REPEATED UAS LIDAR SCANNING OF SNOW SURFACE TO SUPPORT SITE-SPECIFIC AVALANCHE WARNING

Emil Solbakken[1]*, Halgeir Dahle[1], and Tore Humstad[1]

[1] *Norwegian Public Roads Administration, Norway*

ABSTRACT: Site-specific avalanche warning often involves assessment of avalanche hazard in remote avalanche paths with limited observations of relevant snowpack properties. This study introduces a novel approach utilizing UASs equipped with lidar (light detection and ranging) technology to support site-specific avalanche warning for mountain highways. Over a period of 25 days during winter 2023, repeated UAS lidar surveys were conducted in avalanche release areas along the mountain highway Rv.15 Strynefjellet. A semi-automatic processing pipeline was developed to quickly make results available to avalanche forecasters in a simple web application. Published results included shaded snow surface relief, snow depth, snow depth changes over various time intervals and snow surface inclination. Acquired data enabled precise detection of snow depth change and avalanche activity, providing valuable insights into snow accumulation patterns and expected avalanche sizes. In our experience, UAS lidar scanning in avalanche release areas is a viable method for generating high-resolution spatial data on snow depth changes, also in poor weather and low-light conditions. More work is needed to ensure reliable measurements, ease interpretation of results and better understand the impact on forecasted hazard levels. With future improvements, the methodology can contribute to improved site-specific avalanche warnings and increased safety for mountain highways.

KEYWORDS: lidar, UAS, site-specific avalanche warning

1. INTRODUCTION

Snow avalanches pose a significant threat to roads and infrastructure in Norway, and one of the ways to mitigate this threat is through site-specific avalanche warning. This is by the European Avalanche Forecasting Services defined as assessing the likelihood of an avalanche to release and endanger people or infrastructure in specific avalanche paths (EAWS, 2022). These assessments are generally associated with high uncertainty, and they are often made for remote avalanche paths without direct observations of snowpack properties in the relevant release areas. Previous efforts to map snow surface and snow depth in avalanche release areas using uncrewed aerial systems (UASs) have been focused on photogrammetry and optical sensors (Bühler et al., 2016; Peitzsch et al., 2018), which has significant shortcomings when it comes to data collection in poor light conditions. Terrestrial laser scanning (TLS) has also been demonstrated for a variety of purposes (Eckerstorfer et al., 2016; Deems et al., 2013), including operational avalanche warning (Deems et al., 2015). Recent development of low-cost lidar (light detection and ranging) sensors has, however, opened up new possibilities for monitoring of snow depth, being used on both stationary platforms (Ruttner-Jansen et al., 2024) and in UASs (Marshall and Bühler, 2023; McCormack et al., 2024). Combining low-cost lidar with advances in UAS technology, we are now able to monitor remote avalanche release areas also in weather that are associated with increased avalanche hazard. This paper describes our first efforts to use this methodology to support operational site-specific avalanche warning, and discusses current challenges, potential value to forecasters and the road ahead.

2. METHODS

2.1 *Field site*

Field campaigns were carried out along the mountain highway Rv15 Strynefjellet in Western Norway (Figure 1). Here, the road is threatened by several avalanche paths, and daily site-specific avalanche warnings are made by the NPRA to ensure the safety of road users and staff. In this project, we focused on the four avalanche paths that are most likely to produce avalanches reaching the road. The release areas are located from 50 to 1400 elevation meters above the road (900 to 1700 m a.s.l.) and have varying terrain characteristics and sizes, providing a range of operational challenges. Observations normally available to avalanche forecasters include weather observations from stations at approx. 800 and 1400 m a.s.l., images from PTZ (pan, tilt and zoom) cameras, infrasound avalanche detections and manual snow observations collected roughly once a week.

* *Corresponding author address:*
Emil Solbakken, Norwegian Public Roads Administration
Nygårdsgaten 112, 5008 Bergen, Norway
tel: +47 954 40 226
email: emil.solbakken@vegvesen.no

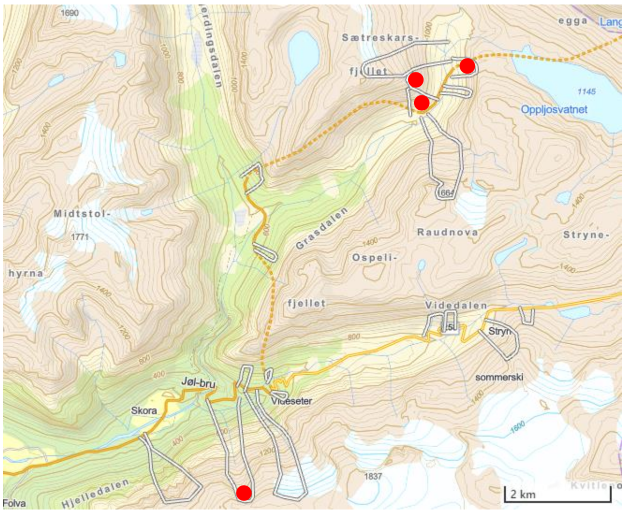


Figure 1: Map of the field site along Rv15 on the western side of Strynefjellet, showing relevant avalanche paths (white lines) and release areas monitored with UAS lidar surveys (red dots).

2.2 Data collection

Field campaigns were carried out on 22 days from January to March 2023. Each campaign consisted of Lidar surveys of 2-4 release areas with subsequent processing of data and publishing of results. The goal was to publish results before noon, in time to be used as input for the avalanche warning to be made the same day. 7 campaigns were assigned to an external contractor, Field Group, while the rest were conducted by the NPRA.

The external contractor used a self-developed UAS with a Hesai XT-32 Lidar scanner, capable of providing survey grade accuracy. They carried out fully automatic flights 60 meters above terrain at a speed of 7.5 m/s. As such, a total flight time of 56 minutes was needed to cover the three release areas in Grasdalen. In addition to the UAS data collection, a base station was set up by the road to collect data for GNSS correction using PPK (post-processing kinematics).

For campaigns conducted by the NPRA, Lidar data was collected using the low-cost DJI Zenmuse L1 Lidar scanner mounted on a DJI Matrice 300 RTK multi-rotor UAV. Flights were carried out semi-automatically, with the pilot controlling the flights to and from the survey areas. Lidar data was collected 80 meters above terrain at a speed of 10 m/s, with flight strips across the slope from top to bottom and automatic calibration of the Lidar at the start and the end of the mission. As the Lidar can only be oriented nadir during survey missions, 30-50% sideways overlap was required to ensure sufficient coverage in the steepest parts of the slopes. Other settings used were dual return mode, 240 KHz sampling rate and repetitive scanning mode. GNSS correction was performed in-flight using the UAV's RTK (real-time kinematics) module.

2.3 Data processing

To minimize processing time, we developed a semi-automatic workflow to process data collected by the NPRA. The workflow consisted of two main steps:

1) Processing of raw point cloud data and generation of LAS-files in the software DJI Terra.
2) Automated processing of LAS-files and publishing of final raster products with a script tool in ArcGIS Pro.

Both steps were carried out on a laptop in the field. The processing required internet connection, but data upload was limited to relatively small raster files and was not depending on fast upload speed.

Processing of LAS-files in step two included classification of ground points to remove vegetation and noise caused by precipitation particles, before generation of digital surface models (DSMs) at two different resolutions. A resolution of four times the average point spacing, typically around 15 cm, was specified for DSMs to be used for detailed shaded reliefs of the snow surface. Other raster products, including maps of snow depth, snow depth change and snow surface inclination, were created from DSMs with a resolution of 0.5 m.

The external vendor used their standard processing pipeline, which involved upload of raw point clouds directly after each flight for extensive post-processing by a dedicated processing team. After post-processing, final raster products were generated and published with the NPRA processing tool.

2.4 Web presentation

Results were presented to forecasters in a simple web application, where the user could select the date and type of result to be viewed. Available results were shaded relief, snow depth change over 1-3 days, snow depth and snow surface inclination. The color scale for snow depth change was adjusted to account for expected measurement uncertainty, only showing changes larger than 10 cm.

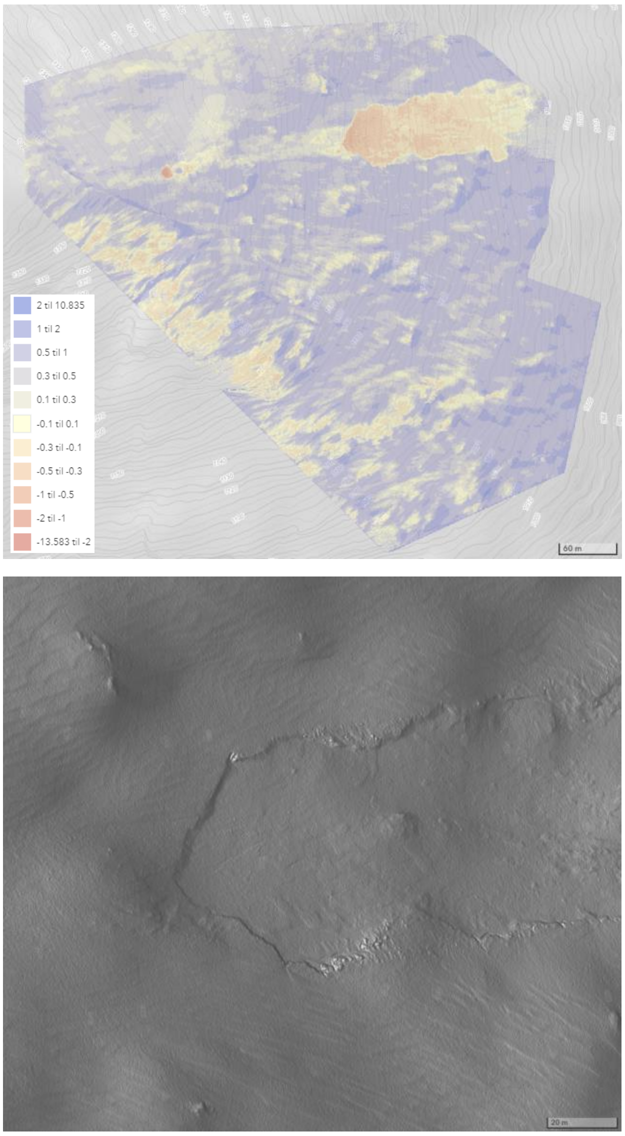


Figure 2: Examples of snow depth change (17-21 March 2023) and shaded snow surface relief (21 March 2023) on the eastern slope of Sætreskarsfjellet (Figure 1), based on data delivered by the external vendor. The figures show extensive snow accumulation after a period of snowy weather and moderate winds from S-SW. Also visible is the fracture line and the relative fracture depth of a slab avalanche, probably triggered by a loose snow avalanche released by avalanche control with explosives.

3. DISCUSSION

3.1 Operational challenges

To be able to deliver data to forecasters also when the avalanche danger is high, flying in adverse weather is inevitable. While we successfully performed mapping campaigns in a range of different weather conditions, including light snowstorms and dense fog, we also identified conditions that might lead to reduced data quality or pose a threat to flight safety. High air humidity was found to reduce the output ground point density, probably due to the water molecules in the air absorbing energy from the laser pulses. Precipitation particles have a similar effect, as many of the pulses are reflected from particles in the air and not the snow surface.

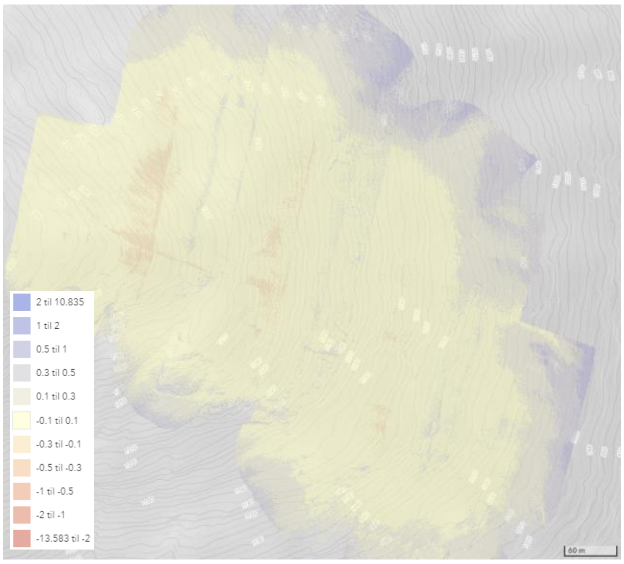
We also believe that strong wind gusts might have affected point accuracy on some occasions, although this is not verified. Topographic wind effects such as leeside turbulence and increased wind speed above ridges were often found to be difficult to predict for the pilot located at the valley bottom, leading to some unexpected flying in wind exceeding the limitations stated by the aircraft manufacturer. The most serious issue we encountered, though, was in-flight icing, almost leading to loss of an aircraft. Icing on rotors or propellers are known to decrease the propellers thrust and can quickly cause loss of control of multi-rotor UAVs. Different ways of mitigating this issue are currently being researched (Müller et al., 2023). Meanwhile, icing will continue to pose a big risk to UAS operations in cold and humid conditions.

In this project, we aimed for doing one measurement a day in periods of expected changes in snow depth. As we had no pilots with the necessary qualifications based near the field site, operations were planned days and weeks ahead according to weather forecasts and pilot availability. This made data collection very labor intensive, and adaptation to the current weather situation practically impossible.

3.2 Data quality and validation

The DJI Zenmuse L1 lidar is probably the cheapest UAS lidar system on the market, and its accuracy and precision are lower than for more expensive sensors. This is also clearly visible comparing results from campaigns conducted by the NPRA and the external vendor. A sensitivity study of using the L1 lidar for snow surface mapping by Salazar et al. (2024) suggests that measured elevation values can be expected to vary with around 10 cm between flights. This is in line or at the lower end of what we have experienced in this and similar mapping projects. While the differences may be found as a general offset between two internally consistent datasets, we often also see larger differences that vary within the datasets and are clearly unrelated to actual changes, both across the survey area and across flight strips (Figure 3).

On the slope scale, low repeatability or precision leads to detection of “changes” in snow depth that are not real. On the scale of snow surface features, low precision can make even surfaces rough and actual surface features less apparent, especially if the point density is low. These errors can be reduced by using better sensors, collecting more data or doing more extensive post-processing, but in an operational perspective the important question is what is good enough for the end user. In this project, we did not include any objective validation of data and relied on the forecasters being familiar with typical errors and being able to evaluate the reliability of the results they were presented. Considering the variety and magnitude of errors found in datasets from the L1 lidar, we believe that it is necessary to both improve data quality and to present some objective measures of reliability to prevent erroneous use and ease the interpretation of results in future projects.



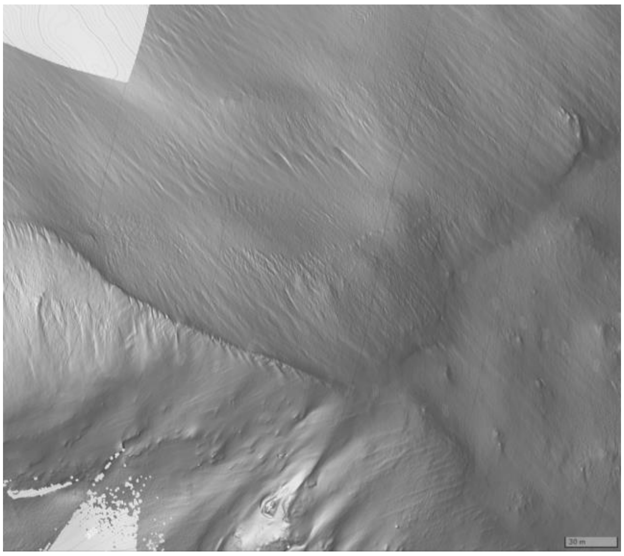


Figure 3: Examples of snow depth change (1-2 March 2023) and shaded snow surface relief (2 March 2023) on the eastern slope of Sætreskarsfjellet (Figure 1), based on data collected by the NPRA. The apparent snow depth changes are not related to actual changes and is caused by systematic errors in the measurements. The shaded surface relief do for the most part show actual surface structures but do also contain linear features and other noise representing measurement artefacts.

3.3 Information value

As far as we know, this is the first attempt to implement day-to-day monitoring of snow surface changes in remote and unequipped avalanche release areas in operational, site-specific avalanche warning. When assessing current avalanche hazard, measurements of snow accumulation and recent avalanches (Figure 2) can provide direct information about likely slab thickness and distribution, which in turn is essential to assess avalanche size and potential runout length. Moreover, building a database of snow surface changes over multiple seasons can allow us to improve our understanding of the processes driving these changes, and make models that are able to predict them.

In a small case study based on data from this project, Haddad et al. (2023) found indications that access to lidar data significantly influenced the forecasters assessment of both avalanche problem, avalanche size and avalanche likelihood, resulting in lower predicted hazard levels. Although more research is needed to understand this influence, the findings suggest a possible direct impact on road restrictions resulting from avalanche warnings. It is hypothesized that access to lidar data have the biggest impact in situations where the avalanche hazard mainly is controlled by wind deposition, and where the forecaster has few other data sources to base the assessment on. Whether that impact is good or bad is decided by both the quality of the provided data, and if the forecaster is interpreting and weighting that information appropriately (McClung, 2002).

Anecdotal evidence from this project suggests that access to lidar data also can enhance the forecaster's confidence in their understanding of current processes affecting the snowpack, without necessarily change the outcome of the hazard assessment. This is especially true in periods of low visibility where little or no other information from the release areas is available.

3.4 Next steps

A key factor for successful use of UAS lidar data in avalanche warning is measurement frequency and flexibility. To achieve this in an operational setting, full automation of data collection and processing might be required to reduce labor cost to an acceptable level. The NPRA plans to do the first test of a drone station in winter conditions in the coming months.

As for the value to avalanche warning, we expect more work to be done on the impact of new data streams in the coming years. This is important to understand how the data influences hazard assessments, and how the data is best presented and weighted.

4. CONCLUSION

We have demonstrated how UASs equipped with lidar technology can support site-specific avalanche warning for mountain highways. Results published to forecasters enabled detailed assessment of snow depth changes and avalanche activity in remote avalanche release areas, also in poor weather and low-light conditions. This can potentially have a big impact on a forecaster's assessment and thus also recommended road restrictions. However, more work is needed to ensure reliable measurements, easy interpretation of results and better understanding of the impact on forecasted hazard levels. With future improvements, the methodology can contribute to improved site-specific avalanche warnings and increased safety for mountain highways.

ACKNOWLEDGEMENT

This research was supported by funding from the Research Council of Norway (project no. 321035), the Norwegian Public Roads Administration (NPRA) and the Norwegian Geotechnical Institute (NGI).

REFERENCES

Bühler, Y., Adams, M. S., Bösch, R., and Stoffel, A.: Mapping snow depth in alpine terrain with unmanned aerial systems (UASs): potential and limitations, The Cryosphere, 10, 1075–1088, https://doi.org/10.5194/tc-10-1075-2016, 2016.

Deems, J. S., Painter, T. H., and Finnegan, D. C.: Lidar measurement of snow depth: a review, Journal of Glaciology, 59, 467–479, https://doi.org/10.3189/2013jog12j154, 2013.

Deems, J. S., Gadomski, P. J., Vellone, D., Evanczyk, R., LeWinter, A. L., Birkeland, K. W., and Finnegan, D. C.: Mapping starting zone snow depth with a ground-based lidar to assist avalanche control and forecasting, Cold Regions Science and Technology, 120, 197–204, https://doi.org/10.1016/j.coldregions.2015.09.002, 2015.

EAWS, The European Avalanche Warning Services: Site-specific avalanche warning, Definitions and Recommendations., 2022.

Eckerstorfer, M., Bühler, Y., Frauenfelder, R., and Malnes, E.: Remote sensing of snow avalanches: Recent advances, potential, and limitations, Cold Regions Science and Technology, 121, 126–140, https://doi.org/10.1016/j.coldregions.2015.11.001, 2016.

Haddad, A., Hendrikx, J., Humstad, T., Solbakken, E., Johnson, J., and Sproles, E. A.: Quantifying the impact of new data streams in avalanche forecasting, in: Proceedings of the International Snow Science Workshop, Bend, Oregon, 136–143, 2023.

Marshall, H.-P. and Bühler, Y.: Airborne and spaceborne snow remote sensing with optical and microwave sensors: A review of current approaches and future outlook for avalanche applications, in: Proceedings of the International Snow Science Workshop, Bend, Oregon, 1052–1057, 2023.

McClung, D. M.: The Elements of Applied Avalanche Forecasting, Part II: The Physical Issues and the Rules of Applied Avalanche Forecasting, Natural Hazards, 26, 131–146, https://doi.org/10.1023/a:1015604600361, 2002.

McCormack, E., Humstad, T., Salazar, S., Frauenfelder, R., Dupuy, B., Hendrikx, J., Dahle, H., and Solbakken, E.: Operational integration of uncrewed aerial vehicles into roadway agencies' snow avalanche risk assessment process, in: Proceedings of the International Snow Science Workshop, Tromsø, Norway, 2024, this issue.

Peitzsch, E. H., Fagre, D. B., Jordy Hendrikx, and Birkeland, K. W.: Detecting snow depth change in avalanche path starting zones using uninhabited aerial systems and structure from motion photogrammetry, in: Proceedings of the International Snow Science Workshop, Innsbruck, Austria, 408–412, 2018.

Ruttner-Jansen, P., Voordendag, A., Hartmann, T., Glaus, J., Wieser, A., and Bühler, Y.: Monitoring snow depth variations in an avalanche release area using low cost LiDAR and optical sensors, EGUsphere [preprint], https://doi.org/10.5194/egusphere-2024-744, 2024.

Salazar, S. E., Hancock, H., Frauenfelder, R., Dahle, H., Solbakken, E., and Humstad, T.: Optimisation of UAV-borne lidar surveys for snow distribution mapping, in: Proceedings of the International Snow Science Workshop, Tromsø, Norway, 2024, this issue.