A NEW HANDHELD CAPACITIVE SENSOR TO MEASURE SNOW DENSITY AND LIQUID WATER CONTENT

Fabian Wolfspeger[1]*, Michel Geisser[1], Silvio Ziegler[2] and Henning Löwe[1]

[1] WSL-Institute for Snow and Avalanche Research SLF, Switzerland
[2] FPGA Company GmbH, Switzerland

ABSTRACT: Quantifying the density (ρ) and liquid water content (LWC) of snow is crucial for any physical process in the snowpack. A widely used method to measure those quantities involves a capacitance sensor that subjects the snow to an electrical field, an idea first introduced by Denoth (1989). While this dielectric measurement principle is known to be well-working from yearlong use of Denoth prototype sensors, such instruments are not yet commercially available. To this end, we developed a new ρ and LWC sensor with the goal of producing a small batch series in the near future. The sensor is a single coplanar capacitor integrated onto a printed circuit board that measures the relative permittivity (ε) of snow. We evaluated the sensor in the field through 13 dry and wet snow profiles and compared ε-values obtained from the new sensor with those measured with a Denoth prototype. An additional validation was carried out in the cold lab on homogenous dry and wet snow samples. Field measurements deviated on average by 0.5 % (RMSE) and lab measurements by 1% (RMSE) from the reference values. A comparison of the snow density, retrieved from ε using the Denoth inversion, with densities from volume weighing revealed an average deviation of about 4 kg m^{-3} (1.3 %). The new sensor provides a reliable instrument to replace the established, but no longer available Denoth sensors. The accuracy of the new (and likewise the old) sensor may be even improved if a better inversion model was available. A thorough understanding of the uncertainties in the dielectric calibration and uncertainties of the empirical permittivity parameterization relating ε, ρ and LWC may therefore lead to improved estimates in the future using the same device.

KEYWORDS: snow density, snow wetness, liquid water content, capacitive sensor, permittivity, dielectric method, snow profile.

1. INTRODUCTION

Quantifying the density (ρ) of snow and its liquid water content (LWC) is crucial to investigate any physical process within the snowpack. While measuring density using the volume weighing method is long-established, determining LWC remains challenging, particularly in field conditions (Colbeck, 1978, Fasani et al., 2023). One promising method to measure ρ or LWC involves a capacitance sensor that subjects the snow to an electrical field, an idea first introduced by Denoth et al. (1982a, 1982b, 1984, 1989, 1994). The principle is based on the fact that air, ice, and water have different relative permittivity values (ε) for frequencies between 0.01 and 1 GHz (Evans, 1965). Thus, depending on the proportions of ice, air and water within a snow volume, the measured capacitance changes. Despite the measurement principle was proven to be well-working from yearlong use of Denoth prototype sensors, such instruments are not yet commercially available. To fill this gap, we developed a new snow density and LWC sensor with the goal of producing a small batch series in the near future.

2. INSTRUMENT SPECIFICATIONS

The new capacitive sensor (NCS) features a relatively large sensor plate (173 x 117 mm), which provides a sufficient measurement volume, but still can be easily inserted into a snow pit wall and is compatible with the controllers of existing SLF SnowSensor or InfraSnow systems (Fig. 1). The sensor is a single coplanar capacitor integrated onto a thin 0.8 mm printed circuit board, as a compromise between strength and flexibility to ensure tight contact with the snow after insertion. The capacitor forms an oscillator together with a quartz crystal, such that any changes in capacitance lead to changes in oscillator frequency (Δf).

* *Corresponding author address:*
Fabian Wolfsperger, WSL-Institute for Snow and Avalanche Research SLF
Flüelastrasse 11, 7260 Davos
tel: +41 81-4170-105
email: wolfsperger@slf.ch

Figure 1: The old Denoth sensor and the new capacitive snow sensor (NCS).

3. INSTRUMENT CALIBRATION

The sensor was calibrated using an empiric ε-Δf relation from measurements on three materials (air ε_{air} = 1; polytetrafluoroethylene ε_{PTFE} = 2.1, polymethylmethacrylate ε_{PMMA} = 2.7) with known permittivity. The setup is shown in Figure 2. Calibration measurements at 0 °C and 27 °C revealed no relevant influence of temperature on the dielectric properties of the materials.

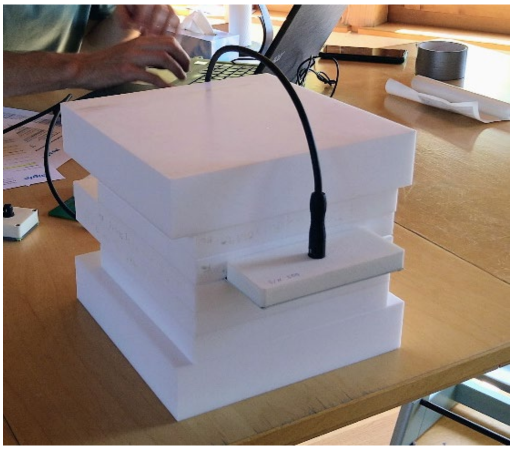

Figure 2: Calibration measurement with PTFE.

A continuous calibration curve was obtained by a 2nd order polynomial fit (Fig. 3). For high permittivity values the maximal raw signal deviation (Δf) among the 8 calibration curves was about 0.4 kHz (shown by the marker width), indicating the need to implement individual sensor calibration factors for each sensor.

4. EVALUATION

We evaluated the sensor in the field based on data revealed from 13 dry and wet snow profiles. First, we compared all ε-values obtained from the NCS with those measured with a Denoth prototype by their root mean square error (RMSE) and correlation coefficient (r). The same comparison was done with the data of each snow profile separately. Finally, we deduced ρ and LWC from ε to express deviation between the sensors by relevant quantities for snow practitioners. In addition, ρ and LWC as calculated from ε were compared with independent ρ and LWC measurements using volume weighing (ρ_{cutter}; n = 1…3), and melting calorimetry (n = 4…6) (Kawashima et al., 1998), respectively.

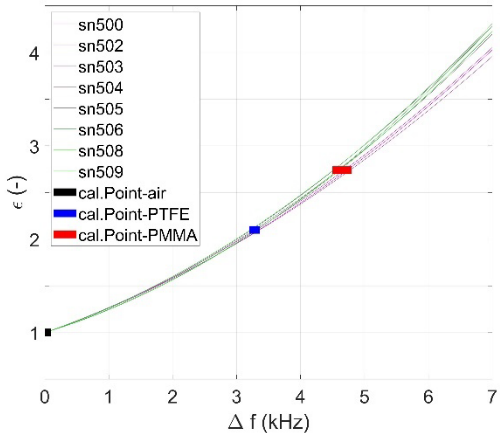

Figure 3: Calibration curves of 8 NCS.

4.1 Field measurements

Over all field measurements, the relative RMSE of ε was 0.5 % comparing NCS measurements to the ones measured with the Denoth sensor. For ε-values below 2 the two sensors were in good agreement (Fig. 4).

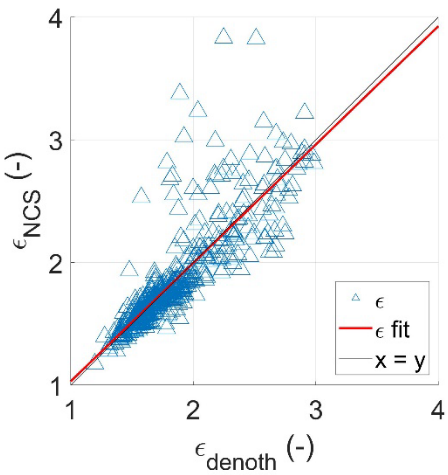

Figure 4: Comparison of all single permittivity measurement revealed from the NCS and the Denoth sensor.

For higher values the deviations between the two sensors increased and a few NCS measurements showed a distinct deviation towards higher values leading to correlation coefficient of only 0.84. The overall linear fit showed that, on average, the sensors agreed well with a slope of 0.97 ± 0.05 (95-confidence interval) and an intercept of 0.07.

The relative (absolute) RMSE over a single snow profile ranged from 0.4 % (0.007) to 3.8 % (0.077) with an average relative RMSE of 1.5 % (Fig. 4). Twelve out of 13 permittivity profiles correlated well between 0.61 and 0.92.

As shown in Figure 6 (right), larger deviations were mainly found if the snow was considerably wet or due to thin layers which were difficult to align horizontally with the measurement locations of the two sensors. Moreover, in some cases high LWC exceeded the measurement range of the Denoth sensor (Fig. 5 right: asterisk marker).

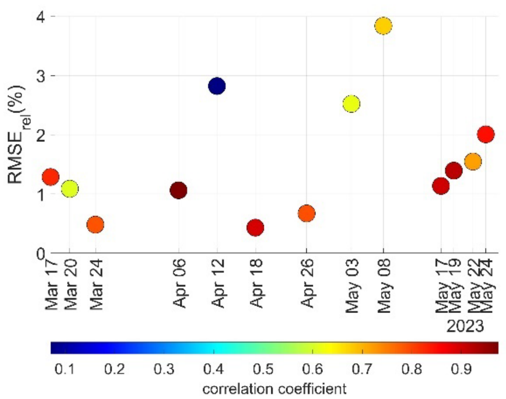

Figure 5: Relative RMSE and correlation coefficients (colors) of each snow profile comparing the permittivity measured with the NCS and the Denoth sensor.

From snow profiles which were clearly below 0 °C the density of dry snow ρ_{dry} was calculated using the inversion of following empirical formula (Denoth, 1989):

$$\epsilon = 1 + 1.92 \cdot \rho_{dry} + 0.44 \cdot \rho_{dry}^2 \quad (1)$$

The retrieved ρ_{dry} deviated on average of about 4 kg m^{-3} (1.3 %) compared to the densities from volume weighing. Figure 7 shows the bias (underestimation) between the two ρ-measurement methods which increased for values above about 200 kg m^{-3}. For both permittivity sensors, relative RMSE (1.3…1.4 %), correlation coefficients (0.75…0.76) and slopes of the linear fit were within a similar range (0.65…0.70).

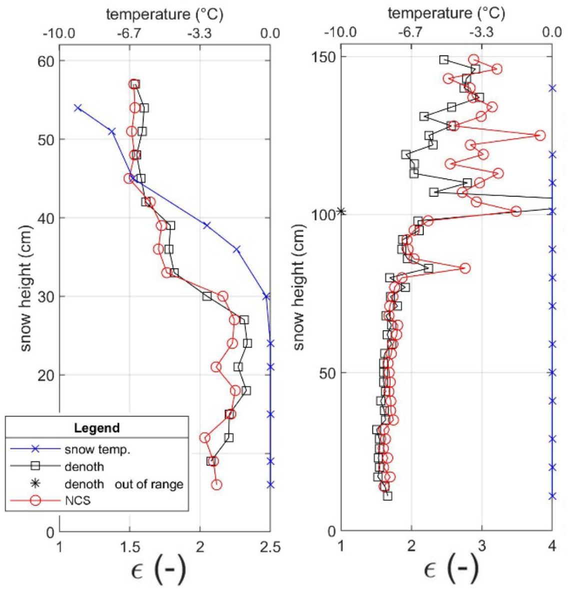

Figure 6: Two permittivity and snow temperature (blue) profiles revealed from the NCS (red) and from the Denoth sensor (black). Left) Profile on April 6th showing small deviations (RMSE$_{rel}$ = 1.1 %; r = 0.98). Right) Profile on May 8th showing partly larger deviations at wet snow layers (RMSE$_{rel}$ = 3.8 %; r = 0.62).

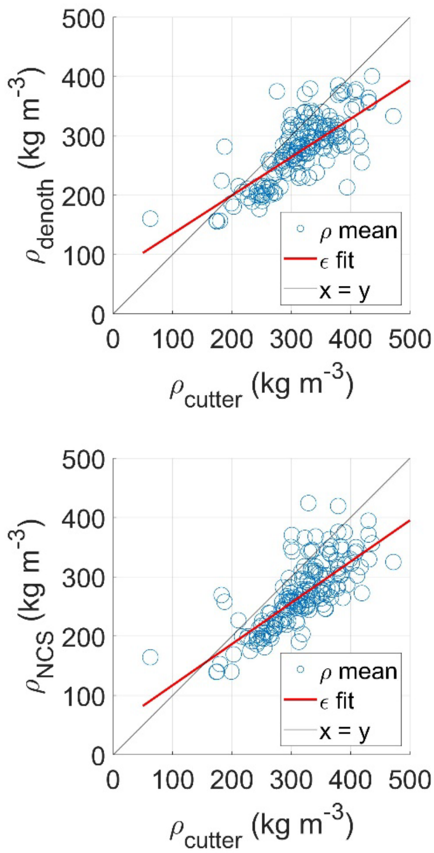

Figure 7: Comparison of the snow density deduced from permittivity measurements with the Denoth sensor (top) and the NCS (bottom).

4.2 Laboratory measurements

To extend the validation to more controlled conditions, transformed and settled natural snow (RG, 1.5 mm), which was stored for several weeks, was used for the laboratory experiments. The SSA measured with an InfraSnow device was 8.6 ± 0.5 mm^{-1}. A defined mass (ca. 4 kg) of snow was sieved (4 mm) into a box standing in an ice bath where a defined mass (236…635 g) of 0 °C water was added and mixed. The wet snow was then filled into another box to optimally conduct the ε measurements (Fig. 8). The air temperature at the cold lab ranged around -0.3 ± 0.4 °C. Snow density was measured (n = 6) by volume weighing before sieving when the snow was still in a dry and sintered state (ρ_{dry} = 472 ± 21 kg m^{-3}) and after the ε measurements (561 ± 47 kg m^{-3}).

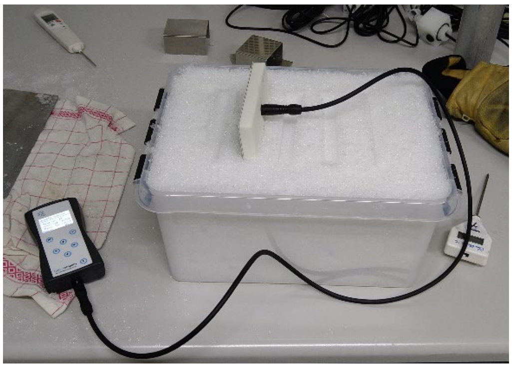

Figure 8: Setting of the measurements in the cold lab on prepared wet snow samples.

The permittivities of the dry and wet snow samples, measured with the two sensors were strongly correlated (r = 0.997, Fig. 9). However, the slope of fit was slightly steeper than the x=y diagonal (1.08 ± 0.08; 95-confidence interval). The relative RMSE between the two sensors was about 1 %, which translates to a difference in ε of 0.03. The reproducibility of the measurements on same snow samples expressed as the standard deviation of 5 measurements ranged from 0.02 to 0.1 for the Denoth sensor and from 0.02 to 0.13 for the NCS.

LWC calculated from the empiric formula (Eq. 2) of Denoth (1989), including the average dry snow density ρ_{dry}, revealed values from -0.3 to 9 vol.% for the NCS (Fig. 6 - colormap), and from 0 to 8.4 vol.% for the Denoth sensor.

$$\epsilon = 1 + 1.92 \cdot \rho_{dry} + 0.44 \cdot \rho_{dry}^2 + 0.187 \cdot LWC + 0.0045 \cdot LWC^2 \quad (2)$$

Both, uncertainties of ε and of ρ_{dry} propagates to the uncertainty of the dielectric LWC measurement. A permittivity deviation of 0.1 increased the calculated LWC by about 0.4 vol.%. A density deviation of -20 kg m^{-3} increased the calculated LWC by about 0.2 vol.%. LWC measurements of the wet snow samples using melting calorimetry revealed distinctively higher LWC between 7 ± 0.6 vol.% and 13.9 ± 1.3 vol.%. As discussed in chapter 5, those data were not used as reference values.

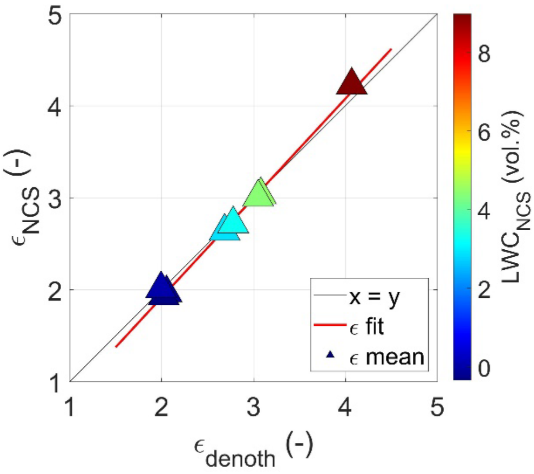

Figure 9: Comparison of the mean (n = 3…5) permittivity, measured with the NCS and the Denoth sensor in the cold lab on prepared dry (n = 3) and wet (n = 5) snow samples. The colors indicate the LWC calculated from ε_{NCS} using Eq. 2.

5. DISCUSSION

We presented a new capacitive sensor which was validated to measure the snow's permittivity validly and reliably compared to an established instrument. For both, the new and the reference instrument, a calibration with known dielectric material constitutes the (ground truth) basis of the measurement principle. Whereas for the Denoth sensor the calibration curve was linearized, possibly to allow an easier two-point calibration (air, PTFE), the NCS is calibrated on three points (air, PTFE, PMMA) using a 2nd order polynomial fit. Deviations between the sensors at higher ε as found on wet snow, could be caused by those different calibrations. To improve the NCS calibration, the inclusion of additional calibration materials with precisely known ε-values between 3 and 5 are foreseen. The propagation of possible calibration uncertainties to the measurement results are so far unknown. They may result from imprecise ε reference values of the calibration materials or from the extrapolation procedure in the calibration curves.

To deduce ρ and LWC from ε, empiric permittivity relations must be used. Present formulation is based on the assumption that ε only depends on ρ and LWC, whereas geometry of the ice matrix and water inclusions can be neglected (Denoth, 2003). As visible in the presented data (Fig. 4), deviations increased with increasing ε. When analyzing the snow profiles in detail, in some cases this might have been caused by a limited sensitivity of the Denoth sensor for high ε-values. However, considering all lab and field data, it appeared that in the upper measurement range, ε_{NCS} tend to deviate towards higher values. To confirm this observation, additional wet snow measurements in the cold lab are needed.

As ε measurements with the Denoth sensor could not be considered as a ground truth, additional independent ρ and LWC measurement methods were used for the comparison. Densities from volume weighing (Fig. 7) were systematically higher compared to the ones calculated from ε. Whereas densities deduced from the Denoth and the NCS are essentially identical. On the one hand, the bias of ρ_{cutter} and $\rho_{NCS/denoth}$ could be caused by an imperfect contact of the permittivity sensor with the snow after insertion. The harder and more brittle the snow is, the more difficult it is to insert the sensor adequately without creating a small air gap on one side of the sensor. Another explanation of the observed deviation of the dielectric and the volume weighing method could lay in the empiric ρ-ε relation (Eq. 1).

LWC values obtained by several repeating melting calorimetric measurements were considerably scattered and had mean values distinctively above the ones deduced from ε. Although the calorimetric measurements had a small water-to-snow mass ratio (1.9…3.9) and were conducted under constant and well controlled laboratory conditions, more efforts would be required to develop a melting calorimeter and a measurement protocol to quantify the LWC with sufficient accuracy and precision to serve as reference method.

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