

DENSITY-INSENSITIVE DETERMINATION OF LIQUID WATER CONTENT IN SNOW USING MICROWAVE ATTENUATION MEASUREMENTS

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ABSTRACT: Wet snow avalanche modeling and forecasting remain a significant challenge, in part due to the limitations of currently available instruments for determining liquid water content (LWC) in snow. Current dielectric LWC probes, such as the Denoth Meter (Denoth 1989) and its improvement by Wolfspurger et al. (2023), rely on the real part of the dielectric permittivity of snow. According to well-established dielectric models (Tiuri et al. 1984), this quantity is strongly density-dependent, requiring a priori knowledge or additional measurements of the dry-snow density and limiting the suitability of such instruments for reliable large-scale or automated measurements. In contrast, the imaginary part of the permittivity, responsible for dielectric loss, is density-independent. To leverage this characteristic, the electromagnetic properties of a microstrip transmission line embedded in snow are exploited at microwave frequencies. The electromagnetic fields traveling along this line extend partly into the snow, where dielectric loss allows LWC determination based on simple attenuation measurements without knowledge of the density. This measurement principle was tested in the snow lab using custom hardware, consisting of a measurement unit with a signal generator and a power detector and an external sensor PCB that is inserted into the snow pit wall. Density insensitivity was confirmed for dry-snow densities in the range of 100 to 400 kg/m³, equivalent to an LWC uncertainty of ± 0.25 %vol. Full-wave simulations predict an LWC sensitivity of approximately 2 dB attenuation per one-percent LWC change, which is supported by preliminary lab experiments. The main challenges remain the preparation of homogeneous wet snow with a defined LWC, the non-stationary distribution of liquid water at higher LWC, and the lack of precise reference measurement systems.

KEYWORDS: Liquid Water Content (LWC), Snowpack Properties, Microwave Measurement, Instrumentation, Remote Sensing

1. INTRODUCTION

Measuring liquid water content (LWC) is crucial to model and predict wet-snow avalanches. A device commonly used is the Denoth Meter (Denoth 1989; Denoth 1994), later enhanced as the New Capacitive Sensor (NCS) (Wolfspurger et al. 2023). Crucially, these capacitive methods respond to both LWC and snow density, so an independent density measurement is always required. This density dependency confines them to manual fieldwork and precludes a practical automatic device for continuous LWC monitoring.

Niederberger et al. (2026) introduced an RF-based method that relies on density-insensitive attenuation measurement, but presented only the sensor with preliminary field verification. This work implements the complete measurement system, consisting of the snow sensor and an external measurement unit, and verifies the measurement principle in the laboratory.

2. RELATED WORK

The measurement principle of Niederberger et al. (2026) is based on the dielectric model of snow by Tiuri et al. (1984), which describes the complex relative permittivity of snow as

$$\varepsilon_{r,s} = \varepsilon'_{r,s} - j \varepsilon''_{r,s}, \quad (1a)$$

with

$$k = 0.1 \theta + 0.8 \theta^2, \quad (1b)$$

$$\varepsilon'_{r,s} = k \varepsilon'_{r,w}(f) + 1 + 1.7 (\tilde{\rho}_s - \theta) + 0.7 (\tilde{\rho}_s - \theta)^2, \quad (1c)$$

$$\varepsilon''_{r,s} = k \varepsilon''_{r,w}(f). \quad (1d)$$

The parameter θ denotes the volumetric LWC ranging from 0 to 10 %, while k is an empirical quadratic correction factor. The relative density $\tilde{\rho}_s = \rho_s / \rho_w$ denotes the density of dry snow relative to that of water. The quantities $\varepsilon'_{r,w}(f)$ and $\varepsilon''_{r,w}(f)$ are the real and imaginary parts of the relative permittivity of water at the operation frequency f .

These quantities can be modeled using a Debye relaxation model (Tiuri et al. 1984)

$$\begin{aligned} \varepsilon_{r,w}(f) &= \varepsilon'_{r,w}(f) - j \varepsilon''_{r,w}(f) \\ &= \varepsilon_{r,w}(\infty) + \frac{\varepsilon_{r,w}(0) - \varepsilon_{r,w}(\infty)}{1 + j 2\pi f \tau}, \end{aligned} \quad (2)$$

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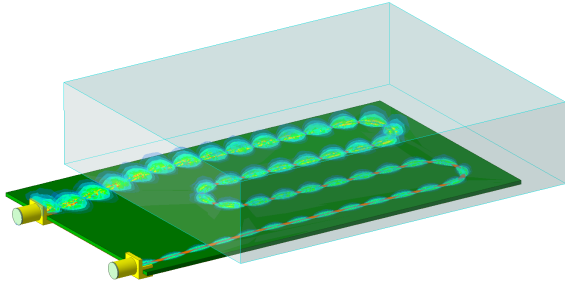


Figure 1: Simulation setup in Ansys HFSS. It consists of the two SMA ports on the left, the meandered microstrip line, and the bulk snow above the PCB. The simulated electric fields are overlaid, attenuated along the microstrip line.

where $\varepsilon_{r,w}(0) \approx 88$ is the static permittivity of water, $\varepsilon_{r,w}(\infty) \approx 4.9$ is its high-frequency limit, and $\tau \approx 17$ ps is the relaxation time.

The proposed measurement principle exploits the fact that the liquid water in snow absorbs part of a microwave signal, while the snow density has almost no effect on this absorption. The working principle of the sensor is shown in Figure 1, where the attenuation along the microstrip line is visible.

3. INSTRUMENT DESIGN

3.1. Snow Sensor

The system uses the snow sensor PCB from Niederberger et al. (2026). It is a PTFE-based PCB with overall dimensions of 176 mm $\times$ 100 mm and a thickness of 1.52 mm, as shown in Figure 2. Two configurations are proposed here: The single sensor, which is the thinnest, and an assembly with both PCBs directly back-to-back, which provides bidirectional coverage in a single insertion into the snow. The back-to-back configuration is shown in Figure 3.

The single PCB was simulated in the full-wave electromagnetic simulator Ansys HFSS. Snow is

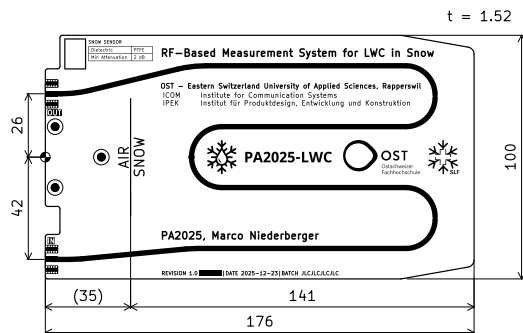


Figure 2: Outline of the designed snow sensor with overall dimensions of 176 mm $\times$ 100 mm.

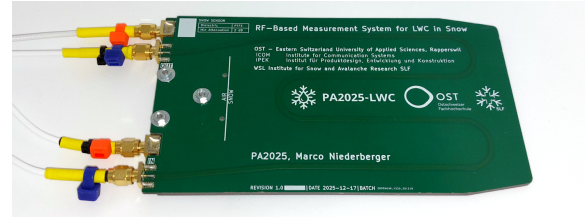


Figure 3: Two sensor PCBs stacked back-to-back, enabling bidirectional sensing.

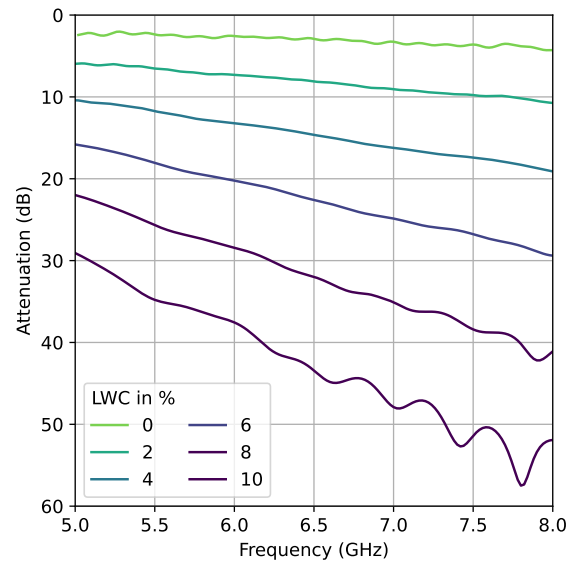


Figure 4: Simulated attenuation for frequencies between 5 GHz and 8 GHz and LWC between 0 % and 10 %, from Niederberger et al. (2026)

modelled as a uniform block with the relative complex permittivity given by (1). Figure 1 shows the modeled PCB and the simulated electric fields that are attenuated along the microstrip line. The attenuation of a single PCB is shown in Figure 4 over an LWC range of 0 % to 10 % and a frequency range of 5 GHz to 8 GHz. It ranges from 2 dB at 0 % LWC to 55 dB at 10 % LWC across the band.

A convergence study to determine the effective sensing range of the sensor is shown in Figure 5. The snow coverage above the sensor was increased monotonically while simulating the attenuation for different frequencies. The point at which the attenuation converges marks the effective sensing range. For all frequencies this occurs at approximately 15 mm. The sensing volume is therefore the sensor area extended by 15 mm above it.

3.2. Measurement Unit

The attenuation of the sensor is measured with a purpose-built measurement unit. It is equipped

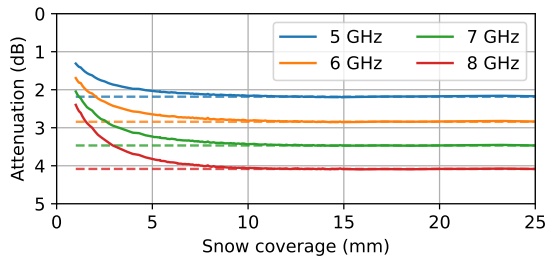


Figure 5: Convergence study of the attenuation versus the snow coverage above the sensor. Beyond 15 mm the simulated attenuation no longer increases for additional snow coverage, which defines the maximum effective sensing range.

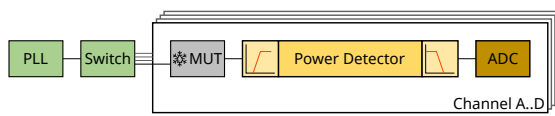


Figure 6: Signal chain of the measurement device: The signal is generated in the Phase-Locked-Loop (PLL), routed via the RF switch through the Material Under Test (MUT). The received signal is then detected by the power detector and digitized in the Analog-to-Digital Converter (ADC).

with four identical channels, allowing two sensor assemblies with two PCBs each, or four single PCBs, to be connected simultaneously.

The signal chain consists of a phase-locked loop (PLL) that generates the continuous-wave signal for the system. An RF switch then routes the signal to one of the four output ports. Here, the cable of the snow sensor is connected, and the signal travels across the sensor towards the corresponding input port of the measurement unit. At the input, the signal is first high-pass filtered to remove unwanted signals and then detected in the power detector. The detector output is low-pass filtered and subsequently digitized by the analog-to-digital converter (ADC) of the controller. Figure 6 shows the entire signal chain.

As shown in Figure 4, the sensor attenuation reaches up to 55 dB. High isolation between the output and input ports is therefore crucial, otherwise the on-PCB signal coupling exceeds the attenuation to be measured.

Several measures achieve this isolation. As shown in Figure 7, the output and input sections are spatially separated, with the remaining circuitry placed in between. This reduces coupling from fringing fields and separates the return currents of the PLL and the detectors. These measures yield at least

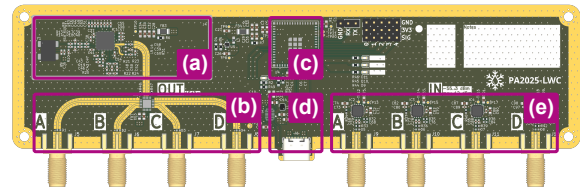


Figure 7: Building blocks of the system and their location on the PCB: (a) the PLL to generate the signal, (b) the RF switches to distribute it to the four output ports on the left, (c) the microcontroller, (d) the power supply, and (e) the four input ports on the right, separated from the output ports.

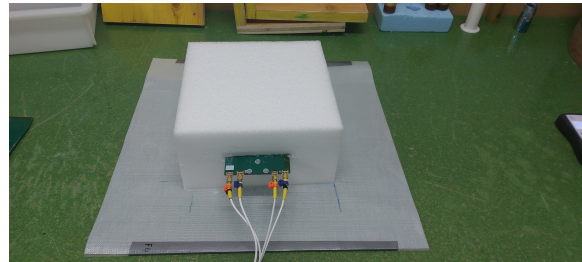


Figure 8: Dry snow block, made by sieving snow into a rectangular form. The measurements were taken in the middle of the snow block.

60 dB of isolation between output and input ports, exceeding the peak attenuation of 55 dB.

4. DENSITY INSENSITIVITY

The dry snow test was conducted to verify the density-insensitivity of the measurement system. Multiple dry snow samples were tested, with densities ranging from 114 kg/m^3 up to 382 kg/m^3 . For each sample, the Specific Surface Area (SSA) and the density were recorded using a micro-CT scan (MicroCT80, Scanco Medical AG, Switzerland). An overview of the samples is given in Table 1. The snow was sieved through a 2.5 mm sieve into a mold, and the subsequent attenuation measurements were taken in the middle of the snow block, as shown in Figure 8. The temperature inside the snow laboratory was maintained at -4°C .

Table 1: Dry snow samples with the density and SSA from the micro-CT measurements.

Sample	$\rho \text{ (kg/m}^3\text{)}$	SSA (mm^{-1})
Dry-Feb-01	114	38.7
Dry-Jul-01	275	12.2
Dry-Feb-02	347	13.9
Dry-Feb-03	382	13.5

The resulting attenuations for the dry snow tests are shown in Figure 9 for densities according to

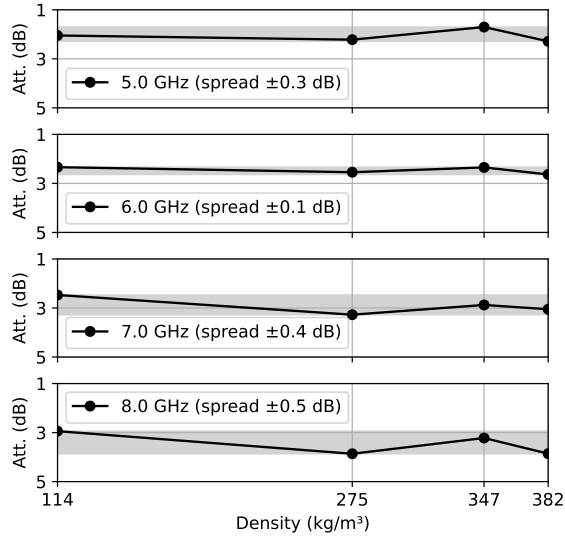


Figure 9: Measured attenuation for different densities, listed in Table 1. The solid line depicts the measured result for different frequencies, and the gray area the range across all densities. All measured results lie within a maximum band of ± 0.5 dB, corresponding to an LWC uncertainty of ± 0.25 %vol.

Table 1. All measured results lie within a ± 0.5 dB band. Using the simulated sensitivity of 2 dB per one-percent LWC, this is equivalent to an LWC band of ± 0.25 %vol. Therefore, the stated density insensitivity of the field test in Niederberger et al. (2026) is confirmed.

5. LWC SENSITIVITY

The second test was conducted to verify the sensitivity to LWC and the absolute agreement between the simulated and measured attenuation. Two different wet-snow preparation methods were tested. In both cases, the snow was constantly kept at 0°C in an ice bath during preparation and mixing. The snow lab was set to 0.5°C , keeping an air temperature between 0.2 and 1°C . In both methods, a defined amount of water was added to the measured mass of snow to achieve the desired LWC. The added water is quantified as the mass ratio

$$\frac{m_w}{m_s} = \frac{\rho_w V_w}{\rho_s V_s}, \quad (3)$$

which, using the densities of water and snow, converts to the volumetric LWC according to

$$\theta = \frac{V_w}{V_s} = \frac{m_w}{m_s} \frac{\rho_s}{\rho_w}. \quad (4)$$



Figure 10: Wet snow block prepared with the first method. The block has many air gaps, and a distinctly wetter layer is visible at the bottom.

5.1. First Preparation Method

The first method used snow from the SnowMaker (Schleef et al. 2014), which was sieved (2.5 mm) and stored for 6 months at -20°C , with a dry density of 330 kg/m^3 . The mixed wet snow was then poured into the mold and an attenuation measurement was performed. After each step, the snow was reused and more water was added to reach a higher LWC. The resulting snow mixtures are shown in Table 2. This method produced rough blocks with many air gaps, and some darker spots on the bottom of the block, as shown in Figure 10. These spots indicate locally increased LWC and thus an inhomogeneous water distribution. They are a result of percolating water as it cannot be held by capillary force when exceeding a certain (grain-size-dependent) water content, usually 3–6 %vol (Fierz et al. 2009). This is an inherent limitation of wet snow measurements.

Table 2: Wet snow samples prepared with the first method, with the density and the calculated LWC using (4).

Sample	$\rho \text{ (kg/m}^3\text{)}$	LWC (%)
Wet-Feb1	425	3.6
Wet-Feb2	461	8.0
Wet-Feb3	484	12.6

The results are shown in Figure 11. The overall trends match the simulated curves; however, all samples appear to have a lower LWC than expected by the calculations from (4). This is most likely due to the highly inhomogeneous water distribution, as most of the water drained down to the bottom, visible in Figure 10. Nevertheless, the agreement in the observed trends indicates that the model captures the frequency dependence of the attenuation, even though the absolute LWC values are offset.

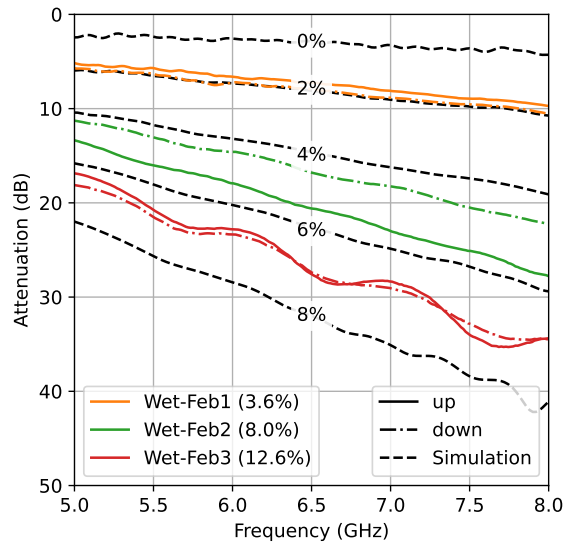


Figure 11: Measured attenuation of the wet snow samples prepared according to the first method. The trends match the simulated curves, but the absolute LWC does not match the model prediction. This is most likely due to the uncertainty from the snow mixing and the inhomogeneous water distribution.

5.2. Second Preparation Method

The second method added the sieving step as previously done for the dry snow, and used dry snow for each sample. As the LWC stayed within the residual regime with no percolation, no dark spots are visible and the overall homogeneity of the block is improved, as shown in Figure 12. The block of the second method was divided into eight zones for the measurement, as shown in Figure 13. For each snow sample a micro-CT was collected, with the results summarized in Table 3.

Table 3: Wet snow samples prepared according to the second method with the density and SSA obtained from micro-CT measurements and the LWC from melting calorimetry.

Sample	ρ (kg/m ³)	SSA (mm ⁻¹)	LWC (%)
Wet-Jul1	471	5.8	1.0±0.3
Wet-Jul2	494	5.5	1.5

The results from the second method are shown in Figure 14. The measured values for the upwards facing sensor are approximately 0.5 % LWC higher than the values reported from the melting calorimetry. For the sensor facing downwards the reported attenuation and therefore LWC is higher than for the upwards facing sensors.

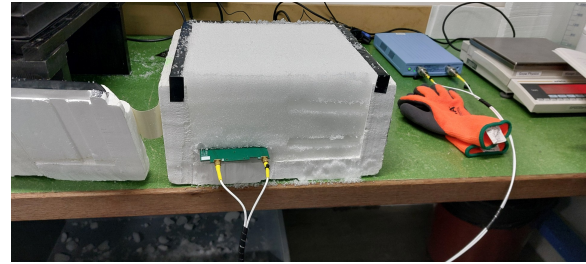


Figure 12: Wet snow block prepared according to the second method. The snow is visually more homogeneous than the block from the first method in Figure 10, and the darker, wetter layer near the bottom is no longer present. The sensor is inserted at position 3F, facing upwards.

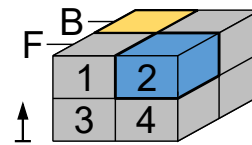


Figure 13: Notation for the snow sample position. The front face is divided into four quadrants, numbered 1 to 4, and each is further split into Front and Back. For the back measurements the snow in front was removed. Blue sample denotes 2F, the yellow sample 1B.

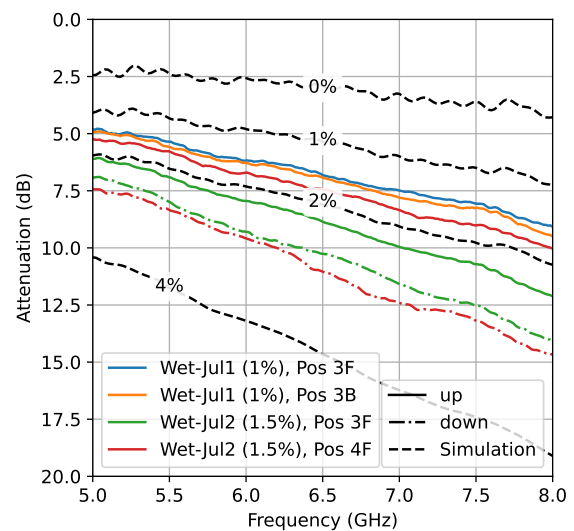


Figure 14: Measured attenuation of the wet snow samples prepared according to the second method. The measured attenuation is higher (wetter) than simulated for the given LWC. For the snow sample *Wet-Jul2*, the downward-facing sensor reports higher attenuation than the upward-facing one. This is likely an artifact of repeatedly inserting the sensor into the same slit, which disturbs the snow around it.

5.3. Discussion

Preparing wet snow samples with a defined LWC and a homogeneous distribution of the liquid water remains challenging, even under controlled laboratory conditions. Two different preparation methods were presented, with a clear preference towards the second method using the sieve and fresh snow for each sample. Additionally, LWC should be kept low to prevent air gaps and percolation induced LWC gradients. The measured attenuation from the first method is significantly lower, most likely due to wetter snow towards the bottom of the snow block, as shown in Figure 10. This problem was mitigated in the second preparation method, which resulted in a more homogeneous distribution of the liquid water.

Nevertheless, even with the improved method the attenuation for the upwards and downwards facing sensor differs by up to 2.5 dB, corresponding to an LWC difference of roughly 1 %. However, this is most likely an artifact of repeatedly inserting the sensor in the same slit, which disturbs the surrounding snow. Considering the challenges associated with preparing homogeneous wet-snow samples, this still demonstrates good sensitivity to LWC at the percentage-point level.

6. SUMMARY AND CONCLUSION

Reliable wet-snow avalanche forecasting is partly limited by the lack of instrumentation capable of measuring the LWC of snow over long periods and without additional external measurements. This work presented a complete RF-based measurement system that addresses this gap, consisting of a microstrip snow sensor embedded in the snow-pack and a four-channel measurement unit. The LWC is inferred from the frequency-dependent attenuation of a microwave signal, which is influenced by the imaginary part of the snow permittivity and is therefore largely independent of snow density. This is the key distinction from established dielectric probes such as the Denoth meter, which rely on the density-dependent real part and thus require an additional density measurement.

Laboratory experiments confirmed the density insensitivity of the method proposed in Niederberger et al. (2026) for dry-snow densities from 114 kg/m³ to 382 kg/m³, with density related deviations smaller than ± 0.25 %vol. Full-wave simulations predict a sensitivity of at least 2 dB per % LWC, and preliminary verification in the snow

lab confirmed the overall fit of the model. Two preparation methods for wet snow were tested, with a clear preference for the one that sieves a mixture of dry snow and liquid water.

The proposed sensor principle relies solely on attenuation measurements, without needing external density measurements, and is mechanically robust, making it well-suited for remote sensing and automated deployment. The simple and inexpensive architecture also enables a wide range of derived sensor designs adapted to different application scenarios. Absolute quantitative agreement across the full range from 0 % to 10 % LWC still requires a more extensive calibration campaign spanning a wide range of snow conditions. Such a procedure is experimentally challenging because well-controlled wet-snow samples are difficult to produce, and is left to future work. Once calibrated, the low complexity and robustness of the system make it a promising candidate for long-term, distributed LWC monitoring for snow and avalanche research.

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