RETRIEVAL OF DIELECTRIC PROPERTIES OF SOFT MATERIALS USING A LOW COST FMCW 24 GHZ RADAR: INVESTIGATING ITS USE AS SNOWPACK DENSITY PROFILER

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ABSTRACT

Monitoring the internal structure of the snowpack is crucial for managing snow-related hazards such as snow avalanches and snowmelt floods. Recently, the availability of low cost, low power and low-profile frequency-modulated continuous-wave (FMCW) radars at 24 GHz has grown thanks to its potential use the automotive sector. This paper proposes the use of a compact and low-cost FMCW radar as an instrument for improving the study of the snowpack, delivering Snow Density and Liquid Water Content in a fast way. The radar is intended to be used as a snowpit instrument, creating density and Liquid water content (LWC) snow profiles and trying to overcome the customary density cutters (slower and operator-dependent). The theoretical equations of the principle are presented and a preliminary validation by means of a laboratory test is done using dry snow mimicking material, providing encouraging results.

Index Terms— Snow Monitoring, FMCW Radar, Liquid Water Content, Snow Density

1. INTRODUCTION

The snowpack is usually analyzed by human operators using manual techniques [1]. Physical parameters such as density of liquid water content (LWC) are obtained to determine the stability of the snowpack and to estimate the quantity of ice within the snowpack that will melt in spring. This analysis implies the use of several well-known tools such as the density cutter or the pocket scale. However, reasonable uncertainties are present when using these instruments. When measuring the density of the snowpack using cutters, and according to [2], variation between cutter types provides measurements that are within 11% of the true density, without accounting for variation due to weighing devices. At the same time, when measuring the LWC of the snowpack, the state-of-the-art in different mountain regions consist of the application of the gravimetric method [3]. However, the application of this technique is often complicated and time-consuming so, in practice, the operators usually estimate the LWC by visual inspection and manipulation of the snowpack, producing operator dependent results with high uncertainties.

Several advanced instruments have been proposed looking to aid the analysis in-situ of the snowpack. Instruments such as the Snow Fork [4] or the Denoth probe [5] have been using in snow research in order to help in the analysis and harmonization of Density and LWC measurements. However, these instruments are not reliable enough in terms of accuracy [6], and in addition they are expensive and not user-friendly.

The use of FMCW radars for snow measurements is well-known[7], especially for remote sensing applications. However, the use of these radars as a in-situ tool for studying the snow properties has not been deeply investigated yet. This paper proposes the use of one of the commercial new-generation FMCW radars working at 24 GHz (initially designed for collision avoidance, it has also been used in snowpack thickness estimation [8]) for retrieving the snow density and the LWC within the snowpack, paving the way for being used as a regular profiling snow pit tool. The radar is used alongside a fixed metallic target (aluminum plate) placed at 30 cm from the antenna, then the antenna's radar and the metallic plate are inserted in the snowpack at different heights to create a density and LWC profile of the snowpack. A graphical description of the system is depicted in Fig. 1.

The equations for estimating the snow parameters are derived and the scientific principle is demonstrated by a laboratory validation using the Sentire™ Radar Module - sR-1200e [7] measuring the dielectric constant of cork. Cork can be used as a dry snowpack *phantom* for testing some radar applications as demonstrated in [9].

The paper is organized as follows: Section 2 illustrates the theoretical background of the proposed technology, Section 3 describes the instrument employed, the experiment is described in Section 4 and its results discussed in Section 5. Concluding remarks are drawn in Section 6.

2. THEORETICAL BACKGROUND

2.1. Snow Density Derivation

The estimation of the density of the snowpack is based on the retrieval of the permittivity of the medium where the electromagnetic wave propagates. Assuming some boundary conditions on the problem, the dielectric permittivity of the medium can be easily estimated by the radar.

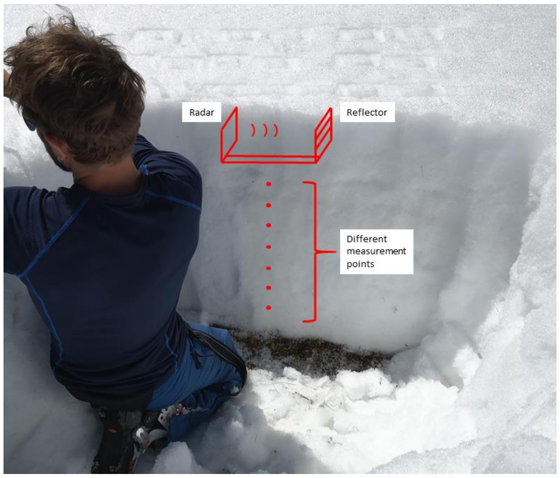

Figure 1. Graphical description of the instrument in the snowpit environment.

These conditions are the assumption of the homogeneity of the snowpack within the sampled area and the knowledge of a fixed target placed at a well-known distance (30 cm in this case). Then, using the well-known following equations:

$$v_{snow}=c_0/\sqrt{\varepsilon_{r\_snow}} \qquad (1)$$

$$v_{snow} = \text{distance/time} \qquad (2)$$

where v_{snow} is the wave speed in the snowpack, c_0 is the constant wave speed in vacuum and ε_{r_snow} is the dielectric constant of the snowpack, it can be assumed that:

$$\varepsilon_{r\_snow} = (c_0 \cdot \text{time-of-flight / distance-to-target})^2 \qquad (3)$$

Keeping the distance as a constant, the relation between ε_{r_snow} and time-of-flight becomes straightforward. However, some radars (and this is the case), provide directly an estimation on the distance-to-target instead of the time-of-flight, assuming the wave is propagating in air. Just by dividing this time by c_0, it is possible to obtain the time-of-flight, yielding:

$$\varepsilon_{r\_snow} =(D_{snow}/D)^2 \qquad (4)$$

Being D_{snow} the *biased* distance-to-target provided by the radar and D the real distance (keeping always $D_{snow} > D$).
Then, several empirical models can be used for relating the dielectric permittivity with the density of the snow. Using, for example the well-known Hallikainen model [10], the snow density can be estimated for snow as follows:

$$\varepsilon' = 1+ 1.83e^{-3}\, \rho_{ds} + 0.02\, LWC^{1.31} / 1+(f/f_0)^2 \qquad (5)$$

$$\varepsilon'' = 0.02\, LWC^{1.31}\ (f/f_0) / 1+(f/f_0)^2 \qquad (6)$$

being ε' the real part of the dielectric constant, ε'' the imaginary part, ρ_{ds} the density of the snowpack without accounting for the water, LWC the liquid water content and f_0 the relaxation frequency (~9.07 GHz). This relation holds considering that according to [11] snow permittivity is extremely stable between 0.6 and 300 GHz.

For dry snow the imaginary part of the dielectric permittivity can be neglected resulting in a straightforward way of estimating dry snow density:

$$\varepsilon'_{ds} = 1+ 1.83e^{-3}\, \rho_{ds} \qquad (7)$$

However, for wet snow the imaginary part should be considered. In order to obtain it and close the problem the method explained in [12] has been used. Using the power drop between a measure in air and the measure in snow it is possible to estimate the material losses. Once the radar has given the material losses per meter one can estimate the imaginary part of the dielectric permittivity (exploiting the fact that $\varepsilon'' \ll \varepsilon'$) as follows [13]:

$$\varepsilon'' = \alpha_{snow}\, c_0 \sqrt{\varepsilon'} / (\pi f) \qquad (8)$$

being α_{snow} the material losses in Neper per meter. This formulation solves the problem both for dry and wet snow.

3. FMCW RADAR DESCRIPTION

3.1. Radar Description

The Sentire Radar Module by IMST is a low cost, low profile, ultra-light radar unit, integrated alongside a waterproof shelter. It works in K-band with a maximum bandwidth of 2.5 GHz. For this work, an integrated patch antenna provided by IMST and composed by one transmitter antenna and two receiver antennas has been used. IMST provides a commercial software that can be use for testing the device and a complete user interface to write new software and extend the post-processing.

The size of the radar system is 114x87x42.5 mm and the weight 280 g. The modulation used is FMCW with two receiving channels.
In order to be consistent with the boundary conditions explained in Section 2, a metallic plate has been attached to the radar placed at 30 cm from the antennas as depicted in Fig. 2.

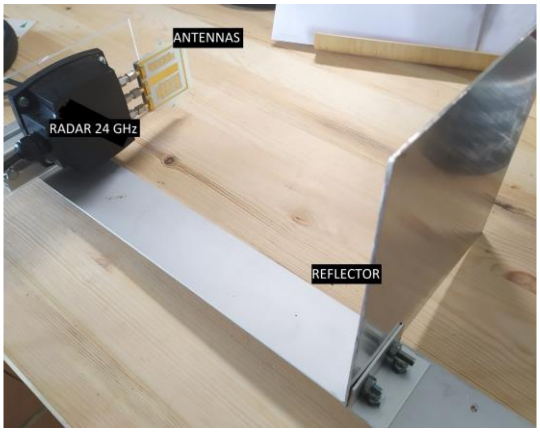

Figure 2. Picture of the system, composed by the radar unit, the antennas and the metal reflector

3.2. Range Resolution

The resolution in range, i.e. the minimum distance required to distinguish two different targets, is usually defined as:

$$\delta_r = 1/ B \qquad (9)$$

where B is the radar bandwidth. However, in this case, the snowpack is assumed to be homogeneous, especially in the wave propagating direction. Thus, we assume that only one target is present, i.e., the metallic plate (and its multiple reflections). In this way, the *apparent resolution* can be improved by padding techniques in the fast Fourier transform process [8]. Modifying the padding configuration of the radar, this results in an *apparent resolution* of ± 0.6 cm.

3.3. Penetration Depth

The penetration depth can be expressed as the distance where the microwave power drops to e^{-1}. However, this value is often not realistic to characterize modern radar systems as they usually work with dynamic ranges even close to 100 dB. For this reason, for estimating the penetrating depth, a more realistic approach derives the radar equations adapted to the medium where the wave is propagating [9]. Using the radar equation [14], the received power can be described as:

$$P_{rx} = P_{tx}\, G^2\, \lambda^2\, \sigma / (4\pi)^3\, R^4\, L \qquad (10)$$

where P_{tx} is the radiated power, P_{rx} the received one, G is the gain of the antennas (supposing all the antennas with the same gain), σ is the radar cross section (RCS) of the target (flat metallic surface RCS), λ is the wavelength, R is the distance-to-target and L is the loss factor associated to the medium. L is expressed as follows:

$$L= e^{(2\, R\, \alpha_w)} \qquad (11)$$

while, according to [14], and exploiting the fact that ε'' << e' it is possible to approximate the dissipation factor as follows:

$$\alpha_w \sim \pi\, f\, \varepsilon'' / c_0 \sqrt{\varepsilon'} \qquad (12)$$

which indeed, can be solved for the worst case, with a medium wet snowpack (ε'=2, ε''=0.15, corresponding to a density of 538 kg/m^3 and a LWC of 4%) resulting in a received power drop of around 75 dB placing a 20cm x 20cm metallic target at 30 cm of distance from the radar. This demonstrates, at least theoretically, that the system should work at least with *moderate* wet snows.

3.4. Antenna's Footprint

In order to know what the radar is measuring, the antenna's footprint in the target can be used. According to the antenna's specifications provided by IMST the azimuth and elevation beamwidth is equal to 32.5º and 12º, respectively. Solving very straightforward trigonometric equations, the footprint on the metallic plate can be estimated as an ellipse with a semi-major axis of 8.74 cm and a semi-minor axis of 3.15 cm. Approximating the sample volume as an elliptic cone, its volume can be calculated following straightforward trigonometric equations as:

$$\textit{Sampling volume} = 1/3\, \pi\, a\, b\, h \qquad (13)$$

resulting in 865 cm^3, slightly bigger than the 500 cm^3 standard Swiss or SIPRE density cutter [2].

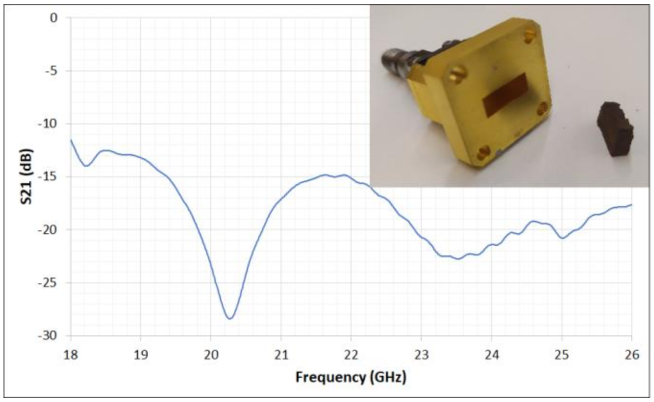

Figure 3. Results for the S21 of the cork piece in K-band, measured with a VNA

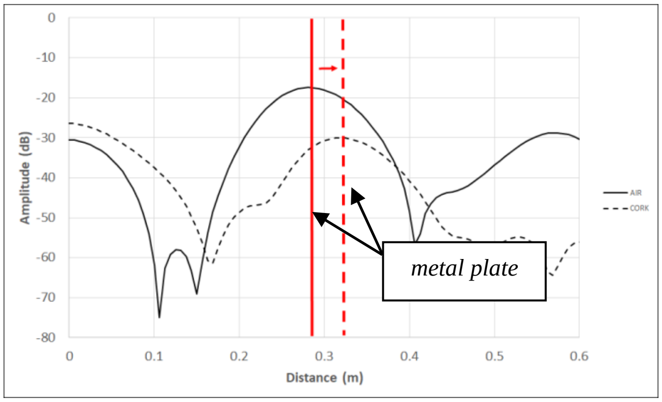

Figure 4. Results on distance provided by the radar system. Radar trace for the air calibration in solid line. Radar trace for the cork characterization in dashed line. Red color indicates the metallic target peak.

4. EXPERIMENTAL VALIDATION

For validating the idea proposed in the previous sections, an experimental test in laboratory has been performed under controlled conditions. As demonstrated in [8], several affordable materials can be used for mimicking dry snow in radar applications. In this case, a block of natural cork has been used for obtaining, first, its dielectric properties and, secondly, its density and LWC (being a low-loss material LWC will be expected to be close to 0).

The radar results are compared with the dielectric measurement of a block of cork made using the well-known technique for dielectric characterization of materials using rectangular waveguides [15], fitting the results with its full-wave simulated model in HFSS. The measurement has been realized using a rectangular waveguide in K-band and a standard laboratory Vector Network Analyzer (VNA). The measured S_{21} of the cork sample can be observed in Fig. 3. We observe that the main transmission zero is placed at 20.3 GHz, which corresponds to a dielectric constant of $\varepsilon_r \sim 1.35$, according to the full-wave simulation of the scenario.

The results of the radar are presented in Fig. 4, which shows the results of the distance-to-target in air and in cork, and the *virtual* displacement between them. Note that for accuracy in the real distance D it will be used the value produced by the radar in air instead of the 30 cm. So, the measurement process will consist in a measurement in air and then a measurement in the material analyzed. With these results, and solving the equations in Section 2, a dielectric permittivity of 1.285+j0.02 is obtained. As previously said, the imaginary part of is so small that can be neglected.

5. DISCUSSION

The validation test, despite of providing encouraging results, can only mimic the case of dry snow. For the wet snow situation, even if the theoretical model holds, further validations in-lab and/or in real snow are needed. The differences between the ε_r measured by the VNA and the estimated by the radar can be associated to the *sampling* of the cork to be introduced in the K-band waveguide. Cork is a quite fragile material and the sampling process of such a small piece is not straightforward.

6. CONCLUSION

In this work it has been presented the use of a commercial 24 GHz FMCW radar as a density and LWC profiler for the snowpack. The mathematical formulation has been discussed demonstrating the possibility of obtaining density and liquid water content from the distance-to-target obtained from the radar, utilizing the well-known empirical models relating the dielectric and the physical properties of the snow. The system has been tested in laboratory with a dry snow mimicking material, providing encouraging results and supporting the initial idea. The results pave the road for a light volume and light weight instrument for create density and LWC profiles of the snowpack. However further tests in real snow are needed and they will be done in the future.

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