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Mapping starting zone snow depth with a ground-based lidar to assist 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 snow-free reference data set was collected in a summer TLS survey. 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 avalanche control settings.

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 affect 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 avalanche hazard assessment, control practitioners, as well as to backcountry travelers. 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, and 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. Deems et al., 2013; Egli et al., 2011; Grünewald et al., 2010; Prokop et al., 2008). 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 from multiple starting zones.

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 positioning data (i.e. from GNSS or registration to 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

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potential for monitoring snow accumulation patterns and operational assessment and planning of avalanche control efforts (Deems et al., 2013).

TLS survey methods have seen increasing use in snow depth mapping as equipment costs have decreased and the technology and processing software have become more available over the past decade. For example, 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. Grünewald et al. (2010) and Egli et al. (2011) 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.

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 (often nighttime) data collection campaigns due to the slow speed of the scanner and limited detection capabilities at longer ranges. TLS technology developments have been improving both speed and range. For example, Prokop (2009) demonstrated measurement at ranges up to 1500 m with scan durations of approximately one hour, improving dramatically on prior survey constraints. The new Riegl VZ-4000 and VZ-6000 laser mapping systems allow similar or greater ranges, with faster data collection and higher 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 over 1000 m with 180° scan durations of 15–45 min (Fig. 1), with similar times and even longer ranges with the VZ-6000 (>5 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 assess the capability of TLS mapping in an operational avalanche control setting.

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; Table 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.

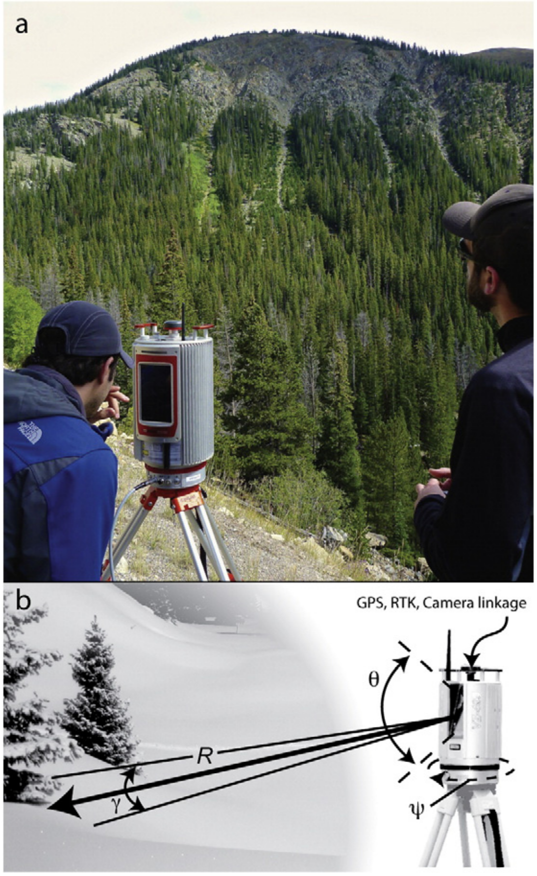

Fig. 1. (a) Riegl VZ-4000 at Steep Gullies scan site #1 during snow-free mapping; (b) schematic representation of scan parameters: range to target (R), beam divergence (γ), vertical angle range and resolution (θ), and horizontal angle range and resolution (ψ) (from Deems et al., 2013).

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) are a commonly-skied backcountry area that are 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 1550 nm, 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 1064 nm wavelength where snow is more reflective and allows for longer-range mapping. However, the 1064 nm 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 (point density) over the target area, while minimizing collection time and post-processing steps (Table 2). Of interest is the pulse repetition