

ADVANCING AVALANCHE SAFETY: RADAR-BASED INSIGHTS INTO SNOWPACK DYNAMICS AND STRATIGRAPHY

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ABSTRACT: Avalanches pose significant risks to human life and infrastructure, so understanding their mechanics is critical for effective forecasting and mitigation strategies. Knowledge of avalanche dynamics is fundamental to the development of predictive models that can save lives and protect property. Existing radar-based avalanche measurement systems, including frequency modulated continuous wave (FMCW) radar, ground penetrating radar (GPR), and ultra-wideband snow sounders (UWiBaSS), can access dormant snowpack parameters to reconstruct the structure. In addition, mmWave radar systems can measure snow suspension density. For the assessment of avalanche dynamics, artificial measuring units (AvaNodes) for in-situ measurements have been developed and tested. These systems provide insight into snow depth, density, and general avalanche flow characteristics such as volume, velocity, and direction. Despite the availability of these systems, there remains a gap in the in-depth analysis of the dynamics occurring within an avalanche. Existing approaches capture the snowpack structure in its resting state. In addition, artificial sensor systems can provide insight into avalanche behavior, but cannot measure the dynamics of the layer structure during an event. The proposed approach, using frequency modulated continuous wave (FMCW) radar, aims to fill this gap by allowing the assessment of layer dynamics within the avalanche. This novel radar-based measurement method aims to improve the accuracy of snow stratigraphy and ablation data collection and analysis, providing a more detailed view of the internal dynamics of avalanches. The development of such radar-based measurements represents a significant advance in snow science and natural hazard analysis. It highlights the importance of technical innovation in improving research results and underscores the potential of radar technologies as versatile tools in snow science. This research opens new avenues for understanding gravitational natural hazards and makes a significant contribution to the safety and management of snow-covered environments. Through a better understanding of avalanche dynamics, prediction models can be refined, leading to improved forecasts and ultimately reducing the risks avalanches pose to people and infrastructure.

Keywords: stratigraphy, avalanche dynamics, radar-based measurement, measurement network.

1. INTRODUCTION

Gravity-induced natural hazards, such as snow avalanches, pose a constant threat to human life and infrastructure. Over the years, various risk assessment methods have been developed and refined, particularly for backcountry skiers, relying on avalanche reports and visual predictors. However, when it comes to protecting infrastructure, such as railways, roads, and buildings, the need for robust and reliable hazard prediction models becomes crucial. Current risk management strategies are based on existing research and empirical data, yet there remains a significant need for further optimization. Achieving this requires an in-depth understanding of avalanche behavior.

A promising approach to gaining such understanding is through the application of simulation models. These models allow researchers to study the behavior of avalanches in detail without interfering

with real systems. In avalanche research, several simulation models have been developed, such as *r.avafflow* and rapid mass movement simulation models. The reliability and predictive power of these models depend on thorough verification and validation processes. Verification ensures that the model is correctly implemented, while validation confirms that it accurately reflects real-world avalanche behavior. As such, a comprehensive and reliable data base is essential for developing these simulation models.

Avalanche research encompasses various sub-fields, including avalanche initiation, fracture systems, dynamics, prevention, and safety measures. Detailed analyses focus on factors such as snowpack stratigraphy, fracture initiation, velocity, environmental influences, and topography. To characterize these aspects, a variety of measurement technologies are employed, including radar, photogrammetry, and pressure sensors. These tools are critical for validating simulation models, as they provide essential data on avalanche dynamics, such as flow characteristics, pressure development, and velocity. However, current technologies have limitations; for instance, radar and photogrammetry offer limited

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resolution, while pressure sensors, although robust, may interfere with the avalanche's natural behavior, potentially introducing bias into the data.

In addition to understanding avalanche dynamics, studying snow erosion during an avalanche event could offer valuable insights into the overall behavior of avalanches. Snow erosion involves the breaking up of the snow cover into particles and has not yet been extensively recorded. Developing a spatially distributed sensor network based on radar technology to measure snow erosion is the primary goal of this research.

The creation of such a radar-based measurement system will provide new data and insights into the internal processes of snow erosion during gravitational natural hazards like avalanches. Understanding the evolution of snowpack stratigraphy and snow erosion during an avalanche is crucial for improving forecasting and flood prediction. This knowledge will enhance our understanding of avalanche dynamics and ultimately lead to better prevention and protection measures. The radar-based measurement system developed through this research will gather critical data on avalanche dynamics, facilitating the optimization of hazard prediction and safety strategies.

2. RADAR-BASED MEASUREMENT FOR SNOW SCIENCE

The analysis and monitoring of avalanche dynamics have greatly benefited from the development of advanced measurement systems, each designed to capture specific aspects of snowpack behavior, snow movement, and the internal processes during an avalanche event. These systems include a variety of radar-based technologies, ground-penetrating radars, motion tracking devices, and optical systems, all of which provide critical data for understanding and predicting avalanche behavior.

In particular, radar measurements have been used for 30 years. Marshall and Koh presented the importance of FMCW radars and gave an overview of the individual measurement methods using radars in snow research [Marshall and Koh \(2008\)](#). The initial application of Frequency Modulated Continuous Wave (FMCW) radars in snow research was documented by Ellerbruch et al. [Ellerbruch et al. \(1977\)](#), Boyne and Ellerbruch [Ellerbruch and Boyne \(1979\)](#), and Ellerbruch and Boyne [Ellerbruch and Boyne \(1980\)](#). They employed an X-band FMCW radar (8–12 GHz) to explore the correlation between the electromagnetic and physical properties of snowpacks. Over several snow seasons, they conducted experiments using both downward-looking FMCW radar mounted on various platforms and upward-looking radar buried in the ground. These backscatter measurements, which varied with snowpack depth, were linked to snow properties such as

density, hardness, stratigraphy, and moisture content. They notably demonstrated that FMCW radar could measure the snow water equivalent (SWE) of dry snowpacks, provided that snow depth was measured independently. Ellerbruch und Marshall einbauen – Bedeutung radar für die Lawinenmessung

2.1 Frequency Modulated Continuous Wave

A radar-based system specifically designed for this purpose offers a vertical resolution of approximately 100 mm, with measurements conducted at a frequency of 40 Hz. This system achieves a distance resolution better than 0.1 m and a time resolution of 300 ms, which are crucial parameters for capturing the rapid changes in snow flow during an avalanche event. The system operates within a time domain window of 12.5 ms, and utilizes a ramp length ($\tau/2$) of 13.5 ms, corresponding to a triangular sweep frequency of 38 Hz [Gubler and Hiller \(1984\)](#).

The radar setup includes a radome, constructed from a 0.08 m thick sheet of polyurethane foam covered by a thin plastic foil, which is positioned at a distance of 0.5 m from the antennas. The radome is designed to endure the substantial pressure exerted by up to 5 m of seasonal snow, ensuring the durability and reliability of the radar system under extreme conditions.

One of the critical challenges in the design of this radar system is the management of noise generation, which can significantly affect the accuracy of the measurements. Key performance aspects include the Q-value, linearity, and amplitude stability of the microwave oscillator, as well as the linearity and amplitude stability of the triangular sweep generator. Additionally, the input noise level of the audio amplifier is a critical parameter, as it influences the overall signal quality [Gubler and Hiller \(1984\)](#).

To mitigate noise, a preamplifier is employed, which produces less noise than the -10 dBm reference signal at the mixer, including the 1/f noise of the detector. The system further incorporates a low noise instrumentation amplifier, which is combined with three filters to refine the signal. The first of these filters is a first-order low-pass filter, which is particularly important given a snow density of 250 kg/m³ and a radar-snow distance of 0.5 m. This filter ensures that domain signal reflectivity changes by less than 20 % for the first 3.5 m (within a 1-10 kHz range), and by less than 60% over the entire range up to 10 m (within a 1-25 kHz range) [Köhler et al. \(2016\)](#).

A second low-pass filter, set at 25 kHz, is used to further reduce noise contributions from frequencies outside the measuring range, thereby enhancing the clarity and reliability of the data collected. The system's performance in terms of noise reduction is quantified by an R^2 value, which ranges from 6×10^{-5} at the low-frequency end to 2×10^{-5} above 5

kHz. These specifications ensure that the radar system provides precise and reliable measurements of dense snow flow height, making it an invaluable tool in avalanche dynamics research.

2.2 Ultrawide Band Snow Sounder

The UWiBaSS (Ultrawide Band Snow Sounder) represents a sophisticated radar system designed to provide high-resolution insights into snowpack characteristics using ultrawideband (UWB) radar technology. Central to this system is the M-sequence UWB radar, which operates across a broad frequency spectrum, offering enhanced range resolution and measurement precision.

The system is equipped with two distinct types of antennas to optimize signal transmission and reception. The transmitting antennas are planar Archimedean spiral antennas, known for their circular polarization, which allows for efficient and wide-angle signal propagation. For receiving purposes, the system employs two Vivaldi antennas, which are oriented at a 90° offset relative to each other. This configuration facilitates the production of two linear receiving polarizations, enabling the system to capture a broader range of reflected signals from various snow surface orientations [Jenssen et al. \(2019\)](#). Signal generation within the UWiBaSS system is based on UWB pseudo-noise, which ensures a wide bandwidth and precise signal characterization. The system's total bandwidth extends from 0.7 to 4.5 GHz, amounting to 3.8 GHz, which is crucial for achieving a high range resolution of approximately 5 cm. This fine resolution enables the detection of subtle variations in snowpack structure, making the UWiBaSS highly effective for detailed snow surface analysis.

The M-sequence clock frequency of the radar is set at 13.312 GHz, which drives the system's high measurement rate of 52 Hz, with a maximum potential rate of 1000 Hz. The radar's MLBS (Maximum Length Binary Sequence) order is 9, corresponding to 511 range bins, which defines the system's capability to distinguish between different signal reflections across its operational range [Jenssen and Jacobsen \(2020\)](#).

The nominal output power of the UWiBaSS system is 17.3 dBm, providing sufficient energy to penetrate the snowpack and return reliable data. The system's unambiguous range in air is approximately 5.9 meters, which, combined with its high-resolution capabilities, ensures accurate measurement of snowpack layers within this range. Despite its high performance, the radar system maintains an average power consumption between 8.1 and 9 watts, making it efficient for extended field operations [Jenssen and Jacobsen \(2020\)](#).

One of the critical technical specifications of the UWiBaSS is its timebase jitter, which is less than 20

femtoseconds (rms). This minimal jitter is vital for maintaining the accuracy of time-domain measurements, ensuring that the radar's range and resolution capabilities are fully realized.

2.3 GEODAR

The GEODAR is a Geophysical flow dynamics using pulse Doppler radar measurement based on an FMCW system. The development of a Frequency Modulated Continuous Wave (FMCW) phased array radar system with Moving Target Indicator (MTI) capabilities represents a significant advancement in the field of avalanche dynamics research. This sophisticated radar system is designed with separate single-transmit and eight-receive modules, which, in combination with its high signal-to-noise ratio (SNR) architecture, ensures the reliable detection and tracking of targets within a snow avalanche, even under challenging conditions [Köhler et al. \(2020\)](#).

Operating at a carrier frequency of 5.3 GHz within the C-Band, this radar system is particularly effective at penetrating powder clouds to illuminate larger particles, enabling detailed observations of particle motion and avalanche flow dynamics. The system employs a baseband signal with a small bandwidth and utilizes a transmit power of 15 W, which is sufficient to maintain signal integrity over significant distances. The maximum operating bandwidth of the system is 200 MHz, and it supports a chirp length of 4 ms, along with a repetition rate of 111 Hz, ensuring precise and continuous monitoring of avalanche events.

An Arbitrary Waveform Generator (AWG) module is employed to generate waveforms onto a 3 GHz carrier frequency. This signal is then translated to the radar's RF operating frequency of 5.3 GHz using an 8.3 GHz oscillator, which modulates the 3 GHz ± 100 MHz chirp signal. The system leverages a diverse set of long ramps, all utilizing the same bandwidth, to resolve both range and Doppler information, critical for accurately capturing the motion and velocity of particles within the avalanche [Köhler et al. \(2016\)](#). The maximum operational range of this radar system is approximately 2.5 km, corresponding to a transit time of about 1 μ s. To capture the dynamics of an avalanche event effectively, a pulse duration of 3.33 ms is required. The system is capable of reconstructing events at a frame rate of 50 Hz, allowing for detailed and real-time monitoring of avalanche progression [Ash et al. \(2010\)](#).

The GEODAR Mark 3 system, a specific implementation of this radar technology, is designed to capture data over a duration of up to 9 minutes, operating at the 5.3 GHz frequency with a wavelength of 57 mm. This system has a penetration depth of approximately 10 meters in dry snow, making it

highly effective for observing and analyzing the internal processes of an avalanche. The ability to capture high-resolution data over such a period is invaluable for understanding the complex dynamics at play during an avalanche, providing insights that are essential for improving avalanche prediction and mitigation strategies.

2.4 mGEODARD

Building upon the GEODAR Mark 3 system, an advanced extension known as the mGEODAR incorporates X-Band Frequency Modulated Continuous Wave (FMCW) radar technology to enhance the resolution and depth of avalanche monitoring. This system operates at a frequency of 10.4 GHz with a 400 MHz bandwidth, providing a substantial improvement in the ability to detect fine details within an avalanche event. The radio frequency (RF) circuitry developed for this radar, known as EREDAR (Erebus Radar), allows for a transmit frequency range from 10.2 to 10.6 GHz, which is critical for capturing the fast-moving and complex dynamics of snow particles in motion [Köhler et al. \(2020\)](#).

A key component of the mGEODAR system is the Direct Digital Synthesizer (DDS), which is clocked at a frequency of 3.48 GHz. The DDS divides the clocked signal by 24, allowing for precise integer arithmetic in all frequency calculations. This enables the generation of a desired frequency ramp, f_{ch} , with a 400 MHz bandwidth centered around 2.4 GHz. The chirp signal f_{ch} is then up-converted with a local oscillator (f_{lo}) to achieve the desired transmit frequency f_{tx} within the 10.2 to 10.6 GHz range [Peters et al. \(2018\)](#).

The mGEODAR system employs two sector antennas (SA15-90-104V-D1 from Cobham), each with a 15 dB gain, for both transmitting and receiving signals. These antennas have a beamwidth of approximately 85° in azimuth and 7° in elevation, enabling a comprehensive capture of the avalanche's vertical flow path. To obtain a complete vertical slice of the flow, the antennas are mounted with a 90° rotation [Peters et al. \(2018\)](#).

The system's deramped signal is recorded using a 16-bit analog-to-digital converter (USB-6361 from National Instruments), which supports a maximum single-channel sampling rate of 2 MB/s. The transmitted signal, with a wavelength of 0.03 m at 10 GHz, allows the radar to achieve high spatial resolution.

The mGEODAR system can operate across three distinct frequency ranges: f_{ch} from 1.9 to 2.8 GHz, f_{lo} from 7.6 to 8.4 GHz, and f_{tx} from 9.1 to 11 GHz, with a maximum pulse bandwidth of approximately 1400 MHz permitted by the DDS. This setup allows for a high-resolution bandwidth of 400 MHz, specifically from 10.4 to 10.6 GHz, and supports a chirp

duration of 0.01 s with a pulse repetition rate of 100 Hz.

To maintain continuous transmission, the system limits the chirp pulse to a bandwidth of 30 MHz, ranging from 10.04 to 10.44 GHz. The detection mode of the radar consists of a burst of 25 pulses, each with a duration of $\tau = 7.5 \times 10^{-4}$ s, and a repetition rate of 10 Hz for these bursts [Peters et al. \(2018\)](#).

These enhancements in the mGEODAR system provide a significant upgrade over the original GEODAR Mark 3, allowing for more detailed and precise observations of avalanche dynamics, particularly in scenarios involving dense snow and large-scale avalanche events. This advanced radar system's capabilities make it a powerful tool in the ongoing effort to improve avalanche prediction and safety measures.

3. MEASUREMENT METHOD

Several radar systems have been developed for snow research, including the FMCW radar systems by Gubler and Hiller [Gubler and Hiller \(1984\)](#) and by Marshall, Schneebeli, and Koh [Marshall et al. \(2007\)](#). These systems have been predominantly utilized for assessing static snowpack stratigraphy and snow depth. Additionally, Ground Penetrating Radar (GPR) techniques, such as the upward-looking GPR developed by Lino Schmid and the Ultrawide Band Snow Sounder (UWiBaSS) by Jenssen, have demonstrated potential. However, they have not yet been applied to the study of dynamic snow conditions. The measurement of snow ablation, as well as the layered structure of the snowpack during an avalanche hazard, is considered a research gap, based on the literature review. In addition, no networks of sensors currently exist to study avalanche data and dynamics. The literature analysis also shows that radar measurements, especially FMCW radar, are very well suited for detecting layer changes in avalanches. For this reason, the measurement method is being developed and refined on the basis of existing systems.

The parameters for dielectric constant and speed are used to record the individual snow layers. The measurement procedure must be able to record both variables simultaneously. For this purpose, the radar measurement method requires two distinct frequency ramps for simultaneous measurement. FMCW radars detect significant changes in density, hardness, and grain size by responding to variations in dielectric properties. These properties are usually discontinuous at snow stratigraphy boundaries, reflecting transmitted radar signals. By monitoring these reflections, individual snow layers can be identified and analyzed for changes in density and liquid water content due to friction and temperature

variations. Marshall's calculations [Marshall et al. \(2007\)](#) are used to calculate the individual layers. To do this, the distance to the boundaries and the refractive index must be defined.

Distance to the boundaries:

$$d = \frac{1}{2} v \delta f \frac{T_{pl}}{B} = \frac{1}{2} \frac{c}{\sqrt{\epsilon}} \delta f \frac{T_{pl}}{B} \quad (1)$$

where

- δf = frequency difference
- T_{pl} = Time span for the transmitted wave
- B = bandwidth
- c = speed of light in a vacuum
- ϵ = dielectric constant

Reflectivity:

$$R_i = |\Gamma|^2 \quad (2)$$

where Γ is the reflection response.

The velocity of snow layers is a critical parameter for understanding avalanche dynamics. This parameter is measured using the Doppler effect, which detects the movement characteristics of individual layers. By integrating Doppler measurements into the FMCW radar system, it is possible to capture detailed velocity profiles of the snowpack during an avalanche. To measure the velocity of snow layers within an avalanche using the Doppler effect, enhancements will be made to the FMCW radar system to incorporate Doppler processing capabilities. The Doppler effect causes a shift in the frequency of the reflected radar signals depending on the velocity of the moving snow layers. By analyzing these frequency shifts, the radar system will be able to determine the velocity profile of each layer. This enhancement involves integrating Doppler signal processing algorithms into the radar's data acquisition system, enabling real-time velocity measurements. The upgraded FMCW radar will calculate velocity by assessing the difference in frequency between the transmitted and received signals, offering detailed insights into the movement and dynamics of the snowpack during an avalanche.

One of the key challenges is incorporating Doppler-based speed measurements into the existing FMCW radar system. Although the Moving Target Indicator (MTI) currently measures avalanche speed across the entire slope, it only captures surface movements external to the avalanche. To overcome this limitation, the system will be upgraded to measure the velocities of multiple layers within the snowpack. This requires augmenting the existing FMCW radar with Doppler components and

developing the necessary signal processing algorithms. Understanding the internal processes of an avalanche—such as changes in layer composition, dielectric constant, density, and speeds—remains a significant challenge. This enhancement aims to address these knowledge gaps by providing a comprehensive understanding of the internal dynamics during an avalanche.

4. MEASUREMENT PROCESS

The individual measurement systems are limited to capturing data at specific points along the avalanche path. To achieve a comprehensive understanding of avalanche dynamics, a complete network of measurement systems must be established across the entire avalanche path. Figure 1 illustrates the fundamental structure of this measurement approach, based on the avalanche path (outlined in yellow) of the cable car gully on the Nordkette in Innsbruck. The yellow dots represent the locations of individual radar sensors used for measurement. The avalanche traverses a distance of 550 meters, with an elevation drop of 38 meters.

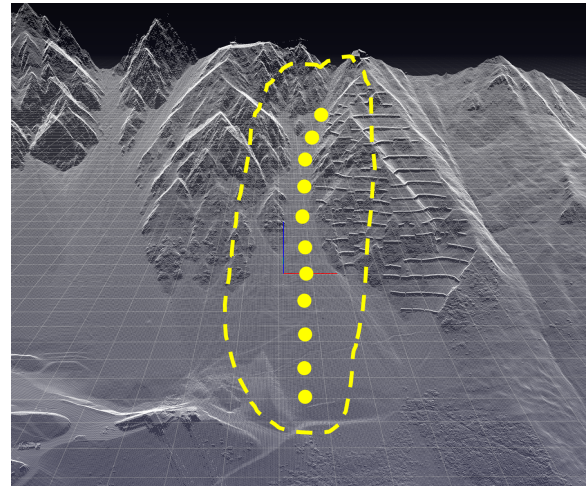


Figure 1: Representation of the measurement procedure based on the avalanche path of the cable car gully on the Nordkette Innsbruck. The yellow dots are the individual radar measurement points.

The measurement systems are strategically installed along the avalanche path in reverse order and are connected to the existing mountain station via cables for power supply and data transmission. Installation is scheduled for the beginning of winter, taking advantage of the environment that allows for continuous measurements. This setup not only records data during an avalanche event but also monitors the ongoing development of the snow cover. It is important to note that the measurement area is also used as a ski slope, and this factor must be considered when analyzing the data. The test site is located within the catchment area of a

city and is regularly monitored for safety, with artificial avalanches frequently triggered for testing purposes.

The measurements primarily focus on these artificially triggered avalanches. Since the measurement systems are positioned within the avalanche path, functional checks are necessary post-event to ensure the systems remain correctly positioned, and that data transmission and power supply are intact. During subsequent data analysis, the data from individual measurement stations will be integrated to provide a complete simulation and visualization of the internal processes occurring within an avalanche.

Figure 2 provides a cross-sectional illustration depicts the path of an avalanche, focusing on the internal layering dynamics as well as the measurement points and radar network utilized to capture key parameters. The diagram highlights the stratification of the snow within the avalanche, showing distinct layers that vary in movement speed and behavior.

The green symbols along the avalanche path represent individual radar measurement points, which are part of a distributed radar system network. This network is crucial for capturing data across different layers of the moving snow mass. The radar sensors are strategically placed to monitor changes in the dielectric constant, particularly at the boundaries between layers. These changes in dielectric constant are indicative of variations in snow density, composition, and moisture content, which can be used to infer the dynamics within the avalanche.

The graphic highlights the stopping and starting points of the avalanche layers. The "Stop Layer" signifies where a specific layer comes to a halt, potentially due to factors like friction or variations in the slope angle. Conversely, the "Start New Layer" marks the beginning of movement for a subsequent layer. These transitions are essential for comprehending the internal dynamics of the avalanche, as each layer exhibits different movement speeds. These variations are influenced by factors such as snow density, slope gradient, and environmental conditions.

The measurement points capture the differential movement across these layers, providing data on how each layer interacts with the others and the underlying terrain. By monitoring the change in the dielectric constant, the radar system can detect shifts in layer composition and movement, offering insights into the internal forces at play within the avalanche. This information is vital for improving the predictive models of avalanche behavior and enhancing risk management strategies.

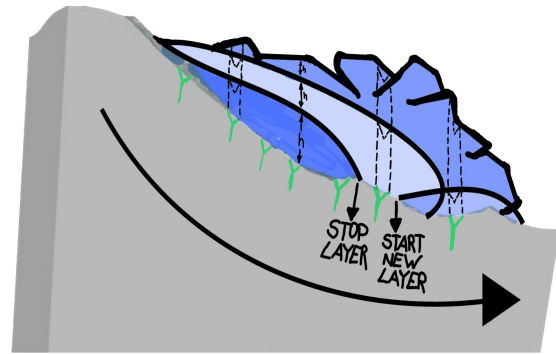


Figure 2: Cross-sectional representation of the measurement procedure along the avalanche path of the cable car gully on the Nordkette Innsbruck. The green symbols represent the individual upward-looking radar systems.

5. CONCLUSION

This study focuses on the application and development of radar-based measurement systems to advance the understanding and prediction of avalanche dynamics. The research particularly emphasizes the effectiveness of Frequency Modulated Continuous Wave (FMCW) radar systems, alongside other cutting-edge radar technologies, in capturing critical data related to snowpack behavior, internal avalanche processes, and snow erosion during avalanche events. These radar systems are demonstrated to be invaluable in providing high-resolution measurements of essential parameters such as snow density, moisture content, and layer stratification, which are crucial for accurate avalanche forecasting and mitigation.

The deployment of these radar systems includes both static measurements, aimed at evaluating snowpack conditions, and dynamic measurements during active avalanche events. The integration of Doppler radar capabilities further enhances the ability to measure the velocity of moving snow layers, thus allowing for a more detailed analysis of avalanche dynamics. This study also highlights the importance of establishing a network of radar sensors along potential avalanche paths to ensure continuous and robust data collection, which is vital for real-time monitoring and timely response.

In conclusion, the research underlines the critical role of advancing radar technology and refining measurement methods in improving avalanche risk management and safety protocols. The continuous development and enhancement of these radar systems are anticipated to make significant contributions to the field of avalanche research, offering deeper insights into the complex interactions within snowpacks during avalanche events and ultimately leading to more effective preventive strategies.

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