Int. Agrophysics, 2005, 19, 75-78

INTERNATIONAL
Agrophysics
www.ipan.lublin.pl/int-agrophysics

TDR and low-frequency measurements for continuous monitoring of moisture and density in a snow pack*

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Received February 4, 2004; accepted February 18, 2004

A b s t r a c t. An in-situ sensor for the simultaneous measurement of density and liquid water content of snow is presented in this paper. The system consists of radio frequency transmission lines of up to 25 m length cast in a flat PVC-band, which can either be set up horizontally to monitor single snow layer properties or sloping from a mast to the soil surface to determine vertical snow pack properties. The dielectric coefficient along the flat-band cable is measured with a time domain reflectometer (TDR) at high frequencies, and with a low frequency impedance analyzer. The performance of the sensor system has been tested during two winter seasons (2001-2003) at a high alpine test site in Switzerland. Overall, the sensing system proved to be quite robust and produced results in agreement with manual snow pack observations.

K e y w o r d s: snow density, moisture, time domain reflectometry

INTRODUCTION

Measuring moisture and density of snow is essential for many applications in snow hydrology, such as optimization of hydro power management, avalanche warning, flood prediction, and investigations of glacier melting due to global warming and climate change. Seasonal snow covers are highly variable both in space and time, especially when melting occurs. So far snow sensors are not suited for long-term continuous measurements (Denoth, 1989; Marsh, and Woo, 1984; Schlaeger, 2002). The performance suffers from their small measurement volume which is not adequate to achieve representative values for natural snow covers with their large spatial variability. Therefore a new sensor has been developed.

MATERIALS AND METHODS

Flat band cable sensor

Instead of the small scale sensors with their rigid and thus inadequate constructions, a flexible flat band cable up to about 100 m in length is proposed which can follow the settlement of the snow cover. A picture of the cable is shown in Fig. 1.

The electrical field concentrates around the conductors and defines the sensitive area of 3 to 5 cm around the cable. The spatial weighting of the measurements in the cross section of the cable is directly related to the energy density distribution.

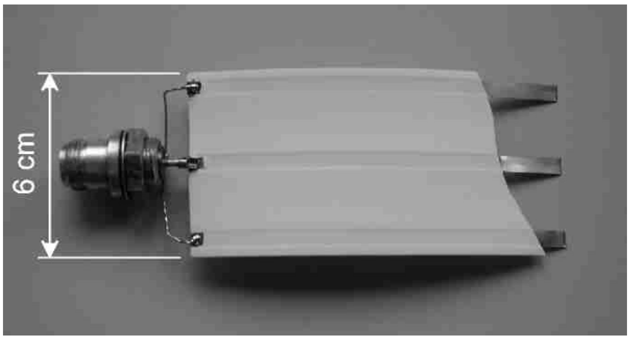

Fig. 1. The PE-insulated flat band cable (short section with uncovered conductor to show connection and geometry).

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*This work has been partly carried out within the EU-project SNOWPOWER, 5th Framework, NNE5/2000/251.

The white polyethylene (PE) insulation reduces heating due to solar radiation and the thin copper conductors have an advantageous low thermal capacity. Nevertheless, air gaps may develop around the flat band cable *eg* due to multiple freezing and thawing cycles.

These air gaps cause under-predictions of the permittivity of the surrounding snow. To detect air gaps and correct the measurement results, the three wire cable is measured twice, with small and with large spacing leading to different measurement volumes. Thus an air gap has different effects on the volume and it is possible to correct it. A correction equation has been derived for calculating air gap size and true permittivity of snow (Huebner, 1999).

Dielectric properties of snow

Dry snow is a mixture of ice crystals (volumetric fraction I) and air (volumetric fraction A). Wet snow contains an additional fraction of liquid water (W). The relative dielectric permittivity of ice, ε_{ice}, and water, ε_w, are frequency and temperature dependent, whereas the permittivity of air, ε_a, is equal to 1. Figure 2 shows the relaxation spectra for water and ice at a temperature of 0°C.

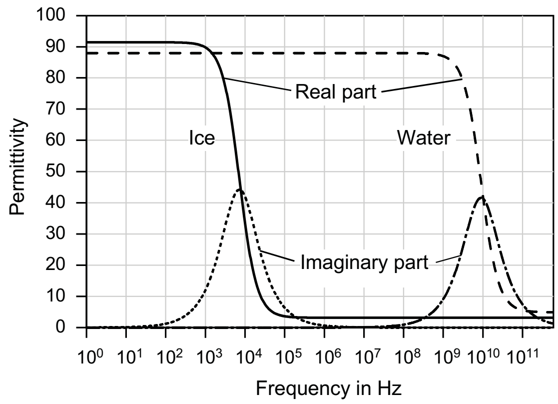

Fig. 2. Relaxation spectra of water and ice at a temperature of 0°C.

The relaxation frequency of ice is much lower than that of water due to the strong bonding forces within the ice crystal. Wet snow has a constant temperature of 0°C, whereas dry snow has varying temperatures below or equal 0°C. Therefore only the temperature dependent permittivity of ice has to be accounted for.

Experimental evidence indicates that the permittivity of ice may be considered independent of both temperature (below 0°C) and frequency in the microwave region and may be assigned the constant value of 3.15 (Ulably *et al.*, 1986). But at lower frequencies *eg* in the kHz-range, the permittivity of ice depends considerably on temperature.

The permittivity of snow, ε_{snow}, is related to the volumetric fractions of the constituents - ice, water, and air, and their dielectric properties. This relation can be described by a mixing rule. Looyenga's formulae (Looyenga, 1965) for spherical intrusions (α=0.3) is in close agreement with experimental results:

$$\varepsilon_{snow}(f,T) = \left(W\varepsilon_w^\alpha + I\varepsilon_{ice}^\alpha(f,T) + A\varepsilon_\alpha^\alpha\right)^{1/\alpha}, \quad (1)$$

with W+I+A = 1 for the unity volume.

Measurement principle

In order to determine the two unknowns, water content and density, two independent equations are required. These are:

$$\varepsilon_{snow}(f_1) = \left(W\varepsilon_w^\alpha + I\varepsilon_{ice}^\alpha(f_1,T) + A\varepsilon_\alpha^\alpha\right)^{1/\alpha}, \quad (2)$$

$$\varepsilon_{snow}(f_2) = \left(W\varepsilon_w^\alpha + I\varepsilon_{ice}^\alpha(f_2,T) + A\varepsilon_\alpha^\alpha\right)^{1/\alpha}, \quad (3)$$

with $\varepsilon_{snow}(f_1)$ and $\varepsilon_{snow}(f_2)$ as permittivity measurements at two frequencies with different water to ice permittivity ratios.

The equation set can be solved for water content, W, and ice fraction, I, using W+I+A = 1. The snow density, D, can be derived from water content, W, and ice fraction, I, as follows:

$$D = W\ 0.9999 + I\ 0.9150, \quad (4)$$

taking into account the different densities of liquid water (0.9999) and ice (0.9150). In order to achieve maximum accuracy, the differences between the water to ice permittivity ratio at the two frequencies should be as large as possible. This can be achieved by using a low frequency (smaller than the relaxation frequency of ice) and a high frequency (higher than the relaxation frequency of ice and lower than the relaxation frequency of water). Typical are frequencies below 10 kHz for f_1 and frequencies between 100 kHz and 1 GHz for f_2.

RESULTS AND DISCUSSION

Field experiment set-up

The new flat-band cable sensor was tested at the high-elevation field site 'Weissfluhjoch' at Davos (Switzerland) at 2550 m a.s.l. One cable was mounted sloping at an angle of 30^o from the bottom to a mast (Fig. 3) with the aim of measuring vertical properties of the snow pack, three cables were placed horizontally on the snow surface at different stages of the winter in order to measure the spatial variability of the liquid water content and snow density, and especially for detecting water conducting zones during the main snowmelt.

Fig. 3. The cable sensor system at Weissfluhjoch Davos (2550 m): the electronic devices in the shelter (left) and the test field with sloping cable sensor (right).

The electronic measurement devices of the system were placed in a shelter approximately 10 m away from the cable sensors (Fig. 3). For the high frequency measurements (100 MHz to 1 GHz) a TDR cable tester 'Tektronix 1502B' was used, the low frequency measurements in the range of 1 kHz to 300 kHz were carried out with an impedance analyzer 'HP-4192A'. A PC and a self-made multiplexer completed the system.

Capacitance and dielectric permittivity of the cables, both for the high and low frequency range, were calculated from the raw signals. The high frequency permittivity for a horizontal cable is shown in Fig. 4. It can be seen that the calibration was successful and small and large spacing mode yielded nearly identical results. We did not find evidence for significant voids around the horizontal cables when we excavated dummy flat-band cables, so that the presence of air gaps around the horizontal cables can be excluded.

From the curve it can be seen that the measurements started at the end of January 2002 and the cable was successively covered with snow. The slight increase of permittivity is caused by the increase in density of the dry snow pack. At the beginning of May, the sharp rise of the curve indicates the start of the melting period, where liquid water penetrates the snow pack. Interrupted by a short cold period at the end of May, when the capacitance stayed constant for a few days, the melting intensified in June. In this state, also variations in permittivity between day and night times due to melting and refreezing processes are clearly visible. At the end of June, the sharp drop in permittivity is caused by the melt-out of the cable and its exposure to air. The determined dimensions of the high frequency permittivity are in the same order of magnitude as that found by Tiuri *et al*. (1984) for similar snow packs.

The low frequency permittivity (at 10 kHz) is given in Fig. 5. It is approximately 5 times higher than the high

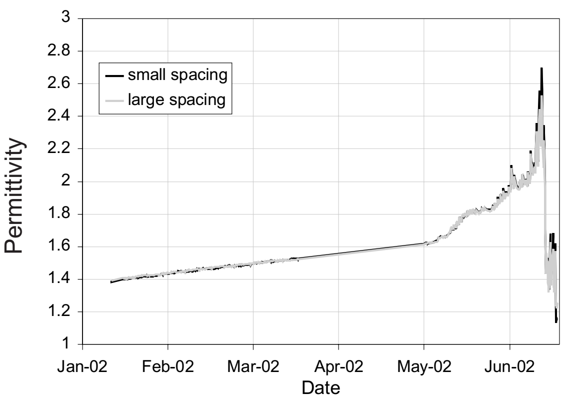

Fig. 4. High frequency permittivity at the lowest horizontal cable.

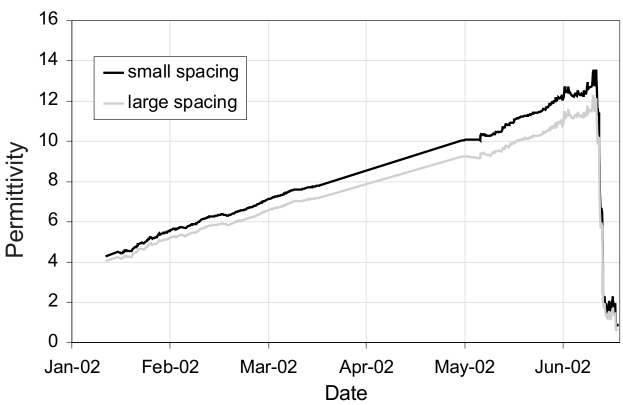

Fig. 5. Low frequency permittivity at the lowest horizontal cable.

frequency permittivity, thus giving the possibility to use the equations from above to determine the density and the liquid water content of the snow pack. The steeper increase of the curve in the dry snow phase compared to the high frequency results is due to the much higher permittivity of ice at the low frequency used (ε_{ice} (10 kHz) = 38.11), which influences the permittivity of the ice-air mixture. Due to the same reason, the variations during the melting phase are less pronounced. The bigger difference between small and large spacing mode for the low frequency permittivity is still a question of adequate calibration in the low frequency range and will be improved in future.

The combination of high and low frequency permittivity measurements finally led to the liquid water content along the horizontal cable, as shown in Fig. 6.

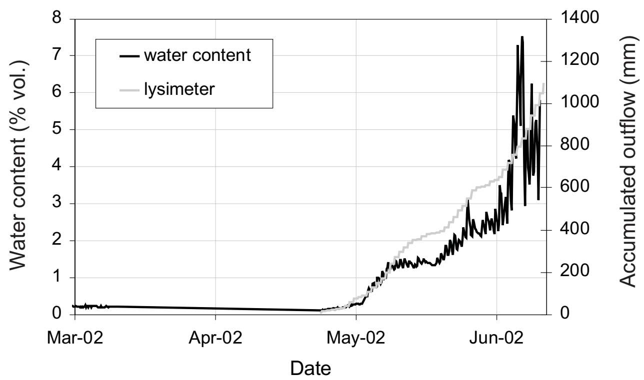

Fig. 6. Calculated liquid water content at the lowest horizontal cable compared to accumulated outflow of lysimeter.

Practically no liquid water was detected with the horizontal cable until the end of April, when the snow pack had reached its maximum height. This is supported by the snow temperature measurements, taken at the same height as the cable, which indicate dry snow conditions due to temperatures well below zero before this period.

Once the snowmelt set in, a steadily increasing liquid water content was measured with the horizontal cable, indicating the downwards penetration of the wetting-front. The cable even reacted remarkably to the diurnal variation caused by melting during the day and refreezing during the night. The natural settling of the snow cover was reflected nicely in the horizontal cable measurements. The snow density (Fig. 7) increased from initially 200 kg m^{-3} to approximately 450 kg m^{-3} at the end of the winter season, which was in accordance with manual snow density measurements. We have no explanation for the high manual values at the beginning of the measurement period. The other horizontal cables located at different depths of the snow pack also reproduced correctly a lower density in the upper part of the profile and a faster compaction during the snowmelt.

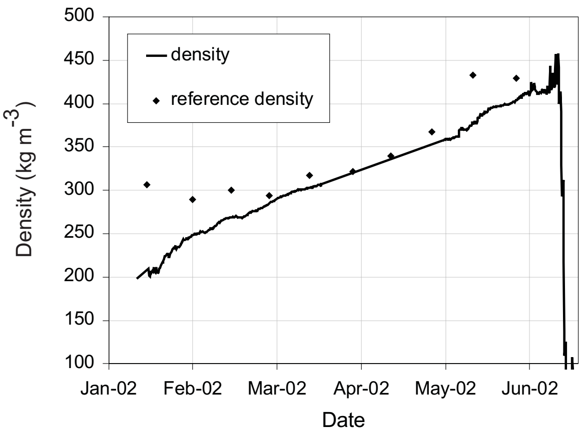

Fig. 7. Density of snow pack during winter 2002 at horizontal cable 2.

CONCLUSIONS

1. It has been demonstrated that dielectric methods are very well suited for snow moisture determination.
2. A combination of high and low frequency measurements gives good opportunity of determining both the liquid water content and the density of the snow pack.
3. The measurement results yielded good correspondence of the snow pack density with manual reference measurements.
4. The determination of liquid water content from measurements of high and low frequency dielectric permittivity gave plausible results both compared to lysimeter data taken on the test field and with regard to the spatial variation of flow fingers that are normally experienced in a natural snow pack.

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