A new handheld capacitive sensor to measure snow density and liquid water content

Fabian Wolfsperger[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

Motivation

+ **Snow density (ρ) and its liquid water content (LWC) is crucial** for any physical process within the snowpack
+ Capacitive sensors **measuring the permittivity of snow (ε)** to deduce ρ and LWC works well (Denoth, 1989; Eq. 1 & 2)
+ BUT **instruments are not commercially available**, e.g. the "Denoth" sensors

→ We developed a new capacitive sensor (NCS) to measure ρ and LWC **aiming to produce a small batch series**

→ For evaluation – ε, ρ, LWC revealed from **NCS were compared to values from a Denoth sensor** and volume weighing (ρ_{cutter})

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

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

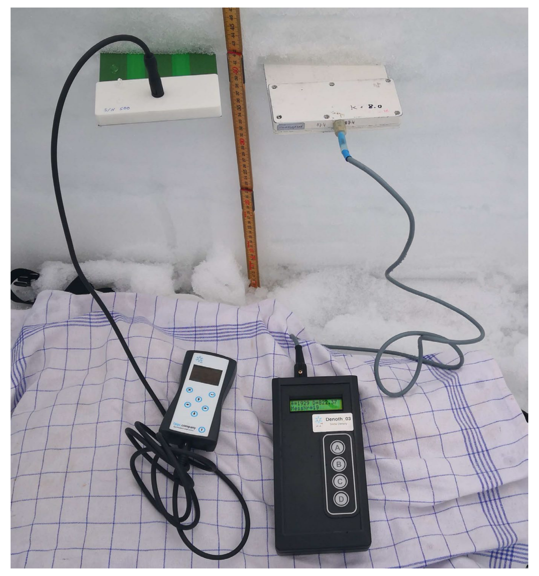

Figure 1: The old Denoth sensor and the new capacitive snow sensor (NCS).

Instrument specifications

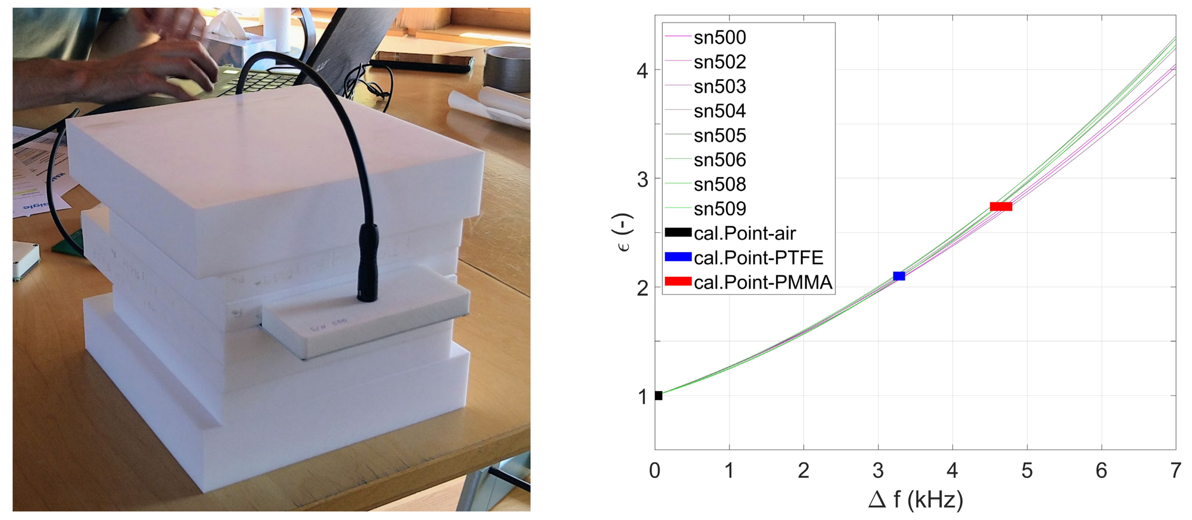

Figure 2: left) Calibration measurement with PTFE. right) Calibration curves of 8 NCS.

+ Single coplanar capacitor (**20 MHz**) integrated onto a thin printed circuit board (173 x 117 x 0.8 mm)
+ Sufficiently **strong but still flexible** to ensure tight contact with the snow after insertion into a snow pit wall
+ Capacitor forms an oscillator together with a quartz crystal: changes in capacitance shift oscillator frequency (Δf)
+ Empirical **ε-Δf relation (calibration) from three materials** with known permittivity (ε_{air} = 1; ε_{PTFE} = 2.1; ε_{PMMA} = 2.7)

Evaluation

13 dry and wet snow profiles – ε_{NCS} vs. ε_{denoth} (Fig. 4):

+ Rel. $RMSE_{\varepsilon}$ = 11.9 %; r = 0.84; ε_{NCS} = (0.97 ± 0.05) ε_{denoth} + (0.07 ± 0.1)
+ Sensors agreed well - but deviations increased with higher values

Single snow profiles – ε_{NCS} vs. ε_{denoth} (Fig. 5 & 8):

+ Rel. $RMSE_{\varepsilon}$ = 3…26 %; average rel. $RMSE_{\varepsilon}$ = 9.7 %
+ 12 out of 13 ε-profiles correlated well: r = 0.61…0.92
+ Larger deviations for very wet snow or due to horizontal misalignments

Comparing methods – dielectric density vs. volume weighing (Fig. 6):

+ Dielectric density calculated from Denoth's empirical function (Eq. 1):
+ $RMSE_{\rho\text{-}dry}$ = 62 kg m^{-3} (19.7 %); r = 0.75; ρ_{NCS} = (0.7 ± 0.08) ρ_{cutter} + (84 ± 26)
+ Bias (underestimation) increased for ρ > 200 kg m^{-3}

Laboratory measurements (Fig. 7):

+ Rel. RMSE = 2.9 % (0.079); r = 0.997; ε_{NCS} = (1.08 ± 0.08) ε_{denoth} – (0.24 ± 0.23)
+ Reproducibility on same snow samples: 0.02 to 0.1 (denoth) vs. 0.02 to 0.13 (NCS)
+ LWC calculated from Denoth (1989; Eq. 2): LWC_{NCS} = -0.3…9 vol.% ; LWC_{denoth} = 0…8.4 vol.%
+ Error propagation: Δε = 0.1 → ΔLWC = 0.4 vol.%; Δρ = -20 kg m^{-3} → ΔLWC = 0.2 vol.%

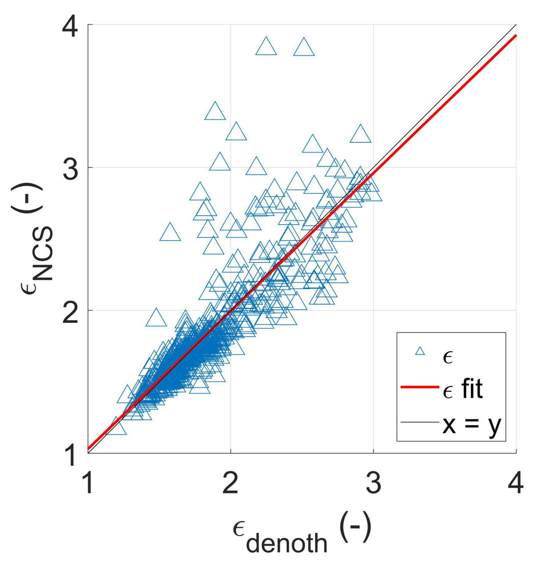

Figure 4: Comparison of all single permittivity measurements revealed from the NCS and the Denoth sensor.

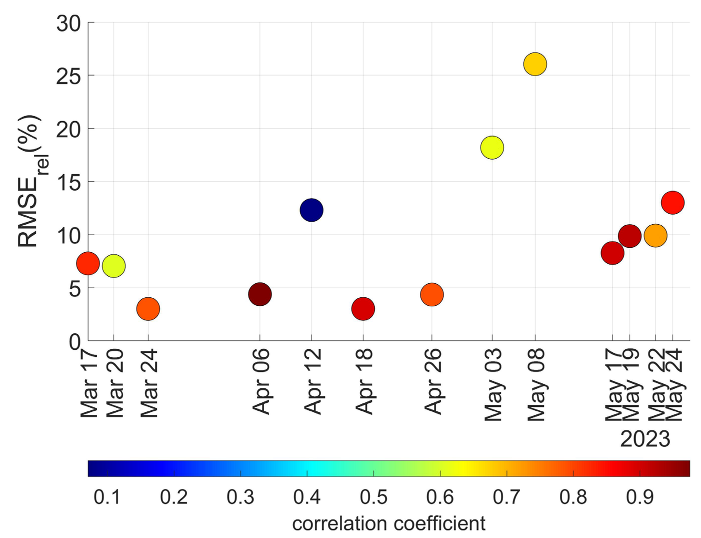

Figure 5: Relative RMSE and correlation coefficients (colors) of each snow profile comparing the permittivity measured with the NCS and the Denoth sensor.

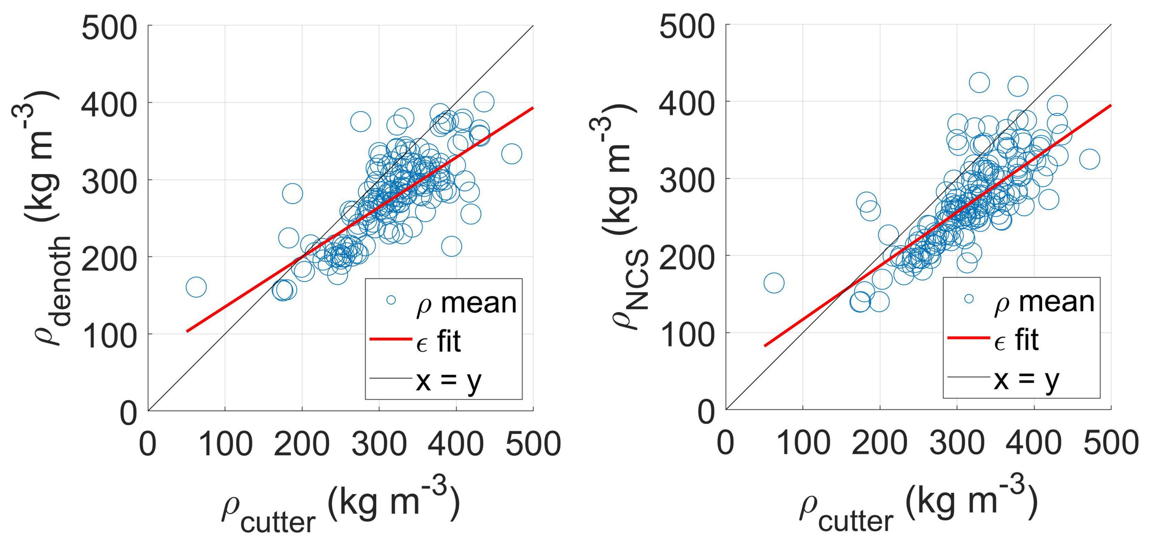

Figure 6: Comparison of the snow density deduced from permittivity measurements with the Denoth sensor (left) and the NCS (right).

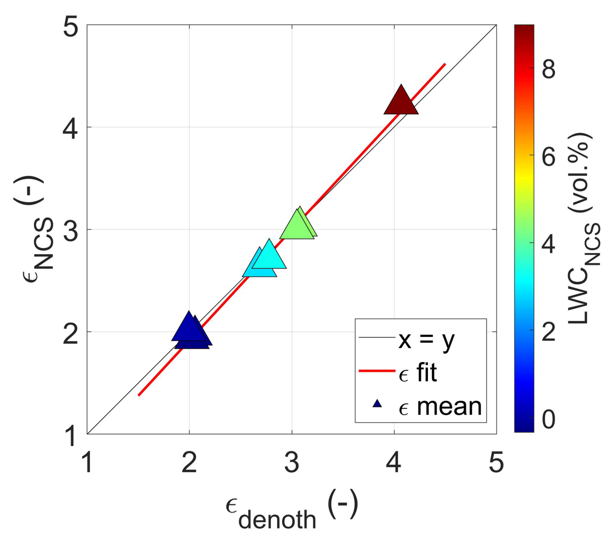

Figure 7: Comparison of the mean (n = 3…5) permittivity, measured with the NCS and the Denoth sensor in the cold lab on prepared dry (n = 3) and wet (n = 5) snow samples. The colors indicate the LWC calculated from ε_{NCS} using Eq. 2.

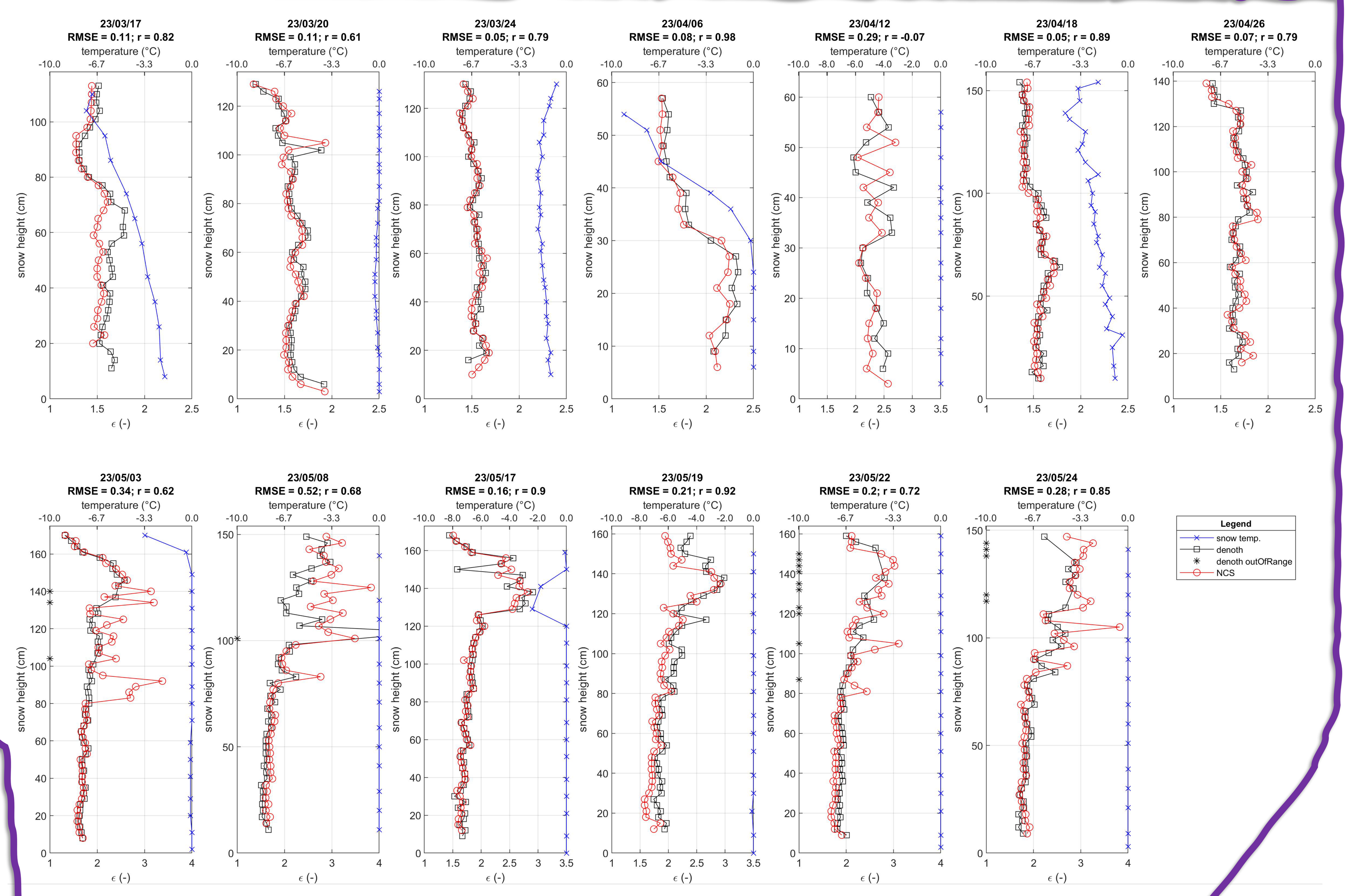

Figure 8: All 13 permittivity and snow temperature (blue) profiles on dry (top row) and partly wet snow (bottom row) revealed from the NCS (red) and from the Denoth sensor (black).

Discussion

+ NCS measured the snow's permittivity **validly and reliably compared to an established instrument**
+ ε_{NCS} and ε_{denoth} deviated in the upper measurement range - unclear if caused by **different dielectric calibrations?**
+ **ρ_{cutter} were systematically higher** than ρ_{NCS} and ρ_{denoth} - maybe due to a poor snow-sensor contact, or limitations of the ρ-ε model?

→ **Efforts on the dielectric calibration & the empirical ρ-ε and LWC-ε models are needed** to improve estimates revealed from the NCS

SLF