DETECTING SNOW DEPTH CHANGE IN AVALANCHE PATH STARTING ZONES USING UNINHABITED AERIAL SYSTEMS AND STRUCTURE FROM MOTION PHOTOGRAMMETRY

Erich Peitzsch[1,2], Daniel Fagre[1], Jordy Hendrikx[2], Karl Birkeland[3,2]

[1] U.S. Geological Survey Northern Rocky Mountain Science Center, West Glacier, Montana, USA
[2] Snow and Avalanche Lab, Department of Earth Sciences, Montana State University, Bozeman, Montana, USA
[3] U.S.D.A. Forest Service National Avalanche Center, Bozeman, Montana, USA

ABSTRACT: Understanding snow depth distribution and change is useful for avalanche forecasting and mitigation, runoff forecasting, and infrastructure planning. Advances in remote sensing are improving the ability to collect snow depth measurements. The development of structure from motion (SfM), a photogrammetry technique, combined with the use of uninhabited aerial systems (UASs) allows for high resolution mapping of snow depth over complex terrain. The primary objective of this study was to determine the feasibility and efficacy of SfM to examine snow depth distribution and variability in complex terrain such as avalanche path starting zones at multiple times during the season. We used a 3DR Solo quadcopter UAS equipped with a Ricoh GR II camera at 90 m above ground level to acquire images of one avalanche starting zone in northwest Montana, USA. We also placed 4 to 13 ground control points (GCPs) around the area of interest to avoid traveling in steep, avalanche terrain. Ground control measurements resulted in 5 to10 cm horizontal accuracy and 5 to 15 cm vertical accuracy for 90 to 95 % of the collected points (a minimum of 100 points collected at each GCP). In-situ measurements of snow depth difference between sampling days ranged from 20 to 60 cm. We processed the images to create point clouds and digital surface models (DSMs). The resolution of the resultant DSMs was approximately 5 cm. Preliminary DSM and point cloud differencing efforts suggest relative change detection of snow depth at 5 to 15 cm resolution. The use of these relatively low cost and easily accessible methods of snow depth data collection will enhance accuracy of snow depth change estimates in starting zones and can be used to inform avalanche forecasting and mitigation efforts.

KEYWORDS: Structure from Motion, UAS, snow depth, photogrammetry

1. INTRODUCTION

Understanding snowpack characteristics, such as the spatial and temporal distribution of snow depth is useful for avalanche forecasting, runoff forecasting, and infrastructure planning. Measurements of snow depth can be collected in-situ or via point measurements from automated weather stations. These data are then used to estimate snow depth for larger spatial extents using interpolation algorithms. The ability to collect snow depth measurements via remote sensing methods has become easier due to the advent of remote sensing products (Tedesco et al., 2015). This increases safety by reducing or eliminating the need to collect in-situ measurements on slopes with potentially dangerous avalanche conditions. Even dense weather station or observer networks in locations like Switzerland (one measurement station per 10 km^2) are still unable to accurately capture snow depth due to complex spatial variability in alpine terrain (Bühler et al., 2016).

* *Corresponding author address:*
Erich H. Peitzsch, U.S. Geological Survey
West Glacier, MT 59936;
tel: +1 406.599.9970;
email: epeitzsch@usgs.gov

Structure from Motion (SfM), is a cost-effective remote sensing photogrammetry technique that improves 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 to produce high-resolution topographic reconstructions of a given area (Westoby et al., 2012). A three-dimensional (3-D) structure and high-resolution digital elevation model (DEM) can be derived from these images and measurements made of the area of interest (Figure 1). Nolan et al. (2015) demonstrated the feasibility of using SfM mapping snow depth on manned aircraft over a relatively large spatial scale (40 km^2) in Alaska, United States. Bühler et al. (2016) used an uninhabited aerial system (UAS) to map alpine terrain with a mean slope angle of 19 degrees, less than the typical slope angle of avalanche path starting zones. The use of SfM in published avalanche studies has been relatively sparse. Conlan and Gauthier (2016) calculated snow depth using SfM and suggest several potential uses in avalanche science. Gauthier et al. (2014) illustrated several case studies using the technique as well. 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 a UAS, 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. Peitzsch et al. (2016) used ad-hoc imagery and SfM to evaluate glide avalanche crown depth and width. They report limitations with lack of ground control points (GCPs). Given the accessibility of this technique, the primary objective of this study is to determine the feasibility and efficacy of SfM to examine snow depth distribution and variability in avalanche path starting zones.

2. METHODOLOGY

The study site is located in the Whitefish Range on the Flathead National Forest in northwest Montana, United States. The slope is approximately 0.1 km^2 and adjacent to a rural road allowing for easy access. It is a known avalanche slope with approximately 152 m vertical difference from starting zone to runout zone with slope angles up to 45 degrees with interspersed bedrock. We collected imagery on three days: February 21, 28, and March 14, 2018. For each sampling campaign, we used a 3DR Solo quadcopter UAS equipped with a Ricoh GR II camera at 90 m above ground level to acquire images of one avalanche path starting zone. We flew cross-slope and up-slope transects with 60% overlap of images using Mission Planner flight planning software to plan the flights and Tower flight application to fly the UAS (Figure 1). Before the flight, we also placed 4 to 15 GCPs around the area of interest to avoid traveling in steep, avalanche terrain, and collected in-situ snow depth measurements for ground verification. At each in-situ point, we collected high resolution Global Navigation Satellite System (GNSS) points (including Global Position System (GPS)) measurements. GCPs allow for georectification (placement in the real world) of the image and subsequent map products.

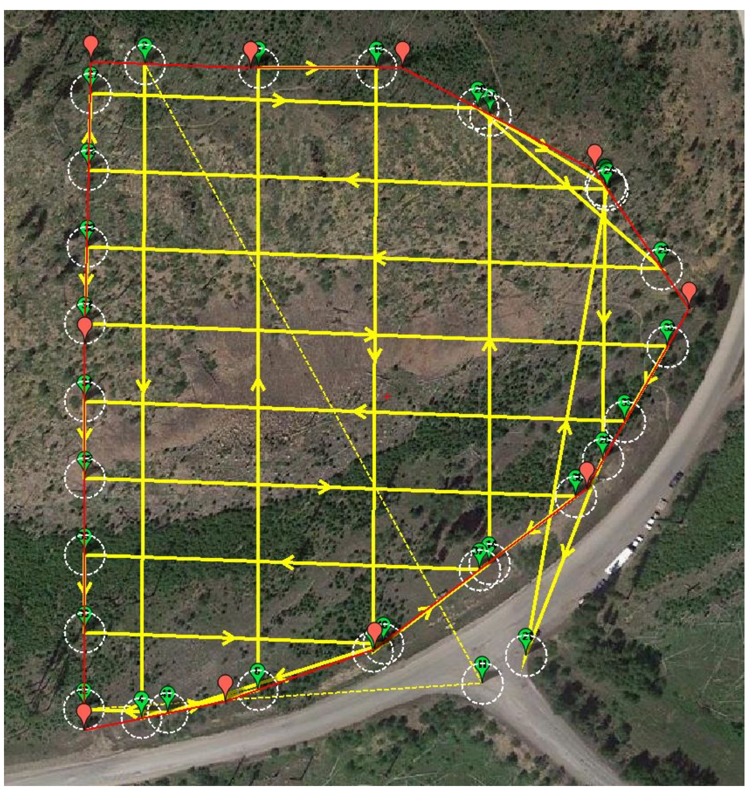

Figure 1: The study site (with the North Fork Road visible below the slope) outlined with red line. The yellow lines designate the UAS flight transects. Green points indicate UAS waypoints.

We collected 294, 251, and 262 useable images on three sampling days, respectively. Following the workflow of Westoby (2012), we uploaded the images from the camera and geo-tagged the images using the UAS GPS. This assists in aligning the images, but these coordinates were not used in geo-rectifying the images. Using Agisoft Photoscan Pro, we completed the standard SfM workflow beginning with aligning images. We then optimized photo alignment and began the error reduction process. This includes obtaining reasonable levels of reconstruction uncertainty (geometry) and projection accuracy (pixel matching errors) using a sparse point cloud. This is done by gradually eliminating a certain percentage of the remaining sparse point cloud points until the uncertainty is reduced. We then imported the GCP coordinates and placed them within the images using a semi-automated method. We then reduced reprojection error (pixel residual errors) to acceptable levels for each point cloud. The next steps included building the dense point cloud, mesh (3D model), texture, and DEMs and orthomosaics. This is the computationally demanding component of the SfM workflow depending on the number of images, quality of point cloud desired, and computational capabilities. Using a Dell Precision 7910 with Intel Xeon CPU @ 2.40 GHz, 32 GB of RAM, and a NVS 315 1024 MB graphics processing unit (GPU), this process required up to 30 hours for "High" quality point clouds and subsequent products. The limitation on this processing machine is the GPU. Finally, we exported digital surface models (DSMs), orthomosaics, and point clouds (.laz) for further analysis. We calculated the accuracy and error for each product. We differenced the DSMs and point clouds in ArcGIS ArcMap and Cloud Compare, respectively, to determine differences in snow depth from one sampling day to the next. We then calculated error between UAS derived snow depth and in-situ measurements.

3. RESULTS AND DISCUSSION

The ground resolution of the raw imagery is 2.49 cm/pixel. The camera locations resulted in up to 7m error in the x-y system, but these were only used to initially align images in a relative space. We used GCPs and associated error for geo-rectification (Table 1). We were able to obtain DSMs with resolutions of 4.97 cm/pix with point density of 405 points/m^2. The DSM obtained by differencing the DSMs from February 21 to February 28 resulted in a mean difference across the slope of -22 cm and our in-situ measured mean difference was -8 cm (Figure 2). This difference of 14 cm between measured and modeled can likely be explained through GNSS accuracy. GNSS measurements at GCPs resulted in 5 to10 cm horizontal accuracy and 5 to 15 cm vertical accuracy for 90 to 95 % of the collected points (a minimum of 100 points collected at each GCP). While this isn't ideal for assessing small storms or snow redistribution differences across a slope, it shows promise that we are able to detect differences or absolute depths on a slope. This is useful when attempting to quantify the amount of wind deposited or redistributed snow in certain areas of any given starting zone or for assessing slab depth over a known weak layer.

Table 1: Control Points RMSE (X-Longitude, Y-Latitude, Z-Altitude)

Date	# of GCPs	X error (cm)	Y error (cm)	Z error (cm)	XY error (cm)	Total (cm)
2018.02.21	13	6.43	6.94	14.23	9.46	17.09
2018.02.28	5	9.49	8.69	7.33	12.87	14.8
2018.03.14	4	4.10	3.39	1.54	5.32	5.5

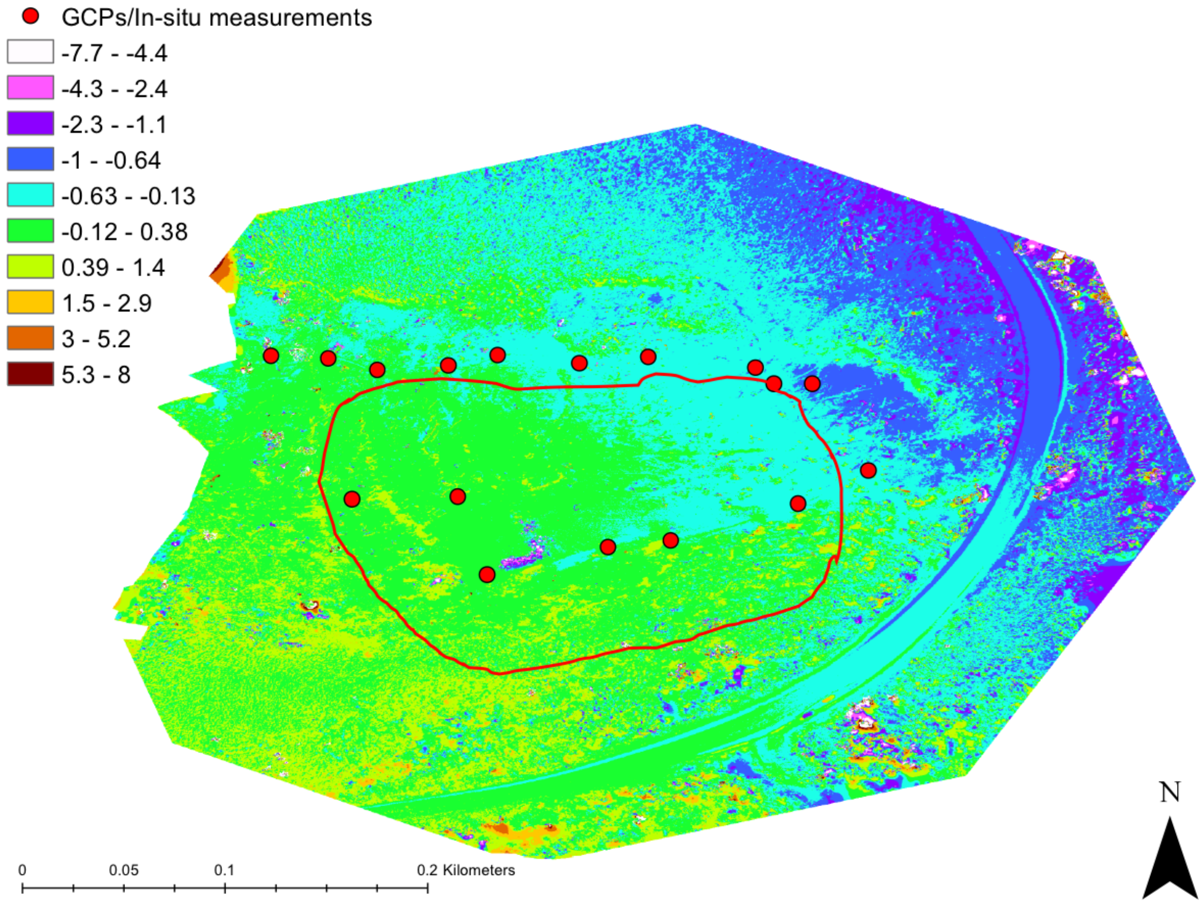

Figure 2: DSM obtained by differencing DSMs from February 21 and February 28, 2018, demonstrating temporal changes in snow depth over the seven day period. Values are in meters. The general boundary of the avalanche path is depicted by the red polygon. Note the curving road around the slope on the right of the DSM.

The DSM obtained by differencing the DSMs from February 28 to March 14 resulted in a mean difference across the slope of 5 cm and our in-situ measured differences were -22 cm. This error on this differencing is likely due to a substantial portion of the slope being snow free with ground surface roughness prohibiting accurate placement of GCPs on subsequent days in the same place. We also only used 4 GCPs this day to test the sensitivity of fewer GCPs.

4. CONCLUSION

The primary objective of this study was to determine the feasibility and efficacy of SfM to examine the temporal snow depth distribution and variability in avalanche path starting zones. We used a 3DR Solo quadcopter UAS equipped with a Ricoh GR II camera at varying heights above ground level to acquire images of one avalanche path starting zone in northwest Montana, USA. We also placed 4 to 15 GCPs around the area of interest to avoid traveling in potentially hazardous avalanche terrain. GNSS measurements at these GCPs resulted in 5 to10 cm horizontal accuracy and 5 to 15 cm vertical accuracy for 90 to 95 % of the collected points (a minimum of 100 points collected at each GCP). In-situ measurements of snow depth difference between sampling days ranged from 20 to 60 cm. We created point clouds and digital surface models (DSMs). These DSMs were then differenced using a GIS. The resolution of the resultant DSMs was 4.97 cm with XY ground control point error rates up to 13 cm. The error between DSM values and in-situ measurement values was 14-27 cm, the latter due to field sampling difficulties of GCPs.

SfM proved to be a useful tool for detecting snow depth change on steep, rocky terrain.

Given the relatively small error values, this technique is capable of capturing accumulation differences of greater than 10 cm between days. Thus, for most active avalanche days, which have accumulations greater than about 25 cm, this method can capture both the increase in depth across the slope as well as the variability in that increase. However, careful attention to the placement of GCPs and/or high resolution GNSS measurements is necessary to reduce error. These techniques and methods are suitable for avalanche practitioners. For example, forecasting operations could determine the snow depth change due to wind loading, or monitor snow depth over the ground cover or known weak layers without exposing personnel to hazardous terrain. The relative low cost also makes this technique accessible to avalanche practitioners.

ACKNOWLEDGEMENTS: We thank Zachary Miller of the USGS Northern Rocky Mountain Science Center for his field assistance and data processing as well as Joe Adams of the USGS UAS Office for consultation. We also thank Simon Trautman and Zachary Guy for their reviews that helped improve this extended abstract.

References

Bühler, Y., Adams, M.S., Bösch, R. and Stoffel, A., 2016. Mapping snow depth in alpine terrain with unmanned aerial systems (UASs): potential and limitations. The Cryosphere, 10(3): 1075-1088.

Conlan, M. and Gauthier, D., 2016. Using photogrammetry to temporally compare snowpack thicknesses and calculate volumes, In E. Greene (Editor): Proceedings of the 2016 International Snow Science Workshop, Breckenridge, Colorado, United States. October 3-7, 2016. , pp. 45-50.

Eckerstorfer, M., Solbo, S. and Malnes, E., 2015. Using "Strucutre-from-Motion" Photogrammetry in Mapping Snow Avalanche Debris. In: K. Kriz (Editor), Wiener Schriften zur Geographie und Kartographie. University of Vienna, Vienna, pp. 171-178.

Gauthier, D., Conlan, M. and Jamieson, B., 2014. Photogrammetry of fracture lines and avalanche terrain: Potential applications to research and hazard mitigation projects. In: P. Haegeli (Editor), Proceedings of the 2014 International Snow Science Workshop, Banff, Alberta, Canada, pp. 109-115.

Nolan, M., Larsen, C. and Sturm, M., 2015. Mapping snow depth from manned aircraft on landscape scales at centimeter resolution using structure-from-motion photogrammetry. The Cryosphere, 9: 1445-1463.

Peitzsch, E.H., Hendrikx, J. and Fagre, D.B., 2016. Using structure from motion photogrammetry to examine glide snow avalanches. In: E. Greene (Editor), Proceedings of the International Snow Science Workshop, Breckenridge, Colorado, USA, pp. 492-500.

Tedesco, M., Derksen, C., Deems, J.S. and Foster, J.L., 2015. Remote sensing of snow depth and snow water equivalent. In: M. Tedesco (Editor), Remote Sensing of the Cryosphere. John Wiley & Sons, Ltd, Chichester, UK.

Westoby, M.J., Brasington, J., Glasser, N.F., Hambrey, M.J. and Reynolds, J.M., 2012. ‘Structure-from-Motion’ photogrammetry: A low-cost, effective tool for geoscience applications. Geomorphology, 179: 300-314.