Proof-of-Concept for a Ground-Based Dual-Receiver Radar Architecture to Estimate Snowpack Parameters for Wet Snow

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Abstract—Snow is an important environmental variable and a primary water resource in many areas of the world. Monitoring seasonal snowpack properties is also crucial for properly managing snow-related hazards such as snow avalanches and snowmelt floods. Recently, an innovative radar architecture, based on the use of two receivers, has been proposed for snowpack monitoring for the case of dry snow, where the snowpack depth and bulk density can be calculated with one single radar measurement, without any kind of external aid. This article presents the extension of this innovative radar architecture for the case of wet snow. The approach to determine, not only the snowpack depth and bulk density but also the liquid water content, is outlined and discussed in detail, along with the experimental validation of the operating principle for two cases.

Index Terms—Downward-looking radar, frequency-modulated continuous wave (FMCW) radar, liquid water content (LWC), snow density, snow monitoring, snowpack, snow water equivalent (SWE), wave speed, wet snow.

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, even for wet snow, information on snow depth ($H_S$), snow density ($\rho_s$), volumetric liquid water content ($LWC$), and snow water equivalent (SWE) are necessary inputs [4]. In particular, it can be worth observing that SWE can be defined either as [4]

$$SWE = HS \rho_s$$ (1)

measured in millimeters of water equivalent (mm w.e.) or in kilograms per square meter (kg/m$^2$). Alternatively, it may be defined as [5]

$$SWE = HS \rho_s/\rho_w$$ (2)

measured in millimeters (mm), where $\rho_w$ is the water density (1000 kg/m$^3$). This second definition is used in this article.

$H_S$, $\rho_s$, and $LWC$ are important indicators for snow stability. In particular, for wet snow, LWC has a crucial impact on wet snow avalanche prediction [2], [6], as well as for the onset of meltwater run-off [7]–[9], and for what concerns the modeling of the climate system, the albedo [10]. SWE is a critical parameter for the reservoirs of hydro-power stations, for hydrological models, and in general for several water use applications [11], [12].

Microwave radars represent a valuable approach to monitor the snowpack, both for remote-sensing platforms, most notably satellites [13], [14], and for ground-based measurements, even for wet snow [15]–[18]. A common limitation for standard ground-based radars is that they cannot determine simultaneously the snowpack depth and the dielectric properties (hence, the physical properties) with a single radar measurement. For this reason, ground-based radars can be 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 measured by other means (e.g., ultrasonic and laser gauges, or water content reflectometers), or using a combination of radars and GPS receivers [17]–[20]. In other cases, different implementations based on multiple radar measurements are used, to achieve a solution relying only on radar signals. These implementations include electromechanical positioning enabling synthetic aperture radar tomography [21]–[24], and implementations under the general domain of the inverse-scattering, migration-focusing, common-offset, and common-mid-points techniques, often with radars mounted on snowmobiles [25]–[31].

However, a priori assumptions can be prone to large uncertainties. Additional devices other than radar increase the complexity of the system, and in some cases still retain potentially large uncertainties, and/or require installations.
above the ground of some components not intended for rapid removal, making them unsuitable for portable measuring systems. Finally, techniques based on classic multiple radar measurements, offering good accuracy in some cases, may suffer from the nonlinearity of the inversion process (e.g., local minima), the need for fortuitously located diffractions (e.g., rocks), the presence of artifacts, and the inconveniences of positioners, snowmobiles, and sleds, if used. In addition, they normally require a large number of different radar offsets to get a good accuracy, but at the cost of a more complex measurement setup.

Recently, a different radar system, based on a novel dual-receiver, stand-alone, frequency-modulated continuous wave (FMCW) radar architecture, was presented for the case of dry snow [32]–[34]. For the first time, it was demonstrated the possibility to measure, at the same time, the snowpack depth HS and the wave speed into the snowpack (thus, the snowpack density ρs and SWE) with only two radar measurements, thus with a very simple, compact, and light system, particularly suitable for portable applications. It is worth observing that a system easy to be portable is a key point to enhance the possibility of obtaining a more detailed spatial representativeness of the snowpack.

In this article, the mathematical approach, along with the experimental verification of the operating principle, is presented for two cases of wet snow. For wet snow, one more variable must be determined, LWC. This requires the development of a new set of equations, and to consider the cross correlation between the complex dielectric permittivity of the snow and the physical parameters ρs and SWE. In particular, for wet snow, not only the times of flight but also the differential power collected by the two receivers are considered. In addition, a study on the achievable accuracy is presented.

This article is organized as follows. Section II discusses the dielectric properties of wet snow, while Section III presents the proposed innovative radar architecture for snowpack monitoring in case of wet snow. Then, Section IV reports the experimental validation of the operating principle, and Section V is related to a discussion about the accuracy of the results.

II. DIELECTRIC PROPERTIES OF WET SNOW

At the frequencies of interest for this work, in the S-band, the snow can be characterized using both the real (ε′) and imaginary parts (ε″) of the relative dielectric permittivity (the former is also known as dielectric constant). These are functions of both snow density and SWE. According to [35], in the case of wet snow

\[ \varepsilon' = 1 + A + B + C/(1 + (f/f_0)^2) \]  
\[ A = 1.83 \times 10^{-3} \rho_{s_0} \]  
\[ B = 0.02LWC^{0.151} \]  
\[ C = 0.073LWC^{1.31} \]  
\[ \varepsilon'' = 0.073LWC^{1.31}(f/f_0)/(1 + (f/f_0)^2) \]  

where ρs0 is the dry snow density, measured in kg/m³, f is the operative frequency, f0 is the relaxation frequency (around 9.07 GHz), and LWC is measured in volume percentage. It may be worth observing that for wet snow, the dry snow density ρs can be derived according to

\[ \rho_s = \rho_{s_0} + \rho_{s_0}LWC. \]  

In general, it can be observed that for wet snow a dependence on frequency holds. However, for a wide range of densities and values of LWC, which cover practically all real-life cases, it can be observed that even if \( \varepsilon'' > 0 \), \( \varepsilon'' \ll \varepsilon' \) for operating frequencies of a few gigahertz. Consequently, for both dry and wet snow, it is possible to apply an approximated relationship between the speed v of the electromagnetic wave into the snowpack and \( \varepsilon' \) [36], indifferently for dry and wet snow

\[ v \sim c/\sqrt{\varepsilon'} \]  

where c is the speed of light.

Then, it is interesting to observe that in many practical cases, the knowledge of the dielectric constant \( \varepsilon' \), hence of the wave speed v, is sufficient to discriminate dry from wet snow. Indeed, normally the density for dry snow is rarely higher than around 450 kg/m³, while moderately wet snow bulk densities often exceed this value and can easily have a minimum LWC quantified in the order of 2%–3%. Therefore, for these typical conditions, the dielectric permittivity, calculated, as an example, at 2.75 GHz, for dry snow is rarely higher than around 1.8 for the relative real part. Instead, for wet snow, the relative real part of the dielectric permittivity often exceeds 2. Consequently, this may help estimate whether the snow is dry or wet without further processing. This can be useful for some applications. For more complete calculation of the properties of the snow, including LWC, the approach is described in Section III.

III. RADAR ARCHITECTURE FOR WET SNOW

The proposed dual-receiver radar architecture, operating principle, results, and possible enhancements are discussed in [32]–[34], in case of dry snow. Here, the operating schema and the mathematical approach are extended for the case of wet snow. First, as anticipated in Section II, for dry and wet snow indifferently, the wave speed into the snowpack can be related to the real part of the relative dielectric permittivity, using (6). Thus, as presented in [34], using two independent propagation paths, the mathematical problem of determining both the snowpack depth HS and the wave speed v into the snowpack can be closed. This allows for explicitly deriving two independent equations for the snowpack thickness D (i.e., measured at right angle to the slope, thus immediately related to HS knowing the inclination of the slope) and the dielectric constant \( \varepsilon' \)

\[ D^2 = (s_2^2T_1^2 - s_1^2T_2^2)/(4(T_2^2 - T_1^2)) \]  
\[ \varepsilon' = c^2(T_1 - T_2)(T_1 + T_2)/(s_1 - s_2)(s_1 + s_2) \]  

where \( s_1, T_1, s_2, \) and \( T_2 \) are the ground distances and the times of flight between the transmitter and the first and second receivers, respectively (Fig. 1).
It is worth observing that the radar schema presented in [32]–[34], leveraging on the idea of multiple radar measurements, only makes use of two radar measurements. These latter are collected using two antennas [32], [34] or even one single antenna working on multipath propagation [33]. Compared with other architectures using a larger number of multiple measurements, mentioned in Section I, this choice may return a suboptimal result in terms of accuracy. However, the radar setups presented in [32]–[34], with only two radar measurements, aim at a portable, downward-looking, compact, and light system. These features are key benefits for several field applications where the radar is placed above the snowpack are of interest, this suboptimal accuracy can be just for the time required for measuring, and then removed. In addition, for those cases where the average parameters of the snowpack are of interest, this suboptimal accuracy can be partially offset by measuring the snowpack more than once at slightly different adjacent locations, and then averaging the results, as demonstrated for dry snow in [34].

For wet snow, $\varepsilon''$ is to be determined. Taking advantage once more of the inequality $\varepsilon'' \ll \varepsilon'$, it is possible to correlate $\varepsilon''$ to the dissipation factor $\alpha_w$ due to the presence of liquid water [36]

$$\alpha_w \sim (\pi \cdot f \cdot \varepsilon'') / (\varepsilon \cdot \sqrt{\varepsilon'}).$$  \hfill (9)

Thus, once $\varepsilon'$ is calculated using (8), and $\alpha_w$ is determined, it is possible to derive $\varepsilon''$. To experimentally measure $\alpha_w$, a differential approach is adopted to minimize uncertainties. In particular, the power levels $P_1$ and $P_2$, detected, respectively, by the first and second receivers, can be related to the dissipation factor $\alpha_w$ using the radar equation [37]

$$P_1 = P_i (G_1^2 \lambda^2 S_1) / ((4\pi)^3 d_1^4 L_1)$$  \hfill (10)

$$P_2 = P_i (G_2^2 \lambda^2 S_2) / ((4\pi)^3 d_2^4 L_2)$$  \hfill (11)

where $P_i$ is the radiated power, $G_1$ and $G_2$ are the antenna gains along the angular direction defined by the tx–rx1 and tx–rx2 paths, respectively, $S_1$ and $S_2$ are the radar cross sections at the end of the snowpack for the tx–rx1 (point A in Fig. 1) and tx–rx2 (point B in Fig. 1) paths, respectively, $\lambda$ is the wavelength, and $d_1$ and $d_2$ are the propagation distances from the transmitter to the first and second receivers, respectively. $L_1$ and $L_2$ are the loss values due to the dissipation factor $\alpha_w$ along the tx–rx1 and tx–rx2 paths, respectively. These latter can be calculated as

$$L_1 = \exp(2d_1\alpha_w)$$  \hfill (12)

$$L_2 = \exp(2d_2\alpha_w).$$  \hfill (13)

Ideally, knowing the values assumed by all the parameters present either in (10) or (11), it would be possible to derive the dissipation factor $\alpha_w$. However, this simple approach is prone to uncertainties. Indeed, the value of some parameters, for example, the radiated power, is difficult to estimate (normal uncalibrated transmitters change their output power according to several working conditions, e.g., the ambient temperature, and the final radiated power is also affected by unpredictable reflections coming from the antenna–transmitter coupling and from the antenna–snow coupling). Instead, the differential comparison between $P_1$ and $P_2$ allows applying a more robust approach, where the absolute values of radiated power are disregarded

$$P_1 / P_2 = (G_1^2 S_1 d_1^4 L_2) / (G_2^2 S_2 d_2^4 L_1)$$

$$= (G_1^2 S_1 d_1^2) / (G_2^2 S_2 d_2^2) \exp(2d_2 - d_1)\alpha_w.$$  \hfill (14)

In (14), a direct relationship between the dissipation factor $\alpha_w$ and the ratio $P_1 / P_2$ between the power received at the first and second receivers is outlined. Indeed, $G_1$ and $G_2$ can be calculated analytically once the antennas are known, and $S_1$ and $S_2$ can be estimated using a formulation for the radar cross section in the near-field regime [38], [39]. At the same time, the differential approach allows for neglecting, in most practical cases, second-order corrections, for example, related to the small variation in reflectivity with the incidence angle, as demonstrated with a practical example in Section IV.

Once both $\varepsilon'$ and $\varepsilon''$ are determined, using (3) and (4), it is possible to calculate the dry snow density $\rho_s$, and LWC. Consequently, using (7), (8), and (14), it is possible to have a simultaneous measurement of $D$ (or HS), $\rho_s$, and LWC. The entire process is summarized in Fig. 2, where also the possibility to discriminate dry from wet snow just on the ground of the real part of the relative dielectric permittivity $\varepsilon'$ is presented, as discussed in Section II. However, the discrimination between dry and wet snow may be difficult in some cases, especially for values close to the threshold presented in Fig. 2 ($\varepsilon' < 1.8$). This is typically happening during the ripening phase of the melting, i.e., when the LWC is low and the wet front is just formed. In this case, it is still possible to apply a conservative approach and solve the complete mathematical problem as if the snow was wet. Then, the appropriateness of this assumption can be evaluated a posteriori in accordance with the values calculated for $\varepsilon''$ and LWC.

IV. EXPERIMENTAL VALIDATION OF THE OPERATING PRINCIPLE

The experimental test of the operating principle for the proposed radar architecture for wet snow took place in two separate test sites in the Italian Alps. The first experimental test was at an altitude of around 2500 m a.s.l. (45°40′10″N 7°18′30″E, April 6, 2017), and the second experimental test was at an altitude of around 2100 m a.s.l. (45°51′50″N
Fig. 2. Work logic for the calculation of the snowpack parameters. $\varepsilon' = c^2$.

7°38’50”E, May 7, 2019). In both cases, the terrain is practically flat. The experimental setup is shown in Fig. 3.

A metal rail is used to support the antennas, which are open-ended WR340 waveguides working from 2.2 to 3.3 GHz. These frequencies provide a reasonable compromise between penetration depth and resolution, for different snow conditions, dry (where the system was already presented [32]–[34]) and wet. The rail is placed in such a way that it is parallel to the snowpack surface, normal to the slope of the terrain. By experience, this is the condition that maximizes the possibility that the rail is parallel to the terrain, which is unknown. The first antenna is used as the transmitter, and the second antenna is manually translated along the rail in two different positions to simulate two independent receiving antennas at distances $s_1$ and $s_2$ from the transmitter. In particular, values ranging from 30 to 40 cm and from 60 to 70 cm are used for $s_1$ and $s_2$, respectively. This can be done because the target is basically static (i.e., no modifications to the composition of the snowpack) during the time required to collect these two measurements. This allows recording two independent radar profiles, as shown in Fig. 4, which are used to calculate the snowpack parameters as described in Section III. It is worth noting that a second-step version of the radar, conceptually identical, but with two physical receivers and a mechanical switch, is presented for dry snow in [34]. This simplifies the measurements, avoiding the care required to translate the antenna along the rail.

It is worth also noting that these values for $s_1$ and $s_2$ are selected to optimize the transportability of the system rather than the accuracy, which in general improves for larger values for $s_1$ and $s_2$, as described in detail in Section V. However, as these two experimental tests are aimed at the validation of the operating principle, a suboptimum accuracy does not impair the demonstration.

Finally, the antenna coupling to the snow surface is maximized by the manual intervention of the operator, who physically places the radar above the snowpack as accurately as possible, aiming at a uniform contact between the antenna apertures and the snow surface. It may be interesting to observe that the radiation patterns of the antennas, when coupled directly to the snow, are different from the patterns of the case where they are allowed to radiate into the air. However, the antennas are not very directive, and the gain enhancement introduced by the direct coupling with the snow does not prevent proper operation of the system. This latter in fact requires the receiving antennas to pick up the signal reflected by the ground, generated by the transmitting antenna. Taking into account that the offsets between the antennas are short, less than 100 cm, this always guarantees in practice good mutual visibility within the reciprocal radiation patterns.

Looking at Fig. 4, several details can be appreciated. First, Fig. 4 shows the raw radar signals, as acquired by the receivers, without any kind of postprocessing (which may be useful, e.g., in view of semiautomatic routines, but at the same time may
complicate the direct, intuitive, interpretation) but normalization with respect to the magnitude of the highest peak. Some internal reflections, and the snow–ground interface, marked by a solid gray line, are visible. For example, for the first test case, the time of flight for the snow–ground interface is slightly less than 10 ns for the first receiver (approximately 9.75 ns), and slightly more than 10 ns for the second receiver (approximately 10.25 ns). Such a difference, approximately 0.5 ns, corresponding to around 15 cm of propagation in air, is in accordance with the system geometry, i.e., snowpack depth and distances between receivers.

The effect of a strong coupling, identified by a peak close to 0 ns, is visible for the first receiver of the first test case. The presence of this effect is strongly affected by local causes, mostly related to the snow-air discontinuity and antenna coupling to the snow. As anticipated previously in this same paragraph, these aspects may play an important role, but given the natural variability of the snow, and the manual operation of the radar, placed above the snowpack, the final effect in terms of coupling may be difficult to predict accurately. However, if present, this strong coupling is normally very far from the snow–ground interface and does not jeopardize the correct interpretation of the latter.

The radar measurements are followed by a manual snowpack analysis, carried out by professional chartered Interregional Association for Coordination and Documentation of Snow and Avalanche Problems (AINEVA) (Italian association for snow and avalanches) experts, according to the Italian standard procedure for manual snow profiling. The manual analysis is performed digging a snow pit ideally at the same location where the radar measurements took place. In particular, the depth is measured with a field ruler, with a maximum estimated error of ±1 cm. Bulk density is obtained probing with a sampler (volume 198 cm³) and weighting with a dynamometer a series of snow samples of known volume taken from the different layers forming the snowpack. In this case, taking into account the resolution of the dynamometer, i.e., 1 g, and to be conservative a sampled volume inaccuracy of ±5%, the maximum error is around ±7%. Thus, combining the maximum estimated error for depth and density, it is possible to estimate the maximum estimated error for the SWE [calculated in accordance with (2), knowing the snowpack depth and density], which is approximately ±7% as well.

The per-layer LWC is determined in accordance with the classic test normally used for the manual analysis (“glove” test) of the snowpack (first test, [4]) or using the Finnish snow fork (second test, [40]), respectively. For the “glove” test, for the case of interest, the error is ±2.5%. For the second test, using the snow fork, the error is 0.5% [41]. The manual estimation of the LWC is a qualitative test, ideally not suitable for quantitative studies [41]. However, the “glove” test remains widely used for field operations [41]. For this reason, despite its poor accuracy, it still provides a qualitative comparison useful to contextualize the radar measurements within the framework of a widely accepted test for field operators. It is also worth observing that the LWC is a parameter possibly with large spatial differences, as the snowpack structure when wet snow is present can be complex [42–44]. This may lead to further inaccuracies, for example, when the location of the manual analysis is not perfectly aligned with the location of the radar measurement. Finally, the maximum expected errors for all other parameters (ρ_d, ε’, ν, and ε’’), are directly calculated based on the errors for HS, ρ_s, SWE, and LWC.

For the first test, the results are summarized in Table I. Concerning the manual analysis, it is interesting to observe that in this case the LWC was measured manually [4], and it was found to be uniform over the entire snowpack, with a wetness index 3 (wet) for all layers. This means that the LWC can range from 3% to 8%, with an average of 5.5%. As anticipated, the poor accuracy for the LWC imposes large inaccuracies to the parameters ρ_d, ε’, ν, and ε’’, as it can be seen in Table I. In particular, the equivalent dry snow density ρ_d ranges from 310 kg/m³ (if LWC = 3%) to 216 kg/m³ (if LWC = 8%), with an average of 263 kg/m³ (if LWC = 5.5%). According to these measurements, the expected ε’ ranges from 1.83 to 2.66 (average 2.22) and the expected wave speed ν ranges from 2.22·10⁸ to 1.84·10⁸ m/s (average 2.01·10⁸ m/s). These values are calculated at 2.75 GHz (the central frequency of the radar system). It is interesting to observe that the variation in these parameters within the radar bandwidth (2.2–3.3 GHz) can be considered negligible (e.g., for the case ρ_d = 263 kg/m³ and LWC = 5.5%, ε’ ranges from 2.24 to 2.20 at 2.2 and 3.3 GHz, respectively). Finally, the expected ε’’ ranges from 0.09 to 0.31 (average 0.19) at 2.75 GHz.

| Parameter | Manual analysis | Radar measurement |
|-----------|-----------------|-------------------|
| HS        | 127 ± 1 cm      | 98 cm             |
| ρ_s       | 318 ± 22 kg/m³  | 402 kg/m³         |
| SWE       | 404 ± 31 mm     | 394 mm            |
| LWC [4]   | 5.5 ± 2.5%      | 4.8 %             |
| ρ_d       | 263 ± 47 kg/m³  | 354 kg/m³         |
| ε’        | 2.22 (1.83–2.66) | 2.27              |
| ν         | 2.01 (1.84–2.22)·10⁸ m/s | 1.99·10⁸ m/s   |
| ε’’       | 0.19 (0.09–0.31) | 0.16              |

On the other side, the dual-receiver radar measurement provides HS = 0.98 m and ν = 1.99·10⁸ m/s. Consequently, the calculated dielectric constant is ε’ = 2.27. At the same time, the ratio P_1/P_2 between the power received by the first receiver and the power received by the second receiver is around 3.53. Then, using (14) with S_2/S_1 = 1.200 and G_1/G_2 = 1.318 (calculated analytically according to [38], [39]; for comparison, the estimated difference in reflectivity at the snow–ground interface because of the different incidence angle is approximately not larger than 1.05, thus validating the approximation presented at the end of Section III), it is calculated that ε’’ = 0.16 at 2.75 GHz. Solving (3) and (4) for the dry snow density and LWC, it is calculated that ρ_d = 354 kg/m³ and LWC = 4.8%; this results in a bulk density ρ_s = 402 kg/m³ and an SWE equal to 394 mm.

For the second test, the results are summarized in Table II. Concerning the manual analysis, it is interesting to observe that in this case the LWC was measured using the snow fork [40], sampling the snowpack with a step of 5 cm. This allowed for
measuring with improved accuracy the bulk LWC for the entire snowpack (LWC = 3.75%). Then, even if the nominal accuracy is 0.5% [41], to account for an extra margin able to account for the difficulties of operating the snow fork in a real mountain scenario, an accuracy of 1% is account for. Nonetheless, the inaccuracies for the parameters $\rho_s$, $\varepsilon'$, $\nu$, and $\varepsilon''$ remain smaller compared with the first test, as can be seen in Table II. In particular, the equivalent dry snow density $\rho_d$ ranges from 341 kg/m³ (if LWC = 2.75%) to 277 kg/m³ (if LWC = 4.75%), with an average of 309 kg/m³ (if LWC = 3.75%). According to these measurements, the expected $\varepsilon'$ ranges from 1.85 to 2.20 (average 2.02) and the expected wave speed $\nu$ ranges from 2.02·10⁸ to 2.21·10⁸ m/s (average 2.11·10⁸ m/s). These values are calculated at 2.75 GHz. Finally, the expected $\varepsilon''$ ranges from 0.08 to 0.16 (average 0.11) at 2.75 GHz.

The dual-receiver radar measurement provides $HS = 0.76$ m and $\nu = 2.11·10⁸$ m/s. Consequently, the calculated dielectric constant is $\varepsilon' = 2.02$. At the same time, the ratio $P_1/P_2$ between the power received by the first receiver and the power received by the second receiver is around 2.11. Then, using again (14) with $S_2/S_1 = 1.200$ and $G_1/G_2 = 1.318$ (calculated analytically according to [38], [39]), it is calculated that $\varepsilon'' = 0.12$ at 2.75 GHz. Solving (3) and (4) for the dry snow density and LWC, it is calculated that $\rho_s = 303$ kg/m³ and $LWC = 3.80\%$; this results in a bulk density $\rho_s = 341$ kg/m³ and an SWE equal to 258 mm.

V. DISCUSSION ON THE ACCURACY OF THE RESULTS

The experimental results reported in the previous chapter account for the possibility for the proposed system to calculate important parameters for both dry and wet snowpacks. The best theoretical accuracy achievable for this calculation is primarily dictated by the accuracy achievable for the measurement of the times of flight $T_1$ and $T_2$. This is affected by a number of factors (e.g., sampling of the radar signal, antenna misalignments, uncorrected biases in the propagation within cables and antennas), but two of them are of primary importance, as discussed in the following.

First, the operating principle requires a flat snow/ground interface, as depicted in Fig. 1 (or ideally the knowledge of the shape of the terrain), to calculate the times of flight and the attenuations of the radar signal between the transmitter and the receivers. In real cases, however, as exemplified by our test sites, the unavoidable and unknown unevenness of the snow–ground interface inevitably determines an error in the measurement of the times of flights. As an example, for a typical case where $s_1 = 30$ cm, $s_2 = 70$ cm, $HS = 100$ cm, and $\varepsilon' = 1.5$, on a flat terrain the theoretical difference between $d_1$ and $d_2$ is around 9.66 cm, and the distance between the two reflection points at the snow/ground interface (points A and B in Fig. 1) is 20 cm ($s_2/2 - s_1/2$). This means that an unevenness of the terrain in the order of 1 cm between points A and B may cause an error in the measurement of the times of flight in the order of 10%, generally much larger than any other source of error. This problem, which is intrinsically random, can be usually mitigated by repeating the radar measurement a number of times, slightly changing the position of the radar above the surface of the snow, and averaging the results, as shown in [34]. It is worth observing that the radar architecture is based on deploying two independent receivers, which do not require external devices or references, other assumptions, or complex movements or postprocessing. This makes possible to realize multiple measurements, for a single test site, in a matter of minutes, thus greatly mitigating any unevenness of the terrain.

The second important factor impacting on the accuracy is the relative separation between the receivers and the transmitter. In particular, taking into account (7) and (8), the partial derivatives with respect to $T_1$ and $T_2$ can be calculated

$$\frac{\delta D}{D} = Q_1/Q_2$$

$$Q_1 = T_2T_1\delta t \left\{ T_2(s_2^2 - s_1^2) + T_1(s_1^2 - s_2^2) \right\}$$

$$Q_2 = (T_2^2 - T_1^2)^2 \left\{ s_2^2T_1^2 - s_1^2T_2^2 \right\}$$

$\delta\varepsilon'/\varepsilon' = 2\delta t(T_1 + T_2)/|T_1^2 - T_2^2|$ (16)

where $\delta t$ is the error affecting the measurement of the times of flight. Now, to better understand how the geometry of the system, most notably $s_1$ and $s_2$, affects the results, (15) and (16) can be plotted for different values of $s_1$ and $s_2$ of interest in practical cases, from 0 to 1.5 m, and for different notable snowpacks with $D = 1$ m and $\varepsilon' = 1.1$, 1.4, 1.8, and 3.5, as shown in Fig. 5. This range of values for $\varepsilon'$ is useful for addressing extreme conditions, from very dry snow to significantly wet snow. As an example, Fig. 5 is realized assuming

$$\delta t = 1/2B$$

where $B$ is the radar bandwidth. In this case, $\delta t$ would equal the radar resolution. This is not directly related to radar accuracy, but it is common practice to use it as a worst case indication, as in all practical cases accuracy will be no worse than resolution. In this case, with a bandwidth $B = 1.1$ GHz, $\delta t$ is approximately 0.45 ns.

First, all cases in Fig. 5 look similar, thus showing no different trend for dry and wet snow. Then, it can be appreciated that when the value of $s_1$ approaches the value of $s_2$, both $\delta D/D$ and $\delta\varepsilon'/\varepsilon'$ reach very high values (note that all points with values exceeding 100% were removed, to avoid saturating the color scale). This corresponds to the cases where the separation between the two receivers is too small. This, in turn,
means that the time of flight $T_1$ is very similar to the time of flight $T_2$. Therefore, since the difference between $T_1$ and $T_2$ is too small, any error on the time of flights would have a large relative impact on the calculation of the snowpack thickness $D$ and dielectric constant $\varepsilon'$. Instead, it can be appreciated that both $\delta D/D$ and $\delta \varepsilon' / \varepsilon'$ decrease when the difference between $s_1$ and $s_2$ increases. This is because the difference between $T_1$ and $T_2$ increases, and any error on the time of flights would have a smaller relative impact on the calculation of the snowpack depth $D$ and dielectric constant $\varepsilon'$.

It may be interesting to observe that for the experimental validation of the operating principle presented in Section IV, the radar architecture is intentionally implemented ($s_1 = 30–40$ cm, $s_2 = 60–70$ cm) to optimize the transportability of the system (mass, volume, complexity) rather than the accuracy. While this choice partially leads to nonoptimized values for the measured errors, the demonstration of the mathematical approach and the operating principle described in Section III are not limited by this aspect. These two aspects combined can explain why in some cases the relative error shown in Section IV is not optimal. Most notably, for the first test case, a relative error of around 22% and 26% affects the measurement of the snowpack thickness and dielectric constant, respectively. On top of these aspects, it is also interesting to observe that a nonlinear relationship between the different physical and electrical parameters of the snowpack holds.

In addition, for wet snow, $\varepsilon'$ and $\varepsilon''$ are determined jointly by both the LWC and $\rho_s$. This can generate a situation where comparatively small inaccuracies translate into large final errors. For example, for the first test case, if the measured LWC was 5.5% (instead of 4.8%), then the error on the snowpack density would improve from around 26% to around 8%.

Thus, while for optimized performance some mitigation strategies are desirable (e.g., larger values for $s_1$ and $s_2$, multiple measurements), the two test cases demonstrated, even under suboptimum conditions, the operating principle, and that the snowpack parameters can be measured even for wet snow.

VI. CONCLUSION

This article presents the experimental results for the demonstration of the operating principle for wet snow of a novel FMCW radar architecture for snowpack monitoring. This novel radar architecture, based on two receivers, can calculate the snowpack depth, bulk density, LWC, and SWE, with one single radar measurement of the times of flight between the transmitter and receivers, and the differential power collected by the two receivers. The mathematical equations, used to solve the problem, are discussed, and the maximum expected errors are addressed, along with possible optimization strategies to reduce them. Two experimental test cases are presented to validate the operating principle.

However, further tests are required to assess the system under a larger variety of conditions and better evaluate the response across different situations. It is also worth observing that at the frequencies used for the proposed radar (S-band), the maximum penetration of the radar signal within the wet snowpack should be evaluated carefully; the larger the LWC, the shorter the penetration depth, which could become insufficient to cover the snowpack depth. For example, when the dry snow density is 300 kg/m$^3$, and the LWC raises from 1% to 10%, the dissipation factor at 2.75 GHz increases from approximately 4 dB/m to approximately 28 dB/m.
However, for seasonal snowpacks, higher LWC is normally related to snowpacks less thick, and this may lead to partial compensation.

An open point remains the interpretation of the radar profile for each receiver, in particular the identification of the snow–ground interface. Semi- or fully-automatic routines are desirable, but their reliability should be verified against complex situations, where a number of factors, including internal reflections, spurious echoes, and nonoptimized antenna coupling to the snow surface, can raise serious obstacles.

Finally, it is worth pointing out that the proposed architecture represents the best solution in terms of compactness, cost, and mass, which are key features for portable instruments. Where portability is not the primary objective, alternatives using more than two receivers, and/or receivers further apart than the offsets considered here, may provide more accurate results.

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