REMOTE SENSING FOR AVALANCHE PRACTICE AND SCIENCE: WHAT HAVE WE ACHIEVED, AND HOW CAN WE ADDRESS WHAT IS STILL MISSING?

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ABSTRACT: Over the past 50 years, remote sensing has evolved from a classified tool for military applications into a public and often freely available source of information. This major democratization of remote sensing has also had a significant impact on snow and avalanche research and practice. Today, ground-, drone-, airplane-, and satellite-based mapping of avalanche outlines and snow depth distributions has become an important and well-validated component of the avalanche information puzzle. However, the technical potential, particularly of drones and satellites, would enable a much broader application of these tools, aimed at spatially explicit mapping with high spatial and temporal resolution. Key limiting factors include restrictive drone regulations and the high costs associated with certain satellite and airplane data products. Remote sensing-based information on snowpack stability, on the other hand, is not yet operationally available. Although first attempts using ground-penetrating radar have been undertaken, and some results show potential for practical application, further research and real-condition testing within avalanche release areas remain necessary.

Here we outline the development of remote sensing from early satellite imagery and aerial photography to recent drone-based data acquisitions and provide an overview of the achievements and operational implementations accomplished by the avalanche remote sensing community. We compile an overview of the remote sensing-based tools that are successfully applied today in snow and avalanche research and identify the most relevant gaps. Based on this assessment, we outline potential tools and approaches to overcome the identified limitations in the future. Remote sensing still holds considerable potential to further advance avalanche science and practice.

KEYWORDS: Remote sensing, drones, satellites, photogrammetry, LiDAR, RADAR.

1. INTRODUCTION

Balloon pilots, the first people in the air, discovered that the view from above is not only exciting, but also helpful for various applications. Figure 1 left shows the initial image from a balloon over the city of Paris. It was recorded as early as 1858. At the beginning of the 20th century, with the development of airplanes, aerial imagery started to be more commonly acquired, fostered by military usage during the two world wars and aerial photogrammetry was also applied (Albertz, 2001). The first satellite image depicting snow cover was recorded by the TIROS-1 meteorological satellite in 1960 (Figure 1, right) and more detailed snow-focused satellite data analyses followed (Barnes and Bowley, 1968; Rango and Itten, 1976; Haefner et al., 1997; Dozier, 1984).

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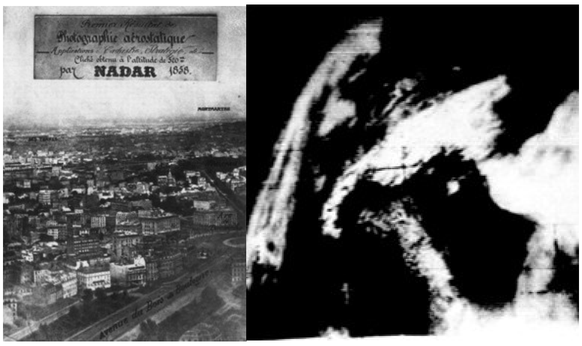

Figure 1: What is believed to be the first aerial imagery taken from a balloon over Paris in 1858 on the left (source: https://parishistoryofourstreets.com/2021/04/28/the-first-paris-aerial-photo/) and first satellite (TIROS-1) image showing snow over the Alps on the 2nd of April 1960 on the right (Singer and Popham, 1963).

With the availability of more airborne and spaceborne platforms and sensors, remote sensing of snow and avalanches was further developed. Large-scale snow cover products were developed based on low spatial resolution satellite imagery (Hall et al., 2002; Foppa et al., 2004; Lillesand et al., 1982).

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Investigations on snow surface characteristics such as grain size, impurities and surface roughness refined the snow observations (Dozier, 1989; Nolin and Dozier, 1993; Fily et al., 1997) by applying an extended radiometric resolution with different wavelengths such as near infrared (NIR) and short-wave infrared (SWIR) based on spectral reflectance curves of snow measured by Warren and Wiscombe (1980).

Snow depth and snow water equivalent were assessed with passive microwave sensors (Ulaby and Stiles, 1980; Chang et al., 1982); however, the spatial resolution (25 km) and the accuracy are limited and do not reliably depict mountain snowpacks. Also, active microwave sensors with higher spatial resolution (up to 20 m) have been applied (Schanda et al., 1983; Shi and Dozier, 2000). But these approaches only work for dry snowpacks and do not work well in steep alpine terrain. To overcome these limitations, first attempts to measure snow depth with photogrammetry from airplanes were performed by Smith et al. (1967) and Cline (1994), before the first LiDAR sensors became available.

Building on these pioneering investigations, remote sensing developed into an important tool for snow and avalanche research and increasingly also for practice. In 2012, at the ISSW in Anchorage, AK, (Bühler, 2012) presented a first review article on new developments in remote sensing for avalanche applications and in Eckerstorfer et al. (2016) a first update was provided. The emergence of drones, starting about two decades ago, enables measurements of relevant parameters also within poorly accessible terrain. Also, the development of new satellite sensors enables large-coverage mapping in remote areas. The most important limiting factors are the available resolutions:

- **Spatial resolution** defining the level of detail that can be identified in the data often also referred to as pixel size or ground sampling distance (GSD).
- **Spectral resolution** representing the spectral bands that can be recorded.
- **Radiometric resolution** defining how many values can be stored and with that the sensitivity of the measurements. This is important because low radiometric resolution (e.g. 8 bit = 256 different values) would result in saturation of the data.
- **Temporal resolution** defined by the time gap between data acquisitions.

In the following, we give an overview and the recently achieved progress for snow depth mapping, avalanche mapping, snow surface mapping and snowpack parameters and identify the most relevant research gaps.

2. SNOW DEPTH MAPPING

The spatial distribution of snow depth (HS) and snow water equivalent (SWE) are critical parameters for avalanche formation but also for further applications such as winter tourism, hydropower generation or ecology. Traditionally, snow depth is measured at point locations either by observers manually or by automated weather stations (Bühler et al., 2024), not capturing the spatial distribution at the local to regional scale.

Remote sensing can map the snow depth distribution spatially continuously over larger areas. Terrestrial (Prokop, 2009; Grünewald and Lehning, 2011; Revuelto et al., 2020) and airborne (Hopkinson et al., 2004; Deems et al., 2006; Painter et al., 2016) LiDAR were successfully applied to map snow depth in mountain terrain (Deems et al., 2013). Photogrammetry from airplanes (Bühler et al., 2015a; Nolan et al., 2015; Meyer and Skiles, 2019; Bührle et al., 2023) is increasingly used for detailed mapping of mountain snow covers. Photogrammetry from satellites is used (Marti et al., 2016; Shaw et al., 2020) but the achieved RMSE accuracies of approximately 50 cm are clearly lower than for the airborne mapping (Eberhard et al., 2021). Laser altimetry from satellites is also applied but measures only transects (Fair et al., 2025). Also radar satellites are used to map snow depth distribution over larger regions (Lievens et al., 2022), however, the achieved accuracies and reliability are comparatively low.

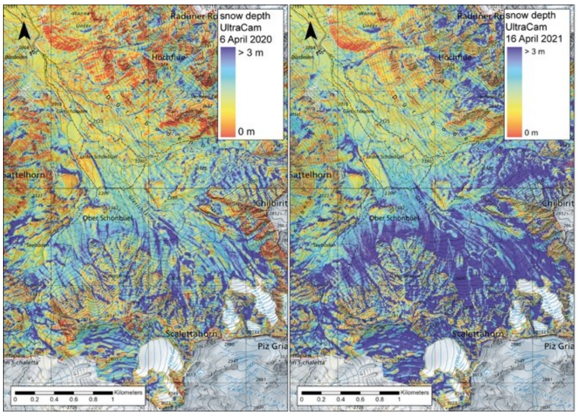

Figure 2: Snow depth distribution mapped with the airborne photogrammetric survey camera UltraCam and a spatial resolution of 0.5 m in spring 2020 and 2021 within the Dischma valley, Davos, Switzerland (Bührle et al., 2023).

Drones, available for roughly two decades, offer flexible and accurate snow depth mapping, photogrammetrically (Vander Jagt et al., 2015; Bühler et al., 2016; Harder et al., 2016; Revuelto et al., 2021) and with LiDAR (Harder et al., 2020; Jacobs et al., 2021). But they are only able to cover smaller areas of a few km^2.

These powerful tools enable a very accurate (better than 10 cm) mapping of the snow depth distribution, and, with a sound estimation of the average snow density, also of the snow water equivalent (SWE). The limiting factor is the temporal resolution, as the flying of airplanes or drones is still quite costly. Therefore, machine learning (ML) approaches are tested to model the daily snow depth distribution, trained with data from drones or airplanes (Daudt et al., 2023; Small et al., 2026). Or in-situ LiDAR instruments are set up to capture short-term snow depth variation (Ruttner et al., 2025). But the reliability of the ML approaches is still quite limited, and the in-situ settings can only cover small areas. Therefore, a large-scale high spatial and temporal resolution snow depth mapping system is still missing. Maybe long-endurance drone systems could be a solution for this, however the legal settings for flying drones beyond visual line of sight (BVLOS) are still very restrictive (https://www.bazl.admin.ch/en/drone).

3. AVALANCHE MAPPING

The detailed mapping of avalanches is essential to build meaningful avalanche cadasters that are the basis for safety-critical applications such as hazard mapping or mitigation measure planning. Traditionally, avalanche outlines are mapped from direct observations by avalanche experts or from field photographs and are depicted manually on maps.

First remote sensing based mapping of avalanches was performed by Vallet et al. (2000) with a helicopter based LiDAR. Gruber and Margreth (2001) used aerial black and white survey imagery to map extreme events of the avalanche winter 1999 in Switzerland. Bühler et al. (2009) applied a surveying sensor on an airplane (ADS40) to automatically map snow avalanches in the region of Davos, which was further refined by Korzeniowska et al. (2017). Lato et al. (2012) then applied very high spatial resolution satellite imagery (Quickbird with 0.6 m) to classify and segment avalanche outlines in Norway and Switzerland.

Since optical imagery depends on cloud-free conditions, radar satellites were tested to map avalanche outlines at first mainly in Norway, Svalbard and Greenland (Eckerstorfer and Malnes, 2015; Vickers et al., 2016; Wesselink et al., 2017; Eckerstorfer et al., 2017; Abermann et al., 2019) because the temporal resolution for the Sentinel-1 satellites is higher towards the poles. A bit later this approach was also tested in the Alps (Karas et al., 2021; Kapper et al., 2023) and with higher resolution radar satellites (Leinss et al., 2020). However, besides the advantage that radar can acquire data also under cloudy conditions and during night, these approaches struggle with mapping the avalanche outlines accurately, and dry snow is nearly transparent to the radar signal in C and X-band (Eckerstorfer et al., 2022).

To cover large regions and to map the outlines including release areas as completely as possible, high spatial resolution SPOT6 data was tasked in rapid mapping mode to map a large part of the Swiss Alps during two avalanche periods in January 2018 and 2019 (Bühler et al., 2019; Hafner et al., 2021). The manually mapped outlines were then applied to develop a deep learning avalanche mapping approach (Hafner et al., 2022) that performs comparably to experts mapping the avalanches manually but requiring hours instead of months (Hafner et al., 2023). This model was further developed to also map avalanches in webcam or drone imagery (Hafner et al., 2024a) including webcam imagery acquired by Fox et al. (2023) as well as for aerial black and white imagery from 1999 (Dal et al., 2024; Hafner et al., 2024b).

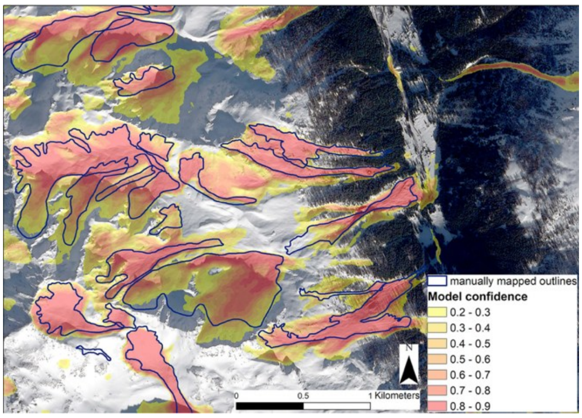

Figure 3: Result of a deep learning model classifying avalanche outlines in optical SPOT6 satellite data over a large part of the Swiss Alps in January 2018 and 2019 (Hafner et al., 2022).

Once again, the approaches developed for avalanche mapping show great promise as a complement to existing databases. However, the temporal resolution remains insufficient. Therefore new high spatial resolution radar satellites with all-weather capability such as ICEYE (Manconi et al., 2024) or UMBRA show great promise but still cover only small regions and are very expensive. Lim et al. (2026) propose a long endurance drone platform to map avalanches over large regions, however, the aviation regulations are currently not allowing such promising approaches.

Figure 4: Difference image of two ICEYE radar satellite scenes, acquired during a bad weather avalanche cycle in February 2026 over Davos, Switzerland. Such high spatial resolution (better than 0.5 m) that can see through clouds is very promising for future avalanche mapping systems.

4. SNOW SURFACE MAPPING

The characteristics of the snow surface are important. If the snow surface could be mapped efficiently before large snowfall events, the locations and extents of potential weak layers could be estimated. An example for such layers of interest are thin old snow layers that transform into depth hoar during periods with clear nights. A layer of surface hoar buried by a large snowfall can turn into a weak layer that contributes to avalanche formation (Schweizer et al., 2003; Dillon et al., 2024). Nevertheless, a continuous mapping of snow surface characteristics in mountain regions is still missing. Bühler et al. (2015b) assessed the potential for optical satellite and aerial imagery for the mapping of different snow surface types such as windblown snow or ice crusts with high spatial resolution. Horton and Jamieson (2017) analyzed the spectral signatures of surface hoar crystals.

Impurities such as dust or soot from fires alter the albedo of the snowpack and also its stability (Dick et al., 2023). Impurities at the snow surface have been investigated by applying various optical remote sensing instruments (Tanikawa et al., 2002; Skiles et al., 2015; Tuzet et al., 2019; Réveillet et al., 2022; Lang et al., 2025).

5. SNOWPACK PARAMETERS

Information on the snowpack stratigraphy and the presence of potential weak layers and slabs are key for avalanche prediction (Schweizer et al., 2003). Snow stratigraphy is operationally measured using snowpits and/or penetrometers at point locations and transects (Pielmeier and Schneebeli, 2003; Proksch et al., 2015). Recently Chies and Di Pietro (2024) developed a drone with an acoustic snow penetrometer allowing the access of avalanche release areas in periods of high avalanche danger (Chies et al., 2024; Di Pietro et al., 2024). The presence of free water in the snowpack is important for wet-snow avalanches (Baggi and Schweizer, 2009; Mitterer et al., 2011) and at the interface between ground and snow for glide-snow avalanches (Fees et al., 2025; Lombardo et al., 2025). Free water in the snowpack can be identified by applying radar satellites (Rott, 1984; Shi and Dozier, 1995; Nagler and Rott, 2000; Rondeau-Genesse et al., 2016).

Large scale information on the evolution of snow wetness has been proposed by using satellite radars (Nagler and Rott, 2000) and recently evolved due to the availability of more frequent SAR acquisitions (Nagler et al., 2018; Dasser et al., 2024). This approach shows potential, but it is still limited by the spatial and temporal resolution currently available.

Spatially continuous mapping of snowpack parameters remains very challenging (Dupuy et al., 2025). Ground penetrating radar (GPR) is tested on the ground (Griessinger et al., 2018; Bonnell et al., 2023), on helicopters (Sold et al., 2015) and drones (Jenssen et al., 2019; Valence et al., 2022; Vergnano et al., 2022). However, a reliable and effective identification of potential weak layers has not yet succeeded.

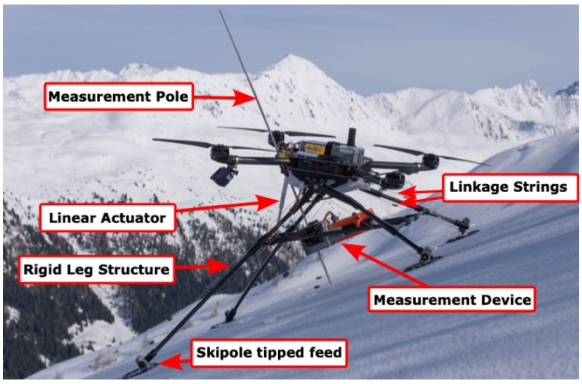

Figure 5: Drone with an acoustic snow penetrometer able to land in steep terrain and sample avalanche release areas efficiently (Chies et al., 2024).

Therefore, the missing puzzle piece is still the large-scale and spatially continuous mapping of potential weak layers and overlaying slabs within the snowpack. With the current miniaturization of multi-band radar instruments, they can be made ready for drone applications. However, extensive testing and validation with in-situ snowpack measurements are still necessary to meaningfully interpret the often ambiguous radar signals.

6. CONCLUSION

Remote sensing has developed into a key tool for avalanche research and some practical applications. The development of drones (RPAS, UAV, or UAS) enables the application of various sensor systems also in poorly accessible mountain terrain. However, the current aviation regulations do not allow for efficient applications over large areas yet. New satellite sensors with higher spatial and temporal resolution also enable larger scale mapping of relevant parameters. Numerous case studies already tested such approaches successfully and the number of applicable satellites is rising fast. However, the processing of the large amounts of data is demanding and most of the new sensors are commercial and therefore currently very costly and difficult to sustain for operational applications.

These promising results still need to be applied to large-scale mapping and modeling efforts that are frequent and reliable enough for practical applications, such as avalanche warnings and mitigation measure planning. Especially mapping the distribution of weak layers in the snowpack in combination with snow depth distribution would allow for more spatially specific avalanche warnings but requires more research and testing as well as the combination of different sensors and platforms.

The achievements of the remote sensing and avalanche communities over the past few decades are impressive. By further combining the technical advances in sensor technology and machine learning with the community research efforts in close collaboration with practice, the listed limitations can be narrowed down in the next years to fully exploit the potential of remote sensing for avalanche applications.

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