Instrumentation for In-situ Snow Liquid Water Measurements

A. Denoth
Institute of Experimental Physics, University of Innsbruck, A-6020, Austria

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ABSTRACT

Various methods for measuring the liquid water content of a natural snow cover are discussed.

An error analysis gives suitable measuring quantities: methods based on the determination of the dielectric function (permittivity and total losses) at frequencies exceeding 10 MHz allow precise, rapid and nearly non-destructive measurements and are highly suited for field applications. The special design of the dielectric sensors depends on the actual measuring frequency: flat plate sensors of various geometries have been developed for use in the radio frequency regime (20 - 50 MHz), recently tested monopole-antennas with different probe-lengths, operated in the 100MHz to 3GHz frequency range have proofed their efficiency, and in the microwave X and K bands (8 to 16 GHz) reflection and transmission measurements have been performed. From broadband measurements of the dielectric function of snow with different stages of metamorphism and different liquid water contents simple relations between water content (volume basis) snow permittivity and density are deduced. Comparative measurements of the vertical distribution of water in a natural snow cover are presented.

INTRODUCTION

The presence of liquid water plays a major role in snow metamorphism, snow mechanics and hydrology and also other branches of snow and soil engineering. In addition, liquid water in a snowpack shows a dominant effect on the reflection, absorption and transmission of electromagnetic waves especially in the UHF and microwave regimes used be remote-sensing techniques.

So, there is an important demand for measurement systems to determine or record liquid water content in situ with high accuracy, high resolution in space and time and with simplicity in operation. Methods commonly used to determine the snow water component are among others the freezing calorimetry and electric methods as for example TDR, free-space reflection/ trans-mission measurement techniques, and relative simple impedance measurement techniques using capacitive sensors. A comparison of error surfaces of various methods shows that the highest accuracy under field conditions can only be achieved by dielectric measurements. Fig. 1a shows a typical error surface for the freezing calorimeter (M: mass of snow relative to the mass of the freezing agent, W(%): volumetric water content, and dW(%): absolute error in percent), and a typical error surface for electric methods using dielectric sensors is given in Fig.1b (P: snow porosity, W(%): volumetric water content, and dW(%): absolute error in percent). Freezing calorimetry shows an error surface which depends strongly on the mass of the snow sample used; the influence of the amount of water present can be neglected. This method requires a very careful operation under field conditions; so the measurement rate is limited to 10...15 per hour. The absolutely lowest measurements errors under field conditions can be achieved by the 'dielectric' methods: dW(%) $\leq$ 0.6%. Compared to the freezing calorimetry, the dielectric methods are practically non-destructive, as no samples have to be physically removed from the snowpack. A more detailed analysis of error surfaces of various methodes used for snow wetness measurements is given by Colbeck, 1978, and Denoth, 1994. Because of the simplicity of operation in the field, the relatively low measurement errors, and the possibility to easy perform snow wetness recordings with microprocessor-assisted devices, the dielectric method is preferred.

For practical in-situ snow wetness measurements, different sensors have been developed and tested recently.

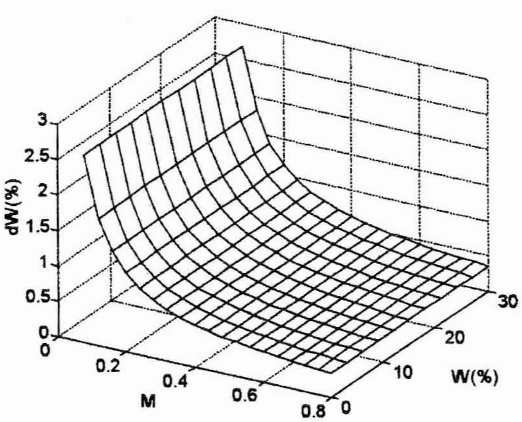


Fig. 1a. Error surface for freezing–calrimetry

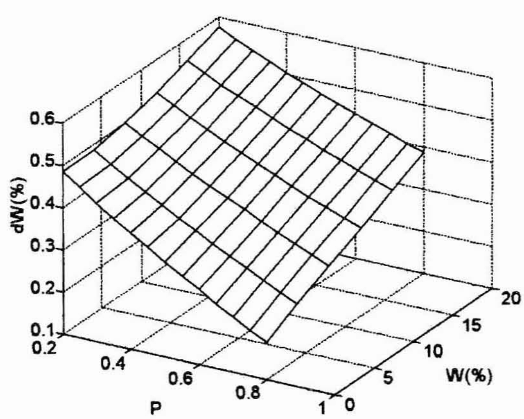


Fig. 1b. Error surface for dielectric methods

INSTRUMENTATION AND SENSOR DESIGN

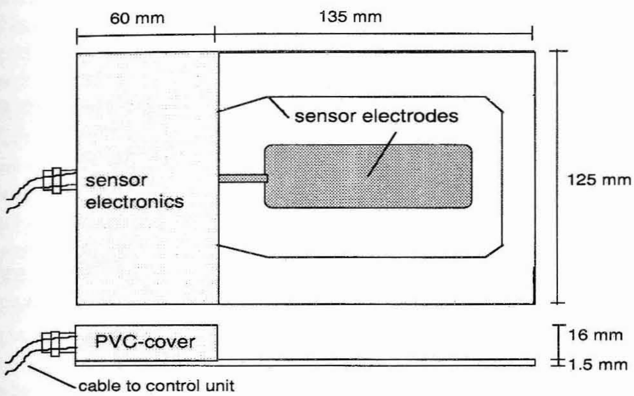
Sensor design and instrumentation depends on the actual frequency of operation. In the range of 20 - 40 MHz flat plate capacitive sensors are used. The monopole-antenna is used for snow wetness detection in the frequency range of 100 MHz up to 3 GHz. Primary measurement quantity using these sensors is the sensor impedance which depends on the dielectric properties of the surrounding material. In the microwave X and K bands (8 to 16 GHz) reflection and transmission measurements have been performed using high-gain horn antennas. From the measured reflection / transmission coefficients snow dielectric (and also magnetic) properties can be derived.

100 - 3000 MHz RANGE

In the frequency range of 100 MHz up to 3GHz a monopole antenna is used as dielectric sensor for snow wetness measurements. Primary measurement quantity is the sensor driving-point impedance. This impedance can easily be measured by a simple vector voltmeter. A scetch of sensor design (with dimensions in millimeter) and a block diagram of the instru-mentation is given in Fig.3.

8 - 16 GHz RANGE

The dielectric properties of snow in the microwave X and K bands have been derived from an analysis of the phase and magnitude of the reflection and/or transmission coefficients of the air/snow boundary by applying a free-space measurement technique. The magnitude and phase of the reflected or transmitted signals are detected by a standard grade microwave vector-voltmeter and a reflection/transmission adapter port. A sketch of the experimental setup for reflection measurements and a block diagram of the instrumentation is given in Fig.4. Details of the measurement procedures are given by Achammer and Denoth (1994).



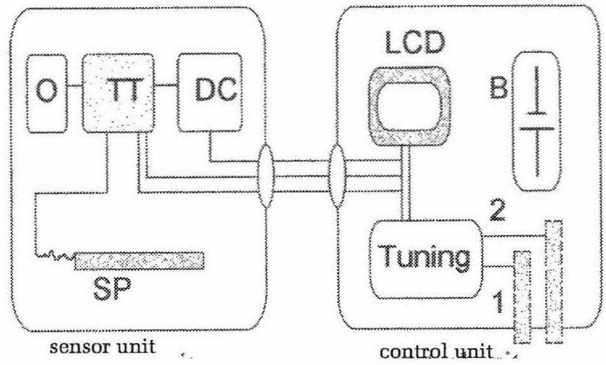
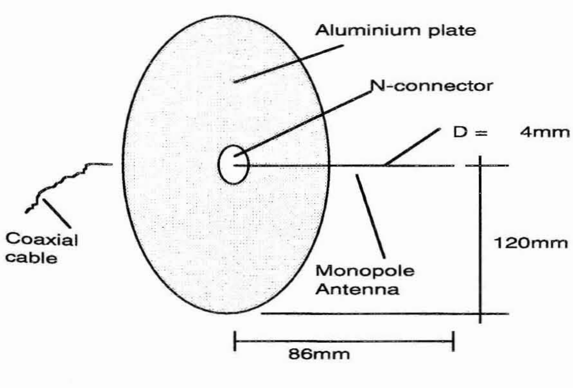


Fig.2. Sensor design (left) and block diagram of instrumentation (right) of the 20-40MHz measurement setup. O: oscillator; TT: twin-T-bridge; DC: down-converter; SP: sensor plate B: battery; 1: Option for manual tuning; 2: Option for automatic tuning

20-40 MHz RANGE

The flat-plate capacitive sensor is connected to a twin-T-bridge which can be tuned manually or automatically by a microprocessor; so continuous recordings of snow wetness are possible. A sketch of sensor design (with dimensions in millimeter) and a block diagram of the instrumentation is given in Fig.2.



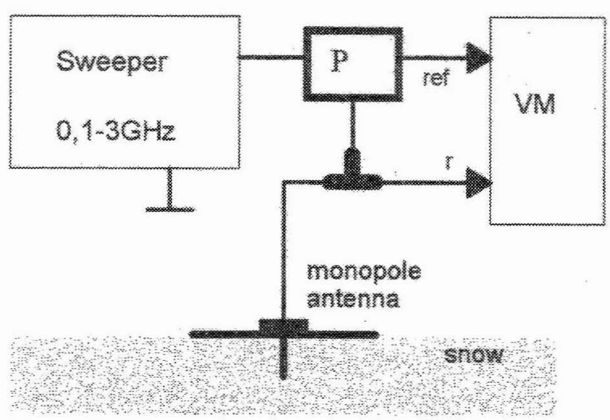


Fig.3. Sensor design (left) and block diagram of instrumentation (right) of the 100-3000MHz measurement setup. P: Power splitter, VM: vector voltmeter, ref: reference signal, r: reflected signal.

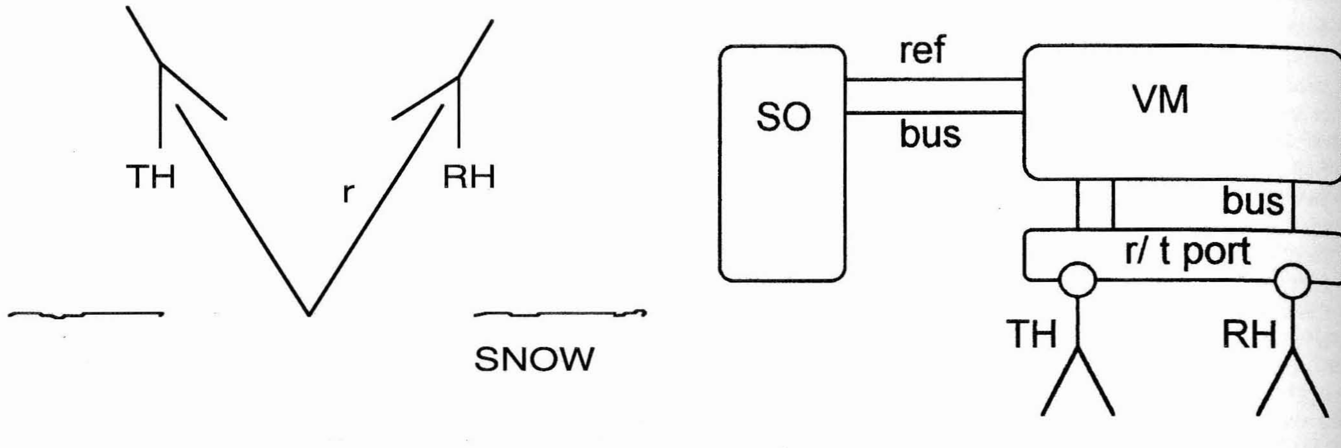


Fig.4. Experimental setup for reflection measurements (left) and a block diagram of the instrumentation for the microwave X and K- band. SO: sweeper oscillator, VM: vector-volt-meter, r/t port: adapter for reflection/transmitting measurements, ref: reference signal, bus:IEEE bus, TH: transmitting horn antenna, RH: receiving horn antenna, r: reflected signal.

MEASUREMENTS

The dielectric function of snow with different stages of metamorphism, and different amounts of liquid water has been measured in the frequency range from 20 MHz up to 16 GHz. Capacitive flat-plate sensors have been used in the radio-frequency range of 20-40 MHz, the mono-pole sensor has been applied in the range from 100 MHz up to 3 GHz, and in the X/K-bands reflection measurements of electromagnetic waves on a smoothed snow surface have been made using the free-space technique. Measurements have been done in situ on a natural snow cover in the Stubai Alps (≈3000 m a.s.l.) and at the Hafelekar (≈1900 m a.s.l.) near Inns-bruck, Austria. Snow wetness has been measured by freezing calorimetry; and snow density has been measured simply by weighing a known volume of snow. Snow porosity has been calculated from the volumetric liquid water content W and snow density. The experimentally found relation between snow mission.

Incremental permittivity E (real part), snow liquid water content W (volume basis), and frequency of sensor operation is shown in Fig.5 as a 3-D wetness calibration plot on a logarithmic frequency scale. E, the incremental permittivity, is defined as:

$$E = \varepsilon' (wet) \; \varepsilon'(dry)$$

ε'(wet) is the (measured) dielectric function of wet snow, ε'(dry) is the (calculated) dielectric function of snow with the same porosity Φ:

$$\varepsilon'(dry) = 1 + 1.76\,(1-\Phi) + 0.37\,(1-\Phi)^2$$

For practical reasons - and accepting a slightly reduced accuracy in determining snow wetness - the very weak effect of water geometry on the snow dielectric function has been neglected, and it results a simple quadratic relation between snow wetness W (in % by volume) and incremental permittivity: $E = \alpha W + \beta W^2$, whereby the parameters α and β depend on the actual frequency f' of sensor operation:

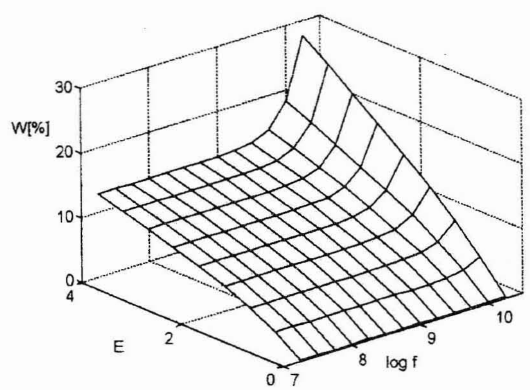


Fig.5 Wetness calibration surface for snow. w(%): volumetric liquid water content, f:frequency (Hz), E: incremental snow permittivity

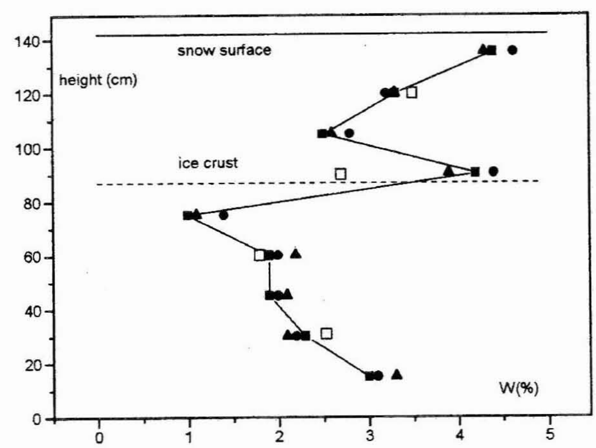


Fig.6 Comparative measurements of a vertical wetness profile in a natural snow cover. Closed squares: freezing calorimeter, closed circles: capacitive sensor, closed triangles: monopole probe, open squares: horn antenna

20 MHz < f < 3 GHz: $\alpha = 0.206$, $\beta = 0.0046$
f $\approx$ 10 GHz: $\alpha = 0.152$, $\beta = 0.0051$

For sensor operation frequencies exceeding ≈4 GHz, the sensitivity of snow dielectric function to changes in liquid water content decreases significantly. So, for practical reasons, it is suggested to operate dielectric wetness sensors at frequencies lower than approximately 3 GHz.

As a practical field application of these sensors a comparative measurement of a vertical wetness profile of a natural snow cover is shown in Fig.6.: Alpine snow (Hafelekar near Innsbruck, ≈1900 m a.s.l, 03 96), 142 cm in depth, and density ranging from 0.4 g/cm^3 on top to ≈0.54 g/cm^3 at the bottom. Due to the relative low spatial resolution of the monopole antenna, data points have been taken only every 15cm (monopole probe and capacitive sensor) and are compared to calorimetric wetness measurements. Reflection measurements using the free-space technique have been made at 0° incidence angle and at a fixed frequency of 8 GHz. Although high-gain horn antennas have been used, the spatial resolution is low, so, data points have been taken only with a 30 cm spacing.

The measurements of snow wetness with the capacitive and monopole probes and the freezing calorimeter show a satisfying aggreement. The increase in snow wetness at the 87-cm level may be due to a high-density snow layer with a thin icy crust. Due to the significantly larger sphere of influence of the free-space technique, measurement with the horn antennas give a mean value of snow wetness, averaged over an area of approximately 30x30 cm^2. So, measurements with the horn antennas may deviate from measurements with the other sensors; this is especially true at regions with high variability in snow wetness.

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