MAPPING STARTING ZONE SNOW DEPTH WITH A GROUND-BASED LIDAR TO IMPROVE AVALANCHE CONTROL AND FORECASTING

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ABSTRACT: The distribution of snow depth in avalanche starting zones exerts a strong influence on avalanche potential and character. Extreme depth changes over short distances are common, especially in wind-affected, above-treeline environments. Snow depth also affects the ease of avalanche triggering. Experience shows that avalanche reduction efforts are often more successful when targeting shallow trigger point areas near deeper slabs with explosives or ski cutting. Our paper explores the use of high-resolution (cm scale) snow depth and snow depth change maps from terrestrial laser scanning (TLS) data to quantify loading patterns for use in both pre-control planning and in post-control assessment.

We present results from a pilot study in three study areas at the Arapahoe Basin Ski Area in Colorado, USA. A-Basin has a large number avalanche starting zones above treeline at elevations up to 4,000 m. The areas represent a range of institutional avalanche management history – the East Wall has been operated since 1970, Montezuma Bowl since 2008, and the Steep Gullies are under study for area expansion. A summer TLS survey produced a zero depth surface. Mapping multiple times during the snow season allowed us to produce time series maps of snow depth and snow depth change at high resolution to explore depth and slab thickness variations due to wind redistribution. We conducted surveys before and after loading events and control work, allowing the exploration of loading patterns, slab thickness, shot and ski cut locations, bed surfaces, entrainment, and avalanche characteristics. We also evaluate the state of TLS for use in operational settings.

KEYWORDS: snow depth, spatial variability, laser remote sensing, avalanche control.

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 Scanners (TLS) 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). 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

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collection from multiple starting zones (~15-45 minutes).

1.1 TLS Measurement of Snow Depth

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.

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).

Until recently, however, TLS surveys have either been limited to very short ranges due to the wavelength and power of the TLS system, or have required long-duration nighttime data collection campaigns due to the slow speed of the scanner and limited detection capabilities at longer ranges. The new Riegl VZ-4000 and VZ-6000 laser mapping systems allow unprecedented range and resolution for mapping surface elevation of snow-free or snow-covered terrain. We have employed the Riegl VZ-4000 in snow-covered mountain environments and reliably retrieved ranges on the order of 3-5 km with 180° scan durations of 15-45 minutes (Fig. 1), with similar times and even longer ranges with the VZ-6000 (6-10 km). This technology is a potentially revolutionary development for remote measurement of snow depth and depth change at high resolutions across complex terrain.

1.2 Pilot Study, 2013-2014

The pilot study described here serves as a proof-of-concept for dataset production and for testing potential avenues for integration of the TLS products with ski area avalanche control operations. Survey scenarios were planned to test a range of operations support roles. Here we present highlights from the pilot study to demonstrate the capability of TLS mapping for research and operational interests.

2. METHODS

2.1 Field Sites

We collected data during the summer (snow-off) and fall/winter (snow-on) of 2013/14 at Arapahoe Basin Ski Area in Colorado, (Fig. 2; Tbl. 1). A-Basin is 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.

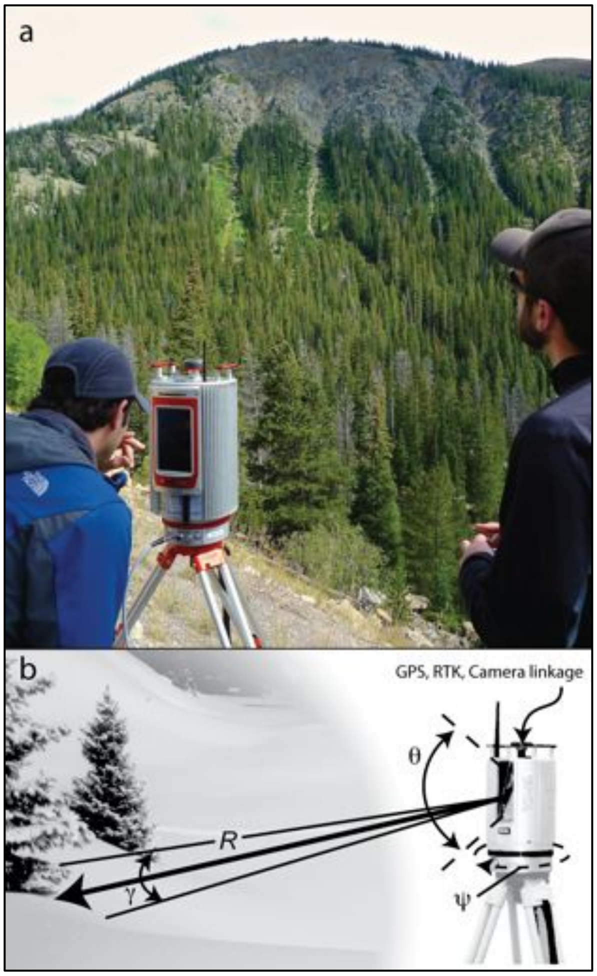

Fig1: (a) Riegl VZ-4000 at Steep Gullies Scan Site #1 during snow-free mapping; (b) schematic representation of scan parameters: range to target (*R*), beam divergence (*γ*), vertical angle range and resolution (*Θ*), and horizontal angle range and resolution (*Ψ*) (from Deems *et al*., 2013).

The survey areas at A-Basin were chosen for safe access to scan positions and to represent a range of avalanche control problems. The East Wall, Montezuma Bowl, and the Steep Gullies areas represent a range of institutional experience: the East Wall (EW; 1.15 km^2) has been actively controlled since 1970, Montezuma Bowl (Z; 0.32 km^2) was part of a 2008 expansion and was the site of a post-control accident in 2013 (Greene and Brown, 2013), and the Steep Gullies (SG; 0.5 km^2)

Fig. 2: Google Earth map view of the A-Basin Ski Area, Colorado, USA. TLS scan areas outlined, with scan positions marked.

are a commonly-skied backcountry area that is part of a planned expansion. In combination, these areas present a range of aspects and slope angles for observing different loading and control events and testing the ability of the TLS system to map snow depth in complex terrain.

2.2 TLS Scan Parameters

The TLS system is deployed on a survey tripod, situated either on bare ground, stomped into the snowpack, or on infrastructure such as a gun mount or lodge deck, depending on conditions. We used two scan positions for each of the East Wall and Steep Gullies areas in order to provide multiple look angles on terrain features to minimize shadowing. The Montezuma terrain was observable from a single scan position. The snow-off scan was conducted using the VZ-4000, which operates at a wavelength of 1550nm, where snow has relatively low reflectance (~10%) and rock/soil is much more reflective (~49%). We used the VZ-6000 for the initial 2 snow-on scans, which operates at a 1064nm wavelength where snow is more reflective and allows for longer-range mapping. However, the 1064nm wavelength is not inherently eye-safe, which limited our surveys to early morning hours prior to ski area opening. We used the VZ-4000 for subsequent surveys, which greatly relaxed the operational constraints while still providing ample range performance.

Scan parameters were chosen to maximize resolution (maximize points/m^2) over the target area, while minimizing collection time and post-processing steps (Tbl. 2). Of interest is the pulse repetition frequency (PRF). The TLS systems used are capable of PRF high enough to fire the next pulse before the prior pulse return has been detected, leading to range ambiguity and requiring manual assignment of points as a post-processing step (Deems *et al*., 2013). We chose the PRF such that minimal range ambiguity would occur.

Tbl 1: Snow-on scan dates, sites scanned, and weather since prior scan: T_{min}/T_{max}; storms and new snowfall; wind speed/direction.

Scan Date	*Scan Sites*	*Weather history*
12.19.2013	Z, EW, SG	-5/+5ºC, 1 period to -30ºC; 3 storms, 198cm new snow; strong SW, W, NW
12.26.2013	Z, EW, SG	-18/-4ºC; 1 storm, 28cm new snow; strong SW, NW
1.17.2014	Z, SG	-23/-2ºC; 4 storms, 132cm new snow; strong W-NW
1.23.2014	Z, EW	-17/-0.5ºC; 0 new snow; moderate/strong NW
2.1.2014	Z, EW	-22/0.5ºC (1hr above 0ºC); 2 storms, 119cm new snow; mod SW, strong W-NW
2.26.2014	Z, EW, SG	-22/-0.5ºC; 2 storms, 107cm new snow; mod SW, strong WSW-NW
3.3.2014	Z, EW	-11/-1ºC; 1 storm, 45cm new snow; strong NW-SW

Raw snow-on data was registered to the snow-off data set, first with a coarse-registration to manually-chosen tie points, and then finalized using the multi-station adjustment (MSA) tool in Riegl's RiSCAN Pro software (Riegl, 2014). We chose to use the TLS internal GPS unit instead of an external system to save data collection time, knowing that the GPS positions for each scan were not accurate enough to give satisfactory registration fits, necessitating the MSA step, which involves

Tbl 2: Typical TLS scan parameter values

Parameter	*Parameter Range*
PRF	50 – 150 kHz
Vertical Angle Resolution	0.15 mrad
Vertical Angle Range	60-120º from zenith
Horizontal Angle Resolution	0.15 mrad
Horizontal Angle Range	0-180º

calculating a 3D coordinate adjustment to minimize the distance between a set of identical features in multiple scans.

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 using the Above Ground Level (AGL) tool.

We colored the point clouds by snow depth/height of snow (*HS*) or snow depth change (*dHS*), and explored several Google Earth, image, and video formats for distribution and visualization.

3. RESULTS AND DISCUSSION

The data collected allow an assessment of the utility of TLS-derived *HS* and *dHS* maps for various operational applications. The following discussion highlights notable results or opportunities from the 2013/14 pilot study.

3.1 Montezuma Bowl

Scan results from Montezuma Bowl on 17 and 23 January highlight the high resolution of the TLS measurement technique, as well as several potential applications and analyses (Fig. 3, 4).

Visible in the 17 January scan are two explosives-triggered avalanches, as well as numerous ski cuts and hand charge craters. The exceptional sensitivity of the TLS instrument is demonstrated by the detection of the traffic control rope line dividing the bowl, as well as around several other roped-off areas. Snow depth patterns show the importance of wind redistribution in this terrain (Fig. 3a).

The *dHS* map shows areas of accumulation and scour/ablation since the 26 December scan (Fig. 3b). Cross-loading and scour of terrain features from southwest winds is quite evident, and cornice growth can be seen all along the ridge, with increases of greater than 2m in the northern half due to loading from northwesterly winds. One slab avalanche occurred in a loaded terrain pocket at a break in slope, as is common, but the complex loading pattern around the crown suggests that slab variability or continuity limited propagation extent. The second fracture line connects rocks, trees, and shallow areas, and the bed surface shows evidence of scour and/or downstepping. Closer to the rope line is a loaded gully with one particularly deep pocket that would certainly warrant caution and control attention (Fig. 3c). Ski cuts and hand charge craters are readily seen on the deep pocket, as well as in the shallow areas surrounding it, suggesting that the control efforts have soundly tested the local stability, targeting deep and shallow areas as well as rock outcrops and terrain convexities. This instance illustrates the potential application of the TLS system for post-control assessment, providing a means to evaluate control results and the size of any remaining hangfire, as well as to examine potential reasons for non-results, e.g. disconnected slabs or

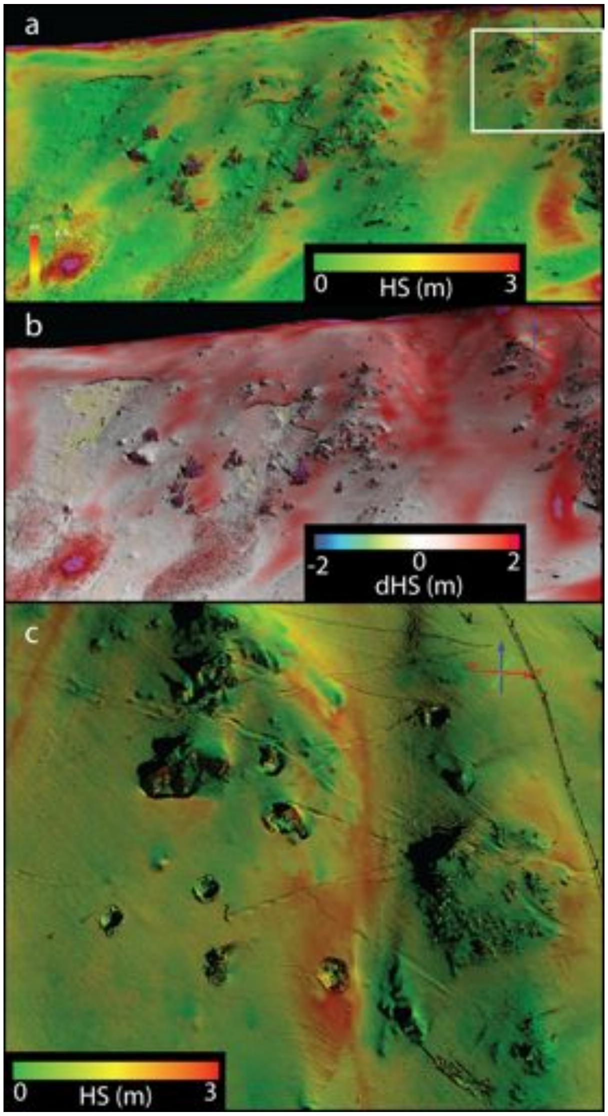

Fig. 3: Montezuma Bowl, 17 January, 2014. (a) *HS*; (b) *dHS* relative to 26 December; (c) *HS* subset showing ski cuts and hand charge craters near a deep snow pocket.

shots placed in locations with deep accumulation. The TLS maps could also be used to digitize shot placement and ski cut locations to populate digital avalanche control records.

The 23 January *dHS* map shows mostly depth reduction since 17 January, with several interesting patterns. The southwest end of the bowl (Fig. 4a, left part of image) indicates minor accumulation, while the northeast half shows pronounced depth decreases; northeast of the control rope line, the mogul pattern indicates that the 0.2-0.5m depth decrease is due primarily to skier compaction. The capability of the TLS system to quantify and map skier compaction could be applied in an operational context to estimate areas in which the compaction is affecting a weak or slab layer of concern.

Substantial depth decreases are also seen south of the rope line, but this area was closed to public skier traffic. Field observations on 23 January note widespread explosives residue on the snow surface in these areas, as well as abundant surface runnels from snowmelt, despite subfreezing air temperatures during this period. Clearly, the reduced snow surface albedo from the blast residue in combination with the southerly exposure of the terrain allowed strong surface melt and depth reduction. Though the TLS *dHS* map cannot reveal the depth of liquid water penetration, or which snow layers were reduced in thickness, coincident manual measurements could be collected to estimate the impacts of the surface melt over the full starting zone.

Cross-sections through the southernmost avalanche crown from 17 and 23 January reveals settlement and either creep effects or snow drift accumulation on the crown face (Fig. 4b). Settlement of the relatively undisturbed snow above the crown measures about 10cm, while below the crown very little settlement is observed, likely due to compaction of the bed surface during the avalanche event. The surrounding area shows 0-10cm of accumulation, suggesting that the actual settlement was greater than 10cm and was offset by drifting snow. The crown face itself has tipped or grown downhill, with increased downslope displacement at the top of the crown, consistent with either differential creep rates (e.g. McClung and Schaerer, 2006) or with drifting snow accumulating on the crown edge as with cornice growth.

3.2 East Wall

We collected two East Wall scans on 1 February, pre- and post-control operations, and the two *dHS* maps reveal numerous slab and avalanche release features, and suggest several applications (Fig. 5). The most extensive avalanche in the dataset was released with a single avalauncher shot

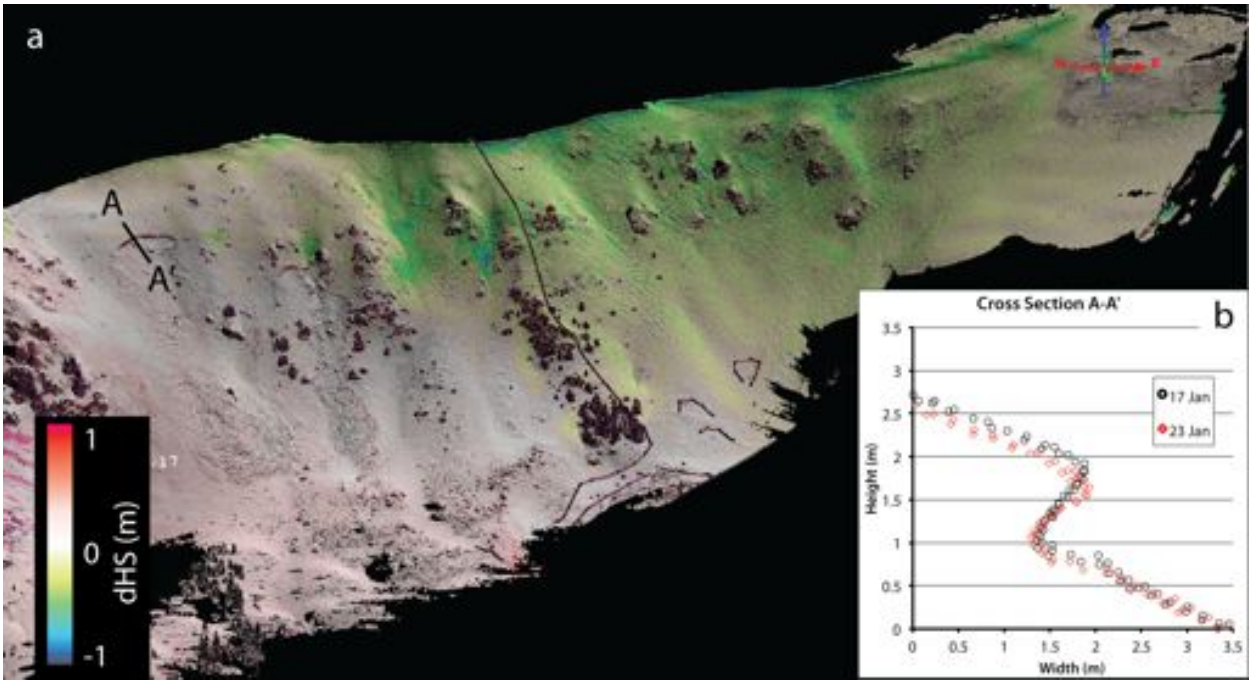

Fig. 4: Montezuma Bowl, 23 January, 2014. (a) *dHS* illustrating skier compaction and snowmelt; (b) cross section along A-A', showing surfaces from 17 and 23 January and settlement plus creep and/or wind drifting over that time period.

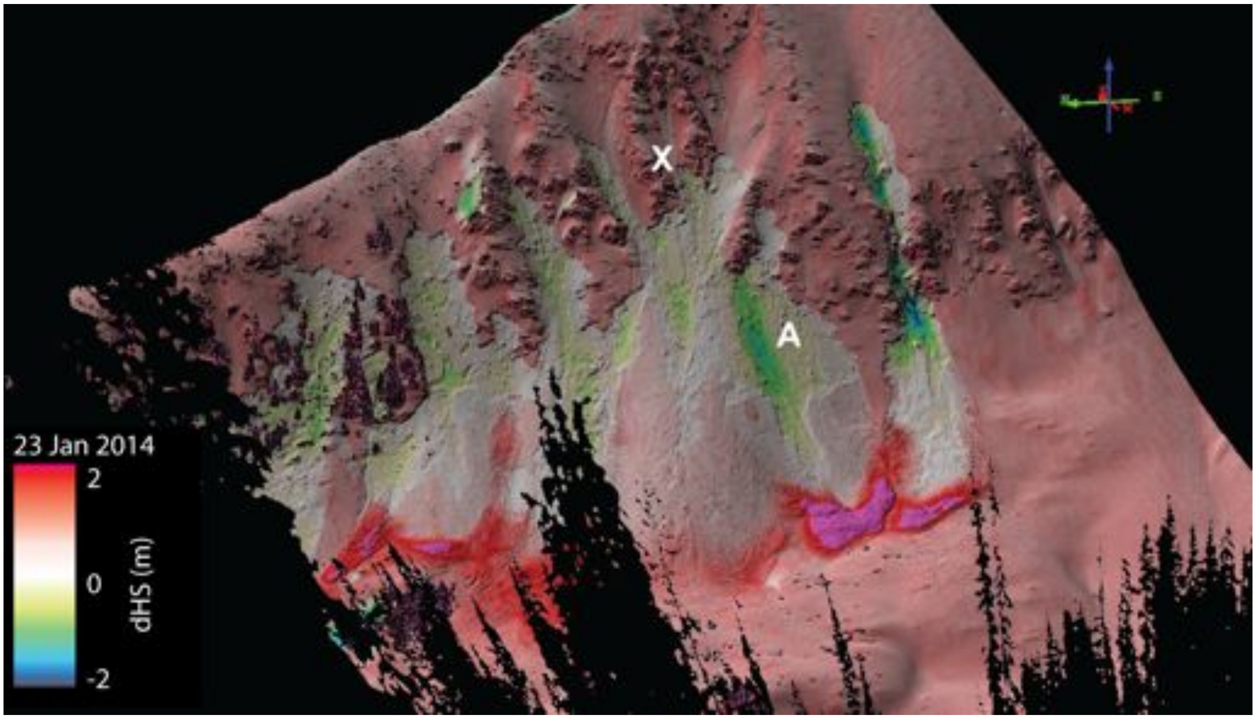

Fig. 5: East Wall on 1 February, 2014. *dHS* relative to 23 January. Large to left avalanche was initiated by a single avalauncher round at point "X". Slab volume calculated for area around "A".

(shot location marked with "X"). The white coloration in the bed surface indicates that the slide ran on the old snow surface (white indicating 0.0m *dHS* since 23 Jan). Green and blue colors show areas where the avalanche scoured into the old snow, and occur primarily within gully features and areas of flow convergence.

Several portions of stauchwall are readily observed, and offer the potential for measurement of slab volume, which is potentially useful for calibration or verification of dynamics models. For example, a rough slab delineation using crown, flank, stauchwall, and flow divides (Fig. 5, area "A") from the post-control data set and applied to the slab area to the pre-control *dHS* map produces a slab volume of 5840 m^3. We calculate the volume of the corresponding debris pile to be 2980 m^3. Assuming an average slab density of 200 kgm^{-3}, the mass of slab and debris balance if the debris density is about 390 kgm^{-3}, which is within the typical debris density range (McClung and Schaerer, 2006). Of course, this simplistic treatment considers neither entrainment (scour is evident in the *dHS* map) nor compaction of the existing snow below the debris, but it is clear that, when combined with field measurements, TLS holds promise as a model validation data source.

3.3 Steep Gullies

The complex terrain in the Steep Gullies area presents numerous scanning and processing challenges. The scan positions were set on the highway shoulder, and were deemed too dangerous to occupy in unplowed conditions. There are very few planar features in the terrain, which complicates feature mapping and data set registration. However, we successfully collected several scans, which reveal snow loading patterns and avalanche character in this unmanaged, "sidecountry" terrain.

Fig. 6a shows a portion of this complex terrain, with several notable drift accumulation areas. As expansion plans proceed, the TLS data could prove valuable for characterizing accumulation patterns that occur under certain storm/wind directions, for use in snow safety plan development and for planning placement of explosives delivery trams. The skier-triggered avalanche in Fig. 6b consists of several disconnected slab pockets and illustrates the terrain management challenges in this area.

4. CONCLUSIONS AND FUTURE WORK

Our results provide exciting insights into snow accumulation and avalanche processes, as well as

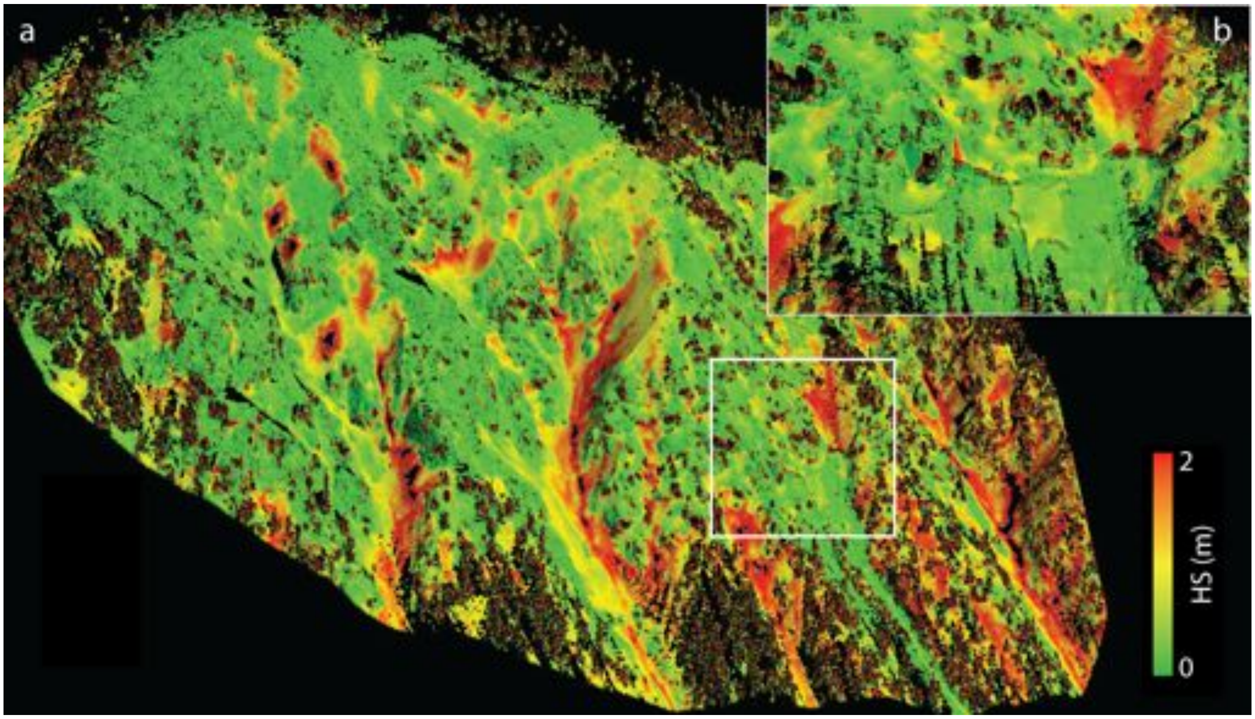

Fig. 6: Steep Gullies on 17 January, 2014. (a) *HS;* (b) subset showing skier-triggered avalanche.

for the potential for informing and supplementing operational avalanche control efforts. We have identified several promising avenues for future development and application, and compiled a set of best practices and lessons-learned.

Our experience on other projects suggests that a static survey of scan locations with a survey-grade GPS system would provide sufficient accuracy to eliminate the coarse registration step, and the additional inclusion of static-surveyed reflector tie points could eliminate the MSA processing step. The time required for post-processing and scan registration would be further reduced by installation of permanent scanner mounts and reflectors. Re-occupation of a scanner mount would minimize scan location uncertainty, and at least one reflector tie point which remains unchanged throughout the season would eliminate the need to manually identify identical features in common between scans. The costs for mounts and reflectors would be more than offset by operator time savings and most importantly would enable rapid turnaround data products for best operational relevance.

Static images of colored point clouds (such as those in this document) provide a sense of the detail captured in the TLS products, but much greater value can be achieved through direct interaction with a 3D dataset. Enabling this interaction is a key challenge for integration with avalanche control operations – ideally data products can be provided without the need for acquisition of or experience with specialized software packages. Our initial efforts suggest that export of images to Google Earth meets several of these goals, but suffers from loss of resolution and detail. Recently released web browser-based point cloud visualization tools offer a potential solution. Integration of products with existing digital avalanche atlases would be useful for control route planning and event documentation.

Different information is contained in the *HS* and *dHS* data products. For operational interests where new slab or storm snow distributions are of primary concern, it is likely that the *dHS* products would be of most utility, especially if scans can be collected prior to and following a precipitation or wind event. In such a case, it is likely that the *dHS* map can safely be assumed to represent the distribution of new slab thickness across the domain. Quantification of loading patterns could also be useful for comparison with experiential knowledge possessed by individuals with a history of conducting avalanche assessment in the area of operation, and for identifying unusual loading patterns that do not fit with conventional wisdom.

Maps of *HS* are likely most useful for identifying threshold depths, e.g. for identifying areas susceptible to high temperature gradients and facet or depth hoar development. Snow depth maps can also be useful for relating manual measurements (of stratigraphy, depth, etc.) to the wider terrain, or conversely for identification of preferred manual measurement locations.

It is difficult to overstate the “wow factor” when examining the TLS *HS* and *dHS* maps. As such, education, public outreach, and marketing opportunities should not be overlooked. In particular, quantification and visualization of complex snow accumulation patterns would be of direct benefit to avalanche education, particularly at higher levels that deal directly with issues pertaining to spatial variation in snow properties.

In addition to refinement and further deployment of the ski area operational support explored in this pilot study, expansion of the TLS mapping techniques to highway control operations would be a natural next step. Assessment and verification of control results would add useful quantitative decision-support data and be a valuable tool in maintaining highway corridor safety. Additionally, our team is developing an autonomous TLS system, meant to constantly monitor and transmit data products from remote locations (LeWinter *et al*., 2014).

TLS technology has advanced rapidly in recent years, and the latest generation of sensor systems has enabled the starting zone mapping described here. As the TLS technology becomes more widely available and at lower cost, the future for avalanche research and application using this powerful tool holds much promise.

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