MICROWAVE MULTI-RECEIVERS RADARS FOR SNOWPACK MONITORING: SNOWAVE

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Abstract

Microwave radars represent an interesting solution to monitor the internal structure of the snowpack because the measurements are practically instantaneous, non-destructive, and can be realized either in an upward-looking or downward-looking configuration, for fixed and portable installations, respectively.

This paper presents an innovative radar architecture based on one transmitter and two receivers. It is able to deliver the depth and the dielectric permittivity of the snowpack. Then, exploiting the relationship between the dielectric permittivity and the snow physical properties, the snowpack density, liquid water content, and snow water equivalent can be retrieved. These parameters are useful to provide an accurate forecast for the avalanche formation as well as for estimating the snowmelt for hydrological purposes.

The basic working principle of the radar architecture, as well as a set of significant experimental validation, are presented.

I. INTRODUCTION

Snow cover is an important variable of the climate system and represents a vital storage of freshwater [1]. On the other hand, it may also play a major role in natural disasters such as snow avalanches and floods [2, 3]. To model the snowpack, continuous information on snow height, snow density, snow water equivalent (SWE) and liquid water content (LWC, i.e., the percentage of liquid water) are necessary inputs [4].

Promising methods for continuously and non-destructively measuring snow properties, which are also suitable for installation in complex terrain, have been proposed, based on ground-penetrating radars (e.g., [5]) and frequency modulated continuous wave radars (e.g., [6]). However, a common limitation of all these systems is that they cannot determine simultaneously the snowpack depth and the dielectric properties of the snowpack without additional inputs. For this reason, these systems are usually complemented in such a way that one or more physical parameters are provided otherwise. In particular, these are calculated on the grounds of a-priori assumptions [5], or measured by other means, including ultrasonic/laser gauges and water content reflectometers [7], or using a combination between radars and GPS receivers [8]. In some other cases, electromechanical positioners aimed at synthetic aperture radar tomography and/or inverse-scattering/migration-focusing/diffraction-curve/CMP techniques, have been applied to solve this problem (e.g., [9]). In any case, all these methods have their own disadvantages in terms of complexity, accuracy, or suitability for installation on steep slopes.

Recently, a different radar system, called SNOWAVE, based on a novel dual-receiver stand-alone frequency modulated continuous wave (FMCW) radar architecture, was presented for the case of dry snow [10] and wet snow [11], including the development of dedicated 3D-printed antennas [12]. For the first time, it was demonstrated the possibility to measure, at the same time, the snowpack height and the wave speed into the snow, without any supplemented information from other devices, assumptions on the snow properties, or indirect solutions.

This paper summarizes the basic working principle, along with the experimental setup and the significant results for a set of Alpine and Arctic campaigns.

II. RADAR ARCHITECTURE

The system architecture is shown in Fig. 1 for an upward-looking installation, thus intended for a system intended to be buried into the ground before the winter season, and remotely controlled. A similar schema can be discussed for a downward-looking installation, intended mainly for portable systems.

The radar comprises one transmitter and two receivers. Each transmitter-receiver pair works as a standard FMCW radar, thus delivering the time of flight from the transmitter to the snow-air interface and back to the receiver. In particular, the time of flight is directly related to the wave speed v into the medium. When two receivers are used, as shown in Fig. 1, the following system can be imposed:

$$T_i = d_i / v \qquad (1)$$

where T_i for i=1,2 are the times of flight from the transmitter to the receivers, and d_i for i=1,2 are the propagation distances from the transmitter to the receivers.

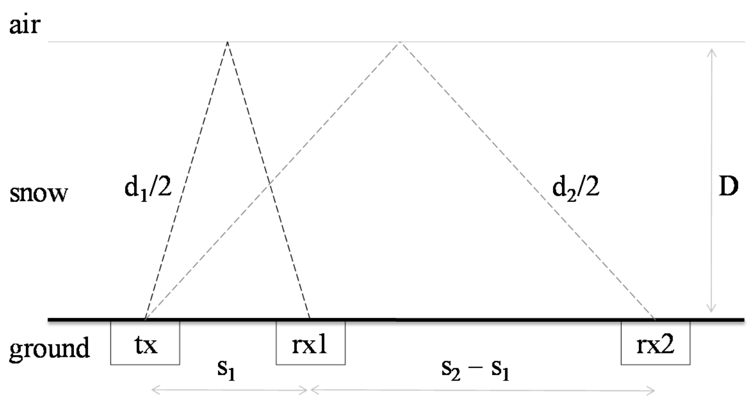

FIG. 1 – Radar architecture schema showing the transmitter (tx) and the two receivers (rx1 and rx2) installed at ground level under a snowpack with thickness D. Drawing not to scale.

The propagation distances can be written as:

$$d_i^2 = (2D)^2 + s_i^2 \qquad (2)$$

where D is the snow thickness, and s_i for i=1,2 are the horizontal distances between the transmitter and the first and second receiver. Manipulating (1) and (2) it is obtained:

$$T_i^2 = ((2D)^2 + s_i^2) / v^2 \qquad (3)$$

which represent a system of two equations and two unknowns, the snow thickness D and wave speed v. The, for all cases of practical interest, for either dry or wet snow, it can be written:

$$v \sim c / \sqrt{\varepsilon'} \qquad (4)$$

where c is the speed of light, and ε' is the real part of the dielectric permittivity of the snow. In the case of wet snow, not only the times of flight are measured, but also the signal attenuation from the transmitter to the receivers, in such a way that also the imaginary part ε'' of the dielectric permittivity of the snow can be calculated [11]. Then, the complex dielectric permittivity is used to calculate the snow density, LWC, and SWE [10, 11, 13].

III. EXPERIMENTAL VALIDATION

The proposed radar architecture was validated in real field tests in Alpine and Arctic conditions. Different prototypes were tested. Standard open-ended WR340 antennas, as well as custom 3D-printed antennas [12], were used, as shown in Fig. 2 and 3, respectively. In addition, the initial prototype was based on two physical antennas, where one of the two is moved along a rail into two different position to mime the presence of the third antenna, taking advantage of the fact that the snowpack is time-invariant for the time required to complete the operation (Fig. 2, left).

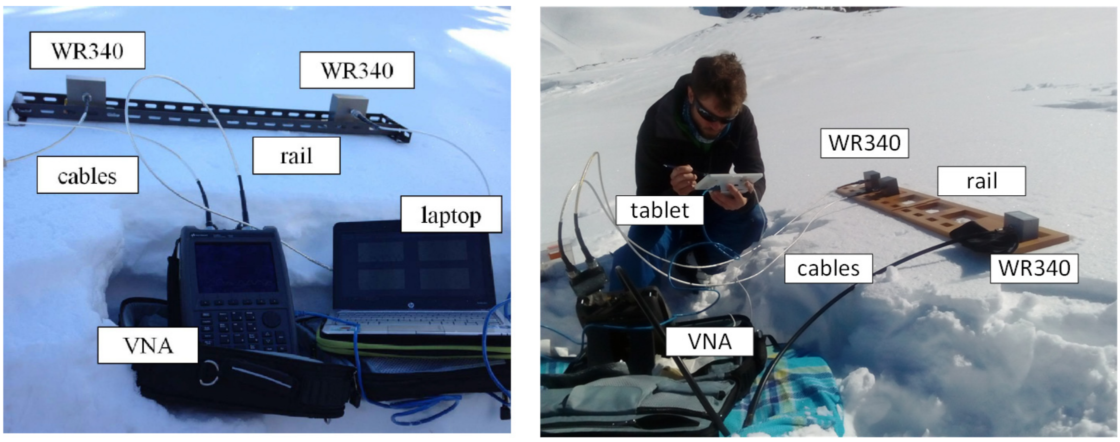

FIG. 2 – Experimental setups using open-ended WR340 antennas: (left) two antennas; (right) three antennas and a switch.

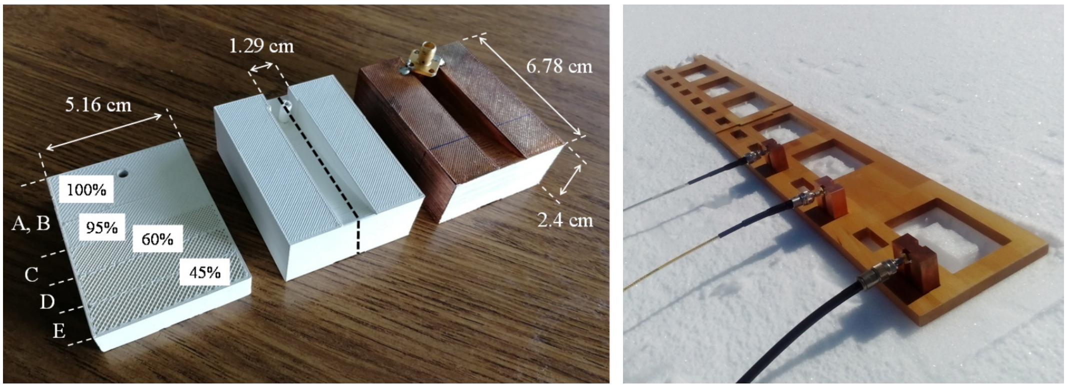

FIG. 3 – Experimental setups using custom 3D-printed antennas: (left) details of the inner structure of the antenna; (right) field deployment.

Instead, a second prototype is directly based on three physical antennas, and a mechanical switch to route the signal to the vector network analyzer (VNA) used to generate and collect the radar signal (Fig. 2, right and Fig. 4). The VNA (Keysight FieldFox) is driven either by a normal laptop (Fig. 2, left) or by a dedicated tablet based on a Raspberry Pi (Fig. 2, right).
After the radar measurements, a manual snowpack analysis took place to benchmark the achieved results. In particular, the snowpack depth was measured, along with density and LWC, averaging respectively the weight of a series of snow samples of known volume and the values retrieved by the Finnish snow fork [14] (Fig. 5).
Overall, for the typical cases, the relative accuracy for the snowpack depth and density was better than around 5%, and in the order of 7% for the LWC. For depth and density, the absolute standard deviation was around ±3.75 cm and 54 kg/m^3, respectively. For the LWC, absolute errors were typically in a range from 1.5% to 13% (Fig. 6).

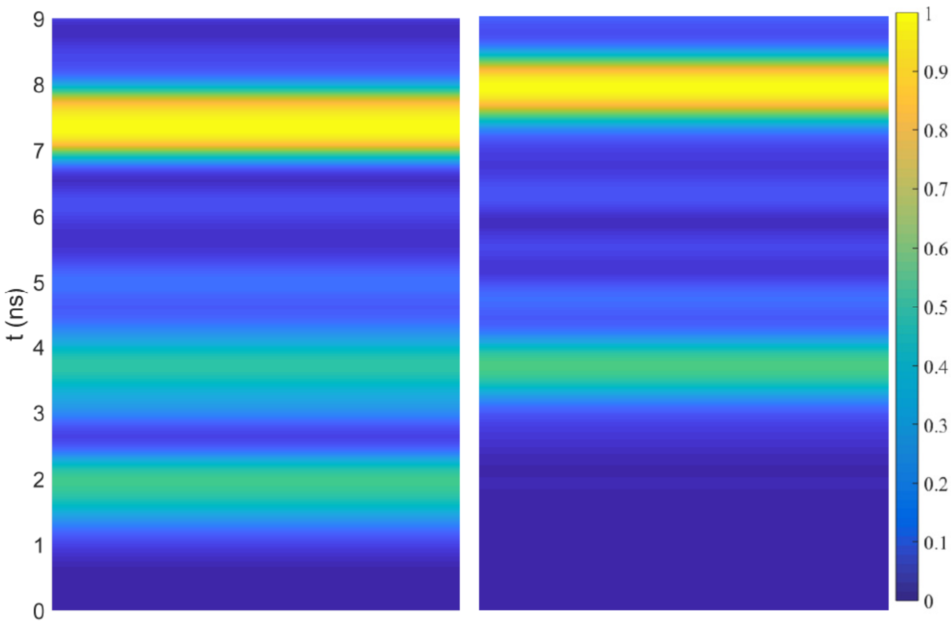

FIG. 4 – Example of radar signal collected by the system: (left) first receiver; (right) second receiver. It can appreciated the strong reflection (yellow color) from the snow-ground interface, at around 7.25 ns for the first receiver and 8 ns for the second receiver.

FIG. 5 – Example of manual analysis of the snowpack, after excavation of a snow pit, to benchmark the radar measurement. In this case, the use of the Finnish snow for to retrieve the LWC at different height of the snowpack can be appreciated.

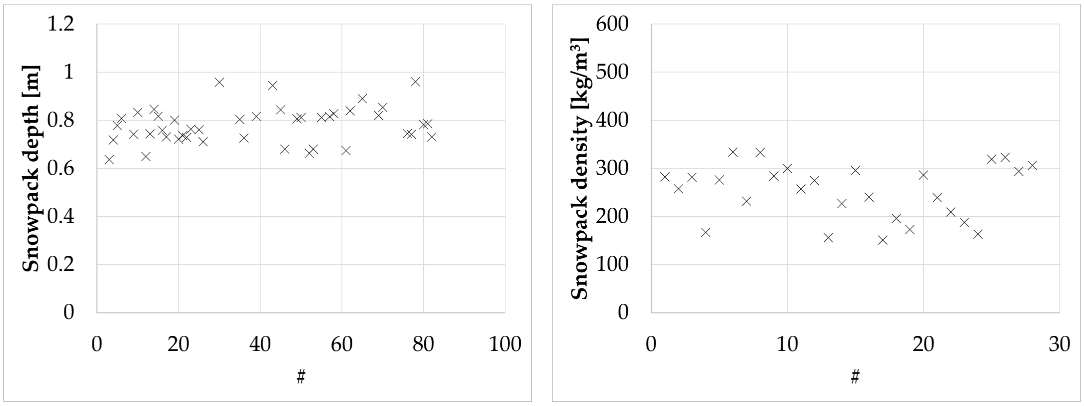

FIG. 6 – Example of the accuracy achieved for the radar measurements: (left) snowpack with a real depth of 82 cm returned an average of 78 cm (relative average error around 5%) with a standard deviation of around ±3.75 cm; (right) snowpack with a real density of 255 kg/m³ returned an average of 257 kg/m³ (relative average better than 1%) with a standard deviation of around ±54 kg/m³.

IV. CONCLUSION

This paper presented the working principle and a selection of significant experimental results about the development of a novel radar architecture for snowpack monitoring. The proposed approach is based on two different receivers, and it allow for investigating the internal structure of the snowpack with rapid and non-destructive measurements, useful in the fields of avalanche prevention and water resources management.

The radar is capable of delivering the snowpack depth, density, LWC and SWE with typical accuracies in the order of 5–7%

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