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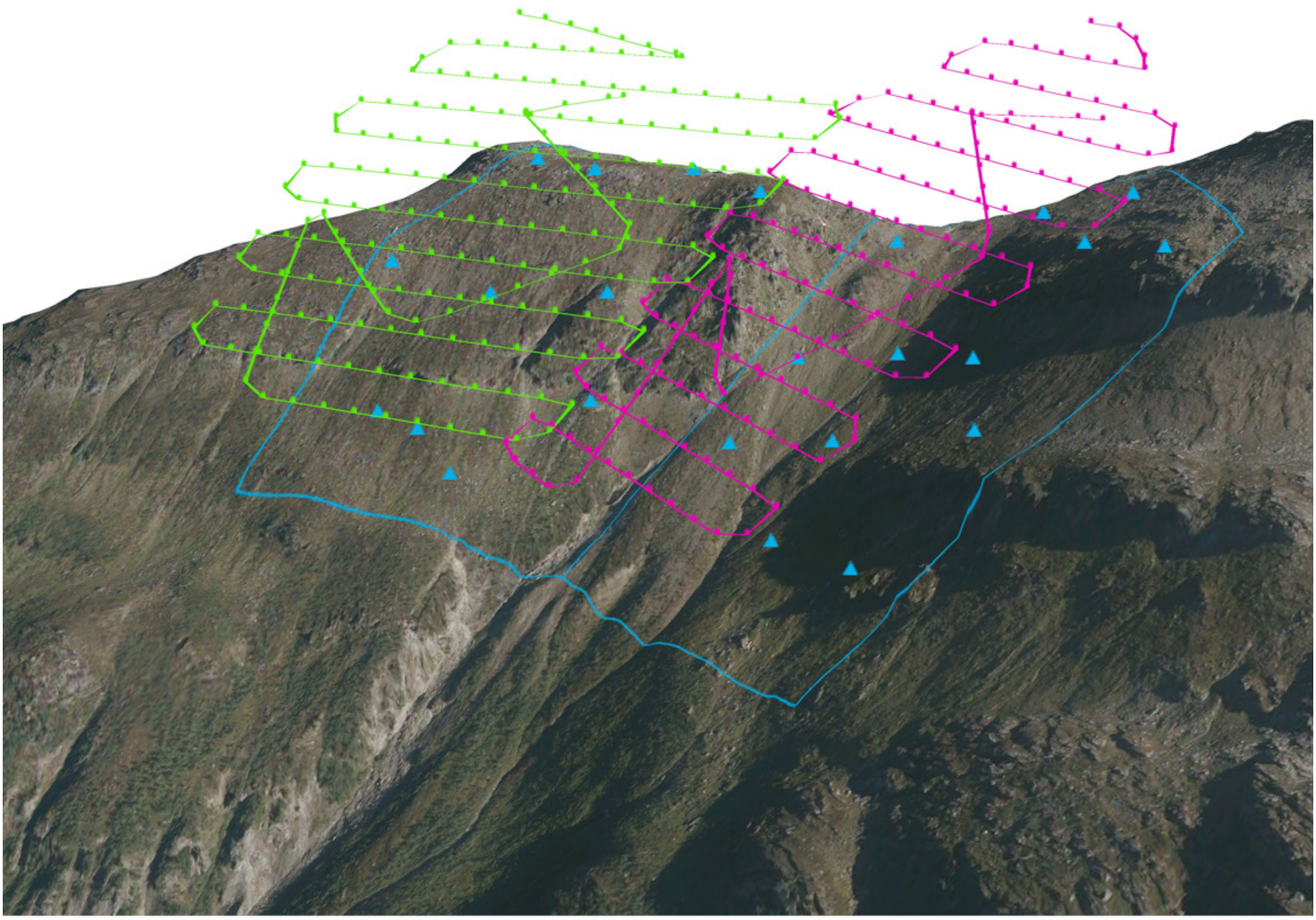
Photogrammetry and Drones for Avalanche Monitoring

Preliminary Field Investigations on Bare Ground and Research Plan for Roadside Avalanche Operations

STATENS VEGVESENS RAPPORTER Nr. 655



NGI NTNU Statens vegvesen

Statens vegvesens rapporter

Tittel
Bruk av fotogrammetri og droner ved vurdering av snøskredfare

Undertittel
Forberedende feltundersøkelser på barmark og utkast til forskningsplan

Forfatter
E. McCormack (red.), R. Frauenfelder, S. Salazar, H. Smebye, T. Humstad og E. Solbakken

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Prosjektleder
Tore Humstad

Godkjent av
Viggo Aronsen

Emneord
snøskred, droner, UAS, fotogrammetri, SfM

Sammendrag
To tidligere feltdemonstrasjoner med bruk av droner (UAS) for som støtteverktøy ved skredfarevurdering for veg, har gitt verdifull erfaring fra operasjoner i vinterforhold med kameraer og ulike sensorer.

Statens vegvesen planlegger nå en tredje fase. Denne er designet for å evaluere praktisk og realistisk bruk av droner i Vegvesen-operasjoner, for å skaffe et bedre beslutningsgrunnlag ved stenging og gjenåpning av veger - eller utførelse av andre risikoreduserende tiltak. En innledende fase med planlegging og feltarbeid på barmark høsten 2019 er utført, sammen med påfølgende dataanalyse vinteren 2019/2020. Neste trinn er planlagt gjennomført på snødekt terreng vinteren 2020/2021.

Denne rapporten dokumenterer resultatene fra feltundersøkelser og foreslår en forskningsplan for de neste undersøkelsene.

Antall sider 18

NPRA reports
Norwegian Public Roads Administration

Title
Photogrammetry and Drones for Avalanche Monitoring

Subtitle
Preliminary Field Investigations on Bare Ground and Outline for Research Plan

Author
E. McCormack (editor), R. Frauenfelder, S. Salazar, H. Smebye, T. Humstad, E. Solbakken

Department
Planning and Engineering Services

Section
Geomechanics

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Project manager
Tore Humstad

Approved by
Viggo Aronsen

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Summary
Two previous field demonstrations of unmanned aerial systems (UAS or drone) to support roadside avalanche hazard assessment, have given valuable field experiences of operating in winter conditions with cameras and different sensors.

The Norwegian Public Roads Administration (NPRA) is now planning a third phase. This is designed to evaluate practical and realistic use of drones in NPRA operations, in order to assist their staff in making more informed decisions when closing and re-opening roadways or to perform other risk reduction measures. The first stage involves planning and preliminary field work on bare ground during the autumn 2019, as well as subsequent data analysis during winter 2019/2020. The next step is planned to be conducted on snow covered terrain during the winter of 2020/2021.

This report documents the results of preliminary field investigations and suggest a research plan for the next investigations.

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Photogrammetry and Drones for Avalanche Monitoring

Preliminary Field Investigations on Bare Ground and
Outline for Research Plan for Roadside Avalanche Operations

May 6, 2020

Contents

1. Introduction

The Norwegian Public Roads Administration (NPRA) has previously conducted two field demonstrations of using unmanned aerial systems (UAS or drone) technology to support roadside avalanche hazard assessment.

Phase 1 was completed in Bjorli, Norway during the winter of 2016 where the NPRA conducted an evaluation of UAS' ability to operate in winter weather and in mountainous terrain in support of snow avalanche monitoring. Vendors flew nine multi-rotor, rotary-wing, and fixed wing aircraft on four increasingly difficult missions in steep mountains in cold and windy winter conditions. The missions ranged from flights over a nearby road and bridge to a 2.3-kilometer-long flight over a 1,300-meter-tall mountain to inspect avalanche features. Results indicated that there was no single UAS that meets all the road administration's monitoring needs, but different types of aircraft could be used in different conditions for avalanche monitoring. The tests confirmed that UAS could be set up to operate next to roads and fly in the typical winter weather in which the NPRA conducts avalanche evaluations. The tests also showed that camera quality and sensor technology are critical to their usefulness[1,2].

Phase 2. The findings from Phase 1 prompted a follow-on two-day Phase 2 field test in April 2018 in Andøya, Norway, where the NPRA evaluated the usability of sensors and cameras mounted on UAS. The test explored Ground Penetrating Radar (GPR) and photogrammetry techniques (Structure from Motion or SfM). This test involved an evaluation team from the Norwegian University of Science and Technology (NTNU), the Norwegian Geotechnical Institute (NGI), and the NPRA[3].

The Phase 2 test demonstrated that GPR output could be used to remotely identify snow layering under an aircraft's flight path. The measurements could be used to interpret the presence of weak layers that could be relevant for avalanche danger assessment. However, interpretation of the raw GPR output was a challenge for non-experts and required post-processing to be useful to the NPRA. The project team felt that GPR technology will need further development to allow avalanche staff to quickly use raw sensor output to identify hazardous conditions in the snowpack.

The team also recognized that GPR had an important added safety benefit; the GPR was also tested in Phase 2 to help identify buried vehicles and humans, but as with the snow layering, interpretation of this output worked best with post-processing.

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[1] NPRA UAS Demo Report 2016, *Evaluating Unmanned Aircraft Systems for snow avalanche monitoring in winter weather and in mountainous terrain, Findings from a demonstration of unmanned aircraft systems (UAS) at Bjorli, Norway*) https://www.vegvesen.no/dokument/basis/fil/17351154

[2] Nordic Roads and Transport Research, *Unmanned Aircraft for Roadside Avalanche Monitoring*, December 2, 2016. http://nordicroads.com/unmanned-aircraft-for-roadside-avalanche-monitoring/

[3] McCormack E., T. Vaa, G. Håland, T. Humstad and R. Frauenfelder. *Evaluating Sensors for Snow Avalanche Monitoring on UAS, Findings from Andøya, Norway, April 16-18, 2018*, STATENS VEGVESENS RAPPORTER Nr. 615 (https://www.vegvesen.no/fag/publikasjoner/publikasjoner/Statens+vegvesens+rapporter).

Digital cameras flown on UAS were used to view surface features of the snow and this visual output was immediately usable to avalanche experts at NGI and NPRA. The use of SfM software to process photographs collected from low cost digital cameras could potentially map snow surface conditions and measure snow depth, both of which are valuable for avalanche hazard assessment. SfM applied to photographs collected both before and after a snowfall could provide valuable data about snowpack depths and snow volumes. Recent work on this topic include a master thesis, supported by the NPRA, published in 2019[4].

In addition, an internal NPRA memorandum written in 2016 by NPRA employee Halgeir Dahle about SfM investigation of the Bispefonna glide avalanche noted that SfM supported the development of a more precise topographic map of the terrain[5].

Overall, the UAS industry and airborne sensor industry is advancing rapidly and the Phase 2 research team felt that the NPRA should continue to explore UAS capabilities and particularly UAS-based SfM applications. Regulatory issues will need to be reviewed to confirm that future use of UASs is in accordance with the current aviation flight rules.

A **Phase 3,** conducted during 2019 and planned to be continued in 2020 and 2021, was designed to evaluate practical and realistic use of drones in NPRA operations while using NPRA staff to assist them in making more informed decisions about when to close and re-open roadways or to perform other risk reduction measures. This effort was divided into Stage 1 and Stage 2. Stage 1, which included planning and preliminary field work, was completed in 2019. A future Stage 2 will depend on funding and the re-organization of the NPRA and is planned to be conducted during the winter of 2021. This report documents the preliminary field investigations and research plans from Stage 1 and will support continuation into Stage 2 of the project as soon as the organizations, personnel, and funding are in place.

[4] Solbakken, E. (2019) MSc thesis in Geology. NTNU- Norwegian University of Science and Technology, September, *Snow surface mapping and change detection in avalanche release areas using a consumer-grade UAS and SfM photogrammetry*, https://vegvesen.brage.unit.no/vegvesen-xmlui/handle/11250/2631360

[5] Dahle, H. (2016). *Fotogrammetri av løsneområde for glideskred ved Bispefonna*, M&R. NPRA internal report, Rapportweb ID 17351154.

2. Background

Throughout 2019, as part of Stage 1 (of **Phase 3**), a project group with members from NPRA, NGI, and NTNU completed a series of teleconference meetings to set goals, to share information and expertise, and to track progress. Field investigations were performed by NGI on Sætreskarsfjellet in Grasdalen, in September 2019 and by NPRA in Lavangsdalen, in October 2019. The locations of the two field investigation sites are presented in Figures 1 and 2, respectively.

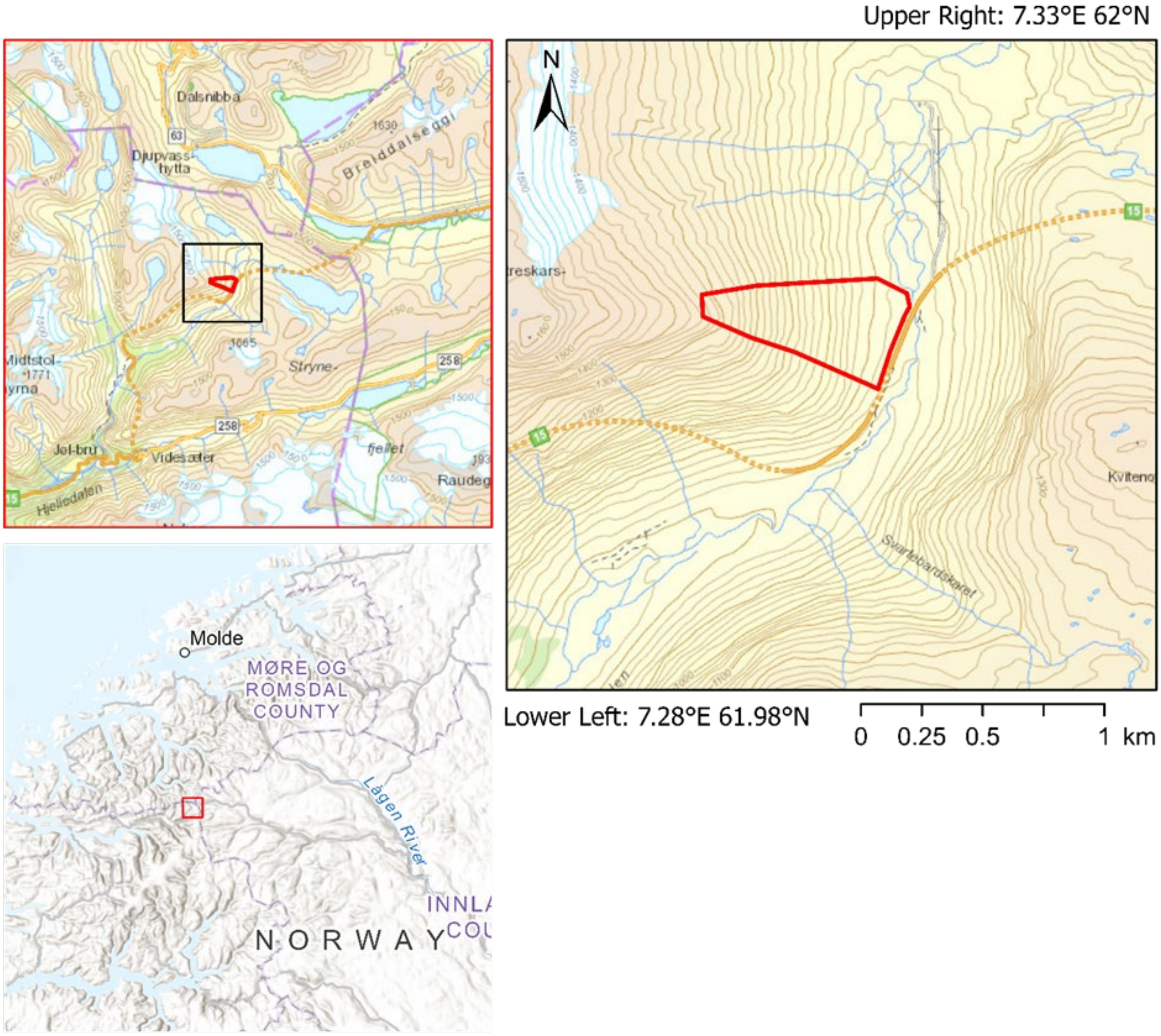

Figure 1. The selected Sætreskarsfjellet avalanche path in Grasdalen, Vestland county. (Source: Geodata AS, The Norwegian Mapping Authority)

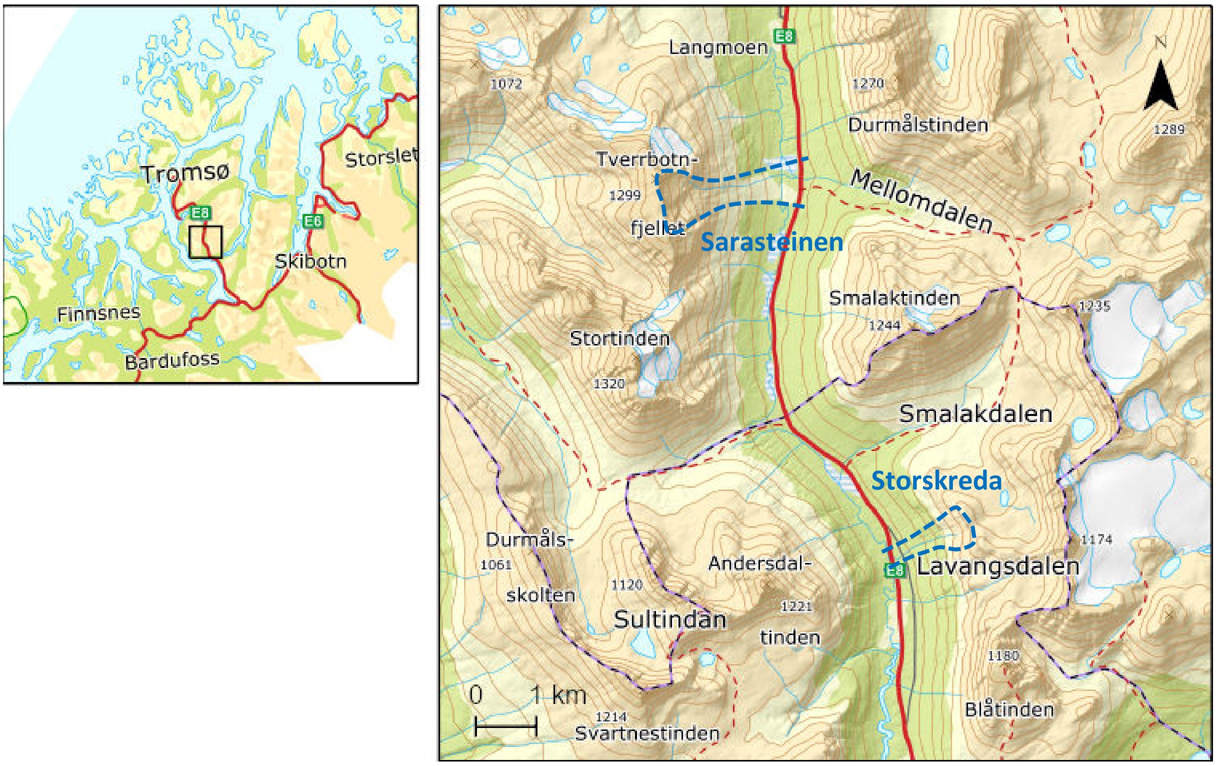

Figure 2. Two test sites as suggested in Lavangsdalen, Troms and Finnmark county. Bare ground mapping was conducted in the avalanche release area at Storskreda. (Source: The Norwegian Mapping Authority)

The **Phase 3** project is part of a multi-year effort by the NPRA to explore if and how UAS technology can support avalanche monitoring efforts. The main objectives being:

- Increasing the number of avalanche site visits for better coverage. If the use of UAS could reduce the time needed for NPRA staff to ski or walk to an avalanche site, the number of locations that staff might inspect during a day in the field could increase.
- Improving remote inspections. Due to steep terrain, many avalanche release areas are inaccessible and must be inspected from a distance. The use of UAS could allow for more effective remote inspections.
- Lowering the risk for NPRA staff in avalanche-susceptible areas. Remote inspections via UAS will render it unnecessary for NPRA staff to move within avalanche-susceptible terrain and hence will significantly increase staff safety.
- Reducing manned helicopter flights to decrease costs and increase sustainability. UAS are already in use by NPRA in place of a manned helicopter for inspecting avalanche sites resulting in economic benefits. A typical manned helicopter flight costs 25,000 NOK, so the ability to replace these flights with UAS usage results in considerable savings. In addition, the carbon footprint of manned helicopter flights is significant. Substituting manned flights with UAS inspections would lead to a more sustainable conduct of operations.
- More accurate data. A final, less tangible benefit is from the use of UAS to provide NPRA staff with better data and more coverage. Specifically, UAS-assisted operations may provide higher resolution data over larger areas with more frequency. The ultimate efficiency and cost savings may ensure safer roads that are opened more quickly.

3. Phase 3 - Further exploration of UAS and SfM

As recommended in Phase 2, the proposed third phase of the project aims to further explore Structure-from-Motion (SfM) as a tool in UAS-based snowpack surveys. SfM can be used to create high-quality 3-D point clouds, comparable to the ones generated by LiDAR surveys, but with much lower equipment costs. The raw SfM data can be collected using digital cameras carried aboard small consumer-grade drones, such as those already owned and operated by the NPRA. The data can be analyzed using commercially available SfM software packages.

The research in Phase 3 is being conducted by personnel from NTNU, NPRA, and NGI.

3.1 Project goal

The goal of Phase 3 is to explore if SfM, applied to digital photographs collected by a small UAS, can support NPRA avalanche monitoring operations. Some of the overall research questions to be addressed include whether UAS-based SfM can:

- provide better or new data in support of roadside avalanche monitoring,
- provide better spatial coverage of snow in locations of avalanche risk,
- support existing techniques currently employed by NPRA professionals (such as snow pits),
- create useful photographs and videos (separate from SfM processing),
- operate in a range of light and weather conditions, and
- be operated remotely (i.e. flying autonomously) to gather data.

A more detailed list of research questions, guiding the Phase 3 research effort, are included in Appendix 3.

3.2 Stage 1 – Preliminary investigations on bare ground

The Phase 3 research effort is divided into two stages. Stage 1 was completed in the fall of 2019 and Stage 2 is planned for the winter of 2021.

Task 1. Fly avalanche areas before snowfall. The initial stage (Stage 1) was completed and included the task of surveying baseline (snow-free) conditions over two test sites to serve as the foundation for future snow depth measurements. One survey was conducted at a site that is located at Sætreskarsfjellet above National Road Rv. 15 in Grasdalen (Vestland county). The other survey was carried out above the European route E8 highway in Lavangsdalen (Troms and Finnmark county). Both these roadways serve considerable trucking traffic and are considered economically important.

For both pre-snow surveys, the following tasks were completed at each test site:

- Avalanche release areas and runout length for the test locations were identified.
- GPS-based flight paths (mission profiles) for the test area were planned.
- Ground control points were placed and independently surveyed.
- Terrain-aware photogrammetric surveys were performed over each test location using small, consumer-grade UAS with onboard cameras.
- The survey data were processed using a commercial SfM software package.

- The accuracy of the resulting products was assessed.
- The findings of each survey were documented.

The pre-snow surveys highlighted several research questions that will need to be further investigated in Stage 2:

- Can data be collected in low-light conditions?
- How can the flight plans be optimized for effective survey coverage with sufficient accuracy, especially since flight time might be a limiting factor in winter conditions?
- What is the requirement for ground control, including temporary or permanent installations/markers, for accurate georeferencing?
- What is the cost-benefit of using an aircraft equipped with more accurate and costlier Real-Time Kinematic (RTK) positioning technology?
- Will automatic flight plans be feasible in steep terrain?
- Can the errors from the SfM method be quantified?

Summaries of the Stage 1 test flights are described below with greater detail in the Appendices 1 and 2.

National Road 15 at Sætreskarsfjellet, Vestland county
In September of 2019, Helge Smebye (NGI) and Emil Solbakken (NPRA) performed UAS test flights at the Sætreskarsfjellet avalanche path in Grasdalen without snow cover.

A GPS-based flight plan was established to ensure sufficient photographic coverage and overlap over the entire 0.23 km^2 path area. UAS mission planning software was used to program automated flight lines and capture intervals. Due to the size of the avalanche path, the flight plan was divided into portions to allow the UAS to return to base periodically for battery changes. Terrain-aware planning was utilized to account for the 500-m elevation change along the length of the avalanche path. Before starting the mission, ground control points (GCPs) were established by placing photogrammetric targets and subsequently surveying the points with a differential GPS Global Navigation Satellite System (GNSS). A total number of 21 targets were distributed across the avalanche path and were visible in the imagery collected by the UAS.

Figure 3. Pictures from field work in Sætreskarsfjellet in Grasdalen. LEFT: View from the avalanche release area on the eastern flank of the Sætreskarsfjellet mountain. A charge of explosives, to be used for artificial triggering of avalanches, is visible in the foreground. RIGHT: Helge Smebye (NGI) launching an UAS flight mission. (Photos: Emil Solbakken)

The photogrammetric survey on the Sætreskarsfjellet avalanche path in Grasdalen resulted in a three-dimensional digital surface model, derived using a SfM processing technique. The model was compared to data from a pre-existing LiDAR dataset commissioned by the federal mapping agency and covering the same avalanche path. The SfM-derived model had an average ground resolution of 2.4 cm. A comparison with the previously acquired 50-cm ground resolution LiDAR-derived model revealed that there was an overall good match, except in areas where dense vegetation and steep rock outcroppings caused localized large differences. The GNSS surveyed elevation of each of the GCPs was compared to the LiDAR-derived terrain elevation at the location of each of the GCPs to determine an average difference of 2.31 cm. GCP accuracy was assessed within the SfM software, revealing an average error of 0.6 cm (Easting), 0.9 cm (Northing), and 0.3 cm (altitude) for a total error of 1.1 cm for all GCPs.

The effect of GCP distribution was determined through a comparison of two SfM-derived models: one model utilized all the GCPs (21 total), distributed along the length of the avalanche path, while the other model only utilized a small subset of the GCPs (six total) concentrated near the avalanche release area and used to adjust the models. The comparison with the LiDAR-derived model revealed that the SfM model that utilized all available GCPs ground control points was more closely matched to the LiDAR-derived model than the SfM model that only used a reduced number of GCPs ground control points. This finding has implications for future UAS-based photogrammetric surveys over snow-loaded avalanche paths, where the risk to personnel safety may be too high to allow for the uniform distribution of GCPs along the length of the avalanche path.

From the survey flights, it was determined that terrain-aware mission planning was critical to account for the 500-m elevation change along the length of the avalanche path. Inaccurate terrain-aware planning could cause differences in flight altitude, resulting in differences in ground resolution and potentially influencing the accuracy of the results.

The technical report describing the Gradalen tests and the findings is included as Appendix 1.

European route E8 in Lavangsdalen, Troms and Finnmark county
In October 2019, Emil Solbakken and Hallvard Nordbrøden (both NPRA) performed a UAS-SfM mapping of the avalanche release area at the avalanche path 'Storskreda' Lavangsdalen. High resolution surface models of the release area were achieved using a consumer-grade UAS for image acquisition and the Agisoft Metashape software for SfM photogrammetric analysis. The models were georeferenced through ground control points, and 24 visible markers were distributed evenly within the survey area and geolocated before the image acquisition.

Two different configurations of ground control were tested: one using all markers for ground control, and one using only markers at avalanche-safe locations above the release area. Enabling all markers for ground control resulted in the highest accuracy with a total root mean square error (RMSE) on markers of 8.9 cm. This surface model was also compared to an existing LiDAR-model at 0.5 m resolution, which gave a mean cell elevation difference of 12 cm and a standard deviation of 47 cm. Using only 10 ground control points in the upper part of the survey area, the total RMSE was 8.0 cm among the ground control points and 18.5 cm on the rest of the markers.

The achieved level of accuracy is within the expectations for surveys of this type. However, several factors were found to limit the quality of the final surface models. The most important of these are high reprojection errors and local surface deformations, likely caused by uncorrected rolling shutter distortion, and large-scale deformation due to insufficient correction of lens distortion. For the surface model established with a reduced number of ground control points, the accuracy was also reduced due to inaccurate scaling and orientation of the model.

Figure 4. Hallvard Nordbrøden (NPRA) surveying a ground control point at Storskreda, Lavangsdalen, during field work in October 2019. (Photo: Emil Solbakken)

The results highlight some of the challenges of using a consumer-grade UAS and indirect georeferencing, especially when the distribution of ground control points is sparse and uneven. However, they also indicate that with improved mitigation of image distortion, strong image geometry and an improved distribution of GCPs, sub-decimeter overall accuracy might be achievable even with a low number of ground control points.

The technical report describing the Lavangsdalen tests is included as Appendix 2. A second test site, Sarasteinen, is also described and suggested for future research.

3.3 Stage 2 – Investigations on snow

The second stage is a follow up on the findings of Stage 1 and is dependent on additional funding. Ideally, the following tasks, which build on the work completed in 2019, will be conducted in 2020 or 2021.

Task 2. Document additional applications of SfM for snow surface and snow pack evaluation. In addition to Emil Solbakken's research a number of efforts exploring SfM on drones for snow analysis have been conducted [6,7,8,9] but most are completed in a research context and may or may not be suitable for an operational environment such as where NPRA avalanche staff needs rapid on-site information to support decisions to open or close roadways. Given that both SfM algorithms and UAS technology are advancing rapidly, the research team, as part of this task, will continue to review and document on-going developments in the use of UAS to evaluate snow conditions.

Task 3. Review SfM and UAS software and equipment. While commercial SfM software already owned and operated by NPRA and NGI was used as part of Stage 1, this effort will consider other software packages to ensure the best software and equipment is being used. Several commercial vendors sell SfM software or there may be open-source software that is usable and suitable for this purpose. This task will evaluate software that can be used to process images collected with a small digital camera payload mounted on a consumer-grade UAS. The research team suggests that image requirements include:

- collecting digital images with a minimum resolution of 12 megapixels, but preferably 20 megapixels,
- output in both JPEG and RAW image formats, and
- image sets of at least 200 images.

[6] Fernandes, R., Prevost, C., Canisius, F., Leblanc, S. G., Maloley, M., Oakes, S., Holman, K., and Knudby, A.: Monitoring snow depth change across a range of landscapes with ephemeral snow packs using Structure from Motion applied to lightweight unmanned aerial vehicle videos, The Cryosphere Discuss., in review, 2018.
[7] Cimoli, E.; Marcer, M.; Vandecrux, B.; Bøggild, C.E.; Williams, G.; Simonsen, S.B. Application of Low-Cost UASs and Digital Photogrammetry for High-Resolution Snow Depth Mapping in the Arctic. Remote Sens. 2017, 9, 1144.
[8] Bøggild, C. E., & Sigernes, F. (2015). Determining Snow Depth Distribution from Unmanned Aerial Vehicles and Digital Photogrammetry (Doctoral dissertation, M. Sc. thesis, Civil Engineering, Technical University of Denmark, 2015. Google Scholar).
[9] Gabrlik, P., Janata, P., Zalud, L., & Harcarik, J. (2019). Towards automatic UAS-based snow-field monitoring for microclimate research. Sensors, 19(8), 1945.

This task will also evaluate the time required to install and to learn how to use the SfM software. This effort will be guided by NGI and NPRA staff with expertise in photogrammetric processing.

Software to plan flight paths and to operate the UAS will also be reviewed since the ability to re-survey previously surveyed paths at a set distance above the ground (terrain following) will be important to the success of the tests.

The equipment used will be further evaluated. This may include different types of aircraft and sensors including infra-red, near infra-red, or active source technology which could be used in the dark or in low-light conditions. In addition, different types of onboard navigation systems, such as RTK, will need to be further evaluated.

The computational cost and time requirements for SfM processing of datasets will be a relevant consideration. Currently, the SfM processing takes several hours to run and can require several more hours to interpret and to extract the parameters of interest. There are UAS mapping companies offering low-fidelity products that allow for rapid mapping, but which do not result in accurate maps in difficult terrain. This will likely change as computer processing speeds increase.

This task will also evaluate how important real time data is for the NPRA avalanche staff and how quickly information is required from SfM-derived products to be useful for NPRA operations.

Task 4. Fly during winter conditions. The test sites at Sætreskarsfjellet and Lavangsdalen will be flown and mapped after snow has accumulated. The ability to re-fly the same test area can be achieved with appropriate survey design, adjusted to the equipment used since the resulting SfM surface model is independent of the exact flying path. These flights would need to occur when the sites are snow loaded and ideally during a time of increased avalanche danger. For evaluation and comparison with the SfM output, the avalanche hazard would be concurrently evaluated by NPRA and NGI staff using snow pits, weather stations, and other tools as well as local knowledge and professional experience.

An important requirement that will be evaluated as part of this task is the need for distributed ground control points (GCPs). If flights are to successfully occur after snowfall, the GCPs will need to be visible on snow-covered ground, while minimizing hazard to personnel by placing GCPs outside of avalanche release areas and avalanche paths.

Two different types of GCPs can be used for photogrammetric surveys. One type consists of temporary GCPs that are placed on site and located using a GPS and only need to remain in place for as long as the images are being captured. If it is desired, the same site can be surveyed again in the future using an entirely different set of GCPs that are placed and located prior to collecting new images, given that the new GCPs are accurately surveyed. For each instance, the GCPs are used to independently geo-reference the three-dimensional point cloud products. It does not matter if the GCPs were put in the same place both times. Georeferencing each product independently is more time consuming because each GCP needs to be surveyed (registered) individually, each time a site is surveyed.

The other type of are permanent GCPs that are placed on site and do not need to be located again for future surveys. However, it is important that these GCPs are not moved between surveys. They also allow slightly easier lining up of point cloud products because there are not two entirely independent geolocated products. However, these points need to remain visible and at the exact same location throughout the winter.

The strategy for GCP distribution depends on feasibility, given the area and accessibility of the survey site and time or other resource constraints. Ideally, the survey team will be able to use both permanent and temporary GCPs and test an approach that minimizes the number of required GCPs by optimizing their distribution. SfM software requires at least three to four GCPs just to orientate the surface model, and these should not be placed along a single axis. However, the number of required points is further increased if ground control points are needed for correcting the surface shape.

An alternative to the indirect georeferencing method is direct georeferencing, where image locations from onboard Real-Time Kinematic (RTK) or Post-Processed Kinematic (PPK) Global Navigation Satellite System (GNSS) receivers are used instead of ground control points. Such technology has only recently been adopted from heavier, industry-grade UAS into lighter, consumer-grade UAS. The benefits of direct georeferencing are a significantly reduced need for GCPs, with even and predictable accuracy throughout the survey area and reduced processing times with less manual intervention. The research team plans to evaluate RTK/PPK-enabled UAS technology, as it becomes increasingly affordable and more operator friendly, with the potential to set the standard for UAS-based SfM mapping in the future.

Overall, for winter surveys, validation of model accuracy in the avalanche release areas are challenging.

Task 5. Compare and assess results. The team's NGI and NPRA avalanche experts would compare the information obtained from SfM with their findings. The SfM can provide measurement of snow depth and high-quality images of the snow surfaces including features such as snow cracks and dry loose-snow avalanches as well as observation of actual avalanche activity. The operational aspect, particularly for roadside operation of SfM would also be evaluated. This includes addressing questions as detailed in Appendix 3. A summary of the main questions that would be assessed in this task include:

- Can UAS collect usable photographs that can be processed using SfM for a range of different weather conditions, and in varied terrain? How can the flight plans be optimized to collect suitable images for processing? What are effective mission parameters, such as image overlap, flight altitude, ground resolution, flight speed, and variation in camera angles (normal to ground and oblique images)?
- How many flights are required to obtain useful information?
- Can SfM algorithms be used to process images containing different snow types?
- Can the SfM output provide information about release zones (e.g. geometry) and avalanche paths (e.g. entrainment along the path)?

- Can the SfM output be used to quantify snow conditions and make it easier to support operational decisions?
- What does the use of SfM require fixed in terms of ground control points? Will permanent or temporary points work? Can the road be used for registration?
- For winter surveys, can the use of reflector-less total stations for validation points compensate for fewer control points? Can these stations be used in inaccessible areas, such as avalanche release zones?
- Is the processed SfM information quickly available in the field on a standard laptop computer? Or does it require access to the cloud? Or is near-real time information usable?
- How much training does it take to use SfM software?
- Does the aircraft and software have NPRA applications beyond snow monitoring?

In addition, the usability of the system (aircraft, flight control software and SfM software) may need further evaluation for routine operational effectiveness including:

- cost and intensiveness of equipment setup and flight operations,
- SfM processing times,
- required amount of operator training,
- aviation flight rules approvals (Luftfartstilsynet) such as beyond line of sight flight[10].

Staff from both NPRA and NGI will have an active role in this task.

Task 6. Document findings. The results will be combined with this interim report to create a report detailing the effectiveness of UAS and SfM usage in different snow conditions to monitor and evaluate avalanche hazard. Decision support models may be developed that could be three-dimensional and interactive and would allow the visualization of features, such as the underlying terrain and snow depth. Consideration will also be given to how this approach fits the NPRA's operational protocols and roadway closure rules, as well as relevant Norwegian aviation rules. Efforts will be made to disseminate project results thought publications from these tests.

Tentative Phase 3, Stage 2 Project Schedule

- Winter 2021: Flights during winter conditions
- Summer 2021: Documentation completed

4. Future Phases

Routine Operations: If UAS-based SfM proves to be promising and provides avalanche professionals with usable information, a logical future project is to determine how this technology can be transferred to avalanche professionals in Norway and beyond. This phase would explore if UAS-based SfM could routinely and quickly support avalanche assessment in the field and determine how to make the adoption of this technology feasible for a range

[10] Information on UAS regulations can be found here: https://luftfartstilsynet.no/droner/nytt-eu-regelverk/

of staff by developing best practices, standards, and training manuals. This might include developing models to provide decision support tools, usable in the field that can support staff as they assess avalanche hazards.

Other technologies: Prior to the reorganization of the NPRA, the project team discussed a vendor-focused evaluation of promising drone-carried technologies (similar to how the technologies were explored during Phases 1 and 2 of this program). This task would provide outside vendors and research organizations the opportunity to demonstrate other promising snow monitoring and snow safety technologies. These technologies could include:

- SfM using infra-red or near infra-red radiation (NIR) images
- LiDAR
- Ultrasound
- Ground Penetrating Radar
- Synthetic Aperture Radar
- Personal Avalanche Beacon Detection
- Other vendor-suggested technologies

Ideally, the selected vendors would be supported for their travel and participation.

5. Conclusion

The NPRA, NTNU, and NGI research team are evaluating if photographs collected by digital cameras flown on small UAS and processed using Structure-from-Motion (SfM) software can be used to rapidly assess avalanche hazards. The use of SfM software to process photographs collected from lower cost digital cameras could potentially map snow surface conditions and measure snow depth, both of which are valuable for avalanche monitoring. The team is also exploring if this visual output was immediately usable to the NPRA's avalanche experts.

The project team conducted pre-snow (bare earth) tests at Sætreskarsfjellet above the National Road Rv. 15 at in Grasdalen (Vestland county) and above European Route E8 in Lavangsdalen (Troms and Finnmark county). At both sites, the project team identified suitable avalanche release areas with runout zones above roadways. In order to complete these flights, the team planned GPS mission profiles above these areas and installed ground control point to assure that the flight path and height resulted in digital photographs that were usable in SfM software. The test sites were flown using small, consumer-grade UAS with an onboard camera which collected the photogrammetric survey data. The team successfully processed the survey data using a commercial SfM software package and evaluated the accuracy of the resulting products.

These "bare earth" flights demonstrated that two people over the course of one day could set up, fly, and obtain usable maps of the terrain of interest that can serve as a foundation for future flights of the same location after snowfall. The second stage of this test will determine if this approach can be used to map snow surface conditions and to measure snow depth and distribution to support the NPRA's ability to monitor avalanche hazards.

Appendix 1 (Sætreskarsfjellet Site)

REPORT

Structure-from-Motion for avalanche paths

UAS-BASED STRUCTURE-FROM-MOTION
MODELLING FOR SÆTRESKARSFJELLET, STRYN
AVALANCHE PATH

DOC.NO. 20190682-01-R
REV.NO. 0 / 2020-01-14

NORWEGIAN GEOTECHNICAL INSTITUTE
NGI.NO

Project

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Document title: UAS-based Structure-from-Motion modelling for Sætreskarsfjellet, Stryn avalanche path
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Client

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Client contact person: --
Contract reference: 970141669

for NGI

Project manager: Regula Frauenfelder
Prepared by: Sean Salazar, Helge Smebye
Reviewed by: Regula Frauenfelder

Summary

The availability of consumer unmanned aircraft systems (UAS) has enabled rapidly deployable airborne surveys for civilian applications. Combined with photogrammetric reconstruction techniques, such as Structure-from-Motion (SfM), it has become increasingly feasible to survey limited areas with very high resolution, especially when compared with other airborne or spaceborne surveying techniques. Contained in this report is a summary of a UAS-based field survey conducted over a snow-free avalanche path on Sætreskarsfjellet in Stryn municipality. A terrain-aware flight plan was established to ensure good photographic coverage over the entire avalanche path. More than 400 images were collected over a 0.5 square kilometre area, which were subsequently processed using a commercial SfM software package. Two digital surface models were reconstructed, each with a 2.4-centimetre ground resolution. Each of the models was generated using a different ground control scenario, one with a distributed, full count of ground control points (GCPs), and another with a concentrated, limited count of GCPs, more representative of a survey scenario when the avalanche hazard is high. Comparison with data from a pre-existing, airborne light detection and ranging (LiDAR) survey over the avalanche path revealed that the SfM-derived model that utilized only a limited number of GCPs diverged significantly from the model that utilized all available GCPs. Further differences between the SfM- and LiDAR-derived surface models were observed in areas with very steep slopes and vegetative cover.

Contents

Review and reference page

1 Introduction

Photogrammetric surveys from unmanned aircraft system (UAS) platforms have become an increasingly practical solution to mapping both small and large areas. There are several challenges to conducting UAS-based surveys, especially in steep, snow-covered, or otherwise inaccessible terrain. Presented herein is a methodology for surveying avalanche-prone areas prior to snowfall using a UAS-based survey technique. The same methodology can subsequently be used during the winter season, after extensive snowfall and/or avalanche events, to deduce relevant avalanche parameters such as snow height, snow distribution and redistribution (due to wind), opening of cracks in the snow surface (e.g. for glide avalanches), and avalanche outlines (of released avalanches).

2 Methodology

2.1 Data collection

NGI personnel identified an East-facing avalanche path on Sætreskarsfjellet in Stryn municipality (Figure 1). The path is adjacent to the exposed stretch of road between the Grasdals and Oppljos tunnels on Rv. 15, separated by two rows of avalanche braking mounds at the foot of the mountain, as depicted in Figure 2. The path was selected due to good accessibility from the road below the path and because there was a pre-existing, high-resolution light detection and ranging (LiDAR) survey dataset that could be used for comparison and quality control.

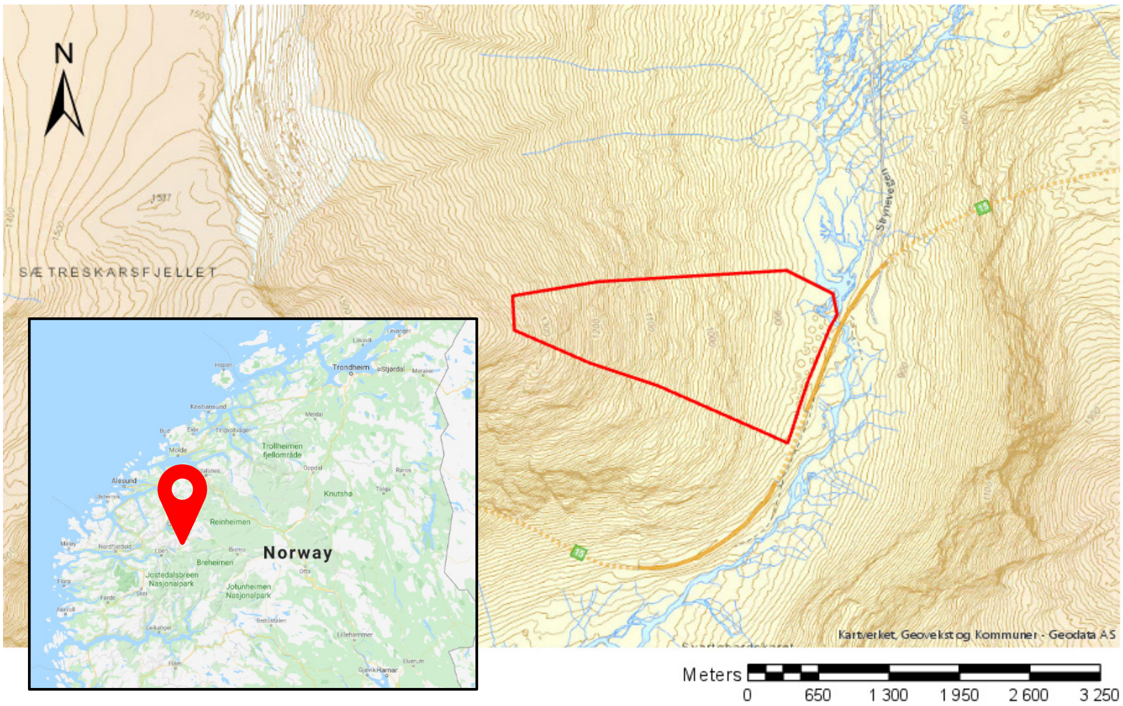

Figure 1: Selected avalanche path (outlined) on Sætreskarsfjellet along an exposed corridor of Rv. 15.

A GPS-based flight plan was established to ensure sufficient photographic coverage and overlap over the entire 0.23 km^2 path area. UAS mission planning software was used to program automated flight lines (Figure 3) and capture intervals. Due to the size of the avalanche path, the flight plan was divided into portions to allow the UAS to return to base periodically between battery changes. Terrain-aware planning was utilized to account for the 500-m elevation change along the length of the avalanche path.

Before starting the mission, ground control points (GCPs) were established by placing photogrammetric targets and subsequently surveying the points with a differential GPS. A total number of 21 targets were distributed across the avalanche path and were visible in the imagery collected by the UAS.

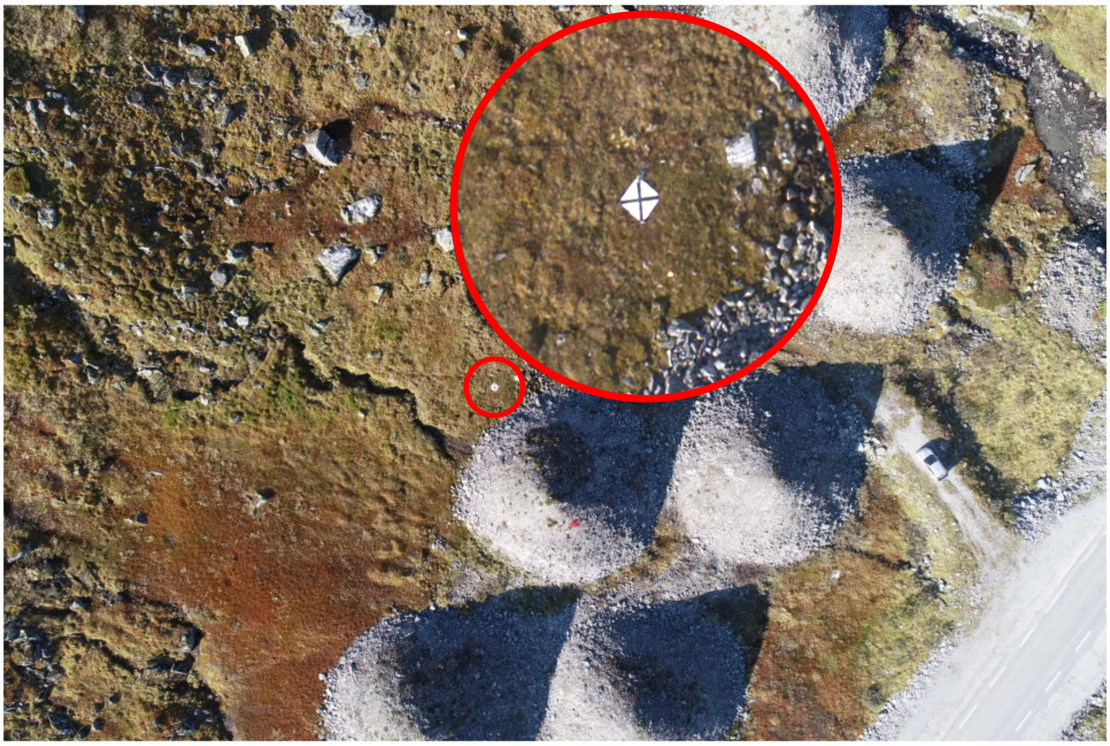

Figure 2: Example of a photograph collected with the UAS, showing the avalanche braking mounds at the foot of the avalanche path on Sætreskarsfjellet; area encircled in red is enlarged (inset) to illustrate GCP placement in the scene.

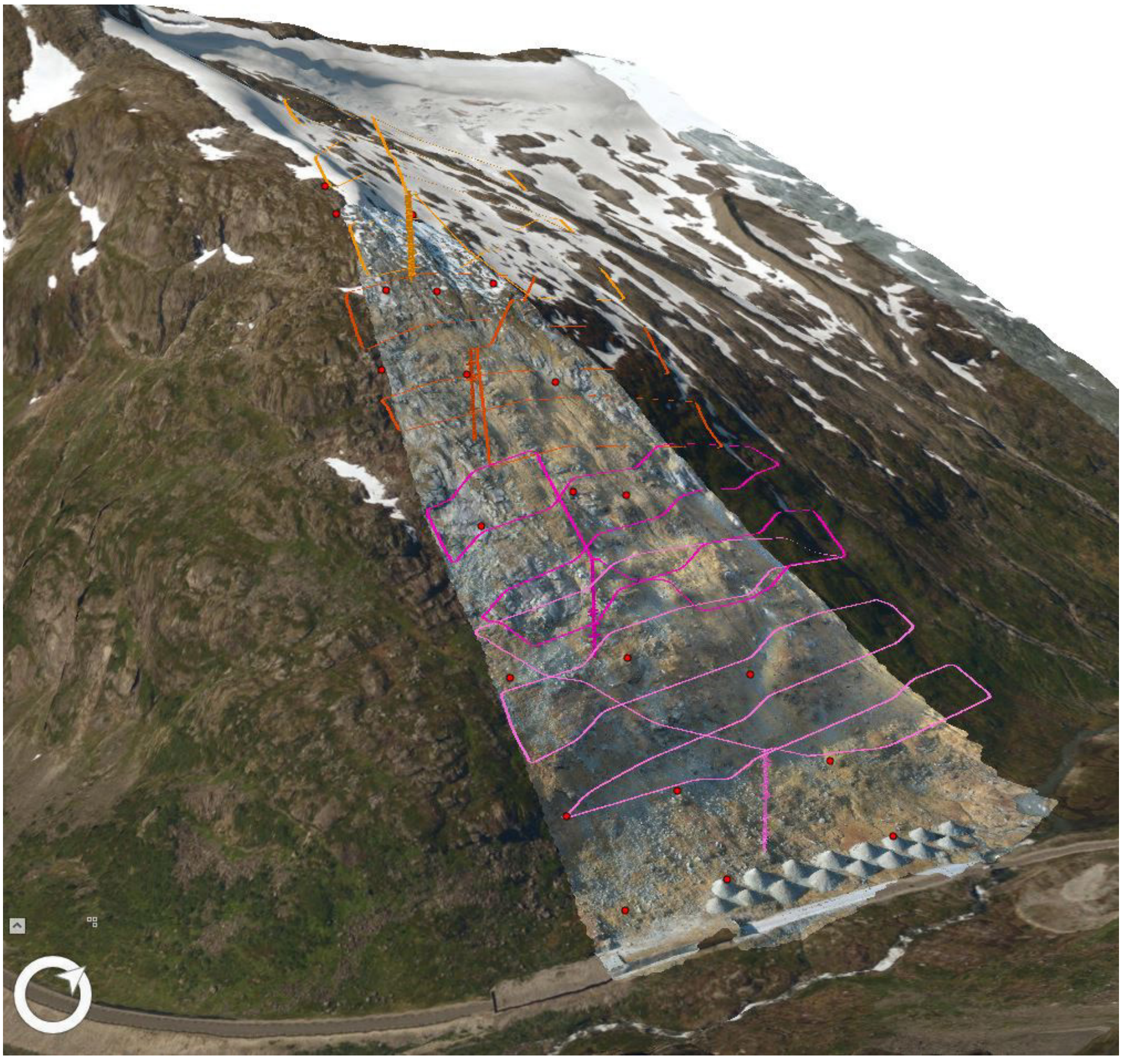

Figure 3: UAS flight lines displayed on top of a Structure-from-Motion-derived orthophoto product, draped over a background terrain model; GCPs are displayed in red.

2.2 Data processing

A total number of 438 images were ingested into Agisoft Metashape software (Agisoft, 2019), a commercial photogrammetric processing software package that utilized a Structure-from-Motion (SfM) algorithm to perform bundle adjustments and to produce a dense point cloud. The independently surveyed GCPs were imported to georeference the resulting model. To test the influence of the number and distribution of GCPs on the accuracy of the model, several iterations were performed with different variations of the control points used to adjust and optimize the model. The points that were excluded were used as checkpoints to indicate the model quality. Additional products that were derived from the point cloud included a mesh, a digital surface model (DSM), and a high-resolution orthomosaic.

3 Results and analysis

The quality of the SfM-reconstructed models was evaluated statistically within the Metashape software. Image overlap was assessed, as depicted in Figure 4, indicating good redundancy across the surveyed area (0.48 km^2) with an average ground resolution of 2.4 cm per pixel. GCP accuracy was evaluated, as depicted in Figure 5, with an average error of 0.6 cm (Easting), 0.9 cm (Northing), and 0.3 cm (altitude) for a total error of 1.1 cm for all points. Total error values for individual control points are presented in Table 1.

Products created during the SfM workflow were exported to ArcGIS Pro and were clipped to the identified avalanche path area (0.23 km^2) for further analysis and comparison with independent datasets, which included a 2012 airborne LiDAR survey that was completed for the Stryn area (BSF Swissphoto, 2014). Contained in Table 1 is a comparison of measured elevations (differential GPS) with the elevations derived from the 2012 LiDAR digital terrain model (DTM) for individual ground control points. The DTM product represented a bare-earth surface model with artefact corrections that was suitable for comparison with the GCPs used in the photogrammetric survey.

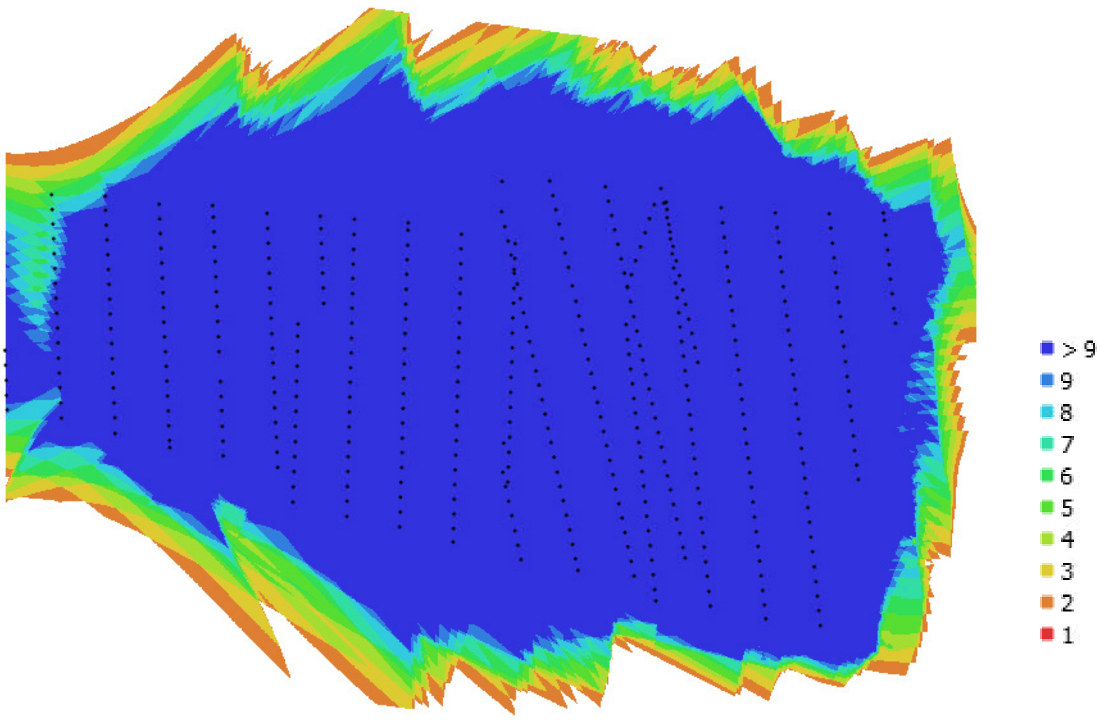

Figure 4: Image overlap for the lower portion of the surveyed avalanche path; camera locations are indicated as black dots and the number of photos, in which individual tie points appear, is displayed in the legend.

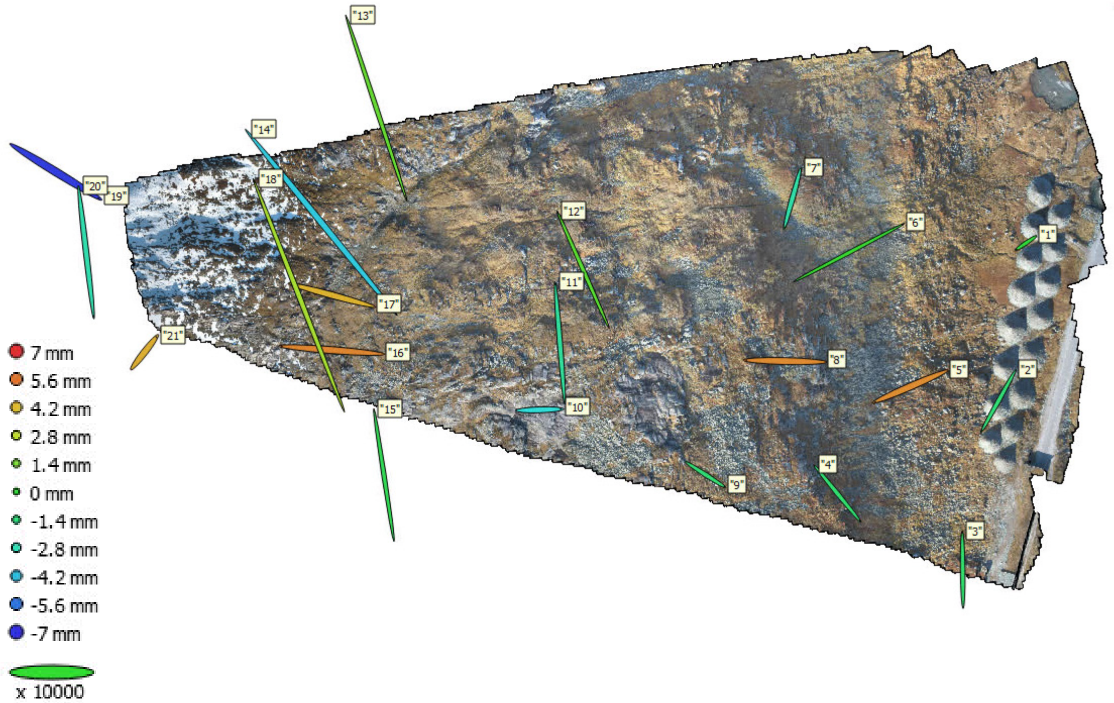

Figure 5: Vectorized GCP quality displayed on top of the resulting model, represented by ellipses with directional (Easting and Northing) error magnitude enlarged 10,000 times, as indicated in the legend, and ellipse colour indicating height (altitude) error; GCP identification numbers, 1–21 are adjacent to the ellipses.

To test the effect of the GCP distribution on the model quality, two SfM-derived models, one that used all 21 distributed GCPs, and the other that only used the six highest-elevation control points (above the avalanche release zone) to adjust the model, were compared to the LiDAR-derived DSM. The DSM product was selected because it provided a more suitable comparison than the LiDAR-derived DTM. The resulting difference models are presented in Figure 6. The SfM-derived models were resampled to the 50-cm ground resolution of the LiDAR data for the comparison.

Table 1: Summary of photogrammetric errors and difference between GNSS measurements and 2012 LiDAR DTM elevations for individual ground control points (GCPs).

GCP	Photogrammetric error		Surveyed elevation (meters)		Difference
	Total (cm)	Image (pixel)	GNSS measurement	2012 LiDAR DTM	(cm)
1	0.20	0.25	879.86	879.89	2.29
2	0.62	0.40	881.66	881.65	-1.90
3	0.67	0.40	879.07	879.14	6.54
4	0.64	0.30	924.27	924.23	-3.73
5	0.86	0.47	918.95	918.96	1.24
6	1.10	0.72	908.90	908.93	3.71
7	0.58	0.36	962.57	962.66	8.94
8	0.87	0.70	999.58	999.76	17.61
9	0.42	0.23	1003.00	1003.21	20.93
10	0.51	0.52	1095.45	1095.45	-0.40
11	1.09	0.53	1108.94	1108.98	3.83
12	1.13	0.55	1094.55	1094.52	-2.86
13	1.73	0.96	1188.41	1188.58	16.73
14	2.15	0.98	1208.29	1208.39	10.24
15	1.18	0.45	1221.71	1221.85	13.89
16	1.04	0.46	1286.20	1286.20	-0.51
17	0.87	0.77	1281.10	1281.06	-3.92
18	2.23	0.86	1276.05	1275.92	-13.36
19	1.13	0.74	1342.13	1342.04	-8.86
20	1.19	0.94	1381.15	1381.02	-13.30
21	0.56	0.67	1355.78	1355.70	-8.58
Total	**1.11**	**0.61**	**-**	**-**	**2.31**

The resulting models diverged significantly with an increase in distance from the control points used to adjust the model, likely due to the 500-m elevation change between the top and bottom of the survey. The comparison between the SfM model that utilized all control points revealed that most areas in the path matched well, while there were also small areas with large differences, which were attributed to vegetation cover and steep slopes (i.e. edges of large boulders), as depicted in Figure 7.

(a)
(b)

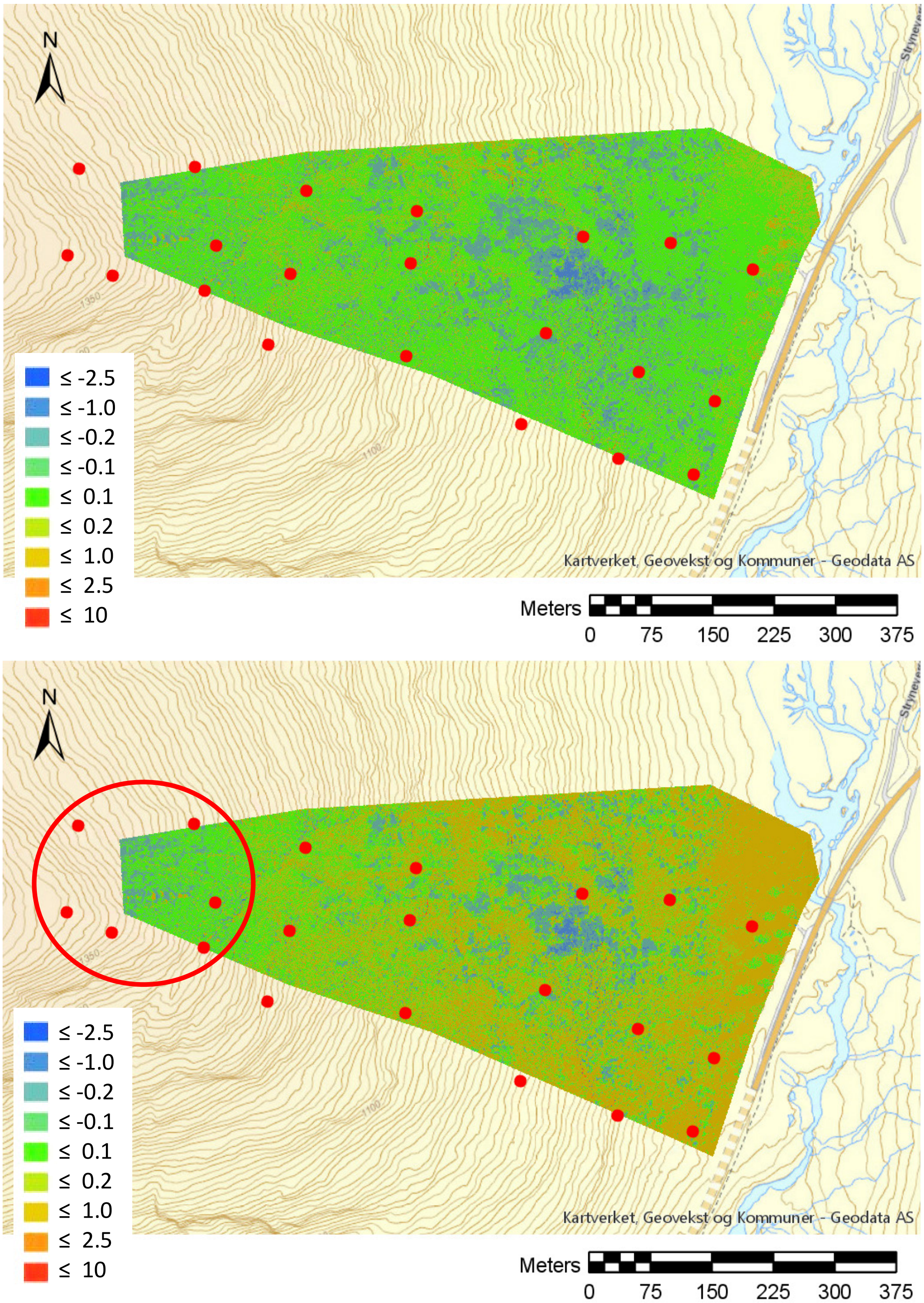

Figure 6: Comparison of two SfM-derived surface models with the LiDAR-derived surface model for (a) SfM model adjusted using all 21 ground control points (depicted in red), and (b) SfM model adjusted using only the top six control points (encircled in red); difference shown in legend in meters.

(a)

(b)

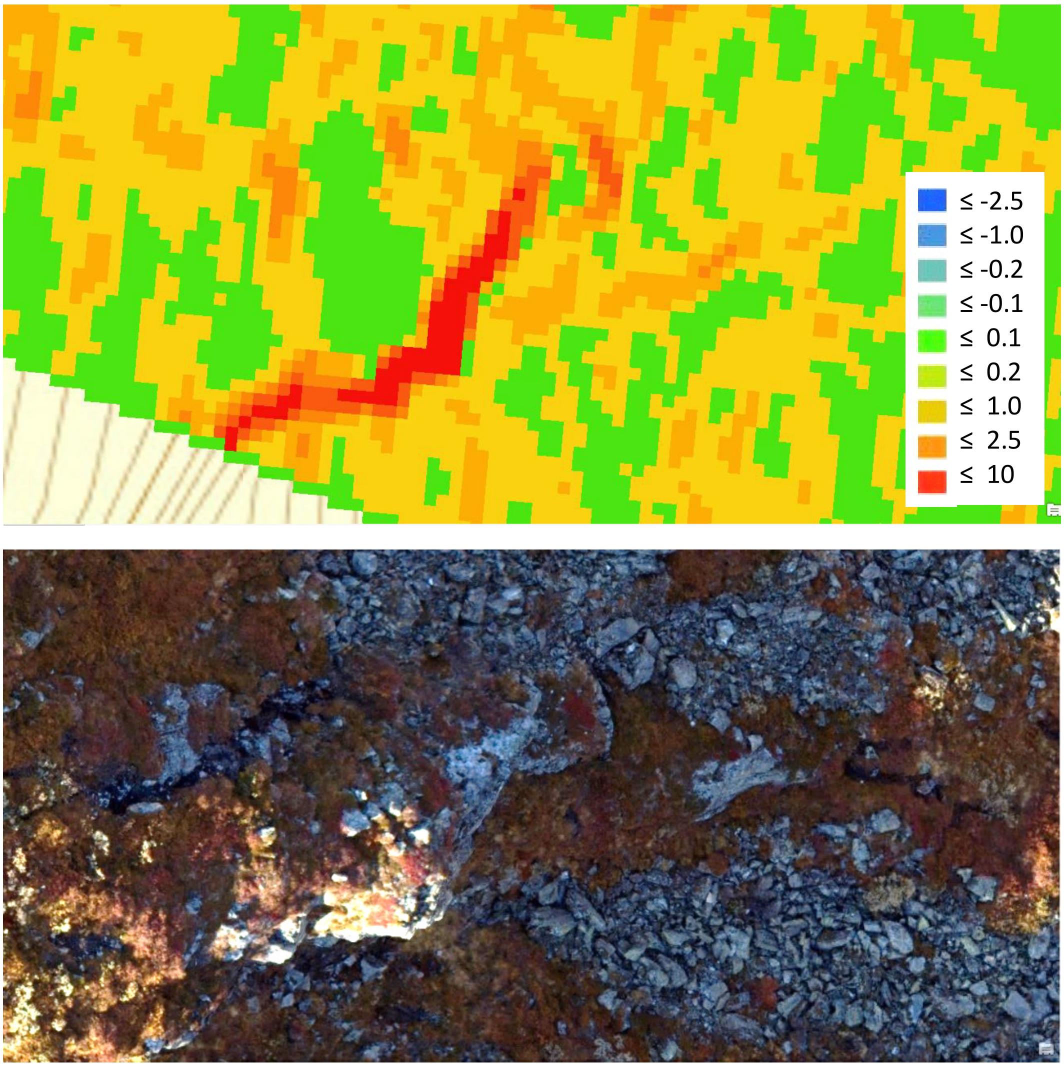

Figure 7: Close-up example of a large difference between the SfM- and LiDAR-derived models, attributed to vegetation cover and the steep slope of a rock outcrop; difference shown in legend in meters.

4 Conclusions

The UAS-based photogrammetric survey on the Sætreskarsfjellet avalanche path resulted in an accurate three-dimensional digital surface model, derived using a Structure-from-Motion processing technique. The model was compared to data from a previously acquired LiDAR survey of the same path. The following conclusions were drawn:

- Terrain-aware planning was critical to account for the 500-m elevation change along the length of the avalanche path. Inaccurate terrain-aware planning may cause differences in flight height, resulting in differences in ground resolution and potentially influencing the accuracy of the results.
- The SfM-derived model had an average ground resolution of 2.4 cm. The comparison with the previously acquired 50-cm ground resolution LiDAR-derived model revealed that there was an overall good match, except in areas where dense vegetation and steep slopes caused large differences.
- The comparison of two SfM-derived models with the LiDAR-derived model revealed that the SfM model that used all available ground control points was more accurate than the SfM model that only used a reduced number of ground control points. This finding has implications for future UAS-based photogrammetric surveys over snow-loaded avalanche paths, where the risk to personnel safety may be too high to allow for the uniform distribution of ground control points.

5 References

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BSF Swissphoto (2014). Flybåren laserskanning LACHSF 21 2012: Delområde Stryn.

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OSLO
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PERTH

NORWEGIAN GEOTECHNICAL INSTITUTE
NGI.NO

Main office
PO Box 3930 Ullevaal St.
NO-0806 Oslo
Norway

Trondheim office
PO Box 5687 Torgarden
NO-7485 Trondheim
Norway

T (+47)22 02 30 00
F (+47)22 23 04 48
NGI@ngi.no

BIC NO. DNBANOKK
IBAN NO26 5096 0501 281
ORGANISATION NO.
958 254 318MVA

ISO 9001/14001
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Appendix 2 (Lavangsdalen Site)

Drift og vedlikehold
Fagressurser Drift og vedlikehold
Geofag Drift og vedlikehold
2020-04-29

Statens vegvesen

Skred

UAS-SfM mapping of avalanche release areas: Preliminary investigations on bare ground

Lavangsdalen, Troms and Finnmark county, Norway

Fagressurser Drift og vedlikehold **C13389-SKRED-01**

Photo: Emil Solbakken

Statens vegvesen

Oppdragsrapport

Nr. C13389-SKRED-01 Labsysnr.

Skred

UAS-SfM mapping of avalanche release areas: Preliminary investigations on bare ground

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Postadr. Postboks 1010 Nordre Ål
2605 Lillehammer
Telefon 22073000

www.vegvesen.no

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		Emil Solbakken	
Prosjektnummer	Oppdragsnummer	Seksjonsleder (navn, sign.)	Kontrollert
	C13389	Viggo Aronsen	Tore Humstad

Sammendrag

Unmanned aerial systems (UASs) and Structure-from-motion (SfM) photogrammetric analysis can be used to acquire topographic surface models of centimeter-level resolution and accuracy. The Norwegian Public Roads Administration (NPRA) has initiated a research project to find out if such technology can assist roadside avalanche hazard assessment. This report describes the preliminary investigations of two potential test sites in Lavangsdalen, Northern Norway; the 'Storskreda' and 'Sarasteinen' avalanche paths. A bare-ground mapping of the avalanche release area at 'Storskreda' was conducted in order to establish an accurate ground surface model and investigate survey procedures relevant for future winter surveys. This work has highlighted some of the challenges of using a consumer-grade UAS and ground control points for georeferencing, especially when the distribution of ground control points is sparse and uneven. The findings also indicate, however, that the required level of accuracy might be achievable with improved mitigation of image distortion and an optimized distribution of control points.

Emneord

CONTENTS

1 INTRODUCTION

Unmanned aerial systems (UASs) are emerging as highly relevant tools in the management of roadside natural hazards. Low-cost, consumer-grade systems equipped with cameras are already frequently used by NPRA staff in evaluation of rock fall hazard, providing valuable information at minimal risk for involved personnel. Aerial imagery shot with these systems can also be used to derive high-resolution topographic models through Structure-from-Motion (SfM) photogrammetric analyses, at accuracies that previously was reserved for the professional mapping industry. Nowadays, industry-grade UASs carry a range of different remote sensing instruments including Ground penetrating radar (GPR), Light detection and ranging (LiDAR) systems and real-time kinematic (RTK) or post-processed kinematic (PPK) GPS-receivers. Following the rapid technological development, such technologies are only expected to become more accessible and relevant in the coming years.

The NPRA has since 2015 been investigating how UAS technology can be used for support in evaluation of natural hazards. Previous studies include detection of rock face deformation (Terratec AS, 2015), vendor demonstrations of different types of UAS and sensor technologies (NPRA, 2016; McCormack et al., 2018), monitoring of the glide avalanche at Bispefonna (Dahle, 2016) and mapping of snow accumulation in avalanche release areas at Tyin (Solbakken, 2019). In addition, an UAS-based system for artificial avalanche release has recently been tested (Farestveit, 2019).

This report is part of the preparations for a possible new project focusing on camera UASs and the application of SfM-based surface modeling for monitoring of avalanche release areas. These preparations have been conducted in collaboration with the Norwegian Geotechnical Institute (NGI). Field work has taken place at avalanche sites in Grasdalen, Stryn and Lavangsdalen, Tromsø. The work in Lavangsdalen has also been supported by the E8 Borealis project[1].

This report documents the preliminary investigations of selected avalanche sites in Lavangsdalen, which was conducted in fall 2019 and forms a basis for further research in winter conditions. The main objectives of this first stage were to:

- Select and prepare test sites in accordance with research goals
- Perform UAS-SfM mapping of bare-ground terrain at the selected sites, to:
    1. Establish a ground basis for future snow depth calculations
    2. Demonstrate UAS survey procedures and SfM processing techniques relevant to the selected sites
- Document findings and make suggestions for further work

The report is organized into a description of the suggested test sites, documentation of the field work at Storskreda, and conclusions and suggestions for further work.

[1] https://www.vegvesen.no/Europaveg/e8borealis/

2 TEST SITES

The Lavangsdalen valley is situated south of Tromsø in Northern Norway. Throughout the valley, the main road connection to Tromsø, E8, is exposed to several avalanche paths where avalanches may hit the road. Mitigation measures such as deflection structures and detection systems are in place, but large avalanches still pose a threat to road users and transportation. Avalanches here are typically dry-snow slab avalanches from release areas more than 1000 m above the valley floor. The release areas are remote and situated mostly in complex terrain that is difficult to access in winter, making evaluation of snow conditions a challenge.

Test sites were selected based on their suitability and difficulty for an UAS-SfM mapping mission. The selected sites, Sarasteinen and Storskreda, are well known avalanche paths that are well defined by terrain features. Storskreda was chosen as an "easy" option, where size and access possibilities might allow the avalanche release area to be mapped by NPRA staff with a consumer-grade UAS. Sarasteinen, on the other hand, is a more challenging option that is suited for testing RTK UASs operated by industry professionals.

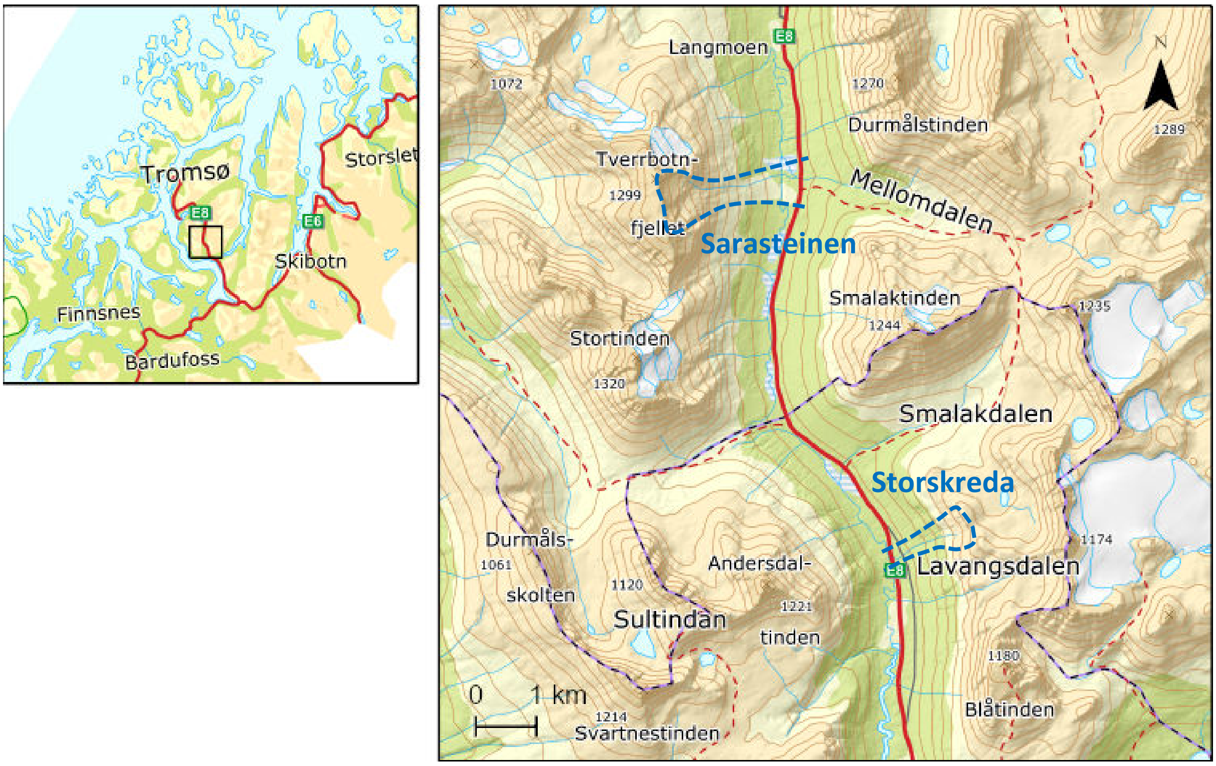

Figure 1. Locations of the suggested test sites in the Lavangsdalen valley; Sarasteinen and Storskreda. They are two of several avalanche paths posing a threat road to users and transportation on highway E8, which is the main road connection to the city of Tromsø. (Map: The Norwegian Mapping Authority)

2.1 Storskreda

The Storskreda avalanche path is listed in the NPRA database with an avalanche on road frequency of 0.05 occurences per year (NPRA, 2020). The road is protected by a deflection dam, but this is relatively small and placed too far north to provide full protection. In the latest large avalanche event at the site, on March 14th 2014, the avalanche passed just south of the deflection dam and stopped in the roadside ditch.

The potential avalanche release area, from which avalanches will be led into to the main avalanche path, is situated from approx. 400 to 750 m a.s.l. in a width of around 500 m. The area faces southwest to northwest, and has an average slope angle of 38 degrees in the northern part and 34 degrees in the southern part. Avalanches are typically caused by wind-loading on eastern wind directions, heavy snow fall or rapid temperature increase (NPRA, 2020).

The top of the release area is located approx. 700 m above and 1.5 km away from where the avalanche path crosses the road. Hence, the area might be in reach of consumer-grade UASs launched from the road. Hopefully, certified NPRA staff might conduct UAS operations at this level after the introduction of new european UAS regulations[2] in 2020. Another option is to launch UAS flights from the top of the release area, which can be safely accessed by foot also in winter.

Georeferencing of photogrammetric snow surface models can be acquired either by using an RTK UAS (*direct* georeferencing), or by placing ground control points in the survey area (*indirect* georeferencing). Options for ground control points are:

1) Temporary markers on the snow surface in safely accessible areas above the release area, deployed close before UAS surveying.
2) Permanent markers deployed before snow fall that remain visible and safe from avalanches throughout the winter.

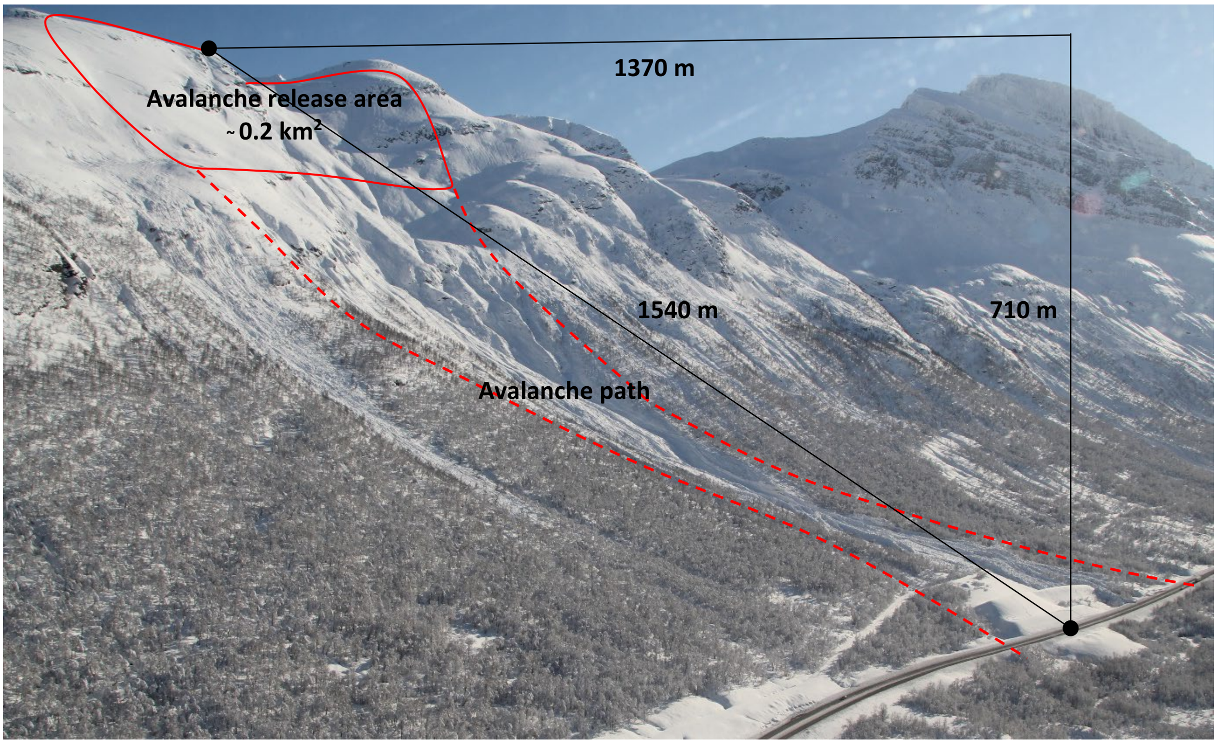

Figure 2. Overview of the Storskreda avalanche path in Lavangsdalen. The photo shows the avalanche debris almost reaching the road from the avalanche on March 14th, 2014. (Photo: Ole-Andre Helgaas, NPRA)

[2] https://luftfartstilsynet.no/droner/nytt-eu-regelverk/

2.2 Sarasteinen

At Sarasteinen, avalanches hit the road with a frequency of 0.08 occurences per year (NPRA, 2020). The road is protected by a deflection dam, but large avalanches might run over or south of the dam. This happened in 2017, when three vehicles were blown off the road, and also in 2019 when the powder cloud reached the road, without hitting any vehicles. The site is now equipped with an avalanche detection system based on infrasound and a remotely controlled camera for monitoring and documentation of avalanche activity.

The avalanche release areas are found in the large, east-facing bowl reaching up to the top of Tverrbotnfjellet (1299 m a.s.l.). Out of several potential release areas within the bowl, the large slope directly below the mountain top is considered most important for the formation of the largest avalanches. Avalanches are typically dry-snow slab avalanches caused by wind-loading on wind directions from southwest to northwest.

UAS mapping of the avalanche release areas will be challenging and most likely require professional equipment and operators. The mountain top is practically only accessible with helicopter, and the release areas are in complex terrain with limited possibilities for deployment of ground control points. Hence, UAS launch from the valley bottom and direct georeferencing during surveying are required. In addition, the UAS must be precisely controlled more than 2.5 km away from a launching point at the valley bottom (see Figure 3).

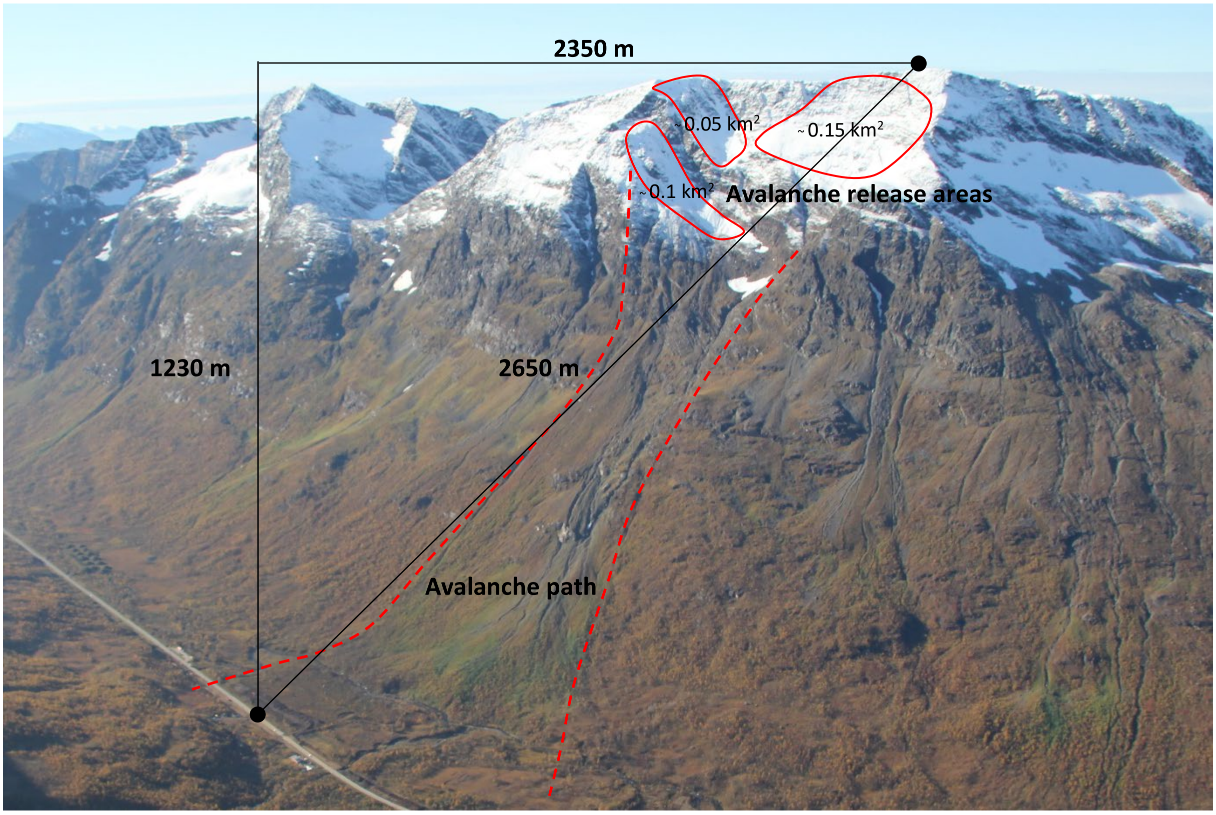

Figure 3. Overview of the avalanche path at Sarasteinen. Indicated avalanche release areas show roughly where the main snow accumulation occurs during winter. (Photo: NPRA)

3 BARE-GROUND MAPPING AT STORSKREDA

Bare-ground mapping of avalanche areas at Storskreda was conducted in fall 2019. The goal was to obtain an accurate ground basis while also demonstrating UAV-SfM methodology and potential accuracy of end-products. In addition, possible adaptations for mapping in winter conditions were investigated. This section contains documentation of the planning and execution of field work, data processing steps and the results obtained.

The mapping was conducted with equipment commonly used within the NPRA, and in compliance with RO1[3] flying regulations. Hence, the methodology described here may be relevant to all NPRA staff using UASs for mapping purposes in steep terrain.

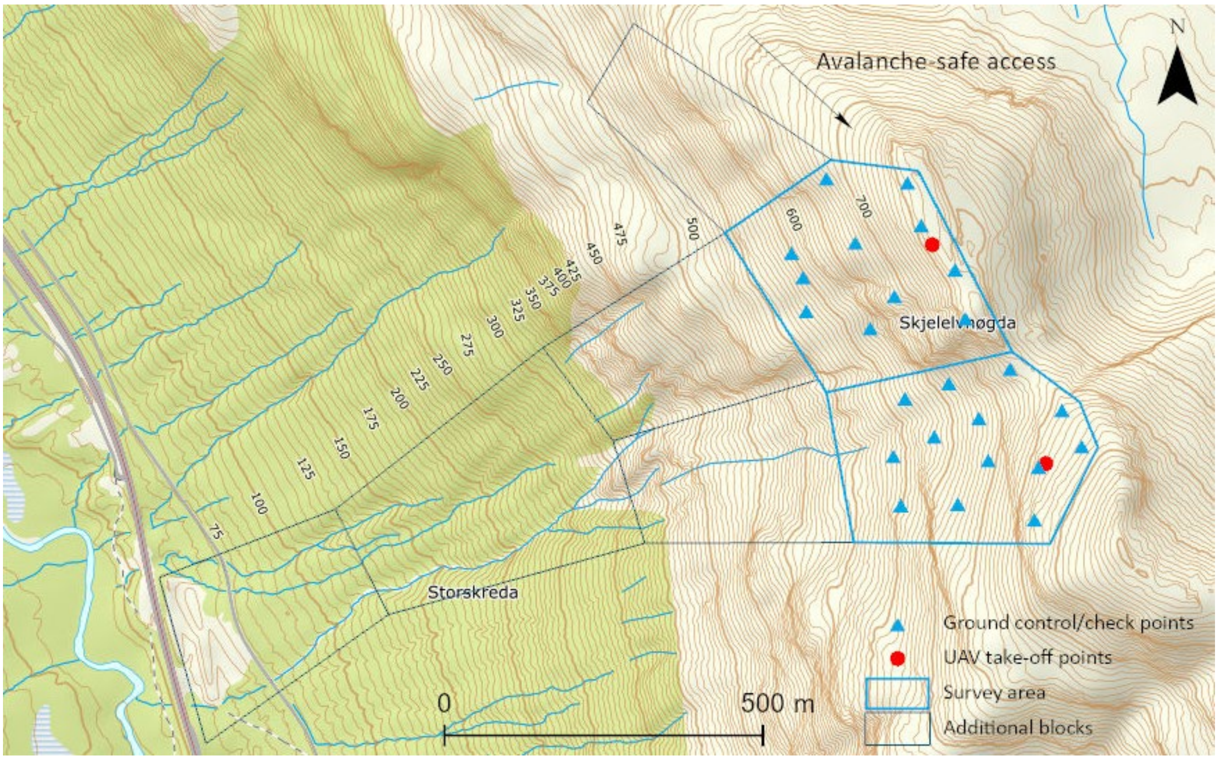

Figure 4. Survey plan for the avalanche path at Storskreda. The survey area represents the two blocks that were surveyed on October 2nd-3rd 2019, wherein preplanned locations for ground control/check points and UAV take-off are shown. The additional blocks show survey areas that can be added to cover the full avalanche path. All blocks represent areas of which terrain and size accommodate for surveying in one flight following the same flight planning principles as described in section 3.1.2. (Map: The Norwegian Mapping Authority)

[3] https://luftfartstilsynet.no/droner/kommersiell-bruk-av-drone/ro1/

3.1 Methodology

3.1.1 Survey area

The surveyed area, shown in Figure 1, was designed to cover release areas leading into the main avalanche path, and to allow for deployment of georeferenced targets at avalanche-safe locations above the release areas. Figure 1 also shows survey blocks that can be added for coverage of the full avalanche area. Due to dense vegetation, however, it was found unlikely that UAV-SfM mapping would give satisfying results in the lower parts of the avalanche path. The area is also fully covered by the Norwegian Elevation Model (NEM), providing terrain elevations at 0.5 m resolution obtained by LiDAR scanning. Focus was therefore put on the avalanche release area, which would also be the most relevant area to cover in the case of avalanche hazard evaluation.

3.1.2 Data collection

Field work was conducted on the 2nd and 3rd of October 2019. On the first day, 24 markers to be used as ground control and check points (GCPs and CPs) were established on preplanned locations within the survey area. Fluorescent spray paint was used to mark crosses of about 0.5 x 0.5 m on even rock surfaces (Figure 3), of which the center points were georeferenced with a dGNSS-system utilizing CPOS correction data. Expected positioning accuracy with this setup is less than 1 cm horizontally and 2-3 cm vertically. The distribution of the markers is shown in Figure 1.

The UAV flight missions were executed the day after. To account for the size and topography of the survey area, the area was divided into a northern and southern block covered by two separate flight missions. The UAV was launched from take-off points in the upper part of each block, and the missions were conducted autonomously according to pre-set flight plans. The UAV used was the ‘DJI Mavic Pro 2’, and the flights were controlled with the application ‘Litchi’.

Flight plans were made using the free software ‘Mission Planner’ and afterwards re-adjusted in an Excel-sheet to account for slope angle. Distance to ground was set to 90 m to obtain images with a ground sampling distance of about 2.1 cm. The flight paths consisted of a regular grid of parallel flights lines to capture overlapping images perpendicular to the ground, and an additional orbit around the center of each region to obtain images at converging viewing angles.

At flying speed 5 m/s and shooting interval 5 s, on average 80 % overlap and 60 % sidelap was obtained within the regular grids. In total 390 RAW images were captured during the two flight missions, which both were 4.9 km long and took 23 minutes to complete. Each of the missions was completed well within the capacity of a single battery, despite windy conditions with peak wind speeds probably reaching 8-10 m/s.

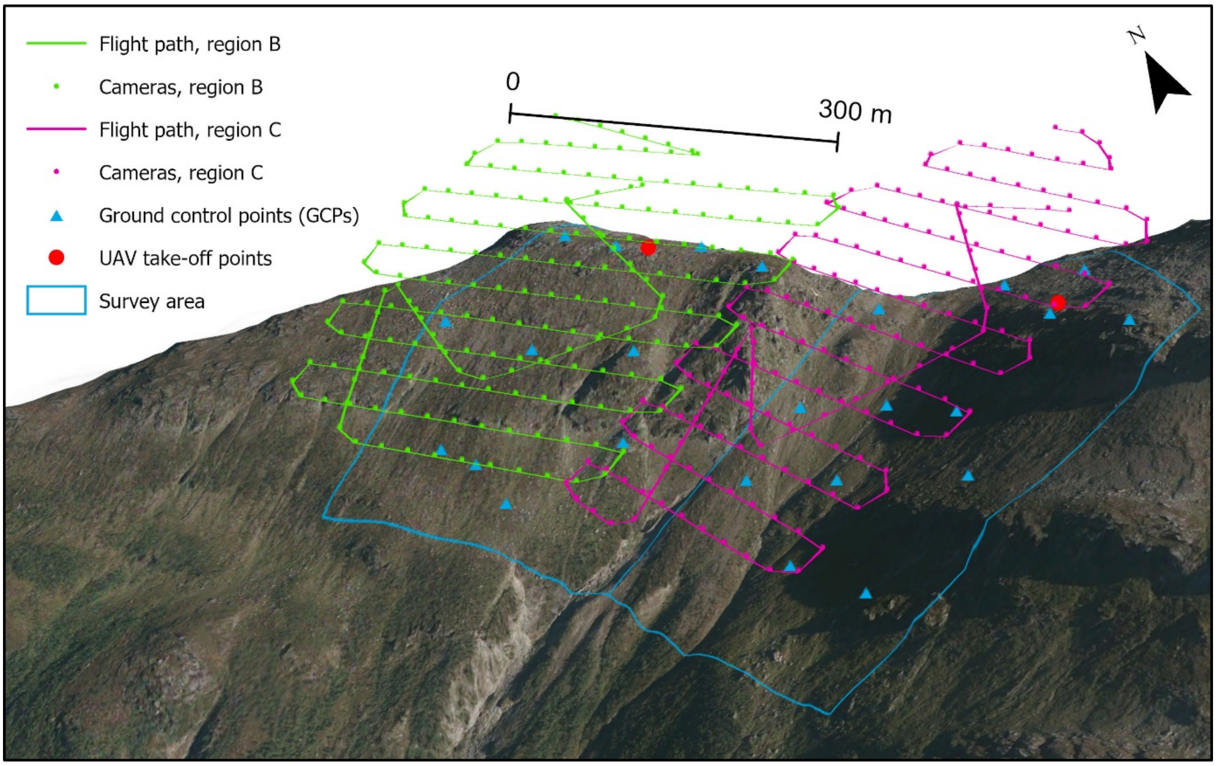

Figure 5. 3D plot of flight paths and camera locations above the survey area at Storskreda. (Ortophoto/ground elevation: Kartverket)

Figure 6. Hallvard Nordbrøden preparing georeferenced markers at Storskreda, Lavangsdalen. (Photo: Emil Solbakken)

3.1.3 Data processing

Photogrammetric processing was performed with the software Agisoft Metashape, which uses Structure-from-motion (SfM) and Multi-view-stereo (MVS) algorithms to calculate 3D-geometries from images. Images were imported without any pre-processing of the RAW files, along with the georeferenced coordinates of the 24 markers to be used for ground control and validation. Photo alignment and self-calibration of camera calibration parameters for the two regions individually indicated neglectable differences in optical properties between the two missions (potentially caused by lens instability, focusing etc.). The two image sets were therefore merged and processed together.

Photo alignment was done with 'generic' preselection and quality 'high', which means images were matched at their original resolution. After photo alignment, targets were identified and marked with the 'guided marker placement' approach which is described in the Metashape user manual (Agisoft, 2019). Further processing was based on the approach by James et al. (2017), which was also followed by Solbakken (2019). This method ensures appropriate input parameters through thorough analysis of photogrammetric errors, camera calibration settings and GCP performance.

The optimal camera calibration model was found to include focal length (f), focal point (cx, cy), three radial distortion coefficients (k1-k3) and two tangential distortion coefficients (p1-p2). For georeferencing, the optimal weighting of markers was obtained with marker accuracy set to 4 cm. Photogrammetric processing was completed with two different georeferencing configurations:

- 24 GCPs: All markers used for ground control.
- 10 GCPs: 10 markers at avalanche-safe locations used for ground control.

Completion of the processing included building dense point clouds at medium quality, before exporting the surface models point clouds, digital elevation models (DEMs) and orthophotos. Exported models were then analyzed and validated in ArcGIS Pro, by comparison with surveyed markers and existing topographic elevation models.

3.2 Results and analysis

Input parameters and errors from the photogrammetric processing are summarized in Table 1, and errors within exported DEMs at different resolutions are shown in Table 2.

Table 1. Summary of photogrammetric and georeferenced errors as obtained within the Metashape software, including the reference settings used. '24 GCPs' and '10 GCPs' represent the three different marker configurations that was used (see section 3.1.3 for explanation). 'RMSE on GCPs' means the root-mean-squared error on markers used for ground control, while 'RMSE on CPs' means the root-mean-squared error on markers used as independent check points.

	Unit	24 GCPs	10 GCPs
REFERENCE SETTINGS			
Marker accuracy	m	0.04	0.04
Marker accuracy	pixels	1.88	1.88
Tie point accuracy	pixels	1.79	1.79
Camera accuracy	m		
RMS REPROJECTION ERRORS			
Tie points	pixels	1.79	1.79
Markers	pixels	1.88	1.88
TIE POINT PRECISION			
xyz, maximum value	m	0.022	0.022
RMSE ON GCPs			
x	m	0.048 (24)	0.035 (10)
y	m	0.044 (24)	0.059 (10)
z	m	0.061 (24)	0.042 (10)
total	m	0.089 (24)	0.080 (10)
RMSE ON CPs			
x	m		0.106 (14)
y	m		0.064 (14)
z	m		0.138 (14)
total	m		0.185 (14)

3.2.1 Photogrammetric errors

Photogrammetric errors include the reprojection errors on tie points and markers, and any systematic deformation of the reconstructed surface related to camera calibration and the correction of lens distortion. Reprojection errors are normally expected to be well below 1 pixel, while the values obtained here are 1.88 pixels on markers and 1.79 pixels on tie points. The main cause of the high reprojection errors are believed to be rolling shutter distortion, which is a well-known issue when using a moving camera with electronic shutter and line-by-line pixel readout.

The amount of rolling shutter distortion is determined by the distance the camera moves between the readout of the first and the last pixel line of an image, in other words by the moving speed and the sensor readout time of the camera. UAS cameras comparable to the one used in this study typically have sensor readout times of 30-50 ms. At the flying speed of 5 m/s, this results in an offset between the first and the last pixel line of up to 40 cm in the moving direction.

In addition to the generally high reprojection errors, systematic variations in reprojection errors across the flight strip directions also indicate the presence of rolling shutter distortion. By enabling the 'rolling shutter compensation' option in the Metashape software, the RMS reprojection errors could be reduced by about 1 pixel. This, however, also led to significantly increased errors on markers, and the compensation was therefore not used.

The overall level of reprojection errors could also be reduced by removal of tie points associated with high errors. Surprisingly, extensive filtering also increased errors on markers. The lowest georeferenced errors were obtained by removing the tie points that were observed in two images only, hence further filtering was avoided. In contrast to general recommendations for tie point filtering (Agisoft, 2019; James et al., 2017), these observations indicate that keeping less accurate tie points in some cases might strengthen the photogrammetric network and contribute to a more reliable surface shape.

3.2.2 Georeferenced errors

The highest georeferenced accuracy was obtained using all markers for ground control, resulting in root-mean-squared errors of 4.4 - 4.8 cm in horizontal directions and 6.1 cm in vertical direction. These errors are not from independent check points, they are however believed to represent overall accuracy as the weighting of GCPs was carefully adjusted to avoid exaggerated fitting of the surface to measured marker coordinates. For comparison, the RMSEs from using markers for orienting and scaling of the surface only was 5.7 cm horizontally and 8.0 cm vertically.

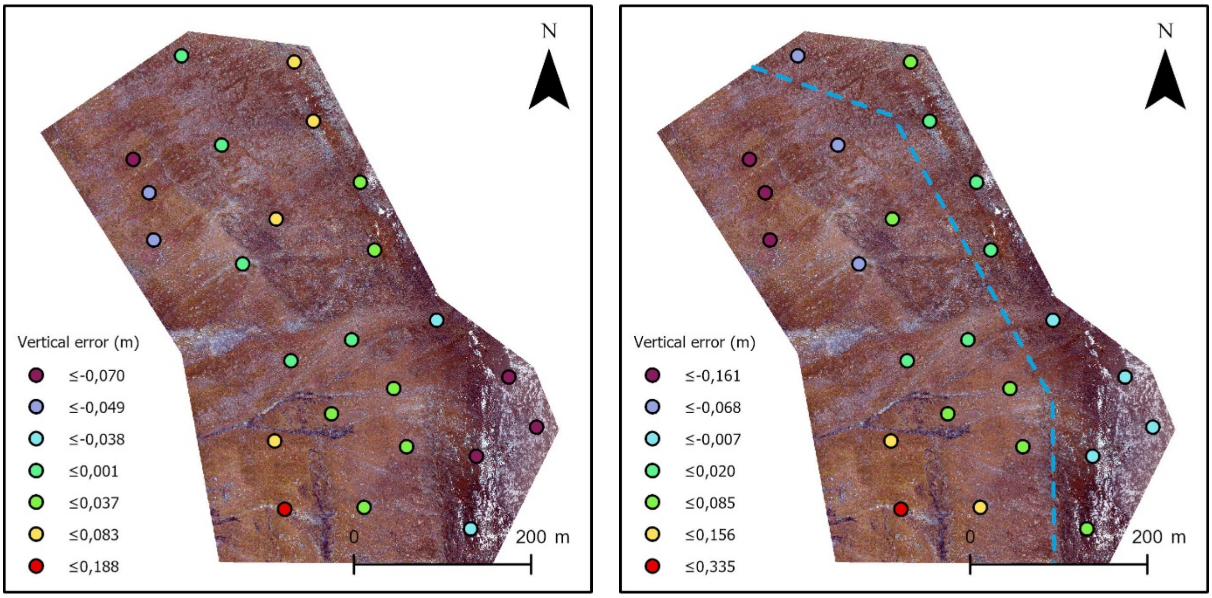

Figure 7. Orthophotos of the survey area with colored points representing vertical errors on markers. LEFT: All markers used for ground control. RIGHT: Markers to the right of the dashed line used for ground control.

As shown in Figure 7, the distribution of vertical errors on markers indicate increasing negative error toward the northwestern and southeastern corners of the survey area, and increasing positive error toward the northeastern and southwestern corner. This trend is present for both GCP configurations and is caused by mis- or uncorrected distortion related to the camera system.

Using the 10 upper markers for ground control (see Figure 7), the RMSEs on the rest of the markers (hereby independent check points) increased to 6.4 - 10.6 cm horizontally and 13.6 cm vertically (Table 1). The distribution of vertical errors (see Figure 7) shows that errors on check points increase with increasing distance to the ground control, which is an expected result of unbalanced distribution of ground control points. Furthermore, a comparison of the surface models (see Figure 9) shows that most of the difference can be attributed to scaling and orientation issues rather than differences in surface shape.

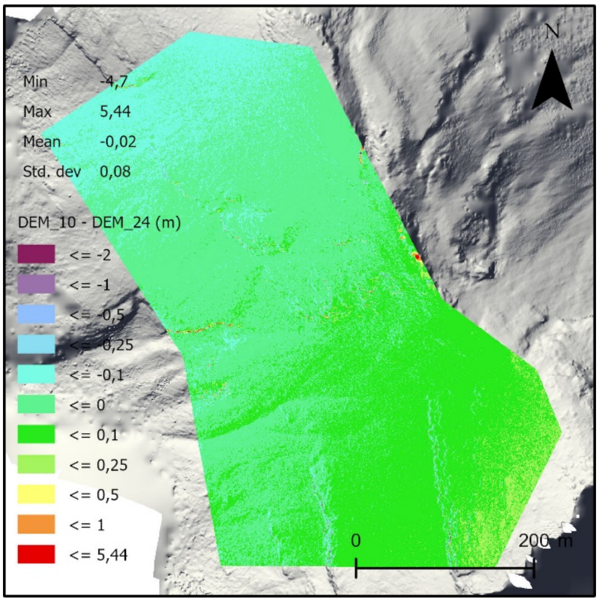

Figure 8. Difference between the DEM_10 and DEM_24 at 0.5 m resolution. Differences are generally small and seems to be mainly related to a variation in orientation and scaling.

Table 2. Root-mean-squared errors of exported DEMs, calculated from all 24 markers. DEM_24 and DEM_10 represent the surface obtained by using all 24 and 10 markers, respectively, for ground control. The locations of the 10 markers are shown in Figure 4.

DEM	Resolution (m)	RMSE (m)
DEM_24	0.25	0.15
	0.50	0.19
DEM_10	0.25	0.16
	0.50	0.18

Looking at the RMS vertical errors of exported DEMs of 0.25 and 0.5 m resolution (Table 2), the two GCP configurations seem to produce equally accurate surface models. This is probably the result of resampling errors outweighing the underlying differences. Most of the markers were established on protruding rock surfaces in steep terrain, which are points where downsampling may lead to especially large shifts in elevation.

3.2.3 Comparison with LiDAR-data

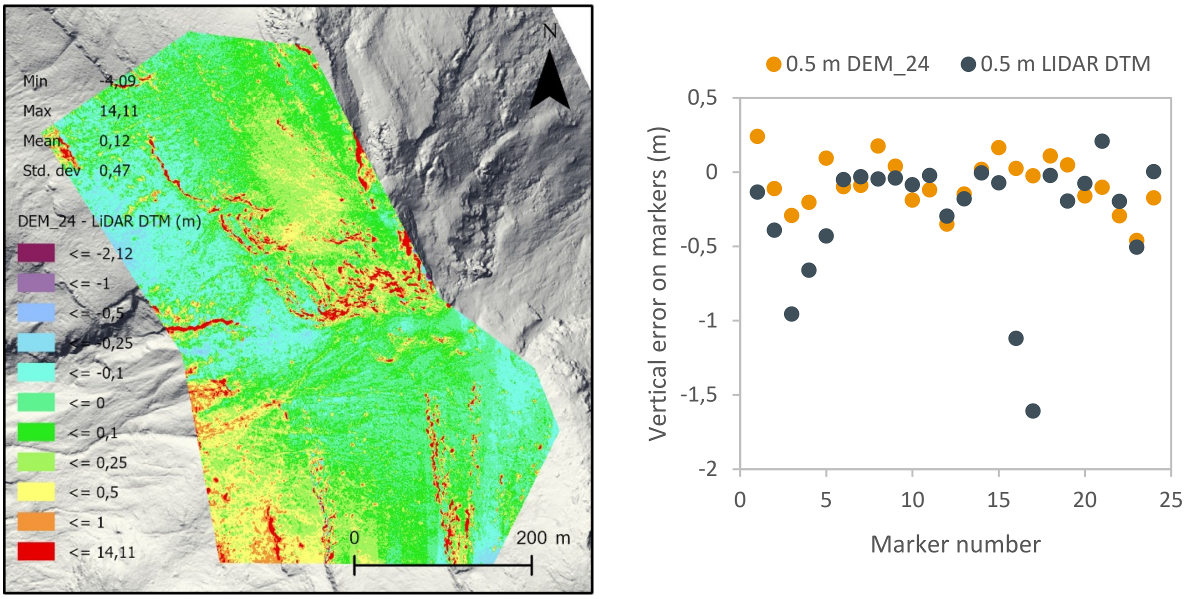

Figure 9. LEFT: Elevation difference between the DEM_24 and a LiDAR DTM from the National Elevation Model of Norway (Terratec AS, 2017). The models are compared within the survey area and at 0.5 m resolution. RIGHT: Vertical errors on individual markers for the compared surface models. The corresponding RMSEs are 19 cm for the DEM_24 and 50 cm for the LiDAR DTM.

The DEM of difference (DoD) from comparing the DEM_24 to the LiDAR DTM at 0.5 m resolution (Figure 9, left) shows a mean difference of 12 cm and a standard deviation of 47 cm. The standard deviation is probably very affected by the difference around cliff bands and very steep sections, which ranges from 1 to 14 meters. Such differences might be a consequence of different survey methods, e.g. different viewing angles causing different resolution in steep terrain, or it can represent an offset due to systematic errors in one or both models.

The comparison also supports the signs of systematic error affecting the photogrammetric surface model, as indicated by the vertical error on markers (see Figure 7 and section 3.2.2) and the high reprojection errors (see section 3.2.1). The DEM_24 is mainly found above the LiDAR DTM in the northeastern and southwestern section of the survey area, and partly below in the northwestern and southeastern section. In addition, there are linear features in the DoD, especially towards the southern end of the survey area (Figure 9, left), that correspond with the UAS flight strip direction.

Errors on individual markers, as shown in Figure 9 (right), are significantly higher for the LiDAR DTM than the DEM_24, partly due to some large outliers. The LiDAR DTM is also associated with predominantly negative errors, meaning that the surface elevations are generally lower than actual terrain elevations. Although high errors on individual markers are expected in rough, steep terrain, the accuracy of the LiDAR DTM is within the survey area found to be relatively low compared to product specifications.

4 CONCLUSIONS

4.1 Main results

The Norwegian Public Roads Administration (NPRA) is together with the Norwegian Geotechnical Institute (NGI) preparing a research project on the use of UAS-SfM mapping of avalanche release areas. The aim is to clarify how this could be an assistance tool in hazard evaluation on roadside avalanche paths. This report documents the initial investigation of potential test sites in Lavangsdalen, Northern Norway. Two sites were selected; the Sarasteinen and Storskreda avalanche paths; and bare-ground mapping was conducted in the avalanche release area at Storskreda.

High resolution surface models of the release area were achieved using a consumer-grade UAS for image acquisition and the Agisoft Metashape software for SfM photogrammetric analysis. The models were indirectly georeferenced through ground control points, which required visible markers to be established on the ground before surveying. Two different configurations of ground control were tested: One using all markers for ground control, and one using only markers at avalanche-safe locations above the survey area.

Enabling all 24 markers for ground control resulted in the highest accuracy with a total RMSE on markers of 8.9 cm. This surface model was also compared to an existing LiDAR-model at 0.5 m resolution, which gave a mean difference of 12 cm and a standard deviation of 47 cm. Using only 10 ground control points in the upper part of the survey area, the total RMSE was 8.0 cm among the ground control points and 18.5 cm on the rest of the markers.

The achieved level of accuracy is within the expectations for surveys of this type. However, several factors were found to limit the quality of the final surface models. The most important of these are high reprojection errors and local surface deformations, most likely caused by uncorrected rolling shutter distortion, and large-scale deformation probably due to insufficient correction of lens distortion.

4.2 Suggestions for further work

The results highlight some of the challenges of using a consumer-grade UAS and indirect georeferencing, especially when the distribution of ground control points is sparse and uneven. However, they also indicate that with improved mitigation of image distortion, strong image geometry and an improved distribution of GCPs, sub-decimeter overall accuracy might be achievable even with a low number of ground control points. The following suggestions are based on experiences made in this work and might be helpful during planning of future research:

- Issues with rolling shutter distortion can be avoided by using cameras that have a mechanical shutter mechanism. If this is not possible, UAS speed during photographing should be reduced as much as possible. Rolling shutter correction tools are often available in software for photogrammetric analyses, but more work is needed to find out if and how these tools can improve georeferenced model accuracy.
- Direct georeferencing, requiring the UAS to be equipped with an RTK/PPK GPS-system, is currently the only way of getting verified, reliable results in areas where

ground control points cannot be deployed. Results obtained with indirect georeferencing suggest that with a strong image geometry, ground control points are mainly needed for scaling and orientation of the surface. This require, however, further work on the distribution of ground control points, and the application of alternative survey methods for model validation, e.g. total station.

Another experience is that photogrammetric processing is time-consuming and requires high computational power. Processing times can be lowered by reducing the number of tasks that need manual intervention, which within the Metashape software can be acquired with automation scripts and the use of standardized targets as markers. Secondly, the computation can be run on an external server with specialized hardware, or by cloud computing. Cloud-based processing options are already offered by e.g. Pix4D, Agisoft and Autodesk. Alternatives for reducing processing time also include reducing the size of survey area, optimizing image overlap and total number of images and reducing the resolution at which the images are matched. The latter will reduce the accuracy of the final product and might be impossible with images of a snow surface with small-scale contrasting features.

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Statens vegvesen
Drift og vedlikehold
Fagressurser Drift og vedlikehold
Postboks 1010 Nordre Ål, 2605 Lillehammer
Tlf: 22073000
Firmapost@vegvesen.no

Appendix 3 (Research Questions)

Phase 3 Research Questions

The research questions for the Phase 3 effort are designed to guide the effort; the questions are classified according to operational challenges:

1. Data acquisition
2. Photogrammetric processing
3. Validation
4. Training and certification
5. Other - logistical and practical issues

Data acquisition	- Is there a particular type of camera that works better for SfM in terms of resolution? o Small UAS (sUAS) with integrated onboard camera (e.g. 12 MP, 20 MP) typical o Custom payloads possible with small platforms and bigger (more expensive) platforms o Important to consider low-light performance of camera
Photogrammetric processing	- Any preferred SfM software? Perhaps the NPRA already has established protocols for SfM software.
Data acquisition	- Are there other variations of SfM such as infra-red that we should consider? o Integration of SfM photogrammetry with thermal infrared (TIR) imagery possible but technically challenging ▪ Georeferencing of images ▪ Mismatch in spatial and radiometric resolutions o Possible vendor challenge? - Should we consider fixed winged aircraft also (increased flight endurance)? o VTOL-fixed wing hybrids available too o Possible vendor challenge?
Training and certification	How does the NPRA find pilots? Does the NPRA train staff in UAS and SfM operations? - Will the NPRA own and operate the UAS? - How will the NPRA work around personal schedules and time off for the geologist? How many people does NPRA have trained to fly UAS?
Data acquisition	- How important is a baseline LiDAR survey? - Are there other sources of information about avalanche prone sections of roadway, that might enhance the SfM information?

<table>
<tr><td>Validation</td><td>- Ground control
    o Will we need to pre-install 'permanent' registration points at all our sites of interest?
    o Quantity and distribution
    o What targets will work best: poles, painted marks, edge of the road, or other features?

- Ground control
    o Test utility of placing ground control points
        ▪ Quantity and distribution vs. time required to survey points</td></tr>
<tr><td>Data acquisition</td><td>   ▪ Year-round accessibility</td></tr>
<tr><td>Photogrammetric processing</td><td>- How to integrate UAS flights into the NPRA’s work flow?
    o How quickly do the SfM results need to be accessed to be useful?
    o What type of internet connection is required? How long will it take to send or upload data files?</td></tr>
<tr><td>Other strategical and practical issues</td><td>- What conditions would warrant flights/imagery acquisition (after winds, new snow, secondary avalanches, or using explosives)? Should we develop a list of "must haves" and "realistic" protocols for acquisition?</td></tr>
<tr><td>Data acquisition</td><td>- When can we not fly (too dark, too windy, low cloud cover, snowing)?
- In what condition will SfM work well? In what conditions will the use of SfM be problematic? Can we quantify these conditions?</td></tr>
<tr><td>Strategic use</td><td>- Are there other criteria for closing roads? This can also be used in our framework for dictating when it would not make sense to fly.</td></tr>
<tr><td>Photogrammetric processing</td><td>- What would a "rapid evaluation" protocol look like for simply getting eyes
- on portions (i.e. a live or almost live camera feed) on the slope that are not visible from the road?
    o Will visual (non-photogrammetric) inspection suffice in some areas?</td></tr>
</table>

Data acquisition	- Is it possible to conduct beyond line of sight (BLOS) flights?
	    o BLOS and expanded visual line of sight (EVLOS) flights not permitted under RO1 without a waiver: https://luftfartstilsynet.no/en/drones/commercial-use-of-drones/about-dronesrpas/ro1/
	- How will regulatory changes in 2020 affect operations?
	- How long does flight planning take for different types of sites?
	- How much of the flight will be autonomous?
	- What kind of guidance will a pilot need to repeat a baseline flight but during avalanche conditions (GPS flight path, etc.?)
	- Test the strengths and weaknesses of current generation drone mission planning software in steep terrain (e.g. Litchi, Map Pilot, UgCS)
	    o Terrain awareness
	    o Gimbal control: nadir images vs. images normal to surface
	    o Oblique imagery
	    o Camera optimization to minimize motion blur (function of ISO setting and flight speed)
	- Prioritization of areas to monitor (e.g. release area vs. runout length)
	- How long does it take to cover x square meters of terrain with a UAS? Can we develop some rules to guide flight times?
	    o Waypoints
	    o Number of photos
	    o Overlap ratio
	    o Ground resolution
	
	Results
	- Can snow depth / volume be determined using UAS-based SfM photogrammetry?
	    o Is it better than current methods of estimation?
	- Is an RTK-enabled UAS more suited to surveying large avalanche-prone areas?

Photogrammetric processing	- Would it be possible to have an online mapping or decision support system as a deliverable for this project or is that more appropriate for follow-on research?
Other	- Do we need to ultimately develop a cost justification for the use of this technology?
Training and certification	- Do we need to develop an NPRA operations manual?

Statens vegvesen
Pb. 1010 Nordre Ål
2605 Lillehammer

Tlf: (+47)22073000
firmapost@vegvesen.no

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vegvesen.no