TDR 2001 – Proceedings of the Second International Symposium and Workshop on Time Domain Reflectometry for Innovative Geotechnical Applications, Charles H. Dowding (Ed.), Sept 5-7, 2001, Infrastructure and Technology Institute at Northwestern University, Evanston, IL, USA. http;//www.iti.northwestern.edu/tdr/tdr2001/proceedings/

CONTINUOUS MEASUREMENTS OF LIQUID WATER CONTENT AND DENSITY IN SNOW USING TDR

Peter Waldner[1], Christof Huebner[2], Martin Schneebeli[1], Alexander Brandelik[2] and Frank Rau[3]

[1]WSL-Swiss Federal Institute for Snow and Avalanche Research, Switzerland; waldner@slf.ch
[2], Forschungszentrum Karlsruhe, Germany; alexander.brandelik@imk.fzk.de
[3]Institute of Physical Geography, University of Freiburg, Germany; frank.rau@ipg.uni-freiburg.de

ABSTRACT

Measuring snow wetness and snow density is essential for many applications in snow hydrology like avalanche warning, flood prediction, optimization of hydro power generation and investigations of glacier melting due to global warming and climate change. So far the snow parameter sensors were not suited for long time continuous measurements when disturbing melting processes around the sensor occur. In many respect the performance moreover suffered from their small measurement volume which is not adequate to achieve representative values for natural snow covers with large spatial variability. Therefore two new sensor have been developed. A light-weight sensor has been designed to position on a snow layer with minimal influence on the snow. This sensor with length 0.3 m is constructed from an aluminum tube of 3 mm diameter. It is convenient for continuous time domain measurement with regard to spatial and temporal variability of snow wetness or density. The other new sensor has a large measurement volume and the capability of monitoring the whole snow cover cycle. It consists of a flat band cable as TDR transmission line up to about 100 m long which is enclosed by snow fall. Time domain measurements or time domain measurements in a combination with low frequency measurements are suited for the determination of both snow wetness and snow density. Besides integral measurements along the flat band cable the possibility of reconstructing vertical snow parameter profiles with sloping transmission lines has also been investigated. Several measurement campaigns demonstrate, on the basis of the measured results, the successful practical application of the methods and sensors developed in this work.

INTRODUCTION

Seasonal snow covers are highly variable both in space and time. Their deposition and depletion represent sporadic rather than continuous processes, the occurrence of which vary with meteorological conditions. After initial deposition of a snow layer, the snow changes by time display a wide range of physical characteristics, from the metamorphism of snow crystals and grains to melting processes and liquid water transport. The vertical arrangement of different snow layers and their properties is essential for avalanche prediction. In addition understanding of water transport phenomena in snow is important to assess the influences of natural and artificial snow on an ecosystem. To study these processes continuous measurements of liquid water content in snow with an adequate spatial resolution are necessary.

Further the total snow water equivalent represents the available supply for filling the reservoirs of hydro power stations. Monitoring temporal snow wetness variations is the key for determining water percolation through the snow pack and the assessment of flood dangers. Therefore several measurement stations at representative sites within a hydrological basin are required. The sensors themselves have to provide mean snow properties of a sufficiently large area at these sites.

During the last decade there have been many efforts to determine snow parameters with radar remote sensing from satellites. This way the mapping of snow parameters on large areas promises with excellent possibilities for investigations of the snow cover in respect to climatological, meteorological, hydrological or glaciological applications. The signal measured by the radar system is composed partly from surface scattering and from volume scattering from the snow pack. It is influenced by liquid water content, snow grain size, snow density, ice lenses and surface roughness. Therefore ground measurements of the snow properties are required to provide information on the key parameters for the radar image interpretation and calibration. These ground measurements have to provide mean snow properties of areas comparable in size with the pixel size of the radar system which is in the order of 20 x 20 m.

With this background in mind we have investigated conventional snow parameter sensors for determining wetness and density and have developed and tested two new sensor systems.

DIELECTRIC PROPERTIES OF SNOW

Wet snow is a mixture of ice crystals, liquid water and air. The permittivity of ice ε_i and water ε_w are frequency dependent as shown in Fig. 1 whereas the permittivity of air ε_a is constant=1. A travel time measurement with time domain reflectometry approximates a frequency domain measurement at about 1 GHz in the case of a typical system configuration (Textronik cable tester 1502B, 20 m coaxial and 40 m flat band cable). Permittivity of ice ε_i is about 3 and of water ε_w about 89 in this frequency range.

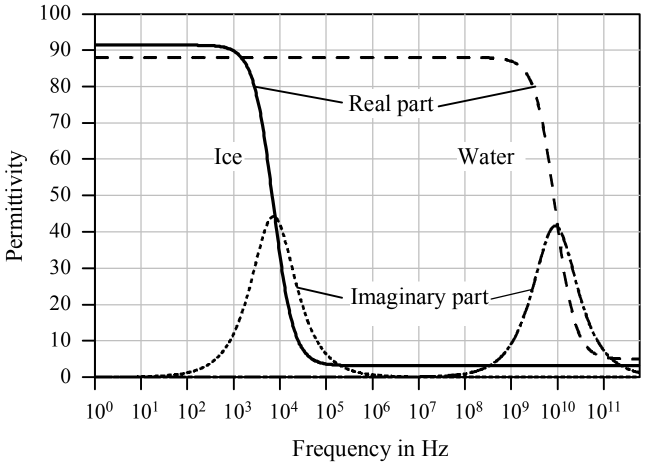


Fig. 1: Relaxation spectra of water and ice.

The real part of the dielectric permittivity of the mixture is related to the volumetric contents of ice θ_i, water θ_w and air θ_a, according to relations like Looyenga's (1965) formula for spherical intrusions (α=3):

$$\varepsilon_d = (\theta_i\, \varepsilon_i^{1/\alpha} + \theta_w\, \varepsilon_a^{1/\alpha} + \theta_a\, \varepsilon_a^{1/\alpha})^{\alpha} \qquad (1)$$

Hence, in case of dry snow, ε_d is mainly related to snow density as given e.g. by Tiuri et al. (1984):

$$\varepsilon_d = 1 + 1.7\,\rho + 0.7\,\rho^2 \qquad (2)$$

They also recommend an equation for the increase of the permittivity $\Delta\varepsilon$ under wet snow conditions with water content θ_w as compared to dry snow:

$$\Delta\varepsilon = 0.089\,\theta_w + 0.0072\,\theta_w{}^2 \qquad (3)$$

Further formulae, most of them similar to (2) and (3), were reviewed by Frolov & Macharet (1999). Although the general validity of these expressions is still under discussion, they will be used as a working model.

A time domain or high frequency measurement of the permittivity of dry snow provides the snow density. In case of wet snow the two unknowns density and water content cannot be determined from only one measurement. One approach is to extrapolate the density development from the latest dry snow measurements which can be distinguished from contaminations of the snow which unpredictably influence the imaginary part of the permittivity. A better solution is to combine high frequency or time domain measurements with a low frequency capitance determination in the kHz domain. Due to the different relaxation spectra two independent measurements allow the derivation of water content and density at the same time.

CONVENTIONAL SENSORS: SPATIAL VARIABILITY

So far the sensors used for time domain reflectometry measurements in snow usually consisted of coaxial lines, two wire lines, microstrip lines or capacitor plates and measure the permittivity of the snow in the surrounding of the sensor (Fig. 2). From the permittivity water content and/or density of the snow can be derived.

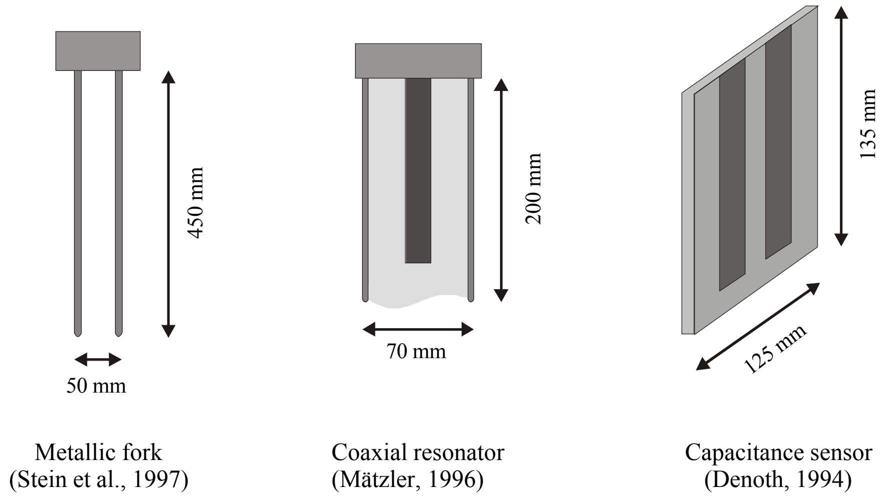


Fig 2: Conventional Sensors for measuring dielectric properties of snow from which water content and density may be derived.

We have used one of these sensors during a measurement campaign to determine spatial variability in a natural snow cover. A 16 m long and about 0.5 m deep trench in the snow was excavated. The water content along the trench was measured with the sensor from Denoth (1994) at two consecutive days in a depth of about 0.5 m below snow surface and with 1 m spacing.

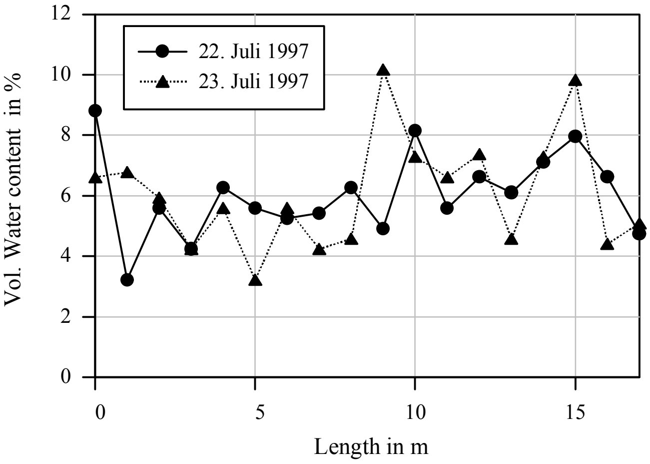


Fig. 3: Water content along a transect in the snow cover measured with the sensor from Denoth (1994).

The measurement results in Fig. 3 show strong fluctuations of the water content which are typical for this time of the year with daily melt phases. When water flow starts rapid changes of the snow pack structure occur and preferential percolation paths emerge (Marsh & Woo, 1984; Schneebeli, 1995; Williams et al., 1999). A high temporal and spatial variability of the snow wetness results. Hence, on one hand, destructive methods are not practical to study temporal evolutions. On the other hand representative mean values of snow wetness require a large number of measurements and consequently an enormous expenditure of work.

LIGHT WEIGHT SNOW TDR SENSORS FOR PROCESS STUDIES

In order to investigate the temporal evolution of the snow wetness continuous measurements with a sufficient resolution in time and space are necessary. In a snow cover a permanently placed sensor faces snow creeping, warming up through solar radiation and hence will influence the snow cover itself. Therefore an adapted TDR sensor with minimal influence of the snow cover was designed and tested. The sensors are light-weight such that they can be posed on top of a new snow layer to be covered during the next snow fall period (detailed description: Schneebeli et al., 1998).

They are constructed from a thin-walled aluminum tube (3 mm diameter, thickness of wall 0.3 mm (Fig. 4). White color reduces the adsorption of solar. In the snow the height of the sensors above ground declines according to snow pack settling.

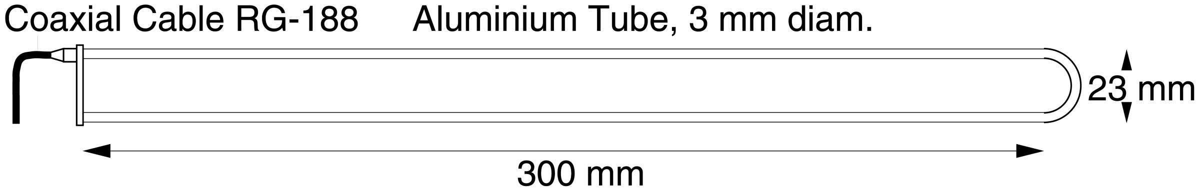


Fig. 4: Sketch of the construction of the light weight snow TDR sensor. The probe is connected by a thin coaxial cable to a cable tester.

In order to investigate the temporal and spatial variation of the water content 40 sensors were posed on top of the snow cover on a slightly sloped open field at 1200 m a.s.l. in the valley Alptal (Switzerland) early in the Winter 1998/1999 (Fig. 5).

The TDR signal was measured and digitized with a Tektronix 1502B cable tester and a coaxial multiplexer. To locate the reflection within the digitized waves the algorithm of (Schneebeli et al., 1998) had to be adapted to wet snow condition. Further it was simplified such that it could be programmed on a standard data logger. Measurement values are smoothed and the first derivative is calculated hereafter. High values of the first derivative define an impedance mismatch. The algorithm defines the different wave section by looking for the first and the last values of the derivative with a certain percentage range of its maximum or minimum.

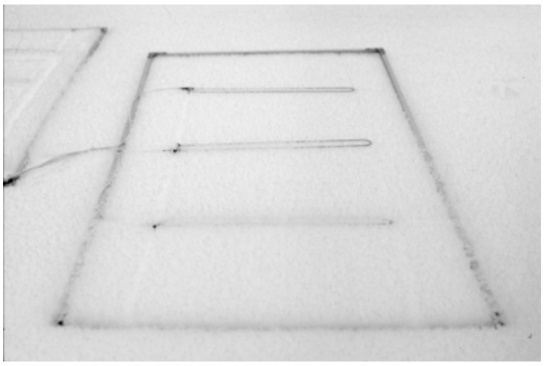


Fig. 5: The light weight snow TDR sensors were mounted on a frame to pose them on the snow cover before the next snow fall period.

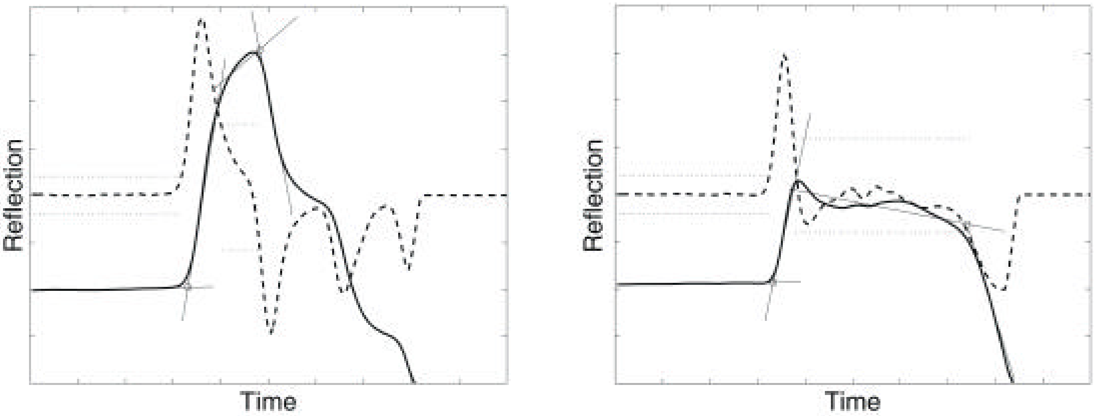


Fig. 6: Digitized Wave form (solid line) from measurements in dry snow (left part) and wet snow (right part). First derivative (dashed) with check lines (dotted) and straight lines adapted to the wave with the intersection defining the start of an impedance mismatch.

At these positions straight lines are drawn through the smoothed signal wave. Intersections of these lines define the start of an impedance mismatch as shown in Fig. 6. During the campaign density measurements were carried with nearby snow pit examinations. The measured dielectric permittivity showed good agreement with permittivity calculated with equation (2) from densities for periods with snow temperatures up to -1°C at sensor height. By individually interpolating density values for each sensor, we were able to estimate snow wetness with equation (1).

Fig. 7 shows resulting liquid water content for 4 sensors that have a typical temporal evolution and variability. The high water contents are explained by a highly saturated base flow of melt water at the bottom of the snow pack that subsequently reached the sensor positions.

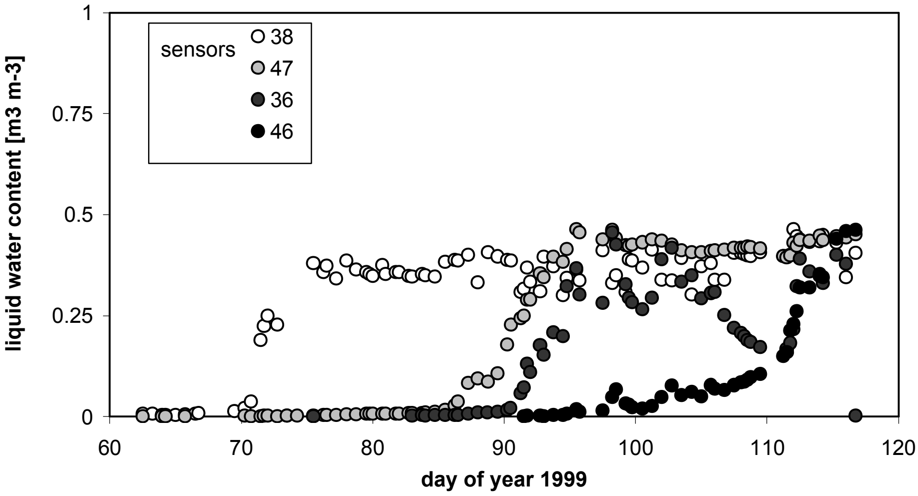


Fig. 7: Typical temporal evolution of the liquid water content for sensors placed 20 cm above ground in the snow cover with 25 cm spacing. Subsequently the sensors register liquid water contents near saturation.

LONG FLAT BAND CABLE SENSORS

The second sensor system which has been developed is especially suited for continuous measurements over long periods (Huebner and Brandelik, 2000). It consists of flat band cables as TDR transmission lines with lengths up to 100 m. They are permanently installed at the measurement site in different heights and enclosed by snow fall. Fig. 8 shows an exemplary installation on a glacier in Switzerland at the beginning of the snow cover cycle when the cables are still in the air.

Fig. 8: Installation of the snow parameter measurement system on the glacier Plaine Morte. The site is located near Crans-Montana, Switzerland, at a height of about 2800 m above sea level and has favorable snow conditions even until June or July.

The flat band cables can be measured with time domain and additionally with frequency domain signals in order to determine snow wetness and density at the same time. The physical background of the measurement, respectively the dielectric properties of snow are reviewed, followed by a detailed discussion of the cable design, system development and experimental results.

FLAT BAND CABLE SENSOR DESIGN AND MEASUREMENT PRINCIPLE

The typical sensing device for time-domain reflectometry is a metallic fork which is inserted in the material under test. Instead of this rigid construction a flexible flat band cable is proposed which can follow the settlement of the snow cover. A picture of the cable together with a sketch of the cross section is shown in Fig. 9.

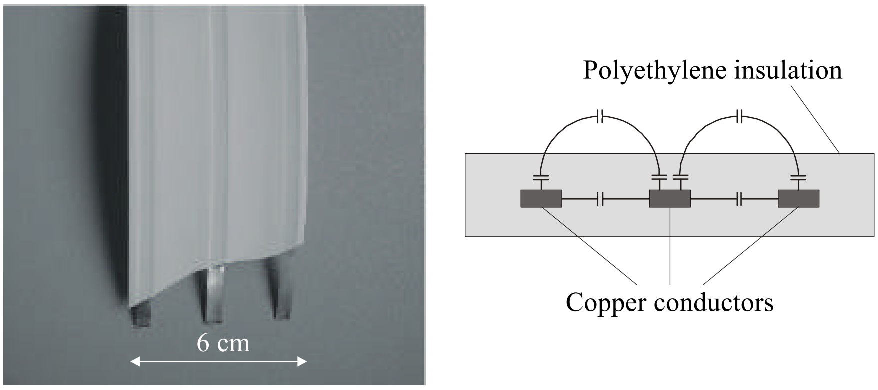
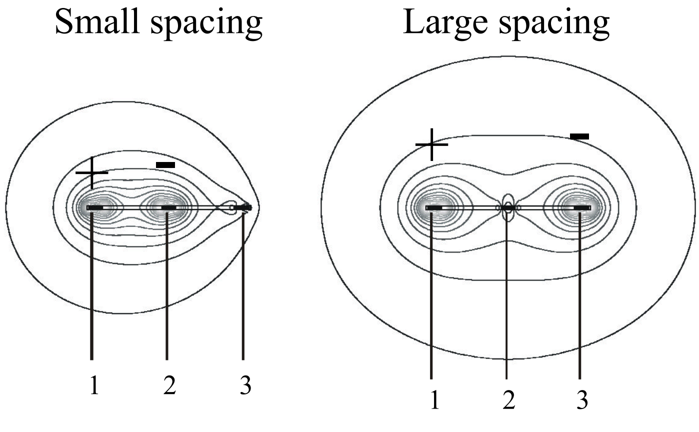


Fig. 9: Flat band cable and its cross section.

The white polyethylene insulation reduces the warming up of the cable due to solar radiation and the thin copper conductors have an advantageous low thermal capacity. Nevertheless airgaps will develop around the flat band cable especially after several months of measurements with multiple freezing and thawing cycles.



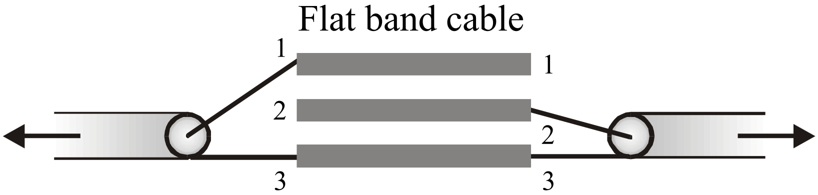


Fig. 10: Three wire flat band cable: Extension of the electromagnetic field for two different connection possibilities. The cable is connected to time domain reflectometer once from the left and once from the right side.

These airgaps cause underpredictions of the permittivity of the surrounding snow. To avoid this and compensate for airgap effects the three wire cable is measured twice, with small and with large spacing as shown in Fig. 10. A correction equation has been derived for calculating air gap size and true permittivity of the snow.

EXPERIMENTAL RESULTS

A complete measurement system was installed on the glacier Plaine Morte (Fig. 8) consisting of horizontal snow wetness measurement cables connected to a time-domain reflectometer via a multiplexer, a weather station, snow height and temperature sensors and a computer for control and data acquisition. The horizontal cables were arranged at different heights over a length of about 40 m to obtain representative data from the snow cover. A typical measurement result for a horizontal cable is shown in Fig. 11.

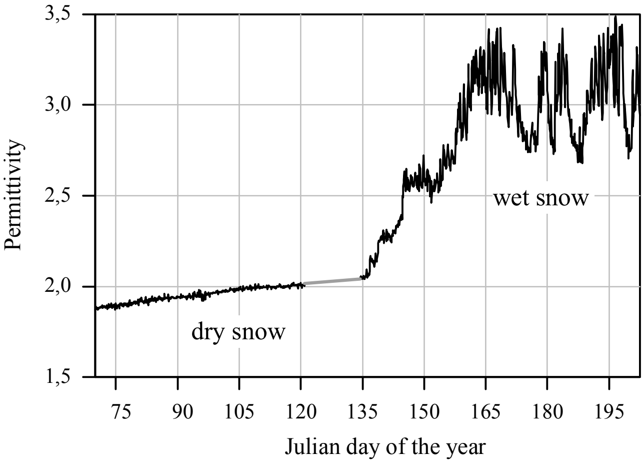


Fig. 11: Permittivity of a snow cover versus time.

One can distinguish between the dry snow and the wet snow phase. In the dry snow phase there is a constant increase in the permittivity which is due to compaction of the snow for higher density. The permittivity can be related to the dry density with equation (1) and increases to about 0,55 g/cm³ at the transition from the dry to the wet snow phase which is around the 135th day of the year. At this time a sharp rise in the permittivity due to melting processes can be observed. In the wet snow phase there are strong daily variations of water content which could be seen at finer time resolution and related to actual weather conditions.

Fig. 12 shows the daily variation of water content at the cables in different heights in comparison with air temperature and radiation balance observations. The increase of the air temperature above 0°C forces melting and an increase in the water content in the upper layers of the snow cover. It takes some time for the melt water to percolate through the snow pack and to reach the lower cable which also exhibits lower water contents and less variations.

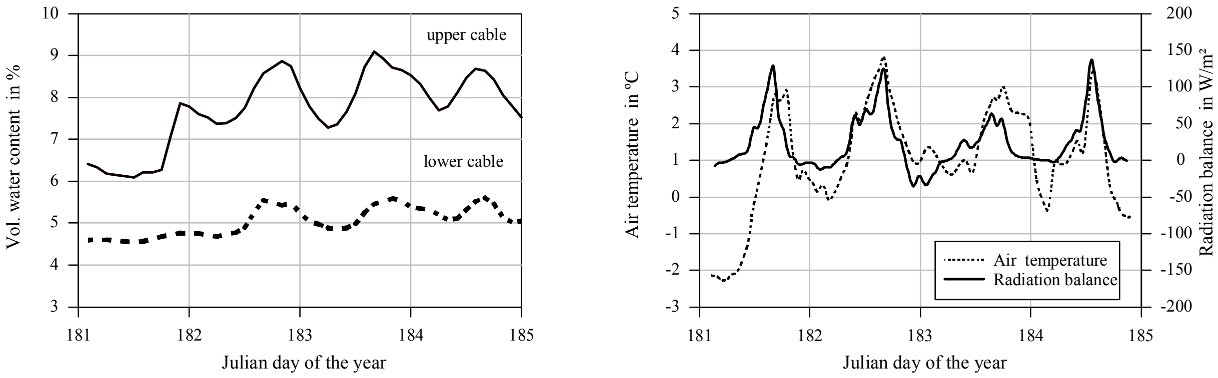


Fig. 12: Daily variations of snow wetness in comparison with air temperature and radiation balance.

Besides the vertical structure of the snow pack strong horizontal variations can also be observed. These horizontal structures are visible in the TDR signal as well as in an aerial photograph of the measurement site (Fig. 13).

Fig. 13 shows the part of the TDR signal which corresponds to the flat band cable. The bumps in the signal are areas of higher water content and have been identified with percolation zones in the snow cover. Percolation zones are paths of preferred water transport and show up as dark areas with accumulated contaminations. The possibility of the TDR to resolve spatial structures can be exploited for a determination of vertical snow pack structures. Therefore a field campaign in the Black Forest has been carried out (Fig. 14).

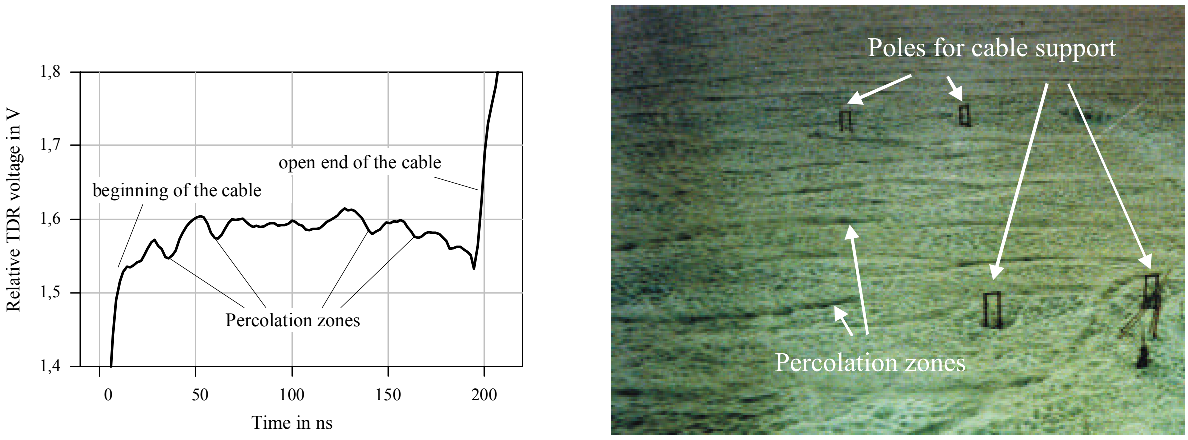


Fig. 13: Horizontal structure of the snow cover as seen in the TDR signal and in an aerial photograph of the site

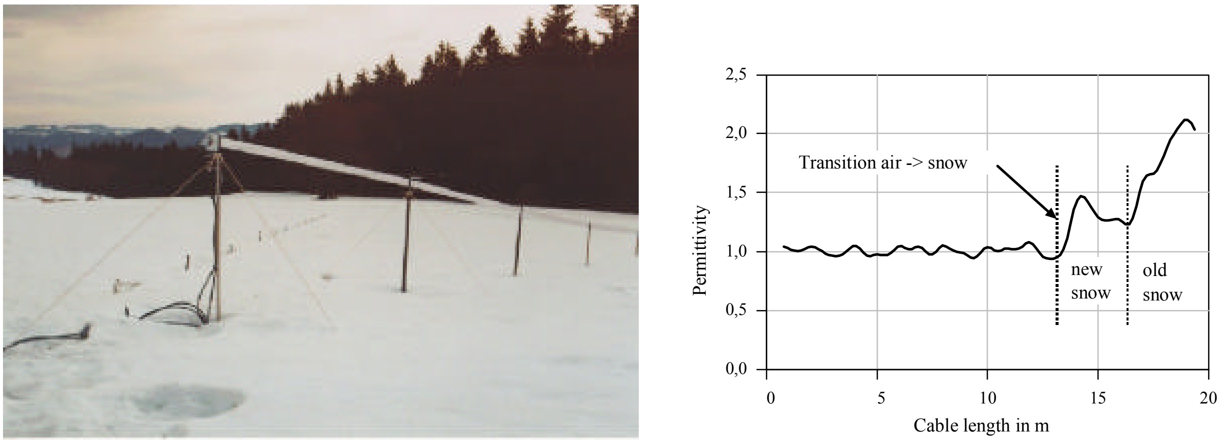


Fig. 14: Sloping cable for vertical profile measurements: installation and measurement results

A 20 m long sloping cable was connected to a computer-controlled time-domain reflectometer. The data was processed with a reconstruction software developed by Scheuermann et al. (2001) in order to determine the permittivity profile along the flat band cable. Though the total snow height during the campaign was less than expected owing to the warm winter weather, the vertical structure of the snow cover with new and old snow layers could be resolved. At the time of writing another field campaign is conducted in Switzerland with emphasis on vertical profile measurements together with simultaneous measurements at low frequencies for density determination.

SUMMARY

Two new sensor system for measuring snow wetness and density have been presented. The first sensor is light weight and especially suited for process studies. It consists of a thin aluminium structure which can be posed on the top of a new snow layer to be covered during the next snow fall period. The results of a field campaign show the high temporal evolution and variability of the wetness in a natural snow cover. The second sensor consists of flat band cables as TDR transmission lines with lengths up to 100 m. The cables are enclosed by snow fall and remain in the snow pack until the end of the season. The main advantages of this sensor are the large measurement volume and the possibility of a continuous monitoring of the snow cover development. This is achieved by a three wire cable design, two measurements at different electromagnetic field penetration depths and an airgap correction algorithm. The performance of the sensor is demonstrated in field campaigns. Monitoring of the snow cover development on representative large areas has been achieved for the first time and allows detailed investigations of the water transport processes through a snow pack. By using sloping cable arrangements the possibility of retrieving vertical profiles of snow properties has been demonstrated. A field campaign in this winter will focus on this task and the simultaneous determination of water content and density with additional low frequency measurements.

ACKNOWLEDGEMENT

This work was partly supported by the Swiss National Science Foundation.

REFERENCES

Denoth, 1994, Snow dielectric measurements. Advances in Space Research, 9, 233-243.

Frolov, A. D. and Macharet, Y. Y., 1999, On the dielectric properties of dry and wet snow: Hydrological processes, 13 (12/13), 1721-1732.

Huebner, C. and A. Brandelik, 2000, Distinguished Problems in Soil and Snow Aquametry: in Sensors Update (Eds. H. Baltes, W. Goepel und J. Hesse), 7, 317-340, Weinheim: Wiley-VCH.

Looyenga, H., 1965, Dielectric constant of heterogeneous mixtures: Physica, 31, 401-406.

Mätzler, C., 1996, Microwave Permittivity of Dry Snow: IEEE Transactions on Geoscience and Remote Sensing, 34, 573-581.

Marsh, P. and Woo, M.-K., 1984, Wetting front advance and freezing of meltwater within a snow cover: 1. Observations in the Canadian Arctic: Water Resources Research, 20 (12), 1853-1864.

Scheuermann, A, Schlaeger, S., Huebner, C., Brandelik, A., and Brauns, J., 2001, Monitoring of the spatial soil water distribution on a full-scale dike model: in Kupfer et al. (eds.), Proceedings of the 4th International Conference on Electromagnetic Wave Interaction with Water and Moist Substances, 347-354.

Schneebeli, M., 1995, Development and stability of preferential flow paths in a layered snowpack: in: K. A. Tonnessen, M. W. Williams & M. Tranter: Biogeochemistry of seasonally snow-covered catchments, Boulder: in IAHS Publication. Vol. 228, 89-95.

Schneebeli, M., Coléou, C., Touvier, F. & Lesaffre, B., 1998, Measurement of density and wetness in snow using time-domain-reflectometry: Ann. Glaciol., 26, 69-72.

Stein, J., Gaetan, L. and D. Lévesque, 1997, Monitoring the Dry Density and the Liquid Water Content of Snow Using Time Domain Reflectometry (TDR): Cold Regions Science and Technology, 25, 123-136.

Tiuri, M. T., Sihvola, A. H., Nyfors, E. G. & Hallikainen, M. T., 1984, The complex dielectric constant of snow at microwave frequencies: IEEE J. Oceanic Eng., OE-9(5), 377-382.

Williams, M. W., Sommerfeld, R., Massman, S. & Rikkers, R., 1999, Correlation lengths of meltwater flow through ripe snowpacks, Colorado Front Range, USA: Hydrological processes, 13(12/13), 1721-1732.