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A Microwave Frequency Range Experiment for the Measurement of Snow Density and Liquid Water Content

Cédric Bermond, Philippe Artillan and Michel Gay

Abstract—This paper presents a new nondestructive characterization system for the extraction of both snow density and liquid water content (LWC). The experiment primarily measures the relative complex permittivity of snow ($\bar{\epsilon}_s$) at microwave frequencies at 4 GHz to 6 GHz. The density and LWC are then deduced with high accuracy from an empirical model of literature that has been experimentally validated in this study.

Index Terms—Snow, liquid water content (LWC), density, snowpack, high frequency characterization, complex permittivity

I. INTRODUCTION

THE knowledge of the snow water equivalent (SWE) of a snowpack, or in an equivalent manner its effective density ρ_s , is important to predict the water resources in the mountains, especially for hydroelectric dams [1] [2]. The effective density typically varies from 0.1 g/cm³ to 0.6 g/cm³. Furthermore, a complete description of the state of the snow must include its liquid water content (LWC), or wetness. The LWC, or wetness, allows for classification of snow in three categories according to the volumetric water. Dry snow is described with LWC = 0, wet snow with LWC = 1%-8%, and very wet snow with LWC = 8%-15%. These data can be obtained by traditional snow pit observations or by several kind of electromagnetic measurement methods, which are all based on the relation between the complex permittivity ($\bar{\epsilon}_s = \epsilon'_s - j\epsilon''_s$) and the duplet (ρ_s, LWC).

First, measurements of the complex permittivity can be directly performed by an operator using a capacitive sensor [3], or a resonant cavity [4]. In order to allow easy, automatic and nondestructive measurements, freespace methods, involving ground directed antennas have been developed. A first method is based on a Ground Penetrating Radar (GPR) which measures the propagation velocity of an electromagnetic pulse in the snowpack [5], [6] and [7]. A second approach is to use a wideband frequency-modulated continuous-wave (FM-CW) radar [8], [9]. The analysis of the delay of reflected signals allows us to describe the physical layers in terms of changes in

real dielectric permittivity. These radars propose a remote monitoring system for the depth of snow [10] or even the snowpack stratigraphy [11]. Finally, the possibility to use an electromagnetic test bench using a vector network analyzer (VNA) to extract very precisely the effective density from the real part of the dielectric permittivity has been demonstrated for a dry snowpack in [12], [13]. However, all these methods only measure a delay time or a phase shift, thus only allowing the determination of the real part of the snow permittivity ϵ'_s . In previous references, the density ρ_s was deduced from this measurement by assuming dry snow ($LWC = 0\%$). Other methods extract LWC , assuming a known average density for snow ρ_s [14].

In this paper, we propose a non-destructive test bench operating in the 4-6 GHz range, based on a two-port VNA two horn antennas setup, measuring the full scattering matrix of a snow sample. A VNA uses a continuous wave frequency sweep without frequency modulation. The sensitivity of VNA measurements is much higher than GPR (the dynamic range reaches 80 dB) and the extraction gives information on both the magnitude and the phase of the signal. Both the real and the imaginary parts of the permittivity can then be extracted, thus allowing for the determination of both the snow density ρ_s and its LWC.

This paper is divided into four parts. Section II presents the frequency dependent model of permittivity used to extract the density and the LWC. Section III describes the test bench and details the calibration procedure with the extraction algorithm. A theoretical demonstration estimates the measurement error and the impact on the extraction of the permittivity. Section IV discusses the density and LWC results, for wet and dry snow. Finally, we will compare the density extract from measurement with the complex permittivity to the density extract from a manual measurement.

II. SNOW PERMITTIVITY MODEL

Several models have been established that describe the complex permittivity of snow $\bar{\epsilon}_s = \epsilon'_s - j\epsilon''_s$ [15], [16] and [17]. Dry snow can be described by Matzler's model [18], which only

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depends on the density. The model proposed by Sihvola and Tiuri [19] also takes into account the LWC of the snow and has thus been chosen for our study. For the sake of completeness, the empirical equations that relate snow density ρ_s and liquid water content W (in % of the total volume) to the complex permittivity are rewritten here:

$$\epsilon'_s = (0.1W + 0.8W^2)\epsilon'_{w'} + (1 + 1.7(\rho_s - W) + 0.7(\rho_s - W)^2) \quad (1)$$

$$\epsilon''_s = (0.1W + 0.8W^2)\epsilon''_{w'} \quad (2)$$

It is convenient to express the relative permittivity of the water in terms of a complex number with $\bar{\epsilon}_w = \epsilon'_w - j\epsilon''_w$. The Debye relaxation allows to compute $\bar{\epsilon}_w$:

$$\bar{\epsilon}_w = \epsilon_{w\infty} + \frac{\epsilon_{wdc} - \epsilon_{w\infty}}{1 + j\omega\tau} \quad (3)$$

with ω as the angular frequency $\omega = 2\pi f$ and f the frequency, τ the relaxation time, $\epsilon_{w\infty}$ the optical (infinite frequency) dielectric constant for $f = \infty$ and ϵ_{wdc} the static value of dielectric constant for $f = 0$. The temperature effect on relaxation time and for 0°C we use $\tau = 17$ ps, $\epsilon_{w\infty} = 4.9$ and $\epsilon_{wdc} = 88$.

On one hand, the imaginary part of the snow permittivity only depends on the LWC. The imaginary part of permittivity the snow becomes high enough for extraction above 1 GHz and it remains almost linear with frequency up to 6 GHz as shown on fig. 1. Moreover, the electromagnetic wave penetration depth between 1 and 6 GHz allows samples to be a few centimeters thick. We thus decided to use this frequency range to extract LWC with a good accuracy.

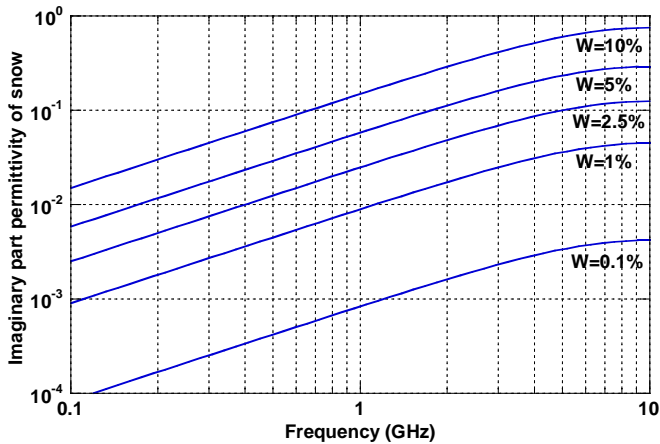


Fig. 1. Imaginary part of the snow permittivity for different values of LWC.

On the other hand, the real part of the snow permittivity depends on both its density and its LWC as shown in fig 2. Below 1 GHz, the real part stays constant with frequency. Above 1 GHz, its behavior strongly depends on the LWC: the higher the LWC, the lower the real part of the permittivity. In order to obtain the density of the snow with good accuracy, the LWC must then be extracted before from dielectric losses. Very

low LWC values such as 0.1% correspond to extracting very low imaginary part of the permittivity at the chosen frequency range such as $2 \cdot 10^{-3}$, which is hardly attainable with a field experiment. However, the high sensitivity of the proposed test bench, which is due the combination of using a free space method (no air gaps between the sample and the measurement device) and an accurate vector network analyzer, allows extracting LWC values greater than or equal to 1% (corresponding to determining imaginary part of permittivity upper than $2 \cdot 10^{-2}$).

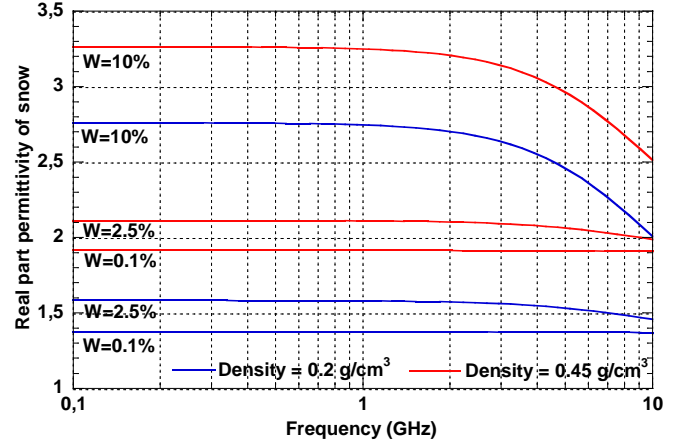


Fig. 2. Real part of the snow permittivity for two values of density and three values of LWC.

We can compute the LWC and the density by inverting the empirical equations given in (1-2):

$$W = \frac{\sqrt{\epsilon''_w{}^2 + 320\epsilon''_w\epsilon'_s - \epsilon''_w}}{16\epsilon''_w} \quad (4)$$

$$\rho_s = W + \frac{1}{14} \sqrt{-224\epsilon'_w W^2 - 28\epsilon'_w W + 280\epsilon'_s + 9} - \frac{17}{4} \quad (5)$$

The next part expounds our freespace test bench with the complex permittivity extraction procedure.

III. MEASUREMENT SETUP

A. Test bench description

As presented in fig. 3, a portable complex permittivity measurement bench has been realized. Two rectangular horn antennas (Pasternack PE9861) are connected to a Vector Network Analyzer (VNA). The measurements of the two-port scattering parameters have been performed in the 4 GHz – 6 GHz frequency range. The material under test (MUT) is a parallelepipedic sample of about 50 cm \times 50 cm and of variable thickness l placed between the two antennas. The antennas must be highly directional (20 dB) to focus the electromagnetic field into the sample and to avoid secondary reflections on the sides of the experiment. Furthermore, the parasitic standing wave due to secondary reflections must be minimized by protecting the metallic supports with absorbers. Finally, one antenna is placed on a micropositioning system in order to provide a fine tuning of the distance between the two antennas for TRL calibration.



Fig. 3. Portable complex permittivity measurement bench.

B. Plane wave approximation

The procedure of material permittivity extraction is based on the plane-wave approximation. The electromagnetic wave generated by the horn antenna of our test bench has been simulated with Ansys Electronics Desktop HFSS solver in order to determine the minimum distance to place the sample, still verifying the plane wave hypothesis. Fig. 4.a presents the magnitude of the electrical field. Its distribution on a transverse section is almost Gaussian with a maximum at the center z-axis. Although this is not strictly a plane-wave configuration, the fact that almost all the energy is concentrated on the central axis and is then retrieved in the receiving horn antenna makes the experiment correctly set up. The most important criteria to avoid interferences between the various paths for the wave is to keep the phase of the E-field almost constant on a transverse section. Fig 4.b shows that the difference of the E-field phase is inferior at 10° on surface of the spot.

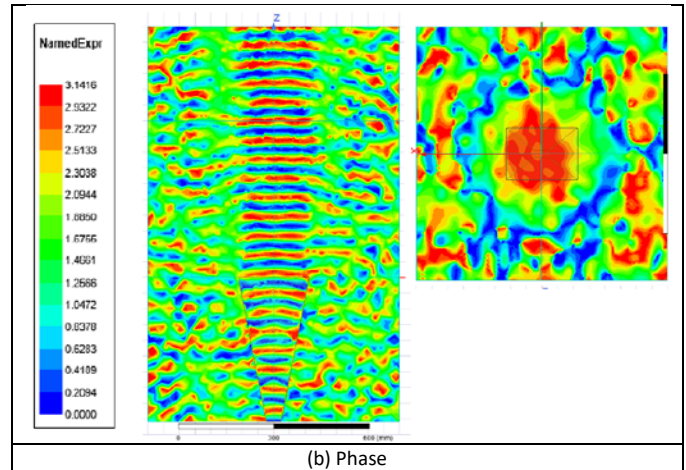
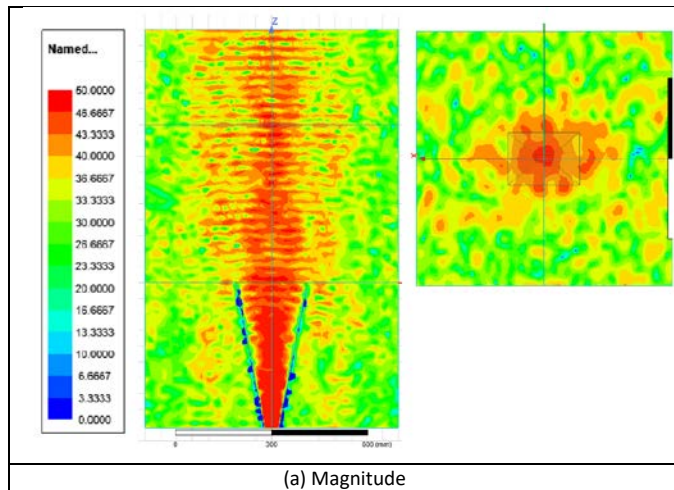


Fig. 4. Numerical modelization of the y-component of the electrical field generated by the horn antenna. (a) Magnitude in dB. (b) Phase (absolute value, in radians).

C. Test bench calibration and complex permittivity extraction procedure

The TRL calibration technique [20] and [21] is well appropriate for freespace measurements because the calibration standards (Thru, Reflect, Line) are easily realized and the characteristic impedance of the propagating waves in freespace is well known. This procedure is developed without time gating and is performed in three steps (cf. fig. 5).

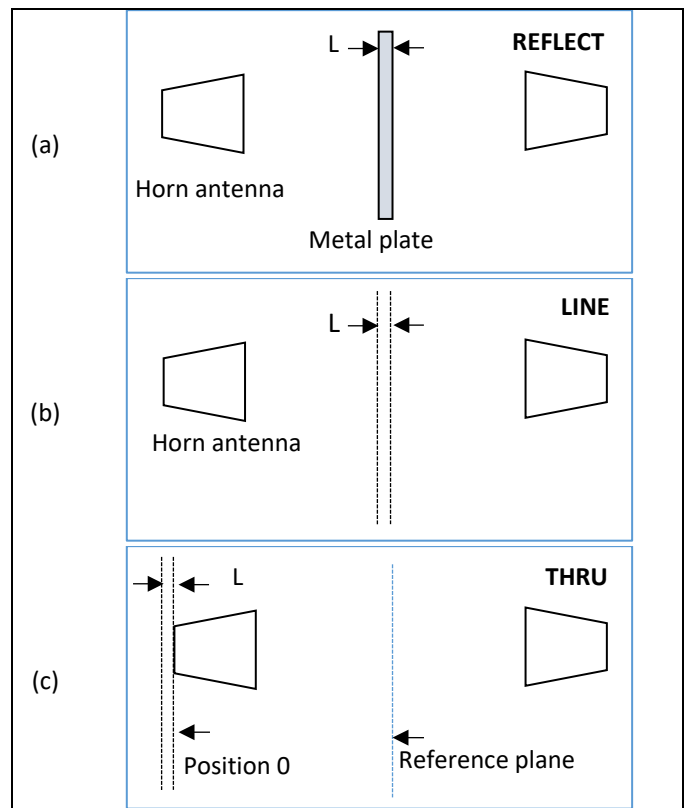


Fig. 5. TRL calibration standards. (a) Reflect. (b) Line. (c) Thru.

The Reflect standard (fig. 5.a) consists of a metal plate of thickness $l_{REFLECT} = 5$ mm, placed between the two antennas. It

allows setting the position of the reference planes for the measurement.

The Line standard (fig. 5.b) is obtained by removing the reflect standard, the distance between the horn antennas being unchanged. The length of the line standard must verify the following relationship for any angular frequency ω to avoid phase mistakes in calibration errors terms:

$$20^\circ < \frac{\omega}{c_0} l_{REFLECT} < 160^\circ \quad (6)$$

where $c_0 = 3.10^8 \text{ ms}^{-1}$

The Thru standard (fig. 5.c) is achieved by moving one antenna forward of the thickness of the Reflect standard.

We then used the Ross-Nicholson-Weir [22], [23] and [24] method to extract of the relative complex permittivity of the MUT. The reference planes are first placed at each side of the MUT sample by measurement post-processing. The reflection and transmission coefficients of the MUT sample are then computed from the four scattering parameters. The complex permittivity is then extracted from the transmission coefficient. The reflection coefficient could be used for high real permittivity samples, but for snow-like materials, the best results are obtained from the transmission coefficient.

D. Extraction uncertainty computation

The uncertainties of the extraction mainly come from the uncertainty of the sample's thickness Δl and the uncertainty of the phase $\Delta\theta$ of the transmission scattering parameter $S_{21} = |S_{21}|e^{j\theta}$. Here we propose a simple computation, based on realistic approximations, of the impact of measurement uncertainties Δl and $\Delta\theta$ on the real part of the snow permittivity ϵ_s' .

For simplicity's sake, instead of using the complex permittivity $\bar{\epsilon}_s$, the computation is made with the complex refractive index \bar{n} .

$$\bar{n} = \sqrt{\bar{\epsilon}_s} = n - jk \quad (7)$$

The coefficient of transmission t is defined as:

$$t = e^{-j\frac{\omega\bar{n}l}{c}} = e^{-\frac{\omega kl}{c}} e^{-j\frac{\omega nl}{c}} \quad (8)$$

Assuming that the reflection coefficient is very small $0 < |r| \ll 1$, the transmission coefficient t can be assimilated to the transmission scattering parameter S_{21} :

$$t \approx \frac{(1 - r^2)t}{1 - r^2 t^2} = S_{21} = |S_{21}|e^{j\theta} \quad (9)$$

The relation between n , θ and l thus becomes:

$$\theta \approx \frac{\omega nl}{c} \quad (10)$$

and the uncertainty on the real part of the refractive index can

be written as:

$$\Delta n \approx \frac{c}{\omega l} \Delta\theta + n \frac{\Delta l}{l} \quad (11)$$

To estimate the typical error of extraction we used the value of real permittivity of dry snow $n = \sqrt{1.6}$ and a thickness of sample with 210 mm. The value $\Delta\theta$ represents the variation of phase during measurement due to the temperature stability of the VNA. We maximize this value with $\Delta\theta = 0.5^\circ$. We consider an error of length during the measurement of the sample $\Delta l = 5 \text{ mm}$. For a frequency of 5 GHz, the error on the permittivity is less than 3%. This result demonstrates the accuracy of the proposed method.

IV. RESULTS

A. Preliminary results on dry snow, system performances

In order to validate the accuracy of the test bench, measurements have been performed with five samples thicknesses different. These measurements were acquired in the massif of Mont Blanc on the roof of the Argentière hut at an altitude of 2700 m (11/11/2020). The snow is considered dry (LWC = 0). The density of the snow was measured at 0.34 g/cm^3 and the temperature of the snow was measured at -3°C . We can notice a high precision of measurement with less than 3% of variation on the real part of permittivity as shown in fig. 6.

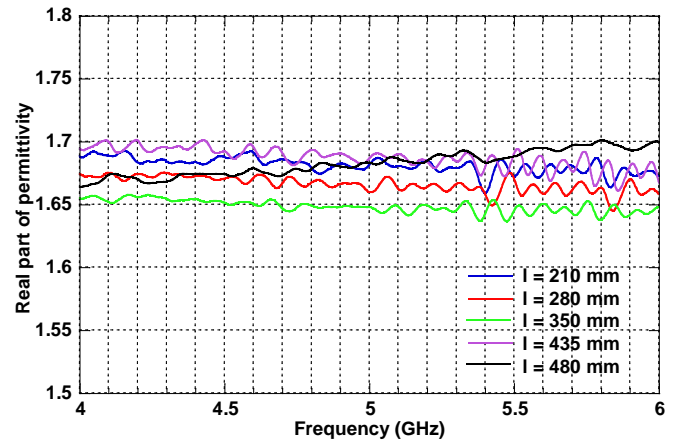


Fig. 6. Real part permittivity of snow from five samples for a density of 0.34 g/cm^3 .

Although the snow is considered dry, the imaginary part of the complex permittivity is not exactly zero as shown in fig.7. The freespace transmission system then has a noise floor and cannot measure values of imaginary parts of permittivity lower than 10^{-2} .

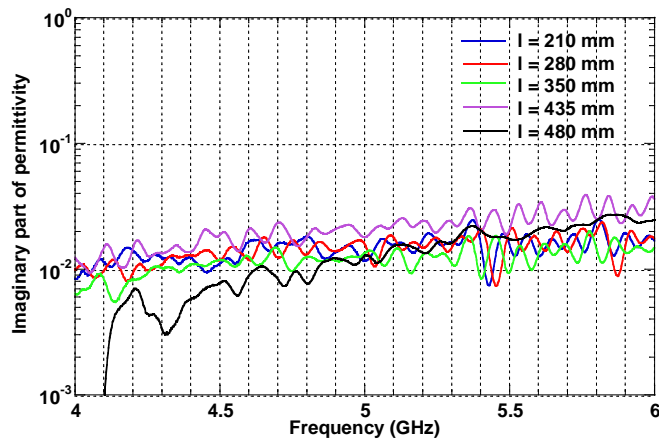


Fig. 7. Imaginary part permittivity of snow from five samples for a density of 0.34 g/cm³.

From the relationship (4) and (5) the LWC and the density were extracted on the frequency range. The fig. 8 shows these results for five samples from 210 mm to 480 mm thick.

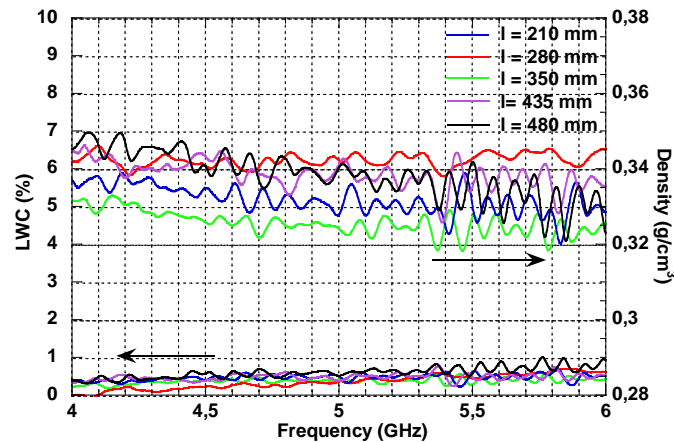


Fig. 8. Liquid Water Content and density extracted from measurement for dry snow.

The density is quite constant versus frequency. The ripple can be explained by the impact of parasitic waves during the measurement. This phenomenon is low and represents only 5% of the average value. The LWC stays constant with the frequency with an average value of 0.5%. Both results demonstrate the accuracy of our test bench.

Table I gives the average value of LWC extracted from the imaginary part of the complex permittivity for the five samples.

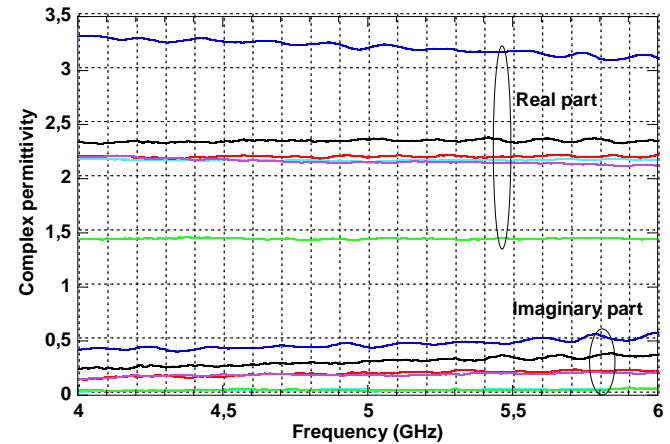
TABLE I
LWC AND DENSITY EXTRACTED FROM MEASUREMENTS

Thickness	Measurements (4 GHz - 6 GHz)		Error relative of density (direct measurement 0.34 g/cm ³)
	Average LWC (%)	Average density (g/cm ³)	
210 mm	0.45	0.339	0.6%
280 mm	0.42	0.333	2%
350 mm	0.35	0.327	3.8%
435 mm	0.60	0.332	2.3%
480 mm	0.36	0.342	0.6%

First, the values are little but not zero for LWC. The empirical noise floor of the test bench is then evaluated to 0.6% for the LWC. Secondly, the measurement system is qualified to measure the density of snow with less than 5% error.

B. Characterization of snow

In this part, we present the extraction of the density and the LWC of any kind of snow. Six samples have been measured, during winter and spring. The complex permittivity of each sample was extracted between 4 GHz and 6 GHz. The extraction process is illustrated as shown in fig. 9. The real part varies between 1.4 to 3.3, corresponding to an increasing density. The imaginary part varies between 0.01 to 0.6 and suggests moisture in the samples.



Date	Place	Date	Place
05/18/20	Val Thorens	01/15/2021	Pipay
02/08/21	Pipay	02/26/2021	Col de Porte
02/08/21	Pipay	04/23/2021	Argentière

Fig. 9. Complex permittivity of snow samples.

From these results, the LWC and the density were then extracted with the relationships (4) and (5) and are presented on figures 10 and 11.

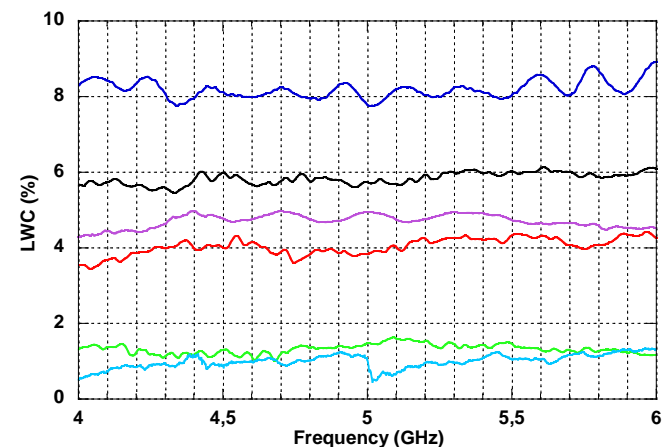


Fig. 10. LWC extracted from measurement of the samples of snow.

As the frequency behavior of the LWC is flat, we have extracted an average value of 4.66% for one sample (Col de Porte 02/26/2021). A commercial sensor named WISE [25],

based on low frequency capacitive measurement [26], has given a very close value of 4.88%, thus validating our approach. The error on LWC is less than 5%.

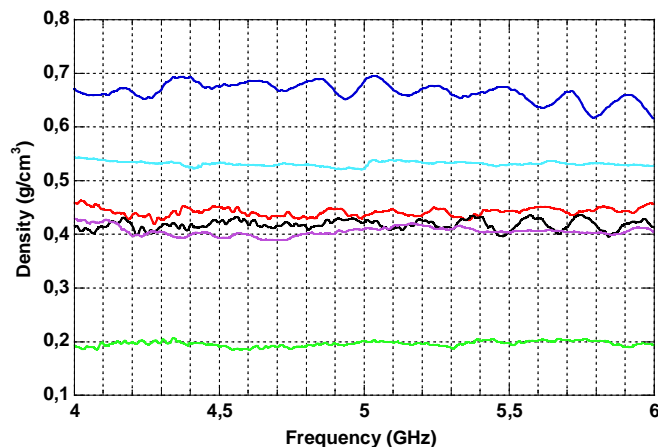


Fig. 11. Density extracted from measurement of the samples of snow.

Each sample has been weighted and its volume has been measured to calculate its density. These values are compared to the extracted density from high frequency measurement of the complex permittivity in table II. The density shows a very good agreement between measurement results with the high frequency extraction and the theoretical model, thus validating the electromagnetic measurement setup and the reverse modeling extracting approach. The error on the density is less than 7%.

TABLE II
SNOW MEASUREMENTS

Sample	Density (g/cm ³)		Error relative of density
	Direct measurement	Average density	
Blue	0.625	0.665	6.4%
Red	0.417	0.441	5.7%
Black	0.391	0.408	4.2%
Green	0.200	0.196	2%
Purple	0.410	0.405	1.2%
Cyan	0.521	0.531	1.9%

V. CONCLUSION

We have developed and validated a freespace test bench to measure the complex permittivity of snow with high accuracy between 4 GHz and 6 GHz. This procedure is based on the measurement of scattering parameters of a snow sample and the use a validated extraction algorithm. Snow properties are then deduced from complex permittivity measurements thanks to a reversed analytical model. On one hand, the density of dry or wet snow can be extracted with a precision of 7%. On the other hand, the liquid water content is precisely measured down to 1% by volume. This work enables the further objective to perform a permanent monitoring in-situ measurement of the effective complex permittivity of the snowpack, thus enabling the computation of the snow water equivalent.

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Michel Gay received the Engineering degree in microelectronics from the Institute of Engineering Sciences of Montpellier, in 1987, and the Ph.D. degree in physics from the University Joseph Fourier, Grenoble, France, in 1999. From 1979 to 1985, he was a Technician with the Institute of Botany and Teacher with the Academy of Montpellier. From 1988 to 2003, he was with Cemagref Grenoble, where he worked as an Electronics Engineer with the research unit of Torrential Erosion Snow and Avalanche. Since 2004, he has been employed as a Research Engineer with the CNRS Laboratory "Grenoble Image Parole Signal Automatique," Saint Martin D'Herès. He was the Co-Leader of four National Scientific projects and three European projects. His research interest includes image processing synthetic aperture radar (SAR), applied to the monitoring of snow and glaciers.