

TOWARDS SYSTEMATIC PATTERNS AND AVALANCHE RISK ANALYSIS WITH CONTINUOUS MONITORING AND EVENT DETECTION ON AVALANCHE SLOPES WITH A NOVEL SENSOR ARRAY BOX IN AUSTRIA

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ABSTRACT: Austria's largest railway infrastructure operator, OEBB-Infrastruktur AG aims to ensure safe and reliable operation of the rail network with minimal closure times. To achieve this goal, technical as well as organizational avalanche protection measures such as risk assessment by internal avalanche commissions are implemented. In addition to the local experience of the committee members, high-altitude weather data, knowledge of the local situation and route-specific 72-hour weather forecasts are important factors in the committee's decision-making. With our research project we aim to support the decision making as well as avalanche risk assessment by providing continuous snowpack data from avalanche slopes. To collect this data we developed a novel sensor box array called SnowBox. The array consists of several sensors boxes which are deployed either by hand or drone at key locations on avalanche slopes at the start of the winter-season or after snowfall events. The sensors provide continuous data on temperature, humidity, position, and movement under the snow-cover during the entire winter period. The data transmission is based on a wireless system with the data being locally stored and accessed via a web platform called SnowView. Moreover, the data is automatically analyzed based on a decision tree together with an event detection algorithm immediately alarming responsible personnel by SMS and email. This paper provides a short overview of the sensor array SnowBox and the web platform SnowView with a focus on analyzing monitoring data and avalanche events from the winter period 2023/2024. Although avalanche slopes in several regions are currently being monitored within the research project, the event analysis is focused on several verified events in the ski resort Arlberg, Austria. Further details on the development process and techniques from the patented SnowBox and SnowView are covered in a different paper.

KEYWORDS: monitoring, avalanche slopes, event detection, systematic patterns, risk analysis.

1. INTRODUCTION

For a safe and reliable operation of Austria's railway network preventing and managing natural hazards is crucial minimizing closure times and enhancing safety. In the mountainous regions of Austria, the railway infrastructure operator, OEBB-Infrastruktur AG employs protective structures and internal avalanche commissions to protect their rail network and operations from avalanches. Relying on high-altitude weather data, historic events, local insights, and route-specific forecasts five avalanche warning levels according to the European Danger Scale as well as specific operational recommendations are given. A key aspect for a thorough assessment in this regard

is a consistent monitoring of potential avalanche slopes.

Our research project on user-friendly and cost-efficient monitoring solutions introduces a novel approach to support decision-making through continuous snowpack monitoring and avalanche risk assessment using the SnowBox sensor array. Deployed manually or by drone, these sensor boxes provide real-time data on temperature, humidity, position, and movement, transmitted wirelessly and analyzed via the SnowView platform. In the development and validation phase the sensor array and the data analytics have been extensively tested on several avalanche slopes in different regions. Focusing on data from the 2023/2024 winter season in the ski resort St. Anton/Arlberg, Austria, the paper presents data on several observed avalanche events. Based on previous data a decision tree and specific algorithms have been developed helping to identify systematic patterns in monitoring data that indi-

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cate avalanche risks and validate detected avalanche events enhancing early warning systems and risk management.

2. AVALANCHE MONITORING

2.1 Avalanche types and focus

Snow avalanches can be categorized according to their release mechanism, namely into loose snow avalanches, slab avalanches, and glide-snow avalanches. Loose snow avalanches start due to a loss of cohesion at the top of the snow-cover, gathering more snow as they descend, forming a triangular shape. Slab avalanches form as a fracture initiates and propagates in a weak snow layer beneath a cohesive slab. Glide-snow release due to a loss of friction between the snowpack and the moist or wet ground. As the interface between the snowpack and the (usually smooth) ground becomes increasingly wet, the friction reduces, leading to snow gliding and often also to glide-snow avalanches. Glide-snow avalanches cannot or at least very rarely be triggered artificially, making prediction of glide-snow avalanches especially important. The focus of the present research has been a continuous monitoring of glide-snow avalanche slopes for an entire winter season.

2.2 Avalanche monitoring devices

Avalanche monitoring devices are crucial for detecting avalanches. The monitoring and detection of avalanches over several winter seasons allows to build consistent databases enabling further insights into avalanche mechanisms, trigger conditions and avalanche risk prediction based on snowpack models. According to e.g. Schweizer, et al. (2004) and Eckerstorfer, et al. (2016) the monitoring devices can be categorized into the following types:

- Snow sensors: Measure snow depth, temperature, and density. Examples include ultrasonic snow depth sensors and snow temperature profilers.
- Weather stations: Monitor meteorological conditions like wind speed, precipitation, and temperature, which are critical factors in avalanche formation.
- Seismic sensors: Detect ground vibrations caused by avalanches, allowing for real-time detection and warning systems.
- Radar systems: Use electromagnetic waves to detect moving snow masses, providing early warning for large-scale avalanches.
- Infrasound sensors: Detect low-frequency sound waves produced by avalanches, enabling long-range detection.

- Drone-based monitoring: Utilizes unmanned aerial vehicles for visual inspection and mapping of avalanche-prone areas.
- LiDAR (Light Detection and Ranging): Provides high-resolution 3D mapping of snow-covered terrain to assess avalanche risk.

2.3 Avalanche snow sensors

In the field of avalanche snow sensors, the mainly used sensors are manually operated for snow profiling using temperature and humidity sensors as well as snow grain size scales for different layers. As temperature measurements are rather straightforward, the detection of liquid water in snow remains a challenge. According to e.g. Techel and Pielmeier (2011) and Denoth (1994) typical methods and devices are:

- Snow forks: Measure dielectric properties of snow to estimate liquid water content at several layers.
- Time-domain reflectometry (TDR): Uses electromagnetic waves to measure water content.
- Calorimetry: Melts a snow sample to directly measure water volume.
- Remote sensing: Utilizes satellite or aerial data to estimate snow water content over large areas.
- Ground-penetrating radar (GPR): Provides non-invasive measurements of snow stratigraphy and water content.

Beyond manual measurements being limited in critical avalanche slopes, there is also ongoing research in short-term monitoring of particle movements and snowpack parameters with artificial trigger conditions (e.g. Erlacher et al. 2018, Neurauder, et al. 2022). However, there is a gap regarding specific long-term observation and safe monitoring devices for avalanche slopes.

3. OUTLINE RESEARCH PROJECT

3.1 Goals and scope of research

In search of a flexible, cost-efficient solution for ongoing monitoring and event detection on avalanche slopes the Austrian railway infrastructure operator OEBB-Infrastruktur AG commissioned a multi-year research project. Starting in 2020 the goal was to develop a solution for direct continuous measurement of snowpack parameters for a winter season. The key parameters temperature, humidity, position, and movement had to be transmitted wirelessly through the snow-cover to a server for online analysis. Furthermore, an automated data analysis and a robust algorithm for

event detection was needed to allow a timely decision-making by avalanche commissions. Furthermore, the solution had to be field-tested on several sites for robustness and applicability. The paper provides an overview on the current state of development of the novel sensor array SnowBox, the online platform and analytics SnowView as well as the results of the field tests with an in-depth analysis of detected avalanche events.

3.2 Novel Sensor Array SnowBox

Under the preconditions of high robustness, continuous measurements, data transmission without external energy supply, as well as a fast and easy deployment by hand or by drones, the developed sensor array was subject to an iterative development process. The latest version of the SnowBox (Figure 1) consists of a small box (10x10x10 cm) with beveled, reinforced corners into which various types of slip guards can be screwed. The SnowBox is waterproof and weights around 1 kg including the slip guard. It allows continuous, multiple measurements of position, acceleration, temperature, and moisture for real-time monitoring of avalanche slopes, sending the data through the snow-cover to a gateway. The data is also stored locally on a SD-Card and can be conveniently accessed via a USB-C adapter. For handling multiple devices, the SnowBoxes can be identified based on an RFID-Chip and are directly connected to the server upon powerup. For collecting the SnowBoxes after the winter period they can be tracked either by GPS-signal or an acoustic signal.



Figure 1: Version 2024 of the branded novel sensor array SnowBox with slip guard (soft tips)

3.3 Web platform SnowView

The web platform SnowView (Figure 2) requires user-credentials for accessing the monitored areas and deployed devices of specific owners. It allows the handling of the deployed devices based on a bidirectional communication (e.g. firmware update, operational parameters, measure interval) distinguishing between the different operational modes testing, deployment, operation, and retrieval.

The web-platform provides an overview of the monitored areas as well as a list of deployed devices for direct access to the data. The monitored areas, the gateways and deployed devices are displayed on a customizable map. Furthermore, the data of all devices for any given time frame are summarized based on the developed decision tree highlighting condition states and events.

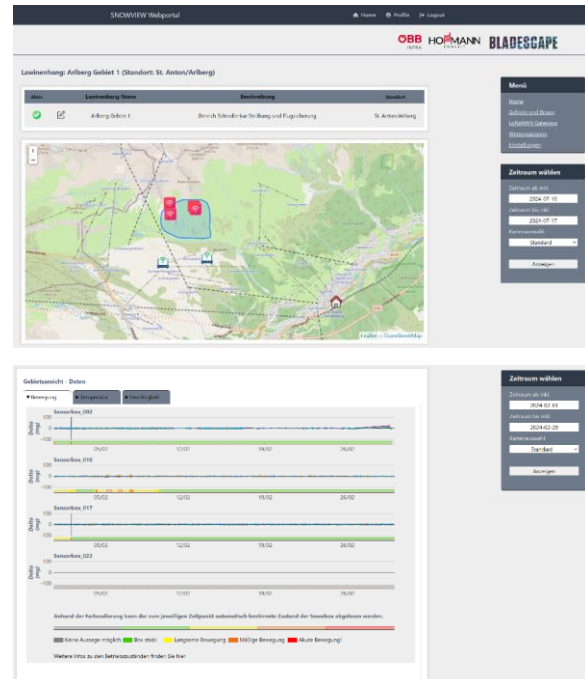


Figure 2: Version 2024 of the web platform SnowView with overview summary (all devices)

For a more detailed data analysis individual SnowBoxes can be accessed from a list providing a direct link to the position on a map as well as the measurement data for the selected time period. The status row provides key information on date of deployment, last retrieved data, and position development (Figure 3). The available data is organized in the tabs position, movement, temperature, humidity, change in humidity, transmitted signal strength, and data table for the last measurements in a given time frame (Figure 4).

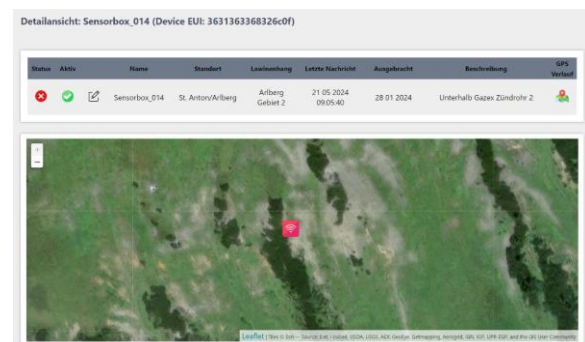


Figure 3: Version 2024 of the web platform with the individual location of a selected SnowBox

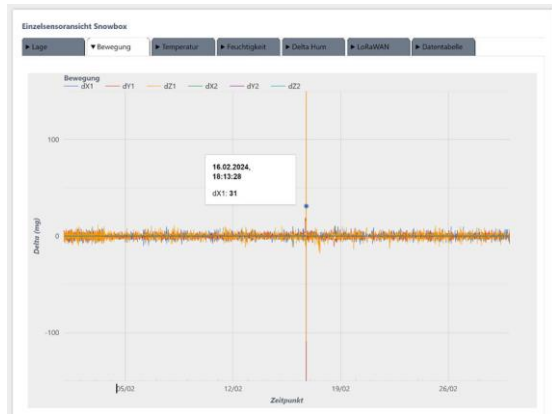


Figure 4: Detailed data analysis with movement indication of SnowBox #14 (16.02.2024 18:13)

3.4 Decision tree and event detection

The movement data of a SnowBox can be tracked based on GPS (surface only) and with a G-Sensor and is in itself not sufficient to reliably detect an event as the device can be moved manually or tilt and roll down on the snow surface. However, if the SnowBox is under the snow-cover, typically no GPS-Signal is available and the temperature sensor provides continuous measurements $\leq 0^{\circ}\text{C}$. Based on these considerations a decision tree can be constructed allowing an automated data analysis and event detection as shown in Figure 5. Combining the data from the SnowBox with data from weather stations and a snowpack model will provide further insights and avalanche risk analysis.

4. APPLICATION AND DATA ANALYSIS

4.1 Selected areas field tests

For the field tests and validation in the winters 2022/23 and 2023/24 typical areas with regular avalanche occurrence either adjacent to train tracks (Mallnitz, Lermoos), in ski resorts (Axamer Lizum, Hafelekarr, St. Anton), or with a stable snow-cover for validation measurements (Niederalpl, Schneeberg) were chosen.

4.2 Event analysis St. Anton/Arlberg

The test site was located in the area of the ski resort St. Anton/Arlberg on slope a well-known for snow gliding and glide-snow avalanches at elevations 1800 – 2500 m asl. The ski resort provided their extensive support in deployment of the SnowBoxes as well as their expertise. Together with these local experts and a thorough analysis of webcam data, a number of events could be identified allowing an independent validation of detected events.

For the given area around 50 events per season could be identified based on webcam data. Table 1 provides insights into 4 medium to large events being both recorded on webcam and detected by the deployed SnowBoxes. In addition, the measurement data of the detected event on the 16th of February 2024 between 18:10 to 18:20 is provided (Figure 6). These results prove the feasibility of a reliable monitoring and detection with the SnowBoxes and SnowView, also indicating possibilities for a quantitative risk assessment prior to events.

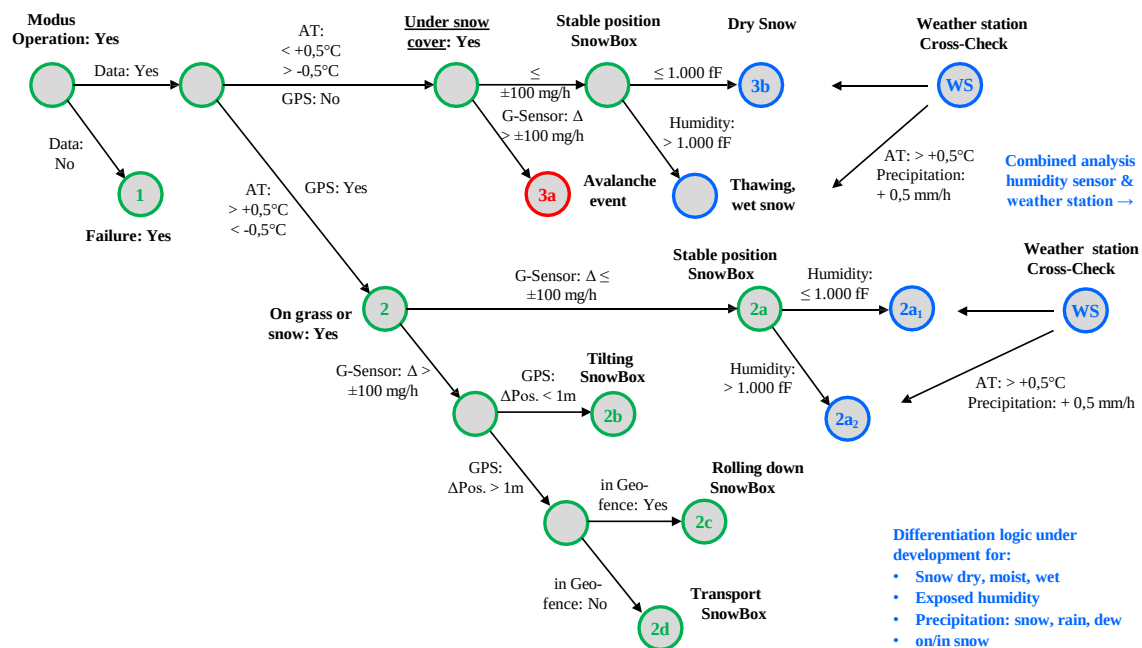


Figure 5: Decision tree for condition assessment and reliable event detection with the SnowBox

Table 1: Selection of detected avalanche events with the SnowBox in St. Anton/Arlberg (2023/2024)

Date/Weather	Before	After	Analysis*
22.04.2023 16:10 – 16:20 AT: + 13,8°C clouded avalanche risk: 2-3 (wet snow)			- recognizable cracks - very warm - large scale wet snow avalanche - detected SnowBox #1
16.02.2024 18:10 – 18:20 AT= + 4,0°C, clouded avalanche risk: 2 (wet, sliding snow)			- recognizable cracks - warm - large scale wet snow avalanche - detected SnowBox #14
11.03.2024 12:40 – 12:50 AT= + 1,8°C clear sky avalanche risk: 3 (wet snow)			- recognizable cracks - above freezing point - large scale wet snow avalanche - went above snow cover detected SnowBox #14
09.04.2024 12:00 – 12:30 AT= + 13,5°C, clouded avalanche risk: 2 (wet, sliding snow)			- recognizable cracks - very warm - medium scale wet snow avalanche - detected SnowBox #12

*The SnowBox allows for a continuous measurement of snowpack parameters. However, for an event to be safely detected the sensor array has to be under the snow-cover and at the location of the event.

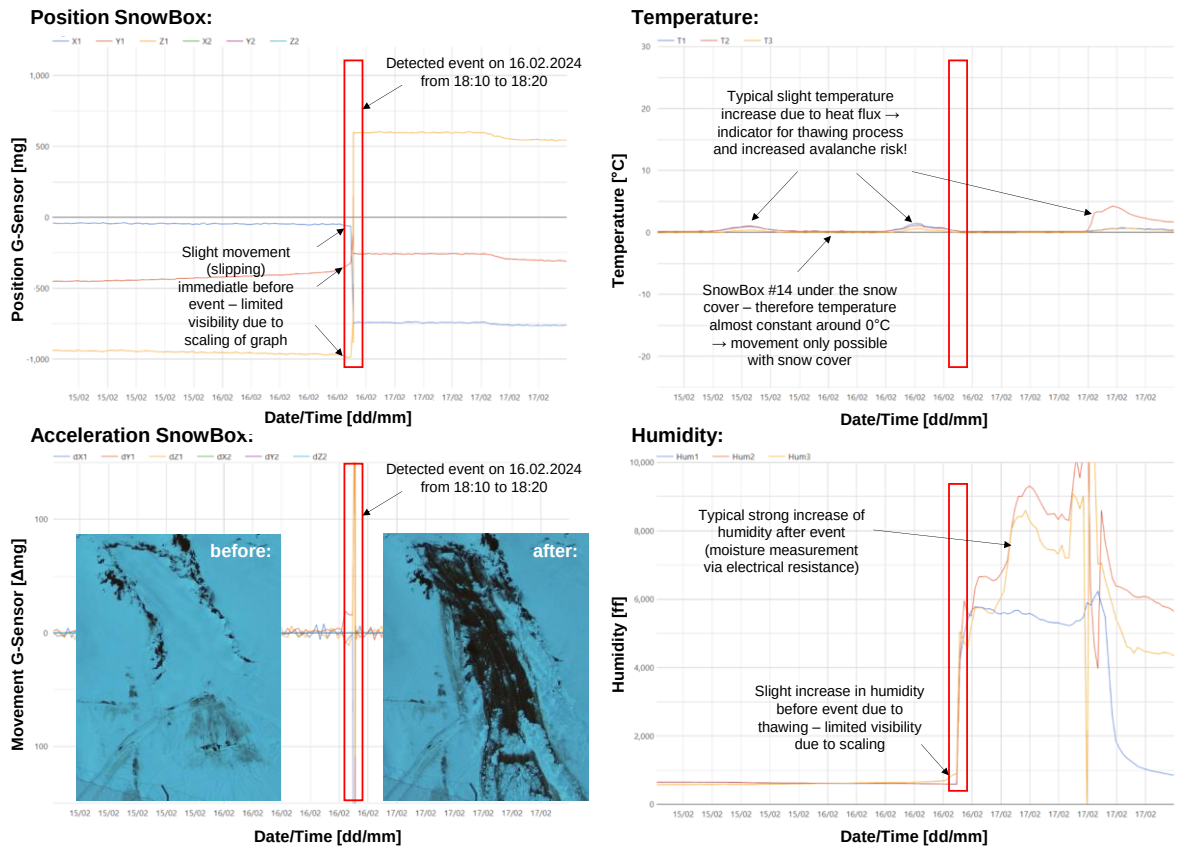


Figure 6: Measurements of the SnowBox #14 for detected event on 16.02.2024 (glide-snow avalanche)

4.3 Avalanche frequency and risk mapping

The systematic monitoring and analysis of avalanche events over several winter periods on critical avalanche areas may also provide further insights into general avalanche risk, possible areas for deployment of SnowBoxes, as well as data for avalanche risk modeling and mapping. As an example, the results of the avalanche event analysis in St. Anton/Arlberg are provided for the winter periods 2022/23 and 2023/24 (Figure 7).

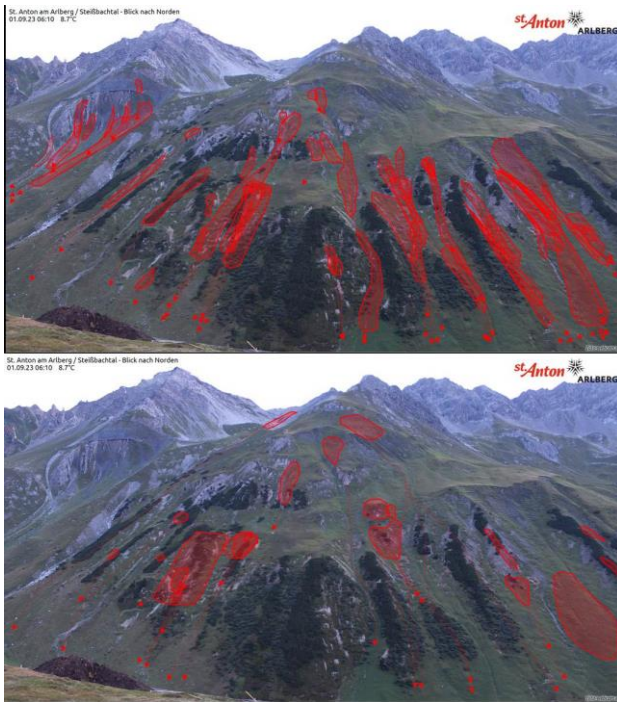


Figure 7: Avalanche events and paths St. Anton in the winter 2022/23 (top) and 2023/24 (bottom)

From a systematic monitoring as well as manual or computer vision based automated webcam analysis for several winter periods together with slope properties, a mapping of avalanche frequency and avalanche risk will become feasible. Figure 8 shows a schematic sketch how such a risk map could look, providing evidence for decision makers in the field.

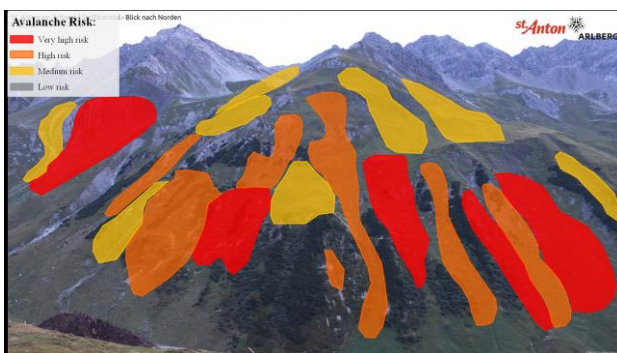


Figure 8: Schematic sketch for avalanche risk mapping based on actual events and slope properties

4.4 Recommended monitoring strategies

The development of efficient monitoring strategies with the sensor array SnowBox and web platform SnowView largely depends on the monitoring goals and expected results, the area of application and the specific topographic situation, and avalanche frequency. In order to achieve good results with the least possible effort the proposed procedure based on the experience from field tests for most areas of application will be as follows:

- Define goals and area of application with expected monitoring results and event warning
- Specific analysis of monitoring area, slopes, and avalanche frequency for a deployment strategy
- Preparation of equipment (SnowBoxes, Gateways, Drones) and training of users
- Monitoring phase either for an entire winter season or a designated time frame (event)
- Result evaluation, validation, and improvement potential with reports and dissemination

5. SUMMARY AND OUTLOOK

This paper presents a novel approach for avalanche monitoring and risk assessment developed by Bladescape and Hoffmann Consult for the Austrian railway company OEBB-Infrastructure AG with support of BOKU University. Within the research project, running from 2020 to 2024, we developed the SnowBox sensor array and SnowView web platform over several evolutionary stages for continuous monitoring of avalanche slopes. The SnowBox is a small, robust device that measures temperature, humidity, position, and movement under the snow-cover. It can be safely deployed manually or by drone at any time and transmits data wirelessly. The SnowView platform provides real-time data analysis and visualization, using a decision tree algorithm for automated event detection and risk assessment. More details on the development process of our system can be found in Hoffmann et al. (2024).

Field tests were conducted at various locations, with a focus on the ski resort St. Anton/Arlberg. Despite limited snowfall in recent winters, several medium to large avalanche events were successfully detected and analyzed. The paper presents four specific events, demonstrating the system's ability to detect glide-snow avalanches and provide insights into snowpack conditions before events occur. The research highlights the potential for using continuous monitoring data to develop avalanche frequency maps and improve risk assessment. By combining SnowBox data with weather station information, webcam data, and snowpack models, the system of-

fers a comprehensive monitoring approach for avalanche slopes and decision making.

Furthermore, the SnowBox and SnowView system shows promise for enhancing avalanche monitoring and risk assessment by avalanche commissions and infrastructure managers. Future developments of the sensor array and web platform could include:

- Refinement of the decision tree and event detection algorithms based on more extensive field data.
- Integration with other data sources, such as weather stations, and snowpack models, for more comprehensive risk analysis.
- Integration of ground temperature and humidity sensors into the SnowBox to detect thawing processes at the boundary layer soil-snow
- Development of avalanche frequency and risk maps based on long-term monitoring data.
- Exploration of machine learning techniques to identify subtle patterns in snowpack conditions that may indicate increased avalanche risk.
- Expansion of the system to cover more avalanche-prone areas, potentially creating a network of monitored slopes.
- Further miniaturization and cost reduction of the SnowBox to allow for more widespread deployment.
- Investigation of additional sensors or parameters that could enhance the system's predictive capabilities.
- Improving the user-friendly interfaces and decision support tool SnowView for avalanche commissions and other stakeholders.
- Building a comprehensive database on observed and validated avalanche events for model validation and avalanche risk prediction

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The development of the sensor array SnowBox and the online-platform SnowView for avalanche slope monitoring and event detection would not have been possible without the generous support and contributions of OEBB-Infrastruktur AG from 2020 to 2024. Furthermore, our thanks go to the local avalanche commissions for our field tests with special thanks for the support of the ski resort St. Anton/Arlberg. Also patenting the SnowBox and the Algorithms on the platform SnowView would not have been possible without the support of FFG.

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