# USING STRUCTURE FROM MOTION PHOTOGRAMMETRY TO EXAMINE GLIDE SNOW AVALANCHES

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ABSTRACT: Structure from Motion (SfM), a photogrammetric technique, has been used extensively and successfully in many fields including geosciences over the past few years to create 3D models and high resolution digital elevation models (DEMs) from aerial or oblique photographs. SfM has recently been used in a limited capacity in snow avalanche research and shows promise as a tool for broader applications. In this study, we used SfM to examine glide avalanches along the Going-to-the-Sun Road (GTSR) corridor in Glacier National Park (GNP), Montana. Glide avalanches pose substantial hazard to railroads, highways, and other infrastructure in many avalanche prone regions around the world, and yet basic measurements of crown depth and ground/snow interface can be hard to observe. Along the GTSR, glide avalanches can impact worker and public safety, but accessing glide avalanche crowns or glide cracks is often prohibited by inaccessible terrain or residual avalanche hazard. We used SfM techniques to derive high resolution DEMs for four glide avalanches that occurred in the spring of 2016. This allowed us to estimate selected full depth glide avalanche dimensions without visiting the site. However, our analysis was limited to qualitative assessments of the glide avalanche dimensions as the high resolution coordinates necessary to analyze the vertical dimension of avalanche crowns were not available. Despite this, our results suggest SfM can be a robust tool for examining glide avalanche crowns and of sufficient resolution to accurately characterize glide avalanche dimensions. Under a warming and more variable future climate, glide avalanches could become a more prevalent problem, and using SfM as a tool to help characterize glide avalanches over a larger spatial area will help us to better document and further understand these phenomena.

KEYWORDS: glide avalanche, Structure from Motion, photogrammetry, Glacier National Park, Montana.

## 1. INTRODUCTION AND BACKGROUND

Glide snow avalanches impact transportation corridors, infrastructure, and recreationists in many mountainous locations throughout the world (Maggioni et al. 2016; Peitzsch et al. 2012b; Simenhois; Birkeland 2010; Stimberis; Rubin 2011). Snow gliding is the downhill movement of the entire snow cover on a slope along the interface with the underlying ground (In der Gand; Zupancic 1966; Jones 2004; McClung; Schaerer 2006). Glide snow avalanches are avalanches involving the entire snowpack that often, but not always, begin as a tensile crack in the snowpack (Clarke; McClung 1999). However, not all glide cracks result in an avalanche and can sometimes melt in-situ (Mitterer; Schweizer 2012; Peitzsch et al. 2015). Glide snow avalanches can occur in both the winter and spring/summer, but are considered a wet snow avalanche due to the presence of free water near or at the ground/snow interface (McClung; Schaerer 2006). Clarke and McClung (1999) further classified glide avalanches as either cold events (those avalanches that occur when most of the snowpack is dry accompanied by air temperatures below 0° C) or warm events (where increasing air temperature and solar radiation appear to be the main drivers of avalanche release).

This type of wet snow avalanche has received increased research attention in recent years. Höller (2013) provides a comprehensive summary of glide snow avalanche research from the early 20$^{th}$ century to present. Recent studies have examined meteorological conditions associated with glide snow avalanche occurrence (Dreier et al. 2016; Mitterer; Schweizer 2012; Peitzsch et al. 2015; Stimberis; Rubin 2011). Other recent work investigated slab mechanics or terrain conditions related to snow gliding and glide snow avalanche release (Bartelt et al. 2012; Feistl et al. 2013; Feistl et al. 2014; Peitzsch et al. 2015). A few studies utilized remote sensing capabilities to aid in understanding

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glide avalanche processes and timing. Time-lapse photography was used to determine timing of avalanche release (Hendrikx et al. 2012; van Herwijnen; Simenhois 2012), and Feick et al. (2012) utilized high resolution satellite imagery to detect glide snow avalanche activity across large spatial scales. Despite this breadth of contemporary work examining glide avalanches, the timing of avalanche release remains a difficult problem for avalanche forecasting operations (Dreier et al. 2016; Reardon et al. 2006; Teich et al. 2013).

Glide avalanches impact worker safety, infrastructure, and recreationists along the Going-to-the Sun Road (GTSR) in Glacier National Park (GNP), Montana, USA (Figure 1). Previous studies conducted in this transportation and recreation corridor aid in glide snow avalanche forecasting (Peitzsch et al. 2015; Peitzsch et al. 2012b; Reardon et al. 2006). However, in-situ measurements of glide avalanche crowns or glide cracks is sparse due to inaccessibility in steep, rocky terrain or residual overhanging hazard. Thus, a quantitative assessment of glide avalanche crowns is rarely, if ever, possible in this terrain.

Investigating crowns is important in order to understand the slab mechanics, the specific nature of the terrain, and the position of the stauchwall on the slope. Bartelt et al. (2012) and Feistl et al. (2014) illustrated the importance of the stauchwall in glide avalanche release. Understanding these components and terrain parameters of glide avalanches could potentially aid in subsequent avalanche mitigation, whether it be active or passive measures.

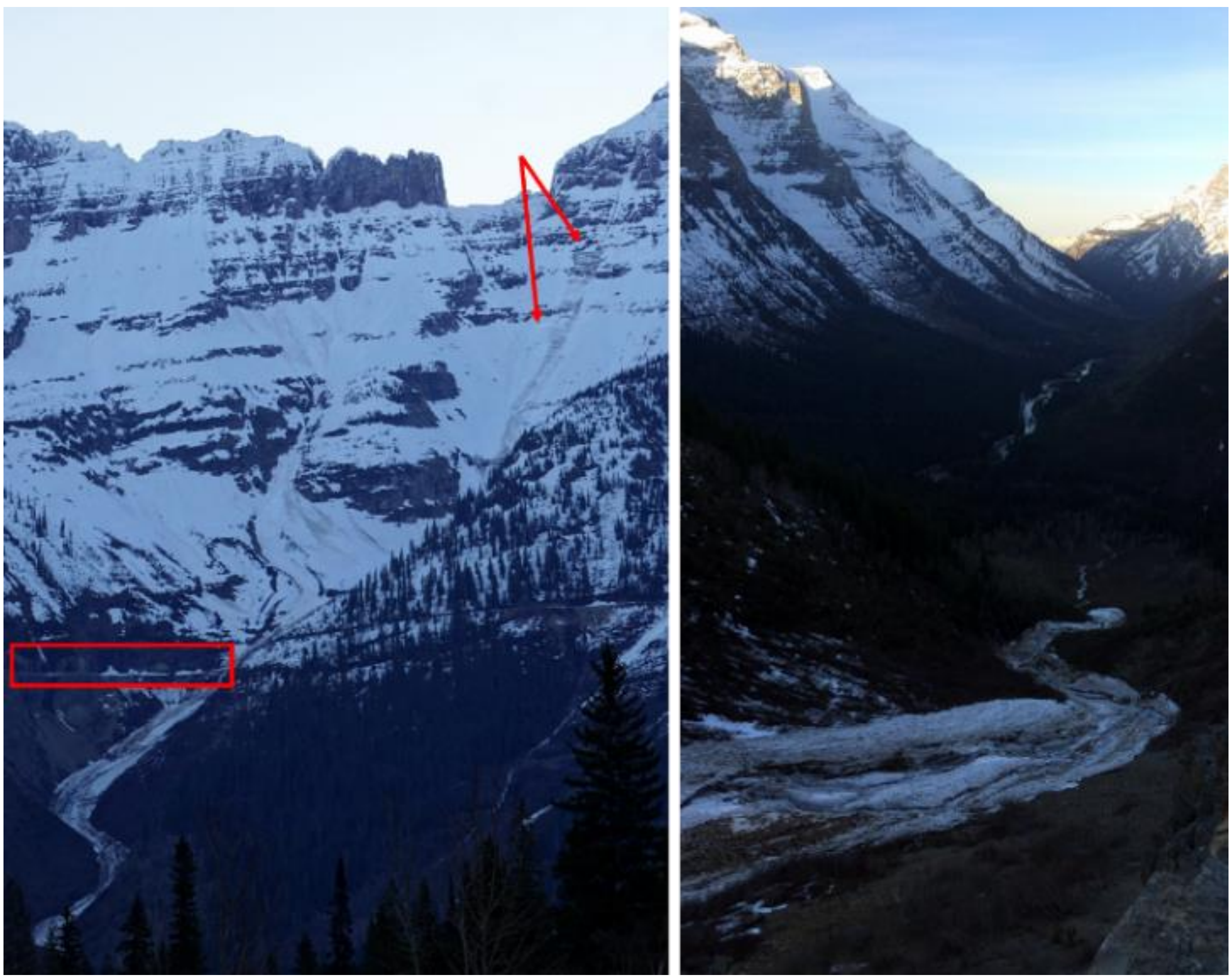


Figure 1: Left image: A glide avalanche (upper arrow) in April 2016 triggered a subsequent large wet slab avalanche (lower arrow) that buried an already plowed road (orange box). Right image: The resultant debris traveled onto snow-free terrain well below the road for a total vertical fall of approximately 1200 m.

In this study, we utilized a photogrammetry method, Structure from Motion (SfM), to gain a better understanding of glide avalanche dimensions in otherwise inaccessible locations. SfM is a cost-effective technique that does not compromise worker safety by allowing remote data collection. SfM is a photogrammetric technique that utilizes a series of overlapping images from a wide array of positions (hence the reference to motion) to produce high resolution topographic reconstructions of a given area. A 3-D structure can be derived from these images and measurements made of the area of interest. Unlike traditional photgrammetric techniques, SfM allows for the geometry of the scene and the camera locations and orientation to be solved automatically without the need for identifying an already established network of known 3-D positions on the landscape (Snavely 2008). Westoby (2012) provides a detailed description of SfM requirements and general methodology as well as illustrative applications in the geosciences.

The use of SfM in published avalanche studies has been relatively sparse. Gauthier et al. (2014) illustrated several case studies using the technique. In that study, the authors examined a crown in detail, investigated an avalanche, and mapped vegetation extent in an avalanche path. Their work using ad-hoc oblique images displayed the promising potential of SfM in these applications.

Eckerstorfer et al. (2015) utilized SfM to examine avalanche debris in Norway. Using an unmanned aerial vehicle (UAV), they acquired over 750 images of their area of interest. They calculated an approximate volume of avalanche debris and were able to make general qualitative assumptions about the flow dynamics of the actual avalanche.

Thus, the use of SfM in investigating avalanches appears promising, cost-effective, and requires relatively minimal field equipment depending on acquisition methods. Given the accessibility of this technique, the objective of this study was to determine the feasibility and efficacy of SfM to examine glide snow avalanches along the GTSR corridor. The objective helped to answer the underlying questions:

- Is SfM a useful tool for investigating glide snow avalanches in an operational avalanche forecasting setting?
- Can we remotely determine the dimensions of glide avalanches using SfM in inaccessible terrain?

## 2. METHODOLOGY

### *2.1 Study Site and Limitations*

The GTSR provides a laboratory to observe and investigate natural wet snow avalanches, including glide snow avalanches, during the annual spring opening of the road (Peitzsch et al. 2012a; Peitzsch et al. 2015; Peitzsch et al. 2012b; Reardon et al. 2006). The road traverses through GNP over 80 km, of which 56 km are closed in the winter and early spring. Formal avalanche forecasting operations commenced in 2003 and continue today through a joint program of the U.S. Geological Survey and the National Park Service.

This area sits atop the Continental Divide, and, as such, displays characteristics of both maritime and continental snow climates (Mock; Birkeland 2000). In the spring, a myriad of avalanche problems, both wet and dry snow avalanche types, impact worker safety and road infrastructure. The study area encompasses avalanche paths on northwest through southeast aspects from 2010 to 2739 m a.s.l. These slopes are located in the headwaters of McDonald Creek upstream of Avalanche Creek, specifically on Heavens Peak (48.7135611°, -113.8558167°) (Figure 2).

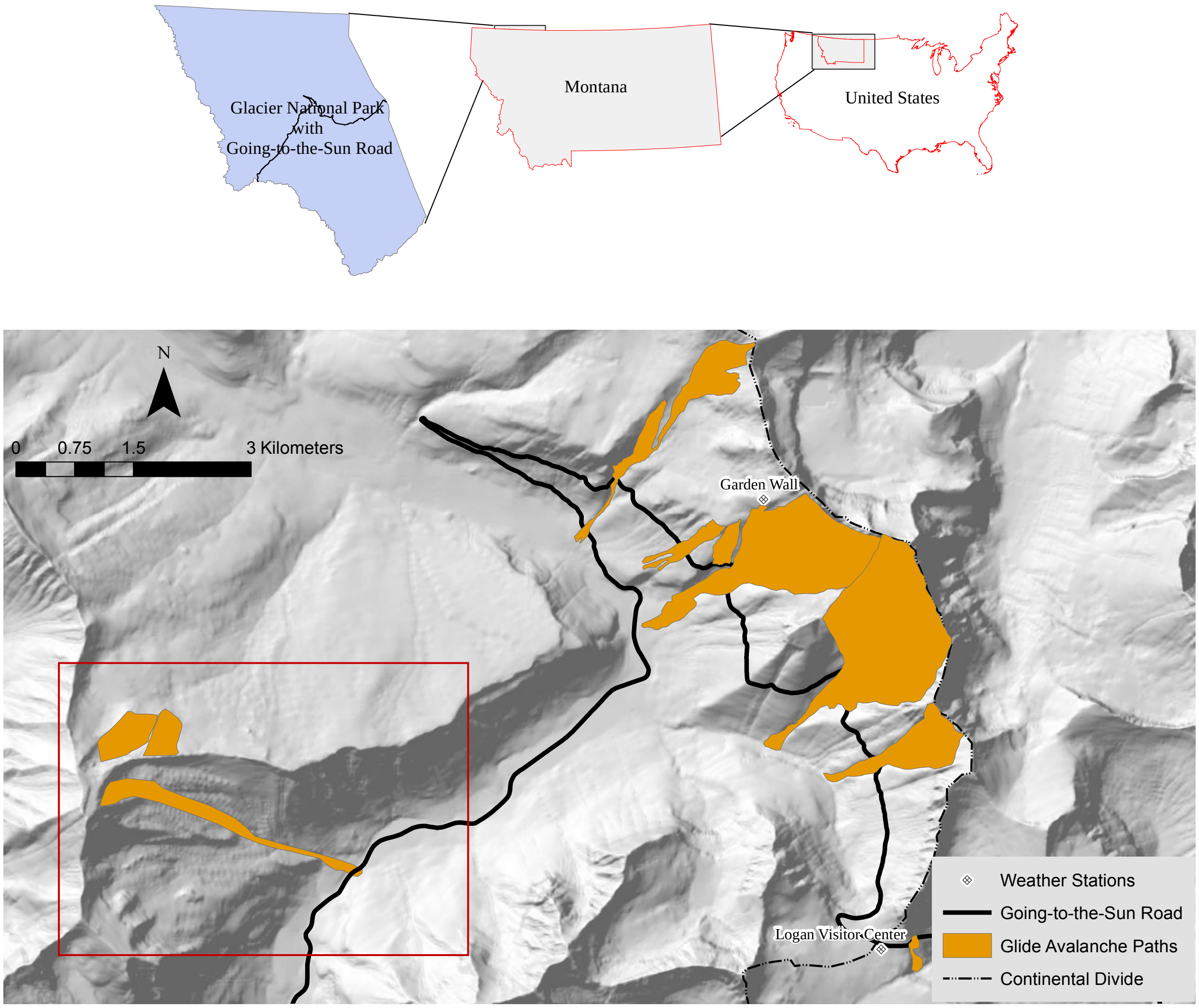



Figure 2: Overview map of the Going-to-the-Sun Road and avalanche paths where glide avalanches occur annually. The red box denotes the specific area examined in this study.

### 2.2 Imagery Acquisition

All images used in the SfM application were oblique images acquired on the ground from the GTSR on 27 April 2016. GNP policies prohibit the use of drones within the boundaries of the national park, and a component of the methodology was to determine the feasibility of using images from locations easily accessed, as part of standard operations, on most days from the road. While aerial photography or oblique airborne photography may prove useful, the objective also included obtaining images in a cost-effective and opportunistic manner.

For this study, we used a Nikon D-7100 DSLR camera with an auto-focus zoom NIKKOR 80-200mm lens. We obtained 12 images from three different camera stations from approximately 6.0 km from the target site (Heavens Peak). The size of each image ranged from 8.5 to 10.0 MB. The images were collected in .JPG format.

While SfM works best with more overlapping images from a variety of locations, we, again, used a small number of images from selected locations. This would allow us to determine the feasibility of using ad-hoc images from avalanche field workers or observers.

### 2.3 3-D Reconstruction Workflow

In this study, we used Agisoft PhotoScan Professional Version 1.2.5 (Agisoft 2016) software for all SfM processing. We also completed select spatial measurements in ArcGIS Version 10.2.2 (ESRI

2014). We used a Dell Latitude E7250 64-bit machine with Intel Core i7 processor and 16.0 GB RAM. This adheres to the basic configuration necessary for processing in Photoscan (Agisoft 2016). The following methodology describes the workflow we implemented to generate DEMs and orthomosaic products.

First, we assured all images were set to the same focal length. For this project, all images were captured with a digital focal length of 200 mm and an equivalent 35 mm focal length of 300 mm. The camera data including orientation were automatically imported when the images were loaded as EXIF data. Since multiple images were taken at each location along the road, these images were then separated into three “camera stations” of three, three, and six images respectively. We then estimated the quality of all of the images. All images were above the suggested 0.5 value (minimum value of 0.769), therefore, all images were used in the reconstruction.

Given the opportunistic nature of the data collection of avalanches, we were unable to set ground control points (GCPs) in the scene/area of interest prior to image acquisition. Despite this, a 3-D model can still be reconstructed without GCPs and is projected in a relative coordinate system based on camera positions. It is also possible to use position coordinates of the camera location itself for later georeferencing. For this stage of the analysis, we attempted three approaches. First, we allowed the software to calculate and reconstruct the scene based on camera locations without coordinates. This resulted in a 3D model, but does not allow further generation of a DEM and subsequent measurements due to the lack of reference coordinates. Next, we utilized coordinates from the camera positions. We utilized a consumer grade GPS (with an approximate accuracy of 1 to 3 m) to acquire these positions. Finally, we utilized reference points on the scene with coordinates acquired from satellite imagery prior to data collection. Three points were easily identifiable in most of the image (with an approximate accuracy of 18 m), and were manually placed on each image. The following steps were then completed twice; first using camera location coordinates for reference and the other using ground control points in the scene for reference.

Next, we aligned the images and generated a sparse point cloud. Given the small number of images, we opted to disable pair pre-selection. We chose key point limits of 40,000 and tie point limits of 4,000. We tested both a sparse point cloud and dense point cloud.

The sparse point cloud generated was then used to build a mesh for experimental purposes to determine processing time expenditure using only the sparse point cloud. The resultant 3-D model and DEM resolution was insufficient for further processing and analysis. Thus, we built the dense point cloud using both “high” and “ultra-high” quality. We chose “ultra-high” quality using the camera coordinate locations. Using reference points in the scene we chose “high” quality settings. The interpretation of the images is the same for all quality settings, but the difference arises in the processing of the images used. As quality settings decrease a step, the image size is downscaled by a factor of four. “Ultra-High” quality settings were used to process the original photos (Agisoft 2016). For both quality settings we chose mild depth filtering. This allowed for small details in the scene to remain, as opposed to aggressive depth filtering that would have smoothed out any depth variations.

Once the dense point cloud was created, we used it to build a mesh. We used all point classes and arbitrary surface type with interpolation enabled. Next, model texture was generated using generic mapping modes and mosaic texture with 4096 as the texture size. Color correction was not enabled, but hole filling was enabled. The resultant 3-D model was proportionally aligned well with no gaps in the desired areas of interest, and was visually satisfactory.

Next, we generated a DEM from the dense point cloud for both methods (using camera locations vs. GCPs, for reference) (Figure 3). The source data was the dense point cloud with interpolation enabled and all point classes used. The last step in Photoscan was to build an orthomosaic (optional). This allows visualization of the actual scene in GIS software and can be draped over terrain in other 3-D visualization programs (like ArcGlobe or Google Earth). The projection for georeferencing was WGS84 (EPSG::4326). For the orthomosaic, we used the DEM for surface generation with a mosaic blending mode and a pixel size of 0.12 m.

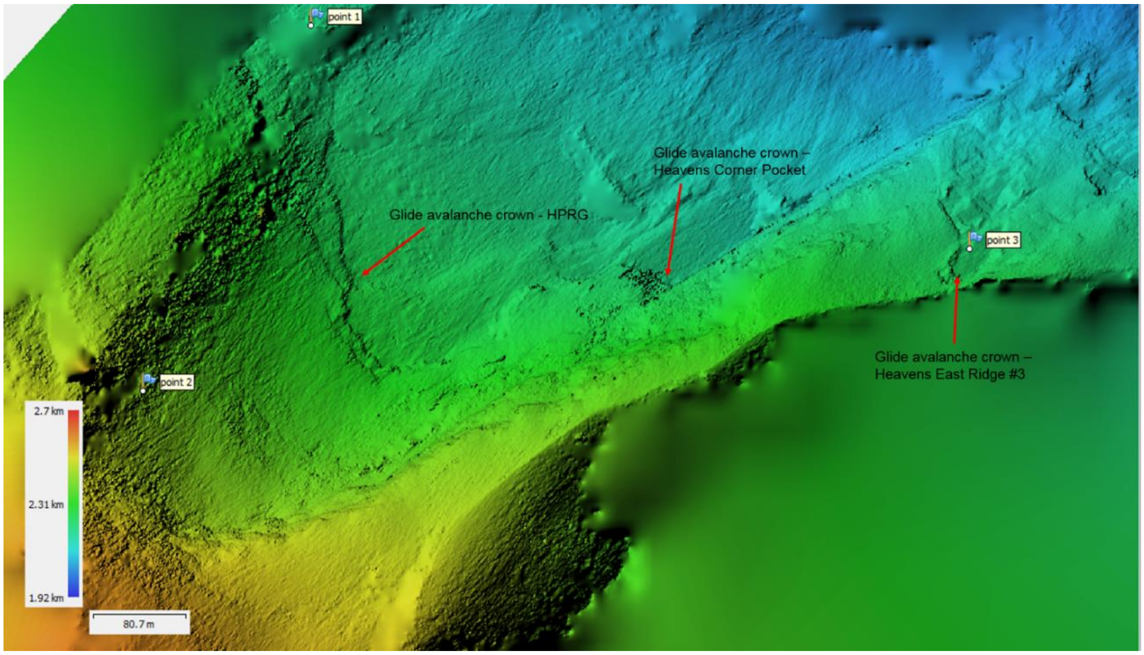



Figure 3: DEM (24 cm pixel size) generated of study site. Three of four avalanche crowns as well as three GCPs are labeled. The crowns are visible in the DEM due to the high resolution.

Finally, the generated DEM and orthomosaic were exported into GeoTiff files for use in ArcGIS. General measurements were made on the crowns including depth and width, but GCP errors prevented further detailed analysis.

## 3. RESULTS AND DISCUSSION

### *3.1 3D Reconstruction*

Processing times for each step certainly decrease as the quality of dense point cloud decreases from “ultra-high” to “high” (Table 1), but the exchange results in lower resolution products. The largest difference, of course, is evident in the processing times of the dense point cloud. Generating a point cloud with only a small number of images (12) at the “ultra-high” setting consumed over 10 hours with given computing power, while, at the “high” level it only required processing time of just under 90 minutes. With more images, choosing “ultra-high” may not be feasible unless a dedicated machine with faster processors and memory was available.

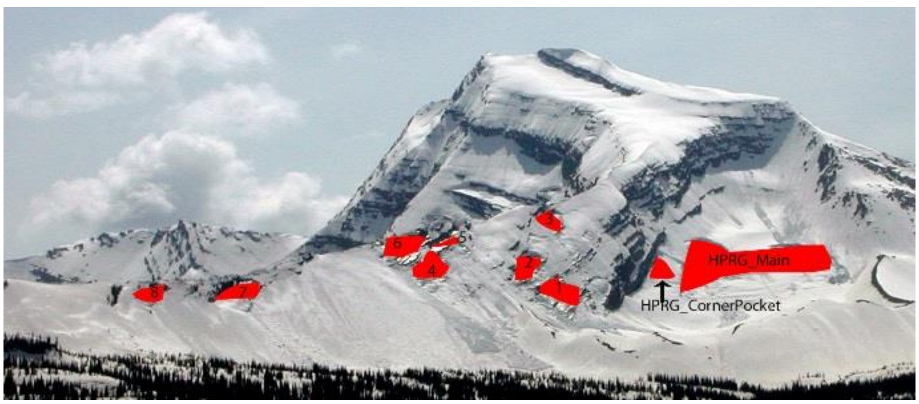
Table 1: Processing times and product resolution for “ultra-high” vs. “high” quality for 3-D reconstruction of a glide avalanche scene.

| *Processing Step* | *Ultra-High Quality Processing Times (HH:MM:SS)* | *High Quality Processing Times (HH:MM:SS)* |
|---|---|---|
| *Image Alignment* | 0:03:30 | 0:03:30 |
| *Dense Point Cloud* | 10:03:00 | 1:24:45 |
| *Build Mesh* | 1:08:00 | 0:10:00 |
| *Model Texture* | 0:03:00 | 0:00:59 |
| *DEM generation* | 0:30:00 | 0:01:10 |
| *TOTAL* | 11:47:30 | 01:39:34 |
| *Processing Step* | *Ultra-High Quality Resultant Resolution/Points/Faces* | *High Quality Resultant Resolution/Points/Faces* |
| *Image Alignment* | N/A (12 images to begin) | N/A (12 images to begin) |
| *Dense Point Cloud* | 34,618,097 points | 7,971,499 points |
| *Build Mesh* | 2,307,873 faces | 542,667 faces |
| *Model Texture* | N/A | N/A |
| *DEM generation* | 0.12 m/pix | 0.24 m/pix |

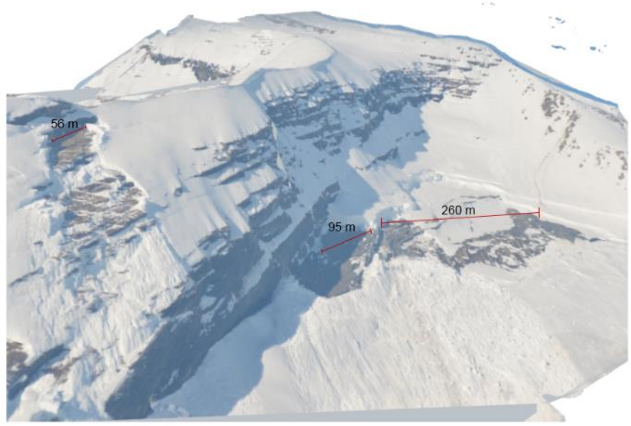
### 3.2 *Limitations*

While the resultant 3D model derived from both quality settings is of high quality resolution and visually satisfactory, it cannot be used for terrain measurements without georeferencing. Given our images were collected ad-hoc and were collected without highly accurate GCPs, georeferencing was possible, but resulted in large errors (up to 18 m). Thus, the measurements we derived in a GIS are not suitable without greater GCP accuracy. Some of the measured crown depths reached over 10.0 m, but with such large errors, these values cannot be used without more accurate GCPs or ground verification. Since avalanche crown depths require high resolution in the vertical dimension (z) for accurate measurement, error rates of this magnitude are unacceptable. However, width measurements of large avalanche crowns are still possible because the width is much larger and the error is well within the bounds of those measurements, though the error rates are still large. These width measurements were checked in a GIS with independent identifiable terrain markers using aerial imagery and a 10m DEM.

The Heavens Peak Remnant Glacier avalanche path (HPRG Main) is a path where glide avalanches occur annually (Figure 4). The width of this avalanche path varies each year, but based on 2016 measurements derived in a GIS from the SfM orthomosaic and DEM it is approximately 260 m +/- 18 m wide. The Corner Pocket avalanche that occurred this year is approximately 95 m wide +/- 18 m. Heavens Peak #3 is approximately 56 m +/- 18 m wide, and Heavens Peak #5 is approximately 109 m +/- 18 m wide (Figure 5).




(a)




(b)

Figure 4: (a) Locations of annual glide avalanche occurrence on Heavens Peak. (b) 3-D image with general width measurements of three of four avalanche crowns on Heavens Peak. Not to scale.

The results show that one limitation to examining avalanche crowns in this study that are inaccessible is adequate ground control points or more accurate camera position coordinates. The first issue can be solved by determining an adequate number of points visible in the overall scene (i.e. rocks not covered by snow) and using them as GCPs. This would only need to be done once, and then these data could be used in subsequent seasons (assuming no movement in the feature). However, accessing the scene may be difficult or time consuming as well. Acquiring these position coordinates in the summer is a possibility as well. The second issue can be resolved by using Real Time Kinematic (RTK) capable GPS units to determine high resolution (1 cm) camera coordinates. This would allow georeferencing without GCPs of any point cloud with high resolution coordinates and result in the ability to calculate height of avalanche crowns with less error (Forlani et al. 2013)

## 4. CONCLUSION

The objective of this study was to determine the feasibility and efficacy of SfM to examine glide snow avalanches along the GTSR corridor. The objective helped to answer the underlying questions:

- Is SfM a useful tool for investigating glide snow avalanches in an operational avalanche forecasting setting?
- Can we remotely determine the dimensions of glide avalanches in inaccessible terrain?

Our results show that for SfM to be a useful tool in glide avalanche crown analysis, acquisition of either highly accurate GCPs or camera locations for subsequent georeferencing is necessary. Since the purpose is to determine dimensions of avalanche crowns without access to the site, then high resolution coordinates are necessary. This is especially true with avalanche crowns given the importance of measuring relatively small variations in the vertical (z) dimension.

The use of SfM in investigating avalanches appears promising, cost-effective, and requires relatively minimal field equipment depending on acquisition methods. Given the accessibility of this technique and a better understanding of the limitations, it is feasible to begin to develop a high resolution dataset of 3-D reconstructions of glide avalanche crowns that can ultimately be used in avalanche forecasting operations along the Going-to-the-Sun Road. Ongoing work at this study site includes acquiring highly accurate GCPs for more robust analysis using these images as well as other images of nearby glide avalanches. Furthermore, this technique could also be applied to historical imagery if adequate GCPs were available in the image – thereby providing an opportunity to review previous historical avalanches with greater accuracy.

## 5. DISCLAIMER

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

## 6. ACKNOWLEDGEMENTS

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