SUPPORTING, EVALUATING, AND PLANNING AVALANCHE CONTROL EFFORTS WITH LIDAR-DERIVED SNOW DEPTH MAPS

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ABSTRACT: Recent studies have demonstrated the applicability and potential for ground-based lidar mapping to support avalanche control operations. High-resolution maps of snow depth and snow depth change derived from repeat lidar surface elevation surveys reveal detailed patterns of accumulation, scour, and loading due to the complex precipitation and redistribution processes in mountain environments. The ability to map starting zone depth patterns from a safe distance provides a unique capability to assess loading patterns, plan mitigation strategies, and evaluate the effectiveness of control efforts.

We present results from two ongoing pilot projects in collaboration with Arapahoe Basin Ski Area and the Colorado Department of Transportation. Applications of the lidar-derived snow depth data products include targeting of explosive rounds, planning of explosives delivery tramway locations, and evaluation of results from Gazex application.

KEYWORDS: Lidar, Spatial Variability, Avalanche Control, Infrastructure Planning

1. INTRODUCTION

The spatial distribution of snow depth in avalanche starting zones exerts a strong influence on avalanche formation and character (Schweizer et al., 2003; 2008). Extreme depth changes over short distances are common, especially in wind-affected, above-treeline environments. Snow depth affects snow density, hardness, and weak layer failure, and therefore the ease of avalanche triggering. Slab thickness and depth to weak layer affects the transmission of a triggering force (e.g. skier or explosives) to a buried weak layer – indeed avalanche control efforts at ski areas are often more successful when shallow trigger point areas next to deeper slabs can be targeted with explosives or ski cutting (Birkeland et al., 1995; Guy and Birkeland, 2013).

Knowledge of the spatial distribution of snow depth, and of differential loading due to precipitation or wind events, is valuable information to the backcountry traveler or practitioner. Snow depth is typically measured manually by insertion of a ruled probe into the snowpack, or at in-situ stations via a sonic ranging instrument. Neither technique allows safe, repeat, non-destructive, spatially-extensive sampling in avalanche starting zones.

In recent years Terrestrial Laser Scanner (TLS) systems have been used for mapping of snow depth and snow depth change (e.g. Prokop et al., 2008; Grunewald et al., 2010; Egli et al., 2012; Deems et al., 2013; Deems et al., 2015). In addition to the spatially-distributed, high resolution measurements, a sizable advantage of TLS over other methods is the ability to sample without exposing observers to avalanche hazard, and without disturbing the snow cover. Recent technological advances allow rapid data collection in multiple starting zones.

1.1 *TLS Measurement of Snow Depth and Avalanche Mapping*

A TLS is an active remote sensing technology that uses laser pulses to measure range to target. By integrating scanner position data (i.e. from GPS or registration with existing survey data) the target ranges are converted into an x,y,z ‘point cloud’ of map coordinates and elevations.

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Subtraction of snow-free from snow-covered elevations provides a high-resolution (cm scale) map of snow depth, a data product which holds great potential for monitoring snow accumulation patterns and operational assessment and planning of avalanche control efforts (Deems et al., 2013).

Recent applications have demonstrated the suitability and applicability of long-range TLS snow depth mapping for avalanche mapping and support of avalanche control efforts (Deems et al., 2015). Prokop (2008) conducted a thorough assessment of the suitability of TLS measurements for snow depth mapping, specifically in avalanche terrain. In subsequent studies, Prokop and colleagues evaluated new scanner capabilities (Prokop, 2009), investigated TLS methods for locating avalanche protection measures (Prokop and Delaney, 2012), integrated TLS measurements with avalanche dynamics models (Prokop et al., 2013a), and evaluated wind-drift modeling with TLS-derived snow maps (Prokop et al., 2013b), clearly demonstrating the applicability of TLS snow depth measurements and its wide range of potential applications. Grunewald and others (2010) and Egli and others (2012) conducted repeat TLS surveys during the melt season to evaluate spatial and temporal change in depth distributions. Maggioni et al. (2013) used combinations of TLS and airborne laser scanning to map snow depth pre- and post-avalanche control in their avalanche dynamics test site. These and other studies have clearly demonstrated that the high precision, high resolution elevation and snow depth data provided by TLS surveys enables a wide array of snow process and engineering studies.

Deems et al. (2105) demonstrated techniques and applications for long-range TLS surveys for support of operational avalanche control operations in a ski area environment. The ability of newer TLS sensor technologies to map wide areas quickly enables high resolution snow depth and change mapping without exposure of personnel or equipment to avalanche danger.

Following on prior work, this study details TLS avalanche mapping efforts specifically targeted at supporting design and planning of avalanche control infrastructure, and at assessing siting, use, and effectiveness of recently installed Gazex exploders.

1.2 TLS Applications for Avalanche Control Planning and Assessment

A multi-year collaboration with the Arapahoe Basin Ski Area (A-Basin) has produced TLS-derived snow depth and snow depth change maps for a range of snow conditions and storm events over several avalanche management areas. These data, presented in Deems et al. (2015), demonstrate the applicability of long-range TLS snow mapping on spatial resolutions and time scales commensurate with operational needs. Further, the snow distribution and avalanche dimension data provide promising avenues for process investigations and dynamics model studies.

A-Basin is in the final planning stages for an expansion of operating terrain, with the proposed expansion including the Steep Gullies area – a commonly-skied backcountry area with complex tree and gully areas and a multitude of potential loading areas and starting zones (Figures 1 and 2). The planned management of the avalanche hazard in this terrain involves a combination of hand- and tramway-delivered explosives, as avalauncher use in the area is considered difficult due to shooting angles, proximity to existing infrastructure, and access challenges. Conventional avalanche control planning relies on expert knowledge and experience with the terrain in question to determine locations of control routes and in situ infrastructure. While manual hand charge routes can be easily adjusted with accumulated experience with the terrain and snow conditions, in situ infrastructure is more expensive and misplacement can result in unnecessary costs and suboptimal avalanche hazard reduction. Repeat snow depth and accumulation maps provided by TLS surveys offer a potential pathway for avalanche control infrastructure planning through more precise targeting of quantified snow distributions.

The Colorado Department of Transportation, in collaboration with the Colorado Avalanche Information Center, manages the avalanche hazard affecting US Highway 6 over Loveland Pass, CO (Figures 1 and 3). A primary challenge in this corridor is the grouping of paths known as the 7 Sisters, which threaten the highway and have starting zones that tend to receive frequent wind loading. Until 2014 these paths were controlled primarily using a truck-mounted avalauncher, however in 2015 operational constraints and an avalauncher accident motivated the installation of a system of 11 Gazex exploders in the 7 Sisters start zones. While Gazex systems have seen successful application in other regions, including Colorado, the switch of control methodology demands an assessment of the effectiveness of the new Gazex system, addressing operational application as well as questions regarding the physical hazard reduction and extent of control results. The suitability of

TLS snow depth measurements to track snow pattern evolution over time, as well as pre- and post-control, made this technology attractive for a study characterizing the Gazex application over the first couple years of operation.

This paper describes these two applications of TLS snow mapping, for planning of avalanche control infrastructure and evaluation of its effectiveness. We see wide potential for incorporation of quantitative snow mapping for avalanche control operations and planning, and these two case studies serve as interesting examples in the highway and ski area sectors.

2. SITES

Arapahoe Basin exists in a high altitude, dry snow, continental environment, with extreme snow depth variability, extensive wind redistribution, and both storm snow and persistent weak layer driven avalanche problems. We began characterizing snow depth distributions in the Steep Gullies in 2013, as described in Deems et al., (2015). The Steep Gullies site is to the west of and adjacent to the current A-Basin ski area boundary (Figures 1,2). The four primary avalanche paths run approximately 500 m vertically from a treeline environment into forested gullies. The starting zone topography is very complex, with a myriad of pockets and hollows representing both connected and disconnected snow loading locations.

The 7 Sisters avalanche paths affect US Highway 6, adjacent to the Loveland Basin Ski Area and the Eisenhower/Johnson tunnels on US Interstate 70 in central Colorado (Figures 1, 3). The site is a very similar climate to the Arapahoe Basin site, being located approximately 5 km to the north, on the opposite side of Loveland Pass. The seven paths run 300 – 400 m vertically from an open, above-treeline environment down into subalpine forest and across the highway. Until 2015 avalanche control in the 7 Sisters was conducted using explosives charges delivered via a truck-mounted avalauncher. Safety and operational considerations led to installation of 11 Gazex exploders covering release zones in the seven paths affecting the highway. The starting zone geometry in Sisters 3 and 4 is relatively confined, while the other starting zones tend to be more open, unconfined, and have the potential for multiple snow loading configurations and thus a wider variety of avalanche concerns.

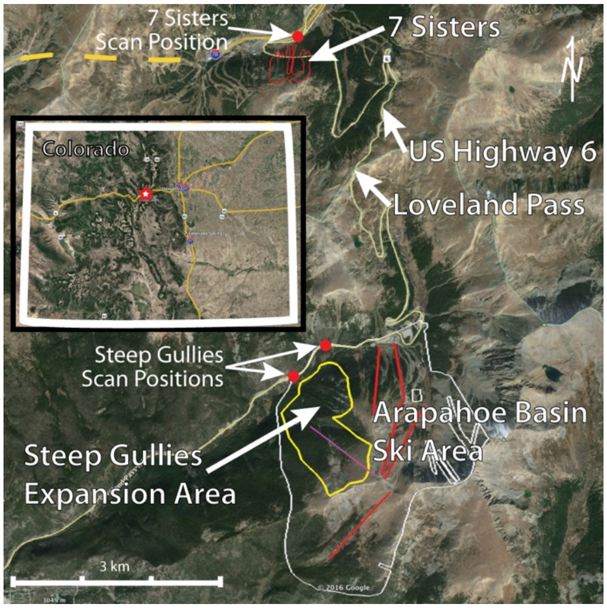

Figure 1: Location map of Arapahoe Basin Ski Area with Steep Gullies expansion area, and Loveland Pass on US Highway 6, with the 7 Sisters avalanche paths.

3. METHODS

3.1 TLS Data Collection

The TLS system was deployed on a survey tripod erected on the US 6 highway shoulder (Steep Gullies) or in the CDOT work yard (7 Sisters), cleared of snow accumulation. We used two scan positions for the Steep Gullies area in order to provide multiple look angles on terrain features to minimize shadowing. For the 7 Sisters we used 3 scan positions for the snow-free scan, to reduce shadowing. A single san position was sufficient for the subsequent snow-on scans in the 7 Sisters, as the work yard location provides good visibility.

Scan parameters were chosen to maximize resolution (maximize points/m^2) over the target area, while minimizing collection time and post-processing steps. Each Steep Gullies scan required approximately 10-15 minutes, while the 7 Sisters scans required about 25 minutes – the scan duration being primarily driven by the amount of terrain mapped.

Raw snow-on data was registered to the snow-off data set, first with a coarse-registration using GPS locations, and then finalized using the multi-station adjustment (MSA) tool in Riegl's RiSCAN Pro software (Riegl, 2016). We chose to use the TLS internal GPS unit instead of an external system to save data collection time, the GPS positions for each scan were accurate enough to give satisfactory coarse registration fits, and the subsequent MSA step, which involves calculating a 3D coordinate adjustment to minimize the distance between a set of identical features in multiple scans, provided the final, fine registration using bare rock features.

The registered point clouds were interpolated to a 0.25m grid, a resolution which minimized feature smoothing while remaining less sensitive to artifacts than a resolution closer to the nominal point spacing of 0.1m. The height above reference surface (snow-off grid, or prior snow surface grid) for each point was calculated for each point cloud data set. We colored the point clouds by snow depth/height of snow (HS) or snow depth change (dHS). Point cloud visualization was conducted in QT Modeler or QT Reader software (Applied Imagery, 2016), and tramline and tower location features for the Steep Gullies were integrated using Google Earth.

3.2 *A-Basin Steep Gullies Tramway siting and adjustment*

Field studies have identified logical access and hand charge delivery locations as well as logical pathways for integration with existing bomb routes. Additionally, a set of candidate tramway tower and wire locations were developed from site visits. To evaluate the candidate tramway locations, tower sites and wire footprints were overlaid on a set of TLS snow depth and slab thickness maps, and access to potential targets assessed. Wire and tower locations were adjusted to optimize the number of targets accessible from individual tram lines and to enable multiple shot placements within single starting zones to allow adaptation to different wind directions and loading patterns.

3.3 *Loveland Pass/7 Sisters Gazex Assessment*

To evaluate Gazex operations, we attempted to target specific storm events and collect 3 scans: pre-storm, post-storm/pre-control, and post-control. These 3 data sets would then allow assessment of pre-control snow depth and storm snow accumulation, as well quantification of control results. Further, in aggregate, the time series of snow depth can provide a unique perspective on the evolution of specific snow drift or loading features throughout the season or in response to specific storm characteristics.

4. RESULTS AND DISCUSSION

4.1 *Arapahoe Basin/Steep Gullies*

Over the past 3 snow seasons we conducted TLS surveys of the Steep Gullies on seven different dates. While some notable variation in drift depth and occurrence is observed among scans, the 13 January, 2016 scan appears to exhibit snow accumulation features common to the other scans, and therefore was used for infrastructure planning purposes (Figure 2). The uppermost portion of Gullies 1 and 2 tends to be scoured of snow, and therefore commonly exhibits low snow depths except in small pockets. These areas are easily reached with hand charges from existing control routes. The upper parts of Gully 4 are also easily controlled via hand charges from safe locations in the trees above the slope. The lower parts of all of the Gullies, and all of Gully 3, require explosives placement via tramways.

The initial tramway layout was based on site visits and experience with skiing the Gullies as backcountry terrain. There are several obvious snow accumulation pockets that the initial layout was designed to capture (Figure 2 – red lines).

Upon comparison of this layout with the TLS data, it was apparent that there were a number of other accumulation features that could also be targeted if the tramline locations were adjusted (Figure 2 – yellow lines), as well as improving workflow efficiency and safety for personnel on control routes.

Considering the intricacies of an expansion effort, the TLS data allowed the ski area to reduce the impact of infrastructure being built in complex terrain, increase the reliability of avalanche mitigation techniques, as well as the reliability and efficacy of shot placement with respect to distance along the tram and height of air blasts. Further, efficient and reliable tramway placement will enhance safety and flexibility by decreasing the exposure of patrollers when controlling complex avalanche terrain and reducing exposure to avalaunchers and blast shields, and by allowing the snow safety team to consider the multiple ways to manage terrain based on closures, gate access and materials infrastructure.

4.2 *Loveland Pass/7 Sisters*

Ten snow-on scans were conducted in winter/spring 2016. Three storms were captured with pre-storm, post-storm/pre-control, and post-control scans (21-31 January, 11-15 March, and 14-17 April). The January storm was typical of

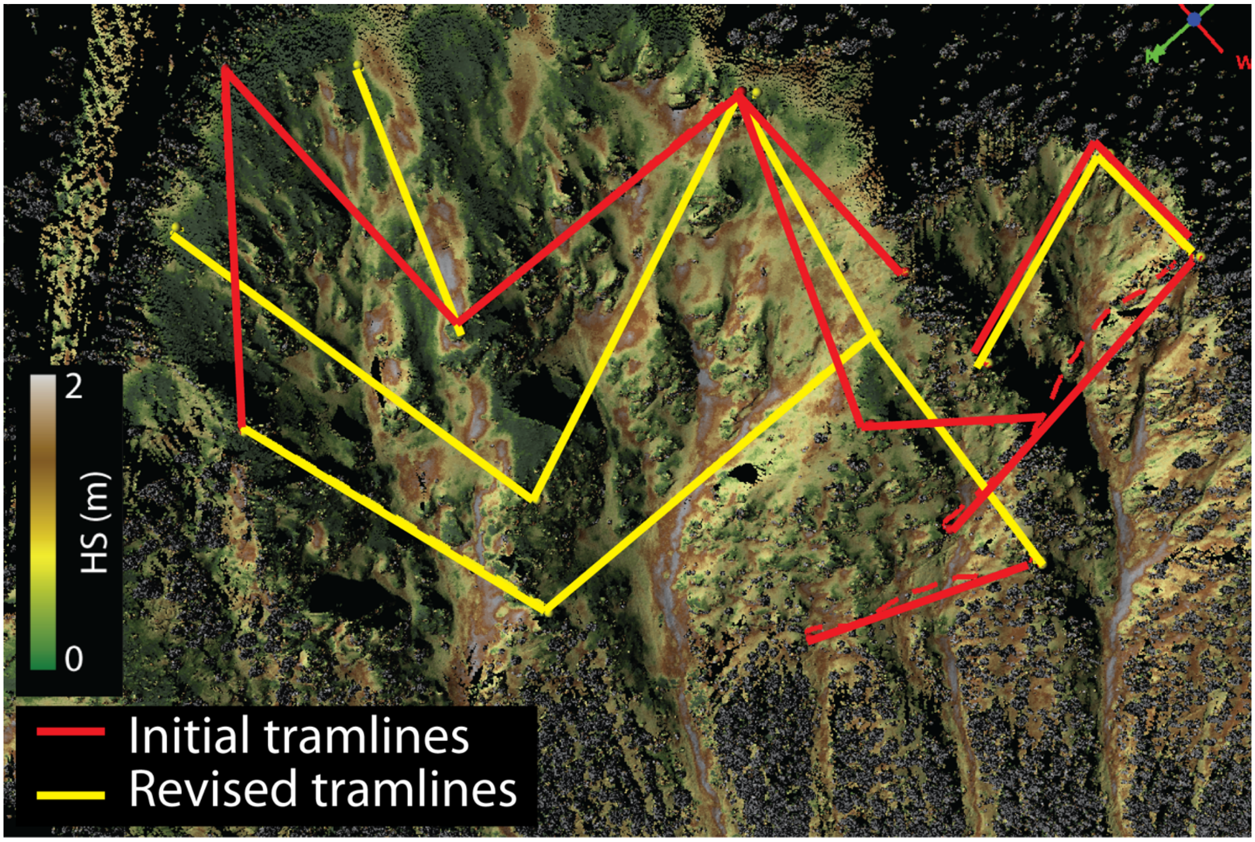

Figure 2: Steep Gullies TLS-derived snow depth, initial candidate tramline locations (red lines), and revised tramline layout (yellow lines).

the location, with winds predominantly from the WSW, cross-loading the starting zones from the west to east. The April storm was an 'upslope' storm, with winds from the ENE, cross-loading the start zones from east to west. The upslope drift patterns are evident in the changes in the snow drift morphology low in the start zone of the 1st Sister (Figure 4 c & d).

The lower Gazex exploder in 1st Sister ceased functioning early in the snow season, due to a mechanical issue. As a result, the drift lower in the 1st Sister start zone remained untouched throughout the season, and progressively buried the exploder (Figure 4 a-d). An initial assessment of the exploder location suggests that it was sited in a suitable location to affect that snowdrift, and winter 2016/17 will offer an opportunity to contrast the drift development with a working exploder.

In Sister 6, a drift pocket develops directly downslope of the lower exploder location (#6 Low), and it remains unaffected by firing in both the January and April control cycles (Figure 5 a-d). One concern of Gazex operation is overuse, whereby firing under marginal or stable snow stability conditions leads to no snow movement but instead work-hardens the snow under the blaster. This work-hardened patch then would have the potential to preclude further triggering, or to serve as an anchor to surrounding, less-stable snow structures. While not a conclusive result, the location and persistence of the drift detected below #6 Low is consistent with the work-hardening concept, and represents an opportunity to examine its evolution in 2016/17 with a reduced firing schedule.

Sisters 3 and 4 are confined, concave start zones, and appear to respond well to Gazex firing, with good results in all control events that we captured (Figure 6). This is important operationally, as these paths hit the road most frequently of all the 7 Sisters. There is also less uncertainty with these paths, as the start zones tend to load in a fairly consistent pattern regardless of wind direction and therefore the variation in release area and location is minimal. Gazex would be expected to work well in paths of this type, and the TLS survey results to date support this expectation.

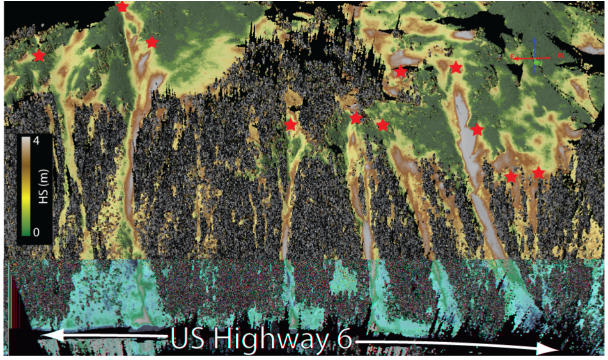

Figure 3: The 7 Sisters avalanche paths, Loveland Pass, colored by TLS-derived snow depth. Gazex locations marked with red stars.

5. CONCLUSIONS AND FUTURE WORK

Our timing was fortuitous with the A-Basin tramline layout application. We had the TLS project ongoing with A-Basin while the Steep Gullies control plan was in development, and the iterative tramway design process – initial design layout followed by assessment with the TLS data products and subsequent design refinement – has been a logical engineering and applied science progression of design followed by testing and redesign. As such, the TLS data have enabled us to test, using spatial snow depth data, a conventional approach to starting zone identification and targeting. While the initial tramway layout was effective at targeting several specific accumulation areas, several other accumulation areas that are less obvious were not well-captured. Reorientation of the tram lines allow multiple targets per wire, versus single targets with the initial design. Additionally, the TLS snow depth maps enable more efficient route planning with the multiple objectives of effective start zone targeting and efficient route progression, likely reducing time spent on control routes.

In future seasons at A-Basin we plan to continue TLS data collection, seeking to broaden the range of accumulation and avalanche conditions in our scan library, and to test the effectiveness of the new tramway layout once it is installed. The TLS snow depth maps not only allow confirmation of release area from positive explosives results, but can also evaluate accumulation features that are missed or are not triggered by explosives application, and can be subjected to further testing or evaluation.

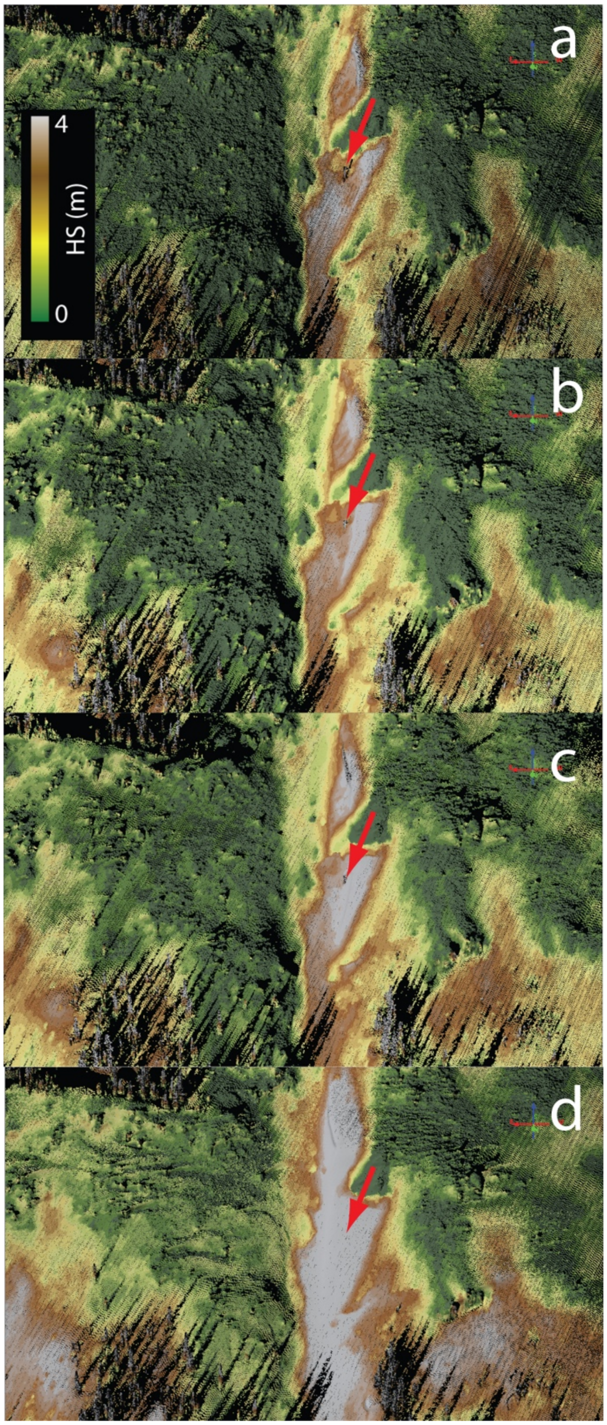

Figure 4: Snow drift evolution in Sister 1. Lower Gazex location marked with red arrow.

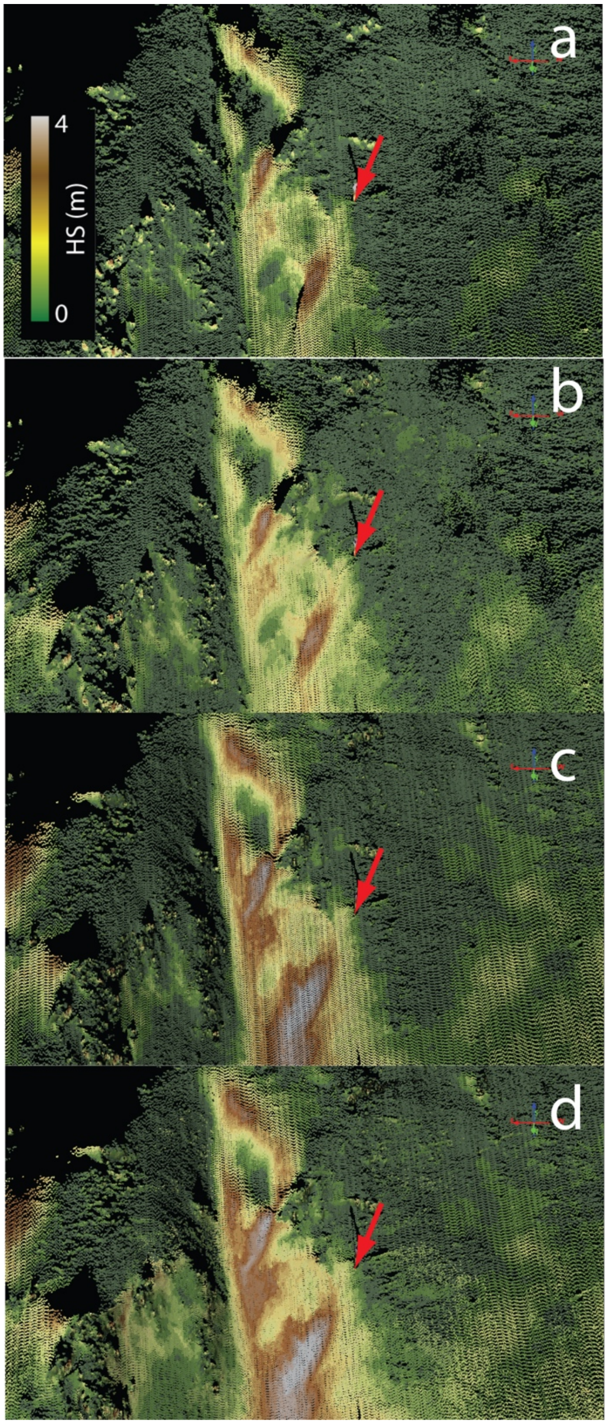

Figure 5: Snow drift evolution in Sister 6. Lower Gazex location marked with red arrow.

We captured a range of storm conditions at the 7 Sisters site, but missed several others due to logistical constraints or conflicts. While the storm cycles we did capture represent a range of different storm types and accumulation patterns, experience with this terrain shows that there are a number of accumulation patterns that could still be surveyed, and for which there are still questions as to how effective the Gazex array will be in reducing the avalanche hazard. We plan further data collection efforts in 2016/17 with the aim capturing different conditions.

The lower exploder in Sister 1 will be operational this upcoming season, allowing us to test the response of the observed drift feature shown in Figure 4 and to evaluate the placement of the exploder. Discussions are ongoing regarding the frequency of firing each exploder. An adjustment in firing frequency could change the behavior of the drift feature in Sister 6 (Figure 5), which can be observed with a TLS time series. The potential also exists to integrate scans with Gazex operations in near real-time. Onsite processing of pre-control scans could indicate the amount of new load present, which could be used to support the decision of whether to fire individual exploders. This capacity would be a valuable integration, allowing firing decisions to be made based on quantified loading data, rather than only on observer experience or conventional practice. Near real-time post-control evaluation would also be valuable for assessment and verification of remaining hang-fire or hazard reduction. Installation of permanent mounts for the TLS system, that could be reoccupied with high positional accuracy, would greatly reduce post-processing time to produce snow depth data products. Permanent mounts or even a permanently installed TLS monitoring system with automated processing could provide data sources for avalanche detection and control result verification. Such systems are seeing development and application for research purposes and could be deployed for avalanche path monitoring in a test environment.

The initial results from the A-Basin/Steep Gullies and the CDOT/7 Sisters TLS applications are promising and have led to important insights. Further application and evaluation on these projects is ongoing.

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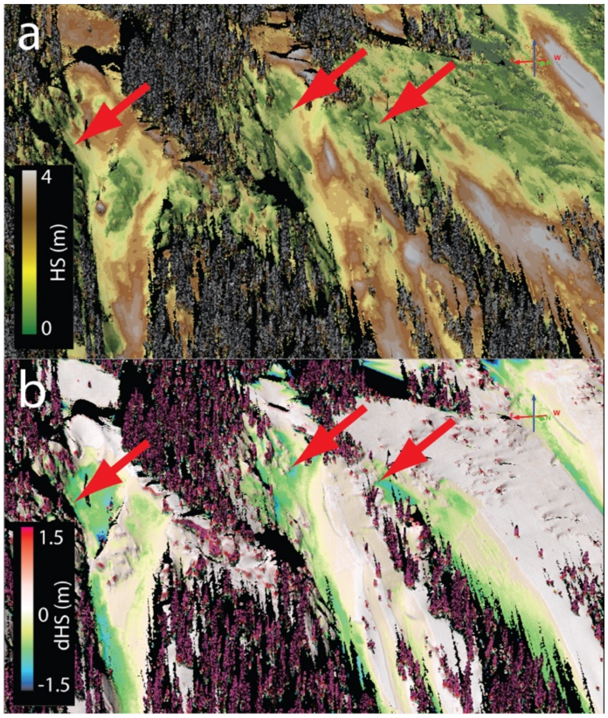

Figure 6: Start zones for Sisters 4, 3, and 2 Low (left to right). Gazex exploders marked with red arrows. Pre-control snow depth is shown in panel (a), and panel (b) shows post-control change in snow depth.

CONFLICT OF INTEREST

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