DRONE DOCKING STATIONS FOR PHOTOGRAMMETRIC SNOW DEPTH AND AVALANCHE MAPPING: POTENTIAL AND LIMITATIONS

Andreas Stoffel[1,2]*, Yves Bühler[1,2]

[1] *WSL Institute for Snow and Avalanche Research SLF, Davos, Switzerland*
[2] *Climate Change, Extremes and Natural Hazards in Alpine Regions Research Center CERC, Davos, Switzerland*

ABSTRACT: A drone docking station is an autonomous hub designed to support the remote operation of drones, thus eliminating the need for on-site personnel. In winter 2025/26, a drone dock was installed at the Weissfluhjoch research site above Davos, Switzerland. Operated by the WSL Institute for Snow and Avalanche Research SLF, the Weissfluhjoch site (2536 m.a.s.l.) is a premier high-alpine facility for snow science. It provides the world's longest continuous series of daily high-altitude snow measurements, dating back to 1936. The DJI Drone Dock 3, which is used at the site, is equipped with a DJI Matrice 4D drone that offers three-directional photography, RTK geo-positioning and terrain following to meet high precision photogrammetric mapping requirements.

The drone docking station at Weissfluhjoch aims to monitor the distribution of snow depth with high spatial and temporal resolution within two perimeters. Perimeter A (0.03 km^2) covers the research site, where various operational and experimental measurements are conducted. Perimeter B (2.2 km^2) includes ski slopes, other ski resort infrastructure, and many active avalanche tracks. Four of these tracks are equipped with Wyssen avalanche towers for proactive remote-controlled avalanche release.

The first winter of operation was characterized by a lack of snowfall and long periods of high-pressure weather. Due to this weather pattern and the fact that the permit for autonomous flights beyond visual line of sight (BVLOS) had not been obtained before the end of May, daily data acquisition was not possible yet. Nevertheless, 25 winter flights were performed for each perimeter.

The high spatial resolution (0.01 m) data from Perimeter A provides valuable insight into the distribution and variation of snow depth at the research site. Even small-scale wind erosion can be observed. In Perimeter B, the focus of interest is snow depth spatial variability, snow drift and avalanche activity mapping at a spatial resolution of 0.1 m.

The drone dock produced high-quality orthophotos and snow depth maps, demonstrating its robust operational potential in the challenging alpine environment. However, the main limitations are the persistent legal constraints on autonomous drone operations and downtime caused by adverse weather conditions, such as precipitation, fog, and high wind speeds and gusts. Sudden air traffic and rapidly changing weather conditions may also endanger the safety of drone operations and precision landings.

Comparing flat-field snow depths to the distribution of snow depths in nearby avalanche release areas acquired with high spatial and temporal resolution provides valuable insights that aim to improve future avalanche hazard management. Placing multiple drone docking stations near mountain resort facilities could create a network, enabling continuous regional coverage. Other potential applications include ski resort operations such as precision snowmaking, ski slope supervision and infrastructure inspection.

KEYWORDS: Remote sensing, UAS, drone dock, photogrammetry, snow depth.

1. INTRODUCTION

Spatially continuous mapping of snow depth (HS) involves measuring or estimating the snow coverage across a study area without data gaps. Traditionally, in situ measurements from manual or automated weather stations are combined with topographic covariates to statistically interpolate continuous grids However, this method is less effective in extreme alpine terrain (Lopez-Moreno and Nogues-Bravo, 2006). Surface models based on remote sensing techniques, often generated by airborne photogrammetry or drone surveys, allow for the calculation of snow depth distributions by subtracting snow-free terrain models from snow-covered surface models. This is possible provided that both models are accurately georeferenced (Eberhard et al., 2021). Airborne

* Corresponding author address:
Andreas Stoffel
WSL Institute for Snow and Avalanche Research SLF, Flüelastrasse 11, 7260 Davos Dorf, CH
tel: +41 81 417 02 43
email: stoffel@slf.ch

photogrammetry uses airplane-mounted surveying cameras to map large alpine regions (> 100 km²) with a vertical accuracy of 0.15 m to 0.25 m (Bühler et al., 2015; Nolan et al., 2015; Meyer and Skiles, 2019). Drones, unmanned aircraft systems (UAS), capture centimeter-scale snow depth variations in smaller areas of a few km^2 via Structure-from-Motion (SfM) photogrammetry (Vander Jagt et al., 2015; Bühler et al., 2016; Harder et al., 2016) or LiDAR systems (Jacobs et al., 2021; Koutantou et al., 2022; Herbert et al., 2024). Key applications of snow depth maps, often combined with estimates of snow water equivalent (SWE), are avalanche forecasting, hydrology and water management as well as ecology and infrastructure monitoring, for example snow loads.

Airborne mapping surveys are mainly campaign-based with limited temporal frequency. Recent advancements in automated and semi-autonomous UAS technologies, such as drone docks, enable a higher frequency of operations as they reduce the need for on-site presence and physical access to hazardous sites and remote areas (Maschler et al., 2026). In winter 2025/26, a drone docking station was installed at the Weissfluhjoch research site above Davos, Switzerland.

This study presents the first field evaluation of a dock-based automated UAS for snow depth and avalanche mapping. We demonstrate the potential and limitations of using a UAS dock to complement in situ measurements, conduct spatio-temporal monitoring, map avalanches and derive additional measures like fracture depth or snow loads. Based on our operational experience, we finally highlight how automated monitoring can contribute to improved ski resort operations.

2. STUDY SITES & DATA

The Weissfluhjoch research site (2536 m.a.s.l.) is a premier high-alpine facility for snow science. It provides the world's longest continuous daily high-altitude snow data series, dating back to 1936. By end of October 2025 a DJI Drone Dock 3, equipped with a DJI Matrice 4D drone, was installed on the roof of the small hut in the western end of the research site (Figure 1). The drone docking station allows for automated flight operations, including take-off, mission execution, landing, recharging and data transfer to a cloud-based storage.

The study covers two areas, shown in Figure 2. Perimeter A (0.03 km^2) covers the flat-field research site and its adjacent area, where various operational and experimental measurements are conducted. Perimeter B (2.2 km^2) includes ski slopes, other ski resort infrastructure, and two ridges with many active avalanche tracks. Four of these tracks are equipped with remote avalanche control towers for preventive avalanche release.

Figure 1: DJI Dock 3 installation on the roof of the small building at the Weissfluhjoch research site.

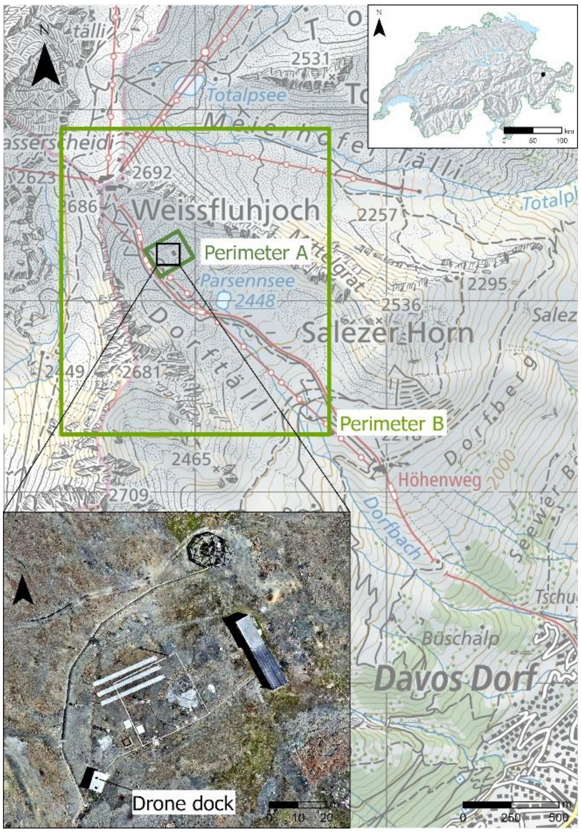

Figure 2: Main map: Study area Weissfluhjoch showing perimeters A and B. Detailed Map: Orthophoto of research site and location of drone dock.

3. METHODS

For the first winter of surveys, we used a semi-automated workflow to monitor the snow depth in the high alpine terrain of the study area. The dock-based UAS's main specifications are listed in Table 1. The workflow consists of flight planning, semi-automated flight execution with an on-site observer, photogrammetric SfM 3D reconstruction, producing high resolution point clouds, orthophotos, and digital surface models (DSMs), followed by a spatial-temporal DSM change analysis. The system is designed for minimal human intervention, enabling frequent and consistent missions.

Dock and UAV model	DJI Dock 3 / M4D
Wide-angle camera sensor size, resolution, photo format	4/3 CMOS, 20 MP, JPEG/DNG (RAW),
Focal length equivalent	24 mm
Operating temperature range	-30 to 50 °C
RTK base station positioning accuracy	Horizontal: 1 cm + 1 ppm (RMS), Vertical: 2 cm + 1 ppm (RMS)
Max. flight time	54 min
Max Allowable Landing Wind Speed	12 m/s
Dock protection level	IP56

Table 1: Main specifications of dock-based UAS installation at the Weissfluhjoch research site.

4. RESULTS

The first winter of operation was characterized by a lack of snowfall and long periods of high-pressure weather. Due to this weather pattern and because the permit for autonomous flights had not been obtained, daily data acquisition was not possible. Nevertheless, 25 flights were conducted for each perimeter in winter 2025/26 with an on-site observer present. The focus of the operation was on the reliability of the dock itself, monitoring snowfall and snowmelt periods, and conducting flights to ensure consistency and accuracy.

Because the dock is installed at an elevated height on a flat roof, snow never accumulated around it. This favorable placement and sufficient permanent heating meant that manual snow removal was unnecessary. Thus, the docking station demonstrated its strong operational potential in the harsh alpine environment.

Photogrammetry on snow is known as a challenging task. Especially fresh snow, homogeneous surfaces and insufficient lightning cause the SfM algorithms to fail (Bühler et al., 2017). Therefore, the flights were mainly conducted on sunny days but even with diffuse lightning the photogrammetry worked on the snow surfaces, which are generally structured by wind.

4.1 Research site monitoring (Perimeter A)

The research site monitoring was performed with flights at 25 m above ground. This led to very high-resolution DSMs and orthophotos of 1 cm spatial resolution. The horizontal accuracy of this setting can be evaluated using ground checkpoints in snow-free areas. However, this has not been implemented yet. The vertical accuracy assessment was conducted calculating the differences of DSMs at 200 randomly distributed points on the flat roof of the large building for ten dates that were free of snow. The resulting overall mean deviation is 0.005 m, and the mean standard deviation (SD) is 0.002 m (Table 2). Thus, the vertical positioning accuracy of the dock-based UAS far exceeds the specification of the RTK base station positioning accuracy given in Table 1. The last two flights from July 2026 were performed on two consecutive days under snow-free conditions. The overall deviations of the DSMs for the entire perimeter were 0.006 m with a standard deviation of 0.02 m, supporting the very high accuracy identified on the roof sub-area.

Date	*Min [m]*	*Max [m]*	*Mean [m]*	*SD [m]*
20260508	0.003	0.029	0.015	0.004
20260526	-0.002	0.014	0.006	0.003
20260528	-0.003	0.011	0.003	0.002
20260531	-0.000	0.010	0.006	0.002
20260604	-0.006	0.007	0.002	0.002
20260608	-0.004	0.014	0.008	0.003
20260615	-0.002	0.012	0.005	0.003
20260625	-0.000	0.016	0.007	0.003
20260702	-0.010	0.003	-0.003	0.002
20260703	-0.004	0.012	0.005	0.002

Table 2: Vertical accuracy assessment for ten surveys on the snow-free roof of the large building at the Weissfluhjoch research site.

Additionally, we validated the snow depth measured by the drone using an automated laser snow depth sensor at the research site (Campell Scientific SDMS-30). Comparing all surveys taken throughout the winter, we found a high level of agreement between the two systems. The mean deviation was 0.012 m, and the mean standard deviation was 0.016 m (Figure 3).

The four drone surveys showing higher mean deviations (> 0.03 m) occurred during the last days

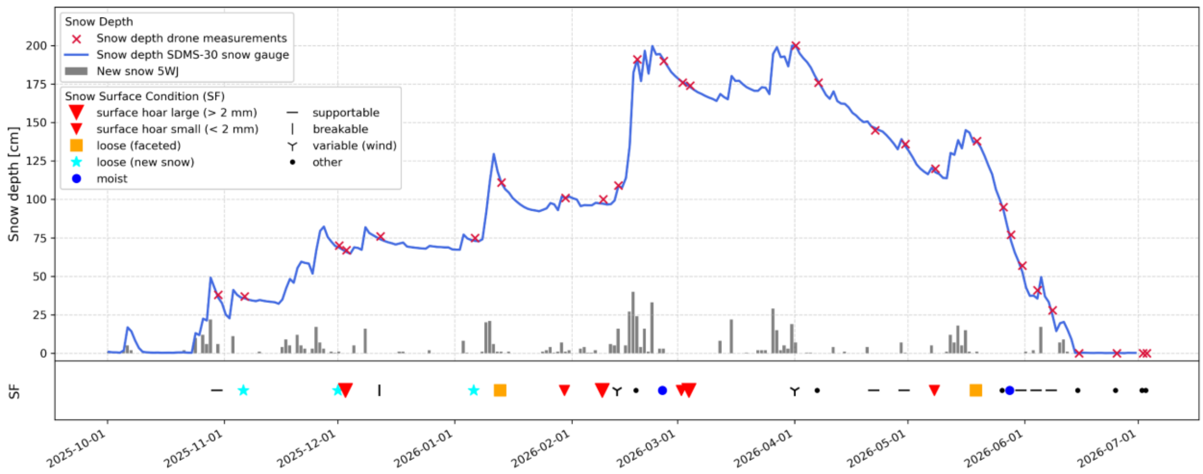

Figure 3: Comparison of drone-measured snow depth and laser-measured snow depth at the SDMS-30 snow gauge location for winter 2025/26 (RMSE: 0.02 m), augmented with daily manual new snow depth and snow surface observations at the 5WJ Weissfluhjoch research site. The drone-measured snow depth is reliable on all snow surface types and independent of absolute snow depth.

with snow cover, when uneven snowmelt processes caused high variability in snow depth. It then became apparent that we cannot compare the two measurement systems at the exact same location because the laser distance sensor is mounted on a horizontal bar, creating noise in the DSMs.

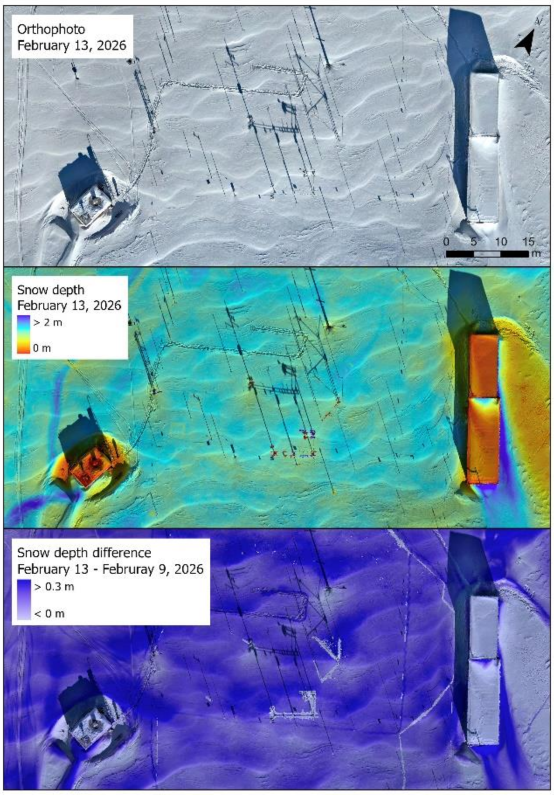

Figure 4: Snow drift observed after the snow fall on February 13, 2026. High resolution orthophoto (top), snow depth (middle) and snow depth difference (bottom) maps from drone survey.

For the first time, the drone docking station allows spatially continuous monitoring of the variability of snow depth at the research site over an entire winter. The spatial-temporal change analysis of consecutive surveys before and after snow fall periods reveal snow drift patterns at high resolution (Figure 4).

Equally interesting is the close observation of the spatial-temporal snowmelt patterns (Haugeneder et al. 2023), as well as monitoring snow loads on buildings' roofs by combining snow depth and SWE measurements at the research site.

4.2 Upper Dorftälli monitoring (Perimeter B)

The upper Dorftälli area was monitored using flights at 100 meters above ground. High-resolution DSMs and orthophotos with spatial resolutions of 10 and 4 cm, respectively, were derived from these flights. The focus of interest for this larger area is snow depth variability, snow drift, and avalanche activity (Figure 5).

Avalanche forecasters may benefit from mapping avalanche activity and size as well as detailed measurements on avalanches like fracture depth (Figure 6). Comparing flat-field snow depths to the distribution of snow depths in nearby avalanche release areas acquired with high spatial and temporal resolution provides valuable insights that aim to improve future avalanche hazard management.

Furthermore, the ski resort management benefits from detailed snow depth information on the slopes and in marked freeride routes, as well as the exact volume of snow reserves, which optimizes snow production and ski slope management. Moreover, a drone dock simplifies the routine inspection of infrastructure in a ski resort.

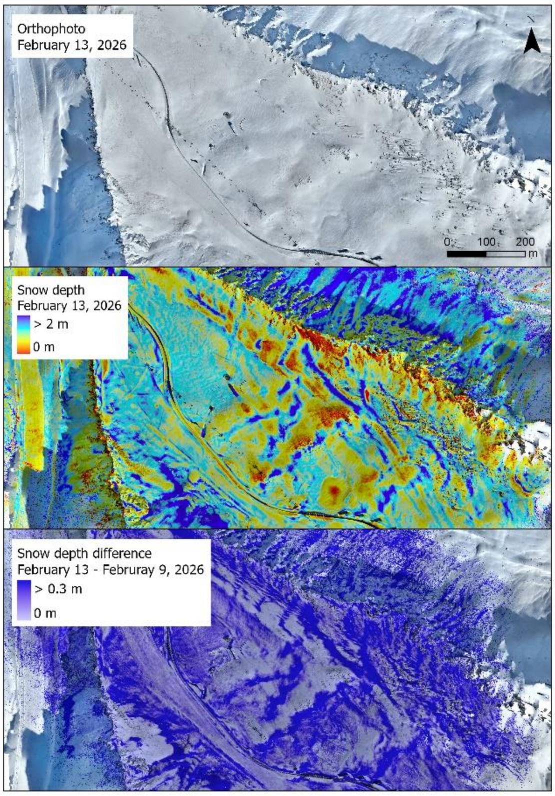

Figure 5: Snow depth variability upper Dorftälli on February 13, 2026. Medium resolution orthophoto (top), snow depth (middle) and snow depth difference (bottom) maps from drone survey.

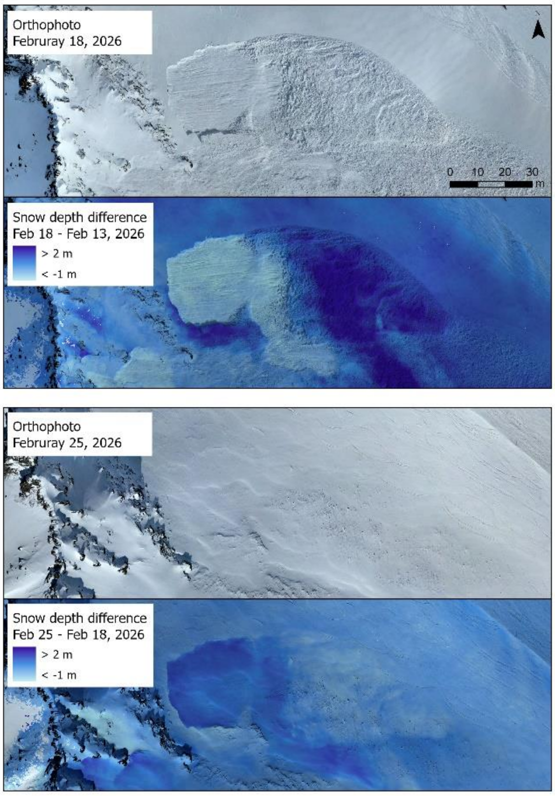

Figure 6: Avalanche observation in orthophoto and snow depth difference map February 18 (top), release areas are fully refilled in the subsequent survey of February 25, 2026 (bottom).

5. DISCUSSION

Maschler et al. (2026) demonstrated the feasibility of geohazard monitoring in mountainous regions by conducting drone-based analyses of unstable slopes and glacial hazards, as well as deposition monitoring following rock-ice avalanches. However, winter deployment was not tested. The drone docking station installed at the Weissfluhjoch research site in winter 2025/2026 is the first successful implementation of a drone dock in the field of snow and avalanche monitoring. This study shows that the dock's operational reliability and level of accuracy allow for consistent surveys throughout the winter.

However, regulatory constraints didn’t allow for automated monitoring in this first season. At the end of May 2026, the special permission for automated flights beyond visual line of sight (BVLOS) for perimeter A was received. Currently an extension of the Specific Operation Risk Assessment (SORA) for BVLOS operations in perimeter B is under review.

Apart from regulatory constraints, dock-based UAS installations require sufficient power supply not only for the charging of the drone, but also for heating and cooling of the system as well as mobile data coverage for communication. Ski resorts usually support this necessary infrastructure. RTK/PPK systems allow for centimeter-scale georeferencing and therefore are required for detailed monitoring applications.

The successful operation of dock-based UAS is challenged by weather and lighting conditions. Adverse weather conditions, such as precipitation, fog, high wind speeds, and insufficient lighting, can cause photogrammetric mapping to fail. Sudden air traffic and rapidly changing weather conditions may also endanger the safety of drone operations and precision landings. However, future LiDAR drones for docking stations will enable night flights, making air traffic risks and lighting issues practically negligible.

CONCLUSIONS

This study demonstrates that automatic, dock-based UAS represent a new approach to the spatial-temporal mapping of the environment with very high spatial resolution, accuracy and consistency, transitioning from campaign-based surveys to automated, frequent monitoring systems. Switching from standard surveys to continuous, near-real-time monitoring allows for the detection of rapid surface changes that would otherwise go unnoticed. Avalanche forecasters as well as ski resort managers benefit from detailed snow depth information. However, the harsh alpine environment remains a challenge for frequent flights at regular intervals. Regulatory constraints currently prevent these systems from reaching their full potential. For example, placing multiple drone docking stations near mountain resort facilities could create a network, enabling continuous regional coverage and innovative applications for avalanche research and practice.

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