GUIDELINES FOR USING PHOTOGRAMMETRIC TOOLS ON UNMANNED AIRCRAFT SYSTEMS TO SUPPORT THE RAPID MONITORING OF AVALANCHE-PRONE ROADSIDE ENVIRONMENTS

PROJECT REPORT

by

Nathan Belz
University of Alaska Fairbanks

Edward McCormack
University of Washington

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16. Abstract

Unmanned aircraft systems (UAS) technology paired with photogrammetric capabilities has the potential to rapidly provide feedback on snowpack data that can be used to monitor and forecast avalanche risks. This research tested Structure from Motion (SfM) (photogrammetry) software with data from unmanned aircraft above roadside avalanche test sites in Alaska and Washington state. The SfM data included accurate information about snowpack depth and snowpack volume, which can help department of transportation (DOT) avalanche experts assess risk and determine whether mitigation was necessary. In addition, the digital images collected for the SfM provided additional useful information. The collection of SfM data has limitations, as successful data collection requires proper ground control points for registration of the images, adequate lighting to collect the digital images required for the SfM process, and the ability to fly the unmanned aircraft to collect the data, which may be limited by both weather and regulations. Overall, the effort determined that SfM provides usable data, and it created a decision support tool to assist DOTs in more quickly responding to and mitigating avalanche hazards, opening roads, or avoiding closing them at all and thus improving roadway reliability for both freight and passengers.

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS				
Symbol	**When You Know**	**Multiply By**	**To Find**	**Symbol**
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
^oF	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	^oC
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS				
Symbol	**When You Know**	**Multiply By**	**To Find**	**Symbol**
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact degrees)		
^oC	Celsius	1.8C+32	Fahrenheit	^oF
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380. (Revised March 2003)

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LIST OF ABBREVIATIONS

AGL:	Above ground level
ATC:	Air traffic control
AKDOT&PF:	Alaska Department of Transportation and Public Facilities
ATO:	Above the take off
BLOS:	Beyond line of sight
COA:	Certificates of Waiver or Authorization
COVID:	Coronavirus disease 2019
DEM:	Digital Elevation Model
DGGS:	Alaska Division of Geological & Geophysical Surveys
DOT:	Department of transportation
DSM:	Digital surface model
FAA:	Federal Aviation Administration
GCP:	Ground control point
GNSS:	Global Navigation Satellite Systems
GPS:	Global Positioning System
LIDAR:	Light Detection and Ranging
NOTAM:	Notice to Airmen
NPRA	Norwegian Public Roads Administration
NVA	Non-vegetated vertical accuracy
PacTrans:	Pacific Northwest Transportation Consortium
PPK	Post-processed kinematic
RMSE:	Root mean square error
RTK-GPS:	Real-time kinematic, Global Positioning System
SfM:	Structure from Motion
TFR:	Temporary flight restrictions
TRF	Temporary flight restrictions
UAF	University of Alaska Fairbanks
UAS:	Unmanned aerial/aircraft system
UAV	Unmanned aerial vehicle
WSDOT:	Washington State Department of Transportation

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EXECUTIVE SUMMARY

Unmanned aircraft systems (UAS) technology (i.e., drones) paired with photogrammetric capabilities has the potential to rapidly provide feedback on snowpack data that can be used to monitor and forecast avalanche risks. These data will assist department of transportation (DOT) winter maintenance staff who operate snow avalanche programs in the PacTrans region (Washington, Idaho, and Alaska), as well as most other transportation agencies with mountains, as they make difficult decisions about when to close and reopen highways in times of high avalanche risk or to deploy other means of avalanche mitigation.

As part of this research, DOT staff working with the researchers tested Structure from Motion (SfM) software (photogrammetry) using data from unmanned aircraft above test sites in Alaska and Washington state. The SfM data included accurate information about snowpack depth and snowpack volume, which can help DOT avalanche experts assess risk and determine whether mitigation is necessary. In addition, the digital images collected for the SfM provided additional useful information. The collection of SfM data has limitations, as successful data collection requires proper ground control points for registration of the images, adequate lighting to collect the digital images required for the SfM process, and the ability to fly the unmanned aircraft to collect the data, which could be limited by both weather and regulations.

Overall, the effort determined that SfM provides usable data, and it created a decision support tool to assist DOTs in more quickly responding to and mitigating avalanche hazards, opening roads, or avoiding closing them at all and thus improving roadway reliability for both freight and passengers.

CHAPTER 1 INTRODUCTION

1.1 Background

A number of western states have important routes below avalanche-prone mountains, so that snow avalanches threaten the roadway and travelers. In the winter, keeping these roads open for safe and reliable travel requires that transportation agencies operate programs to monitor snow conditions, assess risk, and, as needed, conduct expensive artificial intentional releases of avalanches with explosives. Road closures during times of risk impose a high economic cost and greatly affect the reliability of the overall transportation network. In Washington state, for example, I-90, the state's main east-west corridor, was closed for 70 hours during the winter of 2016- 2017 and for 25 hours in 2020-2021 while Washington State Department of Transportation (WSDOT) staff dealt with avalanche concerns (WSDOT 2021). In Alaska, avalanches occurred at Atigun Pass in the 2017 season, one of which trapped four trucks and blocked the road for several days (KTUU 2017, Daily News Miner 2017). Thompson Pass routinely receives snowfall in excess of 12 feet over the course of an hour, and avalanches occur annually. They have isolated the city of Valdez, Alaska, for periods lasting up to a week.

Current avalanche monitoring efforts by departments of transportation (DOTs) include data collection involving visual observation, hand dug snow pits, and stationary sensors combined with weather information. Of interest to avalanche staff are snow depth and snow depth changes because these indicate how much snow is available to be released by an avalanche or can help determine whether a surface has been swept clean by previous avalanches or moved around by wind. The staff also examines the snowpack surface and the surrounding terrain. Features such as cracks in the snow surface, signs of previous avalanches, concave or convex slopes, cornices, and snow anchors such as trees or rocks are indicators of avalanche risk (Avalanche.org 2019).

This effort explored the use of unmanned aerial systems (UASs) carrying cameras to use with Structure from Motion (photogrammetry) software as a tool for gathering information about snowpacks and avalanche risk to support DOT staff as they make decisions to open or close roadway below slopes. SfM can obtain 3-D images from multiple, overlapping images collated from standard 2-D cameras. SfM uses the principle of stereoscopic photogrammetry in which triangulation is used to calculate the 3-D positions of objects from stereo pairs.

A UAS is considered to comprise all components that make an unmanned aerial vehicle (a UAV or drone) work, including the aircraft, locational systems such as GPS, ground control module, transmission systems, cameras and sensors, all the planning and operating software, and the pilot.

In Washington state, as part of this effort, DOT staff and the research team flew three roadside avalanche sites with seven different flights to collect SfM results, which were shown to WSDOT avalanche staff. These tests determined that SfM has value for assessing avalanche risk. The flight also demonstrated challenges with collecting images usable with SfM, including difficulty in flying in bad weather conditions and in areas of restricted visibility caused by trees and terrain. The tests also highlighted the importance of ground control points so that before and after snow images can be registered in the SfM software.

In Alaska, over the course of this project, the avalanche manager in Atigun Pass coordinating with the research team was able to execute 138 flights and acquire nearly 15,000 images for use in the SfM process. The data from these fights were used and evaluated by avalanche professionals and were determined to be useful for determining the level of risk. In addition, the SfM data were compared to other types of snowpack data, and the SfM results were determined to be highly accurate.

1.2 Report Structure

The organization of the report is as follows. A literature review in Chapter 2 explores other relevant uses of UASs to support avalanche monitoring programs, with an emphasis on Structure from Motion (SfM) photogrammetry software carried by UASs. Chapter 3 discusses the field tests in Alaska and Washington as well the equipment and software used in this effort. Chapter 4 discusses analyses of the results of the field test. Chapter 5 makes recommendations for roadway agencies interested in using UASs and SfM operationally for roadside avalanche monitoring. Chapter 6 is a summary of the research and outlines the benefits and challenges of using SfM data derived from digital images collected by UASs for avalanche monitoring. Next steps and further research are also suggested. The appendixes contain supporting material.

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CHAPTER 2 LITERATURE REVIEW

2.1 Literature Review

Small, unmanned aircraft have seen significant technical advances in the past 20 years and have become increasingly affordable, readily available from commercial vendors, and easier to operate. The U.S. DOT has forecasted that there will be 835,000 commercial UASs and 351,000 pilots by 2025 (FAA, 2021). Current generation UASs can be transported in small vehicles and launched from a road or a small truck but are still large enough to be equipped with cameras and sensors that can provide high quality aerial information. In addition, these aircraft can fly without direct human input, autonomously completing preset flight plans.

UASs can be equipped with cameras and sensors to collect snow data, which could be quicker, much safer, and less costly than the existing methods used by DOTs for monitoring snow conditions and avalanche areas. A series of previous tests have indicated that UASs have considerable potential. In 2006 and 2007, working with WSDOT avalanche control staff, studies completed by project team members explored the feasibility of using the relatively new civilian UAS technology as a tool to support avalanche control operations. The tests concluded that UASs could be operated from a roadside by transportation agencies and had potential to support avalanche operations. (McCormack 2009, McCormack and Stimberis 2010a, 2010b).

In 2013, McCormack and Lundquist, coordinating with WSDOT, explored the types of sensors and cameras that could be used to provide high quality aerial information about snow conditions. This study reviewed previous work on remote snow sensing and evaluated a wide range of sensor technologies that could be carried on small UASs. On the basis of the most promising sensors for UAS use, the research team flew two infra-red cameras and one visual camera on a manned aircraft. The findings concluded that for avalanche forecasting, visual cameras can identify areas of cornice formation that can trigger avalanches (Lundquist et al. 2013).

In 2014, McCormack worked with the Norwegian Public Roads Administration (NPRA) to test a small multi-rotor UAS in Norway to determine how such equipment would operate in mountainous terrain in support of avalanche monitoring. The findings suggested the need for additional tests to explore routine, operationally oriented flights of small UASs while dealing with winter weather and rugged terrain.

In 2016, the NPRA sponsored a three-day demonstration evaluating the usability of UASs to support routine avalanche monitoring. This effort tested whether UASs could safely operate in inclement winter conditions and in the steep terrain that generates snow avalanche hazards. Nine different aircraft (including multi-rotor, fixed wing, and helicopters) were flown in a series of flights that replicated the NPRA's typical avalanche monitoring needs. Many of the aircraft (particularly fixed wing) were able to effectively fly in harsh conditions to view distant and inaccessible avalanche release areas. The UAS's photo and video quality were generally good, and several examples were exceptional. A simulated slab snow avalanche in one scenario was quite easy to see with cameras on a small multi-rotor. The evaluation concluded that UASs have considerable potential to support a roadside avalanche program but that additional research to determine the best sensor and camera technologies to provide remote snowpack and avalanche hazards information was needed (McCormack et al. 2017).

In 2018, McCormack led a Norwegian sensor technology test to evaluate whether sensors and cameras carried on UASs could provide avalanche staff with usable avalanche information. A visual camera, used for both real-time viewing and photogrammetry (SfM), was among the equipment flown. Photogrammetry was found to have considerable potential because it did not require an expensive sensor, and it could map snow surface conditions and, with a baseline survey, could also measure snow depth, both of which are valuable for avalanche assessment. The concurrent, real-time camera views of the snowpack were also valuable to the avalanche staff (McCormack and Vaa 2019).

The accuracy of the SfM depends on the ability to geolocate the images typically using ground control points. This image processing technique replicates light detecting and ranging (lidar) technology but with much less costly equipment. And as with lidar, this technology has been used to map snow. Other research efforts have determined the following:

> "SfM is a promising new photogrammetric methodology, which enables the collection of geospatially accurate and high-resolution data, useful in avalanche dynamics modeling and snow depth spatial variability studies." (Eckerstorfer et al 2015).

This technology has been used for snow analysis in several studies, with promising results when applied in a research setting (see for example, Bühler et al 2016, Cimoli et al 2017, Fernandes et al 2018, and Gaffey and Bhardwaj 2020).

Cimoli et al (2017) used SfM in a research setting and noted the following:

> "Of the resulting snow depth maps with spatial resolutions between 0.06 and 0.09 m, the average difference between the UAV-estimated and conventional snow probing depths varied within an acceptable range of 0.015 to 0.16 m."

In a detailed survey of the use of UASs-to understand field-based cryospheric (frozen earth) research, Gaffey and Bhardwaj (2020) concluded that unmanned aerial vehicles (UAVs) have emerged as a viable and inexpensive option. Their review explored recent applications to measure snow cover, one of the most common usages of UASs. Given its frequent use in the cryosphere, SfM was evaluated, and the report determined that snow is challenging for SfM algorithms "because of the high reflectance of homogenous surfaces and lack of contrast." The report also stressed the importance of ground control points. Gaffey and Bhardwaj's review, however, did not mention the use of UAVs or sensors for avalanche monitoring, and the examples cited were research-based and not designed to support the routine snow condition data collection s required by many roadway owning agencies.

Another recent study conducted an evaluation of SfM snow depth distribution maps of an experimental five-hectare site in Spain (Revuelto et al, 2021). The evaluation tested different commercial UAVs and collection methodologies, and it used both fixed wing and multi-rotor unmanned aircraft. Three different ground control methods (fixed points, an iterative closest point (ICP) algorithm, and real-time kinematics (RTK)-GPS positioning) were examined. Data were collected under contrasted snow surface characteristics and at different altitudes. Lidar data were used to develop ground truthed snow depths. The findings showed, for the best case, a root mean square error (RMSE) below 0.23 meters for snow depth, and maximum snowpack volume deviations were less than 5 percent. Different flight altitudes did not produce significant differences in the snow distribution maps. The study concluded:

> "that under good illumination conditions and in relatively small areas, affordable commercial UAVs provide reliable estimations of snow distribution compared to more sophisticated and expensive close-range remote sensing techniques. Results obtained under overcast skies were poor, demonstrating that UAV observations require clear-sky conditions and acquisitions around noon to guarantee a homogenous illumination of the study area."

A study in Switzerland evaluated the strengths and weaknesses of collecting snow depth measurement using photogrammetric mapping techniques on different platforms, including the use of small UASs over a 1.5-mile square area at 7,700 feet (Eberhard et al 2021). The photogrammetry derived measures (processed in Agisoft Metashapes) were compared to manual snow depth measurements. The report concludef that UAS images were "an economical and flexible method for mapping snow depth with high accuracy." The study found an RMSE value of 0.16 m and high spatial resolution, but the coverage of the UAS was limited.

Only a handful of studies have specifically explored the use of UASs to support roadside avalanche data collection. One such Norwegian study explored the use of small, consumer-grade UASs to collect SfM data by mapping several known roadside avalanche paths, but doing so pre-snowfall during bare earth conditions (McCormack et al, 2020). The flights demonstrated that two people over the course of one day could set up, fly, and obtain usable, high resolution surface models of the release areas of interest that could serve as a foundation for future flights of the same location after snowfall.

The Norwegian study used 24 spray painted "Xs" as ground control markers and explored the use of all 24 markers and only ten of the markers located in avalanche-safe locations above the survey area. The resulting surface model was compared to existing lidar data, and as expected, use of all 24 markers resulted in the highest accuracy, with a total RMSE on markers of 8.9 cm and a difference of 12 cm and a standard deviation of 47 cm. Using only ten markers in the avalanche safe areas resulted in a total RMSE of 8.0 cm among the ground control points and 18.5 cm on the rest of the markers.

The British Columbia Ministry of Transportation and Infrastructure (2020) commissioned one of the few studies found to specifically explore the use of UASs to support roadside avalanche data collection. The project tested different UASs and explored the use of different SfM processes to understand snow-covered surfaces and estimate snow depth. They also used the technology to visually inspect slide paths and built a data portal. The study found that multirotor UASs (as opposed to fixed rotor) were the most practical as part of an avalanche program, but a major constraint was flight duration. The report also concluded that the snow depth measurement accuracy varied considerably depending on the methods used. Sole reliance on a built-in Global Navigation Satellite Systems (GNSS) receiver on the aircraft led to unacceptable inaccuracy, but this inaccuracy was considerably reduced by using ground control points. The most accurate measurement was obtained using post-processed kinematic (PPK) techniques (a GPS correction technology) resulting in an RMSE of 28 cm for snow depth measurements.

2.2 Summary

The findings from the literature review confirmed that UASs can operate in the rugged terrain and frequently bad weather where and when snow avalanches occur. Other studies exploring snowpack depth measurements found that photogrammetry applied to images collected by small UASs can result in usable and accurate snowpack depth information except where there were limitations due to lighting conditions. The RMSE for snow depth found in these studies varied between 8 and 28 cm. Ground control markers were noted to be as important to the accuracy of measurements, with their locations and numbers being site specific.

A gap among these studies is that they focused on data analysis and not necessarily on data collection in real-time operational conditions, as required by roadway operating agencies that need rapidly collected data to support critical decisions to open or close roads. Thus, the literature review did not find research focused on flights from roadsides in all weather conditions or on pragmatic issues such as connecting the different UAS flights, acquiring data, processing data, and placing the output directly into a format that supports a transportation agencies' routine avalanche operations.

CHAPTER 3 TEST FLIGHTS

This chapter discusses the series of tests completed in Alaska and Washington state to evaluate the aircraft's ability to fly in realistic field conditions above avalanche-prone roads while collecting data for SfM analysis. These test sites were selected where the WSDOT and the Alaska Department of Transportation and Public Facilities (AKDOT&PF) conduct routine roadside avalanche monitoring and control operations.

The chapter also reviews the UASs and software used for the flights. In most cases this equipment was used because it was already owned and operated by WSDOT and the AKDOT&PF. This equipment was also used because it both represented typical equipment that DOTs operate and because the UASs could collect the digital images required for SfM analysis.

3.1 Test Flights

Collectively, the University of Washington/ University of Alaska Fairbanks team, and the two participating DOTs flew almost 150 flights at the pre-selected roadside locations. The tests allowed the exploration of UAS operations, the collection of images, and the application of SfM to avalanche hazard monitoring by the two roadway agencies in varied terrain, snow conditions, and weather.

Given the seasonal snowpack limitations and COVID concerns, several pre-snow (bare earth) tests were completed after the flights over snow had been conducted. Since this project was, in part, concerned with accuracy of the SfM, the sequence of the pre-snow and post-snow flights did not impact the findings. Of course, in an operational setting, bare earth data before snowfall data would be necessary to provide DOT avalanche staff with near or near-real-time data on snow depth and volume.

The other reason, in an operational situation, a pre-snow test would be important would beto determine staging or parking areas for the DOT vehicles and landing areas for the UAS aircraft and to develop the GPS flight (mission) profiles for flights after snowfall.

3.2. Alaska Test Locations

The tests in Alaska occurred at Atigun Pass, which is located approximately 320 miles north of Fairbanks on the Dalton Highway (see figure 3.1). The pass itself is 4.3 miles long with numerous chutes that produce avalanche activity on a regular basis (see figure 3.2). Table 3.1 highlights the natural and artificial avalanche activity in Atigun Pass from 2015 to 2020. On average, 39 avalanche events reach the road, and an additional 38 avalanche events block the road entirely in a given year. The environment in Atigun Pass is extremely challenging for UAS operations because lighting conditions are limited/poor because of the high latitude above the Arctic Circle, and significant winds and blowing snow in the winter can affect the quality of the SfM product. There were also limitations related to altitude restrictions in that many of the release zones are at a high elevation (approximately 5,000 feet), and the internal altitude unlock features did not work in some of the flight modes for the DJI UAS used by the AKDOT&PF (e.g., terrain following). Additionally, there was limited air space near and along the Alaska pipeline that was nearby, but ADOT&PF had special air space permissions to overcome this limitation.

Figure 3.1 Large vehicles and AKDOT&PF machinery on the Dalton Highway at Atigun Pass

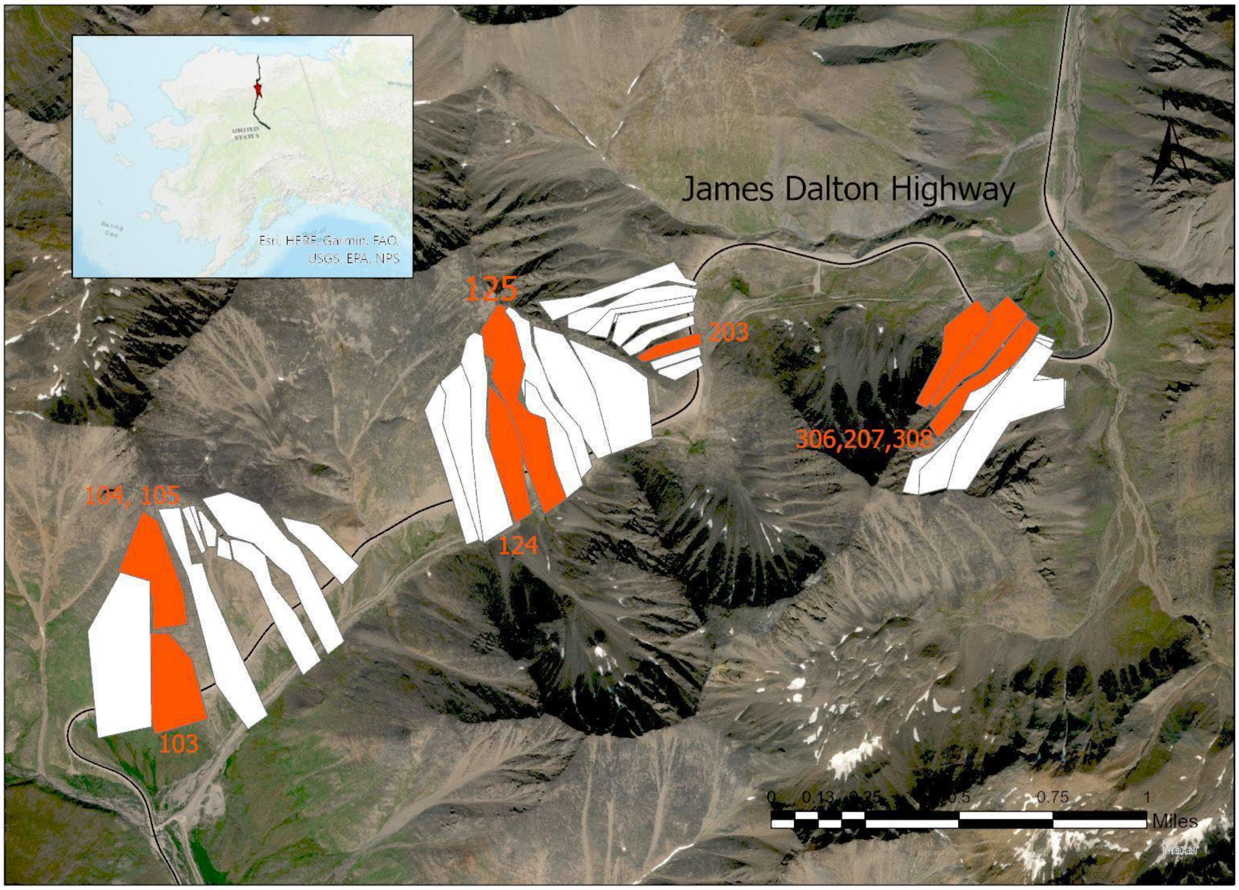


Figure 3.2 Avalanche zones of interest in Atigun Pass along the Dalton Highway

Table 3.1 Natural and artificial avalanche activity in Atigun Pass, 2015-2020

		2015-16		2016-17		2017-18		2018-19		2019-20		
		Artificial	Natural	Artificial	Natural	Artificial	Natural	Artificial	Natural	Artificial	Natural	Total
100	Blocked Road	7	11	5	21	20	19	4	18	12	12	129
	Partial Road	7	14	2	15	1	16	2	14	5	11	87
	No Road	14	48	24	18	46	38	29	36	10	10	273
200	Blocked Road	5	2	2	1	7	3	1	0	3	1	25
	Partial Road	52	1	3	0	1	8	1	5	3	0	74
	No Road	7	5	5	0	11	11	7	15	4	2	67
300	Blocked Road	7	0	4	2	6	5	0	1	7	0	32
	Partial Road	1	2	4	3	6	9	0	5	0	4	34
	No Road	12	17	14	8	10	33	14	24	8	13	153
Total		112	100	63	68	108	142	58	118	52	53	874
Percent		52.8%	47.2%	48.1%	51.9%	43.2%	56.8%	33.0%	67.0%	49.5%	50.5%	

3.2.1. Baseline Data

To provide a set of baseline data, the Alaska Division of Geological & Geophysical Surveys (DGGS) used Structure-from-Motion (SfM) photogrammetry from a manned, fixed-wing platform to produce a digital surface model (DSM) and orthoimagery datasets of Atigun Pass during snow-covered surface conditions on April 9, 2015, and April 3, 2016 (figures 3.3 and 3.4). These surveys provided end-of-winter, snow-covered surface elevations for deriving snow depth distribution models with repeat surveys during snow-free conditions. These data collections will be released as raw data files with open end-user licenses, and they are publicly available at https://dggs.alaska.gov/pubs/. Details about the collection of the baseline data can be found in Appendix A.

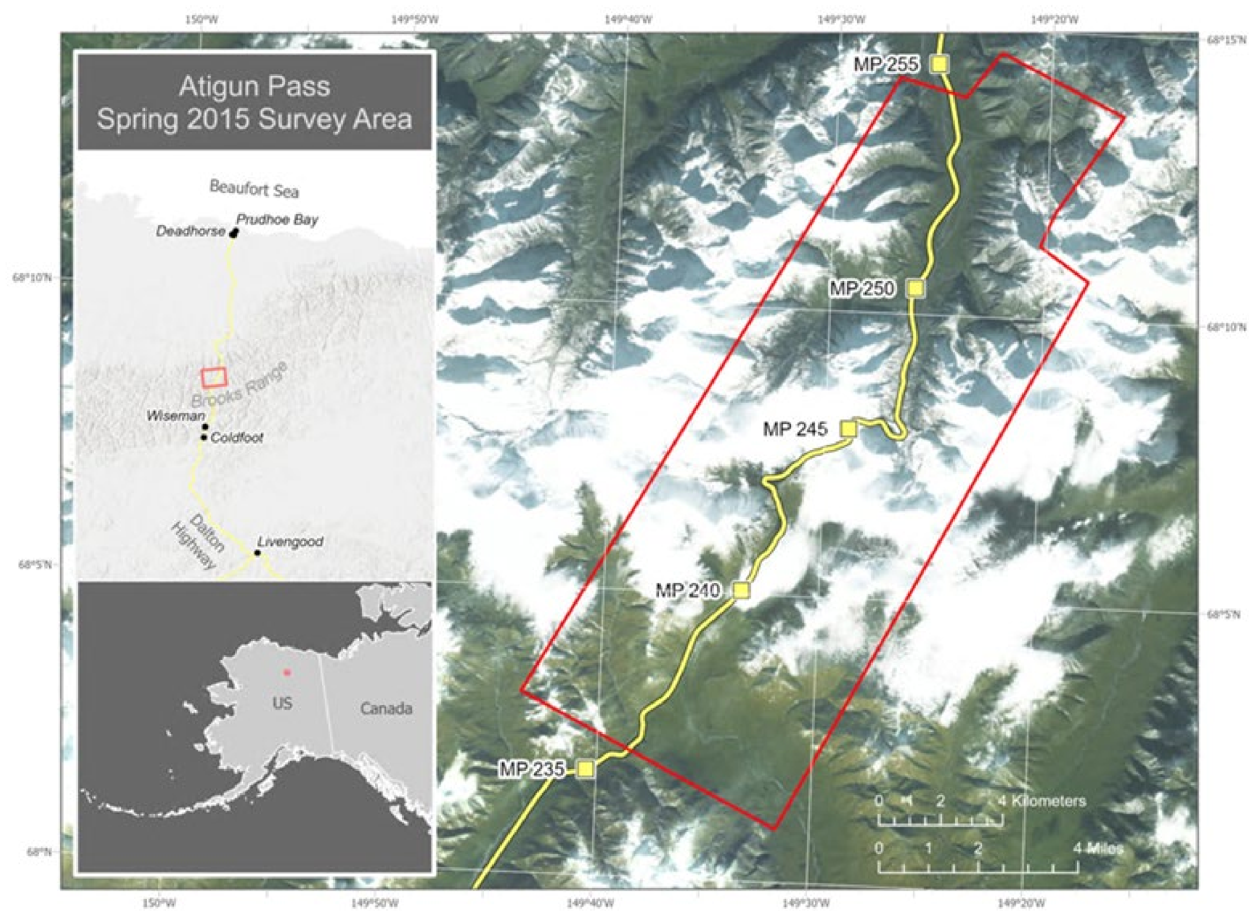


Figure 3.3 Location map of 2015 survey area with orthoimagery

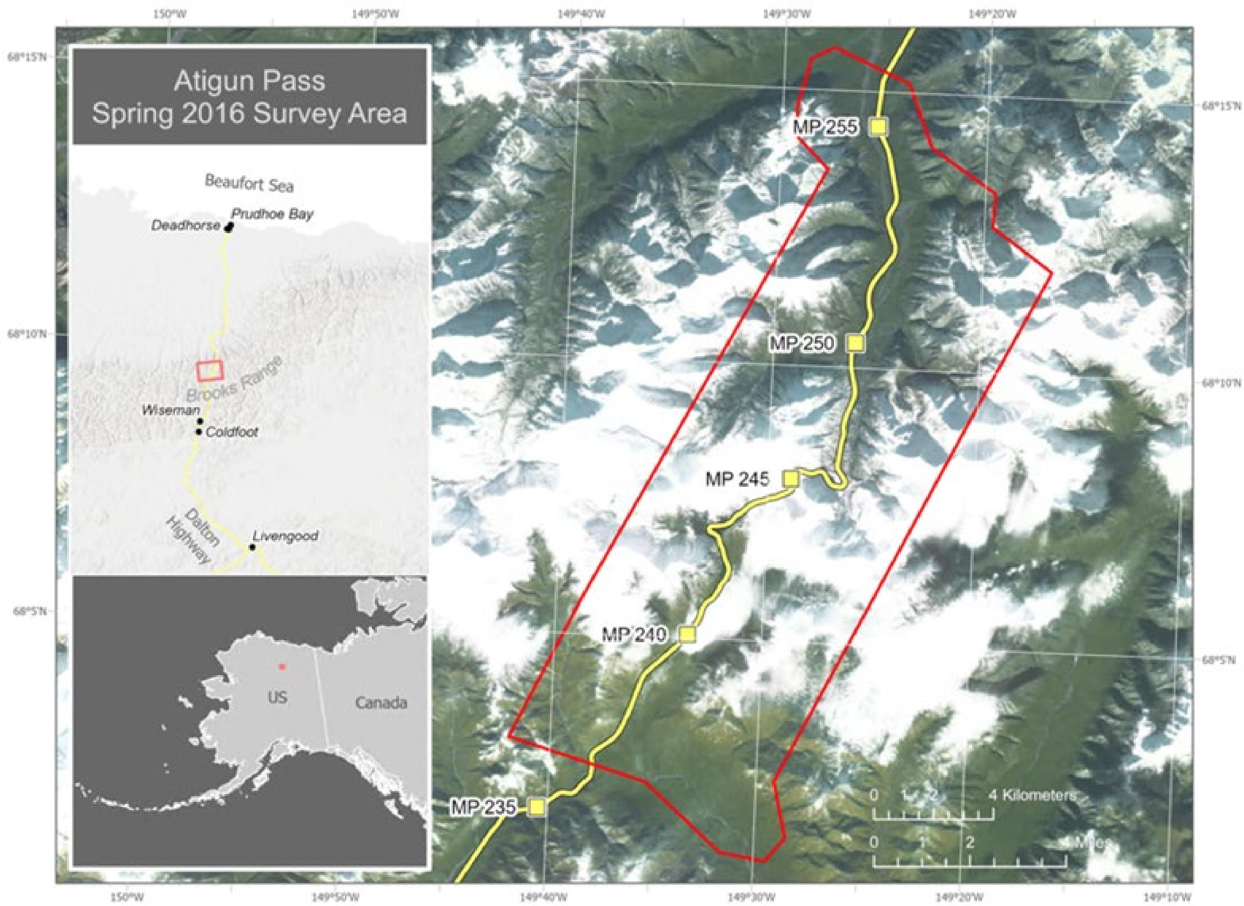


Figure 3.4 Location map of 2016 survey area with orthoimagery

3.2.2. Hardware Selection Considerations

The UAS most readily available to Alaska DOT&PF staff was a DJI Phantom 4 RTK (see figure 3.5) that was provided to the Avalanche Specialist from the Northern Region Survey Division. This aircraft had a flight duration of about 30 minutes. The DJI M300 RTK was also a consideration and had a flight duration of up to 55 minutes. Both platforms are excellent for photogrammetry. By comparison, the Phantom 4 RTK had a 20-MP sensor, and those data are of very high quality. With a 45-MP sensor, staff can fly higher, save time collecting data in the field, and still get 0.1-ft vertical accuracy. Table 3.2 shows a comparison of prices and capabilities of select DJI UAS products.

Figure 3.5 DJI Phantom 4 RTK (a) and DJI controller (b) being used in Atigun Pass, Alaska

Table 3.2 DJI aerial systems general specifications (Source: DJI)

	Phantom 4 RTK	M300 RTK + P1	M300 RTK + L1
All In Price	~$12,000 $	~$35,000 $$$	~$45,000 $$$$
Camera	20MP Global Shutter	45MP Global Shutter	20MP Global Shutter
LiDAR	n/a	n/a	Yes
Accuracy	0.1'	0.1'	0.3'
Complexity	Medium	Medium	High
Good For	Most projects	Large projects, high detail requirements, challenging flight conditions	Vegetated project sites

Because of the high latitude and mountainous terrain, the project team also used a DJI D-RTK 2 Mobile Station, which was a high-precision GNSS receiver that helped improve satellite acquisition, positioning, and relative accuracy during UAS operations.

In general, flights were executed in Terrain Following mode, with pre-programmed flight paths for avalanche chutes of interest. Because the mountainous terrain exceeded the maximum above the take off (ATO) altitude of 500 m for the Phantom RTK platform, the pilot was unable to operate flight plans that exceeded that altitude. This was overridden by taking off from a higher location and then manually flying to a chute location before beginning flight plan operations.

3.2.3. Airspace and Regulatory Considerations

There were several unique factors that could affect UAS operations in Atigun Pass. First, the Dalton Highway that passes through Atigun Pass is co-located with the Alyeska Pipeline. Alyeska routinely executes monitoring flights by plane and helicopter through the airspace of Atigun Pass. Second, the elevation differences and use of smaller personal aircraft in the airspace of Atigun Pass meant that private aircraft also fly through the area regularly. Both these activities increased concerns about airspace control and occupancy. Lastly, because the AKDOT&PF maintenance crew utilizes howitzers for avalanche mitigation and control, they have already been approved to use FAA-issued Certificates of Waiver or Authorization (COA).

The COA and special airworthiness approvals authorize UAS flight operations to be contained within specific geographic boundaries and altitudes but require coordination with an air traffic control (ATC) facility. They typically require the issuance of a Notice to Airmen (NOTAM) describing the operation to be conducted.

Additionally, under standard FAA 107 flying rules, one must fly within 400 ft. above ground level (AGL), which in practice means that the aircraft cannot fly straight up to reach the top of the mountain but must follow the terrain. Some aircraft manufacturers (e.g., DJI) limit the maximum altitude the UAS can fly from the takeoff point to the initial point of acquisition.

3.2.4. Software Utilized

For reporting and display, the project team recommends Google Earth as an absolute minimum. The advantages of using Google Earth are that it is free and relatively user friendly. However, other mapping platforms such as the ESRI products or Propeller would be necessary depending on the types of analyses required. Below are listed the other software packages used in the acquisition and processing phases. The following software and end-user packages were utilized for this project in Alaska:

- *Airdata UAV* provides flight data analytics for preventive maintenance, regulatory reporting, general aircraft health, and flight performance. Airdata was used to catalog the details of each flight and weather conditions.
- *GrafNav* by Novatel is a GNSS waypoint post-processing software. UAV positioning and velocity, which was based on real-time GNSS technology, was limited by real-time

transmission of correction data. Positional accuracy was improved by using this post-processing product.

- *Python* is a programming language that can be used to integrate several language systems across hardware and software to automate and optimize workflow. Here it was used to streamline the post-processing of the aerial imagery.
- *Agisoft Metashape* is a stand-alone platform that performs photogrammetric processing of digital images. Agisoft allowed for the integration of Python coding.

3.3 Washington State Tests Locations

The Washington state test sites in the Cascade Mountains were the following:

- Granite Mountain (above Interstate-90, flight not completed)
- West Shed Area (above Interstate-90)
- Chinook Pass (above State Route 410).

3.3.1 I-90 Tests

WSDOT's avalanche staff identified four sites along Interstate 90 (I-90) in the Cascade Mountains as locations that required routine avalanche monitoring, forecasting, and mitigation. Figure 3.6 shows the avalanche areas on I-90 and Snoqualmie Pass that are of concern for WSDOT. I-90 over Snoqualmie Pass reaches 3,022 feet, and this pass averages more than 450 inches of snowfall each winter and is a major travel corridor with a typical daily traffic volume of 28,000 vehicles (WSDOT, 2021).

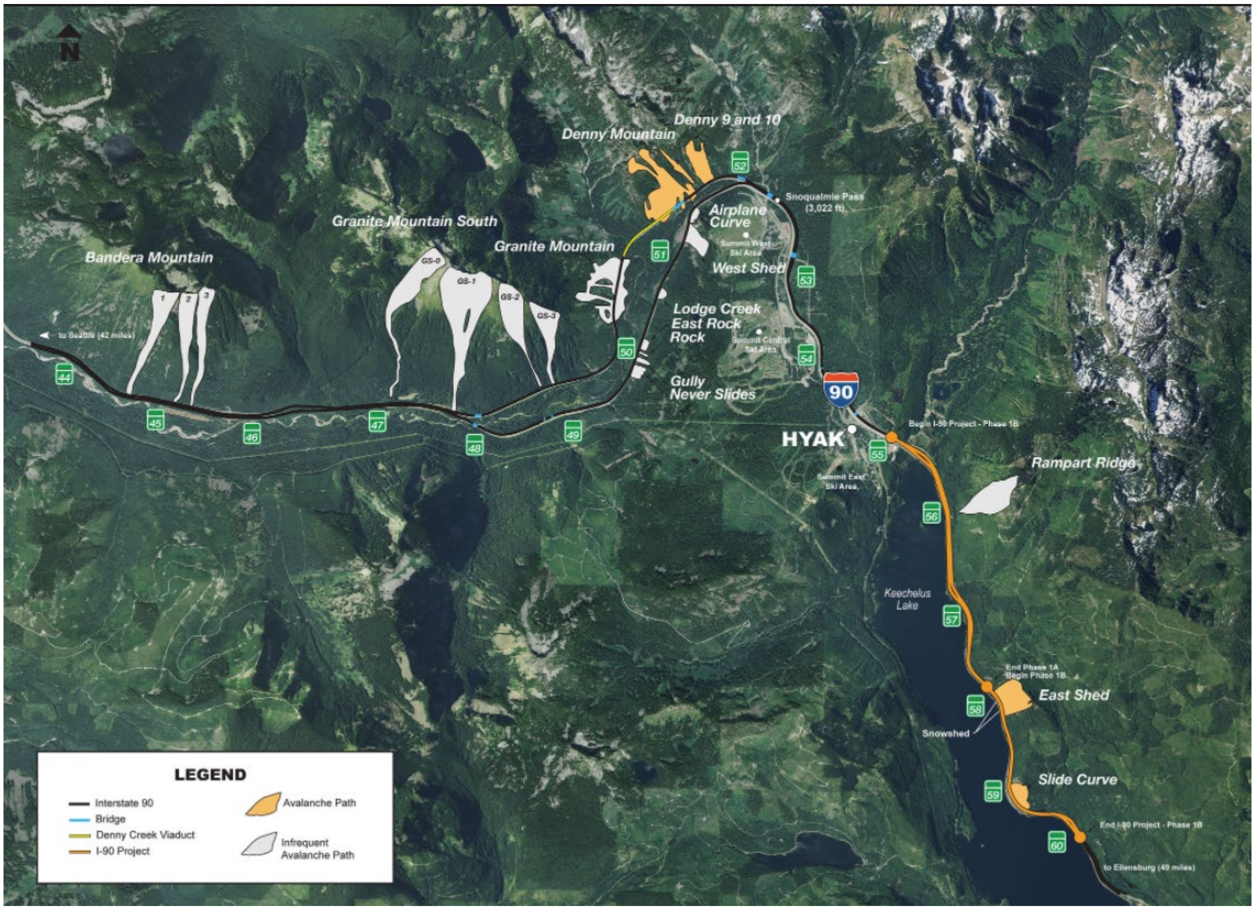


Figure 3.6 I-90 Avalanche areas over Snoqualmie Pass (Source WSDOT, 2021)

The initial test site was on Granite Mountain on the northside of I-90. Granite Mountain is 5,600 feet high with avalanche slopes above the west lanes of the roadway. The WSDOT pilot attempted to fly this area, but the site could not be flown because of the inability to meet the line-of-sight requirements for flying a drone under FAA Part 107 Regulations (FAA 2020) and because of WSDOT's standard operating procedures. According to these regulations, the UAS pilot must be able to take over manual flight at any time and determine which direction to fly the aircraft to avoid a collision. WSDOT staff were unable to find a location on Granite Mountain close enough to see the UAS to prevent possible collisions with trees or the mountainside. It was difficult to see the entire flight area, and the test area was too far away to gauge the position of the airframe and identify potential hazards. This situation highlighted limitations concerning UAS usage that will be discussed later in this report.

WSDOT's avalanche staff had an alternate location on the south side of eastbound Interstate-90 (a panorama of the site is shown in figure 3.7) known as the West Shed slide area.

This location is above the eastbound lanes of I-90 and includes a catchment area for snow slides. WSDOT avalanche staff monitor this area both for avalanche risk and to determine how full the catchment area is with snow that has slid from above. WSDOT crew successfully flew the West Shed area on the following dates and with the listed equipment.

- November 5, 2019 (bare earth) (a DJI Mavic Enterprise Dual)
- March 9, 2020 (with snow) (DJI Mavic Enterprise Dual)
- February 10, 2021 (with snow) (DJI Phantom Pro RTK)
- April 1, 2021 (with snow) (Mavic Air 2).

Figure 3.7 Panorama of West Shed test site at Snoqualmie Pass

The WSDOT pilot used DroneDeploy Terrain Aware software set at 300 feet above ground level (AGL) to avoid trees. The WSDOT system calibrated the maps in DroneDeploy with measurements from Google Earth Pro. Ground control to register the digital images was an issue. The pilot noted that by spray painting some X's on the side of the highway, the marks could be used as ground control points and would allow registering the maps for more accuracy. The first two flights, with a DJI Mavic Enterprise Dual, used a stock controller and iPad. Later flights used a DJI Phantom Pro RTK with DJI Pilot UAS control software. The SfM software used was DroneDeploy, which utilized flight automation, image capture, and terrain model building features.

Each flight over the West Shed test area took about 8 to 10 minutes, not including set-up time. Terrain Aware was used for later flights, which improved the ability of the aircraft to fly a consistent distance above the ground or snow and improved SfM accuracy. There were initial accuracy problems with the registration of the images, but they were addressed by using fixed objects in the flight area to re-register the earlier photos.

The project team viewed the resulting SfM results in Terrain Aware software with a screenshot such as that shown in figures 3.8 and 3.9. A WSDOT Technology Resource Program Specialist operated the aircraft and completed the SfM process, and WSDOT's Avalanche Forecast Supervisor evaluated the results. By using images from different flights on different dates, the Resources Specialist demonstrated to the Avalanche Forecast Supervisor how snow depth could be determined at various locations in the test area and at different times (i.e., different flight dates) and demonstrated how the snow depths changed over time. These measurements were not confirmed with manual probing.

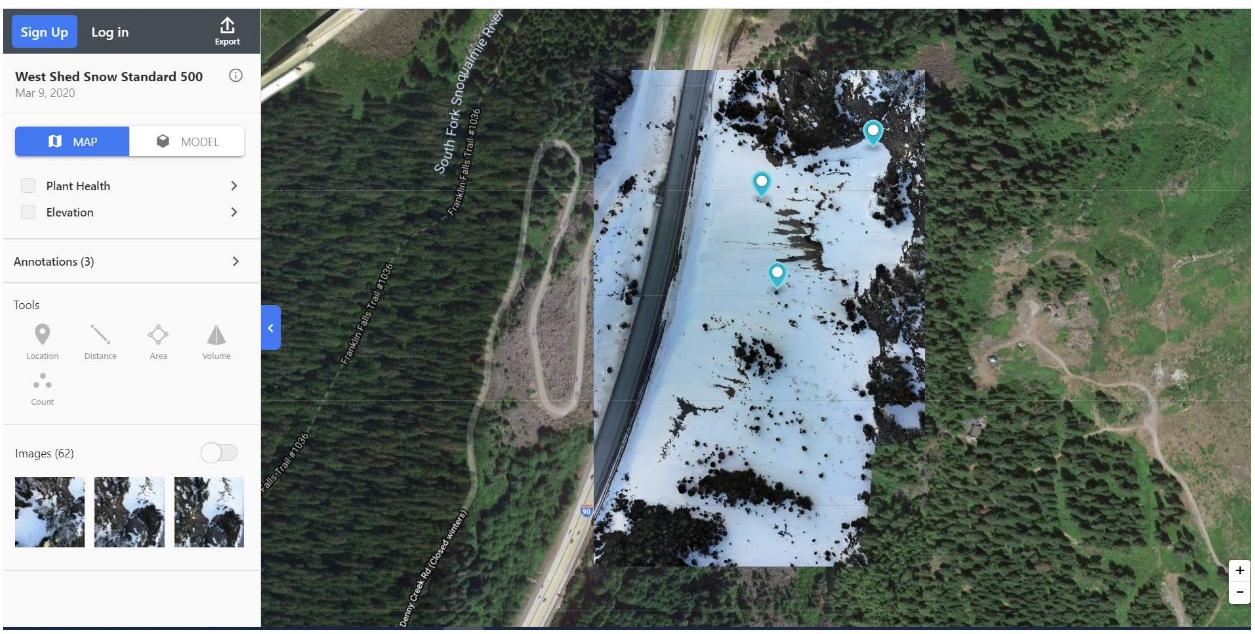


Figure 3.8 Screenshot of West Shed test site in SfM software

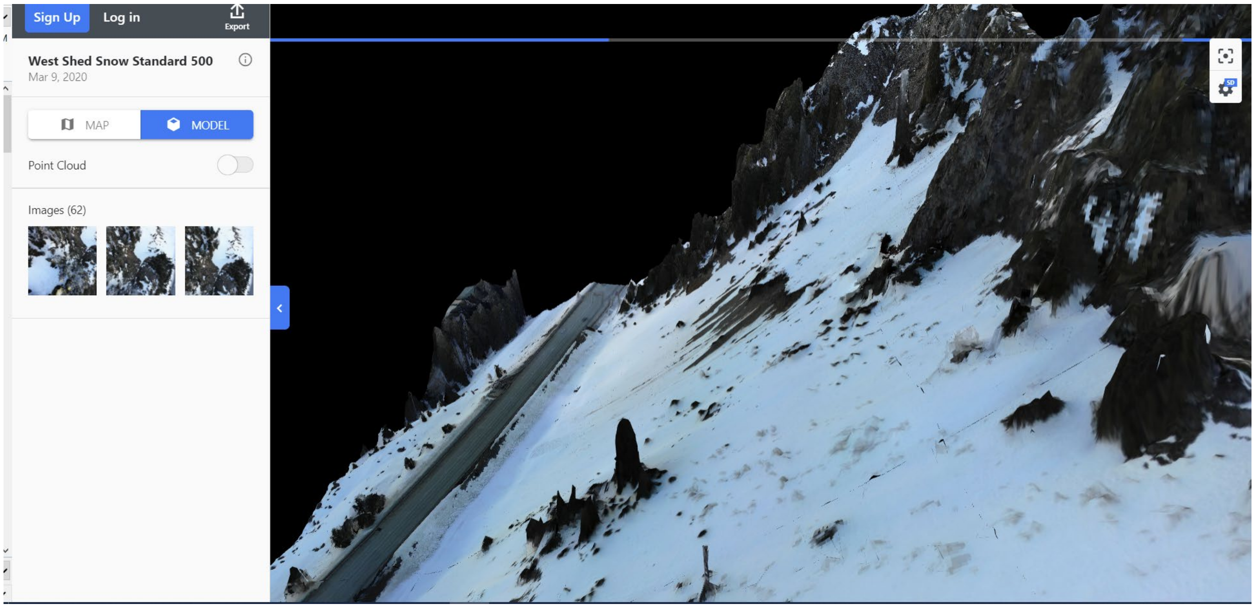


Figure 3.9 Example of the West Shed SfM model

3.3.2 Chinook Pass Tests

The second series of flights in Washington state occurred at Chinook Pass (State Route 410) in the Cascades Mountain in Central Washington. Chinook Pass (elevation 5430) is closed each winter because of high avalanche hazards and poor road conditions and is reopened with snow plows, typically in late May. The reopening process requires avalanche monitoring to ensure the safety of the WSDOT maintenance crews. The project flights focused on a slope (Saddle Bowl Knobs) above the north side of the roadway that WSDOT staff monitor while opening the roadway after routine closure for the winter. The project team flew this site on May 27, 2021, while there was snow. At the same time, the team skied to the test area and used probes to manually determine snow depth every 10 meters for a 100-meter vertical and horizontal cross-section. The cross-section was marked with spray paint so that it would show up on the images collected by the UAS at the same time.

WSDOT next flew the bare earth flights on July 27, 2021. This allowed for a comparison of SfM snow depth with manual measurements. The DroneDeploy images are shown in figure 3.10. The project's SfM staff were unable to compare the bare earth flight with the flight with snow because of the inability to register the before and after snow images. This was related to an inability to find suitable ground control points. The team searched for other bare earth data from previous lidar flights from a variety of organizations, but none was found that covered the test area. This situation emphasized the need to set up adequate ground control points.

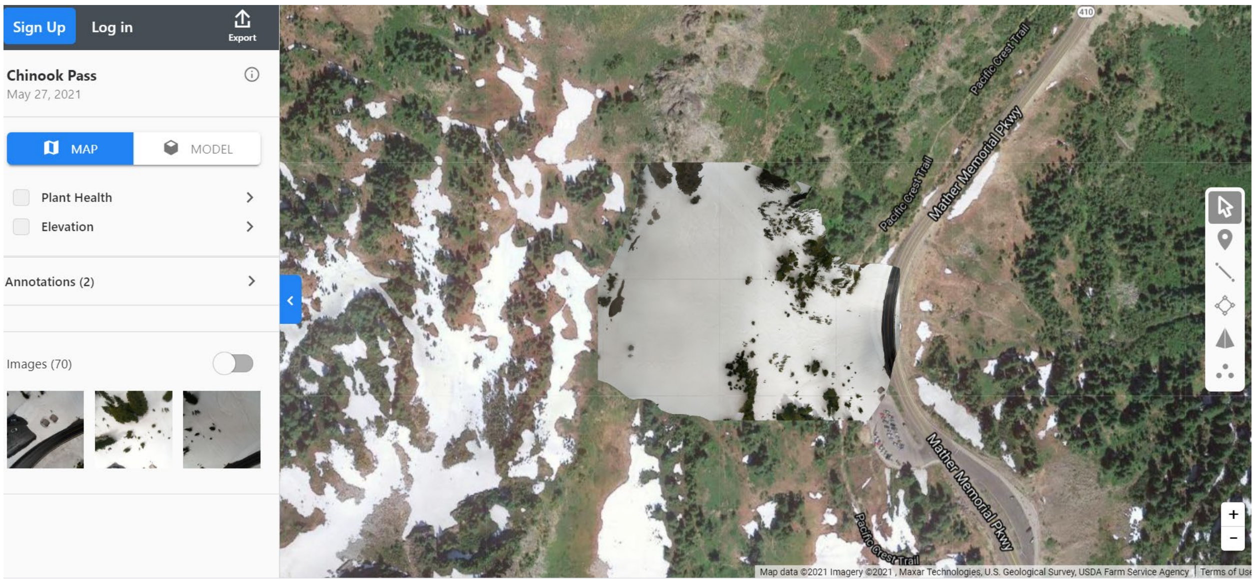


Figure 3.10 Saddle Bowl images collected by DroneDeploy

3.3.3 Equipment and Software Utilized

The UAS most readily available to WSDOT staff was a small (1.1-kilogram) battery powered DJI Mavic Enterprise Dual quadrotor, which had a flight duration of about 30 minutes (figure 3.11). The aircraft was flown manually with a stock controller and used a small iPad for a control screen. DJI Pilot software was used for manual flights to perform tree clearance and altitude checks, and DroneDeploy autonomous flight software was used for subsequent automated flights and photo capture. This aircraft had a gimballed camera (a range of cameras are available), and the aircraft cost around $3,300.

Figure 3.11 DJI Mavic Enterprise Dual UAS (Source DJI 2022)

The SfM software used for the majority of test flights in Washington was from DroneDeploy, which also controlled the UAS during autonomous data collection. DroneDeploy is designed for mapping and capturing aerial data. The software has several pricing options, with a business license running about $300 a month and enterprise options for multiple users with negotiable prices.

Another aircraft used for several of the test flights in Washington was a DJI Phantom Pro RTK. This small (1.4-kilogram) quad rotor system was designed for surveying and mapping and had RTK GNSS built into the aircraft. This system with controller and camera cost around $8,400.

For this research, all the test flights and SfM analysis in Washington state were scheduled and completed by a trained WSDOT pilot who was a Technology Resource Program Specialist in the Information Technology section of WSDOT's Maintenance Division.

CHAPTER 4 ANALYSIS OF RESULTS

The research team assessed the usability of the SfM data qualitatively by using input from the DOT's avalanche staff and quantitatively in terms of the accuracy of the SfM-derived snow measurements. The team also explored the usability of the UAS system and evaluated the technology for routine operational effectiveness, including intensiveness of equipment set-up and flight operations, SfM processing times, and required amount of operator training.

4.1 Washington Flight Tests

Six flights at three locations with known avalanche risk were conducted in Washington. These flights were conducted in conjunction with WSDOT's avalanche forecasting staff. The findings included the following.

Ground Control Points. After the flight imagery had been processed, it was apparent that fixed ground control points (such as "Xs" made of paint) would improve the accuracy of the sfM results and ease of processing and interpreting them. Lack of suitable ground control points were the reason that data from the two Chinook Pass flights could not be matched to the manual snow depth probe measurements. Ground control points up the avalanche slope away from the roadway were the most important for overall accuracy. At the top of the West Shed site, WSDOT has a communication tower and buildings, which WSDOT staff noted would be an easy location from which to add control points.

Snow Depth Information. The Avalanche Forecast Supervisor indicated that knowing snow depth is important at the I-90 West Shed for forecasting avalanche risk. One element is simply having information about snow depth up the slope above the road, indicating the likelihood and magnitude of an avalanche. In addition, at the West Shed site, a snow catchment area is next to the road, and it is important to know how much capacity is left in the catchment area (how deep the snow is)after slides. Accuracy of the snow depth in inches is suitable for forecasting at this site.

Lighting. SfM depends on digital imagery and contrast, so correct lighting is important to capture the images required for DroneDeploy.

Data Processing. Because the West Shed site is relatively small, after the flight, processing of the DroneDeploy data took about 3 to 4 hours of computer time, which was suitable for WSDOT's needs.

UAS Pilots. Ideally the avalanche forecaster would also be the UAS pilot so that they could collect the data in the field in a timely manner. The flight profile could be pre-set (as was done for the four West Shed flights) so it would be possible to automatically, routinely, and consistently fly an area of interest.

4.2 Alaska Flight Tests

Over the course of this project, the AKDOT&PF avalanche manager in Atigun Pass was able to execute 138 flights and acquire nearly 15,000 images for use in the SfM process, a summary of which is provided in figure 4.1.

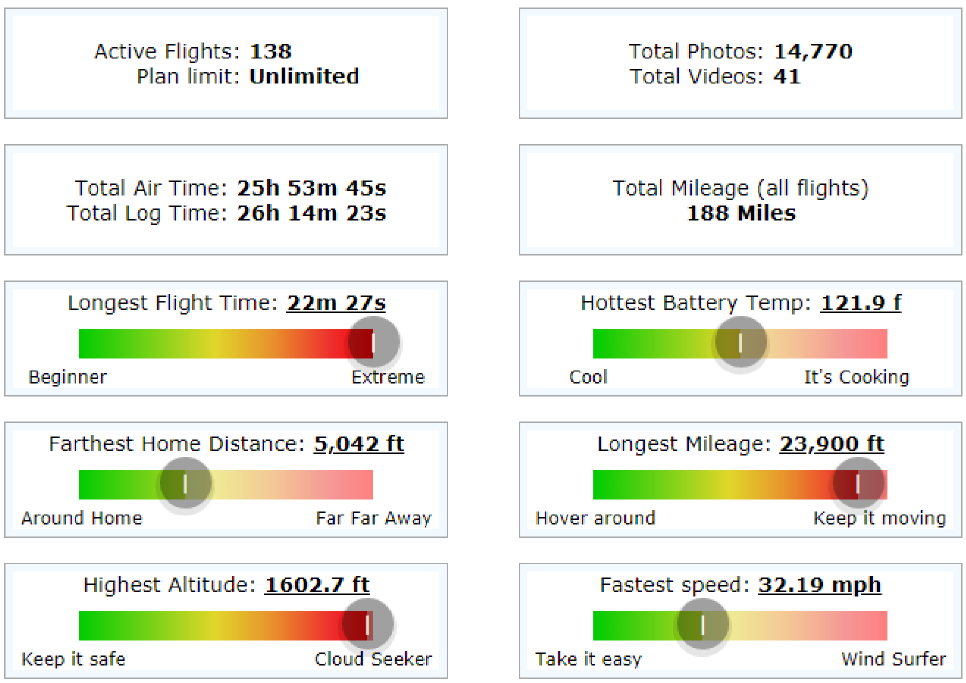


Figure 4.1. Flight summaries for 2019-2020 and 2020-2021 seasons in Atigun Pass.

Because many of the avalanche zones in Atigun Pass were very large, they required several flights to acquire a spatially complete product because of battery and flight time limitations. Figure 4.2 shows an example of the three flights that were necessary to capture the entirety of Path 306.

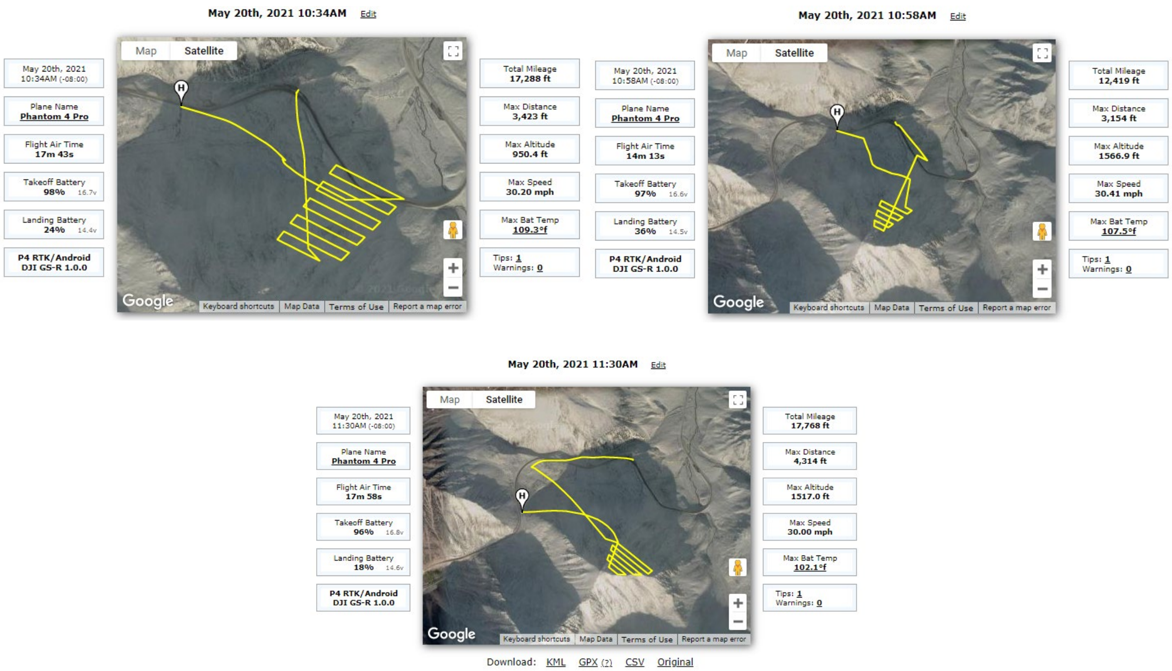


Figure 4.2 Flights executed on May 20, 2021, before a mini slab release in Path 306.

4.2.1 Workflow and Data Products

A detailed workflow was developed to process the UAS imagery into an SfM product to be used by the DOT avalanche staff. The process involved multiple steps. An example of the product generated from this workflow is shown in figure 4.3. The accompanying processing report for this event can be found in Appendix B. This SfM product was generated after a small avalanche occurred in path 112 because of a large wind loaded cornice. A small remaining portion of the cornice can be seen near the top of the figure, with a corresponding image at the top right and some of the debris that was cleared from the road near the bottom right of the image.

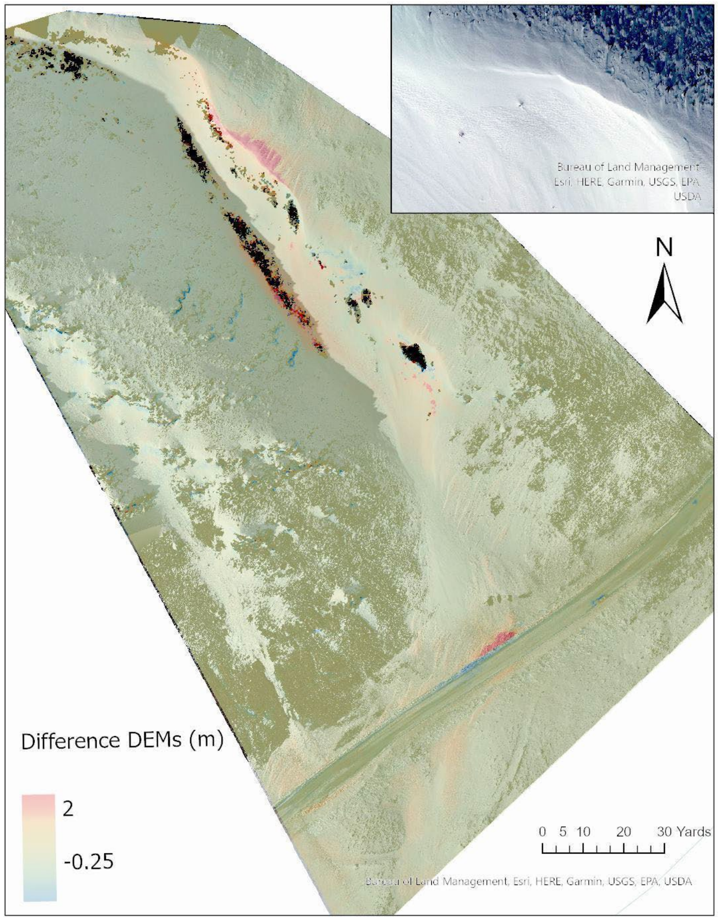


Figure 4.3 SfM product from Path 112 showing a cornice feature and a small avalanche debris pile near the highway.

The SfM product generated for the 306 path natural slab release that occurred on May 22, 2021, is shown in figure 4.4. Three small debris fans can be seen in red (roughly 1 m of deposition) near the top right of the image before the highway. The avalanche path is clearly seen in blue toward the bottom left of the image, centered in the SfM product.

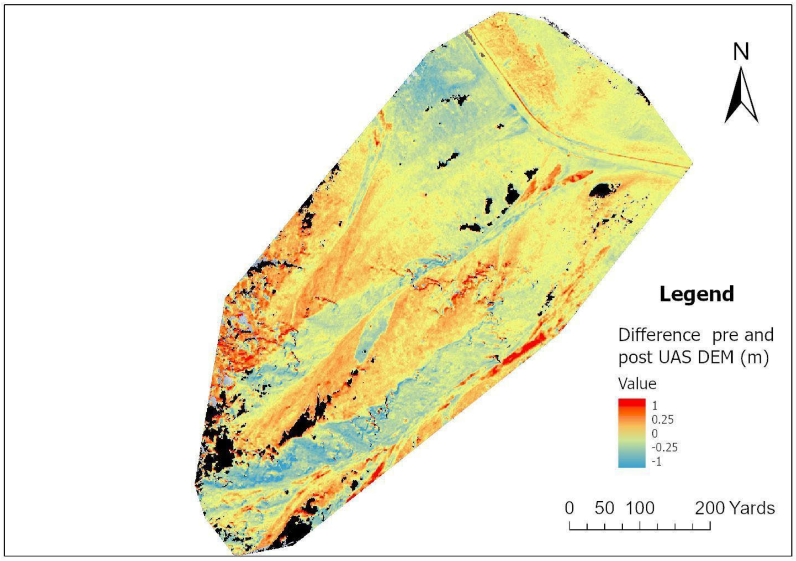
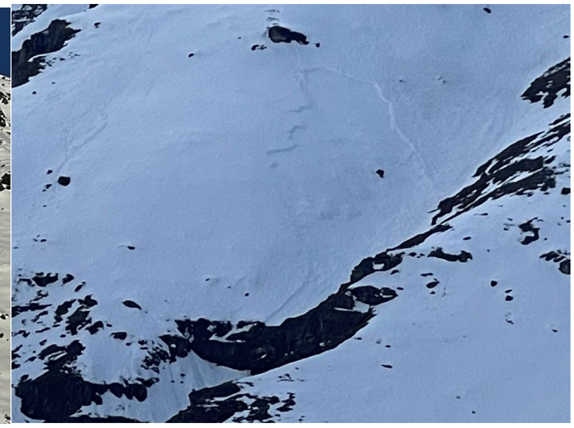


Figure 4.4 SfM product generated for the 306 natural slab release

Figure 4.5a shows Path 306 on May 20, 2021 (when the pre-event flights shown in figure 4.20 occurred). Figure 4.5b shows the slab release, and figure 4.5c shows the debris runout that stopped just short of the highway.

(a) (b)

(c)

Figure 4.5 Avalanche Path 306

To validate the SfM snow depth models derived from the SfM software, magnaprobe readings of snow depth were obtained at the divide of Atigun Pass near a SNOTEL weather station (see figure 4.6). The magnaprobe allows for differential readings of the relative location of a plastic disc on a metal probe, which are georeferenced by using a GPS receiver (see figure 4.7). SfM was obtained before taking the magnaprobe readings, and the comparison of the two snow depth products can be seen in figure 4.8. One can see that the two products generally agreed with each other, with the exception of readings where snow depths exceeded the capacity of the magnaprobe sensor of 130 cm (e.g., reading #50 and reading #225). Excluding these locations, the SfM product and the magnaprobe data did not deviate from each other by more than an average of 9 cm.

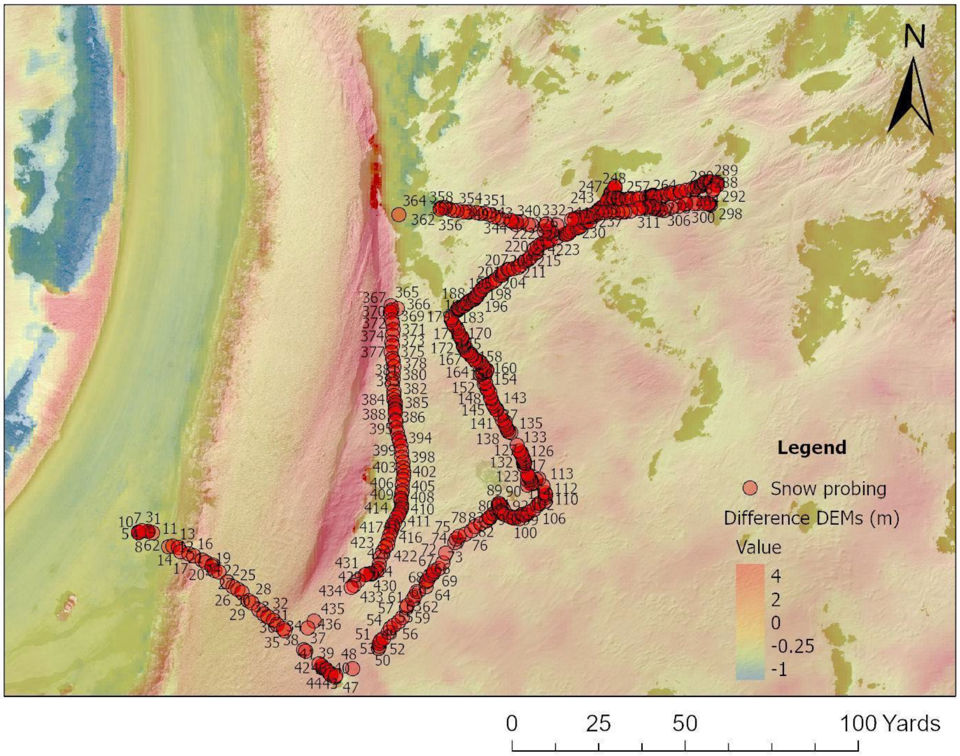


Figure 4.6 Magnaprobe readings and SfM DEM differential product from May 20, 2020

Figure 4.7 Magnaprobe equipment in Atigun Pass on May 20, 2020

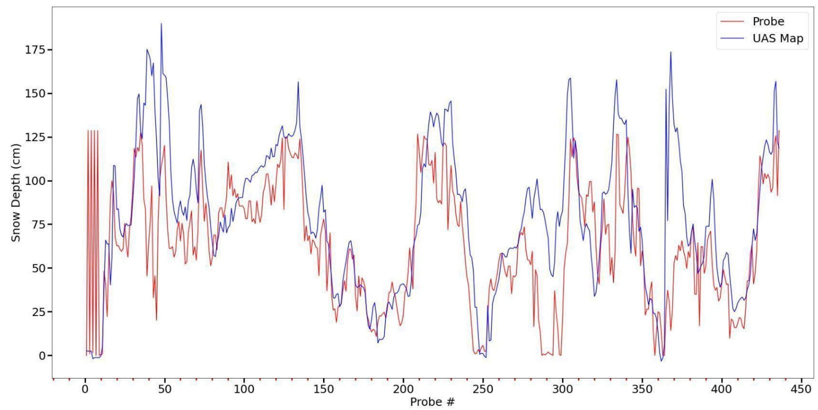


Figure 4.8 Comparison of magnaprobe and UAS DEM from May 20, 2020.

CHAPTER 5 RECOMMENDATIONS

This chapter provides guidelines and recommendations for using UASs and SfM to monitor and forecast avalanche hazards. The focus is on supporting staff at roadway owning and operating agencies, such as state DOTs, who both monitor avalanche hazards and make decisions about whether to open or close roadways on the basis of the level of hazard. This SfM-derived information may also be used to determine whether operations using explosives should be used to create artificial avalanche release.

5.1 Input from the DOTs' Avalanche Staff

The project team worked with staff from WSDOT and AKDOT&PF who participated in the test flights and evaluated the results to develop recommendations for using SfM with UAS data. As part this research, DOT staff interviews were guided by the following questions:

- Can SfM data support your avalanche staff?
- How usable is the snow depth data from SfM?
- Limitations: Where and why might SfM and drone use be limited or not of value?
- Equipment: What type of equipment (drone, software, and computers) is needed?

The interviewees included the followimg:

- AKDOT&PF UAS/Drone Program Coordinator for the Division of Statewide Aviation
- Northern Region AKDPOT&PF Avalanche Program Manager for Atigun Pass
- Northern Region AKDPT&PF Maintenance and Operations Chief Supervisor
- WSDOT Avalanche Forecast Supervisor
- WSDOT Technology Resource Program Specialists (UAS pilot and SfM expert).

Overall, the DOT staff from both Alaska and Washington concluded that SfM had value for measuring and quantifying the nature of the snowpack and for monitoring avalanches. One staff member noted, "The data are essential for better forecasting of avalanche conditions." The full interview responses are found in Appendix B.

In Washington state, the volume of the snow derived from SfM was of value, whereas in Alaska the snow depth was more relevant. This reflects the mechanisms that generate avalanches at the roadside test sites. In Washington, snow accumulation over time was the most important issue in the test areas, whereas in Alaska at Atigun Pass snow moved by wind and any resulting snow accumulation and increased snow depth were indicators of avalanche risk. Staff from both organizations noted that the accuracy of the snow measurements derived from the SfM used in this project was suitable.

Staff from both agencies noted that pre-set flight profiles were good to have for consistency and to make the data collection process efficient. Ground control points at the flight areas were seen as important for improving both data processing and the accuracy of the results, but the numbers and locations of ground control points varied depending on the size and characteristics of the flight areas. If the pilot needed to maintain visual contact with the aircraft, a staff member from WSDOT mentioned that siting of the launch and landing area was relevant and perhaps needed to be determined ahead of time.

SfM products over time had value in that they could also be compared to determine changes in snow distribution. The use of SfM had several secondary benefits, including the ability to quantify snowpack features and to help as a training aid to increase institutional knowledge. The digital images collected before processing in SfM software also could be directly used by the avalanche staff to assess risk, and in many cases that would be the only way the personnel could look at avalanche starting zones in steep or dangerous areas.

The WSDOT staff noted that images from UASs also could be used in social media to let the public better appreciate the situation in the mountain, such as stalled vehicles, queues, or roads covered with avalanche debris, and for posts such as "We moved XXX cubic feet of snow today to get the roadway open."

Staff from both agencies wanted the SfM data processed locally so that the results would be available as soon as possible. WSDOT said tha near-real-time results would be fine.

The UASs already operated by each agency and used for the test flights were generally noted as suitable for collecting SfM data, but in Alaska one staff member desired longer flight durations to avoid multiple battery swaps for larger flight areas.

Staff from both agencies felt that avalanche staff should be trained as UAS pilots (have a part FAA 107 drone pilot license) and the UAS should be a standard piece of equipment. In Alaska, the FAA UAS regulations were not always found to be "friendly" to efficient operation, but both agencies recognized that they needed to operate within FAA rules. Flying beyond line of sight was a major limitation due to FAA Regulation 107. However, staff noted that in some cases it is possible to get permission to fly beyond line of sight. This includes temporary flight restrictions (TRF), certificates of authorization (COAs), and waivers.

Weather and lighting were clearly seen by all the DOT staff as a limitation to the use of SfM. Light was obviously relevant to SfM because this technology is based on digital images. Too much wind, too low temperatures, and icing were all noted as challenges. One person commented, "SfM may not be as valuable during storms as one would wish." In Washington state, obstacles such as trees also were also found to be a possible problem while conducting flights.

Cost of the UAS was mentioned as a concern, but one staff member noted that once a flight program had been set up and proven, the costs could be marginally not too bad for operations. One of the biggest costs may be contingency funding for damaged or lost aircraft.

Lidar was mentioned as both a replacement and supplement to SfM. In addition, lidar data collected by a variety of sources (i.e., non-UAS) could be used as the pre-snow, bare earth, Digital Elevation Model (DEM) for UAS SfM flights. Also, lidar was noted to have the advantage that it could be used in the dark.

5.2 Recommendations for UAS Flight Capabilities

UAS systems (aircraft + camera) should be able to routinely fly in winter weather and in mountainous terrain and should also be operable from DOT vehicles. The following are critical capabilities for UAS flight (adapted from McCormack and Vaa (2019)):

- Operate in colder temperatures (an ability to operate in temperatures down to -15 C),
- Fly in winds (an ability to operate in winds of up to 10 meters per second),
- Fly at altitudes (an ability to operate up to 1500 meters above the launch site),
- Have sufficient flight endurance and flight speed to be able to complete an effective surveillance and return to a safe landing site (an ability to conduct a surveillance at a location of up to 2000 meters from a launch site),
- Fly pre-determined and preprogrammed courses autonomously,
- Be sufficiently portable so that the UAS can be transported in standard DOT maintenance vehicles and be launched beside roads,
- Have safety features beyond the required return-to-home capabilities,
- Provide a live video feed of selected features (slide paths, snowfields, etc.), and
- Provide high quality (600 dpi or better with detailed resolution) recorded images of the features investigated for visual inspection and for use with SfM.

WSDOT, AKDOT&PF, and University of Alaska Fairbanks (UAF) all owned commercial UASs that could address these criteria and that were suitable for routine winter operations and used in this project.

5.3 Recommendations for GPS-Based Flight Control Software.

This research used several different software packages that allowed programming of the UASs' flight path to support photogrammetric-derived snow condition mapping. These packages supported a flight path over a roadside avalanche hazard area that needed to be consistent and repeatable for the SfM results to be effective. A number of possible options use GPS, including software that comes packaged with UASs (e.g., the DJI fly app), commercially available packages (DroneDeploy), and a range of open source applications such as Ardupilot.

5.4 Recommendations for Photogrammetric Tools

The SfM tool provided near-real-time quantitative avalanche assessment measures, including snow depth, and high-quality images of the snow surface. In general, SfM software used for avalanche monitoring needs the capability to

1. Collect imagery
2. Align the imagery (using feature detection, keypoint filtering, and other processing tools) for sparse point cloud development
3. Develop dense point clouds
4. Geo-reference the three-dimensional point cloud, and
5. Report errors in parameter estimates.

There are commercially available packages to process images usable with UASs, including a few designed specifically for UASs such as DroneDeploy.

The SFM photogrammetry process used in this project to quantify snow depth depends on several key factors that can make or break the process as well determine whether the output is usable. SfM software is an off-the-shelf tool tailored to a wide range of skills and with variable numbers of steps to get to the desired product. The photogrammetry process is also computationally intensive. The process of matching hundreds of features per picture from hundreds of pictures per survey, building a 3-D point cloud, and deriving a digital elevation map can take ten minutes on a powerful computer, but hours and more are not uncommon. The software that is the easiest to use and addresses the required computational hardware is often in the cloud. Commercially available examples of this software include Propeller Aero and

DroneDeploy. In our study environment, using cloud services was not practical because of poor Internet bandwidth. Also, the above programs are only one step of the process and do not address overall workflow.

The objective of getting snow heights from UASs is intertwined into several critical steps that are often handled by geotechnical personnel. The steps include the following:

1. Flight planning to cover the desired area
2. Professionally operating the camera
3. Depending on the spatial accuracy requirements, operating survey equipment
4. Ingesting sensor data into software and processing the data into a DEM
5. To derive absolute snow height values, subtracting the recent DEM from a snowless DEM
6. Tailoring the snow height figure to make it meaningful.

While SfM photogrammetry has made strides toward operational simplicity in the agriculture industry, the focus was and is on 2D flat agricultural fields. Mapping more complex mountain slopes has typically been handled by professional geotechnical personnel, who have the required skills to handle the steps outlined above. In addition, the process for monitoring avalanches depends on comparing a single survey with pre-snow data, which is a more involved task.

SfM photogrammetry input data are simply pictures, and the device carried on UASs is a camera. Thus, SfM is a logical choice to avoid buying specialty hardware. However, for good photogrammetric products, images with the least amount of lens distortion are required. Early models of cameras on UASs focused on wide angle lenses for video capture and overlooked the "fisheye" effect. Recent manufacturers have produced UASs, even at the lower tier, that have wide lenses with minimal distortions. The photogrammetry software developers have learned to make corrections to these cameras by building a database.

While capturing a scene with a camera is the most elementary task for UASs, there are notable limitations due to lighting conditions. When mountainous environments are mapped in winter conditions, light conditions are a critical consideration. In this study, the best results were with direct sunlight on the snow. Indirect sunlight can yield good products, but they can result in large cavities in shadowed areas. For example, shadows can often cover gullies, which are important to quantify the total snow volume that can potentially cause an avalanche and cover a road. Gullies are usually full of snow but are typically feature poor, which can challenge the SfM process when direct light is key. Ridges that often get better light have more exposed rocks (because of eroded snow) have more features, and therefore, are more robust for teasing through the photogrammetric process.

Adequate imagery capture for the SfM process requires high overlap capture, which increases the flight time by maybe 1 to 2 orders of magnitude. This is a major drawback for this technique as opposed to video capture or lidar scanning.

5.6 Recommendation for Training DOT UAS Pilots

The Federal Aviation Administration (FAA) requires commercial (as opposed to recreational) UAS pilots to operate under a Part 107 commercial operations certificate. Pilots operating aircraft under 55 pounds can operate under Part 107 and may fly at night and over people and moving vehicles. A pilot must be at least 16 years old, understand English, be in a physical and mental condition to safely fly a drone, and pass an initial aeronautical knowledge exam: "Unmanned Aircraft General – Small (UAG)." The certificate requires passing a knowledge test taken for a $175 fee at an FAA approved testing center (FAA 2020). Practice tests and commercial training courses are available to help obtain this remote pilot certificate.

WSDOT has a number of UAS pilots, but none is part of the avalanche staff. AK DOT&PF is currently discussing the need for regular and routine training and recertification.

5.7 Summary

A successful SfM product is greatly influenced by the quality of the images used. To that end, UAF and the Alaska Division of Geological and Geophysical Surveys (DGGS) developed a set of image acquisition considerations to be used in the flight planning and execution.

- Plan flights in advance and ensure that they achieve sufficient image overlap (90 percent forward and 60 percent to the side) to avoid gaps/holes and distortion effects.
- When flying in mountainous terrain, import a DEM of the area into the flight planning software to preserve the high overlap discussed and ensure a higher level of accuracy of the flight execution.
- Ensure that there is direct sunlight on or some illumination of the snow surface (i.e., avoid dimly lit or “flat light” conditions).
- Outfit the UAS with a camera that has minimal lens distortion (i.e., not a “fisheye”) to increase the accuracy of the mosaic model.

- Use a UAS with a survey-grade differential or Real-Time Kinematic (RTK) GPS to achieve a snow height difference that is sub-meter.
- Consider that the photogrammetry process is computationally intensive, which means that the process requires either a powerful (typically a “gaming-style”) computer or a good Internet connection to transfer the data (i.e., imagery) for cloud-based processing.

In advance of imagery acquisition, the research team surveyed several benchmarks in the Atigun Pass area. From those, a network of ground control points was established, to be used for rectifying and validating the SfM models.

The following points are recommended for using SfM:

- Acquire a bare earth product at least 1 meter in resolution/pixel size (can be DSM, lidar, or SfM).
- Develop interagency collaborations with those responsible for managing and executing survey, photogrammetry, maintenance, and UAS coordination operations.
- Develop a robust set of ground control points that are well-distributed throughout the areas of interest.
- Camera and related equipment should be of good enough quality to provide high resolution imagery with minimal lens distortions.

With the dataset from Alaska, the researchers found that that they could easily achieve < 10 cm accuracy with the Phantom 4 RTK aircraft alone. Airspace in Atigun is not necessarily conducive to this type of operation because of the high latitude and significant relief, which can shadow satellite signals, impacting GNSS accuracy. The addition of the DRTK 2 systems significantly improved the level of accuracy. That said, accuracy is not as important if there are snowless features with which to resolve discrepancies and systematic errors can be rectified in the post-processing phases. For validation purposes, we determined that geolocation of UAS imagery using known and visible points, rather the rectification thereof, , was more reliable than use of the magnaprobe data, which relies solely on GPS that can be unreliable because of limited connection to satellites at high latitudes.

SfM provides results that are sufficient for the purposes of operational assessment of avalanche risk. This requires following a very specific protocol to achieve these results. Obviously, this does not provide information on stratification, water content, etc., so other tools and techniques may still be necessary. This research showed that the process can be streamlined and semi-automated, but the process relies heavily on a carefully crafted flight plan constructed by a well-trained operator. Processing the data in a timely manner is a challenge, especially in the field. Waiting for results when conditions are time-critical may not be an option. That said, SfM provides critical information for maintaining a temporally consistent and spatially robust record of snow depth.

CHAPTER 6 CONCLUSIONS

Digital images of roadside avalanche areas collected by UASs and processed with Structure from Motion software provided usable and timely data on snow depth and snow volume to support avalanche hazard monitoring. Using project data, the researchers determined that it is easy to achieve < 10 cm accuracy in terms of snowpack depth with a common and commercially available Phantom 4 RTK quadrotor UAS.

Working with our DOT partners, we determined that SfM provides benefits that are sufficient for the purposes of operational assessment of avalanche risk. Used with bare earth (pre-snow) data, the SfM output can provide DOT staff with information on snowpack depth and volume. Repeated flights could provide data on snow accumulation. The digital images collected for SfM processing also provide valuable and more immediate information to avalanche experts. All these sources of information could support both the assessment of avalanche risk and implementation of mitigation actions such an artificial release using explosives or howitzers to intentionally trigger an avalanche. The ultimate efficiency and cost savings from the use of this technology will ensure safer roads that are opened more quickly.

Collection of such SfM information requires following a very specific protocol to achieve these results and has limitations due the equipment used, regulations, and the environment flown. Obviously SfM does not provide information on snowpack stratification or water content, so other tools and techniques may still be necessary to fully assess avalanche risk.

6.1 Benefits

The use of UASs and SfM has potential benefits for roadway agencies with responsibility for avalanche assessment. These include the following:

6.1.1 Increased Coverage and Improved Remote Inspection

The use of UASs to collect data can reduce the need for DOT avalanche staff to travel by snowmobile or on foot or skis to avalanche sites and thus can increase data collection efficiency and the avalanche release zone area of coverage that can be examined. Because of steep terrain, many avalanche release areas are inaccessible and must be inspected from a distance, which UASs can facilitate. This benefit is due both to unprocessed digital images viewed directly in the field and to SfM output. The unprocessed images also have benefits for DOT personnel when used with social media and outreach to show the public near-real time conditions on winter roadways.

6.1.2 Improved Safety

Remote inspections via UASs can make it less necessary for DOT staff to move within avalanche-susceptible terrain and thus significantly increase staff safety. In more general terms, the use of UASs can provide better and more timely avalanche monitoring data, which can support more accurate mitigation measures, such as artificial releases to intentionally trigger the avalanche, and can better guide road closure decisions, resulting in less risk to roadway users.

6.1.3 More Accurate and Quantifiable Snow Data

A less tangible benefit is from the use of UASs to provide DOT staff with better and more consistent measurement of snowpack conditions. Specifically, UAS-assisted operations may provide higher resolution data over larger areas with more frequency. In addition, SfM data collected with set (repeated) flight paths guided by GNSS software can provide information on snowpack depth and volumes at set locations over time. SfM can provide critical information for maintaining a temporally consistent and spatially robust record of snow depth, but achieving this will require training. Trends related to avalanche activity can be identified, which can support more accurate monitoring. In addition, these data collected over time can support institutional knowledge that can be used to train new staff.

6.1.4. Improved Operational Knowledge of UASs

The use of UASs for many applications by DOTs will certainly increase over time. The knowledge and experience gained by avalanche staff in the use of this technology will benefit use of UASs for other operations (surveying, mapping, aerial images, etc.) and the assessment of other natural hazards (landslides, rock falls, flooding, etc.).

6.2 Challenges

Several challenges must be addressed to achieve a successful SfM procedure to aid in the monitoring and mitigation of avalanche risk to highways and the traveling public.

6.2.1 Environmental

These challenges mainly involve weather, which can impact UAS operation. The small portable UAVs used in this effort and common to many DOTs have operational limitations due to an inability to fly in high winds. Icing conditions and snowfall can also limit flights, while extremely cold temperatures can degrade battery life and reduce flight duration.

Given that SfM depends on digital images, a major environmental limitation is lighting. SfM requires images with contrast and discernible features. Bright conditions can produce poor results. Conversely, SfM does not work in nighttime conditions without light. This can be a major limitation in high latitude arctic or subarctic areas with long nights. At times, Atigun Pass was not conducive to this type of operation because of the high latitude (68 degrees north) and the significant relief that shadowed satellite signals, impacting location-based GNSS accuracy. The addition of the DRTK 2 systems significantly improved the level of accuracy. That said, accuracy is not as important if snow-free features (poles, rocks, etc.) are available to help resolve discrepancies and rectify systematic errors in the SfM post-processing phases. Ground control points were used in both Alaska and Washington and were critical for supporting usable findings. For known and active avalanche release areas, setting up fixed ground control points (poles, paint marks, etc.) or locating existing features (guard rails or building edges) could be necessary for successful data collection.

6.2.2 Geographic

In this research, a geographic limitation was exemplified by the WSDOT UAS pilot's decision to not fly a test because of limited visibility at the site and a requirement to not fly beyond line of sight (BLOS). The issue was linked to both trees obscuring visibility (less of a problem at Atigun Pass) and steep terrain. Other geographic limitations could be jurisdictional. In Washington state, the Chinook Pass test site was next to a national park that did not allow drone flights and could potentially limit operations. At the Alaska test site, the UAS operational software had built-in, above-ground flight height limitations that notably affected the operations requiring multiple flights from different staging areas and complicated the collection of images. Ideally, the flight area should be flown before active avalanche monitoring operations to set up GPS-based flight paths, identify ground control points, and, if lidar data are not available, determine bare earth conditions. A final consideration is that safe staging or parking areas close to the avalanche release zone being examined need to be available to operate the aircraft. In some cases, this may require a DOT to plow a spot for use by the UAS operator.

6.2.3 Operator/User

In both states, the UAS operators were trained pilots. The Alaska flights were conducted by the DOT's avalanche expert, who was also a pilot, which simplified and facilitated both flight operations and data collection. In Washington state, the flights were completed by a DOT UAS operator who needed to be scheduled to collect data and who was not part of the avalanche staff. Given the unpredictability of snowfall and avalanche operations, the need to schedule flights would not be feasible for a long-term avalanche program. In general, a successful program would require the DOT avalanche staff to be able quickly operate UASs in the field, and this suggests that they need to be pilots with an FAA Part 107 commercial operations certificate. Related to this is the need for timely data processing of the digital images in the SfM software. Processing the data quickly is a challenge, especially in the field. Waiting for results when conditions are time-critical may not be an option. This may require specialized training. This project showed that the SfM process can be streamlined and semi-automated, but the process relies heavily on a carefully crafted flight plan constructed by a well-trained operator. For AKDOT&PF specifically, where the avalanche manager is also partially responsible for operating maintenance equipment, operating drones would take away from those other activities (multi-tasking).

6.2.4 Equipment

The equipment, aircrafts, and flight control software used in this project were already in use by both DOTs and are commercially available. SfM software was purchased by UAF for the project. In general, this equipment was suitable for collecting images for use with the SfM software, but the Alaska DOT UAS, designed for surveying, with a better camera and GPS, provided a much superior data product. The equipment was also easily portable in standard vehicles, which simplified operations. A usable UAS with operation and SfM software (not including training costs) could be acquired for less than $10,000 to $15,000 (the Phantom RTK is about $8,000, SFM software $2,000 to $4,000).

Battery operations, exacerbated by cold temperatures that reduce battery efficiency, highlighted some limitations for our test. At the Washington test site, suitable data were collected in one flight, while in Alaska some sites required multiple flights because of limited battery life and the large acquisition areas.

The cameras used need to have minimal lens distortion (i.e., not a “fisheye”) to increase the accuracy of the mosaic model.

6.2.5 Regulatory.

All operations in this project could be conducted without FAA Notice to Airmen (NOTAM) and were conducted within view of the pilot, thus avoiding the need for more complicated BLOS rules. Any DOT that plans on operating UAVs will need to review the rules for commercial operations FAA Unmanned Aircraft Systems, found here:

https://www.faa.gov/uas/. In general, most DOTs tend to adhere to FAA rules, but there also may be internal DOT policies related to UAS operation.

6.3 Implementation

Roadway agencies interested in implementing the use of SfM with UAS data to monitor avalanche hazards should at minimum have the following:

- A road with consistent and known avalanche risk, with nearby parking or other roadside space to operate UASs,
- Ground control points in or around the avalanche release zone,
- Regular approval to fly this area,
- A trained pilot with an FAA Part 107 commercial operations certificate,
- Commercial UAS equipment designed for surveying, with a good camera and GPS,
- SfM software and staff able to run the software,
- Computer equipment to process the raw SfM data, and
- Staff members with expertise in interpreting avalanche risk from static snow depth and snow volume data and from the changes in snow volume and depth over time data.

6.4 Next Steps and Further Research

This effort suggested areas in which further research and documentation could potentially improve the use of SfM with UASs and support roadside avalanche monitoring. These areas include the following:

- Conduct additional controlled field experiments to assess the accuracy and parameters of the snowpack measurement (mainly snow depth and snow volumes).
- Develop a manual of recommended guidelines, tools, and practices on the effective use of SfM with UASs for roadway agencies with avalanche monitoring programs.
- Evaluate the costs and feasibility of training and licensing DOT avalanche staff as UAS pilots.
- Explore the use of lidar technology as a replacement for or enhancement to SfM. One attraction of SfM is that it is perceived as a lower cost substitute for lidar and perhaps more suitable for use with UASs in areas where there is increased risk of aircraft loss or damage. Lidar designed for UASs is commercially available and becoming less expensive. Lidar also can be used in low light situations that are not suitable for SfM.

- Explore other sensor technologies that can be carried on a UAV and that might provide useful data about snow, such as ground penetrating radar, infra-red, and multispectral imaging.
- Explore other aircraft types such as fixed wing or those with vertical take-off and landing abilities and alternative power sources such as liquid fuels. One limitation in this project was related to aircraft performance. The aircraft used were all battery powered multirotors with flight duration under one hour.
- Explore the development of databases to save the information from repeated flights over known avalanche areas. This could support quantification of snow conditions and the relation of this information to the level of avalanche hazards. This would also support automating and creating a turnkey processing engine for avalanche forecasters to use. The UAS data could be stored via an image server, which could be made available through ARCGIS online.

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APPENDIX A: COLLECTION OF BASELINE DATA

Aerial Photogrammetric Survey Details

Area data of the test area were collected by using a fixed-wing, manned (a Cessna 180) airborne platform. A Nikon D800 camera with AF-Nikkor 28-mm f/2.8D lens was used to collect 36.2-megapixel JPEG photographs (7360 x 4912 pixels per image), which were compressed for optimal quality. During the aerial survey, the photograph coordinates were determined by using an OxTS GPS-IMU system and a Cirrus Digital Systems intervalometer that linked the camera shutter release to the GPS-IMU. The camera was mounted inside the aircraft with the GPS antenna positioned over the camera. The GPS antenna offset (X=0.3, Y=0.0, Z=0.94) was corrected during GPS post-processing to solve for the camera coordinates. A Trimble 5700 GPS receiver with a Trimble Zephyr four-point feed antenna was deployed at a landing strip approximately 38 km north of the center of the survey area and was used as the GPS base station for horizontal and vertical control during the aerial survey.

The 2015 and 2016 aerial photogrammetric surveys resulted in 60 percent side lap and 80 percent end lap coverage. The 2015 (2016) survey produced 2,052 photos (1801 photos) with 0.194 m per pixel (0.197 m per pixel) ground resolution. The 2015 (2016) survey was flown at an average elevation of 1,200 m (1,120 m) above ground level and covered approximately 250 km2 (210 km2).

Photogrammetric Dataset Processing

We processed aerial survey GNSS data (camera coordinates and trajectory data) by using GrafNav GNSS Post-Processing Software, Version 8.40.5121 using post-processing kinematic (PPK) methods. Camera coordinates were automatically registered to image filenames to create a camera exterior orientation file for import into the photogrammetric software, Agisoft Metashape Professional. The exterior orientation file provided the X, Y, and Z position for each photograph taken during the survey. Yaw, pitch, and roll information were not recorded during the flight.

Aerial stereo-photographs were imported into the commercially available Agisoft Metashape Professional software (Version 1.6.3 build 10732). Photos were processed in Metashape on a Windows PC to align aerial photos, georeference aerial photos using ground control points placed on photo-identifiable markers, edit the sparse point cloud, optimize the bundle block adjustment, construct the dense point cloud and triangulated irregular network geometry, and export the mosaicked natural color (RGB) orthoimagery and digital surface model GeoTIFFs.

<u>Orthoimagery</u>

The mosaicked orthoimagery was a four-band, 16-bit unsigned GeoTIFF file. The 2015 (2016) orthoimagery had a GSD of 0.1957 m (0.2039 m) per pixel, and the “No Data” value was set to 256.

<u>Digital Surface Model</u>

The 2015 and 2016 DSMs represented surface elevations, for example heights of vegetation, roads, rock outcrops, buildings, bridges, etc. The digital surface model (DSM) was a single-band, 32-bit float GeoTIFF file, with a ground sample distance of 1 meter. The No Data value as set to -3.40282306074e+038.

The project team did not collect any ground control points for these surveys. All data were processed and delivered in NAD83 (2011) UTM6N and vertical datum NAVD88 GEOID12B.

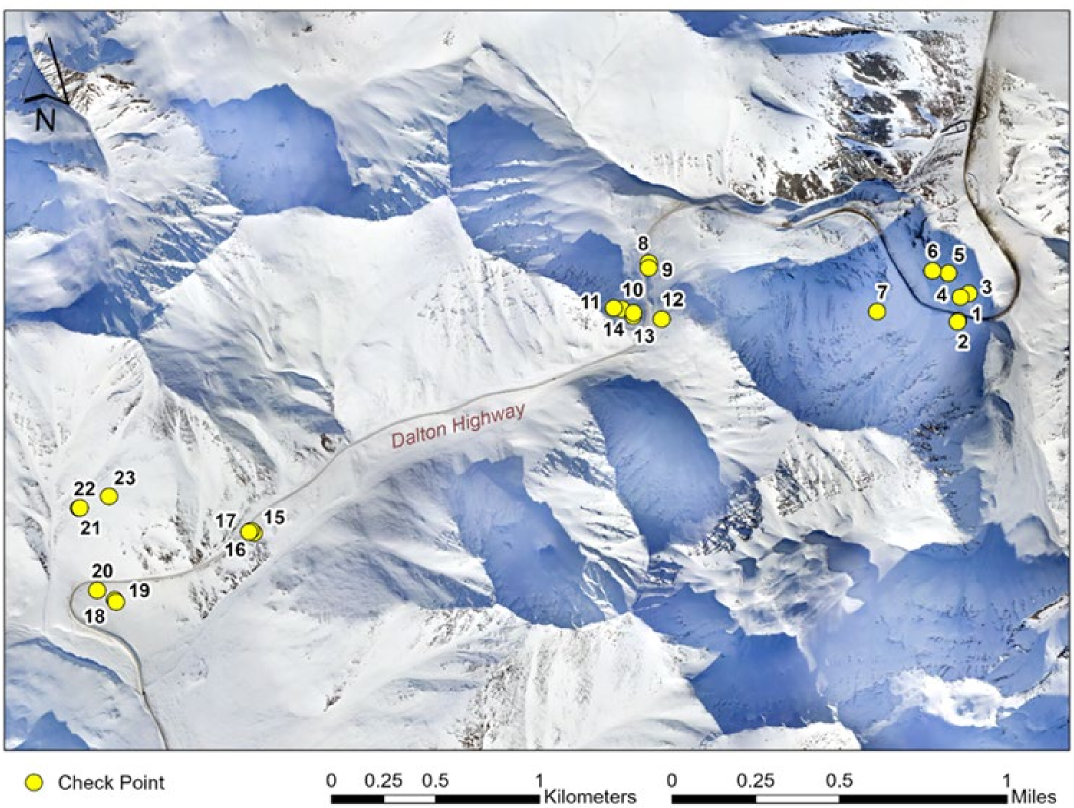

Figure A.1 Locations of synthetic photo-identifiable check points that were used to evaluate the horizontal accuracy of the 2015 final products

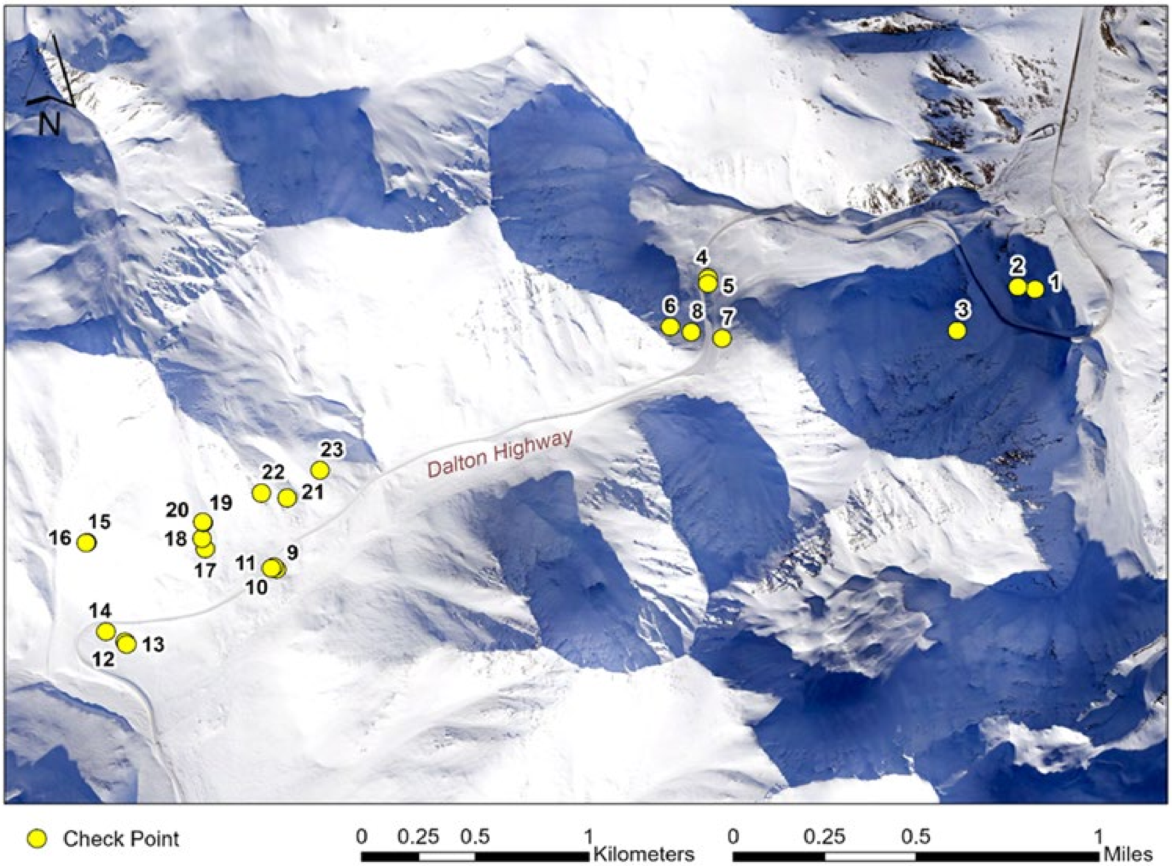

Figure A.2 Locations of synthetic photo-identifiable check points that were used to evaluate the horizontal accuracy of the 2016 final products.

<u>2015 Horizontal and Vertical Accuracy</u>

The average camera location error was 0.021711 m in the X direction, 0.023757 m in the Y direction, and 0.048731 m in the Z direction, and the resulting total error was 0.058399 m. The team assessed the horizontal accuracy of the DSM and orthoimagery by comparing the locations of 23 synthetic control points; these were natural features that were photo-identifiable in both the 2015 orthoimagery and in a newer and georeferenced orthoimagery derived from SfM photogrammetric data collected in 2020 . The calculated mean offset was (residual) to -1.1882 m in the X-direction and -0.1657 m in the Y-direction, with a standard deviation of 0.2689 m and 0.2809 m for the X- and Y-directions, respectively, and a root-mean-square error (RMSE) of 0.2537 m (0.0669 m in the Y-direction). We applied a horizontal transformation of 1.1882 m in the X-direction and 0.1657 m in the Y-direction. Using the same synthetic points, we evaluated the final error of the adjusted products to have a mean offset (residual) in the X-direction of -0.0121 m (RMSE of 0.0576 m) and in the Y-direction of -0.0069 m (RMSE of 0.0444 m).

The vertical accuracy of the DSM was assessed by comparing the elevation values of 9,114 points in the XY-shifted DSM against a lidar-derived digital terrain model (2011) in the Quick Terrain Modeler software. We measured a mean offset of 0.4754 m between the two DSMs. We reduced the offset to 0.2249 m by performing a vertical transformation of the photogrammetry-derived DSM. We used 6,613 new points to determine the non-vegetated vertical accuracy (NVA) of the DSM. The DSM NVA was calculated to have an RMSE of 0.4056 m.

2016 Horizontal and Vertical Accuracy

The average camera location error was 0.0369826 m in the X direction, 0.0370004 m in the Y direction, and 0.0635994 m in the Z direction, resulting in a total error of 0.0823506 m. We assessed the horizontal accuracy of the DSM and orthoimagery by comparing the locations of 23 synthetic control points; these were natural features that were photo-identifiable in both the 2016 orthoimagery and in a newer and georeferenced orthoimagery derived from SfM photogrammetric data collected in 2020. We calculated the mean offset (residual) to -1.2919 m in the X-direction and -0.4093 m in the Y-direction, with a standard deviation of 0.4722 m and 0.2372 m for the X- and Y-directions, respectively, and an RMSE of 0.2861 m (0.0981 m in the Y-direction). We applied a horizontal transformation of 1.2919 m in the X-direction and 0.4093 m in the Y-direction. Using the same synthetic points, we evaluated the final error of the adjusted products to have a mean offset (residual) in the X-direction of -0.1633 m (RMSE of 0.0806 m) and in the Y-direction of -0.0170 m (RMSE of 0.0959 m).

The vertical accuracy of the DSM was assessed by comparing the elevation values of 4,550 points in the XY-shifted DSM against a lidar-derived digital terrain model (2011) in the Quick Terrain Modeler software. We measured a mean offset of 1.2905 m between the two DSMs. We reduced the offset to -0.1437 m by performing a vertical transformation of the photogrammetry-derived DSM. We used 1,390 new points to determine the NVA of the DSM. The DSM NVA was calculated to have an RMSE of 0.2228 m.

Data Consistency and Completeness

The DSMs and orthoimagery were visually inspected for data errors such as pits, border artifacts, and shifting. There were a few holes in the data over mountain peaks and ridges because of clouds present during the survey.

Snow Distribution

Maps of snow distribution can be developed from these photogrammetry-derived products and existing digital terrain data. As an example, figures A-3 and A-4 illustrate end-of-winter 2015 snow distribution in Atigun Pass and the broader area, which were computed by subtracting the 2015 DSM from a 2011 bare-earth, lidar-derived digital terrain model.

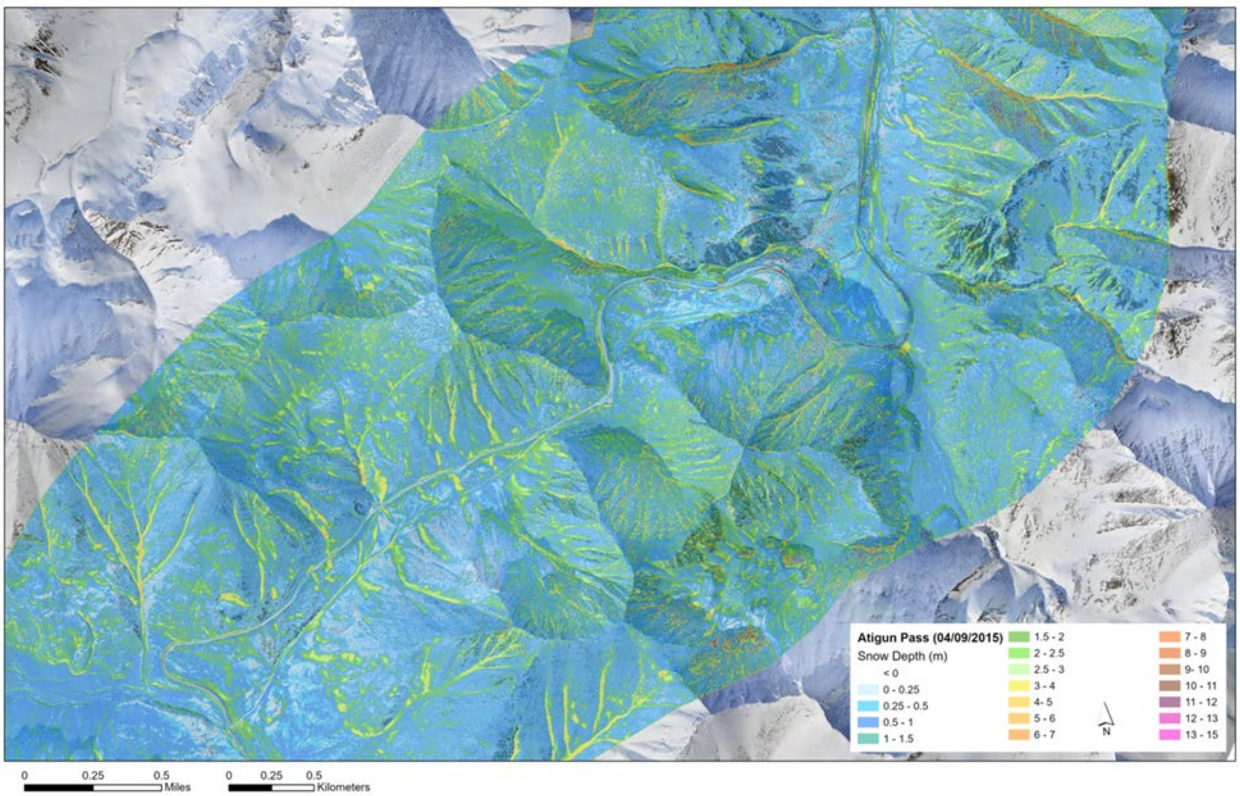

Figure A.3 2015 photogrammetry-derived snow distribution at Atigun Pass.

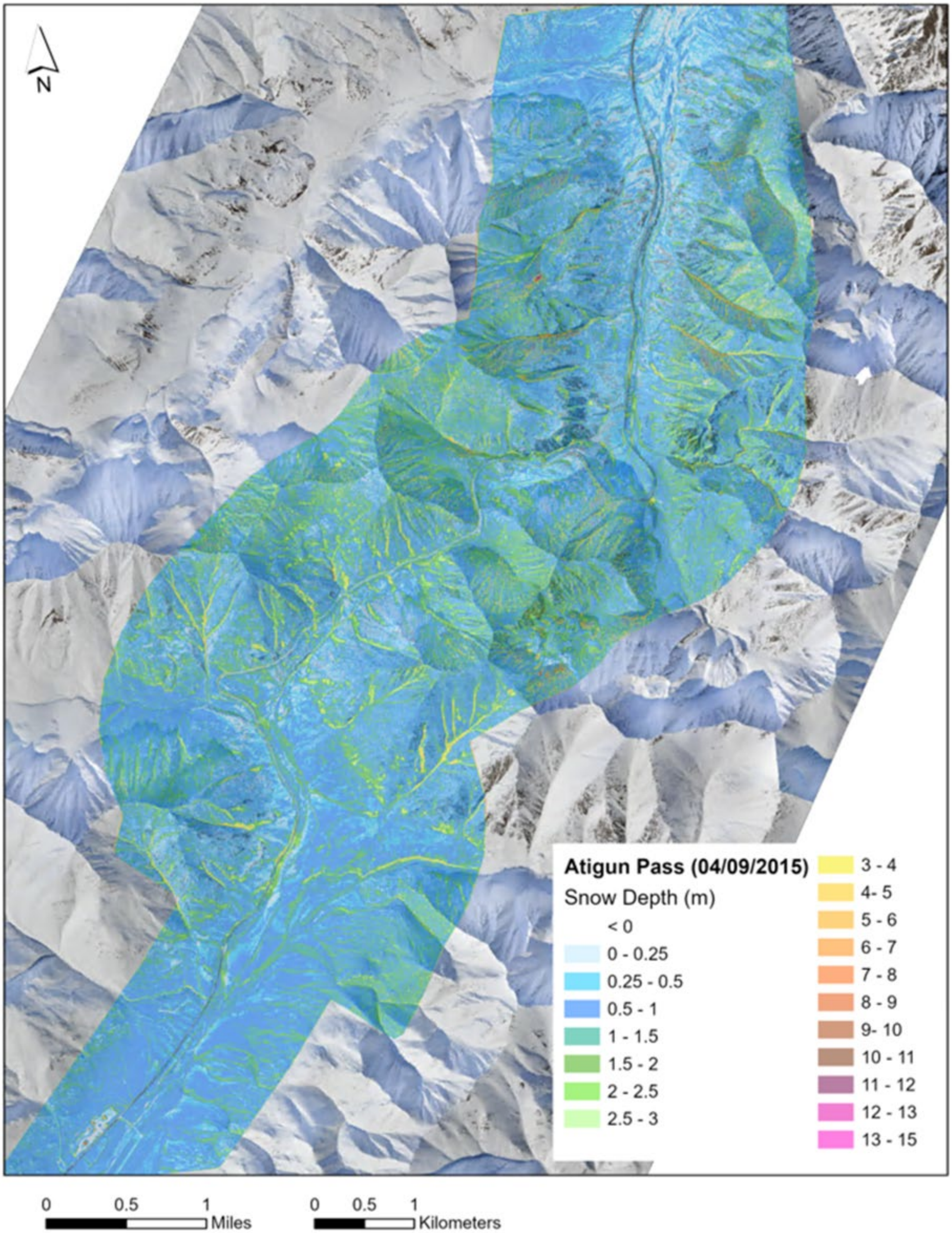

Figure A.4 Broad view of 2015 photogrammetry-derived snow distribution at Atigun Pass

APPENDIX B: DATA PROCESSING WORK FLOW

The following outlines the work flow used to collect and process the data in SfM software.

Input data (e.g., imagery from the drone, KML files created by the avalanche practitioners specific to the area of interest):

1. Drone imagery
2. KML files -pre-defined vector files (KML)
   a. Vector files of the chutes of interest (VFCI)
   b. Vector files of known hazards (VFNHz), area of typical cornice buildup, or common fracture in the snow that can lead to an avalanche.
   c. Vector files of chute sections (VFCS)—provides snow volume whithatch is the actual potential snow-load that could cover the road. The snow volume is provided in cubic yards and in a number of a typical "dump-truck," which is 10 to 15 cubic yards.

The avalanche practitioner creates a working folder in which to store the UAS imagery and is referenced in the workflow process to pull from automatically when the SfM process is initiated.

A (e.g., Python code, Agisoft Metashape, API Python, and other Python spatial libraries such as Rasterio and Fiona)

1. Agisoft Metashape is a well-known photogrammetry software. In this project we explored using its Python API.
2. Python 3.7 is a version of Python scripting language that handles all processes as well as commanding the Metashape through the Python API.
3. Python libraries Rasterio and Fiona for raster and vector file analysis.
4. Python Pandas for managing dataset tables.
5. Python Matplotlib for figure displaying.

The subsequent workflow consists of four primary steps as follows:

1. Run a master processor (seeks for new data, keeps track of historic data sets of the area of interest, and handles subprocess data processing).
2. Initiate the photogrammetry process:
   a. Import pictures and processes use by photogrammetry software.

b. Import camera location file with the desired geographic projection (Alaska State-plane zone 4, NAD1983 in meters EPSG 26934). Altitude is converted from ellipsoid to geoid.
c. Process the images in the photogrammetry software Alignment step on "high." This step scans the images for hundreds-thousands of distinct features (set of pixels), creates feature matching, and solves a model for location orientation and other camera parameters such as lens distortions.
d. Import ground control point (GCP) as a checkpoint to calculate the offset between a known location and the mosaic created from the drone imagery.
e. We selected the crudest (lowest) dense cloud option because we did not need overly high detail for our products, which saved on storage space and computation time.
f. We used a filter within Metashape that removed pixels with poor overlap.
g. Create a digital elevation model (DEM) at 1-m resolution and orthomosaic 0.1-m .tif files. A second orthomosaic in the KMZ format is also created. The KMZ files are easy to work with on Google Earth, which eliminates requiring and mastering geospatial software.
h. In some places, because of a lack of overlap or poor mosaicking, there were cavities in the data, the point cloud. When creating the DEMs, the Metashape default is to fill the cavities based on interpolating pixels around the cavities. We disabled that feature when creating both the DEM and orthomosaic. Because the area of the survey included steep mountains and cliffs, we did not smooth the data with interpolation techniques.
i. The photogrammetry process also creates a PDF report with feedback regarding the flight survey, e.g., overlap, as well metrics regarding the process quality.

3. Produce spatial products and derivatives.
    a. Next, the process uses the respective VFCIs to clip the mosaic to only the gully of interest.
    b. The process uses an available snow-less DEM (e.g., from summer or a different source lidar) to calculate the absolute snow height by subtracting DEM_summer from DEM snow.

c. The process also uses the most recent flight over the specific snow gully to create the respective snow change between flight acquisitions.
d. The process then uses VFNHz and VFCS to calculate the various metrics of hazard and snow load potential in absolute terms (using step b) and relative-recent change (using step c) to inform the avalanche practitioner of the changes and approaching critical conditions.

4. Exchange data and interface with the program.
   a. The program resides in a powerful desktop, Dell-Alien, with one solid-state 1-TB disk and a 10-TB spinning disk.
   b. The Alien computer is in the DOT Candalar Camp, on the network.
   c. The 10-TB spinning disk is a shared drive, and so the avalanche practitioner has access to it from his or her computer.
   d. At the end of a flight, the avalanche practitioner copies the flight data to the Alien shared spinning drive using his or her own computer.
   e. After the software completes processing the data, the products are placed in a product folder within the original folder.
   f. The avalanche practitioner, using his or her own computer, logs onto the shared drive to review the processed data products.

APPENDIX C: INTERVIEWS WITH TRANSPORTATION AGENCY STAFF

Question: Can SfM data support your DOT's avalanche staff?

From WSDOT Avalanche Supervisor:

- Yes, SfM on a UAS has value
- Will allow quantification of the snowpack volume in avalanche release zones, in snow catchment areas next roads and determine how much snow is left after an avalanche.
- Support snow depth measurement
- The result can be used as a training aid for less experienced employees, and they can relate numbers to the situation in the field
- Quantification is good for WSDOT's social media "we moved XXX cubic feet of snow today"
- The digital photos from the process have value to the forecasters
- As a side benefit, drones can take pictures of stalled vehicles, queues, etc that portray the situation at the pass after a major snowfall and be posted in social media.

From the Alaska DOT&PF UAS Coordinator:

- Can be used for forecasting to support better decision making.
- Data can be used for assessment of future RACs as well as monitoring mitigation efforts pre- and post-storm.

How usable is the snow depth data from SfM?

From WSDOT's Avalanche Supervisor:

- Accuracy of the snow depth is less important than volume in most cases. For WSDOT near-real time is data ok. The WSDOT has computer capacity at their Snoqualmie Pass office (Bullfrog) that can handle SfM data, so processing is not a big concern.

From the Alaska DOT&PF UAS Coordinator:

- Accuracy of depth for AKDOT is incredibly important since slabs can often be 3" or less. Near-real time data is preferred. Atigun Pass/Chandalar Camp has a new computer for processing SfM.
- The data is essential for better forecasting of avalanche conditions.

- Data accuracy is relative to volume calculation however 3cm GSD seems to be doing the trick.
- SFM results will always be available after processing as surface needs to be compared to bare earth.
- The goal with the research project is to automate and create a turnkey processing engine for forecasters to use. UAS data will be stored via image server which will be made available through ARCGIS online.

From Alaska DOT&PF Atigun Pass Avalanche Manager:

- SfM products can be compared to previous ones to find changes in snow distribution that happen over time.
- Photos taken from drones are a very valuable tool. In many cases that is the only way where you can look at a starting zone well. Valuable pre and post events.
- It does not matter who processes it. What does matter is how soon the avalanche professional can get the resultant products. Ideally it would be processed locally.

<u>Operations: What would be needed to make UAS with SfM routinely useful?</u>

From WSDOT Avalanche Supervisor:

- Avalanche staff at WSDOT should be trained as UAS pilots and have a UAS in their vehicle as a standard piece of equipment.
- Yes pilot in Alaska should be trained
- Pre-set flight profiles are good to have consistency and to make the data collected process efficient.
- Weather conditions: visibility is the main challenge related to photography and flight rules"

From Alaska DOT&PF UAS Coordinator:

- Completely automated flight missions
- All UAS operators must have part 107 drone pilot license
- Ideally would have a drone in avalanche staff vehicles as standard equipment, however M&O funding is limited and UAS are costly
- Depends on accuracy requirements, if RTK is available then ground will be used for QC check
- Lidar can be used at the location to create bare earth DEM

From Alaska DOT&PF Atigun Pass Avalanche Manager:

- The whole suite is what is needed to make SfM useful (e.g., drones, processing software, etc.)
- The avalanche staff are the ones who know at any time what they could use from the drones, so it would be best and more efficient if they were the pilots, with a drone readily available for their use. Preset flight programming will make it more efficient to gather needed data, especially over a large area.
- Ground control points are important in assuring the quality of the data obtained.
- The value of SfM data is most advantageous with preset flights, thus one knows the area to be surveyed, and knows that there is a previous flight that covers that area. However, from our experience after getting the D-RTK unit as part of the operation, the accuracy has been so good that we have reduced (not eliminated) the usage of ground control points. The confidence in the accuracy level has been very high.
- Bare earth data in these areas is in my mind less important for the survey results UNLESS the goal is for Total snow. I think the greatest value most of the time will be comparing snow surface DSM's with previously obtained ones.
- However, if terrain following routines are to be used for flight, then a reasonably accurate base-line DEM is necessary.
- On the contrary to the above, having a high-quality baseline DEM of your flight area could possibly be of value as a tool for QC of SfM products.

<u>Limitations</u>

From the WSDOT Avalanche Supervisor:

- Limitations related to weather are important, too windy you cannot fly, maybe too cold.
- Line of sight a major limitation due to FAA reg 107. However, in some cases you can get permission to fly beyond line of sight.
- Staging locations: If we need to maintain visual contact with the drone, particularly around the interstate, then we limit which slopes/areas we can assess. Ideally the drone flies away on its own and performs the task without much assistance
- The Chinook Pass test site site is partially in Mount Rainier National Park which does not allow any UAS flights.

- Lighting is a limitation. SfM requires reasonable light for images to be useful
- Processing time. Maybe a limitation? WSDOT has enough computer capacity in their maintenance office to process the SfM. In addition, in most cases getting results in a few hours is fine
- "Visual/range - Here again is a limit due to how far away the drone can fly. We lost visual "with the drone near the top of the west shed due to distance"
- SfM may require ground control points
- "Weather conditions: visibility is the main challenge related to photography and flight rules"
- "Staging locations: If we need to maintain visual contact with the drone, particularly around the interstate, then we limit which slopes/areas we can assess. Ideally the drone flies away on its own and performs the task without much assistance"
- "Visual/range - Here again is a limit due to how far away the drone can fly. We lost visual "with the drone near the top of the west shed due to distance"
- Obstacles - We've twice come close to or hit trees. I'm assuming this is a matter of programming the flight to a higher elevation."

From Alaska DOT&PF UAS Coordinator:

- In areas lidar is not available
- Wind and icing conditions including precipitation are no fly conditions
- Lidar can be flown at night compared to photogrammetry
- If you can drive a truck to location, you can launch a drone there
- FAA regulations can be mitigated through TFRs COAS and Waivers
- Cost is the primary barrier to entry as platforms are over $30,000

From Alaska DOT&PF Atigun Pass Avalanche Manager:

- Weather, primarily. There are wind and visibility limitations for SfM. So during snow or windstorms, it will most often not be of use to fly. Darkness and flat light is also limiting. Since avalanches are often related to these windy and snowy conditions, SfM may not be as valuable during storms as one would wish. Set up time can be worked down to a minimum once flights have been standardized. And staging areas should be well defined.

- FAA regulations are not always friendly to efficient operation, but we must work within their rules.
- Costs can be a limitation, however once a flight program is set up and proven, the costs could be marginally not too bad for operations. One of the biggest costs at that time may be contingency funding for damaged or lost drones.

Equipment

From WSDOT Avalanche Supervisor:

- Seems like equipment is not a major limitation. Most drones will work.

From Alaska DOT&PF UAS Coordinator:

- The drone that Gordon uses comes from the AKDOT&PF UAS program, it gets returned at the end of every season and then loaned out for other uses throughout the rest of the year. Initially, Gordon was borrowing a Phantom 4 from Northern Region M&O. BUT, this did mean that Gordon had unimpeded access to the drone for the entirety of the avalanche season. Ideally, AKDOT&PF would like to use a combination of RTK multirotor (M300) and D-RTK base stations to improve image quality and reduce flight times.

From Alaska DOT&PF Atigun Pass Avalanche Manager:

- We have been using the P4RTK drone with the D-RTK ground stations, with various software and computers.
- The P4RTK is good for about 15 minutes of flight. More available flight time would be beneficial. I have had to use as many as 3 batteries to complete some surveys. This more than triples the time needed (as in most of these cases much of the battery power is used in getting to and from the area to be surveyed.