

MAPPING A GLIDE AVALANCHE WITH TERRESTRIAL LIDAR IN GLACIER NATIONAL PARK, USA

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ABSTRACT: Thorough documentation of large avalanche events is important for forecasting efforts, infrastructure planning, and investigating the processes involved in avalanche formation and release. However, due in part to the isolated and dangerous nature of avalanche terrain, collecting in-situ, spatially continuous, and quantitative information surrounding avalanches remains difficult. Advances in remote sensing continue to address this knowledge gap. For example, terrestrial laser scanners (TLSs) can produce snow depth measurements at fine spatial resolutions over large areas. Repeat data acquisitions between precipitation events also allow for depth quantification atop an interface, as well as precise estimations of release volume and runout area after avalanche failure. Here, we explore the benefits of TLS-derived documentation from a large avalanche event by examining the development and release of a glide avalanche that occurred in Glacier National Park, Montana, USA, during the spring of 2022. Three sets of lidar point cloud data were acquired in the Haystack Creek drainage, focused on a well-known glide avalanche site. Lidar scans were collected after glide cracks emerged but prior to glide failure, and shortly (~ 1.5 days) after avalanche occurrence, in addition to a snow-free scan later in the year. With this temporal dataset, we were able to account for and visualize the spatial variability of snow depth across the avalanche start zone, such that we could precisely calculate the release volume (18674 m³) and average start zone depth (3.3 m) of the avalanche. Furthermore, TLS data were used to map the extent of the runout area and entrainment zone.

KEYWORDS: Glide avalanche, TLS, lidar, depth mapping, visualization.

1. INTRODUCTION

The spatial distribution of physical snowpack characteristics in avalanche zones is a key determinant of avalanche formation and character (Schweizer et al., 2008). Substantial changes in snowpack properties over short spatial scales are not uncommon in mountainous environments, particularly in heavily wind-affected terrain (Deems et al., 2013). Knowledge of differential loading and spatial distributions of various physical snowpack properties is an advantage for avalanche forecasting and mitigation practitioners. For example, it has been demonstrated that avalanche control efforts are often more successful when targeting shallow regions adjacent to deep thicker slabs (Guy and Birkeland, 2013). Traditional observations of snowpack properties often involve discrete, manual measurements, potentially exposing personnel to dangerous terrain hazards, and yielding only spotty, spatially discontinuous datasets (Deems et al., 2015). These manual observations are especially unsafe for glide avalanches because they include the entire season's snowpack and their release is challenging to predict. Recent advances in remote sensing technologies, including Terrestrial Laser Scanning (TLS) and Structure from Motion (SfM) photogrammetry,

have provided the opportunity for high-spatiotemporal resolution snowpack observations while sampling non-destructively and reducing practitioner exposure to hazardous terrain (e.g., Egli et al., 2012; Maggioni et al., 2013; Miller et al., 2022; Prokop et al., 2015).

Here, we build on the aforementioned studies leveraging recent advancements in TLS technology to remotely collect snow depth data via elevation differencing. We collected TLS data surrounding a large glide avalanche in the spring of 2022. Using this elevation data, we produced maps of total snow depth before and after the avalanche, as well as change in snow depth. Like Prokop et al. (2013a and 2015), we are interested in the potential utility of using TLS-derived products as both validation and input data for avalanche dynamics models. Thus, we used the change in depth map to delineate the start zone, calculate release volume, and observe the extent of entrainment and runout of a large natural glide avalanche.

2. METHODOLOGY

2.1 *Study site*

Our study Area-of-Interest (AOI) was a 0.78 km² region of the Haystack Creek drainage beneath Mount Gould, located in the Lewis Range of Glacier National Park (GNP), USA (Figure 1a – d). The area features high-alpine terrain with an intermountain snowpack and a variety of avalanche problems. Considerable spatial variability in snow depth and other

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physical snowpack characteristics is common. We selected this site to observe the Haystack glide avalanche, an annual glide event that occurs in late spring when meltwater lubricates the underlying bedrock. The area also allowed for relatively safe access to lidar scan positions from the Going-to-the-Sun Road (GTSR) (Figure 1b – d), the primary traffic artery of GNP. From the glide release area (Figure 1c), avalanche debris is funneled through one or more steep drainages to a bench roughly 400 m long, before spilling into a steep descent toward the GTSR

along the perennial portion of Haystack Creek. Whether or not the glide avalanche impacts the GTSR largely depends on if the avalanche debris flow had sufficient momentum to clear the bench, where the slope is consistently less than 20°. Thus, the Haystack glide avalanche can be innocuous or a severe danger, depending on the year, and the size is difficult to predict. In the spring of 2022, the slide stopped before the outlet of the bench (Figure 1c – d). The avalanche was classified as “GS – N – R4 – D3 – G” by professional observers.

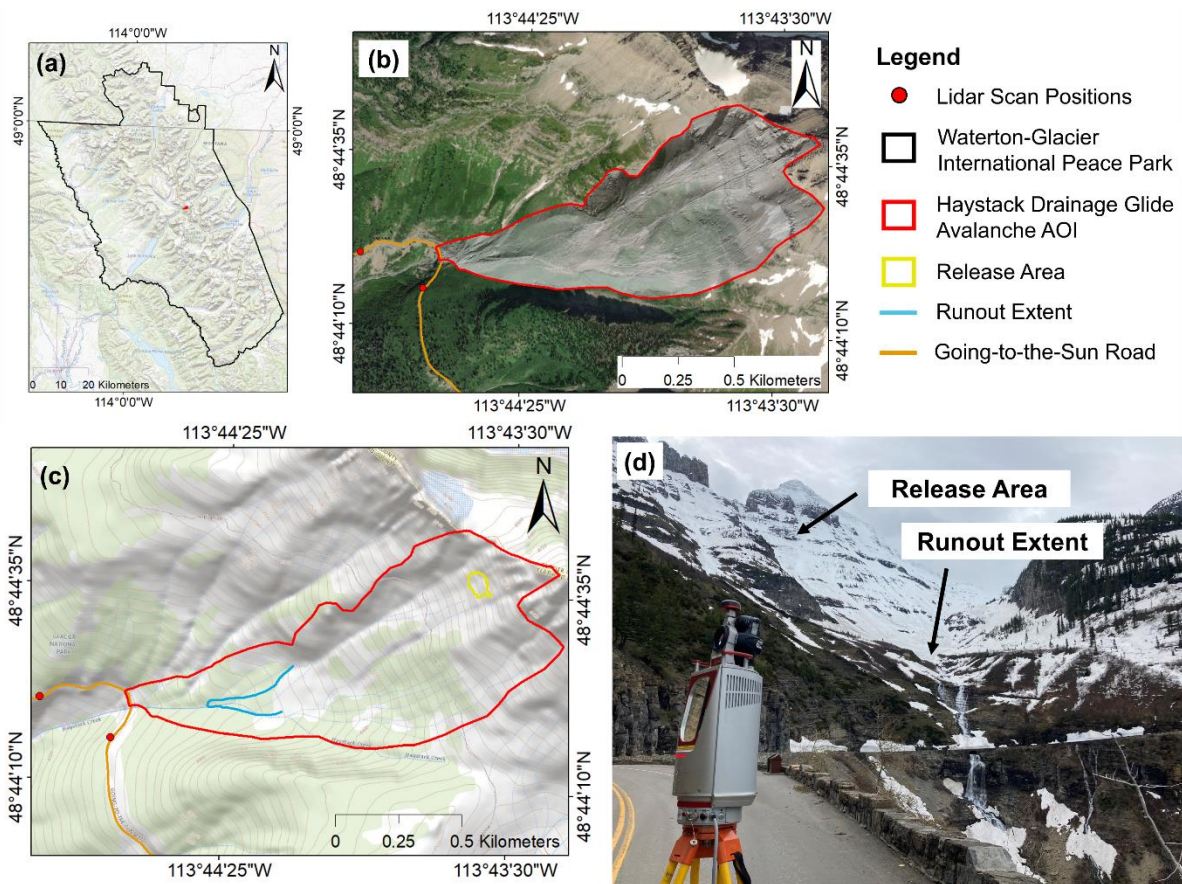


Figure 1: General location of the study AOI within the Waterton-Glacier International Peace Park (a), transparent hillshade of the AOI over aerial imagery (b), topographic view including the extent of release area and runout from the 2022 event (c), and photograph of the northwestern scanning position along the GTSR (d).

2.2 Scanning and registration

We acquired TLS data using a tripod-mounted Riegl VZ-6000 long-range terrestrial scanner (Figure 1b), operating at 1064 nm, during each of three outings surrounding the glide event of spring 2022. For each outing, we obtained data from two scan positions along the GTSR (Figure 1a), which reduced terrain shadowing, once aligned. We collected two “snow-

on” datasets, both pre-slide (17 May) and post-slide (03 June), as well as one “snow-off” dataset (18 October) later in the year. The slide released on the evening of 01 June, with no precipitation occurring between then and our data acquisition the morning of 03 June. The crown and release area can be seen both from photography and in the corresponding point cloud (Figure 2a and 2b, respectively).

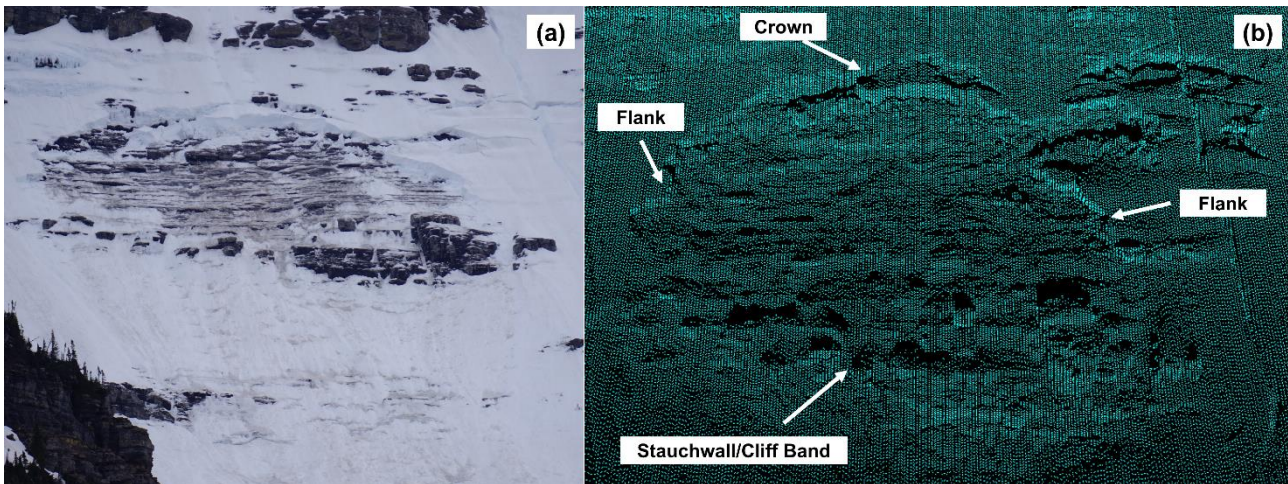


Figure 2: Photograph of the Haystack glide crown and release area (a) compared to a point cloud with relevant features labeled (b), both acquired on the morning of 03 June 2022. Photograph courtesy of the U.S. Geological Survey.

Regarding scan parameters, we set the pulse repetition frequency to 30 kHz to maximize range and selected a 0.02° vertical/horizontal step increment to optimally straddle spatial resolution (point density) and collection time, with scan durations of about 20 – 30 minutes. We mounted small circular reflectors to trees throughout the scan field-of-view for initial scan alignment, then further refined registration with manual coarse alignment, and finally with Riegl's semi-automatic, iterative Multi-Station Adjustment (MSA) workflow, taking care to avoid alignment based on snow surfaces between dates (Deems et al., 2015; Riegl, 2015a). Alignment (both coarse and MSA) across scanning dates centered on exposed cliff faces and large vegetation, as well as permanent GTSR infrastructure. For depth mapping via differencing, relative alignment between scans is the most important matter. However, we also underwent global registration to incorporate basemaps and other external datasets into our data visualization. To accomplish this, we leveraged in-situ collected GPS points, acquired via Emlid Reach RS2 systems, corresponding to each tie point and scan position. Once relative and global registration was complete, we exported point clouds from Riegl's proprietary RiScan software into R and ESRI's ArcMap for further processing. Using terrain filters available in RiScan, we removed vegetation points prior to exportation. Resulting clouds had point spacing of $\sim 11 - 14$ pts/m², depending on the date.

2.3 *Map production*

We converted all registered point clouds to raster format using a natural neighbor triangulation. Raster

grid size was 1 m, a resolution that: was sensible given our point spacing, minimized smoothing and preserved the integrity of terrain variability, and still permitted reasonable processing times. We rasterized the vegetation-filtered point clouds for each scanning date, thus creating Digital Elevation Models (DEMs). Next, we differenced DEMs between the three scan dates to create three corresponding maps: snow depth on 17 May (pre-slide), snow depth 03 June (post-slide), and change in snow depth between snow-on scans (03 June depth – 17 May depth) to visualize the effects of the glide avalanche.

3. RESULTS AND DISCUSSION

We differenced snow-on DEMs (Figure 3a – b) with the snow-off 18 October DEM (Figure 3c) to create maps of total snow depth on both 17 May (Figure 3e) and 03 June (Figure 3f). Extreme spatial variability in snow depth is apparent, even across small spatial scales; on both dates, most of the area of interest has snow depths < 1 m, while the largest pockets contain regions of depth > 7 m. Most snow is packed into start zones between cliff bands and drainage funnels (Figure 3e – f). The maximum depth of snow in the release area on 17 May was 7.2 m, with an average of 3.3 m ($\sigma = 1.6$ m) and a total release volume of 18,674 m³. The dramatic change in start zone depth between 17 May and 03 June is evident (blue arrows in Figure 3e – f), as the slide failed at the ground-snow interface. Particular stages of the slide can be observed in Figure 3d, or the three-dimensional rendering in Figure 4a, which illustrates the change in snow depth before and after the avalanche.

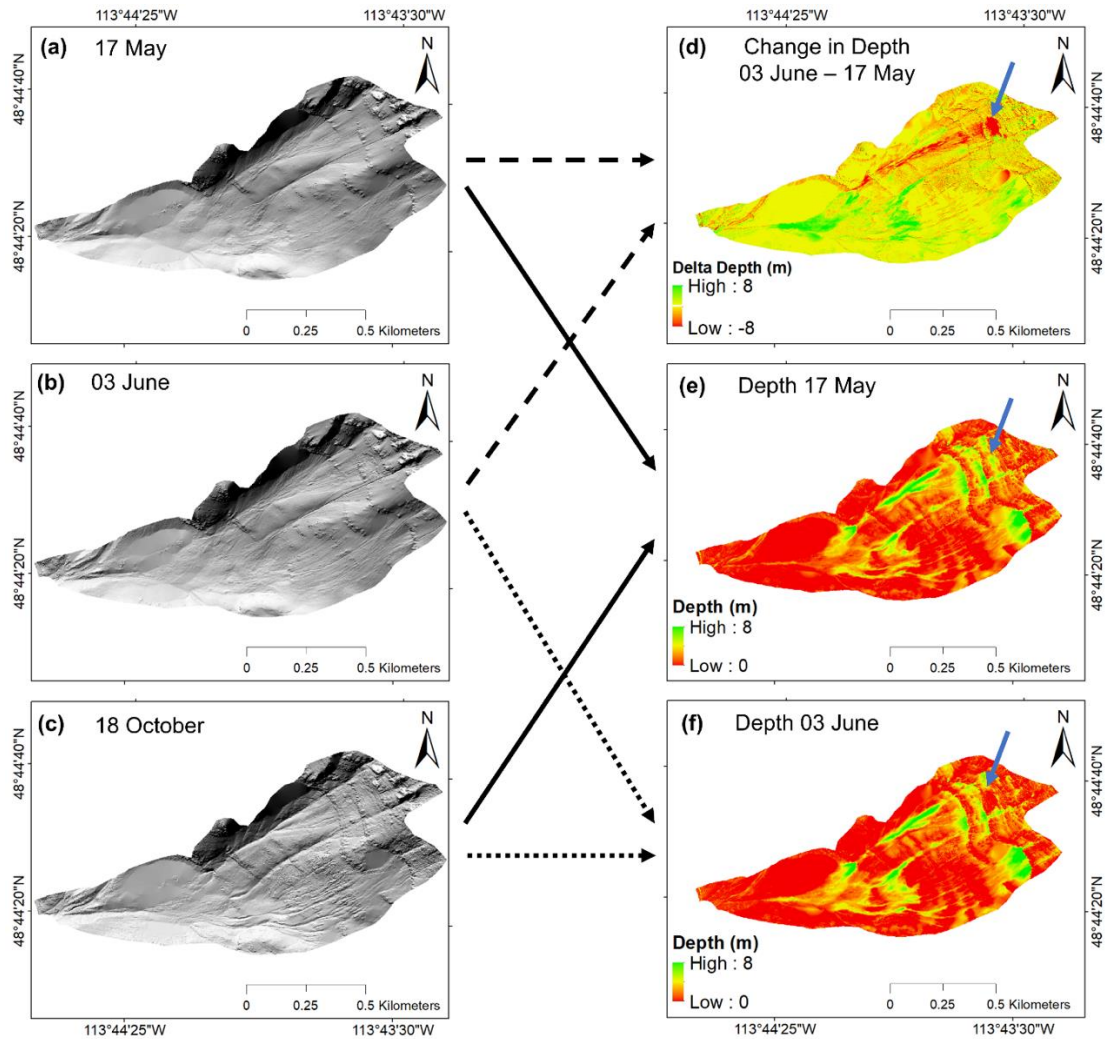


Figure 3: Differencing of snow-on DEMs (a and b) with a snow-off DEM (c) to produce maps of total snow depth (e and f) as well as change in snow depth (d). Arrow line types between map panels (dashed, solid and dotted) indicate the DEM pairs used for DEM differencing for a given snow depth map. Blue solid arrows point to the avalanche release area.

In addition to the extreme loss of snow cover in the start zone, an entrainment zone can be observed (resulting in a reduction of snow depth) along the path, before transitioning to a deposition area at the bottom of the drainage and into the bench, represented as an increase in snow depth. Outside of the avalanche

path, a small reduction (7 cm on average) in snow depth is present due to melt and settlement. Changes in depth along a transect through the release area and into the entrainment zone are illustrated in Figure 4b – c.

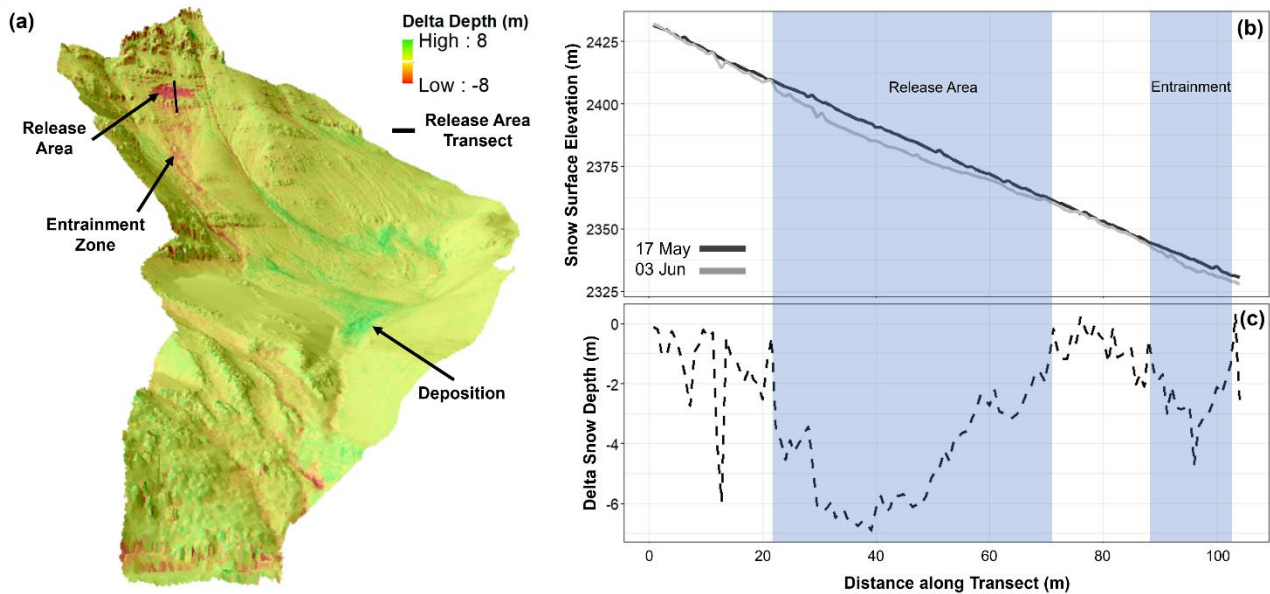


Figure 4: Three-dimensional rendering of change in snow depth from 17 May to 03 June 2022 (a) and graphical analysis of depth along a transect (b and c). Above the release area, depth is relatively constant between dates, with the exception of a couple large glide cracks. The release area terminates in a cliff band, where surface elevations again converge, before larger residuals appear due to entrainment.

4. CONCLUSIONS

In the work presented here, we demonstrate the utility of TLS for snowpack mapping and avalanche evaluation. To the best of our knowledge, this marks the first study to leverage a TLS spatiotemporal analysis toward surveying a large glide avalanche. We show the efficiency of TLS in creating powerful visualizations for avalanche forecasting and decision-making, as well as the ability to quantify parameters such as release volume in a matter of hours. Future work could leverage these maps and quantifications toward predictive and/or dynamics modeling. For instance, repeat analyses over multiple seasons could allow for remote identification of critical glide crack widths which may denote impending failure. Similarly, release volume could be loosely related to runout extent. Critical values of the former that could endanger roads and infrastructure may be identified, particularly for an annual avalanche occurrence such as this. Last, as alluded to in Section 1, we designed this study with an eye for back-calculating the avalanche in a dynamics model such as RAMMS. We anticipate that TLS-derived data products, such as release volume, spatially variable start zone depth maps, snow-on DEMs, etc., may improve the results of dynamics simulations. Further, it is understood that maps of depth change, and subsequent delineation of runout extent, deposition volume, and entrainment zones, can be used in the validation of dynamics models. However, this work is ongoing and requires further investigation.

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DISCLAIMER

Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the U.S. Government.

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