SAR REMOTE SENSING AS A SUPPORT TOOL FOR OPERATIONAL AVALANCHE FORECASTING

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ABSTRACT: Synthetic Aperture Radar (SAR) remote sensing has increasingly been exploited for snow and avalanche research to derive spatially explicit information. For example, models have been developed to detect wet snow, measure snow depth, and reconstruct avalanche activity by identifying avalanche deposits. These models have demonstrated their effectiveness in retrieving snow cover information over time, allowing the derivation of valuable historical records for specific regions. Such information is crucial for avalanche-related land-use planning, which relies on the occurrence and extent of past extreme avalanche events. It also supports the development of reference datasets to validate and improve snowpack and avalanche hazard modelling approaches. However, the role of SAR in operational avalanche forecasting remains less straightforward, as SAR data are typically collected at multi-day intervals and primarily provide information on current or past conditions, whereas public avalanche forecasts are issued daily to support short-term forecasting. This temporal mismatch raises an important question: how can SAR data meaningfully contribute to operational avalanche forecasting? In this study, we address this question from the perspective of a forecaster. Rather than viewing SAR as a standalone tool, we frame it as an additional layer of information that can support field observations and the monitoring of snowpack conditions. Using real-case examples from the Livigno Avalanche Center (Italy) and Tromsø (Norway), we show how SAR-derived information can help update or confirm the spatial distribution of key avalanche-relevant features and highlight areas where field evidence is sparse. Specifically, we show how SAR-derived products are translated into the improvement of avalanche forecasting throughout a winter season. Overall, this work argues that the value of SAR for operational avalanche forecasting lies not only in snowpack monitoring, but also in its ability to provide independent, spatially extensive snapshots that can strengthen the forecast process, improve the consistency of public avalanche forecasts, and bridge gaps between field observation and snowpack spatial variability.

KEYWORDS: Synthetic Aperture Radar; remote sensing; wet snow; snow depth; avalanche deposits.

1. INTRODUCTION

Avalanche forecasting relies fundamentally on the acquisition of different physical snow parameters and avalanche activity observations (McClung, 2000). These data, traditionally acquired through field surveying, are increasingly complemented by data coming from instrumentation (e.g., automatic weather stations) and numerical snowpack modelling (Morin et al., 2020). Independently, satellite remote sensing has been developed as a means of monitoring snow parameters at different spatial scales (Westermann et al., 2014). Since early studies demonstrated the sensitivity of microwave remote sensing to seasonal snow cover (Mätzler, 1987), Synthetic Aperture Radar (SAR) has become an increasingly preferred tool, as it enables all-weather, day-and-night monitoring, not only of the snow surface, but also of internal snowpack parameters and macroscopic features such as avalanche deposits (Tsai et al., 2019). For a better understanding of SAR working principle and data processing techniques refer to Flores-Anderson et al. (2019). Among the best-known SAR platforms is Sentinel-1, equipped with a dual-polarization C-band sensor and operational since 2014, with a maximum revisit time of six days in its current two-satellite configuration. Sentinel-1 data are made freely available by the European Space Agency (Potin et al., 2014).

In the snow monitoring field, SAR products have been successfully tested primary for three main applications: wet snow (WS) detection; snow depth (HS) retrieval; avalanche deposits mapping. Since the dielectric constant of wet snow at microwave frequency is significantly larger than the one of dry snow (Mätzler, 1987), signal penetration is strongly inhibited, and the backscatter is

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consequently reduced compared to dry snow or snow-free conditions. This property enables wet snow mapping through amplitude change detection algorithms, such as in Nagler and Rott (2000). Conversely, the lower dielectric constant of dry snow makes HS retrieval less straightforward, especially at C-band (Strozzi et al., 1997). To this end different techniques have been developed, such as phase-delay interferometric approaches (Rott et al., 2003) or amplitude change detection coupled with polarimetric indices (Lievens et al., 2022; Mariani et al., 2026a). Finally, SAR-based avalanche deposits mapping exploits, within a change detection framework, the significant backscatter increase at the avalanche deposit location in post-event conditions with respect to that of pre-event undisturbed snow (Malnes et al., 2015). This technique is valid for both dry and wet snow avalanches (Eckerstorfer et al., 2016; Keskinen et al., 2022; Mariani et al., 2026b). In recent years, machine learning techniques have been increasingly employed to support avalanche mapping (Bianchi et al., 2020; Bianchi and Grahn, 2025; Gatti et al., 2026; Leinss et al., 2020).

Even if SAR remote sensing of snow properties is a well-defined and active research topic, its application in operational avalanche forecasting remains limited, and, to our knowledge, no public avalanche forecasting service operationally uses SAR data in its operations. In the present work, from the perspective of an avalanche forecaster, we show how SAR-based products, despite their limitations, can assist the avalanche forecasting procedure and can be coupled with traditional models and manual observations. In Sect. 2 we briefly recall different SAR-based snowpack monitoring techniques together with their limitations. In Sect. 3 we discuss SAR potential from the perspective of an avalanche forecaster. In Sect. 4 we present some application examples from Livigno (Italy) and Tromsø (Norway), where the Livigno Avalanche Center (Alpsolut S.r.l.) operationally performs Sentinel-1 based SAR monitoring for avalanche forecasting purposes. Finally, we conclude in Sect. 5.

2. SAR MONITORING OF SNOWPACK

2.1 SAR data and preprocessing

For all SAR-based snow products presented in this work, Sentinel-1 Ground Range Detected (GRD) images have been downloaded from the Copernicus Data Space Ecosystem (2026) and processed following the standard preprocessing chain reported in Mariani et al. (2026b). Images from different acquisition geometries are used: Sentinel-1 always acquires in the early morning during descending passes (North to South) and in the afternoon during ascending passes (South to North), usually one day apart.

2.2 Wet snow detection

Wet snow detection is achieved through the method first introduced by Nagler and Rott (2000) and later adapted to Sentinel-1 by Nagler et al. (2016). This method applies a threshold to the backscatter ratio computed between a current SAR acquisition and a reference image. The latter is obtained by averaging one or more images acquired under dry-snow or snow-free conditions. Because C-band signals only interact with the uppermost wet part of the snowpack, the method cannot distinguish whether the detected wetness originates at the surface or deeper within the snowpack. Furthermore, vegetated areas present strong biases (Manickam and Barros, 2020). The standard product is generated on a 100 m grid.

2.3 Snow depth retrieval

Snow depth mapping follows Mariani et al. (2026a), using variation in a dual-polarimetric index computed between each winter acquisition and a summer reference image. The method retrieves HS only under dry snow conditions and for Local Incidence Angles (LIAs) greater than 30°, with an MAE and an RMSE between 20 cm and 30 cm. Moreover, forested areas are invalid for HS monitoring (Ying et al., 2025). Importantly, Mariani et al. (2026a) demonstrate that some snowpack properties, like density and grain size, affect HS retrieval, making amplitude-based snow depth products potentially unstable in heterogeneous mountain terrain. This is a problem that must be considered when exploiting SAR for operational avalanche forecasting. The product is generated on a 50 m grid.

2.4 Avalanche monitoring

Automatic avalanche deposit detection is performed using the Convolutional Neural Network model presented in Gatti et al. (2026). It can be applied in near-real-time, detecting avalanches during a winter season, or retrospectively, reconstructing all avalanche deposits since the start of the Sentinel-1 mission in 2014 (Eckerstorfer et al., 2017; Mariani et al., 2026b). Due to its spatial resolution, Sentinel-1 cannot detect avalanches of size one (small avalanches), with the best detection performance being for avalanches of size class greater than three (Gatti et al., 2026). As shown by Mariani et al. (2026b), this neural network model works for both dry and wet snow avalanches, however specific areas and particular variations in the snow conditions can lead to biases.

3. DEVELOPMENT

3.1 Why has SAR not yet been adopted for operational avalanche forecasting?

The limited adoption of SAR for operational avalanche forecasting is related to a combination of practical and technical limitations. SAR platforms have their own revisit time, which is not daily everywhere. The revisit time can be defined as the time needed by the satellite to acquire images over the same location, and differs from the repeat cycle, which is the time needed to acquire images over the same location with the exact same acquisition geometry (i.e., heading and incidence angle). As reported in Attema et al. (2008), for the two-satellite Sentinel-1 configuration, the revisit time varies from around one day at high latitudes to about three days at mid-latitudes, while the repeat cycle remains fixed at six days worldwide (see Figure 1). Clearly, WS and HS retrieval directly refer to the acquisition date. On the other hand, concerning avalanche detection, pre- and post-event images are subsequent acquisition of the same geometry, meaning that even if a new detection is available in few days, this always refers to a six-day window prior to the acquisition date (Eckerstorfer et al., 2017; Leinss et al., 2020).

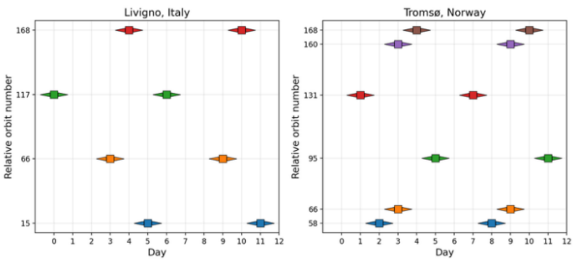

Figure 1: Sentinel-1 passages over Livigno and Tromsø with the current two-satellite configuration (summer 2026). Each color represents a different acquisition geometry identified by its Relative Orbit Number.

Beyond these temporal constraints, SAR data can be complex to interpret without background knowledge of microwave-snow interactions. This is particularly true for WS and HS retrieval, where the results quality varies substantially with snowpack properties and SAR acquisition geometry, with HS retrieval becoming potentially unfeasible during the melting season (Brangers et al., 2024; Mariani et al., 2026a). Avalanche detection is similarly affected: variable snow conditions between pre- and post-event acquisitions strongly influence the occurrence of both false positives and false negatives (Mariani et al., 2026b). Finally, SAR data processing can be computationally intensive and requires specialized technical expertise.

3.2 SAR as an additional, conventional data source

Conventional data sources used in operational avalanche forecasting include periodic field observations, such as snow stratigraphies and stability tests (McClung and Schaerer, 2006), snowpack modelling (Lehning et al., 1999; Mayer et al., 2023), numerical weather models, automatic weather stations, and avalanche records (Schweizer, 2003). The strengths and limitations of each of these data sources are well understood within the avalanche forecasting community. Rather than relying on a single source, forecasters integrate multiple types of information and combine them with their own expertise (LaChapelle, 1980; McClung, 2002).

Similarly, SAR-derived snow products have inherent limitations, but they can complement these conventional data sources. Regular satellite acquisitions provide spatially continuous snapshots of snow conditions over large areas, offering information that avalanche forecasters, with their experience, can interpret and critically evaluate in the context of all available evidence. This additional perspective can help improve the overall understanding of the avalanche situation, while the resulting assessment can be updated as new observations and satellite acquisitions become available. Furthermore, SAR-derived products enable field observations to be extrapolated spatially, extending local measurements to a broader regional context. Conceptually, this is not fundamentally different from a forecaster conducting field observations to characterize the snowpack and establish a sound basis for subsequent forecasts. The key advantage of SAR is that it provides large-scale information remotely, including in inaccessible or hazardous terrain, although with its own set of limitations.

3.3 Small-scale and large-scale applications

A peculiarity of SAR is that it can support avalanche forecasting at different spatial scales. Following the distinction introduced by Statham et al. (2018), large-scale applications cover an entire region, typically corresponding to sparsely and poorly monitored areas, where the forecasting activity aims to describe a general hazard situation across broad sub-regions. Conversely, small-scale applications are related to more detailed forecasting activities for a specific location, where observations are comparatively dense and the forecasting activity focuses on describing avalanche hazards at the scale of individual slopes or mountain massifs.

4. APPLICATION EXAMPLES

4.1 Wet snow monitoring

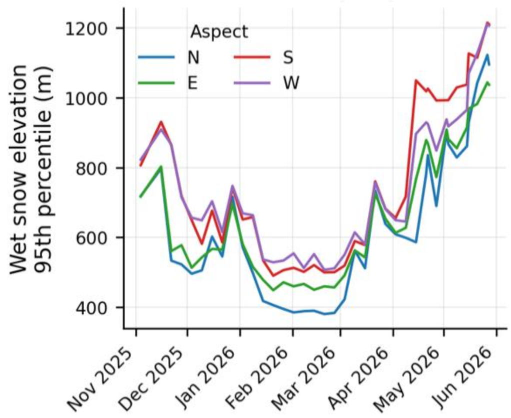

Figure 2: Seasonal evolution of the maximum wet snow line for each aspect in the Tromsø region, winter season 2025/26.

On a large scale, SAR-based WS products can be used to retrieve the wet snow line after rain-on-snow events and throughout the season, or localize sub-regions potentially affected by wet snow problems. Figure 2 reports an example of wet snow cover extent evolution trough a season from the Tromsø region. Since vegetated areas are affected by significant biases (Manickam and Barros, 2020), the wet snow line never descends below 400 – 500 m a.s.l. The late December peak corresponds to a widespread rain-on-snow event below 900 m a.s.l., followed by a general temperature decrease leading to refreezing at all aspects. Wet snow elevation begins to differentiate again with the onset of the spring season.

On a small scale, when WS instability is flagged by external sources, such as snowpack modelling or snow stratigraphies, SAR can provide a snapshot of the WS extent over individual slopes, spatializing this point-wise information. The availability of both morning and afternoon acquisitions further allows the minimum and maximum extent of the wet snow problem to be envisioned (see Figure 3).

4.2 Dry snow monitoring

On a large scale, HS retrieval highlights regional spatial variability, a crucial information for avalanche size estimation. Nevertheless, the most interesting application of this SAR technique is on a small scale, through accumulation and erosion maps, a product still in the development phase. Accumulation and erosion maps can be computed as the local Z-score of HS within a 300 m moving window, using HS acquisitions from a single relative orbit to preserve a consistent viewing geometry. Areas with Z > 0 indicate relative accumulation, while areas with Z < 0 indicate relative erosion. Since forested areas are invalid for HS monitoring (Ying et al., 2025), they are excluded from the computation. Importantly, the Z-score partially compensates for the instability of HS retrieval associated with varying snowpack properties, making these maps more reliable than HS maps (however, the quantitative HS information is lost).

As visible in Figure 4, areas with a positive Z-score, associated with snow accumulation (blue),

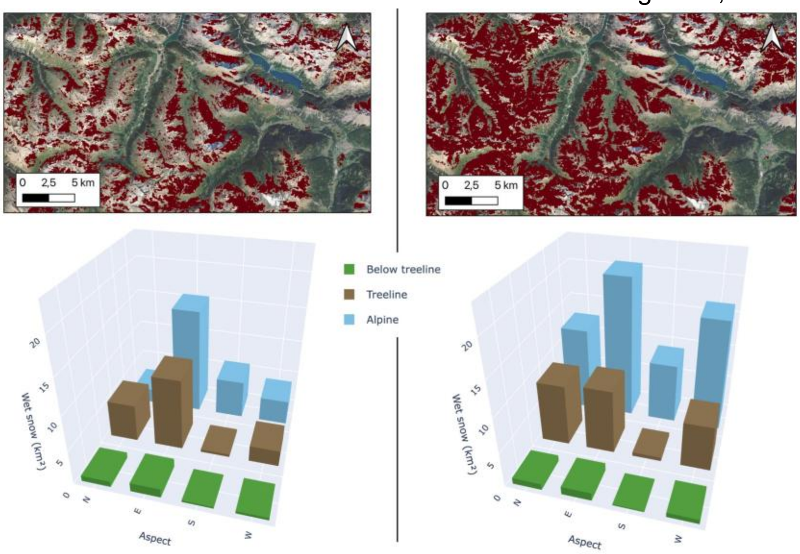

Figure 3: Examples of wet snow cover extent variability in the Livigno area for different aspects and elevation belts. Wet snow is depicted in red on the maps.

are mainly found below ridges, on north-facing slopes or in bowls and gullies. On the other hand, areas with a negative Z-score (red), are generally found along steep or south-facing slopes and ridgelines. Importantly, unrealistic location of accumulations and erosion areas allow forecasters to recognize an invalid SAR acquisition (i.e., affected by significant biases). The spatial heterogeneity of HS can be used to broadly estimate the potential fracture propagation length in the presence of persistent weak layer problems and to identify potential wind-loading hotspots in avalanche starting zones. In addition, this map helps assess the representativeness of existing automatic weather stations, supports the selection of sites for new installations, and facilitates route planning for field observations in avalanche terrain.

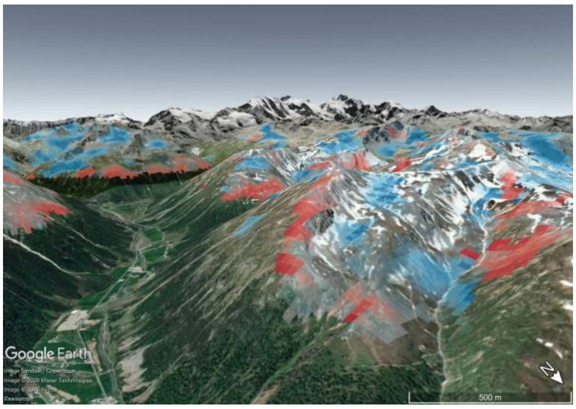

Figure 4: Example of accumulation and erosion map for the area of Livigno, March 2026. Red indicates negative Z-score (HS below the local average), while blue indicates positive Z-score (HS above the local average).

4.3 Avalanche monitoring

On a large scale, SAR-based automatic detection of avalanche deposits has multiple applications. Historical reconstruction of avalanche deposits allows the creation of heatmaps, representing avalanche deposit frequency per pixel. These maps can be used for land-use and route planning in avalanche terrain. Conversely, near-real-time monitoring can be utilized after heavy snowfalls to identify the most affected areas by examining the spatial variability of avalanche activity. Moreover, as done in Mariani et al. (2026b), an Avalanche Activity Index (AAI), similar to the one proposed in Schweizer et al. (2020), can be computed (see Figure 5). In general, large-scale monitoring enables the generation of precious datasets that can be used, for example, to train and validate machine learning models. A further important application at the large scale concerns the validations of avalanche reporting. In extensive or remote forecasting domains, limited accessibility often delays field observations, so avalanches may be reported well after their release, under conditions substantially different from those at the time of failure (e.g., after general snowpack stabilization). This creates ambiguity: the reported avalanche may belong to a previous instability cycle, requiring no further action, or it may be a genuinely recent event pointing to an underestimated instability, warranting further investigation or even a bulletin revision. SAR-based detection, by providing an independent estimate of release timing, can help resolve this ambiguity by double checking the events.

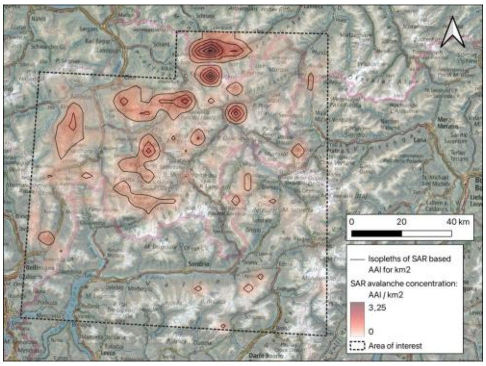

Figure 5: SAR-based avalanche concentration for a 100 x 100 km area around Livigno following a snowstorm event in February 2026.

On a small scale, avalanche detection allows forecasters to quantify the magnitude of the avalanche cycles (see Figure 6) and to validate the avalanche danger level reported in the public avalanche forecasts. Tracking avalanche deposits throughout the season also helps identify mountain slopes that have already released an avalanche, providing insight into the spatial distribution of remaining hazardous locations, particularly during prolonged periods dominated by long lasting persistent weak layer problems dominating the general avalanche situation. In addition, near-real-time SAR-based avalanche detection can support the prioritization of artificial avalanche release interventions and help quantify the residual risk to infrastructure. Indeed, in Livigno SAR avalanche detection is actively used to program artificial avalanche release missions. Although the SAR revisit interval is not daily, this information may still become available earlier than manual observations, particularly during extended periods of poor weather and limited visibility or in remote areas.

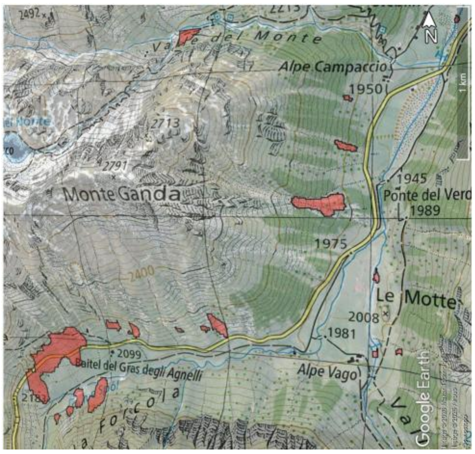

Figure 6: Example of avalanche deposits detection (red polygons) following a major avalanche cycle in Livigno, February 2026.

5. CONCLUSION

SAR monitoring of snow and avalanches is an active research topic, yet its application in avalanche forecasting remains limited. This gap likely stems from the multi-day revisit frequency of current SAR platforms (e.g., Sentinel-1) and from a limited mutual understanding, between SAR and avalanche forecasters, of the advantages and limitations of each monitoring technique.

In this work, exploiting real examples from the Livigno Avalanche Center (Alpsolut S.r.l.), we explained how SAR-based snow monitoring products can be integrated into operational avalanche forecasting. Specifically, we showed how the retrieval of wet snow, snow depth, and avalanche deposits can be incorporated into daily forecasting activities. Like any other data source, each of these products has its own limitations, which forecasters can partially mitigate through integration with traditional observations and their experience. Specifically, SAR platforms provide a snapshot of several snowpack characteristics every few days that can be evaluated by forecasters with a basic knowledge of microwave interaction with snow, allowing them to extract meaningful information, mentally track the evolution of snow between acquisitions, and recalibrate public avalanche forecasts objectively.

We further argue that satellite data, combined with numerical weather models, represent the only viable information source in remote and poorly monitored areas. Future work should proceed on two fronts: refining SAR-based estimation algorithms – led by remote sensing experts – and developing more sophisticated data integration procedures – led by avalanche forecasters. Bridging these two communities, by clearly communicating the advantages and limitations of each SAR-based product to forecasters, remains a key step toward the operational adoption of SAR in avalanche forecasting.

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