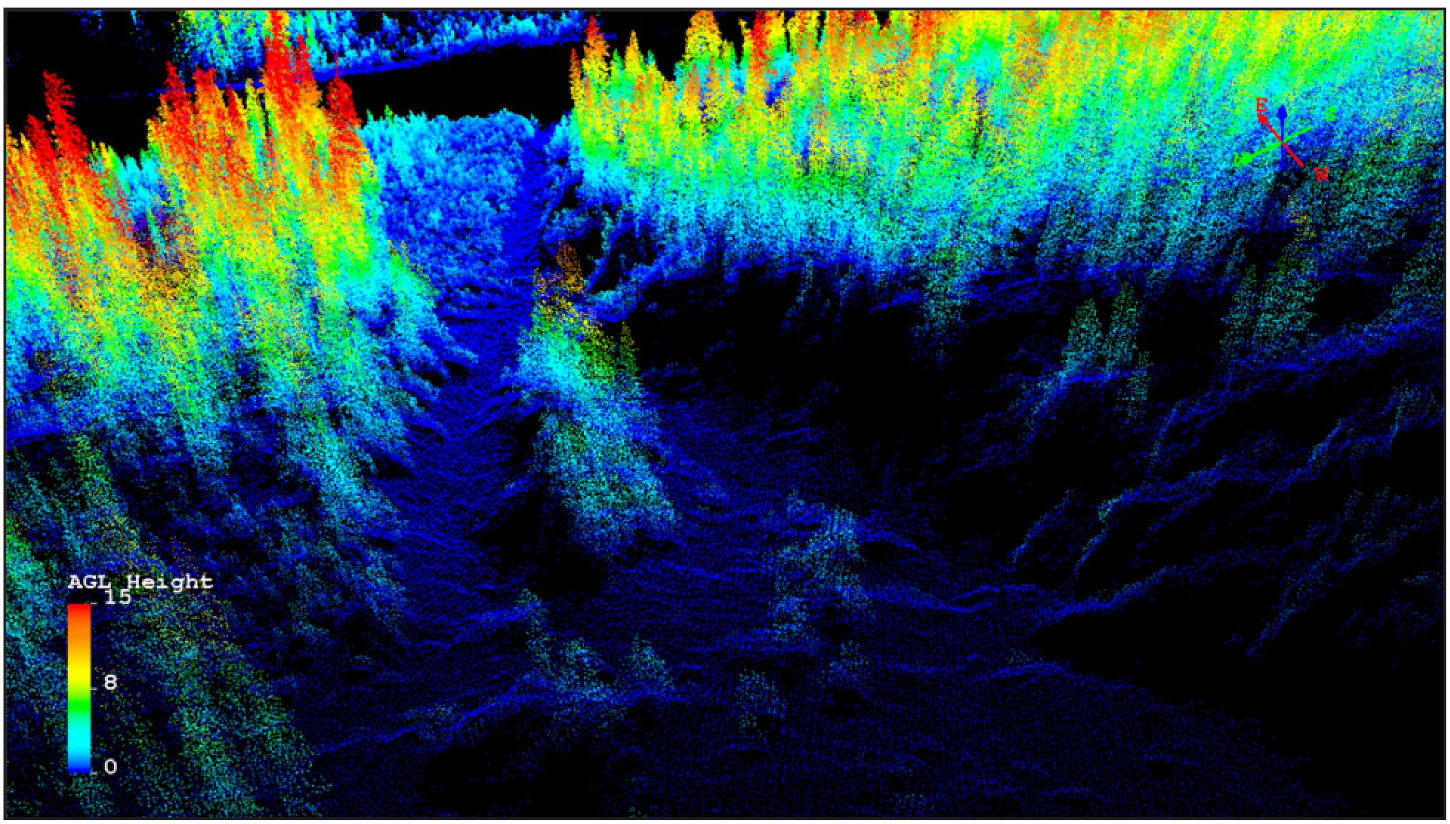

Figure A4: View of snow-free scan looking downhill within Sister #3. Point colors as in Figure A1.

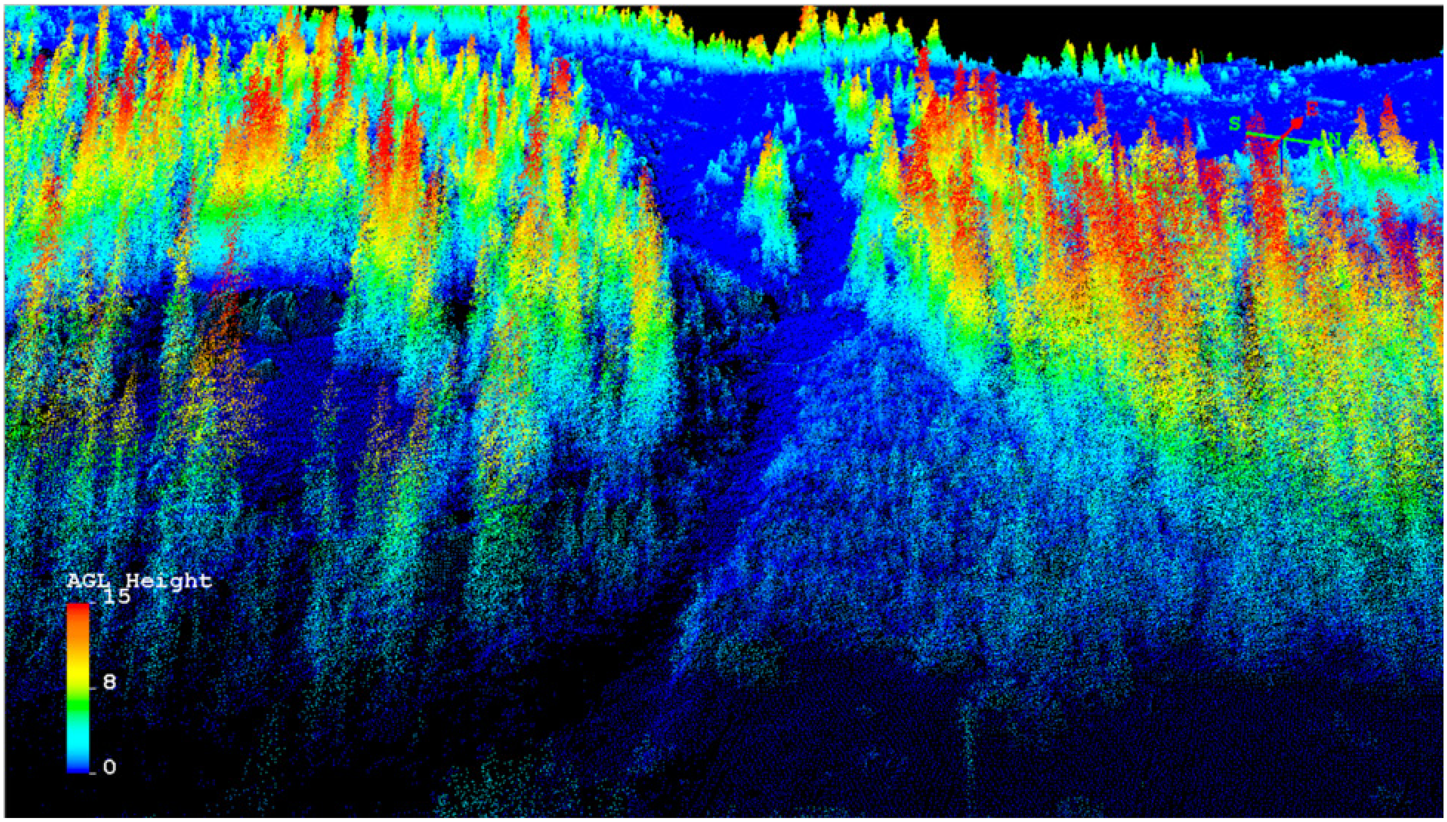

Figure A5: View of snow-free scan looking up Sister #3. Point colors as in Figure A1.

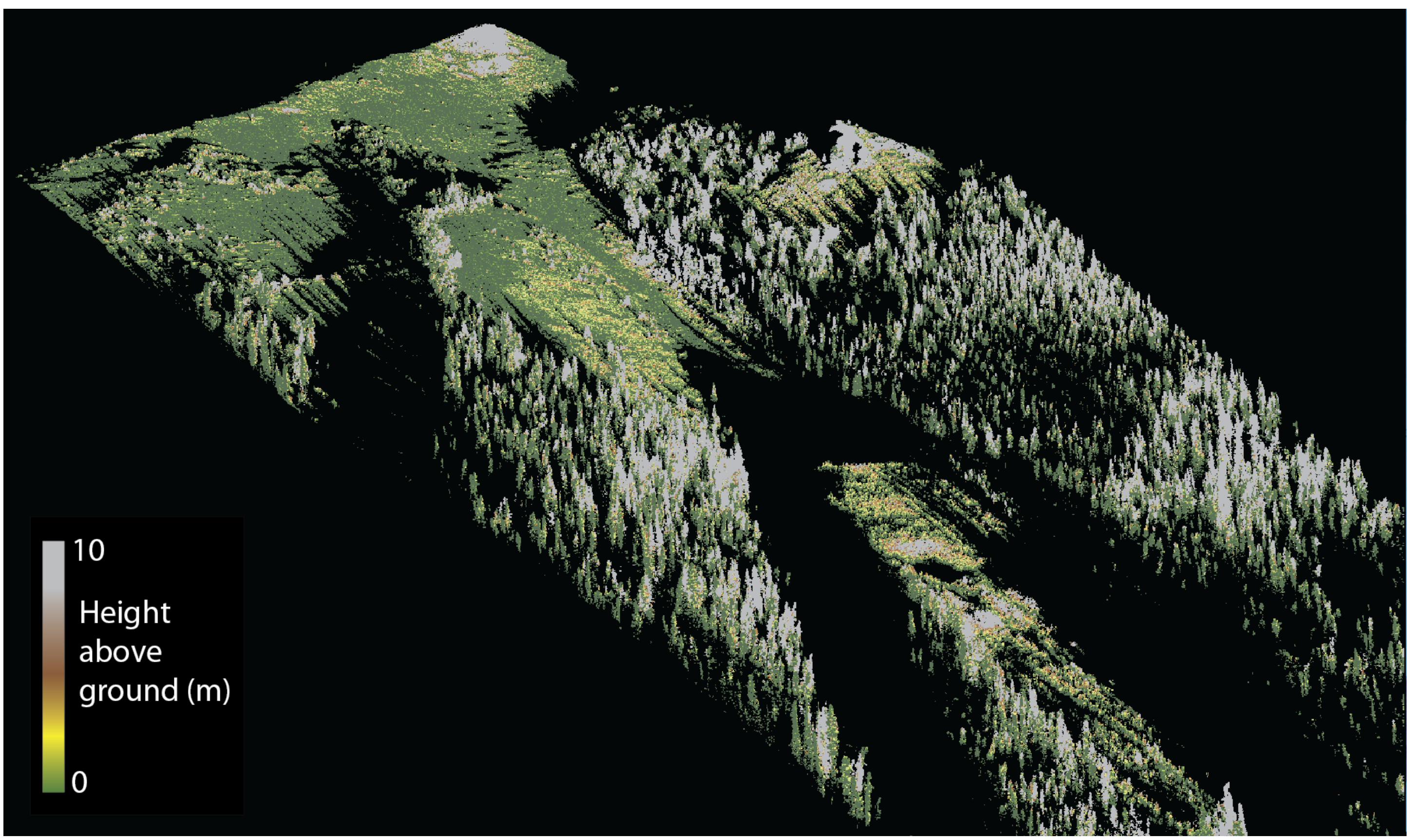

Figure A6: Image from snow-free scan of Stanley path, summer 2015. Points in image are colored by height above ground.

Appendix B

Scan Data Processing Methodology

Source data

Raw scanner data were georeferenced using Riegl's proprietary RiSCAN Pro and exported in Laszip format (.laz; compressed LAS). Frequently a large amount of in-air noise (usually due to blowing snow) exists, and every scan contains high-numbers of points near that scanner that add data volume without being relevant to the terrain of interest (Figure B1).

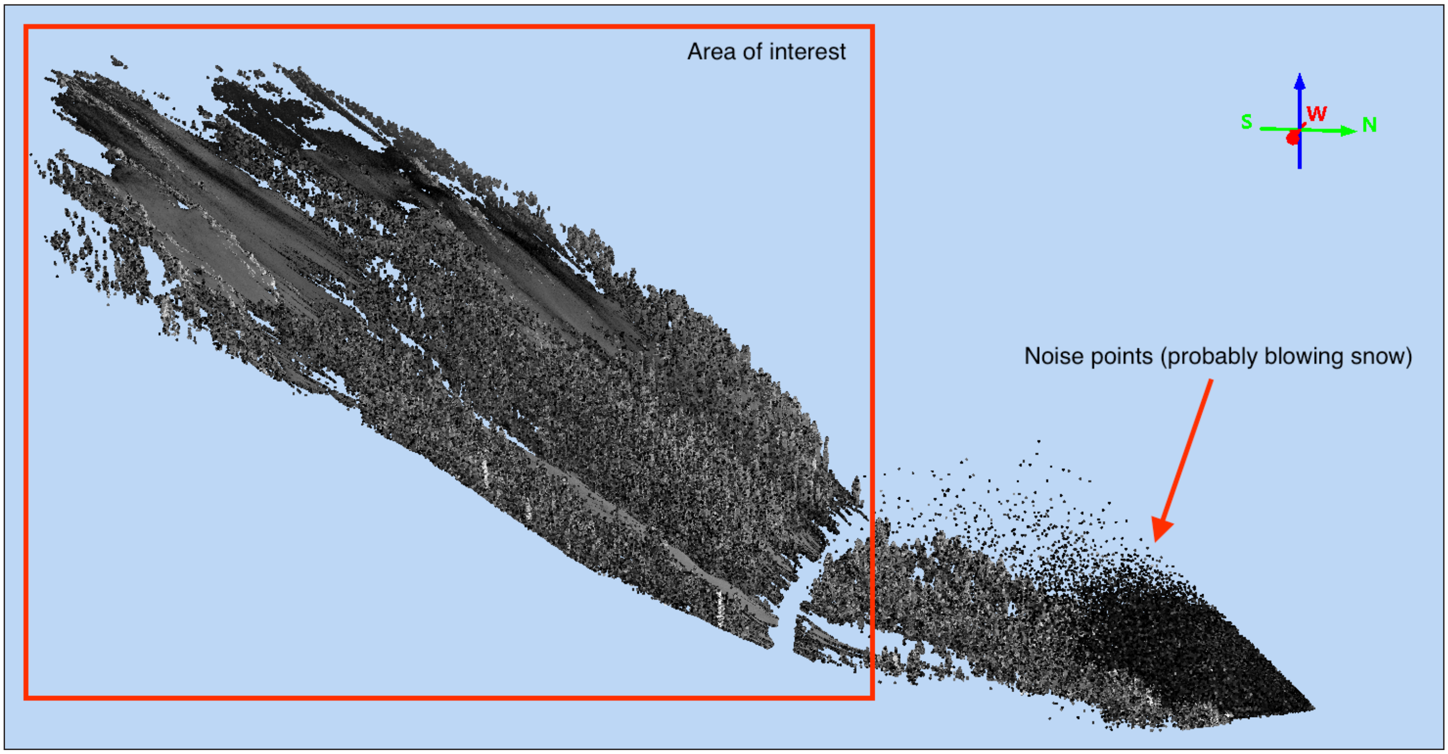

Figure B1: Annotated scan from 2017-04-28 of the Seven Sisters. View is oblique, looking across the avalanche paths.

Additionally, all trees in the scan were removed, as only the bare earth surface and bare snow surface are needed for HS measurements.

Generating reference surfaces

The first step is to post-process the point clouds, as delivered from Riegl, completing the following steps via a PDAL (Butler, et al., 2018) pipeline:

1. Read in the LAZ data and label it as UTM 13N / NAD83(2011) Epoch 2010.00, NAVD88 vertical orthometric datum.
2. Crop the data to a pre-defined area of interest.
3. Use the outlier filter to add the classification value "7" (Low point/Noise) to all noise points.
4. Classify all points using the *smrf* (Pingel, Clarke, & McBride, 2013) filter, ignoring noise points.
5. Write out the data to a LAZ file.

Full resolution, classified point clouds might look like Figure B2.

Using the full resolution, classified points, bare-earth (or bare-snow) surfaces are created for each scan. The bare-earth surface from the snow-off scan is the reference surface for all snow depth (HS) calculations, and bare-snow surfaces from snow-on scans are used for snow depth change (dHS) calculations.

To create the bare-earth/bare-snow surfaces, another PDAL pipeline is used to read in the LAZ files and build a 0.5m elevation raster from all points classified as '2' (ground; Figure B3).

Calculating snow depths

Once the reference surfaces are built, the vertical distance (depth of snow in the vertical) between a

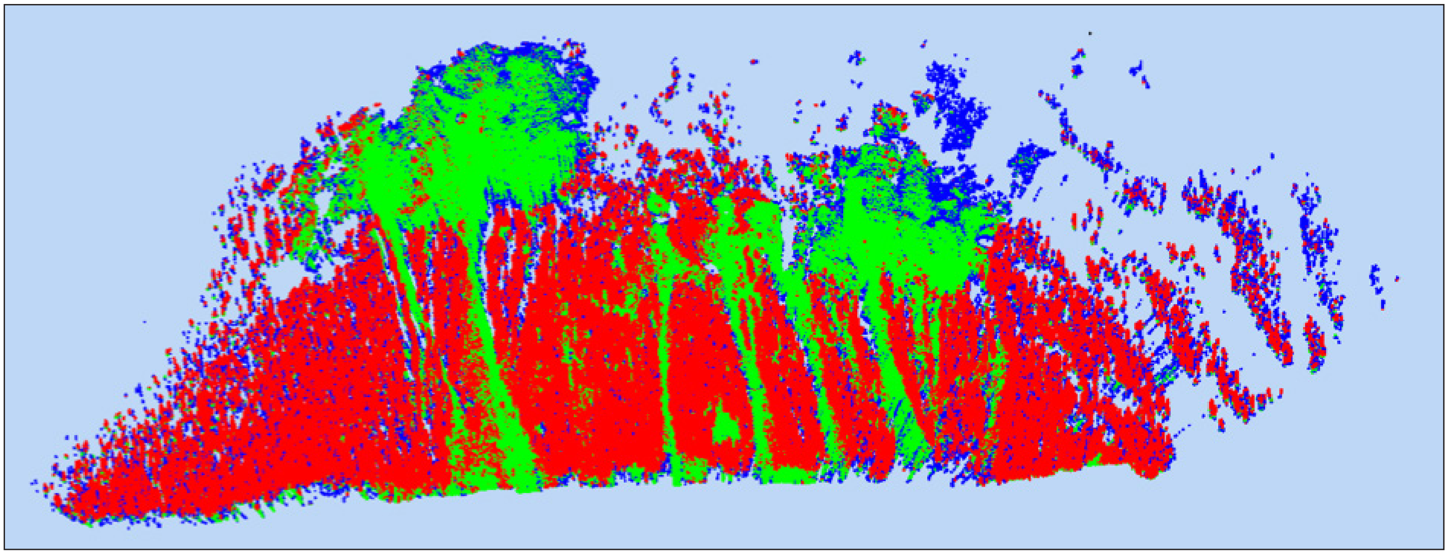

Figure B2: Filtered and classified point cloud, colorized by classification (green: ground/snow, blue: noise, red: non-ground/snow).

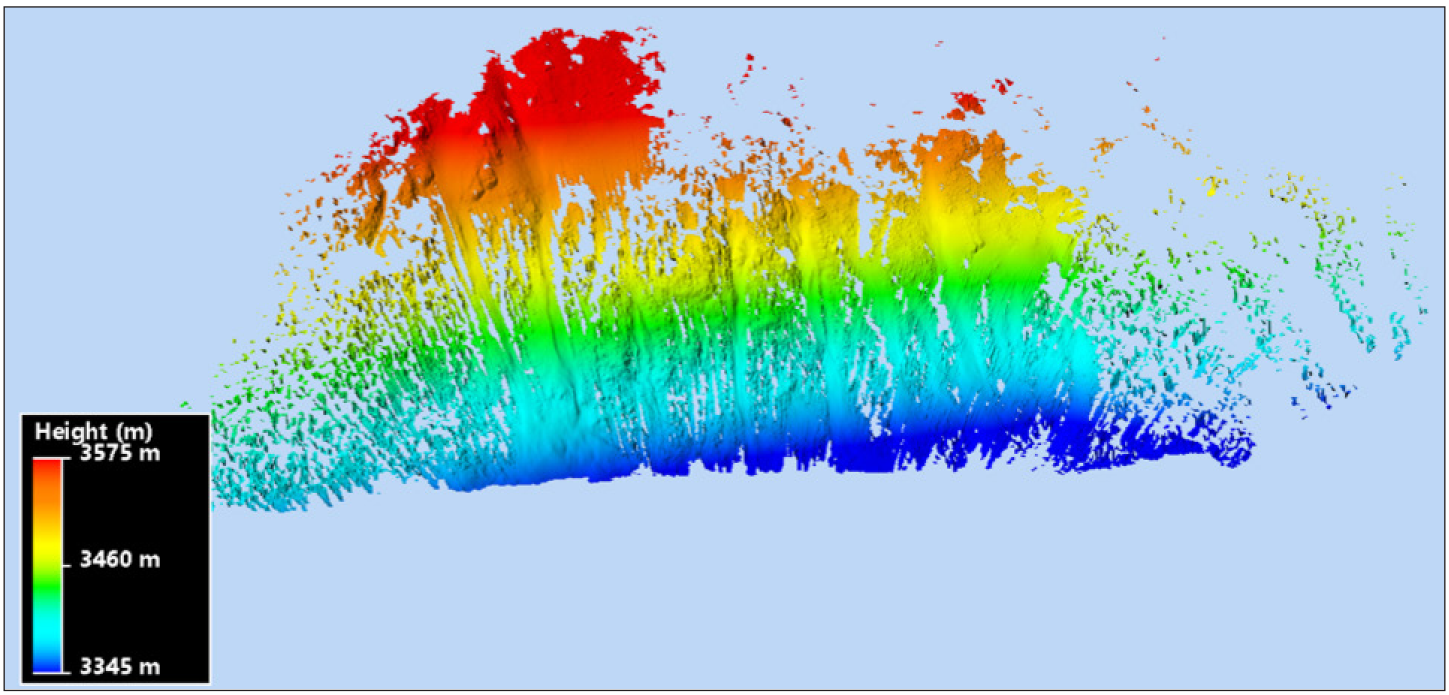

Figure B3: Example gridded bare-earth surface elevations.

snow-on point cloud and the bare-earth raster can be calculated. In lieu of a native PDAL perfectly suited for the job, a custom solution was built, implementing the following steps:

1. Read in LAZ data.
2. Select ground/snow points (class '2' as identified by filters.smrf).
3. Assign the GpsTime field into the Red field on each point. The LAS format uses a two-byte unsigned integer to store color values – this step casts the Red field as a double for the next step.
4. Insert elevations from the bare-earth raster into the Red field using the colorization filter.
5. Filter out all points where the bare-earth elevation is less than zero, including all points that don't have a bare-earth elevation (the colorization filter assigns a low negative value for all points where it doesn't have a raster cell).
6. Run a Python script which calculates the difference between the Red field and the point's Z value and assigns the result (HS) to the GpsTime field.
7. Remove all points with a negative HS.

8. Assign a color scheme to each point, based on the HS (stored in GpsTime).
9. Writes the data out to a LAZ file.

The HS calculation python script in step 6 simply calculates the difference between the Red field (bare earth elevation) and "Z" (snow surface elevation) and stores it in GpsTime. After everything is done, the product is a point cloud, colorized by HS, with the actual HS value stored in the GpsTime field. The GpsTime field is used because support for custom attributes in LAS/LAZ files is unreliable. PDAL can write extra dimensions, but not all visualization/processing software can handle them. For this dataset, the GpsTime field is superfluous, and its double data type in the LAS format is a convenient place to store arbitrary double data.

The example in Figure B4 shows that the ground/snow classification isn't always perfect, with many tree "stumps" were left behind (i.e. some tree points classified as ground), leading to the red (high) HS values in the image. Nevertheless, the snow distribution in the avalanche paths is well-captured.

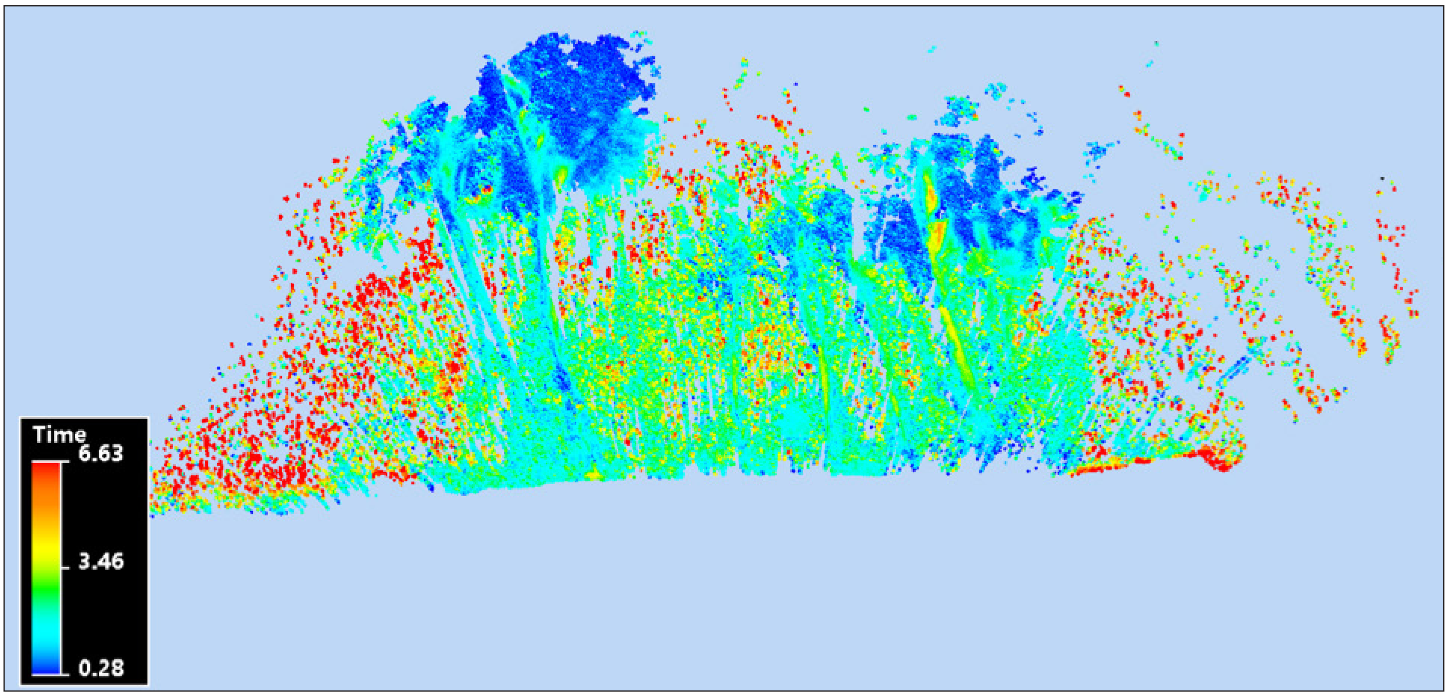

Figure B4: Example point cloud colored by HS values (stored in the GpsTime field in the LAS file, hence the "Time" label on the color legend).

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