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Statens vegvesen

Evaluating Sensors for Snow Avalanche Monitoring on UAS

Findings from Andøya, Norway, April 16-18, 2018

STATENS VEGVESENS RAPPORTER Nr. 615

Tittel
Evaluering av instrumenterte droner ved håndtering av snøskredfare

Undertittel
Resultater fra test på Andøya, 16.-18. april 2018

Forfatter
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snøskred, droner, UAS, GPR

Sammendrag
Statens vegvesen inviterte til todagers feltdemonstrasjon på Andøya i april 2018 for å evaluere bruk av instrumenterte droner ved vurdering av snøskredfare.

Testen viste at georadar, eller bakkepenetrerende radar (GPR), på droner kunne identifisere lagdeling i snødekket. Rådata var utfordrende å bruke i felt, med etterbehandlede data viste seg å være nyttige. Georadar kunne også identifisere begravde kjøretøy og mennesker under snøen. Også dette virket best ved etterbehandling.

Markedet for droner og luftbårne sensorer er i rask vekst, og Statens vegvesen bør utforske videre potensialet ved bruk av slikt utstyr. Forhold vedr. regulering av droner må imidlertid avklares for å bekrefte om framtidig bruk av droner vil være i tråd med gjeldende regelverk.

Rapporter fra Romvesen AS og Norut er vedlagt.

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Evaluating Sensors for Snow Avalanche Monitoring on Unmanned Aircraft Systems

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Summary
The NPRA sponsored a two day field demonstration in April 2018 in Andøya, Norway to evaluate the usability of sensors on UASs for snow avalanche monitoring.

The test found that output from ground penetrating radar (GPR) on UAS could identify snow layers. Raw GPR output was challenging to interpret on site, but post-processed data proved to be useful. The GPR was also able to identify buried vehicles and humans but again this output worked best with post-processing.

The UAS industry and airborne sensor industry is growing rapidly and the NPRA should continue to explore their capabilities. Regulatory issues will need to be reviewed to confirm that future use is according to the regulations.

Reports from Romvesen AS and Norut are attached.

Pages 26

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September 12, 2018

Executive Summary

The Norwegian Public Roads Administration (NPRA) recognizes that unmanned aircraft systems (UASs) have applications that potentially supports their mission. The NPRA sponsored a two day field demonstration in April 2018 in Andøya, Norway to evaluate the usability of sensors on UASs for snow avalanche monitoring. This demonstration is a follow-on of a test in March 2016 where Norwegian UAS vendors demonstrated their system's ability to operate in mountains in winter weather.

This test explored the ability of ground penetrating radar (GPR), photogrammetry (structure from motion or SfM) and digital cameras to detect characteristics of the snowpack that are relevant for avalanche hazard monitoring. The GPR sensors were also tested for their ability to detect humans and vehicles buried in snow.

The test found that GPR output could identify snow layers important for snow avalanche hazard monitoring but the raw GPR output was challenging to interpret and required post-processing to be most useful. GPR technology will need further development to more effectively relate raw sensor output to hazardous conditions in the snow pack. This may require software to interpret GPR output in real-real time as the GPR systems are operated in the field. Both organizations supplying GPR sensors for this test have indicated that they now have a better idea of NPRA's need and can build more usable systems. The GPR was also able to identify buried vehicles and humans but again this output worked best with post-processing.

Digital cameras on UAS were used to view surface features of the snow and, at his time, this visual output was the most usable to the avalanche experts at NPRA since the other sensor technologies tested required post-processing. The use of SfM derived from digital cameras can potentially map snow surface conditions and measure snow depth both of which are valuable for avalanche hazard assessment. SfM used both before and after snow fall could provide valuable data about snow pack depths and snow volumes. It is recommended that photogrammetry (SfM) surveys on small UASs be further explored by the NPRA.

The UAS industry and airborne sensor industry is growing rapidly and the NPRA should continue to explore their capabilities. However, regulatory issues will need to be reviewed to confirm that Norwegian regulatory environment will support the routine use of UASs by the NPRA.

The NPRA may want to formalize or explore further the uses of smaller UAS already operated by NPRA staff. It could be valuable for the NPRA to offer training related to operations, flight regulations, and safety of these aircraft and open up the use of these small UAVs to more employees. This could include for operations beyond snow avalanche monitoring including geological surveys and mapping the extent of rock falls, floods, debris flows and landslides.

INTRODUCTION

Staff at the Norwegian Public Roads Administration (NPRA) recognize that unmanned aircraft systems (UAS) (also commonly known as drones) and the cameras and sensors they can carry are increasingly available and potentially have applications that support NPRA's data collection, natural hazards detection, and transportation system monitoring needs. The NPRA, following up on a test in winter of 2016, funded a two day demonstration at Andøya evaluating sensors on UAS used to support snow avalanche monitoring. The findings will be used to provide greater knowledge about the possibilities and limitations of the use of sensors to support snow avalanche monitoring and will also be used to develop guidelines for UAS usage by the NPRA.

BACKGROUND

Small unmanned aircraft are increasingly capable, affordable, and commercially available. There has been a wide range of transportation-related applications of this technology including for natural hazards monitoring, infrastructure inspection, surveying, and mapping (1).

The Norwegian Public Roads Administration is responsible for maintaining roads that are in a cold, northern climate often with severe winter weather. Part of the NPRA's mission is to monitor and react to snow avalanche hazards in steep areas above their roads. A common situation is where a road is closed due to a snow avalanche (this also applies for rock falls and landslides). NPRA's geological staff are required to determine as quickly as possible if it is safe to reopen the road or if it is necessary to do roadway clearance work. If clearance is required, NPRA staff evaluate if it is safe for the maintenance workers removing snow debris. This can be a challenging evaluation since the clearance activity can take time thus increasing the workers exposure to avalanche risk. In addition, the assessment challenge is also greater if there are multiple avalanche release zones.

NPRA staff uses a variety of means to view and evaluate the slide area including roadside observations with binoculars and travel by foot, ski, snowmobiles, and manned helicopters. If the geologist is able to adequately view the release area and the avalanche path, they typically can make a quick assessment whether to open the road or to keep it closed.

Given the growth of commercially available UASs and of lighter weight sensors able to be flown on these aircraft, the NPRA wanted to determine if these technologies could replace or enhance their current methods of monitoring avalanches. One notable motivation was the possibility that UASs could make avalanche monitoring safer by permitting staff to view avalanches without traveling close to the avalanche release area or without having to fly expensive manned helicopters in the mountains. The use of UASs potentially could support more effective monitoring, perhaps with a quicker response time.

Beyond some tests in Washington state, USA (2) and tests by NPRA in 2015 (3) in 2014/2016 (4), there has been limited exploration or applications of UASs for operationally focused, roadside snow avalanche monitoring and control.

In winter of 2016, The Norwegian Public Roads Administration (NPRA) completed an evaluation of UAS's 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 ranging from flights over a nearby road and bridge to a 2,3 kilometer flight to a 1,300 meter mountain to inspect avalanche features. Results indicated that there is no single UAS that meets all of the road administration's monitoring needs but different types of aircraft could be used in winter conditions for avalanche monitoring (4).

One major conclusion of the 2016 test was that camera quality and sensor technology are critical to the usefulness of UAS for avalanche monitoring. The aircraft are simply a vehicle to carry cameras and sensors to an area of interest. In the 2016 demonstration, the photo and video quality general was good and several were exceptional suggesting UASs with cameras could partially replace the need for NPRA observers to travel into avalanche assessment areas. The project concluded that NPRA should continue to monitor sensor technology and consider testing technology that is mature, commercially available, and could be flown on small UASs.

The Andøya test in 2018 was motived by this 2016 test at Bjorli, and was specifically designed to explore the use of sensors on unmanned aircraft. The research team found there are already research and applications that indicate sensors such as infrared (IR), LiDAR and camera-based photogrammetry can provide information about snow pack and avalanche risk (see for example 5, 6, 7, 8, 9, 10, 11, 12). These sensors all had the potential ability to evaluate snow pack features. Measuring snow volumes or depth, and detecting weak layers under the snow were of particular interest. However, many of these sensors were not used on UASs.

An additional review of current sensors usage was completed to confirm the possible technologies that could be used or tested.

LIDAR, which stands for Light Detection and Ranging is a technology that uses light in the form of a pulsed laser to measure variable distances to the Earth. LIDAR designed for UAS are commercially available (12, 13, 14) but only a few researchers have used LIDAR on UAS to look at the snow surface and the distribution of snow (12, 15). As an example, a 2017 Italian study compared LIDAR readings to manual probing and found that "UAS represent a competitive choice among existing techniques for high-precision high-resolution remote sensing of snow" (15). However, this use of LIDAR for snow depth typically requires a baseline survey when the snow is absent. LIDAR could potential be also used to survey the surface of the snow to look for features that indicate avalanche hazards such as cracks in the snow but little research was found.

Photogrammetry (sometimes referred to structure from motion or SfM) can obtain 3-D images from multiple images collated from standard 2-D cameras. As with LIDAR, this technology has been used to map snow including by some of the Andøya demonstration participants. They determined that "SfM is a promising new photogrammetric methodology, which enables the collection of geospatially accurate and high-resolution data, useful in avalanche dynamics modeling and snow depth spatial variability studies" (16). This technology is often seen as a lower cost alternative to LIDAR and has been applied for snow analysis in a number of studies (7, 8, 10, 11, 12, 15, 16).

Ground penetrating radar (GPR) uses electromagnetic radiation (radar) pulses to emit energy into the ground to image the subsurface and can detect reflected signals from subsurface features. When the radar energy encounters a buried object or a denser layer it may be reflected back to the surface. A receiving antenna can then record the variations in the return signal. GPR has often been used on carts or sleds but more recently GPR has been flow on manned aircraft and used for glaciology and searching for avalanche victims. Less common is the use of GPR for assessment of avalanche risk. Swiss researchers, for example, used GPR to measure snow properties but these were not on a UAS (17). GPR which can be mounted in drones are commercially available but use for snow condition monitoring was not found. GPR requires operation at a low height and at a consistent altitude which could be a challenge on steep mountain slopes.

THE ECONOMICS OF UAS USAGE FOR THE NPRA

The NPRA has an active snow avalanche monitoring and control program with approximately thirty engineers and scientists working with snow avalanches. NPRA staff estimates that 30% of their time involves avalanche work for an investment of around 15.000 hours per year. Assuming an average annual salary of NOK 623.000 (salary table level 70) and a 30% benefit rate yields a rough average cost for avalanche work of 560 NOK per hour. This translates into 8.5 million NOK per year spent on just avalanche-related salary activities by NPRA staff. If you add to this travel and other non-salary costs for the NPRA avalanche staff which could double the cost, NPRA direct investment in avalanche activities cost could approach 16 million NOK yearly. Thus, in terms of direct cost, NPRA's investment in avalanche monitoring is significant. This does not include the even more significant but indirect social and economic costs of mobility that is lost by people and goods due to road closures related to snow avalanches.

In some cases, UASs can provide deeply detailed visual data for a fraction of the cost of acquiring the same data by other means. The hourly cost of operating a UAS can range from almost nothing (i.e. a UAS owned by the NPRA and flown by staff member) to an hourly rate to contract out a UAS from a vendor. The company Romvesen estimates the cost per hour to contract out a UAS ranges from 564 NOK per hour for a basic system with a camera to up to 1.245 NOK per hour for a bigger UAV system with GPR. This is roughly in-line with other sources that suggest the average cost to contract out a UAS is equivalent to 1.500 NOK per hour (18). This relatively modest cost to operate a UAS suggests several scenarios where UAS could result in economic saving for the NPRA.

<u>Increased number of site visits or better coverage</u>. If a UAS could reduce the need for NPRA staff to ski or walk to a site, and allow for more remote inspections, the number of locations that staff might inspect during a day in the field could increase reducing the cost per site.

<u>Reduced manned helicopter flights</u>. UAS are already in use by NPRA in place of a manned helicopter for inspecting avalanche sites resulting in a notable economic benefits. A typical manned helicopter flight costs 25.000 NOK (including VAT) so any ability to replace these flights with UAS usage results in considerable savings given that 3 hours of UAS flight, in comparison, would cost around 4.000 NOK. This cost is an order of magnitude estimate and does not necessarily factor in additional costs such as pilot training, transport cost, administrative costs, and other types of overhead. None the less, the cost of operating a small UAS per hour will typical be much less than manned helicopters.

More accurate data. A final, less tangible benefit, is from the use of UAS to provide NPRA staff with better data which can be more detailed or have better coverage in term of size of the area that can be inspected. The ultimate efficiency and cost savings here is safer roads that are opened more quickly.

PROJECT GOALS

The purpose of the demonstration was to evaluate the use of UASs by NPRA to support avalanche monitoring operations. The specific goals were to:

1. Allow vendors an opportunity to present the capabilities of their sensors, and to a lesser extent, their aircraft, to staff from the Norwegian Public Road Administration (NPRA) and from other Norwegian institutions.
2. Provide unmanned aircraft vendors an opportunity to demonstrate that their sensor systems can operate and can support NPRA's interest in routinely and operationally using this technology for snow avalanche monitoring.
3. Support innovation in the Norwegian UAS industry.

The main requirement of the demonstration was to determine if UAS mounted sensors output could support the NPRA's avalanche experts. The format was to compare field results collected by NPRA's experts with results from the sensors on the UASs.

This required the review team dig test pits to look at layers and compare what they found to what the sensors on the drones found. This demonstration explored if the sensors could detect the following snow features linked to avalanches (19):

- **Snow pack composition**: Snow deposition rates and depth varies depending on the temperature, wind, and location. This creates a snow pack with weak and strong layers which change over time as the snow settles and consolidates. It is the relationship between layers that is closely examined for avalanche hazard forecasting. Weak layers combined with a slope greatly increase the chance of a snow avalanche.
- The **snow depth** is of interest because it indicates how much snow is available to be released by an avalanche or can help determine if a surface has been swept clean by previous avalanches.
- **Snow pack surface and the surrounding terrain** can indicate avalanche risk to experts. They look for feature such as cracks in the snow surface, signs of previous avalanches, concave or convex slopes, cornices, and snow anchors such as trees or rocks.

An additional capability considered was if the sensors could detect buried humans and vehicles. GPR has been explored as tool to find buried avalanche victims although not on UASs (20, 21). This could be an important safety consideration when conducting avalanche monitoring operations or for search and rescue operations.

PARTICIPANT SELECTION

Based on knowledge developed in the 2016 Bjorli test, the project team contacted a number of different organization who either operated UASs or indicated they had or were developing sensors that could measure snow conditions. Several of the vendors were uninterested, unable to participate because their sensor technology was still in a prototype stage, or the funding provided to participate was not enough to support their involvement.

Three organizations were selected because they had suitable technology, were willing to participate or had an interest in developing systems specifically for use by the NPRA in roadside avalanche monitoring. The selected vendors were:

- The Northern Research Institute (NORUT) operates the Arctic Centre for Unmanned Aircraft Systems out of Tromsø. The center has a research program that is developing a UAS GPR systems specifically to support avalanche monitoring.

- Romvesen is a Norwegian company that is a supplier of drone and sensor services. They operate a GPR sensor system initially designed for land mine detection but also promising for detecting conditions in a snowpack. They also have photogrammetry (SfM) technology.

- Andøya Space Center (ASC) is partially owned by the Norwegian Ministry of Trade and Fisheries and is a solution provider for UAS support and operations. ASC provided both logistics support for this test and demonstration of UASs able to operate in mountain climates and for beyond line of sight (BLOS) operations.

This demonstration's evaluation team had experience with avalanche monitoring, UASs operations, winter road maintenance, and technology evaluation. The team members and their areas of expertise were:

- Torgeir Vaa, Senior Principal Engineer at NPRA, winter maintenance and technology
- Edward McCormack, Civil Engineering Professor at NTNU, transportation technology evaluation
- Gunne Håland, Geologist at NPRA, avalanche monitoring and control
- Tore Humstad, Geologist at NPRA, avalanche monitoring and control
- Regula Frauenfelder, Norwegian Geotechnical Institute, technical lead for remote sensing and GIS

FLIGHT APPROVAL AND TEST LOCATIONS

All the flights were coordinated by the Andøya Space Center (ASC) in an area close to the town of Andenes in northern Norway. ASC was selected as the supporting agency for the aviation aspect of this test. Their involvement facilitated the test because they could provide accommodation and meals and help with the regulatory arrangements with the Norwegian Aviation Authorities (Luftfartstilsynet). ASC has permanent danger areas covering the whole of Andøya island and are able to perform unrestricted operations with seven days' notice. In addition, operations could be conducted within the control zone (CTR or controlled traffic region) of Andøya Airfield within minutes of notice. ASC had procedures and staff trained for communication with Luftfartstilsynet and Avinor for activation of areas used for UAS operations.

Three sites around Andenes were used for the test. Figure 1 shows the overall test locations.

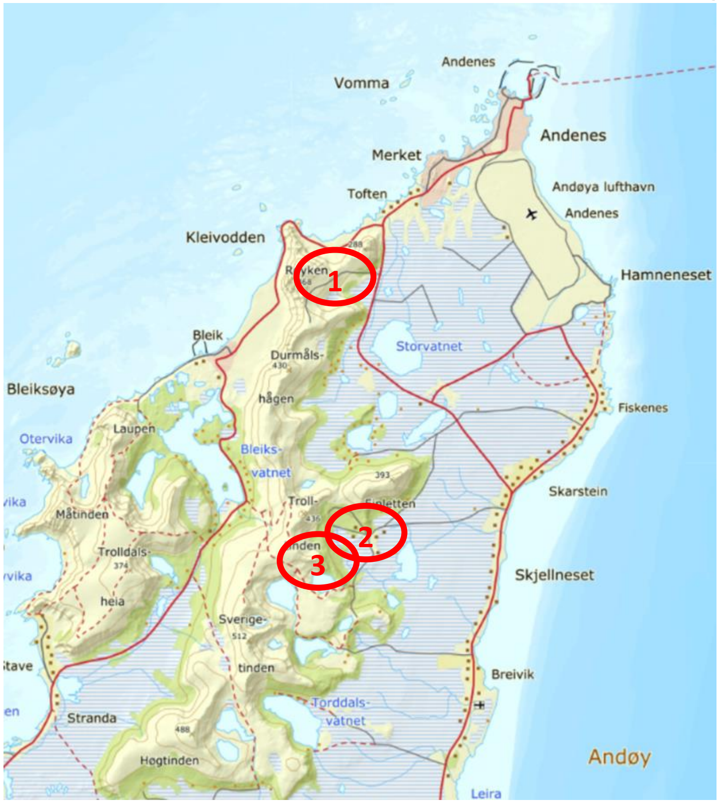

FIGURE 1 Overall Test Locations (map: norgeskart.no)

Site 1. This location was at 320 meters height on the side of Rorken (Figure 2) and site was used for exploring GPR's ability to detect layers and snow depth. A 50 meter long transect was created using poles and snow pits were dug every 10 meters (Figure 3). Detailed information about snow layers and depth was collected using hand dug snow pits at the transects[1] .The NORUT avalanche expert noted:

> "The snowpack at site one consisted of wet snow in the upper 70 cm with an estimated liquid water content of 3-8 %, whereas the lower 50 cm had a liquid water content of 0-3 %. Pronounced layering was mostly missing the upper half of the snowpack, whereas two prominent melt-freeze crusts were found towards the bottom of the snowpack . Densities ranged between 444 and 571 kg/m^3, likely a function of the liquid water content and the large grain sizes."

[1] Information and illustrations from the snow pits can be found in the regObs database:
http://www.regobs.no/Registration/160355
http://www.regobs.no/Registration/162769
http://www.regobs.no/Registration/160212
http://www.regobs.no/Registration/162770
http://www.regobs.no/Registration/160219

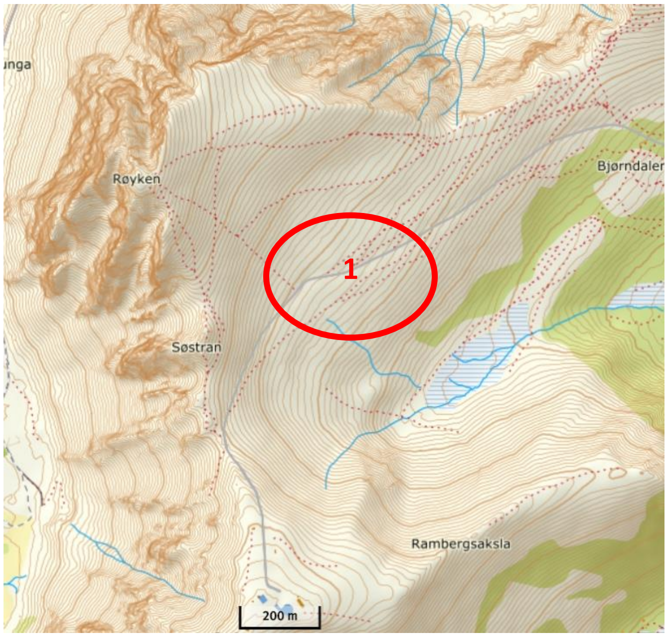

FIGURE 2 Site 1 Location (map: norgeskart.no)

FIGURE 3 50 Meter Snow Pit Transect at Site 1 (photo: Tore Humstad)

Figure 4 shows the layering and features in the snow pack at this test location[2].

[2] A snow profile is here: http://www.regobs.no/Registration/160355

FIGURE 4 Snow Layers at Site 1 (photo: Regula Frauenfelder)

The NORUT and Romvesen GPR systems were flown along the transect[3] . A simulated human burial was also tested at this location using both a metal plate and person buried in the side of a snow bank.

Site 2 was a lower site outside a former military base (Skarsteindalen) which was picked because it potentially had dryer, more layered snow. This site was approximately 25 meter of altitude (Figure 5). A 50 meter transect was also created with several snow pits (Figure 6). A derelict vehicle was also buried and it was used to determine if GPR could detect it.

[3] The transect is illustrated here: http://www.regobs.no/Registration/160355

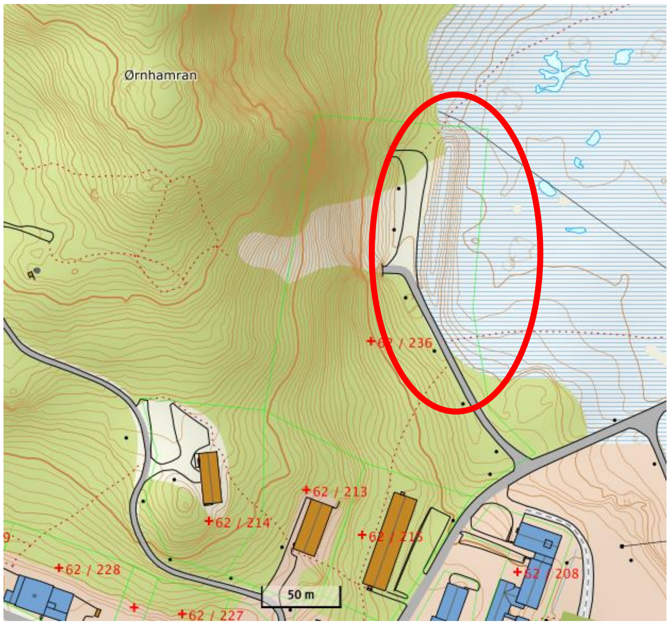

FIGURE 5 Site 2 Location (map: norgeskart.no)

Figure 6 Site 2 Transect (photo: Tore Humstad)

Site 3 was a remote site that included the remains of several older slab avalanches and cornices on the north side of Breiviktinden at approximately 330 meter altitude and 1,4 kilometer from a parking lot used as a launch for the UASs. Figure 7 is a map of the site and figure 8 shows the slab avalanche. This site was used to test the SfM and camera as well ASC's relay based UAS system.

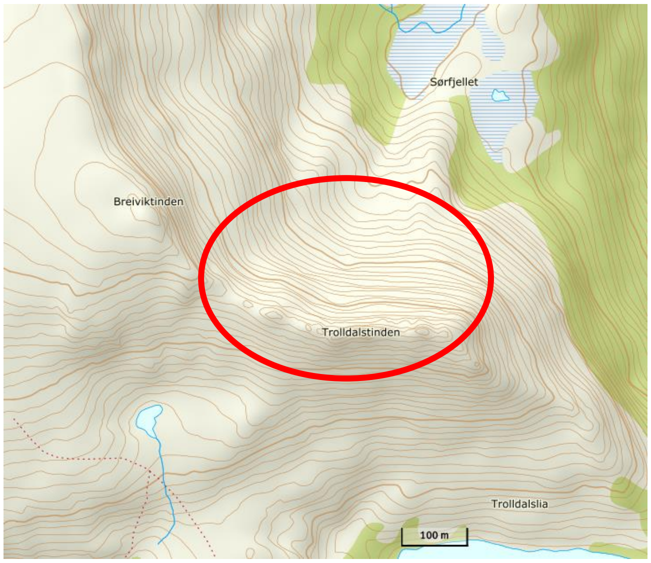

FIGURE 7 Location of Site 3 (map: norgeskart.no)

FIGURE 8 Slab Avalanche at Site 3 (photo: Gunne Håland)

The weather for both days was calm, with a high of about 10 C degrees and sunny. The warmer temperature was not ideal for the test because it resulted in wet snow which saturated the snow pack and resulted in less distinct layering to detect. The wet snow also increased the water content in the snow pack which negatively impacted the strength and quality of the GPR returns.

TEST RESULTS

Both Romvesen and NORUT, completed project reports which are included in the appendices. Both organizations presented post-processed sensor data and provide technical details in their reports.

Ground penetrating radar (GPR) and snow conditions.
GPR was tested at sites 1 and 2. In both cases, the results from the GPR were compared to snow pits dug by the NPRA review team[4].

NORUT
NORUT flew a ground penetrating radar (GPR) that was a ultra-wideband snow sounder (UWiBaSS) UWB sensor developed by the German company Ilmsens. The GPR weighed around 4 kilogram, consumed about 9 watts of power, and used three antennas (one emitting and two receiving). The GPR was capable of 5 cm resolution and was mounted on a Kraken Octocopter with a payload of 11,5 kilograms (Figure 9). Lidar was used to measure flight altitude.

FIGURE 9 Aircraft used by NORUT (Photo: Torgeir Vaa)

The NORUT system was tested on snow layers at Site 1 on the snow pit transect. The GPR data, as received in the field was not usable without post-processing. After post-processing,

[4] Snow profiles for the test sites:
http://www.regobs.no/Registration/160355
http://www.regobs.no/Registration/162769
http://www.regobs.no/Registration/160212
http://www.regobs.no/Registration/162770
http://www.regobs.no/Registration/160219

NORUT's GPR was able to find the wet snow surface and the interface between the ground and the snow which was about 120 centimeters under the snow pack. Four snow layers were detected.

NORUT concluded that their system:

> "showed that the radar was capable of resolving snow stratigraphy in wet snow conditions."

However, they also noted that deploying their system in dry snow was easier and commented that dry snow made it easier to detect weak snow layers in "avalanche starting zones" and for "determining the depth and spatial distribution of weak snow layers that can collapse under stress from overloading and release a dry slab avalanche."

NORUT staff also noted

> "that with a (GPR) spatial resolution of 5cm, a thin weak layer is not detectable. While we can resolve layering, it is mostly the thick hard layers that show clear reflection in the radar plots. We can then infer from the occurrence of these layers that there might be adjacent weak layers using our process knowledge."

In other words, the weak layers are often the thinnest layers. But the occurrence of thick, dense and often impermeable layers, as detected by GPR, can tell an avalanche experts something about the likelihood of a weak layer being present.

NORUT staff also commented that

> "Thin layers can occur in any type of snow. Wet snow decreases penetration depth using the radar frequencies that our GPR operates in so layering can be detected both in wet and dry snow, however, in dry snow, deeper lying layers are detectable.

Romvesen
Romvesen flew GPR at both sites 1 and 2. For the test at both sites, a quad copter equipped with the SPG-1700 GPR 700 sensor was used (Figure 10). Their team included a staff member from Geoscanners AB who provided the GPR system, who was an expert at analyzing the images received in the field and who completed the post-processing of the data.

FIGURE 10 Aircraft used by Romvesen (photo: Edward McCormack)

Romvesen in their technical report noted the:

> "demonstration has shown the viability of using a GPR system mounted on the drone"

and the:

> "comparison of the layer mapping data shows reasonable matching of the results to a particular layer that can be found in the test pit data as well."

The Romvesen expert demonstrated that he did not need to post-process the results to determine the different layers. However, Romvesen they also noted that their system was not optimized in terms of positional accuracy and flying speed and an antenna for different frequency would have obtain a better resolution to detect the thinner layers seen in the Site 1 snow pack.

Romvesen reported the results from the layer mapping at Site 2 were slightly better than the one from the first site. Post-processing with layer marking (interpretation) was used to get the most out of the raw data.

Ground penetration radar and buried people and vehicles

GPR was also tested at sites 1 and 2 to detect buried objects and people. The buried objects at Site 1 include a small metal plate inserted into a snow bank and person buried in the side of a snow pack (Figure 11). Site 2 included a vehicle which the project team arranged to have completely buried under a mound of snow (Figure 12).

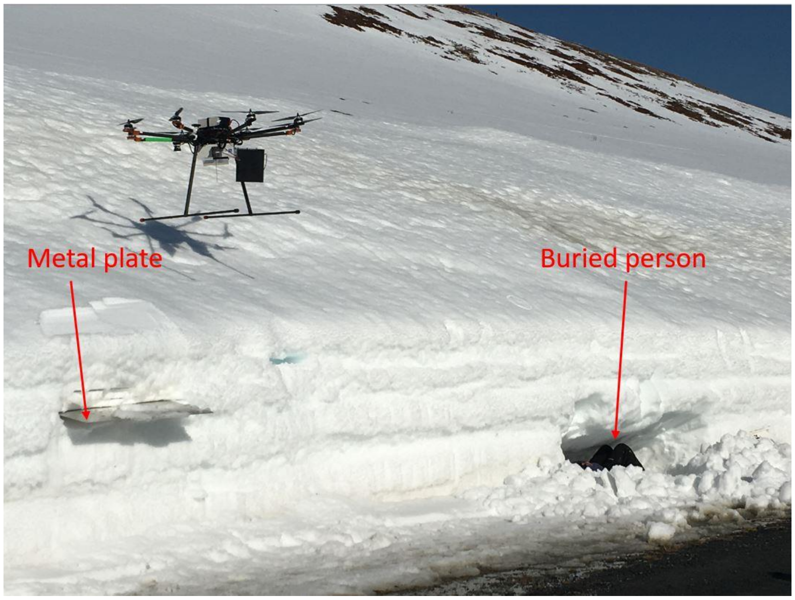

FIGURE 11 Buried Person and Metal Plate at Site 1 (photo: Regula Frauenfelder)

FIGURE 12 Buried Vehicle at Site 2 (photo: Tore Humstad)

NORUT

NORUT's GPR system was used at Site 1 to seek the buried plate and person and required four overflights because of the precision required to detect the objects. After post-processing, the GPR clearly detected both the plate and human target(Figure 13).

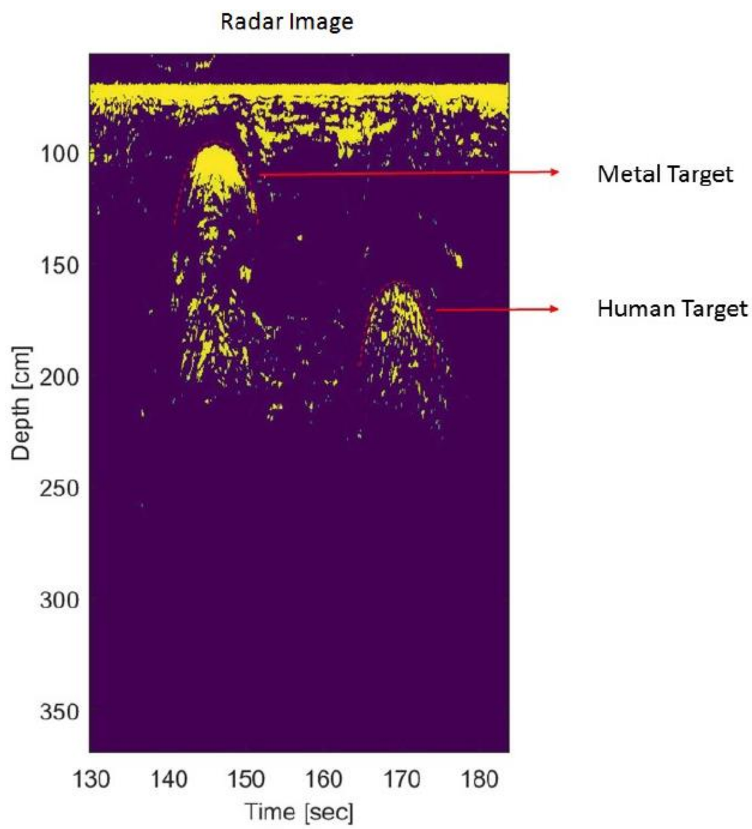

FIGURE 13 Post-processed GPR Image Showing Buried Objects at Site 1 (illustration: NORUT)

However NORUT noted:

> "with a field of view of approximately 0.35 m in diameter when flying 1 m over the snow surface, a very tight grid needs to be flown in order to cover an avalanche debris with a missing person or car."

Romvesen

Romvesen flew GPR to find the buried objects at both sites 1 and 2. The Romvesen participants concluded that:

> "data collected over a metal plate and a person under the snow yielded data readable in the field."

However, this ability to detect a buried object from data in the fields still required a trained eye. Figure 14 shows raw GPR data results from the Romvesen system with additional colored lines added to aid in analysis.

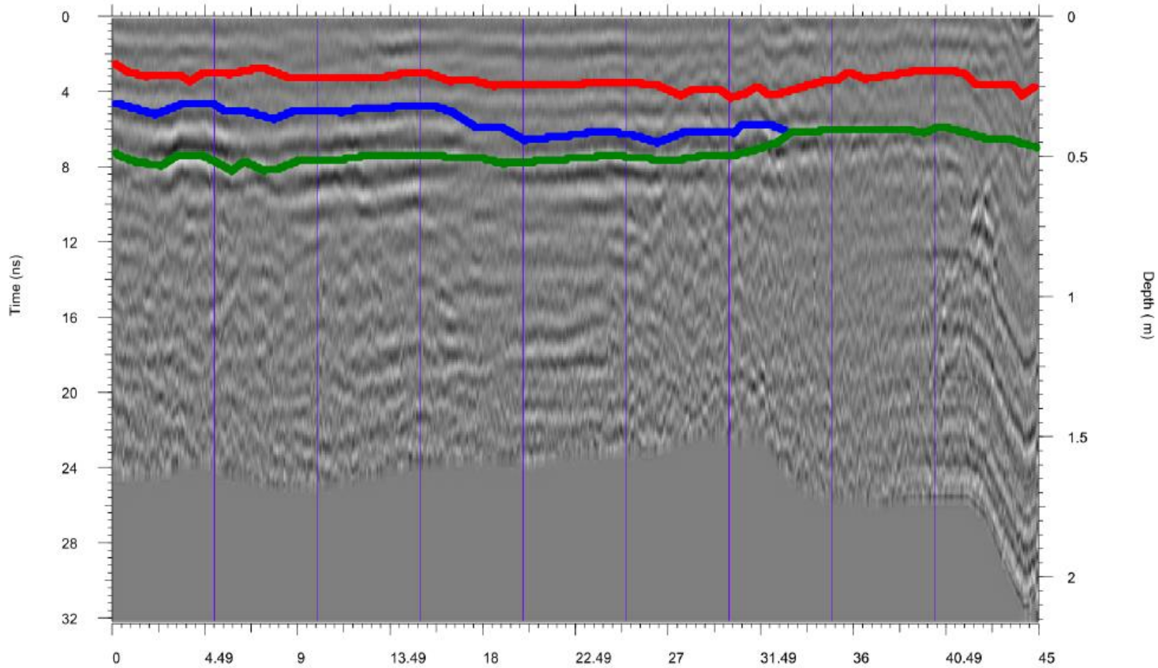

FIGURE 14 Results from GPR flight at Site 2 with Post-processing Graphics (illustration: Romvesen)

Romvesen note the buried vehicle at Site 2 was ”visible and clear”. As with the snow layer, post-processing enhanced the ability to detect the buried objects.

Romvesen concluded that:

> “For the search and rescue applications the demonstration has shown that it is possible to locate a larger metal target (car) under the snow with ease and it would be possible to use the system as is right now. Smaller targets with less reflectiveness of the signal (human body under snow) are visible, but not as easy to interpret without some experience in interpreting the GPR data. “

Cameras and Photogrammetry

The test also included several flights to demonstrate results from digital cameras. These flights were conducted at Site 3 (the slab avalanche) by ASC and Romvesen.

ASC

ASC operated a relay system where one pilot operated both an inspection drone equipped with full-format camera and a link-drone with radio communication link. Both drones were small/medium multi-rotors aircraft running on battery. The camera on the remote drone provided high quality digital and video output.

Example of the visual camera output can be seen in figure 15.

FIGURE 15 Real-time Images of the Slab Avalanche at Site 3 (photo: Regula Frauenfelder)

Romvesen

For the flight at Site 3, Romvesen used a DJI Inspire 2 drone with a Zenmuse X7 camera and a 16 mm lens. The images were collected by manually flying a grid over a target area with flight altitude varying between 30-120 meters. They noted that they compensated for the steep angle of the hill with extra images. Technical details are provided in the Romvesen report in the appendix.

Photogrammetry (SfM) requires post-processing of the raw image collected by the 2-D camera. The processed result combined with video provided a good overview of the snow surface conditions. Figure 16 on the left side shows video result while the right side shows SfM output with color bands for different altitudes.

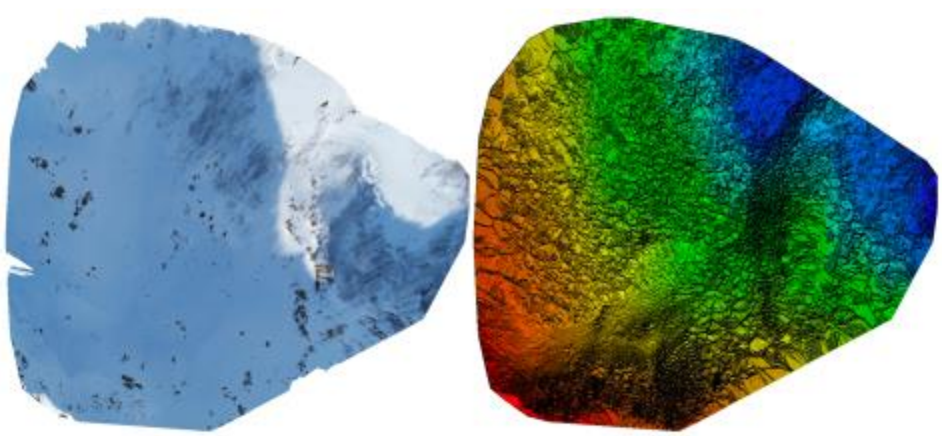

FIGURE 16 Video (left) and Photogrammetry Output (right) (Photo: Romvesen)

OVERALL RESULTS AND CONCLUSIONS

Over the two days of the test, about 20 flights by UASs carrying GPR, and high quality camera used for both photogrammetry and visual inspection were completed. The following points summarize the findings.

<u>While the GPR can identify snow layers, interpretation is needed.</u>

The GPR output could identify snow layers but the raw data collected in the field required skilled interpretation. The operators of Romvesen sensor systems were able to interpret the raw output and report out real time information about some aspects of the snow. However, this required an operator familiar with GPR output. Both Romvesen and NORUT post-processed the data to account for variability in the height of the sensor and to enhance the reflection of layers. Depending on the skill and time required to post-process the raw GPR data, this could be problematic in field situations such as the need for information to decide to close or open a road due to avalanche risk where usable snow pack data is quickly required. In other, less time sensitive situations, such as plowing open a road that has been closed for winter, the usage of post-processed GPR output is more feasible.

Weak layer properties in snow vary considerably depending on the nature of the weak layer which can be related to factors such as buried surface hoar, faceted snow, depth hoar, and the boundary between cohesive/less cohesive snow layers. This suggests an effort to tie snow layers as identified by GPR to the hardness scale used by NPRA' experts (knife, pencil, finger, etc.) as they dig snow pits. This is needed to demonstrate that GPR can effectively locate layers of interest to avalanche professionals. This process is also necessary to evaluate how GPR would work in different conditions (wet or dry snow, etc.).

The training of NPRA staff to interpret unprocessed GPR-signals in the field is possible but may not be an ideal approach. A sensor system that is the most operationally useful to NPRA should have real-time processing of feature detection (e.g. "signals from buried objects") and feature tracking (e.g. spatial tracking throughout a transect of detected layer in snow pack). In order to be useful for the NPRA, the GPR system has to detect appropriate snow layers, track relevant features internally, and return the algorithm-interpreted results to the operator, in near real-time.

Both Romvesen and NORUT have indicated that they now have a better idea of NPRA's needs and in the future it should be possible to:

- develop better software to more quickly/effectively post process snow related data,
- have GPR technology (mainly adjusting the antenna's frequency) better adapted to snow packs, and
- include better control systems for unmanned aircraft including altitude control and locational references.

In the longer term, as the GPR technology and software develops and matures, it could have several benefits for NPRA.

- A assessment of conditions using GPR could be quicker than using a hand dug pit reducing costs or allowing for more slopes to be evaluated.

- A GPR can enhance NPRA's program by providing snow profiles in greater quantity and more spatial variation but with less quality as compared to hand dug pits. A snow pit as dug for an avalanche risk assessment typically determines conditions at a point location, whereas a UAS flown GPR could fly a transect or grid and assess risk at a range of locations with variable aspects, altitudes, snow depth, slopes, and wind loading and could confirm the extent of findings made by NPRA experts. This could provide a more detailed picture of avalanche risk.

<u>The GPR could identify buried objects.</u>

The GPR was able to identify buried objects and humans. As might be expected, a large metal vehicle provided a stronger signal than a metal plate or a human. As with snow layers, the interpretation of the raw GPR returns required skill and post-processing improved the ability to "see" the buried objects.

While GPR's capability to detect buried objects is not directly related to avalanche monitoring, this could enhance the value of UASs used by the NPRA. In particular, identifying buried vehicles when clearing a road after an avalanche could be useful.

The use of GPR to detect buried objects could also increase the cooperation between the NPRA and organizations responsible for search and rescue, such as the Police and the Red Cross. A NPRA UAS equipped with GPR, combined with NPRAs' knowledge about avalanche conditions and risk, could provide Norway with a tool that reduce the consequence of avalanches and benefits a number of organizations.

<u>The cameras could identify surface features.</u>

The avalanche experts at the demonstration noted the visual output from the UASs was more usable in the short term than the output from the sensors that were tested. One NPRA avalanche expert also noted that UAS camera output was more usable than the view from a manned helicopter because the UAS often could fly closer to features of interest.

NPRA staff already uses small UASs that work reasonable well. However, larger UAS which can both carry a bigger camera that can provide higher quality pictures of surface conditions and are capable of traveling to more remote avalanche hazard locations would improve the information usable for avalanche monitoring. The use of SfM derived from cameras also can provide measurable surface details that might enhance assessment of the snow pack. SfM used both before and after snow fall could potentially provide valuable data about snow pack depth and about estimated avalanche volumes.

<u>The use of relay aircraft to fly beyond line of sight has potential.</u>

ASC use of two aircraft to build a relay system for beyond line of sight has potential for monitoring avalanches in areas that are beyond radio line of sight. ASC's two aircraft systems is already approved by Luftfartstilsynet for normal operation, without further restriction other than the regulations set up for operations using Beyond Visual Line of Sight (BVLOS) rules. The operation is also approved with one pilot operating both drones simultaneously.

Future Steps

The demonstration suggests a number of areas for the NPRA to continue to evaluate and consider UAS. Several of the points are similar to the ones raised by the 2016 vendor test at Bjorli.

The UAS and airborne sensor industry is growing rapidly and the NPRA should continue to explore their capabilities. UAS and sensor technology, capabilities, availability, and affordability have improved greatly. This growth has enhanced the potential of this technology to address NPRA's need in terms of avalanche control and winter operations. One product of this demonstration was that the participating Norwegian vendors now have a better idea of the needs and operational requirements of the NPRA. Both Romvesen and NORUT indicated that in the future they could better customize their systems and add new technology to address the challenges seen in the demonstration. The members of this demonstration evaluation team generally felt UAS usage had the potential to address the NPRA's needs. This suggests that NPRA should continue to track and explore both UAS technology and sensor usage.

Photogrammetry (SfM) surveys on small UASs should be further explored. SfM output can map snow surface conditions and measure snow depth both of which are valuable for avalanche hazard assessment. SfM is low cost, especially when compared to LIDAR, and can potentially be used on imagery captured by small UASs already owned and operated by the NPRA. SfM, paired with commercially available software, can be used with common digital cameras. This approach has considerable potential for NPRA - assuming staff can be trained in the use of the SfM software.

The NPRA could evaluate the usability of SfM by measuring known avalanche start zones before any snow has fallen and again during times of high avalanche danger. Comparing the two situations could provide an indication of snow depth - as has been completed by other research efforts (8, 10, 11, 15). Simultaneously, the ability of SfM to display snow surface conditions could also be evaluated for usability by NPRA's avalanche staff. As an additional benefit, SfM could also be used to monitor unstable rock slopes and land slide areas.

The NPRA should track the regulatory issues may impact the usability of UASs. Past Norwegian aviation rules have made it more difficult to fly to observe terrain features that are out of sight over the tops of mountain and ridges or down valleys due the requirement to fly in Visual Line of Sight (VLOS). Regulations in Norway have opened up for beyond line of sight (BVLOS) operations as long as the operator is professional, using a required organizational setup with routines and procedures, much like an airline company. Professional operators (such as ASC) may operate BVLOS below 400 feet above ground level, where most of the operations for the NPRA would be conducted, with a 12 hour notice for the publishing of a NOTAM (Notice to Airmen). This is a reasonable approach if the NPRA identifies known areas that need to be routinely monitored or areas such as Trollstigen that require seasonal operations to open after winter closures. If the situation requires, a segregated airspace can be opened within 30 minutes through the Police and Avinor (who operates civil airports in Norway).

These finding highlight one potential capability of UAS that is underutilized – these aircraft can fly autonomously. In theory no or minimal human input is required. This suggests that these aircraft could fly missions without observers involved and could be used in inaccessible areas and in poor visibility. This is possible in low populated areas, with a NOTAM sent out 12 hours in advance.

If the NPRA continues to use UAS, additional research will be needed to clearly lay out in what situations (emergency or routine flights), by what operator (NPRA or a professional operator) can fly under what rules (VLOS or, BLOS).

The NPRA may want to formalize or further explore the uses of smaller UAS operated by NPRA staff. NPRA staff already operates a number of small UASs. It could be valuable for the NPRA to offer training related to operations, flight regulations, and safety of these aircraft and open up the use of these small UASs to more employees. For the NPRA's UASs, there would be applications beyond just winter snow surveillance including geological surveys, mapping and potentially emergency usage such as mapping the extent of floods or debris flows. The possible benefits of a UASs to the NPRA, beyond just snow avalanche monitoring, could be large.

If there was enough of these systems owned and operated by the NPRA and spread throughout the NPRA regions, this type of aircraft could be available on short notice if needed for urgent projects or emergencies.

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APPENDIX 1: ROMVESEN TECHNICAL REPORT

Blaalid
10/5-2018

DEMONSTRATION OF AIRBORN GPR-SYSTEM FOR STATENS VEGVESEN

Demonstration goals and requirements

The demonstration took place on April 17th and 18th 2018 at Andenes, Norway. The demonstration is held as a joint operation by Geoscanners AB providing the GPR system and Romvesen AS providing the drone-system. The demonstration was aimed at avalanche researchers (both academics and working for Statens Vegvesen, NTNU and University of Washington) and Search & Rescue application of the system. For the avalanche assessment it would be needed to get the drone equipped with the SPG-1700 to fly over an area and collect the information about the layers in the snow. For the Search and rescue teams, proving that finding a person or a car covered with snow is possible with the drone equipped with the SPG-1700.

Demo site conditions

Two test sites were visited and the conditions were not ideal due to the fact that this late in the winter the amount of snow is low and that the snow that still exists tends to be melting rapidly. Water propagates through different layers making the snow layers harder to distinguish.
First site allowed for the metal plate, person under the snow (Figure1.) and snow layering data over a stretch of ~60meters to be collected (Figure 2). Some on site demonstration of the live data and quickly processed data was shown on the spot. Data was shown in a bit more detail in the afternoon debrief meeting. Test pits were dug over the snow layer collection path to see if the data can be matched.

Figure 1. Metal plate and the person under the snowpack

Figure 2. 60 meters path to check for snow layers

The second site on the second day included a vehicle under the snow (Figure 3.) and a new ~45m path to collect the data over layered snowpack (Figure 4). Test pits were dug over the snow layer collection path to see if the data can be matched. Since it was conveniently parked nearby, a data collection over a car on the road (Figure 5.) was collected as well.

Figure 3. Car under the snow

Figure 4. Snow layer mapping

Figure 5. Car parked on the road (not under the snow)

Collected data results

First site

Data collected over a metal plate and a person under the snow yielded data readable in the field. Processed data can be seen in Figure 6.

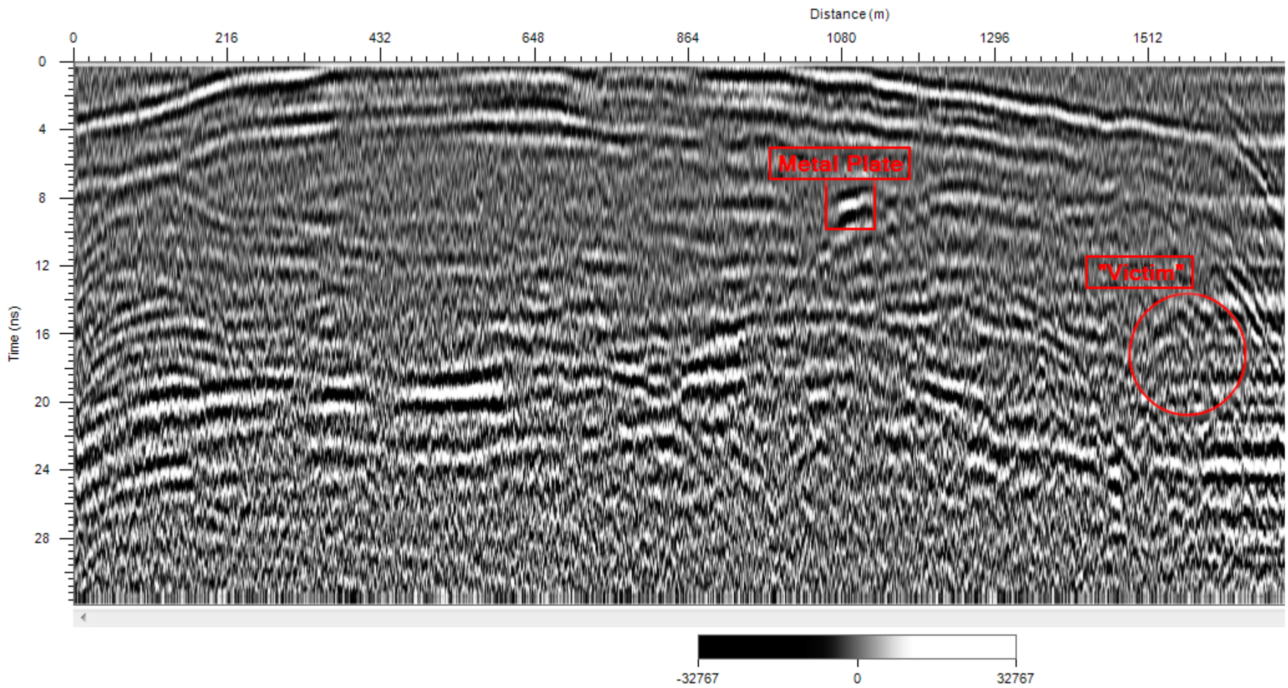


Figure 6. Metal plate and a person under the snow marked in the data

Data collected over the snow layer did show promissing during the collection, but in order to get the most of the data, post-processing and then evaluating the data (layer mapping) is the reasonable way to deal with the results. Example of the visual output of the data can be seen in Figure 7. More detailed information (including the numerical value output) is available inside folder «Test data».

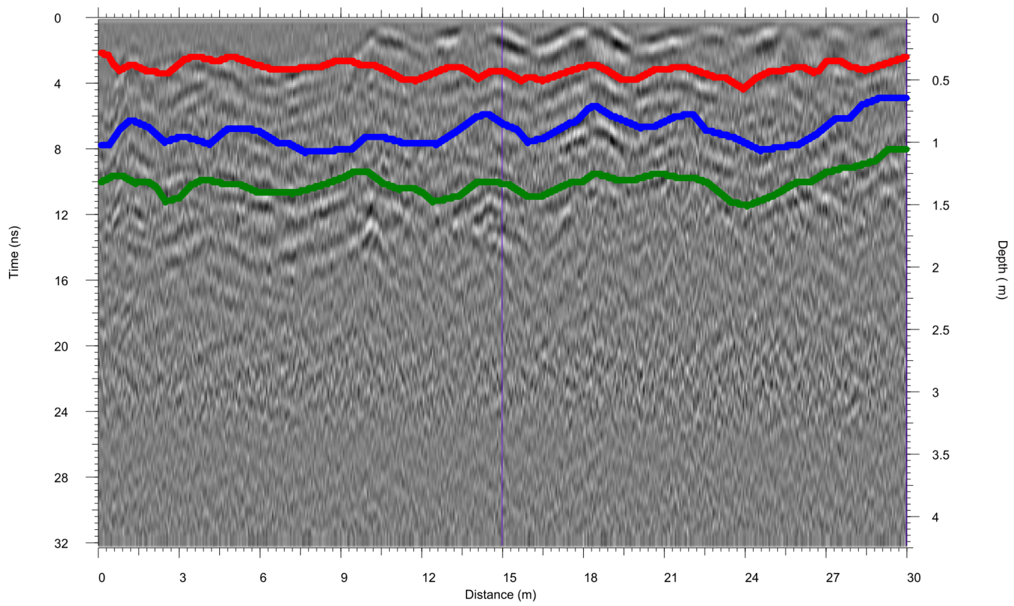


Figure 7. Layer mapping on the first site

Second site

Results from car under the snow were visible and clear even during the collection and can be compared to the reflection of the car parked on the road as seen in Figure 8. The results can be seen in more detail inside folder «Test data»

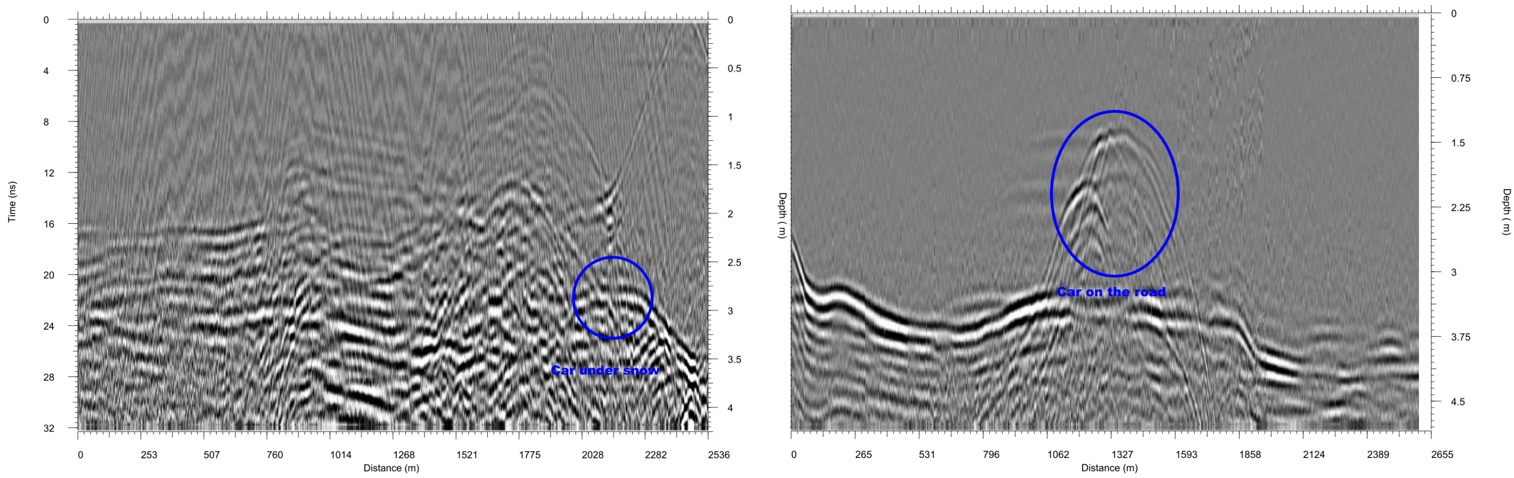


Figure 8.Car under the snow (left) and car parked on the road (right) data reflection patterns

Results from the layer mapping on the second site are slightly better than the one from the first site. Nevertheless, the process of dealing with the data collected for this purpose is the same like on the first site and some post-processing and layer marking (interpretation) is suggested after collecting the data in order to get most out of the collected data. Example of the visual output of the data can be seen in Figure 9. and more detailed information (including the numerical value output) is available inside folder «Test data».

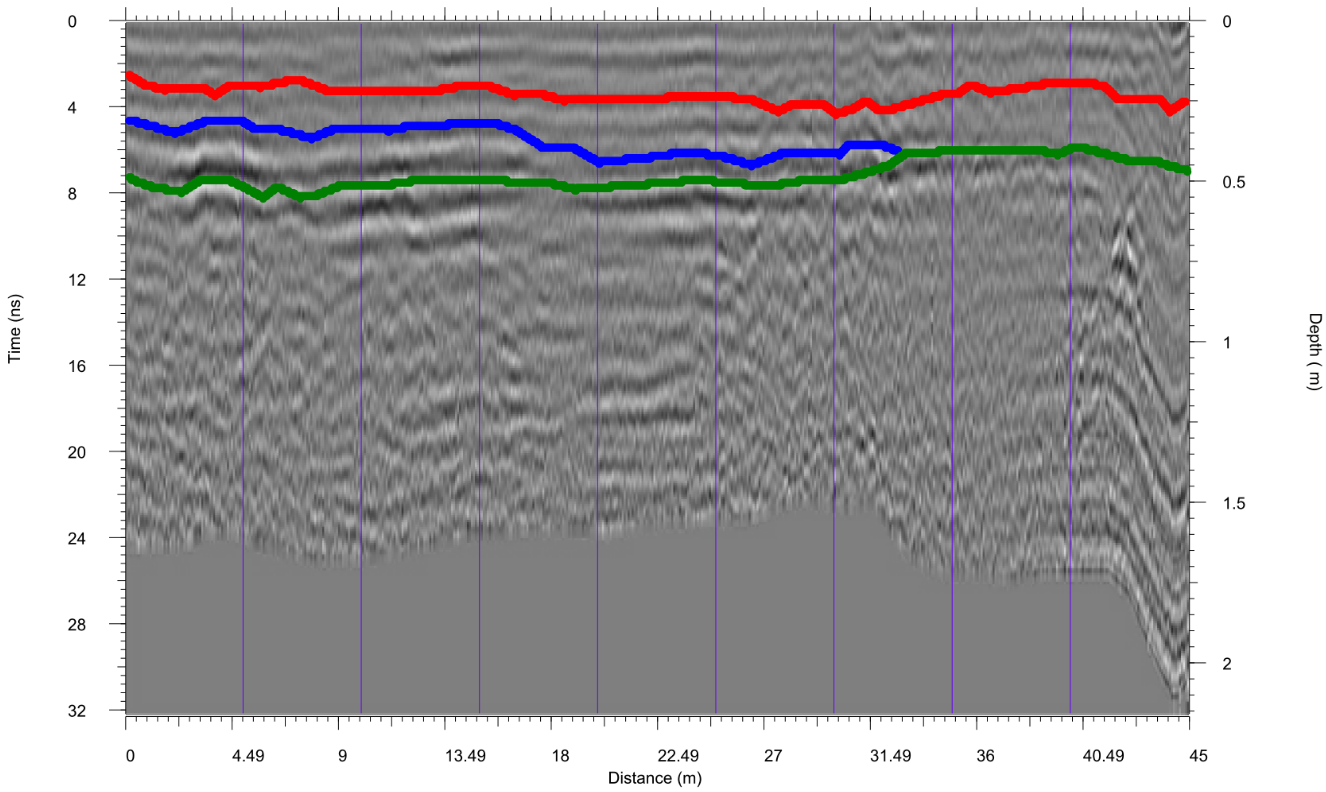


Figure 9. Layer mapping result example of the second site

Layer mapping data correlation

The data provided from the test pits dug (Figure 10.) over the path is the final assessment that needs to be done. The test pits on both sites are related to the distance in meters from the starting point of the collection. One should keep in mind that the GPS used during the demonstration was not a precise RTK solution, so a conversion between time mode and distance mode was done presuming the speed of flying was constant. This could lead to some discrepance between the results, but for this dataset is the closest we can get.

Figure 10. Example of the data test pits dug on the layer mapping tests

The data observed from the test pits is very detailed and shows a larger number of layer contacts than what we could pick from the collected GPR data. It is likely necessary to use a higher frequency antenna to get the required resolution to see the thinner reflections, but on the other hand that would imply lesser penetration. An overall conclusion is that the selected antenna would need to balanced and follow the predominant requirement of the survey: either have the high resolution with lack of penetration or opt to have a deeper penetration with a capability to interpret the thicker and more prominent layers. The comparison between the results is therefore focusing on finding a match between the GPR mapped layers and a layer in the test pit data. In a scenario where these thicker and more different layers are the critical ones for generating the avalanche trigger/slide there is no reason not to proceed with the data collected in this way. The detailed reports for the test pits (Figure 11.) can be seen inside folder «Test data»

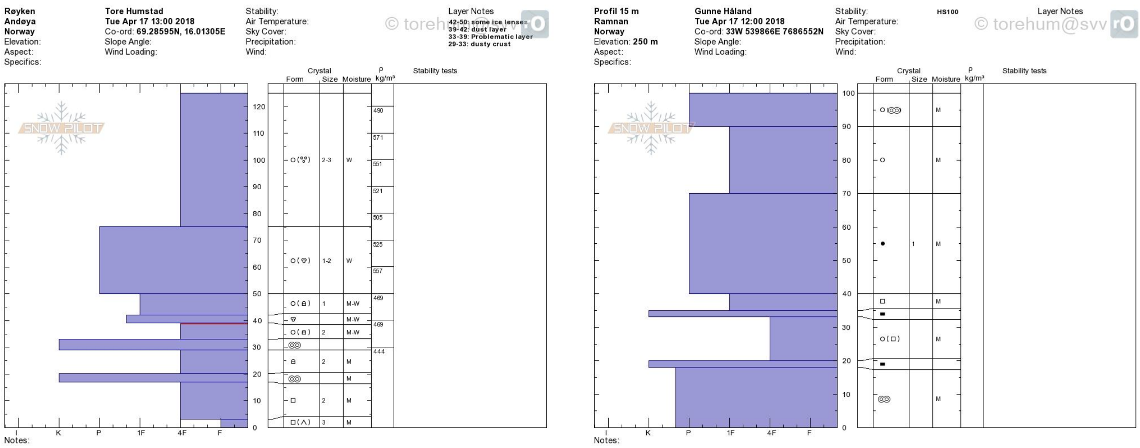


Figure 11. Example of the test pit data

Comparison of the numerical values obtained from the mapped layers is shown in Table 1 for the first site and in Table 2. for the second site.

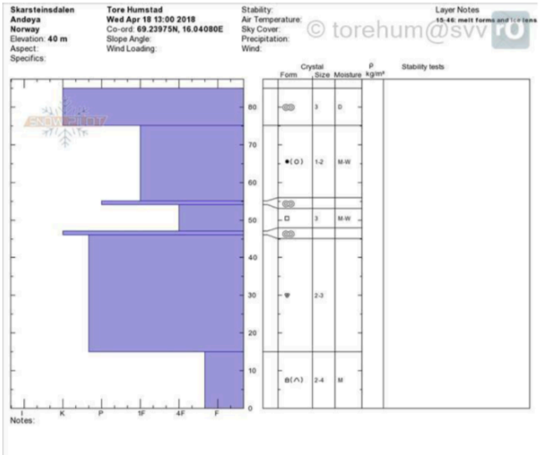
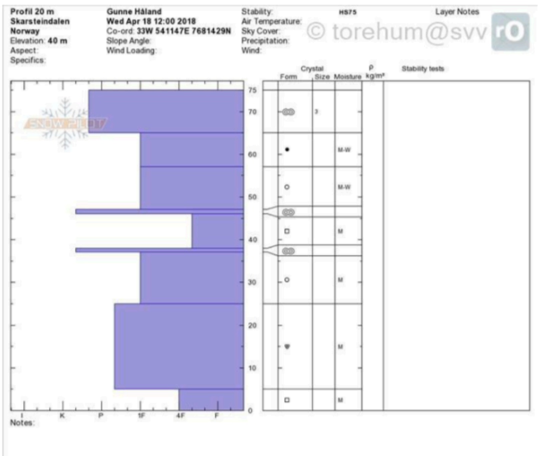
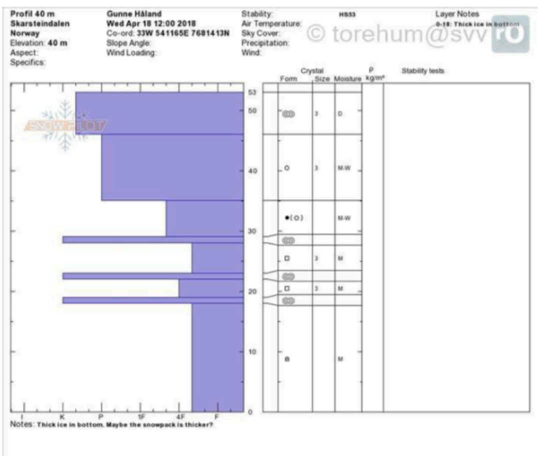
Distance from the start(m)	Test pit result	GPR data result (3 layer contacts; m)	Comment
0m		0.31	Mismatch
		0.59	Potential match; ~0.55m
		0.94	Potential match; ~0.9m
20m		0.46	Matching result
		0.84	Potential match; ~0.75m
		1.0	Potential match; ~0.75m+0.18 Ice at bottom
40m		0.36	Matching result
		N/A	Not visible
		0.76	Potential match; ~0.53m+0.18 Ice at bottom

Table 1. Test result comparison for the first site

Observing first site numerical values obtained from the mapped layers and comparing it to the test pit data is shown in the table below (Table2)

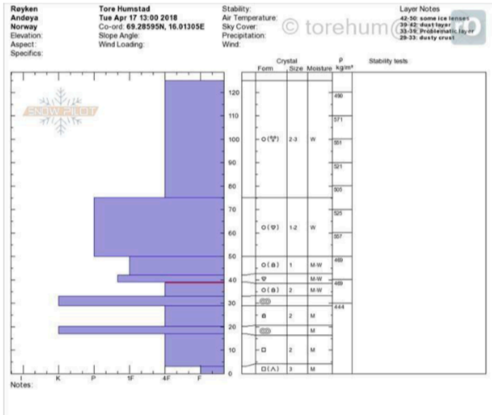
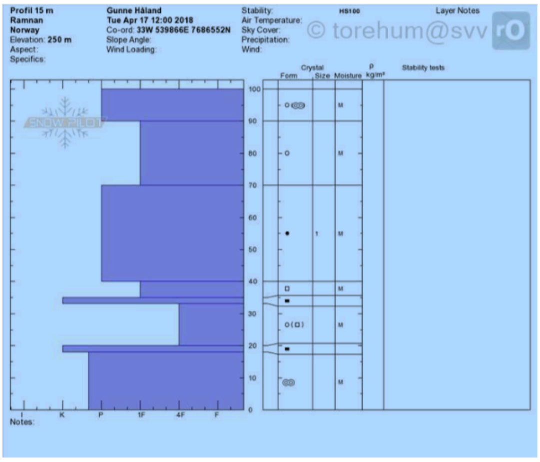
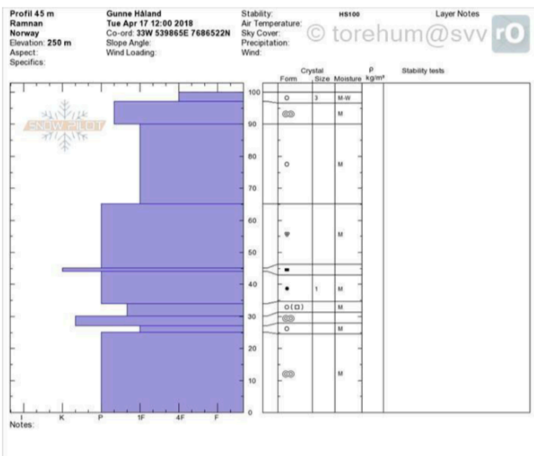
Distance from the start(m)	Test pit result	GPR data result (3 layer contacts; m)	Comment
0		0.264	Potential match; ~0.3m
		1.02	Mismatch; 0.75m
		1.32	Matching result
15		0.424	Potential match; ~0.4m
		0.84	Potential match; ~0.9m
		1.32	Mismatch; 1m
45		0.12	Mismatch
		0.47	Potential match; ~0.45m
		0.94	Potential match; ~1m

Table 2. Test result comparison for the second site

Conclusions

The demonstration has shown the viability of using a GPR system mounted on the drone. The benefits of the system like this would be higher movability, and easier access to dangerous/inaccessible locations.

The comparison of the layer mapping data shows reasonable matching of the results to a particular layer that can be found in the test pit data as well. We believe that matching of the results would be even better if the data collected with the drone and the test pit data would use a common higher precision positioning system that could be provided by the RTK GPS solution. The evaluation of the relevance of the matched results is to be provided by the team of avalanche researchers, so any feedback from them is going to be valuable to us.

For the search and rescue applications the demonstration has shown that it is possible to locate a larger metal target (car) under the snow with ease and it would be possible to use the system as is right now. Smaller targets with less reflectivness of the signal (human body under snow) are visible, but not as ease to interpret without some experience in interpreting the GPR data. Training and using the equipment would naturally lead to an operator with proper skills, but autopiloting the drone, in order to keep the height and speed constant would be the first step in making data much easier to understand. Additional steps can then be made to try and implement automated data inspection algorithms to speed up the process of data interpretation.

With this positive demonstration results achieved further development is suggested in clear set of requirements: getting better GPS positioning, implementing drone auto piloting options, providing different GPR systems with choice of resolution and penetration to fit individual requirements of the survey better. Design of relevant visualization of results for the designated task, 2D/3D.

Numeric values of signal, can together with input and classification of different snow/ice types provide us with set values for different layers. Values that again can be color coded for ease of interpretation of visualized results.

DEMONSTRATION OF AVALANCHE MAPPING USING PHOTOGRAMMETRY

Demonstration goals and requirements

The demonstration took place the 18th 2018 at Andenes, Norway. The demonstration was held by Romvesen AS providing the drone-system and the photogrammetry software. The demonstration was aimed at avalanche researchers (both academics and working for Statens Vegvesen, NTNU and University of Washington) and Search & Rescue application of the system. For the avalanche assessment it would be needed to get the drone equipped with visual sensors to fly over an avalanche and perform a grid mapping of the interesting areas.

Demo site conditions

One test site were visited, it was a few days old avalanche that where located 1,4 km from the start location of the drone. Height above start location where maximum 400 meters. The avalanche had released at the top of the mountain ridge, with a breaking edge of approximately 800 m. Weather and visibility was good, so it was ideal conditions for mapping with visual sensors.

Figure 1. Avalanche location

Used equipment and procedure

For this test we used a DJI Inspire 2 drone with a Zenmuse X7 camera and a 16mm lens (in full-frame equivalent, 24mm) The images was collected by manually flying a grid over the breaking ridge at a speed of 3-5 m/s, shutter 1/1000. Flight height above ground varied between 30-120 meters. Compensating the steep angle of the hill with extra images taken horizontally against the mountain side to get good coverage of the breaking ridge. No ground control points (GCP) where used, only regular onboard GPS for geotagging (+/- 0,5m vertical and +/- 1,5m horizontal).

Collected data results

Collected images where uploaded to Pix4D Cloud, and processed in cloud software. Processing time took about 1 hour and 10 minutes, results data where immediately available in cloud viewer for measurements and inspection. See «Quality report» in results folder or view online in provided link. Average ground sampling distance (GSD) was 3,33 cm, and covered area was according to report 19,3421 ha. The quality of flown grid was confirmed by the quality report, see figure 2.

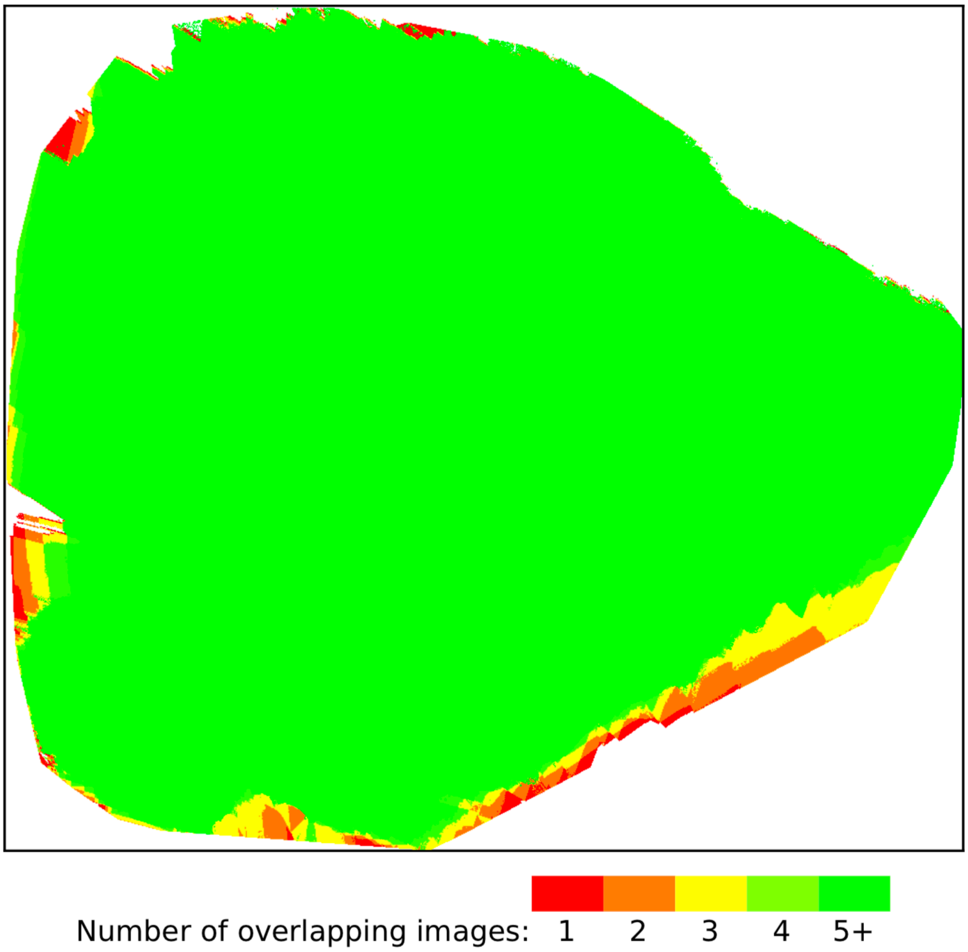


Figure 2. Number of overlapping images computed for each pixel of the orthomosaic

If we take a closer look in the quality report, we see that the grid is not perfect and there are large areas with fewer matching points between flight corridors. This does not mean that the model is bad, it would rather suggest that these areas are the areas with lower accuracy. When we did the test, we focused on the parts of the avalanche that the geologists wanted to look at. This was the top of the breaking point, the part were the breaking ridge went nearly straight vertical and turned into a nearly horizontal line heading towards north-east. These three areas where corridor mapped, with extra images horizontally. As you see in figure 3, these three corridors have very dense matching points.

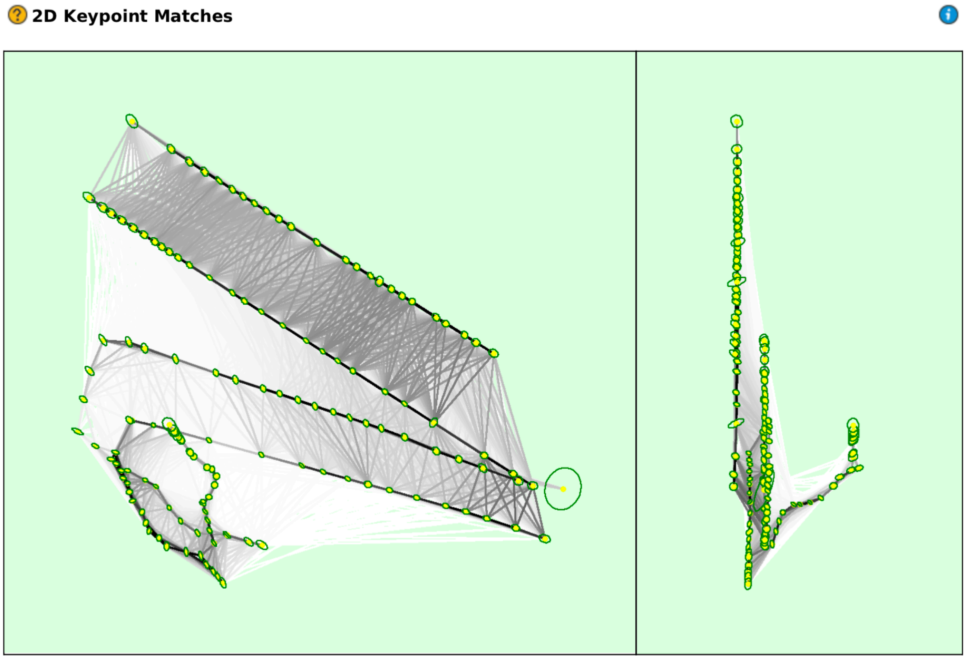


Figure 3. 2D Keypoint Matches

Generally, one can expect an error of 2-3 times GSD in vertical and 1-2 GSD in horizontal. We have a GSD of 3,33cm, this gives us an average accuracy of 6,66 to 9,99 cm in height and 3,33 to 6,66 cm in horizontal. Meaning an average accuracy between 1 to 3 pixel of dataset. This depends on camera, drone, overlap, flightpath, texture, edges, reflections, etc..

We measured the height of the breaking line in the generated point cloud, and found varying heights on different locations. Our measurements did also relate to the predictions from the geologists. The output results can be found inside the «Test data» folder, or by using the link to online cloud viewing.

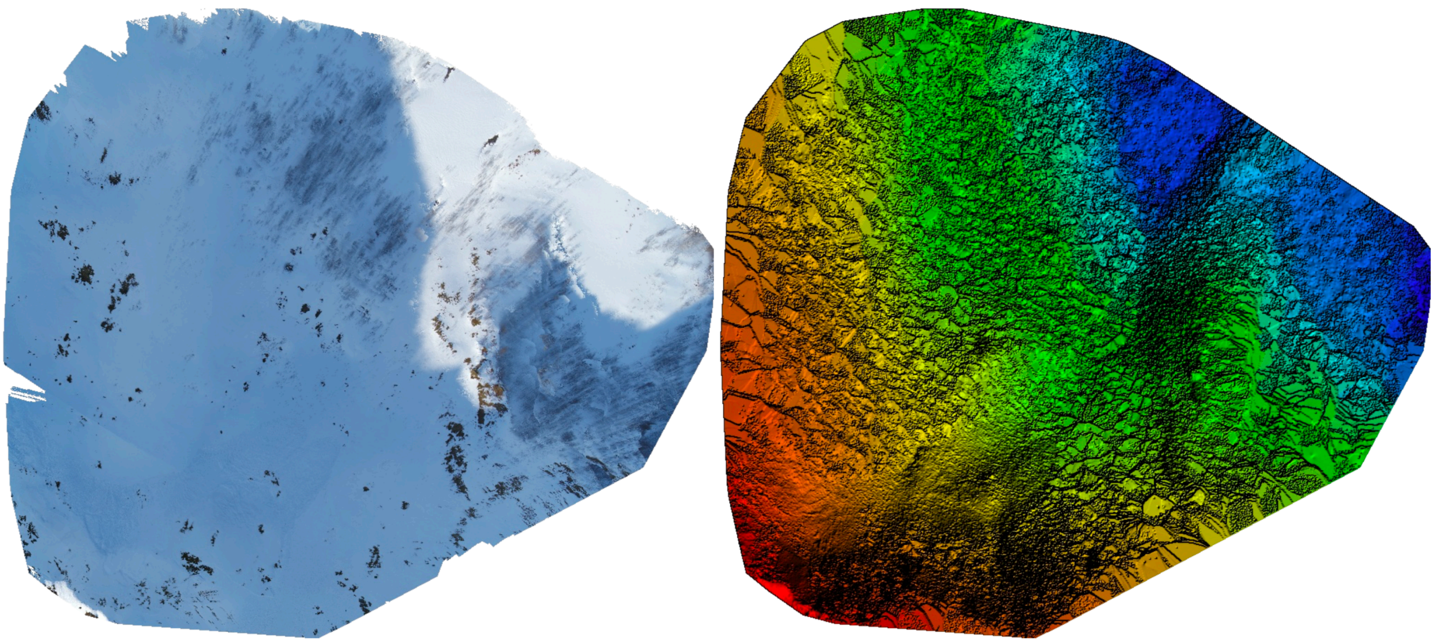


Figure 4. Orthomosaic and corresponding sparse Digital Surface Model before densification

Conclusions

The demonstration has shown that photogrammetry together with live video, will be a very good tool for assessing avalanches. The generated models wont be absolute georeferenced without the use of GCPs or RTK GPS, but for the proposed use it doesn't seem to play a big role. If used with RTK GPS, the results would be a little better and with «absolute» georeference. If we compare to airborne LiDARsolutions; that at best have an accuracy of 3-5 cm (costs 2,15 million NOK), while take into account that the accuracy of the GNSS reference points, used for base stations, lies as well «only» within 3 to 5cm. Photogrammetry can actually be a more precise solution, depending on flight height and camera (sensor/lens).

Cheap solutions like the DJI Phantom 4 Pro drone combined with Pix4Dmapper photogrammetry software, would be the preferred tool for the given task at the moment. RTK GPS are as I know moving fast downwards into the semi-pro drone segment, and could be a reasonably cheap system already next year.

The photogrammetry software can also be used to measure areas, both 2D and 3D, and for volume calculations. Cloud service is also good for deployment in field and no access to computer, images can be uploaded to cloud directly from Pix4D-app, processed in cloud and ready for use within hours (depending on number of images and size).

Regarding delivery of solutions and equipment

Romvesen AS delivers a lot of different drone systems/sensors, and are delivering complete drone solutions for large companies both National and International. We can assist with the development of operation manuals and training of personell. For more information see our webpage; www.romvesen.as or contact us directly.

Future testing and development

We hope this demonstration will let us start an research and development project together with Statens Vegvesen, where we can use their expertise knowledge about avalanches for further development and testing of our current GPR antennas and coming prototypes. We see it as a natural collaboration and a necessity to get first hand information from future end users and first responders.

Ove Kristian Leirgulen
CEO

APPENDIX 2: NORTHERN RESEARCH INSTITUTE (NORUT) TECHNICAL REPORT

REPORT

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UAV-BORNE UWB RADAR FOR SNOWPACK SURVEYS

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TITEL: UAV-BORNE UWB RADAR FOR SNOWPACK SURVEYS

Summary:

In this report we summarize the capabilities and technical characteristics of our UAV-borne UWB radar system, designed for conducting snow surveys. We developed an ultrawideband snow sounder that is capable of imaging snow stratigraphy with a 5 cm range resolution. The radar can be carried by an octocopter UAV in order to carry out airborne snowpack surveys.

During a demonstration on Andøya, we showed that the radar was capable of resolving snow stratigraphy in wet snow conditions, as well as detecting a buried person under 1.5 m of wet snow. In this report, we present the results of the demonstration in detail. We furthermore discuss capabilities and incapabilities of our radar system and offer a list of future steps to bring it to an operational status.

Keywords: UWB-radar, snow survey, UAV

Notes: -

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1. Introduction

Ground penetrating radars (GPR's) have a wide range of applications, spanning from subsurface surveys to high-resolution object detection. Especially ultra-wideband (UWB) systems that operate in the GHz-band have penetration capabilities and range resolutions that are able to extract information from complex stratigraphical targets.

However, GPR's are conventionally deployed on the ground, by dragging an antenna with direct ground contact. Mounting the GPR and its antenna onto a snowmobile or carrying it by person works well for surveys of an undisturbed, flat snowpack. However, in more complex terrain or over rough avalanche debris, an airborne GPR is of significant advantage.

We have therefore developed an UAV mountable GPR (Figure 1). During the development process we were solving the problems of 1) constructing a light, compact and portable device, with 2) high range resolution and the ability to penetrate the snowpack from an airborne platform, as well as 3) an autonomous flying UAV with high payload capabilities and engine redundancy.

2. UAV-borne radar system

Figure 1: UAV-borne radar system. The UWiBaSS is the grey box mounted beneath the UAV, with the transmitting antenna (grey plate) and both receiving antennas (black sheets) visible.

2.1.1 Radar

The ultra-wideband snow sounder (UWiBaSS) is a ground penetrating radar (GPR) that we developed for UAV-mounted surveys of a layered snowpack over ground or sea ice (Figure 1). The focus of the radar development was therefore on constructing a light, portable device with cm range resolution, to detect prominent snow layers.

The radar consists of an m:sequence UWB radar sensor developed by the German company Ilmsens (https://www.uwb-shop.com/), custom designed spiral and Vivaldi antennas, and a single board acquisition computer with processing software. Besides weight, size and range resolution, unambiguous range and incident power at target were central design parameters. Unambiguous range describes the range from which a transmitted radar pulse can be reflected and received before the next pulse is transmitted. This property dictates how fast the UAV can fly above the snow surface, in our case at a maximum speed of 2-3 m/s. Incident power at target depends on antenna gain, height above target (snow surface) and radar amplifier parameters. These properties dictate how high the UAV can fly above the snow surface, in our case currently maximum 5.75 m. These described radar properties are summed up in Table 1, describing the UWiBaSS key characteristics.

Table 1: Characteristics of the UWiBaSS.

Characteristic	***Value***
System bandwidth	5.05 GHz (0.95 - 6 GHz)
Range resolution	~5 cm
Unambiguous range in air	5.75 m
Weight	~4 kg
Field of view (from 1 m above surface)	0.35 m diameter
M-sequence clock frequency	13.312 GHz
Measurement rate	32 Hz (max 1000 Hz)
Total power consumption	~9 W

The radar has a total of three antennas, of which a planar spiral antenna is the transmitting antenna and two Vivaldi antennas, mounted in 90 degrees offset to each other are the receiving antennas (Figure 1). This experimental setup is used to detect potential phase differences between the targets radar cross section. These phase differences might become a problem with increased flight elevation above snow and thus an increased footprint of the radar signal. Larger antennas would solve such problems, however, are due to their size and weight not desirable.

2.1.2 UAV

The UAV currently in use to carry the UWiBaSS is an octocopter. The 'Kraken' Octocopter has a maximum takeoff weight of 20 kg. With an empty weight of 8.5 kg, batteries and payload of 11.5 kg can be lifted. Each of the 8 engines has a maximum rated thrust of 8.45 kg using 18 x 6.1-inch propellers. Kraken uses 6 cell Li-Pol batteries (currently at 30 Ahr). For navigation and control, a 'pixhawk2' autopilot running 'arducopter' is used. A lidar, mounted on one of the 8 arms accurately measures the distance to the ground. It is set up with a 'Here+' GPS system allowing for the use of RTK and very accurate positioning. 'Kraken' can be set up with a 'MBR 144' radio system to operate a 15 mbps radio link.

3. Methods

3.1 Campaign setup & deployment

Our radar system can be either flown manually or autonomously. In the latter case, the UAV automatically follows a pre-defined track, with set speed and height above ground. Currently, the system only allows for VLOS campaigns as the UAV has no camera mounted and lacks obstacle detection sensors in the front.

The UWiBaSS can be fully operated with three switches (board computer on/off; radar on/off/logging) that are mounted on its outside. Survey data is downloaded after the mission with a WLAN cable and processed for a first quick look.

From arriving at a campaign site to deployment, it takes approximately 15-20 min. Preparation work includes mounting propellers and battery on the UAV, antennas on the UWiBaSS and setup of the ground control station as well as radio communication with the airport tower.

3.2 Postprocessing of radar data

An inherent property of antennas is that the incident field reflected from a target will be integrated at the receiving end of the antenna. Hence, the field of view of the antennas will be averaged when the transmitted signal returns to the receiving antennas. This means that a single measurement illuminates a 3D volume of snow, approximately 0.35 m wide and as deep as the snowpack, when the radar is 1 m above the snow surface, but only returns a 1D average of the returned energy.

The radar data is first correlated with the transmitted signal to produce the impulse response of the medium within the radar range. Additionally, some processing to compensate for non-linear antenna effects is performed. The radar traces are then stacked together to form a 2D image of the snowpack. Each pixel intensity is represented in terms of voltage returned to the antennas. By squaring each pixel, we now represent the pixels in terms of power. This can help to analyze the data as some noise is removed from the image. A histogram equalization and thresholding procedure is also added to distribute the pixel intensities evenly while suppressing low level pixels to reduce noise.

4. Results

We collected radar data from two campaigns. The first was a roughly 50 m transect in wet snow along a road (Figure 2). The second deployment was a slow overflight over a buried person and a metalplate at different depths (Figure 4). The goal of these two different campaigns was to assess the UWiBaSS' capabilities of resolving snow stratigraphy and detecting a person and an object. Both challenges have real-world applications and are thus of critical interest.

4.1 50 m transect

Figure 2: Setup of the 50 m transect with snowpit locations indicated every 15 m. Photo by Tore Humstad.

We found challenging snow conditions in the transect, which required some postprocessing of the radar data. The snowpack consisted of wet snow in the upper 70 cm with an estimated liquid water content of 3-8 %, whereas the lower 50 cm had a liquid water content of 0-3 %. Pronounced layering was mostly missing the upper half of the snowpack, whereas two prominent melt-freeze crusts were found towards the bottom of the snowpack (Figure 2). Densities ranged between 444 and 571 kg/m^3, likely a function of the liquid water content and the large grain sizes.

The radar image shows a clear first reflection that indicates the wet snow surface, roughly 40-50 cm below the UWiBaSS (Figure 2). A significantly weaker reflection from the ground surface is visible at a depth of 160 cm, which corresponds to a snow depth of 120 cm taking into account the permittivity of wet snow. Four clear reflections within the snowpack indicate the transition from a soft layer to a hard layer to a softer layer at roughly 75 and 50 cm in the in-situ stratigraphy, as well as the two prominent ice layers.

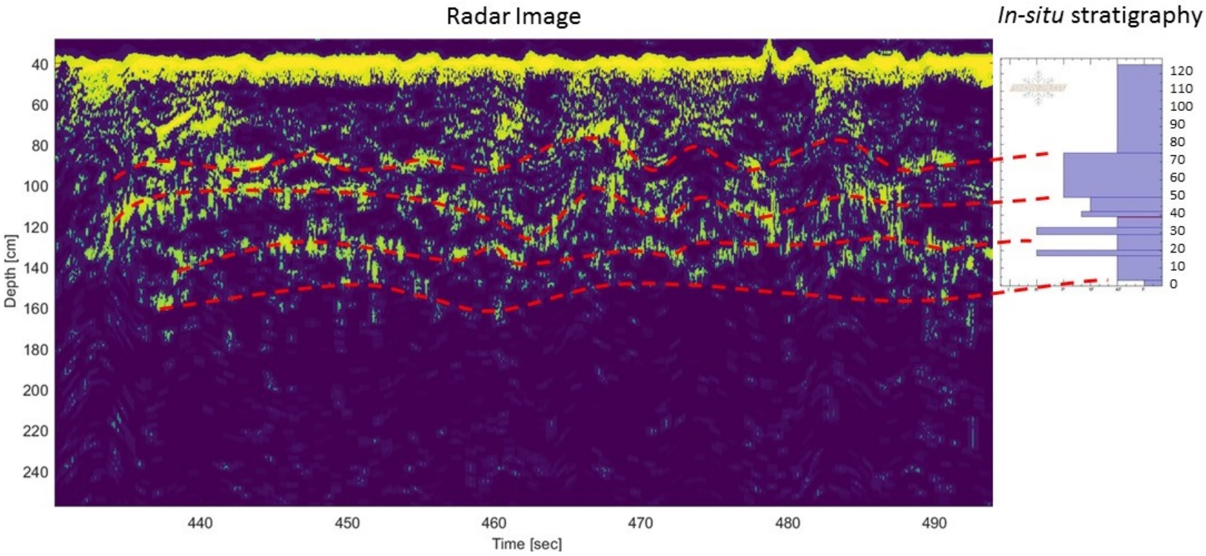

Figure 3: Left panel: Radar image showing intensity variations in backscattered energy (yellow means more energy) through snow depth (y-axis) and time (=distance on the x-axis). Right panel: In-situ stratigraphy from a snowpit dug in the transect. Blue columns show hand hardness of the different snow layers (horizontally elongated column indicates hard snow). The red dashed lines indicate our interpretation of the radar image.

4.2 Buried person & metal plate

In similar snow conditions to the 50 m transect, into the side of a snowbank, a metal plate and a person were buried. We flew the UWiBaSS four times over both targets, with the best result shown in Figure 5. Below the clearly visible snow surface, two hyperbolic reflections are visible, indicating the metal plate and the person buried in the snow.

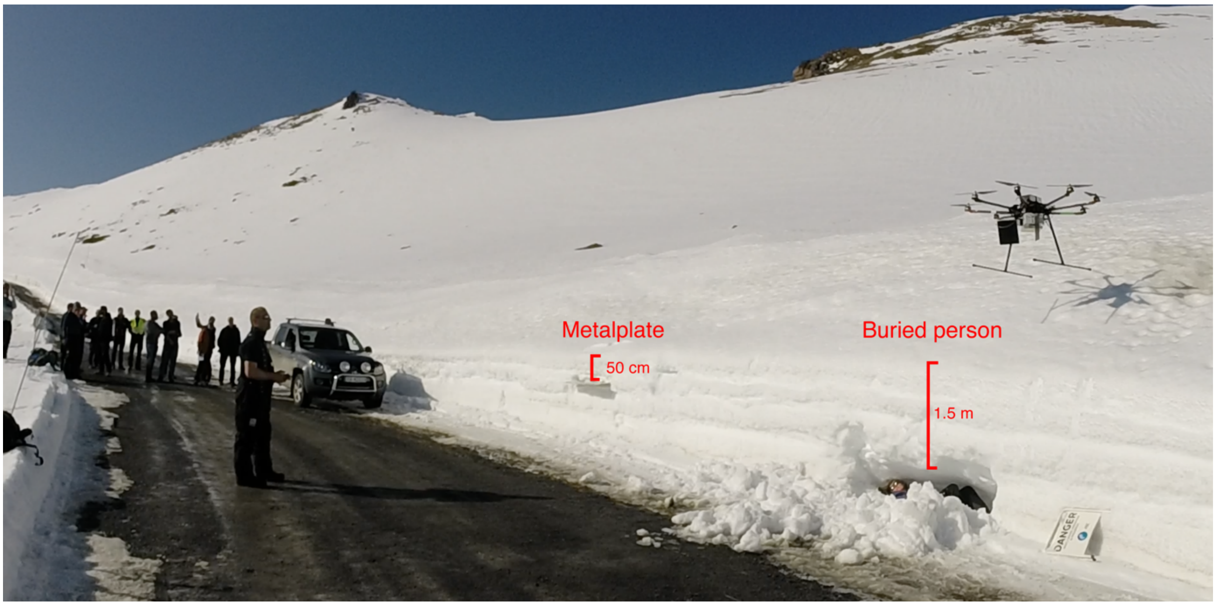

Figure 4: Setup of the object burial test with a metalplate and a buried person 50 cm and 1.5 m below the snow surface.

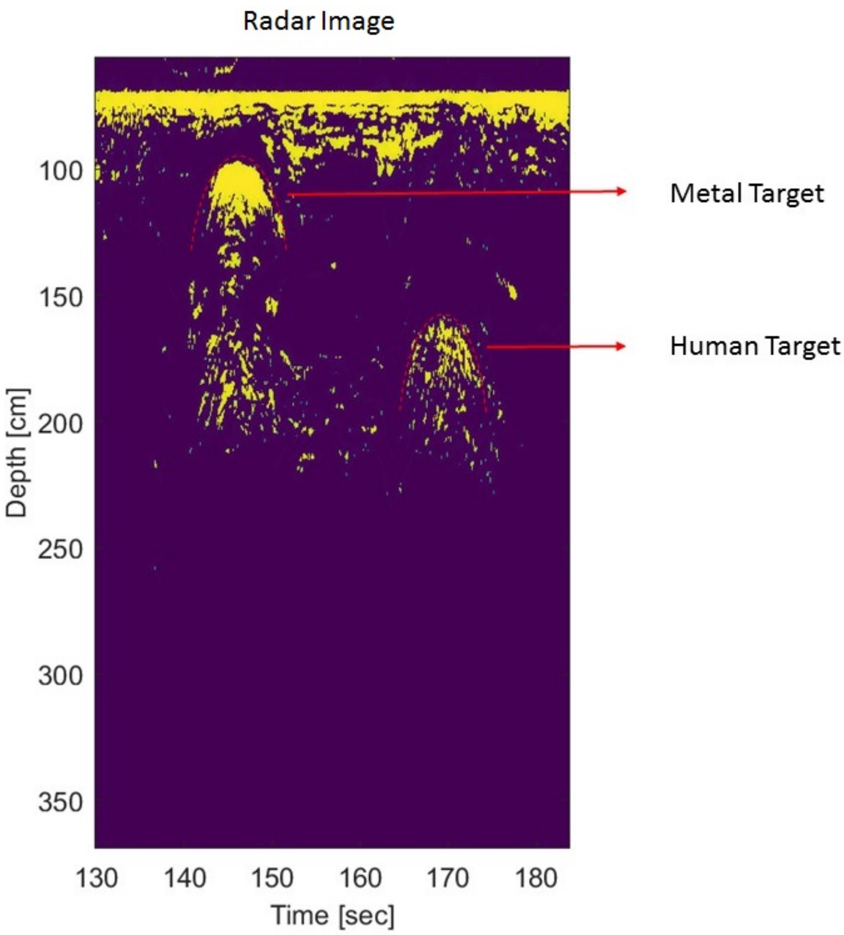

Figure 5: Radar image showing variations in backscattered energy (yellow means more energy) through snow depth (y-axis) and time (=distance on the x-axis). The red dashed lines indicate the target hyperbolas typical for strong point reflectors.

5. Discussion

Both hardware and software of the UWiBaSS and the UAV worked perfectly during the campaigns. Our pilot Ándre Kjellstrup safely maneuvered the system within cm over the snow surface in manual mode, ensuring optimal radar penetration and range resolution. However, the first results from post-processing of the radar data in the field yielded no results, which we assigned to the incapability of the radar waves in the 0.95 - 6 GHz band to penetrate wet snow. After further post-processing of the data, we achieved the results presented above.

5.1 Capabilities and incapabilities of the UWiBaSS

The UWiBaSS is optimized to resolve detailed snow stratigraphy as well as to detect objects, like cars and persons in dry snow. The focus on dry snow stratigraphy comes from the vision to deploy the system in avalanche starting zones, determining the depth and spatial distribution of weak snow layers that can collapse under stress from overloading and release a dry slab avalanche. In order to achieve this ambition high vertical resolution has been traded against high penetration depth in wet snow which can be obtained using lower radar frequencies.

Weak snow layers are in the order of 1 cm thick; thus their detection is very difficult. Nevertheless, we have shown in the results above, that distinct layer differences are detectable. Weak snow layers are in almost all cases always found adjacent to harder layers or right above or below ice layers. Thus, detecting distinct hardness changes or ice layers can be used to infer the presence of a weak snow layer.

The UWiBaSS as demonstrated above is also capable of penetrating wet snow, with liquid water content of up to 8 %. Some post-processing techniques are currently required to enhance the information content not readily visible. Moreover, as a buried person was also clearly detectable, the range of snow conditions in which the UWiBaSS can be deployed is large, making it a system that can be applied throughout the entire winter. A limiting factor for the detection of the buried person was, that in four overflights, only one time the person was visible in the radar data. Likely, in that successful case we flew the UAV very slowly at a very low height above the snow surface. With a field of view of approximately 0.35 m in diameter when flying 1 m over the snow surface, a very tight grid needs to be flown in order to cover an avalanche debris with a missing person or car.

5.2 Capabilities and incapabilities of the UAV

The 'Kraken' octocopter has been designed to test the UwiBaSS under controlled circumstances. It has not been optimized for operational use with regard to flight time or particular operational scenarios where real-time sensor navigation, data processing and visualization is needed. However, we have developed tools for operational use of UAV's (nlive and cryocore) that are currently used for other applications such as iceberg tracking. 'Kraken' could be set up with these operational tools in order to handle more complex missions.

5.3 Next steps

We are currently working on a second radar with a larger ambiguous range in the air of 42 m. This will allow to raise the field of view from about 0.35 m to 7.14 m in diameter, thereby opening up the grid, however, leaving the range resolution constant at 5 cm. By flying higher and thus safer above the ground, missions further away from the pilot, than demonstrated during the campaigns are feasible, even without further upgrades of the UAV from its current status.

6. Conclusion

We have demonstrated our UAV-mounted ultra-wideband GPR called UWiBaSS during two campaigns on Andøya. The system was designed to resolve snow stratigraphy and detect objects in dry snow. We successfully detected prominent snow layering in wet snow conditions as well as the detection of a metal plate and a person buried at different depths beneath the snow surface. We furthermore demonstrated a deployment of our system within roughly 15-20 min as well as capabilities of flying our UAV with the UWiBaSS manually within 40-50 cm above the snow surface.

For a fully operational system, the next steps are the development of a GPR that can be flown higher above the ground, an UAV with better capabilities of flying autonomously also BVLOS and a real-time processing of the radar data during the mission. Nevertheless, a radar expert would be required to interpret the radar data in real-time in the current configuration. Automatic detection of buried persons or cars could possibly be remedied using an artificial intelligence approach for on-board machine interpretation of the radar signals. Such detections could then be followed by automatically flagging of the objects and geotags targets in the radar data.

In conclusion, we are interested in further developing the radar, in scientific and technical exchange with other developers and in further test campaigns and potential real-world application with The Norwegian Road Administration.

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