SNOWAVE: A NOVEL FMCW RADAR ARCHITECTURE FOR SNOW COVER MONITORING

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ABSTRACT: Snow avalanches are a persistent risk for several Alpine infrastructures. Cost-effective strategies for risk mitigation invariably require avalanche forecasting tools, based upon knowledge of several physical parameters of the snowpack. Currently, the most common measuring method for these parameters relies on manual analysis of snowpack through in-situ excavation of snow pits. This method, although time-consuming, is usually very accurate, but for safety reasons it cannot be applied when and where most needed (e.g. along critical slopes under bad weather conditions). In order to get around these constraints, systems based on the use of microwave radars have been proposed. Such systems can deliver a rapid, non-destructive, and possibly automatic analysis of the snow structure. While very promising, however, standard radar architectures cannot deliver, without external aids, measures of snow depth and its physical parameters at the same time, thus strongly limiting the accuracy and applicability of this approach. This paper presents a novel stand-alone dual-receiver FMCW radar architecture, called SNOWAVE, capable of simultaneously measuring propagation distance, wave speed and attenuation within the medium. In this way, snow depth, density, and liquid water content can all be estimated at the same time without the aid of additional sensors. Experimental results from field tests at elevations above 3000 m in the Italian Alps are also presented to show the feasibility and potential of this innovative approach.

KEYWORDS: snow cover monitoring, snowpack monitoring, snow stratigraphy, upward-looking radar, dual-receiver architecture, liquid water content (LWC).

1. INTRODUCTION

Snow avalanches are a persistent risk for Alpine countries, threatening the safety of residents and winter tourists (some 20 million individuals per year, accounting for a 30 B€ turnover). Transalpine traffic (100 million metric tons of goods per year) is also very vulnerable (Centre for Climate Adaption, 2017). Cost-effective strategies for large-scale risk mitigation inevitably require avalanche-forecasting tools to properly manage road closures, evacuations, artificial releases. Such forecasting, however, at present still relies largely on manual snowpack analysis. Although very precise, manual analysis also exhibits several disadvantages, most notably it is very time consuming and it is rarely feasible when and where most needed, i.e., in the avalanche release zones during snowstorms and in dangerous conditions (Schweizer, 2014).

Solutions based on microwave sensing have been investigated for several years now. Systems buried into the ground before the winter season, and most notably upward-looking radars, appear to be the only viable approach satisfying two important constraints. The first is to deploy an unmanned automatic system directly in the avalanche release zones and along typical avalanche paths; the second is, quite obviously, to be immune from avalanche damage (Mitterer et al, 2011; Okorn et al, 2014; Schmid et al, 2014; Heilig et al, 2009; Heilig et al, 2010). However, traditional upward-looking radars, often derived from commercial ground penetrating radars (GPRs), cannot determine the physical distance from the target (i.e., snowpack thickness) and, at the same time, the propagation constant in the medium. On top of the snowpack thickness, knowledge of the propagation constant is fundamental because it relates to the snow density and liquid water content (LWC), which are in turn fundamental parameters for the avalanche forecasting tools. To solve for this ambiguity several methods have been applied. These include a-priori assumptions on the average snow properties, which potentially imply large errors: more than 20 cm have been demonstrated in literature. Other methods include additional aids such as ultrasonic gauges, laser gauges, Global Positioning System (GPS) receivers, or water content reflectometers (Mitterer et al, 2011; Okorn et al, 2014; Schmid et al, 2014; Heilig et al, 2009; Heilig et al, 2010; Godio et al, 2015; Schmid et al, 2015). The main disadvantages of these solutions lie either on the use of above-ground devices (thus

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spoiling a major advantage of buried systems), or on the complexity of the system (which requires the co-ordination of different devices and dedicated calibrations, a major problem for the successful exploitation of this type of system on a medium-to-large scale. This paper presents a novel architecture for an upward-looking radar designed to deliver the internal stratigraphy of a snowpack, taking into account the possibility to determine, at the same time, both the snowpack thickness and dielectric permittivity. This is achieved using a dual-receiver radar architecture, able to provide the required number of equations with no use of external aids. Experimental results from the field are presented to demonstrate the viability of the idea.

2. DIELECTRIC PERMITTIVITY OF SNOW

At microwave frequencies, the dielectric permittivity of snow is a function of the snow density and LWC (Hallikainen et al, 1986). In particular, dry snow (LWC ~ 0 %) is often characterized using only the real part of the dielectric permittivity, thus with a one-to-one relationship between the snow density and the relative dielectric constant, being the imaginary part negligible (Hallikainen et al, 1986):

$$\varepsilon' = 1 + 1.83\,\rho \qquad (1)$$

where ρ is the snow density measured in g/cm^3. On the other hand, wet snow requires the use of both the real and imaginary part of the dielectric permittivity to be described, and both parameters are function of the snow density and LWC (Hallikainen et al, 1986). Typical dry snow densities for Alpine conditions ranges from around 90 kg/m^3 to around 450 kg/m^3. Typical wet snow densities exceed 400–450 kg/m^3 and can reach values higher than 600–700 kg/m^3. LWCs for wet snow are often evaluated up to around 10–12% of the volume, since values in excess of 12% have no additional effects on the instability of the snowpack (Heilig et al, 2009; Heilig et al, 2010; Godio et al, 2015). A remarkable exception to the classification presented above is represented by ice, with a density approaching 800–900 kg/m^3 and a negligible LWC. Table I summarizes all relevant data at 1 GHz. It can be observed that, for wet snow, the imaginary part always remains much smaller (i.e., not more than roughly one tenth) than the real part.

3. DUAL-RECEIVER RADAR ARCHITECTURE

The schematic drawing of the system architecture is shown in Fig. 1. The working principle is shown in detail in Pasian et al, 2018, but it is reported here for completeness and self-consistency, along with a specific discussion on some practical aspects related to the expected implementation of an upward-looking radar.

A trench is excavated into the ground at the avalanche release zone before the winter season.

TABLE I. MINIMUM AND MAXIMUM SNOW DENSITY, LWC, AND DIELECTRIC PERMITTIVITY AT 1 GHZ, FOR TYPICAL ALPINE SNOW (HALLIKAINEN, 1986)

Snow	**Density (kg/m^3)**	**LWC (%)**	ε'	ε''
dry	90	~ 0	1.2	~ 0
	450		1.8	
wet	400	3	2.1	0.03
	700	12	4.3	0.21
ice	800	~ 0	3.1	~ 0
	900			

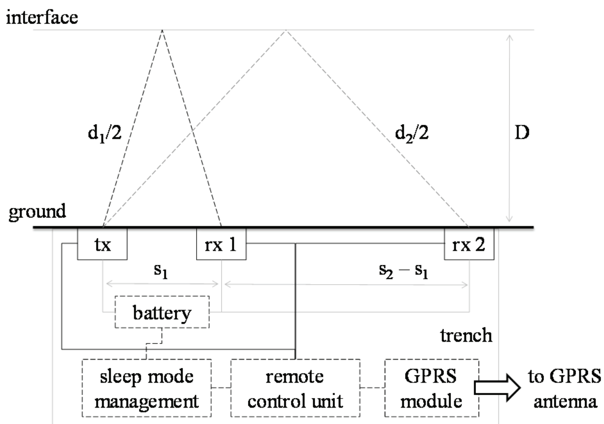

Figure 1. Schema of the upward-looking radar. Drawing not to scale.

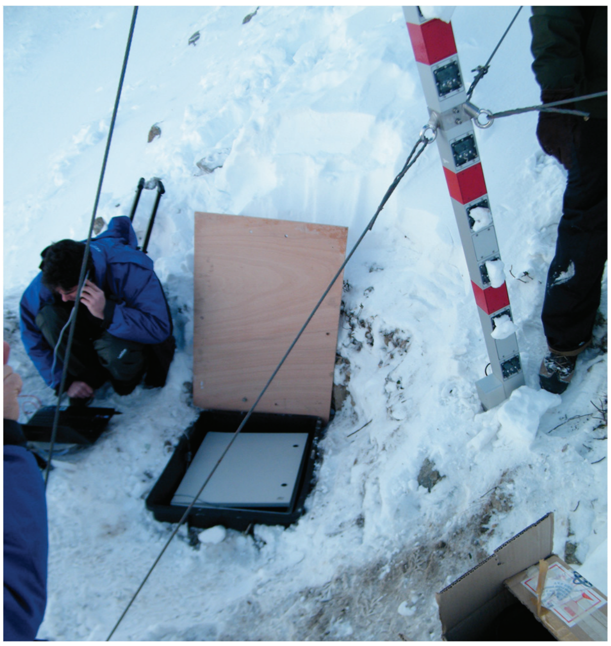

Figure 2. Example of trench for buried system.

The excavation is sealed using a waterproof box with a microwave-transparent window (e.g. made out of wood) on the box face looking outwards. The idea is exemplified in Fig. 2, where a similar preparation is carried out in the framework of research and development activities related to the study of innovative avalanche sensors.

The radar comprises one transmitter and two receivers (Fig. 1), connected to their own radiators (e.g., open-ended waveguides, or custom 3D printed antennas (Espin-Lopez and Pasian, 2018).

The power supply is provided using standard truck batteries and DC-DC converters. It is assumed that the snowpack is monitored at regular intervals, once per hour, along the entire winter season (December to May, for a total of 6 months and around 4000 measurements), and that between measurements the system is designed to fall into sleep mode. In addition, the estimated power consumption for the entire system is around 15 W, according to available datasheets. With these assumptions in place, it was reckoned that one single battery (12 V, 100 Ah) is enough to deliver around 1 minute of energy for each measurement. Taking into account that the radar measurement is practically instantaneous, this means that the most of the energy for each measurement is spent on system wake-up and data transmission, as described in the next paragraph.

The system is meant to be remotely controlled using a GPRS module, also employed to send the collected data to the master station, conveniently located in a safe place, accessible all year round. In particular, the GPRS antenna (not shown in Fig. 1) is the only device above ground, since it has to be installed in line-of-sight with the master station. For this reason, the antenna must be installed outside the expected avalanche path, e.g. on a nearby large rock. To this aim, a small pipe is deployed slightly below the ground surface to route the cables required to link the GPRS module - buried to the side of the radar system - to the GPRS antenna. This type of pipes, as long as 100 meters and even more, are common practice in mountain regions for different type of general construction works, such as buried electric and phone lines.

Each transmitter-receiver pair is designed to work as a standard Frequency Modulated Continuous Wave (FMCW) radar, thus delivering the time of flight measured between the transmitter-receiver plane and the target. For snowpack applications, the target is the interface between the snow and the outer air, or even the interface between different inner snow layers. In any case, because of how snow deposits, the interface is always supposed to be a discontinuity plane parallel to the transmitter-receiver plane. Using more than one receiver, it is possible to solve for the ambiguity of the propagation within an unknown medium, and calculate the wave speed in the medium. This in turn makes it possible to translate the time-of-flight information into a physical distance to the interface, and to estimate the dielectric permittivity. The FMCW outcomes can be written as:

$$T_1 = d_1 / v \tag{2}$$

$$T_2 = d_2 / v \tag{3}$$

where T_1 and T_2 are the times of flight from the transmitter to the first and second receiver, respectively, v is the wave speed in the medium and d_1 and d_2 are the propagation distances from the transmitter to the first and second receiver, respectively. These propagation distances can be expressed as:

$$d_1^2 = (2D)^2 + s_1^2 \tag{4}$$

$$d_2^2 = (2D)^2 + s_2^2 \tag{5}$$

where D is the snow thickness, and s_1 and s_2 are the horizontal distances between the transmitter and the first and second receiver, respectively. Substituting (3) and (4) into (1) and (2):

$$T_1^2 = ((2D)^2 + s_1^2) / v^2 \tag{6}$$

$$T_2^2 = ((2D)^2 + s_2^2) / v^2 \tag{7}$$

The system identified by (6) and (7) can now be solved for either the snow thickness D or the snow wave speed v. It is interesting to observe that the parameters s_1 and s_2 can be tuned to meet practical requirements in terms of system encumbrance, as well as to optimize the accuracy of the achievable results (Espin-Lopez et al, 2018).

4. DISCUSSION

According to the data on the dielectric permittivity presented in Section II and Table I (i.e., imaginary part smaller than around one tenth of the real part), the wave speed v is practically dictated by the real part only. Therefore, it is possible to apply an approximated one-to-one relationship between wave speed v and the real part of the dielectric permittivity ε':

$$v \sim c / \sqrt{\varepsilon'} \tag{8}$$

where c is the speed of light. Moreover, when the real part falls within the 1.2 – 1.8 range, according to Table I this automatically identifies dry snow, and a one-to-one relationship between the wave speed v and the snow density ρ measured in g/dm^3, is obtained using (8) and (1):

$$\rho \sim 0.55\,(c^2 / v^2 - 1) \tag{9}$$

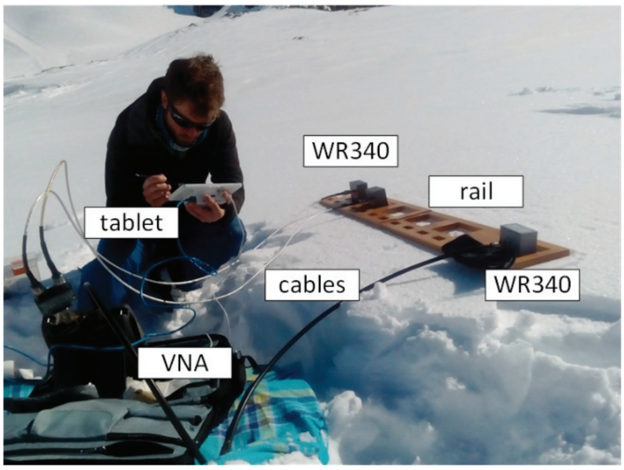

Figure 3. Photograph of SNOWAVE during an experimental test in the Alps.

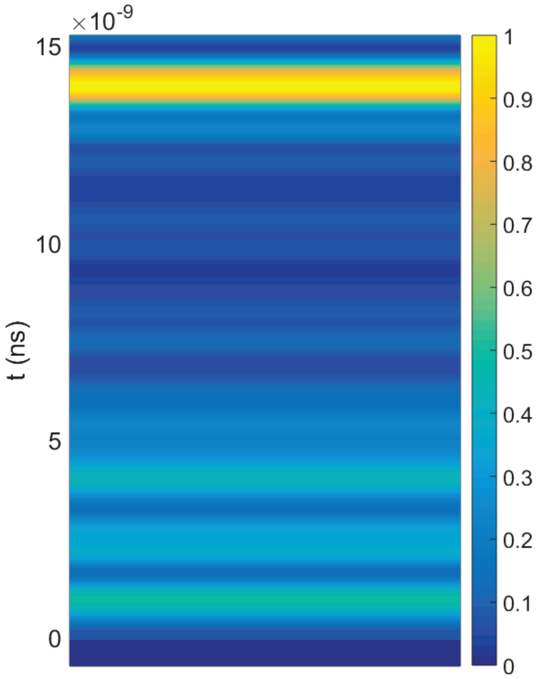

Figure 4. Radar trace for the first receiver, with s_1 = 30 cm.

On the other hand, when a real part of the dielectric permittivity greater than 2.1 is found, according to Table I this identifies wet snow (excluding the case of ice), but in this case it is not possible to derive a direct relationship between the real part (hence, the wave speed v) and the snow density and LWC. To this aim, it is required to introduce an extra condition to calculate also the imaginary part. In particular, a straightforward approach is to detect not only the time of arrival, but also the attenuation between the transmitted and the received signal. Although this part of the approach is not outlined in detail in this paper, it is interesting to observe that once both the real and the imaginary part are known, it is also possible to solve for the ambiguity of the ice. Indeed, even if the real part of the dielectric permittivity for ice can be comparable to that of wet snow, the imaginary part for the former is negligible, while for the latter can achieve significant values.

5. EXPERIMENTAL VALIDATION

The feasibility of the radar architecture presented in Section III has been demonstrated with an experimental test in the Italian Alps. The field test took place in the Cervinia Ski Resort (Valle d'Aosta, Italy) at an altitude of around 3000 m. The test was performed in April 2018, with dry snow. Fig. 3 shows the setup of the test.

It is worth observing that for this feasibility test a downward looking configuration was implemented. Indeed, this configuration retains the possibility to test the working principle of the proposed radar architecture, while dropping the logistical problems related to a buried installation.

The setup is composed of a two-port vector network analyzer (VNA) from Keysight (FieldFox N9916A) used to generate the FMCW signal and to receive the backscattered echo, three open-ended WR340 antennas, working from 2.2 GHz to 3.2 GHz, three coaxial cables to connect the VNA and the antennas, and manual radiofrequency switch to allow a rapid and effective connection of the two-port VNA to the three antennas. The antennas are mounted on a wooden rail to guarantee precise positioning of the antennas themselves.

In order to verify the accuracy of the radar measurements, two professional experts from the AINEVA (Italian Interregional Association for Snow and Avalanches) analyzed the snowpack through traditional techniques, and provided the data used to benchmark the radar results.

In particular, the manual snowpack analysis returned a snow depth D = 1.64 m and density ρ = 339 kg/m^3 (ε' = 1.62, v = $2.36 \cdot 10^8$ m/s). On the other hand, the radar provided D = 1.58 m and ρ = 407 kg/m^3 (ε' = 1.74, v = $2.27 \cdot 10^8$ m/s). As an example, a typical radar trace for one of the two receiver is shown in Fig. 4. The normalized amplitude of the backscattered echo is depicted in color scale, and it can be observed that the snow-ground interface emerges at a time-of-flight of around 14 ns. It can be appreciated that the error with respect to the nominal values is better than 4% for the snow depth and density.

6. CONCLUSION

This paper presented a novel radar architecture, based on the use of multiple receivers, able to deliver, at the same time, both the snowpack thickness and dielectric permittivity. A detailed discussion on the expected implementation for an upward-looking installation is provided, along with experimental results obtained with a downward-looking prototype, which demonstrated the feasibility of the idea.

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