THE AVALANCHE TEST SITE IN LECH AM ARLBERG, AUSTRIA: PAST, PRESENT AND FUTURE

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ABSTRACT: For more than 20 years a unique avalanche test site in the ski resort of Lech am Arlberg, Austria at the slopes of Mohnenfluh Mountain is used for snow and avalanche research. Located close to Warth-Schröcken, which is considered the snowiest ski resort in the Alps that records an impressive average annual snowfall of approximately 10,7 m of fresh snow and its south-east exposure loaded by predominant north-westerly winds in 2200 altitude meters serve as perfect conditions for scientific analyses of different processes regarding snow properties and snow processes as well as avalanche release and avalanche dynamics. 6 avalanche-blasting towers allow for controlled remote triggering of avalanches in multiple paths, with typical avalanche release width ranging from 10 to 80 m and avalanche lengths ranging from 50 to 350 m. In an average winter about 50 to 100 avalanche events can be analyzed. In the past, pioneering work was conducted at the test site such as the first terrestrial laser scanning measurements of snow surfaces scientifically analyzed for snow and avalanche research or the first detections of avalanche events using distributed acoustic and seismic fiber optic sensing. Moreover sophisticated snowdrift models were validated at the test site and the functionality of avalanche protection measures was tested and improved. At the moment the scientific measurements focus on an accurate knowledge of 3-dimensional conditions of snow pack properties and avalanche events in high temporal resolution. Next to common automatic weather and snow sensors, 4 automatic LiDARs survey spatial snow depth at any time in parts of the test site and in combination with manual conducted LiDAR measurements full spatial snow depth at the test site is collected. Additionally acoustic and seismic distributed fiber optic sensing deliver high resolution (1 – 5 m) data of snow pack properties and avalanche events. Two avalanche radars detect automatically avalanches and deliver avalanche speed measurements. To summarize data about size, speed and intensity in terms of seismic signals of avalanche events is collected in high accuracy and temporal resolution and satellite remote sensing data is validated. We present and discuss the current measurement set-up and the data quality delivered and we invite researches interested in such data to join us at our research site!

KEYWORDS: avalanche, snow properties, test site, Alps.

1. INTRODUCTION

The snow and avalanche research site in the ski area of Lech am Arlberg, Austria was chosen in winter 2003/04 due to research cooperation with the local ski resort. The slope is situated on the lee side of a ridge on the south-east face of Mohnenfluh (Figure 1 and 2). The summit of Mohnenfluh reaches up to 2544 m. The 'test slope' extends from just beneath the blasting towers downwards, until the beginning of the ski run. The start point is located at about 2337 m and its end point is located just before the beginning of the ski run, at 2245 m altitude. The length of the avalanche path within the test slope is about 300 m. The slope itself is not part of the prepared skiing area, but can easily be accessed from Steinmaehder lift top station, which is situated at 2298 m altitude. The proximity to the infrastructure of the skiing area allows for easy transport of the entire instrumentation. Furthermore, fast access to the instrumentation is ensured. This is important so that measurements can be performed spontaneously e.g. immediately after heavy snowfall and consecutive blasting. Steinmaehder top station is not only very useful in terms of transportation matters but also acts as warm and dry housing for delicate measurement units. There is a separate room where a secure installation location, power supply, heating and web access are provided. As the test slope is located just beneath the ridge, a lot of snow is accumulated there. This is caused by wind

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loading. Hence, the probability of snow avalanche activity is enhanced, as more snow is available and the snowpack can get tightly packed because of the acting wind. Avalanches endanger frequently the ski run underneath the test slope, so 6 blasting towers ensure controlled avalanche initiation and events. The researchers are welcome to survey the blasting activity of the ski-patrollers and use the data for research purpose. As the research site is limited in length the investigations focus rather on avalanche formation and slab release than avalanche dynamics of large avalanche events and is more similar to the full-scale avalanche test-site at Lautaret Pass, French Alps, (Thibert et al., 2015) than to the one in Vallée de la Sionne, Valais, Switzerland (https://www.slf.ch/en/about-the-slf/instrumented-field-sites-and-laboratories/natural-hazard-research-sites-and-facilities/investigating-snow-avalanche-dynamics/)

Pioneering research activities have been carried out at the test site such as the first scientific terrestrial laser scans of the snowpack and avalanche snow mass displacement (Prokop, 2007; Prokop 2008). Moreover avalanches could be successfully detected using distributed acoustic and seismic fiber optic sensing measurements for the first time (Prokop et al., 2013, Prokop et al., 2014). This resulted in an avalanche monitoring and detection system currently used to detected avalanches along roads (Torquet et al., 2024). Studies concerning wind loading and snow distribution patterns have been performed and physical numerical snow drift models were developed and validated (Schneiderbauer and Prokop 2011) Another applied research project investigated the functionality of the snow catcher, and snow fence type of protection measure that is supposed to catch the snow of avalanches and therefore retards the movement of an avalanche after it has been initiated, that is in its path or run out zone (Gleirscher et al., 2012) The study site delivered data for numerous student projects and resulted in successful thesis submissions (e.g.: Wirbel, 2013; Jungmayr, 2013; Schneiderbauer, 2010; Prokop, 2007)

2. CURRENT INSTALLATIONS

Current innovative installations are built in the framework of two international research projects: In “RSnowAut” ground truth of the dimension of the snowpack and snowpack properties and their change in time is investigated using a set of different (low-cost) LiDAR systems to validate satellite remote sensed data. In “DAS-SA” distributed acoustic and seismic sensing of snowpack and avalanches are executed via the deployment of fiber optic cables in the slope and within the snowpack and changes in snow pack properties and avalanche events are measured in real time. A network of automatic weather and snow investigation techniques allows for the determination of atmospheric conditions as well as physical snow pack properties. Avalanche detection and speed measurements of avalanches are provided by coherent pulse-Doppler radar.

2.1 Automatic weather and snow stations

The basis for understanding climate, atmospheric and snow pack conditions at our test area is a network of automated weather and snow stations. 4 stations deliver data for air and snow surface temperature, wind speed and direction, relative air humidity, global radiation, snow depth and to certain extend precipitation. All stations are in a vicinity of max. 2000 m to the test site, one of such stations is located in the middle of our test site to gain information about the local conditions there (see figure 4 left image). One station is located at the top of the closest single standing peak at Kriegerhorn and is part of the avalanche warning station network, to cover regional weather patterns, see data here: https://lawinen.at//charts/vbg//grafik3T/LECH_KRIEGERHORN.png. Close to our test site we have also a flat field station to collect rather non-influenced data at the same altitude as our test site for comparison. As our test site is south-east exposed, we have a 4th station on a northern exposed slope to cover differences of weather and snow pack conditions driven by exposure. Additionally wind speed and direction is measured at the ridge of our test site, to understand local ridge wind patterns. See the overall installation map:

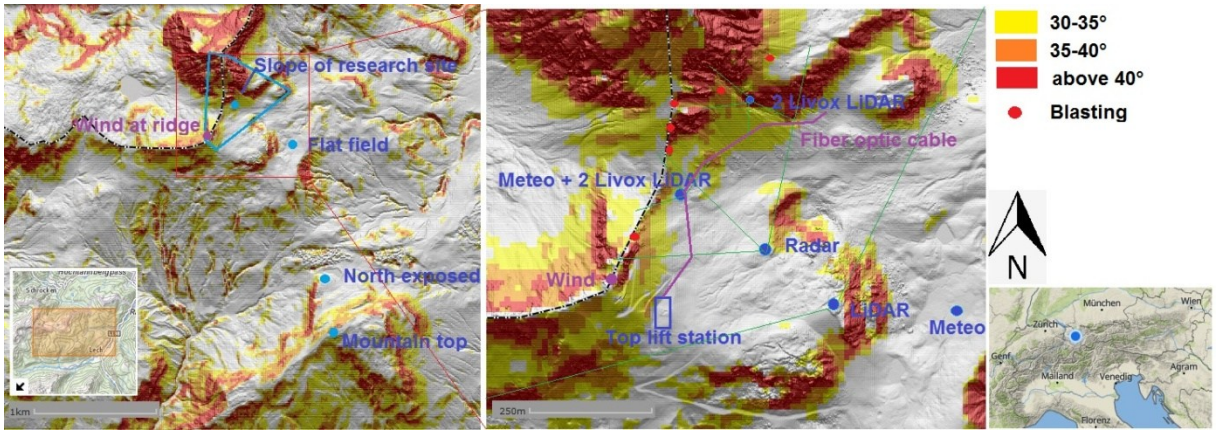


Figure 1: Location of the measurement units at the snow and avalanche research site in Lech am Arlberg: Left: Location of the automated weather and snow stations, Middle: Location of the most important measurement devices. Right: Location in the Alps.

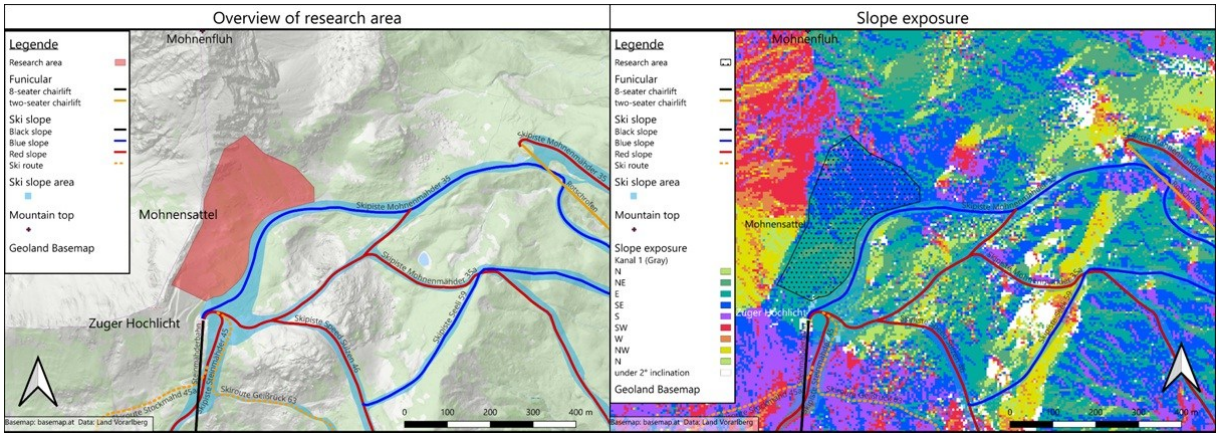


Figure 2: Left: Location of the research area within the ski resort; Right: Slope exposure map

2.2 *Terrestrial laser scanning*

The snow and avalanche test site was initially chosen for terrestrial laser scanning measurements to collect data about changes in time of the spatial snow depth distribution. Heavy snow loading due to snow drift events as well as frequent avalanche events occurring at the slope guarantied significant changes in the dimensions of the snow pack. So the first successful scientific terrestrial LiDAR measurements of snow changes due to avalanche formation processes and avalanche events could be measured (Prokop, 2007 and 2008). The devices used present the development of terrestrial laser scanners and their technical advances over time. Starting with Riegl's LPMi800ha and LPM2K, which have been rather slow laser profilers, the technology improved and LPM-321 and finally VZ-6000 were in use. While in the early 2000's the duration of a scan with high resolution took several hours, a scan of the whole slope takes now about 15 min. The accuracy increased as the food print size significantly decreased due to a smaller beam divergence. All devices run using a laser wave length in the range of 900-1100 nm, which is favorable for snow and ice surfaces. Currently the test slope is surveyed from one position that covers the whole area of interest (see Figure 3). The data is now used to validate results of other instruments e.g. low cost LiDARs, calculates mass displacement of avalanche events, and, delivers input as well as validation data for physical snow drift or snow pack models.

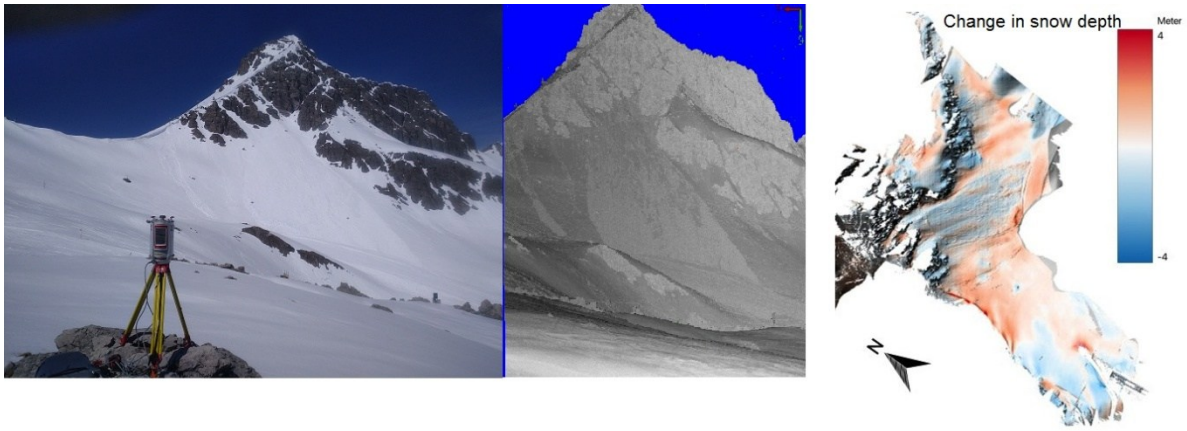


Figure 3: Avalanche events from 11.04.2026 measured via terrestrial laser scanning. Left: Installation of the device. Middle: Intensity image of reflectance of different surfaces e.g. snow, rock, fresh avalanche. Right: Differential map (DoD) of snow depth changes showing the volume of snow transported by the avalanches.

In the current research project (RSnowAut) we utilize low-cost automotive LiDARs to provide real time snow depth maps that are used for avalanche forecasting and decision-making for the first time and used a hand held Oyster LiDAR (Gölles et al. 2022, Kapper et al. 2023). After satisfying results we installed four Livox Avia LiDARs at two different locations, each monitoring a range of about 150 m to cover important parts of our test area similar to Ruttner et al., 2025. We test our measurement set-up against a commonly used laser scanner (Riegl VZ6000) and a continuous 1-d laser (Lufft SHM31). The advantage of such permanent installations is the possibility of measuring the snow pack evolution in high time frequency. Any time a reliable spatial snow depth measurement covering an area of 600 m (four LiDARs in action) in a point resolution of 10 cm can be conducted. At our avalanche prone slope we are able to follow the accumulation of snow due to snowdrift and/or snow precipitation as well as melting and mass movement of avalanche events in a spatial content. After filtering the data and calculating differences, snow depth maps are displayed in real time on a web page to improve decision making (https://avalanchemonitoring.com/en/). Due to our experience we suggest using Livox Avia's for a range of 150 m, but not more!



Figure 4: Installation of automotive LiDARs to collect spatial snow depth maps at two different locations at our test site: Left: Main hub where power supply exists and alternative measurements to validate Livox data e.g. 1-D LiDAR Lufft SHM31 and automatic weather and snow station. Middle: Location of 2 additional Livox Avia LiDARs in an energy self-sufficient installation. Right up: LiDAR reflectivity data of a scan from the test site. Right low: Sample snow depth map from the spatial snow depth distribution April 10th 2026.

2.3 *Distributed fiber optic acoustic and seismic sensing*

During the 2026 winter season, we made some improvements to our existing DAS system that has been installed for measuring snow-avalanches and other related phenomena occurring at our test slope since 2012. The associated Fiber Optic (FO) cable has been deployed for 600 meters from the DAS interrogator, a model Febus A1-R (Figure 5). The FO cable was trenched 20 cm underground in the first 300 meters and, then in the snowpack in the vicinity of a weak layer. The FO cable was running mostly at the same altitude, to make an iso-topographycal installation and maximize the gain in physical/geometrical information about the snow-avalanche (e.g. frontal dimension, duration). The DAS acquisition parameters included 8 meters of Gauge Length, re-sampled 8 times (i.e. DAS channel spacing is 1 meter). Strain-rate data are acquired with 500 samples per seconds. Pulse Width was set as large as 2 meters (about 10 nanoseconds). The DAS interrogator and associated data post processing and data transmission units are placed in the top lift station in a warm, dry, and safe environment (see Fig. 5).

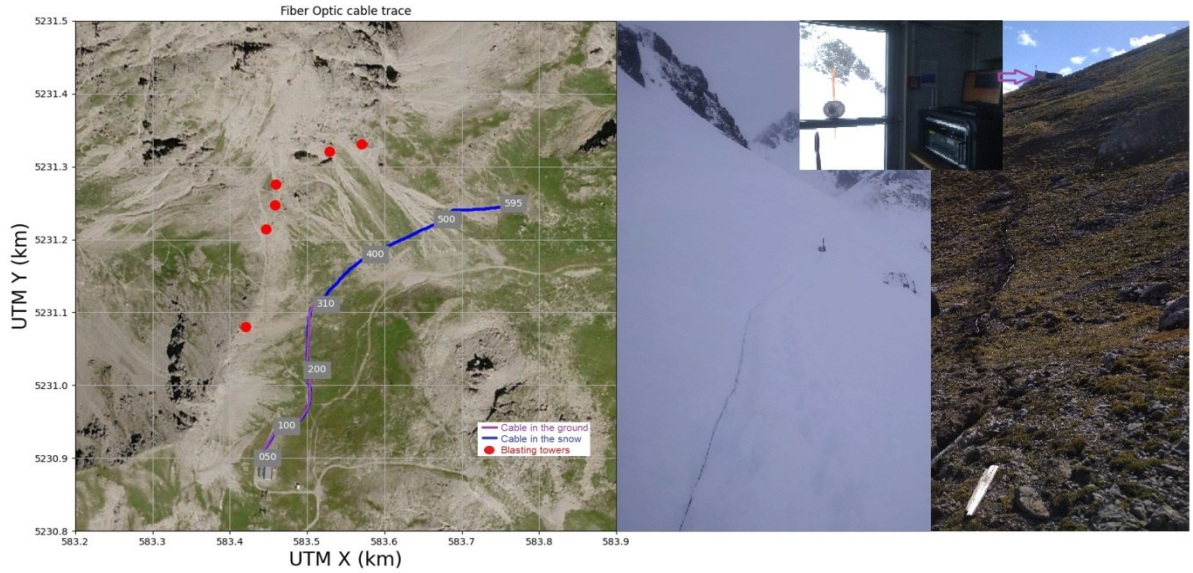


Figure 5: Geometry of the Fiber optic (FO) cable used in the experiment. Purple line: deployment of the FO cable in the ground, blue line deployment of the FO cable in snow (as seen in the pictures). Numbers indicate the distance (m) along the FO cable. Red dots show the position of the bombing turret for triggering snow-avalanches. Small picture of the instrumentation inside the top lift station.

As an example of data we like to show a unique event happening at night 17th February 2026 at 0:48 am. During dark night with light snow fall the system was able to detect the collapse of the weak layer (Event A) and 2 small consecutive small avalanches (Figure 6) at the part of the cable that was inserted in the snowpack happening naturally. The avalanche event was also confirmed by the radar measurement, see 2.4)

Waterfall view of the raw strain-rate data from the DAS system. Data batches are 1-minute long. Starting time is written on top of the graph. Colors indicate Strain-rate value. Distance along the cable is represented in the y-axis, while time form the beginning of the file is represented on the x-axis. The colored boxes show the main signals (all occurred in the 300-to-600 meters section of the cable, lower portion of the waterfall view). Event A is the targeted “Weak layer collapse”. Event B is a precursory seismic event occurred in the snow pack few seconds ahead of the collapse. Event C are seismic events occurring in the coda of the Snow Avalanches. The two small snow-avalanches occurred at the end of the collapse are marked.

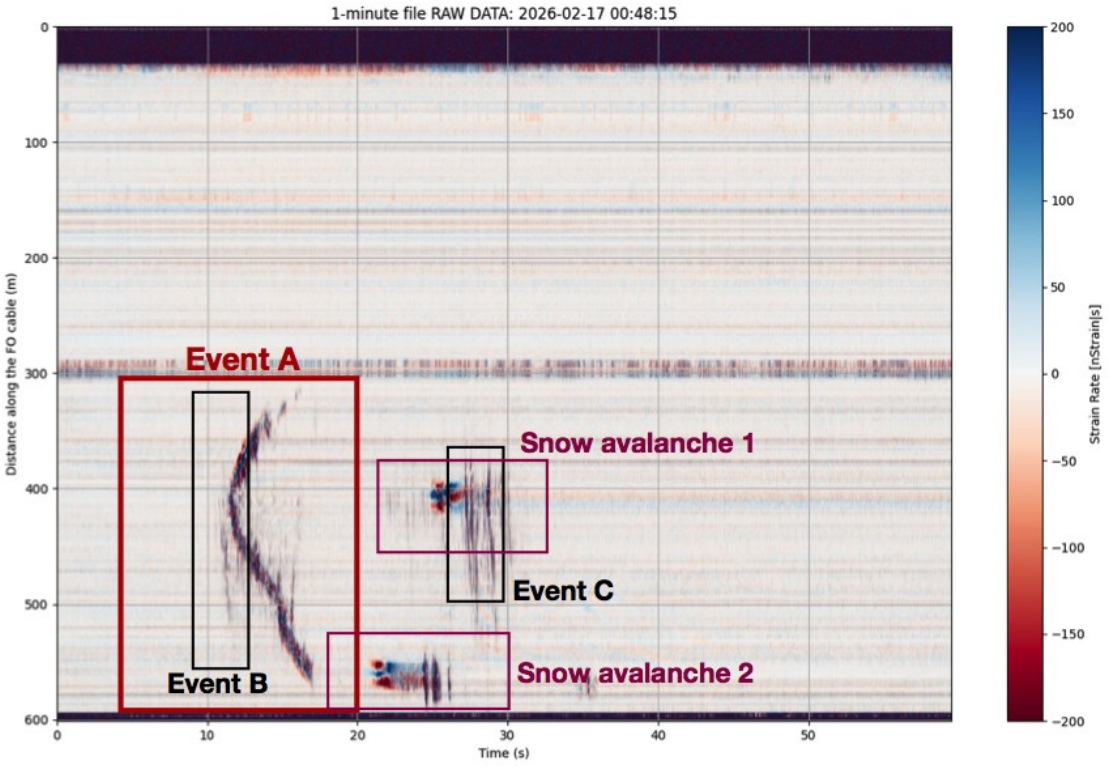


Figure 6: Waterfall view of the raw strain-rate data from the DAS system. Data batches are 1-minute long. Starting time is written on top of the graph. Colors indicate Strain-rate value. Distance along the cable is represented in the y-axis, while time form the beginning of the file is represented on the x-axis. The colored boxes show the main signals (all occurred in the 300-to-600 meters section of the cable, lower portion of the waterfall view). Event A is the targeted “Weak layer collapse”. Event B is a precursory seismic event occurred in the snow pack few seconds ahead of the collapse. Event C are seismic events occurring in the coda of the Snow Avalanches. The two small snow-avalanches occurred at the end of the collapse are marked.

2.4 Pulse-Doppler radar

The radar operates on the principle of coherent pulse-Doppler radar. It transmits high-frequency pulses at 10.425 GHz through a parabolic antenna toward the detection area. Reflected signals from objects in the monitored area are collected by the same antenna and directed to the receiver.

Within the receiver, the echoes are sampled and converted into digital data by analog-to-digital converters. A Fast Fourier Transform (FFT) is then applied to determine the Doppler frequency spectrum and, consequently, the velocities of detected objects. The resulting data are processed and displayed through a user interface or forwarded to the radar’s automatic alarm-generation software

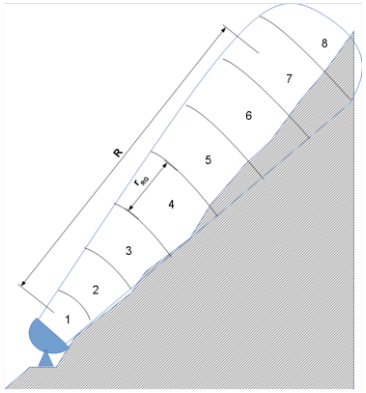


Figure 6: Scheme of typical detection situation with different range gates numbers n, range gate length r_{RG} and a range R.

Figure 6 shows the illumination of a mountain slope with a discrete pulse with a pulse length T. The pulse length **T** in time corresponds to the range gate length $\mathbf{r_{RG}}$ in space with the speed of light **c** by:

$$\mathbf{r_{RG}} = \mathbf{T} \cdot \mathbf{c} \qquad (1)$$

As this pulse spreads along the slope we get in each n^*r_{RG} distance of the radar a velocity spectrum of all moving objects in the slope at the same time. From Figure 6 we get the conclusions that the beam direction of the antenna should be oriented almost parallel to the slope in order to illuminate the maximum range of the slope. The space-resolution is equal to the range gate length rRG.

The pulse repetition frequency of the RADAR device is up to 90 kHz, this means that every second data from 90000 pulses are processed, which gives about 3 frames per second for the analysis. The maximum range for detecting moving objects (even snow) with a cross section of 1m² in heavy weather condition (rain/snow) is 2 km. The range gate length is chosen between 15 m and 250 m and it is possible to measure velocities between 1 km/h and 300 km/h.

For customer users, a simplified online viewer is provided (Figure 7). Users can either watch the scene live when an artificial avalanche is triggered, allowing them to verify the success of the blasting—including its magnitude, location, and extent—under any weather conditions, or load stored data into the viewer. The stored data also serve to document the blasting operations throughout the year. The radar is active 24/7 and automatically sends alarms via email and SMS

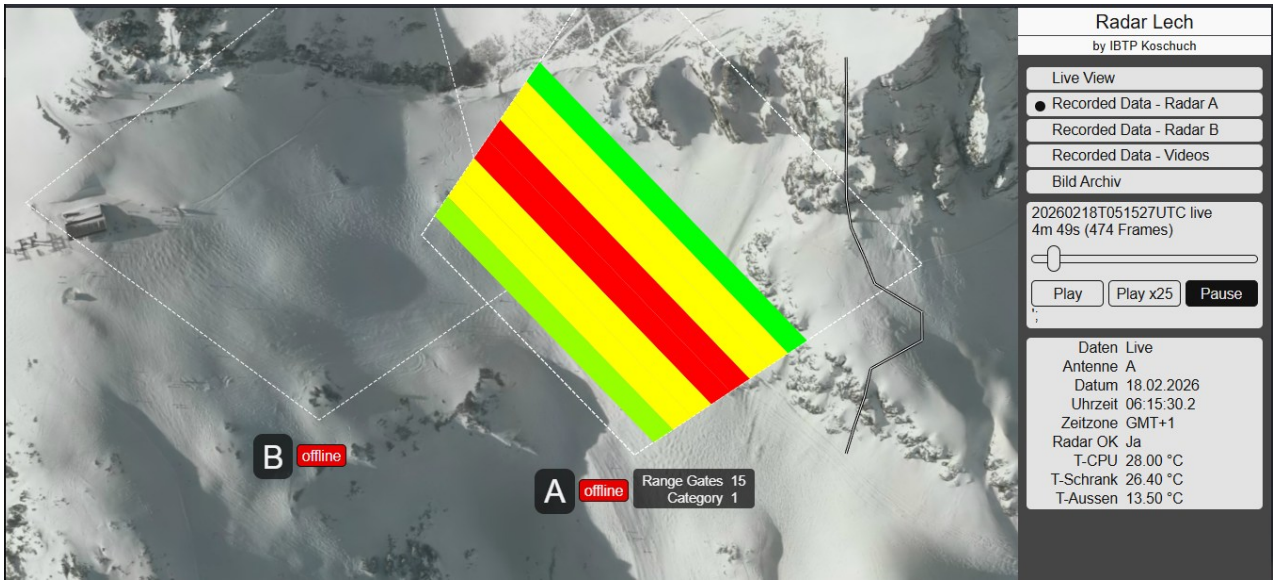


Figure 7: Example of an avalanche from 18.02.2026 as shown in the viewer for the user.

3. CONCLUSIONS

Since more than 20 years the snow and avalanche test site at the ski resort of Lech am Arlberg serves as an ideal place for snow and avalanche research. The collaboration with the ski resort allows for easy access to the test site as well as logistical support. Pioneering scientific work has been completed at the test site and current research projects establish unique scientific installations that deliver interesting data of snow cover properties, avalanche formation and properties of avalanche events. The current key facilities are a network of different LiDAR instruments that validate each other e.g. cheap automated LiDARs that deliver data in real time with a measurement range of 150 m as well as expensive very long range LiDAR (range of 4000 m); snow cover dimensions can be accurately measured at any time. Moreover fiber optic cables have been dug in the ground as well as deployed into the snow pack, in this way the collapse of a weak layer and its speed could be measured for the first time using distributed acoustic and seismic sensing (DAS). DAS and a radar system is also used to detect and monitor avalanche events, the devices are validating each other and deliver data of avalanche speed and avalanche

properties and dimensions. We welcome interested scientist at our test site to collaborate with us, we are happy to share our data and give further insides about our installations!

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