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A capacitive soil moisture sensor

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Abstract

A new sensor for field measurements of the water content of natural soils has been developed. The measurement quantity is the complex permittivity at a frequency of 32 MHz; it is derived by an impedance measurement with a capacitive sensor of a fork-like geometry, which was found to the best geometry for field use. The impedance is measured with a twin T-bridge which has been optimized to cover the extremely large range of permittivities of natural soils. An analysis of measured soil permittivities showed a dominant influence of liquid water content on dielectric permittivity, whereas soil-specific parameters such as grain-size distribution, chemical composition and bulk density have only a negligible influence at this comparable high measurement frequency. The loss factor, however, depends strongly on both the type of soil and the water content. In addition, comparative studies with commonly used measurement methods such as the thermogravimetric method and time domain reflectometry showed satisfactory agreement. As an application of practical interest, a field measurement of a vertical water content distribution at a snow–soil interface is presented.

1. Introduction

Soil moisture is an important quantity in fields such as soil physics, botany and agriculture; the most useful definition for it is the volumetric water content W, with $W(\%) = 100(V_w/V_s)$, where V_w is the total volume of water in the soil and V_s is the total volume of all soil components. Typical values of W range up to 60% because the porosity of most soils, i.e. the volume of liquid and gaseous fractions related to the total volume, is between 40% and 60% (Hartge, 1991).

For soil water measurement various methods are commonly in use; the most important ones are the thermogravimetric method, time domain reflectometry (TDR) and electromagnetic methods such as impedance measurements. With all these methods

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an average liquid water content in a specific volume is derived; the effective measurement volume, however, depends on the method used, so measurement results may differ because of the high spatial variability of water distribution in natural soils.

The thermogravimetric method (Gardner, 1987; Hartge, 1991), which is the standard calibration method, requires the removal of soil samples and is extremely time consuming; also, measurements are not repeatable. In the present study, a cylindrical soil sample (taken by a soil sampling ring of 5 cm height and 80 cm^2 cross-section) was weighed before and after oven-drying at 105°C, typically for 48 h. The measured gravimetric water content was converted to the volumetric water content, W; in this paper only the volumetric water content is used.

TDR determines dielectric permittivity from the propagation time of a guided needle- or step-shaped electromagnetic wave; pulse rise times are typically in the 0.1–1 ns range (Malicki and Skierucha, 1989; Roth et al., 1992). The wave guide usually consists of two or more parallel metal rods which extend to a length of typically 20 cm; this might be a serious problem in stony soils and in soils rich in rootlets. The use of considerably shorter TDR guides (miniprobes) has been reported by Malicki et al. (1992). TDR is simple in application and data evaluation if the material to be measured can be treated as a low-loss or loss-free dielectric material. However, if dominant parts of the spectrum of a TDR pulse are in a frequency regime where ϵ'' cannot be neglected (which may occur also in the lower gigahertz range owing to relaxation processes in 'bound' water), data evaluation becomes more complicated. In the present study, for comparative TDR measurements a Type TRASE 6050 XI system from Soil Moisture Equipment (Santa Barbara, CA, USA) was used.

Soil water measurements by capacitance techniques (impedance probes) operate typically in the radio-frequency regime from 10 MHz up to several hundred megahertz; the measurement quantity is the soil dielectric constant. This has been measured using different electronic concepts and a variety of differently shaped capacitive sensors; for example, by the change of 'fringe capacitance' of coplanar electrodes using a VHF admittance bridge of laboratory standard grade (Thomas, 1966), by the change of frequency of an HF oscillator using annular electrodes especially designed for the detection of soilwater content profiles (Bell et al., 1987), by impedance measurements of a cylindrical probe made up of a coaxial arrangement of a centre tine surrounded by six tines using a laboratory vector voltmeter (Ungar et al., 1992), or by measuring the reflection coefficient of an open-ended coaxial cable probe especially designed for measuring in layers of the order of 1 cm in thickness using a microwave reflectometer (Brisco et al., 1992).

Because of the limited applicability for field measurements of thermogravimetry and capacitive sensors operated with laboratory instruments, and the possible problems associated with TDR when applied to highly conductive and very wet soils, a battery-powered portable dielectric probe based on an impedance measurement with a high-frequency twin T-bridge has been developed and compared with the standard methods TDR and gravimetric sampling.

2. Materials and methods

To find a suitable measurement frequency for the portable soil moisture dielectric probe,

Table 1
Characteristic parameters of soil samples used

Soil type		Location	Bulk density ($g\ cm^{-3}$)	Organic fraction (%)
A	Soil under pasture	Inn valley near Innsbruck	1.12	< 5
B	A_H-horizon of brown earth	Inn valley near Innsbruck	0.73	≈ 8
C	Humus	Botanic Gardens Innsbruck	0.28	Not measured, ≫ 10
D	Sandy soil	Wipptal, Tyrol	1.75	≈ 0
E	0–20 cm:	Kühtai, Tyrol, 2000 m a.s.l.,1 June 1994	0.81	< 3
	A_H-horizon;		1.43	
	> 20 cm: C-horizon of alpinerankers			0–1

preliminary measurements of soil dielectric function have been performed in the laboratory using standard equipment: a two-port vectoranalyzer (Rohde and Schwarz ZPV (Munic, Germany), tuner ZPV-E1 and feed-unit ZPV-E2) in combination with a programmable synthesizer (Phillips (Eindhoven, Netherlands), PM5193). A symmetrical plate condenser of 150 cm^3 effective measuring volume was filled with a soil sample and was connected to the feed-unit by a coaxial cable; the measurement quantity was the amplitude reflection coefficient of the test material using the simple T-junction method. The intrinsic soil dielectric function (permittivity and loss) was derived from the reflection coefficient. Details of the measurement procedure and data reduction have been given by Gschnitzer and Eller (1994). Liquid content of the individual soil samples was measured by thermogravimetry as described in the Introduction. Some characteristic parameters of soil samples used in this investigation are summarized in Table 1. Samples A–D have been collected for laboratory measurements. Parameters of the soil used for a field measurement of a vertical profile of water distribution are given in Soil Type E.

3. Soil dielectric function

The dielectric function of a variety of soils has been measured in a wide frequency range from 500 kHz up to 95 MHz using a simple plate condenser and a vector network analyser. A detailed analysis of the dielectric response of soil shows, in general, a significant effect of water content but—especially at lower frequencies—also an influence of soil texture (characterized by grain-size distribution), structure (geometrical arrangement of the solid soil fraction) and the actual chemical composition (Gschnitzer and Eller, 1994). Measurements of soil dielectric function by Hoekstra and Delaney (1974) and Ulaby et al. (1986), and measurements by Gschnitzer and Eller (1994), show ϵ' (the real part of the dielectric function) to be independent of frequency and to depend only weakly on soil type in the specific frequency range extending from 30 MHz up to approximately 200 MHz.

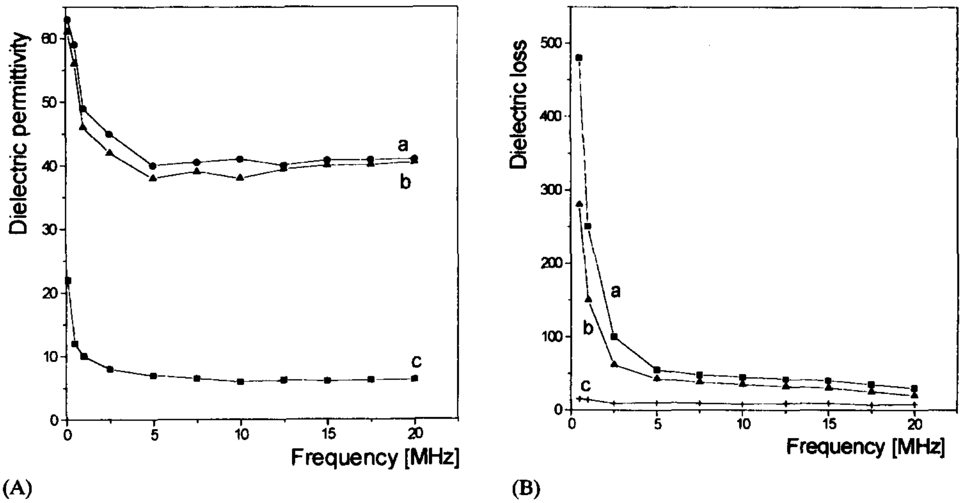

Fig. 1. (A) Dielectric function and (B) dielectric loss of a specific soil sample (Type A) at three wetnesses: a, $W = 65\%$; b, $W = 55\%$; c, $W = 7.4\%$.

Therefore, to minimize the specific effects of texture, structure and effects of ionic conductivity, a relatively high frequency of 32 MHz has been chosen for the operation of the soil moisture measurement device. Fig. 1 shows the typical 'low-frequency' dielectric response of a selected soil sample with different liquid water contents (soil under pasture, Type A in Table 1). Liquid water content has been determined using the thermogravimetric method. Fig. 1(A) represents the dielectric permittivities (ϵ') and Fig. 1(B) the dielectric losses (ϵ'') in the range up to 20 MHz. Both ϵ' and ϵ'' depend strongly on water content and show a

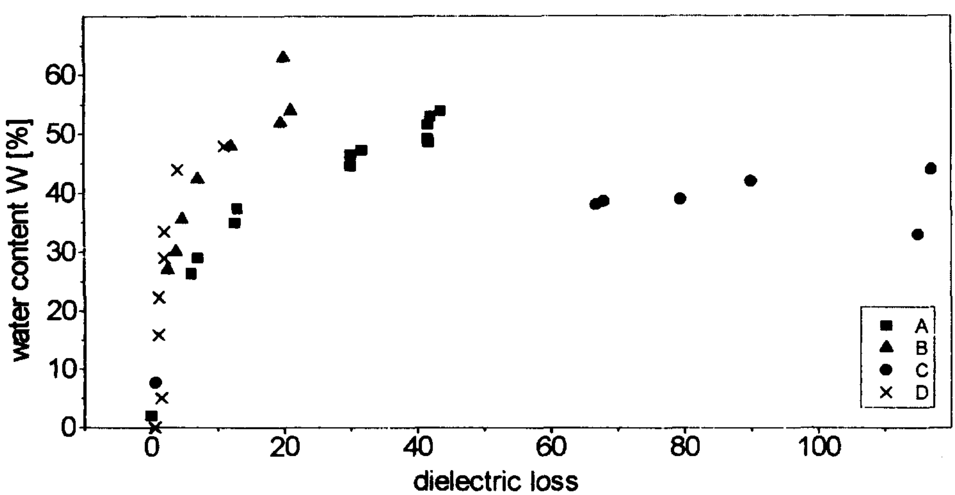

Fig. 2. Dielectric losses ϵ'' (35 MHz) vs. water content $W(\%)$ for different types of soils. A, Soil under pasture; B, A_H-horizon of brown earth; C, humus; D, sandy soil.

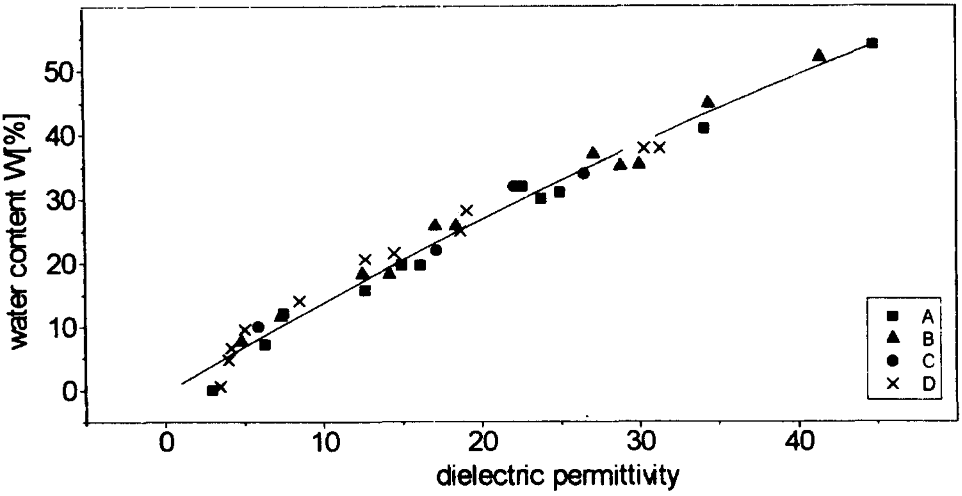

Fig. 3. Dielectric permittivity ϵ' (35 MHz) vs. water content $W(\%)$ for different types of soils, shown together with a least-squares fit (continuous line). A, Soil under pasture; B, A_H-horizon of brown earth; C, humus; D, sandy soil.

marked variation with frequency, owing to low-frequency relaxation processes and ionic conductivity. The influence of liquid water content on ϵ'' and ϵ' for various soil types (soil under pasture, A_H-horizon of brown earth, humus, sandy soil; soil characteristics are given in Table 1) is demonstrated in Figs 2 and 3, respectively; soil water content was measured by thermogravimetry (TG). Fig. 2 shows the effect of W on ϵ'': the dielectric losses at 35 MHz depend not only on liquid content but also on soil type, so no unique relation $\epsilon''(W)$ can be derived. This holds for a frequency range up to 95 MHz, the upper limit of the present measurements. Fig. 3 shows the effect of the water content on ϵ' for different types of soils: the influence of water content is dominant; careful analysis shows a weak effect of soil type. For most practical purposes, however, the weak influence of characteristic soil parameters such as texture, structure and chemical composition can be neglected. Therefore, for water measurements using dielectric (capacitive) sensors operating at frequencies in the range of 25 MHz up to approximately 200 MHz a specific characterization of soil type is not necessary. A regression analysis between volumetric water content $W(\%)$ and the relative dielectric permittivity ϵ for $W \geq 3\%$ gives a relatively simple relation:

$$W(\%) = 1.484\epsilon' - 0.006\epsilon'^2 - 0.332$$

with a correlation coefficient of $r^2 = 0.979$. At liquid water contents less than approximately 3% an increasing influence of soil type and soil porosity has to be expected: the relative importance of the permittivity of soil solid constituents increases compared with the permittivity of the water component at low liquid volume fractions (Hasted, 1973).

4. Measurement system

For practical purposes of field measurements of soil water content a battery-operated

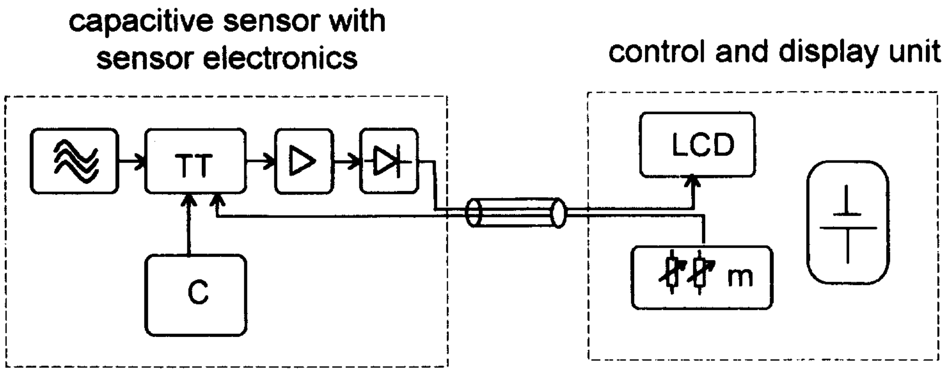

Fig. 4. Block diagram of the soil moisture measurement device. TT, Twin T-bridge; C, capacitive sensor; LCD, data display; m, manual tuning.

system has been developed: dielectric permittivity ϵ' (and total losses ϵ'') are derived from an impedance measurement using a twin T-bridge (Scaife, 1971) and a capacitive sensor with a fork-like geometry. The system consists of two separate parts: the sensor with sensor electronics and the control- and display-unit, which are connected by a multiwire shielded cable. Cable length is 2 m; it can easily be extended to a length of 5–6 m if required. A block diagram of the measurement system is shown in Fig. 4; a sketch of the

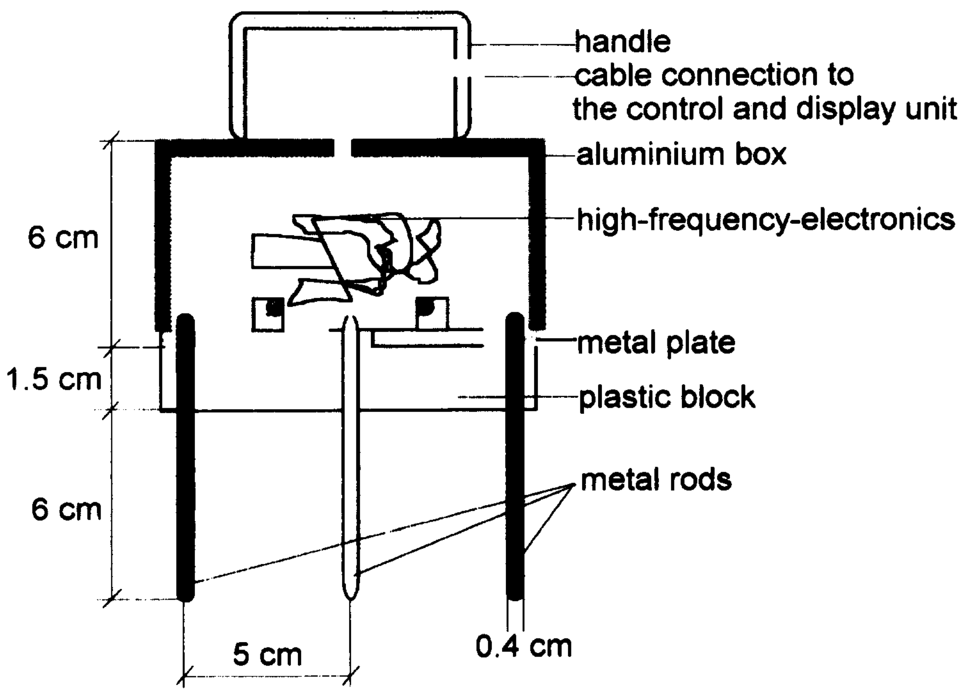

Fig. 5. Sketch of the capacitive sensor; dimensions are given in centimetres.

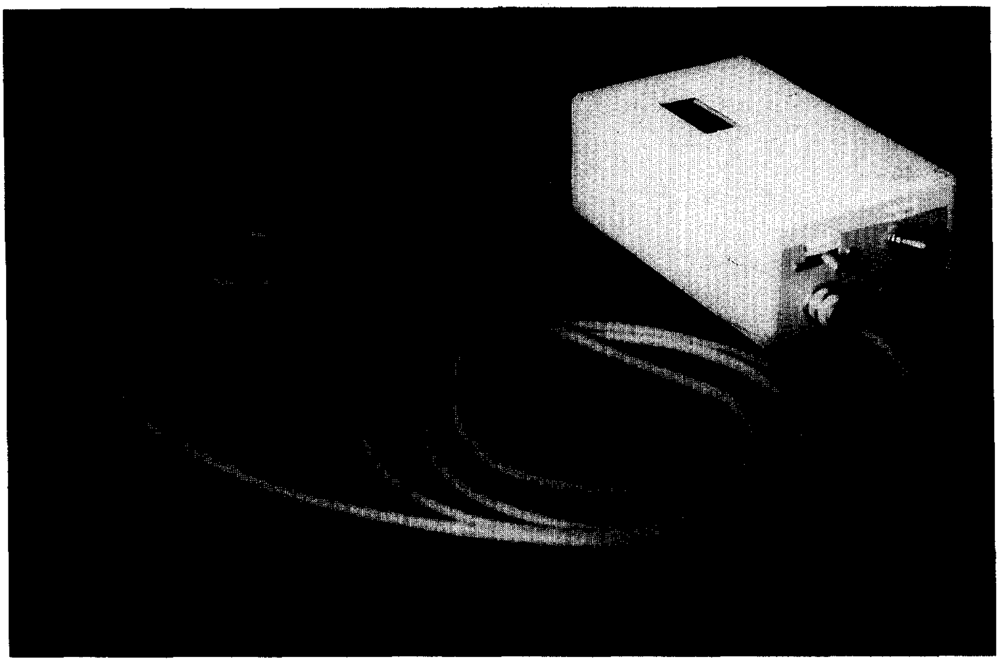

Fig. 6. Photograph of the soil moisture measurement device.

capacitive sensor unit and a photograph of the measurement system are given in Figs 5 and 6, respectively. For electronic simplicity a standard frequency of 32 MHz is used for sensor operation; the twin T-bridge has been optimized to cover the extremely large range of permittivities and losses of natural soils. For easy sensor application to a large variety of soil types a fork-like geometry has been selected: the sensor consists of three coplanar metal rods with a spacing of 5 cm, a length of 6 cm and a diameter of 4 mm. With this arrangement of electrodes soil permittivity is determined in an effective cylindrical measuring volume of 100 cm^3 (details have been given by Gschnitzer and Eller (1994)).

5. Comparative measurements and field application

Fig. 7 shows laboratory measurements of soil water content (per cent by volume) by the capacitive method, *W*(CM), compared with measurements by TDR, *W*(TDR), and thermogravimetric measurements, *W*(TG). As the soil type has practically no influence on these measurements the individual soil samples have not been characterized for this comparative study. Measurements were done consecutively: first with the capacitive probe, then by TDR and finally by TG. Observed small differences in measured soil water content by the different methods are due to unavoidable inhomogeneities in water distribution and the different measurement volumes of the individual sensors: The TDR and the capacitive probes sense water in a nearly cylindric volume of 20 cm length and approximately 7 cm^2

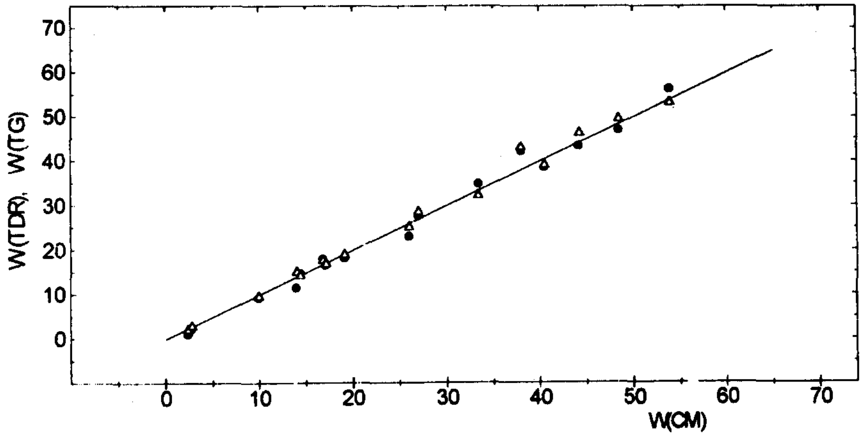

Fig. 7. Volumetric soil water content, $W(\%)$, measured by TDR (●) and by TG (▲) compared with measurements by the capacitive probe, W(CM).

cross-section (approximately 140 cm^3) and of 6.5 cm length and approximately 12 cm^2 cross-section (approximately 100 cm^3), respectively; the soil sampling ring had the dimensions 80 cm^2 cross-section and 5 cm height (400 cm^3). The comparative measurements showed a good correlation between the individual test series: for CM compared with TDR, $r^2 = 0.991$, and for CM compared with TG there was an insignificantly lower correlation, $r^2 = 0.984$.

A typical field application with this capacitive sensor is given in Fig. 8. It shows a water

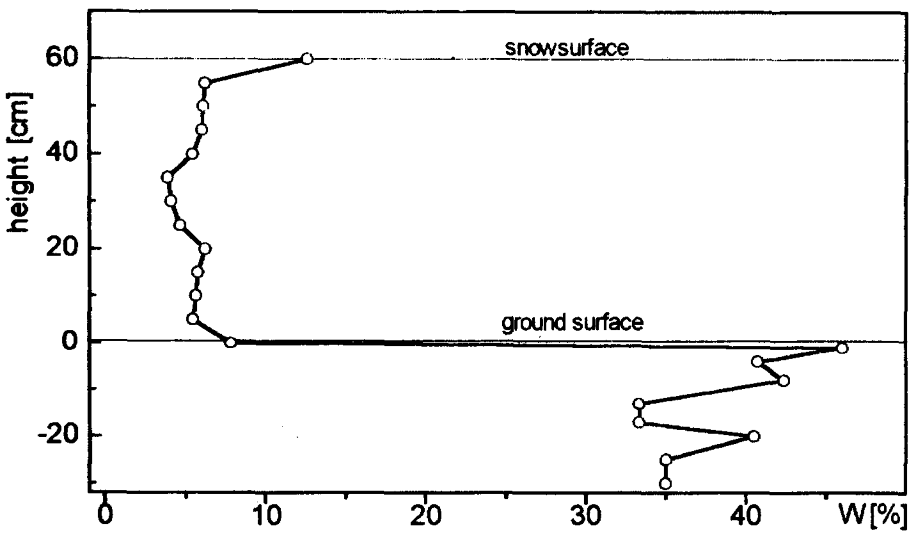

Fig. 8. Vertical water distribution at a snow–soil interface (Kühtai, 6 January 1994).

profile at the snow–soil interface (Soil Type E, Table 1; snow type: old coarse-grained spring snow). Snow and soil liquid water content has been measured with the same instrument, where only the sensor geometry has been optimized for the specific requirements for measurements in soil or snow. Details of the 'snowsensor' geometry have been given by Denoth (1994). Measurements at a snow–soil interface are of basic interest for water balance investigations and for water percolation studies related to avalanche research.

6. Summary

At 32 MHz (and higher frequencies) the soil dielectric permittivity is uniquely correlated with the volumetric water content, with a relatively high correlation of $r^2 = 0.979$. No significant soil-texture effect on permittivity has been detected, which is in accordance with observations of other workers (see, e.g. Thomas, 1966; Hoekstra and Delaney, 1974; Ulaby et al., 1986). The possible effects of different amounts of 'bound-water' compared with the amount of free 'bulk-water' is below the resolution of this instrument and can be neglected, so soil water content can easily be derived by a simple capacitive measurement. The measurement system developed allows an easy and quick in-situ measurement of water content with a relative error $E(W)$ of about 5% or less. A slightly reduced accuracy has been observed with measurements in very wet ($W > 25\%$) humus, consisting of highly conductive organic constituents. The device is battery operated and designed for manual tuning; an electronic enhancement to increase the measurement range and resolution is in progress. Furthermore, measurement of liquid water content is possible in both soils and snow with the same instrument, which is a great advantage compared with other methods.

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