GROUND TRUTH VALIDATION OF SATELLITE REMOTE SENSED AVALANCHE DATA IN AUSTRIA

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ABSTRACT: Over the past decade, mapping avalanches in satellite imagery has proven to be a promising and rapid approach to monitor and analyze avalanche activity in specific regions. The Sentinel-1 mission has provided free all-weather synthetic aperture radar data since 2014, which has proven suitable for avalanche mapping in Norway; Greenland and Switzerland. The avalanche detection system from the Norwegian Research Centre NORCE is currently run in operational use by the Norwegian avalanche warning service. In the same way, an automated avalanche detection, monitoring and forecasting tool for Austria based on satellite images could greatly improve, e.g., the assessment of avalanche risk, avalanche danger rating, and hazard mapping. In the framework of the international research project „RSnowAut" ground truth validation of the Norwegian detection algorithm is executed using multiple techniques. This presentation focuses on the outcome of validations using high resolution spatial snow depth data provided by 1) terrestrial laser scanning by Riegl VZ-6000 laser scanner 2) mobile laser scanning by MOLISENS utilizing automotive LiDAR systems and 3) SfM-photogrammetry. All validation methods provide 0.5 m (and higher) resolution point cloud data in cm accuracy of the snow surface after avalanche events. This allows for a precise localization of avalanche release areas, avalanche tracks and avalanche depositions in run out zones. Investigating several avalanche cycles in winters 2023 and 2024 for the Arlberg region reveals advantages and limitations of the detection algorithm. We discuss those e.g. shadowing of slopes by mountainous alpine terrain, difficulties in detecting dry powder snow avalanches and accurate localization of wet snow debris.

KEYWORDS: Avalanche detection, satellite remote sensing, LiDAR, avalanche warning

1. INTRODUCTION

The main objective of this study is to pave the way to an automated monitoring system of avalanches for Austria making use of Copernicus Sentinel-1 SAR imagery. To achieve this goal we test the Norwegian Research Centre NORCE avalanche detection algorithm for the use for Austrian Alpine regions. Within this paper we focus on the validation of the satellite remotely sensed avalanches using spatial snow depth mapping techniques. Current used sensors and methods of detecting avalanches are ground-based avalanche radars, geophones, trigger lines, infrasonic sensors, distributed fiber optic acoustic and seismic sensing, and snow depth measurements (Prokop et al. 2013, 2014, 2024; Schimmel et al. 2017). As only spatial snow depth mapping gives accurate information about the spatial extend of an avalanche it is the most suitable method to validate the avalanche events and their extend localized by the NORCE avalanche detection algorithm.

Since more than 15 years, terrestrial laser scanning has widely been used for high resolution snow depth mapping in centimeter accuracy (Prokop, 2008; 2009; Deems et al., 2013). From the beginning the users of the technique were attracted to investigate the conditions in avalanche starting and avalanche run out zones to cover different properties of snow pack and avalanche dynamics (Prokop et al., 2015; Prokop and Procter, 2017). With the development of very long range laser scanners (e.g., RIEGL VZ-6000) that allow scanning of snow surfaces with a suitable laser wavelength of 1,064 nm along ranges of up to 6 km, the method started to interest also avalanche forecasters (Deems et al., 2015; Hancock et al., 2018) and other snow mapping techniques such as structure from motion (SFM) photogrammetry and snow distribution modeling approaches were validated (Bernard et al., 2017; Schön et al., 2018). Accordingly we use different laser scanning devices to

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measure spatial snow depth distributions and to validate our satellite borne data. Comprehensive reference data of local avalanche releases is indispensable to validate and improve algorithms for avalanche detection in satellite images and to monitor locations with high-risk potential. Also for this work qualitative ground truth measurements of individual slopes for benchmarking the avalanche detection algorithm is essential. For that purpose, we collected ground truth data by using the RIEGL VZ-6000 as a conventional terrestrial laser scanner (TLS), as described above. Additionally, the potential of state-of-the-art automotive LiDARs to substitute the expensive classical TLS is currently being investigated. We used a MOLISENS (MObile LIdar SENsor System), was developed by the Virtual Vehicle Research GmbH and the University of Graz (Gölles et al. 2022).

2. MEASUREMENT SET-UP

Copernicus Sentinel-1 SAR imagery has currently a temporal resolution of 12 days. So information regarding occurring avalanches can only been made every 12 days. This is certainly not enough for daily avalanche forecasting, therefore we focus in our ground validation routine in particular on specific avalanche cycles and investigate the quality of the spatial coverage of the detection algorithm. Avalanches were firstly detected visually and photographs were taken. In case a LiDAR sensor was on site and available we scanned specific avalanches. Using state of the art LiDARs we followed the methodology described in Prokop 2008 and Prokop and Panholzer 2009. To increase the spatial coverage of the LiDAR measurements we also used automotive LiDARs. The mobile data logger called MOLISENS (MObile LIdar SENsor System) was used to collect Global Navigation Satellite System (GNSS), inertial measurement unit (IMU), and automotive lidar data as described in Goelles et al. (2022). Currently, MOLISENS is extended with additional connectivity options to also encompass data from automotive radar sensors and Lufft weather stations. The latter are able to measure temperature, air pressure, humidity, wind, and precipitation. The system enables the use of the mentioned sensors in remote areas as it is relatively small, lightweight, and battery powered. Successful measurement campaigns were completed, e.g., in a glacier cave in Svalbard and in a stalactite cave in Austria (Goelles et al., 2022). In the future, MOLISENS_ext should allow us to detect and quantify avalanches within a radius of about 400 m, with a spatial resolution of a few cm, and a temporal resolution of 10–20 Hz. We plan to install this setup on individual slopes in order to monitor snow height and the spatial extend of avalanches. For that purpose, lidar, radar and weather data will be collected before, during, and after avalanche blastings. The collected data are then used for benchmarking and validating the automated avalanche detection based on satellite data and ML algorithms for selected slopes. TLSs like the RIEGL VZ-6000, which have been used for ground truth acquisition in the past, have various advantages compared to automotive lidar sensors, e.g., higher accuracy, precision, and a higher number of targets per pulse. The RIEGL VZ-6000 comes with the clear advantage of a very high spatial resolution as well as a much greater range. On the other hand they are comparably heavy and have a larger form factor compared to the automotive lidars. Furthermore, TLS have a higher power dissipation compared to automotive lidar sensors. The advantages of automotive lidars for ground truth data acquisition is their small size, high temporal resolution and low eye safety class. A significantly lower price of automotive lidar sensors compared to conventional TLS would allow to install them with higher spatial density, e.g., on multiple slopes of a ski resorts.



Figure 1: Data acquisition of ground truth data using A: MOLISENS mobile lidar sensor system and B: Riegl VZ-6000 terrestrial lidar at ski resort Lech am Arlberg, AUSTRIA. An avalanche was scanned with both system to assess the quality of the MOLISENS data.



Figure 2: Large glide snow avalanche scanned using Riegl VZ-6000 terrestrial lidar at ski resort Lech am Arlberg, AUSTRIA

3. RESULTS

3.1 Senteniel-1 SAR imagery

As a case example we focus on the area of the ski resort Lech am Arlberg, AUSTRIA. The coverage of Sentinel-1 SAR imagery and its quality is given by the quantity of orbits (Figure 3). The more orbits covering a certain area the better the quality of the avalanche detection algorithm is expected.

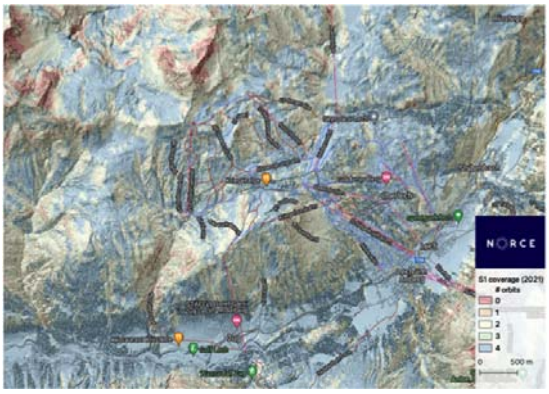


Figure 3: Quantity of orbits covering the test area at ski resort Lech am Arlberg, AUSTRIA.

We now running NORCEs avalanche detection algorithm for an avalanche cycle before March 28th 2023. Several avalanches could be detected for the test area and are displayed in Figure 4.

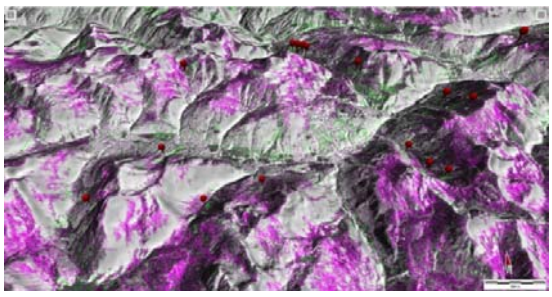


Figure 4: SAR data processed and visualized in 3D over Lech am Arlberg during 28 March 2023. Avalanches detected are indicated by a red needle.

3.2 MOLISENS lidar

The advantage of the mobile automotive LiDAR system MOLISENS is the fast scanning speed and the mobility of the system. We could ski around at Lech am Arlberg ski resort and measure 6 avalanches on one day. The avalanches covered are indicated in Figure 5.



Figure 5: Avalanche paths scanned with MOLISENS during fieldwork In January 2023.

The raw data from MOLISENS is processed with our Python Package called pointcloudset. The package is open source and we made some improvements and bug fixes. The highlight being support for data from ROS2 and a command line tool to investigate if the dataset has suitable data for processing. The in MOLISENS used LiDAR Ouster OS1-64 is a fixed line scanner, which means that distances between scan lines Increase with distance. The data shows that the avalanche deposit can be separated from the surrounding area in the point cloud as it can be seen in Figure 6.

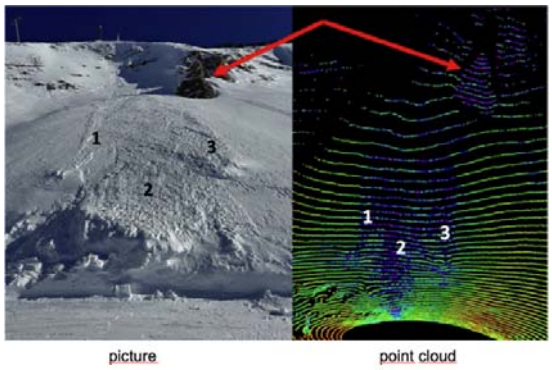


Figure 6: Picture and the corresponding point cloud recorded with MOLISENS and Ouster OS1-64 in Lech in January 2023.

3.3 LiDAR measurements Riegl VZ-6000

Avalanches have been measured using state of the art terrestrial laser scanners extensively (Prokop 2008, 2009, Prokop et al. 2015; Schaffhauser et al. 2008). The accuracy and range achieved is still not reached by any other snow depth mapping technique. In this study we achieved an accuracy of 5 cm, determined by reproducibility tests. We show here an example of an avalanche measured at Lech am Arlberg, AUSTRIA (Figure 8 avalanche 3) that was also covered by the Senteniel-1 data (Figure 7) The accuracy reached by the TLS measurements

provides great validation data for NORCEs avalanche detection algorithm.

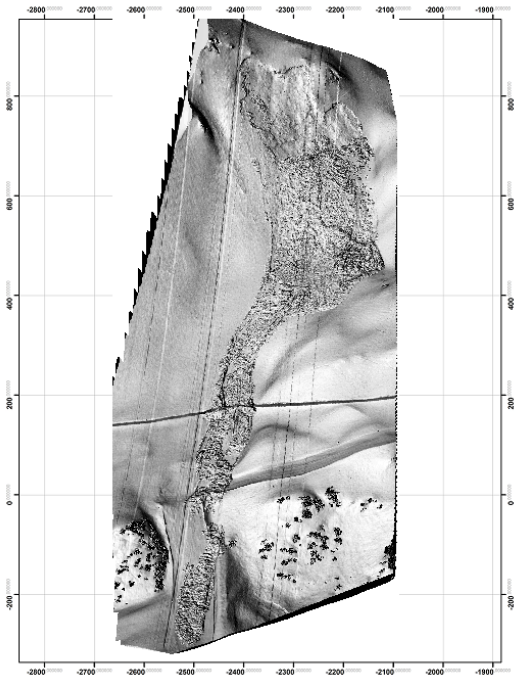


Figure 7: Hillshade of the avalanche measured using Riegl VZ-6000 laser scanner in a range of up to 1500 m in cm accuracy.

3.4 Validation of NORCEs avalanche detection algorithm

With geo-referencing the LiDAR data we looked what avalanches were detected by NORCEs avalanche detection algorithm. In our field campaign in January we measured 6 avalanches using MOLISENS (Figure 5). Unfortunately none of those avalanches were detected by the algorithm. Those avalanches have been powder snow avalanches and problems in detecting dry powder avalanches have been reported before. Also the long time interval between 2 Senteniel-1 data collections might have precluded the algorithm to work. More successful was our case example of a wet avalanche cycle in March 2023. Here the algorithm detected 7 of 9 avalanches as seen in Figure 7.

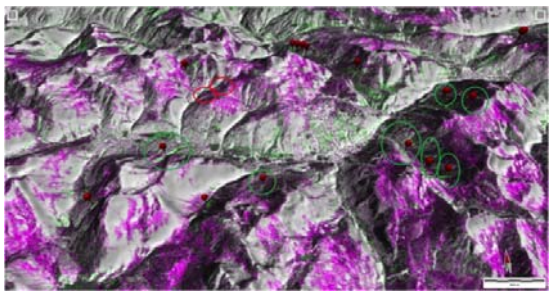


Figure 7: Avalanches detected by NORCEs avalanche detection algorithm. Green circles indicate detected avalanches while red circles indicate not detected avalanches.

If we look at the avalanche events that were not detected by the algorithm it is surprising that they are large avalanches with defined slab avalanche release areas and significant wet avalanche debris that is usually easily detected by the algorithm as seen in Figure 8 and 9.



Figure 8: 2 slab avalanche release areas not detected by NORCEs avalanche detection algorithm (1 and 2 red circles). One avalanche release area detected by the algorithm (3 green circle)



Figure 9: Wet avalanche debris running over a ski run of avalanche 2 in Figure 8.

Other detected avalanches in this avalanche cycle have been smaller than those not detected. The reason for not detecting is not the size of the avalanche is shadowing and low orbit coverage. As seen in Figure 3 only one or 2 orbits covering the area were the not detected avalanches occurred while 2 to 4 orbits are covering the detected avalanche areas.

4. DISCUSSION AND CONCLUSION

We validated NORCEs avalanche detection algorithm that utilizes Senteniel-1 SAR data. A significant limitation is currently the time frequency of 12 days of Senteniel-1 satellite. With the lounge of Senteniel-1C the return period of the satellite will be reduced to 6 days. For operational avalanche warning on a large scale the

algorithm, however, is able to deliver additional important information of avalanche occurrence in particular of wet avalanche cycles. Only avalanches that happened in shadowing areas with very low orbit coverage were not detected by the algorithm but still more than 70% of the avalanche events were covered which is an important information of the stability of the snowpack. The detection of dry powder snow avalanches remain difficult, so far we suggest to limit the application of the algorithm only for wet avalanches. For slope scale detection of avalanches as needed by avalanche commissions in ski resort or for infrastructure responsible decision makers that need to decide on a daily basis, the detection algorithm does not add significant information to the authorities. They usually know when avalanches occur on their slopes of interest, they need to know confidently all types of avalanche events and they need to know when an avalanche happens as soon as possible which is precluded by the time frequency of the Senteniel-1 SAR measurement.

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