Determination of Snow Water Equivalent for Dry Snowpacks Using the Multipath Propagation of Ground-Based Radars

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Abstract—Determining snow water equivalent (SWE) in a fast and nondestructive way is a key request for many hydrologists and snow scientists. To this aim, microwave ground-based radars represent a viable solution, but often the simultaneous measurement of both the snowpack depth and density (the key ingredients for the SWE) is very complex, inaccurate, or requires difficult procedures and equipment. This letter presents a novel radar technique for self-standing calculation of the SWE that can be applied to bi-static radars. This technique, based on the multipath propagation of the radar signal into the snowpack, only requires a radar with two fixed antennas, without any other device, movement of the antennas, or a priori empirical assumptions. This makes such a technique particularly suitable for light and portable radars for rapidly probing large areas, providing, for example, an innovative validation means for satellite-based microwave remote sensing methods. The proposed technique was demonstrated using a stepped frequency modulated continuous wave (FMCW) radar in field conditions for dry snow, delivering results for snow depth and SWE, benchmarked by manual analyses of the snowpack, with a mean absolute error better than 5 cm.

Index Terms—Frequency modulated continuous wave (FMCW) microwave ground-based bi-static radar, multipath, snow water equivalent (SWE), snowpack monitoring.

I. INTRODUCTION

Snow water equivalent (SWE) is an important parameter describing the amount of liquid water, potentially related to the snowpack. SWE can be calculated as

\[ \text{SWE} = \frac{D \rho}{\rho_w} \]  

(1)

where \( D \) is the snowpack depth, \( \rho \) is the snow density, and \( \rho_w \) is the water density (1000 kg/m³). This information is useful in several applications, including climate modeling and water management for hydroelectric power plants and agriculture [1], [2]. A number of approaches, based on ground-based in situ monitoring [3], [4] and/or space-based remote sensing (e.g., using the signal from global navigation satellite systems [5], [6], passive microwave radiometers [7], [8], active [9]–[13], and signal-of-opportunity radars [14]), are proposed to monitor the snowpack, possibly deriving the SWE, over large areas.

However, over large and remote areas, for example, an entire mountain basin, in situ monitoring is complex, costly, and difficult to be carried out, especially over difficult ground (e.g., steep slopes). At the same time, satellite remote sensing may not provide the required spatial and/or temporal resolution, especially on complex terrain (e.g., mountains) [15]–[17].

For these reasons, the availability of portable, fast-deploying devices able to measure the SWE at several different locations, at arbitrary repetition rates, over large areas, is interesting. In addition, they would be valuable also for calibrating/validating satellite-based measurements. To this aim, ground-based microwave radars represent an effective solution, due to the nature of the measurement, which is practically instantaneous and nondestructive. However, for measuring the SWE, the radar needs to determine both the snow depth and the snow density. Unfortunately, this is an ill-posed problem, as the snow depth can be calculated from the time-of-flight of the radar signal only if the wave speed is known, but the latter is driven by the snow density, which is unknown in the general case.

For solving this problem different techniques are employed. These include 1) a priori hypothesis on the snow density; 2) the use of additional devices measuring either the snowpack depth or density; and 3) approaches derived from ground-penetrating radars (GPRs), for example, based on the best fitting of the diffraction curve (common offset, common midpoint) or on the migration analysis [18]–[26]. However, these techniques have their own flaws. For example, 1) a priori assumptions can lead to large errors; 2) additional devices increase the system complexity, and in many cases are not suited for portable systems; and 3) GPR-based techniques require fortuitously located diffractions, antenna displacement strategies or mechanisms, and are potentially prone to inaccuracies typical of inverse techniques, such as local minima, artifacts, and computation time and effort [27].

An alternative to these techniques is represented by a different radar architecture, sketched in Fig. 1(a), which makes use of two different receivers, recently presented in [28].
In this case, two independent propagation paths (thus, two independent measurements for the time of flight), from the transmitter (tx) to the first and second receiver (rx1 and rx2, respectively), are available to provide two independent equations. This way, the two unknowns, i.e., the snowpack depth \( D \) and the wave speed \( v \) into the medium, can be determined, thus, rigorously closing the mathematical problem. However, this architecture works with three antennas, which require precision during the reciprocal alignment. In view of a portable solution, where the radar is most likely transported partially dismounted, and assembled in situ, this is a delicate procedure.

This letter presents an innovative solution for ground-based microwave radars aimed at snowpack monitoring. Following the idea of using two different receivers, these are virtually realized by exploiting the multipath propagation between the air-snow and the snow-ground interface. This means that the radar system only comprises two, instead of three, antennas, greatly reducing the overall encumbrance and alignment aspects, thus improving the portability and the easiness and rapidity of deployment. This idea, which is particularly suited for monitoring the SWE over large areas, is experimentally verified for dry snow during field campaigns in 2019 in the Italian Alps and in Lapland. This letter is organized as follows. Section II describes the architecture of the adopted approach and the underlying equations, while Section III presents the practical implementation, along with the experimental results. Section IV draws the conclusions.

II. MULTIPATH RADAR ARCHITECTURE

Starting from the working principle presented in [28], and briefly summarized at the end of Section I, here, the second tx–rx pair is replaced by taking advantage of the multipath propagation in the first tx–rx pair, in most cases a nondesirable effect. This is, in the ideal case of a homogeneous snowpack, the shorter wave path between the transmitter and the receiver will bounce only once in the snow-ground interface. Moreover, there will be a longer wave, which can be called the second path, bouncing twice in the snow-ground interface and once in the air-snow interface [Fig. 1(b)]. For completeness, the extension of this same idea would bring to the identification of multiple longer wave paths, bouncing multiple times both in the snow-ground and in the air-snow interfaces, thus creating multiple targets placed at a well-known distance depending on the geometry of the problem. It is worth noting that the hypothesis of a homogeneous snowpack does not introduce a limitation, as real stratified snowpacks, for what concerns applications related to the SWE, can be, in most of the cases, traced back to their average, homogeneous, equivalent snowpacks.

These multipath targets usually represent a nondesirable effect on radar applications. However, for the case under analysis, if at least the first multipath target could be detected, the two different wave paths would close the mathematical problem rigorously. In particular, the time-of-flight \( T_1 \) and \( T_2 \) associated with the first and second path, respectively, are

\[
T_1 = d_1/v \quad \text{(2)}
\]

\[
T_2 = d_2/v \quad \text{(3)}
\]

where \( d_1 \) and \( d_2 \) are the propagation distances for the direct and second path, respectively. These distances can be expressed as

\[
d_1^2 = (2D)^2 + s^2 \quad \text{(4)}
\]

\[
d_2^2 = (4D)^2 + s^2 \quad \text{(5)}
\]

where \( D \) is the snowpack depth, \( s \) is the horizontal distance between the transmitter and receiver. Substituting (4) and (5) into (2) and (3)

\[
T_1^2 = ((2D)^2 + s^2)/v^2 \quad \text{(6)}
\]

\[
T_2^2 = ((4D)^2 + s^2)/v^2. \quad \text{(7)}
\]

Then, for dry snow, a well-known approximated relationship between the wave speed and the dielectric constant \( \varepsilon' \) of the medium can be used [29]

\[
v \sim c/\sqrt{\varepsilon'} \quad \text{(8)}
\]

where \( c \) is the speed of light. This way, manipulating (6)–(8), it is possible to solve the mathematical system for the snowpack depth \( D \), the wave speed in the medium \( v \), and the dielectric constant \( \varepsilon' \)

\[
D^2 = s^2(T_1^2 - T_2^2)/4(T_2^2 - 4T_1^2) \quad \text{(9)}
\]

\[
v^2 = 3s^2/(4T_1^2 - T_2^2) \quad \text{(10)}
\]

\[
\varepsilon' = c^2(4T_1^2 - T_2^2)/3s^2. \quad \text{(11)}
\]

Finally, for dry snow, a simultaneous estimate of \( D \) and \( \rho \) is achieved, given that between \( \varepsilon' \) and \( \rho \) holds [29]

\[
\varepsilon' = 1 + 1.8310^{-3} \rho \quad \text{(12)}
\]

where \( \rho \) is measured in kg/m³.
III. EXPERIMENTAL SETUP AND RESULTS

For the demonstration of the working principle of the multipath architecture, the transmitter and the receiver operate according to a stepped frequency modulated continuous wave (FMCW) configuration. The central frequency $f_0$ and bandwidth $B$ are 2.75 and 1.5 GHz (from 2.0 to 3.5 GHz), respectively. The radiators are open-ended WR340 waveguides, working on the fundamental TE$_{10}$ mode. The S-band has been selected for an optimum compromise between penetration depth on dry snow, and achievable resolution.

The measurement setup was composed of two open-ended WR340 waveguides acting as antennas, one used as a transmitter while the other used as a receiver. The latter is placed at two different distances $s$ (either 30 or 70 cm) from the transmitting antenna, to study the response of the system with two different configurations. A metal rail was used both for supporting the antennas. This allows for selecting distances $s$ for the antennas from 20 to 100 cm. Therefore, the two values selected for the demonstration of the proposed approach (30 and 70 cm) exemplify the achievable results for short and long separation between the transmitter and the receiver. In particular, it is expected that better results can be achieved for longer separations [30].

A portable Vector Network Analyzer (VNA), from Keysight (FieldFox N9916A), was used for generating the microwave signal, and a portable PC was used for processing the received signal (Fig. 2). The processing consisted of performing the Inverse Fast Fourier Transform to the received signal applying a Nuttall window for reducing sidelobes.

A. Field Campaigns and Experimental Setup

Two field campaigns have been performed for testing the system on real snowpack data. The first campaign (C1) was developed near to the village of Pila (Aosta) in the Italian Alps ($45^\circ40'10'' N$ $7^\circ18'30'' E$). The campaign started on the 4th of February, ending on the 8th of February, 2019 and was performed at an altitude of around 2500 m above sea level (a.s.l.) in a shadow place with no inclination. During the whole campaign, the snow conditions were dry. The number of measurements done was 5. The second campaign (C2) was developed close to the facilities of the Finnish Meteorological Institute (FMI) in Sodankylä, Finland ($67^\circ22'00'' N$ $26^\circ39'05'' E$) at an altitude of 179-m a.s.l. This campaign started on the 18th of March and ended on the 12th of April, 2019. During the entire set of measurements used to validate the approach presented in this letter, the snowpack was dry. The number of measurements done was 37.

The radar measurements were compared with manual measurements on the field, performing each time a snowpit. During the C1, all the manual measurements were done with a density cutter of 198 cm$^3$, and the density was measured with a vertical resolution of 10 cm, averaging all the measurements for obtaining the bulk density and the SWE. During the C2, a set of measurements (C2_1) was validated with the same density cutter of C1, while another set of measurements (C2_2) was taken around 30 m away from C2_1 and was validated using an SWE tube provided by FMI [31]. In any case, for all campaigns, as manual measurements are destructive, the precise site for each snowpit is slightly moved sideways with respect to the previous one.

Before each manual measurement, directly above the site where the snowpit is planned to be realized, radar measurements (in most case, six) were done, averaging the collected data for producing the final result, in accordance with standard radar processing for fixed targets (as it is for snowpacks during the few seconds required), where multiple rapid measurements are used to enhance the equivalent signal-to-noise ratio.

A radar trace was recorded both for $s = 30$ cm and $s = 70$ cm. For each trace, the first (direct path) and the second (multipath) snow-ground echo were identified. An example of a trace for the receiver placed at 70 cm from the transmitter is shown in Fig. 3. To improve the identification of the second echo from the ground, a possible zone where this second echo should be, is calculated. In particular, after measuring the time of flight for the first echo, and taking into account the geometry of the problem and the possible values for the dielectric constant of dry snow (ranging from 1 to 2), the possible zone can be delimited (a gray area in Fig. 3). It is worth noting that, in some cases, the identification of the second echo can be misled by a weak snow-ground reflection or vice-versa by a strong reflection within the snowpack (e.g., due to an icy layer). In these cases, the collected data is discarded, and the radar measurement repeated.

B. Results and Discussion

Results for the C1, C2_1, and C2_2 are shown in Figs. 4–6, respectively. In particular, in all cases, the real value
Fig. 4. Results for the snowpack depth $D$ and SWE for the experimental campaign C1. Dots and crosses indicate results related to the radar measurement with $s = 30$ cm and $s = 70$ cm, respectively. Solid and dashed line indicates the ground truth for $D$ and SWE, respectively.

In all cases, solid and dashed lines represent the snow depth $D$ and SWE, respectively, measured with the manual analysis, is compared with the radar measurements for $s = 30$ cm and $s = 70$ cm.

In particular, for C1 and C2_1, a manual measurement per day was done, resulting in a time series of five and nine days for C1 and C2_1, respectively. For C2_2, in some cases, two manual measurements per day were done, resulting in a time series spanning 21 days. For the longer campaigns, C2_1 and C2_2, where the effect of the time evolution of the snowpack is naturally more evident, the radar measurements were able to track the expected behavior (known as packing of the snowpack). In particular, the snowpack depth $D$ tends to get smaller, while the SWE tends to remain constant because of the gradual increase for the snowpack density.

Overall, the results are summarized graphically in Fig. 7 and in terms of root mean square error (RMSE) and mean absolute error (MAE) in Table I. As anticipated, it can be appreciated that, on average, the radar measurements are better for a larger antenna separation $s$. This is due to a larger difference in the propagation distance between the direct and second path, which reduces the correlation between the two measurements, hence, improving the results when solving the mathematical problem. For $s = 70$ cm, an MAE of 4.7 and 3.6 cm is achieved for the snowpack depth $D$ and SWE, respectively. In addition, the results are grouped around the diagonal line in Fig. 7, thus showing no significant bias. In relative terms, the achieved MAE implies a relative error of around 5% and 20% for the snowpack depth $D$ and SWE, respectively. The larger dispersion for the SWE is mostly due to the fact that it is calculated as the combination of two independent parameters, depth $D$ and density $\rho$, as shown in (1). Therefore, the two independent uncertainties contribute, statistically, to enlarge the dispersion for the SWE.

| Campaign | Snowpack depth $D$ | Snowpack depth $D$ | Snowpack SWE | Snowpack SWE |
|----------|-------------------|-------------------|--------------|--------------|
|          | $s = 30$ cm       | $s = 70$ cm       | $s = 30$ cm  | $s = 70$ cm  |
| C1       | 4.9 / 4.3         | 6.7 / 6.1         | 10.7 / 7.3   | 3.4 / 2.9    |
| C2_1     | 8.2 / 7.4         | 4.6 / 3.8         | 11.1 / 9.5   | 3.4 / 2.8    |
| C2_2     | 8.1 / 6.6         | 6.5 / 4.7         | 5.8 / 4.7    | 5.3 / 4.1    |
| **TOTAL**| **7.6 / 6.4**     | **6.1 / 4.7**     | **9.1 / 7.0**| **4.7 / 3.6**|

TABLE I

(LEFT) RMSE AND (RIGHT) MAE FOR THE RADAR MEASUREMENT FOR THE DIFFERENT CAMPAIGNS. ALL VALUES ARE IN cm.
IV. CONCLUSION

This letter presented a radar technique able to calculate the snowpack depth, density, and SWE, particularly suited for portable radars. The proposed technique is based on multipath propagation, and it is completely self-standing (e.g., it does not require assumption on the snowpack density, external devices, complex antenna movements, and/or post-processing inverse techniques). It was experimentally validated against manual snowpits during three field campaigns with dry snow, showing an MAE better than 5 cm for both depth and SWE.

According to the application, this error can be improved, for example working with an antenna separation larger than 70 cm, and this can be of interest for monitoring specific sites, for example, for validating satellite data. On the other hand, if the radar is used to sample at many different places an entire mountain catchment, for example, for water resource management, where errors are expected to be averaged out, smaller antenna separations can be used to improve the compactness and portability.

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