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# Monitoring the Unfrozen Water Content of Soil and Snow Using Time Domain Reflectometry

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Time domain reflectometry is a technique that can be used to indirectly measure the in situ moisture content of soil. Previously, this method was not used in the field to continuously monitor the liquid water content because of the influence it had on the wetting, drying, freezing and thawing cycles of the soil. The principal objectives of this field investigation were, apply the TDR technique to monitor the unfrozen water content in the soil, utilize this technique to determine snowmelt infiltration into seasonally frozen soils, and explore the feasibility of using the TDR technique to monitor snowmelt percolation in the snowpack. An additional goal of this paper was to explain in a straightforward manner how to use the TDR technique to obtain the liquid water profile in a soil. Various configurations of parallel transmission lines were installed horizontally at various depths in the soil and also in the snowpack. This technique gave a good delineation of the unfrozen water content with depth in frozen soils. Results looked promising in snow if in situ snow density measurements were taken along with the TDR measurements.

## INTRODUCTION

Recently, a new method called time domain reflectometry (TDR) has been used to monitor water content in unfrozen soils [*Davis and Annan*, 1977; *Topp et al.*, 1980]. It is an indirect method of soil moisture determination based on the relationship between the relative complex dielectric constant (which is not necessarily a constant) and the volumetric unfrozen water content of the soil. The use of the TDR method to measure the relative complex dielectric constant of materials was first described by *Fellner-Feldegg* [1969]. Reported in this paper is an extension of the above work, specifically, the application of the TDR technique to the determination of unfrozen water content in a frozen medium.

There are three main objectives to the paper.

1. Explain in a straightforward manner how to use the TDR technique to obtain the liquid water profile in a soil.
2. Show how the TDR technique was used to monitor the unfrozen water content continuously in the field and to monitor snowmelt infiltration into the soil.
3. Illustrate the feasibility of using the TDR technique to monitor snowmelt percolation and unfrozen water contents in the snow.

*Schmugge et al.* [1980] did an extensive review of methods for unfrozen soil moisture determination, including their advantages and disadvantages. *Anderson and Tice* [1973] reviewed the methods used to determine the unfrozen water content in frozen soils. Basically, all were laboratory techniques. At that time, the only method to determine continuously the unfrozen water content profile in the field without too much disturbance was to use the gamma ray method in combination with temperature probes and laboratory derived soil freezing curve (volumetric unfrozen water content versus temperature). According to *Schmugge et al.* [1980], the dual energy collimated beam gamma rays method has the following advantages and disadvantages.

*Advantages*

1. Data can be obtained over very small horizontal or vertical distances.
2. The measurement is nondestructive.
3. The average moisture content can be determined with depth.
4. The system can use automatic recording.
5. It yields simultaneous results of bulk density and total water content (including ice).

*Disadvantages*

1. Large variation in bulk density and moisture content can occur in highly stratified soils and limit spatial resolution.
2. Field instrumentation is costly and difficult to use.
3. Extreme care must be taken to ensure that the radioactive source is not a health hazard.

Another disadvantage of this method for determining unfrozen water content is the necessary use of temperature probes in the profile as well. A method is needed that would be as precise as the gamma ray method but less expensive, simpler to use, and more adaptable for field use. Furthermore, this method should have its advantages without its disadvantages, and it should also be applicable for unsaturated as well as saturated soils.

With the above advantages and disadvantages in mind, we assessed the time domain reflectometer technique for measuring unfrozen water contents. The applicability of the TDR method to measure unfrozen water content in frozen soils was studied under laboratory conditions [*Smith and Patterson*, 1980] and the technique appeared quite promising for field conditions. *Topp et al.* [1980] developed a curve relating water content and the relative complex dielectric content of unfrozen soils. Results obtained from ice/water mixtures [*Smith and Patterson*, 1980] and snow/water mixtures [*Sweeney and Colbeck*, 1974] plotted by *Smith and Patterson* [1980] also agreed with that curve. These results suggest that the TDR method can also be used to monitor snowmelt percolation in the snow using Topp's relationship. The TDR method has all the desirable characteristics of the gamma ray method except that presently it does not yield bulk density or

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total water content. Also, the instrumentation is not yet commercially available for automatic continuous recording.

Three practical problems still limit the use of the TDR technique in frozen and unfrozen soils. First, the TDR probes are usually put vertically in the soils [*Davis and Chudobiak*, 1975; *Topp et al.*, 1982*b*] to obtain a water profile with depth. Second, water flowing along the vertical probes affects the wetting and drying cycles of the soil over long measurement periods. Third, the freezing and thawing cycles are also affected by the high thermal conductivity of the probes, particularly metal probes.

Starting with the premise that the TDR method could be successfully used in the laboratory to measure the unfrozen soil moisture content, we initiated a program to evaluate this technique in the field. Various configurations of probes and transmission lines were utilized at a field site 10 km north of Fairbanks, Alaska in a birch-aspen stand. This paper presents the basic theory behind this technique, a field evaluation, and some preliminary data on the unfrozen water contents in seasonally frozen soils and snowpacks.

## THEORY

Since most hydrologists, foresters, agronomists, meteorologists, and engineers who might be interested in using this technique are not electronic specialists, a discussion of basic capacitance theory follows. In this discussion we will see how time domain reflectometry is related to the measurement of the relative complex dielectric constant which is a component of the capacitance. We will also see how to relate the relative complex dielectric constant to the unfrozen moisture content of the soil. The capacitance $C$ is a constant of proportionality that relates the potential difference $V$ between conductors to the amount of equal but opposite electric charges $Q$ in each of them:

$$Q = CV \tag{1}$$

This is analogous to Darcy's equation, where $Q$ is the flux, $V$ the hydraulic gradient, and $C$ the hydraulic conductivity. The capacitance or capacity of two plates (conductors) to hold electric charges depends on the voltage across the plates and on the insulating material (also called the dielectric) between the plates. Two metal plates with the dielectric is called a capacitor. The capacitance of a capacitor is given by the equation

$$C = (K\varepsilon_0 a)/d \tag{2}$$

where

$a$ area of the plates on one side, m$^2$;
$d$ distance between plates, $m$;
$K$ relative complex dielectric constant of the dielectric;
$\varepsilon_0$ permittivity of free space, F/m.

Capacitance is quite dependent on the geometry of the two conductors. For example, the capacitance of a coaxial cable [*Ramo et al.*, 1965] is given by

$$C = (2\pi K\varepsilon_0 L)/\ln (b/a) \tag{3}$$

where

$L$ length of the cable, m;
$b$ inside radius of outer conductor, m;
$a$ radius of inner conductor, m.

As can be deduced from (2) and (3), the capacitance is also dependent on the relative complex dielectric constant, which is in turn an important property that characterizes the capacity to store electric potential energy under the influence of an electric field. The relative complex dielectric constant isn't really a constant for most materials; it has a real and an imaginary part that are frequency dependent [*Topp et al.*, 1980]:

$$K = K' + j\{(\sigma_{dc}/\omega\varepsilon_0) + K''\} \tag{4}$$

where

$K$ complex dielectric constant;
$K'$ real dielectric constant;
$K''$ dielectric loss;
$\sigma_{dc}$ dc conductivity;
$\omega$ angular frequency;
$j = (-1)^{1/2}$.

A transmission line can be either balanced or unbalanced. A transmission line is balanced when the voltages of the two conductors at any transverse plane are equal in magnitude and opposite in polarity with respect to ground; otherwise it is unbalanced [*Markus*, 1966]. An example of an unbalanced transmission line is a coaxial line; a parallel transmission line is usually balanced. The complex dielectric constant of a material can be determined from the propagation of a pulse along either a balanced or unbalanced transmission line. The velocity of a pulse ($v_p$) along a transmission line is given by

$$v_p = L_r/t \tag{5}$$

where $L_r$ is the physical length of the transmission line or length of the probe, in meters and $t$ is the time of propagation, in seconds. From distributed circuit analysis, we know that at high frequencies and for a nonmagnetic material

$$v_p = c/(K)^{1/2} \tag{6}$$

Combining the last two equations gives

$$K = (ct/L_r)^2 \tag{7}$$

where $L_r$, the length of the line, is set by the user and $t$ is determined by using a time domain reflectometer.

> The TDR technique measures both the real and imaginary parts of the complex dielectric constant (equation 4), and hence the term "apparent dielectric constant" ($K_a$) is sometimes used. For low loss materials, $K \cong K'$ and hence $K_a \cong K'$.

[*Patterson and Smith*, 1980, p. 206]. The term $K$ will be used to denote the relative complex dielectric constant throughout the rest of this paper. For a more detailed description of electrical losses in soils, see *Davis and Chudobiak* [1975].

The determination of soil water content using the time domain reflectometer technique is based on the relationship that exists between the relative complex dielectric constant of the soil and its water content. Studies done previously [*Davis and Annan*, 1977; *Topp et al.*, 1980] show that the relative complex dielectric constant of a dry soil doesn't vary significantly with density, texture, salt content, or temperature between frequencies of 1 MHz and 1 GHz. Because the relative complex dielectric constant of liquid water is about 20 times higher than either soil or ice [*Von Hipple*, 1961], the relative complex dielectric constant of the total soil will vary primarily due to changes in the liquid water content. The relationship between the relative complex dielectric constant $K$ and soil water content $\theta$ is determined by measuring the travel time of an electrical pulse in a known length of transmission line inserted in a soil of known water content. The study of *Patterson and Smith* [1980] showed that the predicted volumetric unfrozen water content using the relationship of *Topp et al.* [1980] and the measured values using a dilatometer were in close agreement ($\pm 1.5\%$ in volumetric water content for silt loams). Therefore the same calibration curve developed in unfrozen conditions can be used in frozen soil to estimate the unfrozen water content, $\theta_{uf}$.

## MATERIALS AND METHODS

A time domain reflectometer and a transmission line were used to measure $K$.

> The time domain reflectometer consists of a pulse generator which produces a fast rise time step, a sampler which transforms a high frequency signal into a lower frequency output, and an oscilloscope or any other display or recording device.

[*Fellner-Feldegg*, 1969, p. 616]. The lower frequency output contains frequencies between 1 MHz and 1 GHz. Normally, $K$ can be measured in the frequency domain or in the time domain. In the frequency domain, a pulse is sent at one frequency in the transmission line and $K$ is measured at that frequency. For a complete characterization of $K$, numerous measurements must be made over a wide frequency range. In the time domain, a pulse is sent which contains all frequencies simultaneously. The pulse travels along the transmission line and any electrical discontinuity (such as a change in dielectric, a change of dimensions of the transmission line, or short circuit) will send a reflected pulse to the generator. The reflected pulses are visible on the recording display and permit the determination of the beginning and the end of the probe. The reflected pulse will have a certain magnitude in voltage which will vary according to the type of electrical discontinuity encountered on the line. The ratio of this voltage to the incident voltage is called the reflection coefficient. With the probes and soil forming a capacitor, the length of the electromagnetic trace between the beginning and the end of the probe permits you to calculate $K$ using (7).

### *Instrumentation*

A time domain reflectometer (Tektronix model 1502) was used to measure the relative complex dielectric constant $K$. To calculate $K$ of a transmission line of unknown dielectric, the velocity of propagation, $v_p$, on the instrument is set to a certain value and the length of the trace, $L_{et}$ is read on the oscilloscope. Then the following conditions prevail:

$$t_{et} = L_{et}/v_p \tag{8}$$

When $t = t_{et}$, combining (7) and (8) yields

$$K = [(L_{et}c)/L_r v_p]^2 \tag{9}$$

When $v_p$ is set to $c$, then they both cancel out in (9), giving

$$K = (L_{et}/L_r)^2 \tag{10}$$

### *Transmission Lines*

Two types of unbalanced transmission lines were used in the field.

*Type 1: 300-ohm parallel TV line antenna wire.* Listed from the TDR unit to the end of the probe, we had a static suppressor, 50-ohm coaxial cable, 50- to 75-ohm transformer, 75-ohm coaxial cable, 75- to 300-ohm TV transformer, 300-ohm TV transmission line, and two parallel rods to measure dielectric properties of the soil. The two parallel stainless steel rods and part of the 300-ohm line were inserted in the soil, and the whole system (rods and soil) served as a capacitor. The rods were 0.3 cm in diameter, 17.7 cm long, and placed 2.5 cm apart. To connect the probes to the TV lines, the stainless steel probes were threaded to hold the pressure terminal connectors of the line between two nuts. Large charges of static electricity can build up on people and objects in the laboratory during the cold and dry winter months. Caution should be exercised if the TDR unit is used or stored in the laboratory. At the beginning of the 50-ohm coaxial transmission line, a static suppressor (a standard accessory to the 1502 TDR cable tested) was used because the unit could be easily damaged by small charges of static electricity (over 5 volts).

*Type 2: 50-ohm coaxial line.* A static suppressor was put at the outlet of the TDR unit, followed by a 50-ohm coaxial cable and two parallel rods. This line had probes that were 45.7 cm long; the spacing and diameter of the probes were the same as the previous line. At the end of the 50-ohm transmission line the cable was split for 5 cm, twisted, and then looped between the nuts on the probes. The split was insulated with electrical tape.

This type of transmission line was also used to monitor $K$ in the snow. The probes were 91.4 cm long and were embedded in styrofoam at each end to provide a rigid support. The styrofoam blocks were 14.7 cm long, so the effective length of the probe was 62 cm.

### *Calibration Curve*

To relate the complex dielectric content $K$ to the unfrozen water content $\theta$, data were generated using a 5-bar pressure plate extractor (Soilmoisture Equipment Corporation, model 1600). Five polyvinyl chloride (PVC) tubes, 7.7 cm inside diameter and 18 cm high, were packed with Fairbanks silt loam from the site at an average dry density of 1.3 g/cm$^3$. A piece of thin fiberglass cloth was taped on the bottom of the PVC tube to retain the soil. The oven dry (24 hours at 105°C) soil was added in increments of 5 cm and packed using a rod. A set of parallel probes spaced 1.5 cm, center to center, and 17.7 cm long were then inserted vertically by hand in the soil. A wooden guide was used to make sure that the probes were inserted parallel. The probes were then connected to a 50-ohm coaxial line (type 2 transmission line).

The five replicates were then put in the extractor and water was added outside the samples to a level of 5 cm and allowed to soak for 24 hours. Distilled water was then added almost to the top of the sample (17 cm) to complete saturation. Water was added outside the PVC tubes to avoid trapping air in the soil sample. The sample was allowed to saturate for two more days. In both cases the extractor was closed. TDR measurements were taken when the water was 3 cm from the top and at saturated conditions. Afterwards, the water outside the samples was removed using a vacuum line. The pressure plate extractor was then started. TDR readings and weights of the soil samples in the extractor were taken over a range of water contents. After each weighing, a small volume of water was added around the samples to insure a good contact between the soil and the plate.

### *Determination of the Electromagnetic Length*

*Angle effects.* When the probes are installed in the field, they might hit a rock or a root and deviate slightly from being

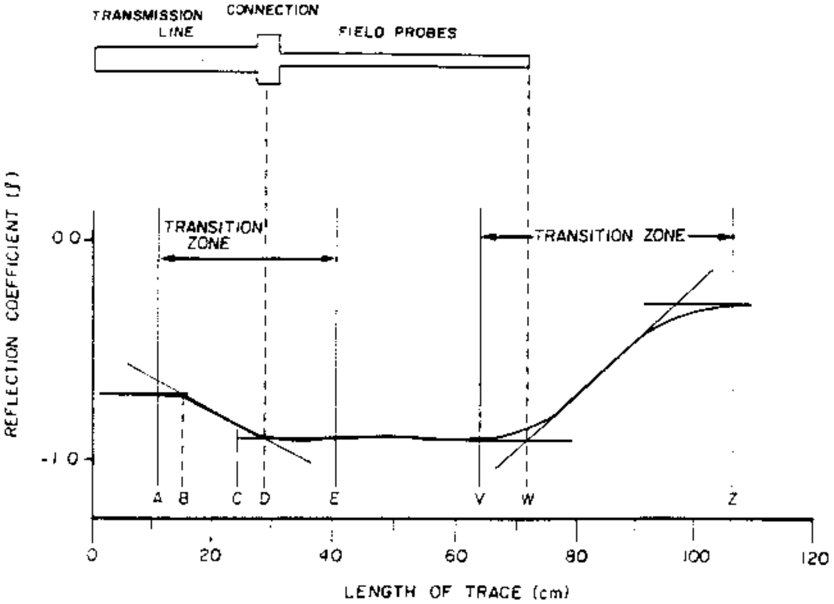

Fig. 1. Electromagnetic trace of a 300-ohm line (control plot, April 27, 1981; 5 cm deep). The physical length of the probe is 17.7 cm.

parallel. If the two probes are not parallel to each other, the quantity of material between them can be either greater or less than expected. The length of the electromagnetic trace will vary accordingly, possibly leading to erroneous results. This possibility was evaluated in the following manner. In the first experiment, one set of probes 91.4 cm long, supported by cardboard, was put in the air with different arrangements. The spacing at the beginning of the probes was always 2.5 cm; at the end of the probes, the spacing was 1.0, 2.5, 4.5, and 6.5 cm. There was also a special design which we call the triangle arrangement: the horizontal spacing at the end and the beginning of the probes is the same and equal to 2.5 cm, but at the end, one probe is vertically down by 1 cm. The air was used as a dielectric standard because its dielectric constant is known. In the second experiment, a set of 17.7-cm-long probes were embedded upward in a block of styrofoam 3 cm thick and put into a 2000-ml pyrex beaker. The vertical probes had an effective length of 15 cm. Fairbanks silt loam was used as the dielectric material. The soil was added and packed (as previously described) to a dry density of 1.3 g/cm$^3$, simulating the density observed in the field. The volumetric water contents were 0 and 43%. Probe spacings for TDR measurements were varied in the same way as in the previous experiment with air.

*Transition zones.* Due to power loss, imperfect connections between the transmission line and the parallel probes, and an imperfect open circuit at the end of the probes, the electromagnetic trace on the oscilloscope exhibits transition zones. These zones render the determination of the electromagnetic length $L_{ef}$ of the probe more difficult.

The determination of the beginning and end of the probe can be done through the use of tangents to the trace. A case is shown in Figure 1 for a 300-ohm line. A profile view of the probes is shown in the upper part of the figure, starting with the TV line followed by the nuts at D and finally the probes. The transition zones on the trace are A–E and V–Z, where D is the beginning of the probes and W is the end of the probes. The trace goes down at point A because the impedance of the soil is lower than the impedance of the 300-ohm line. The determination of W with tangents is first reported by *Smith and Patterson* [1980].

Two traces of 50 ohm are illustrated in Figure 2. Trace 1 shows a case where the soil is dry. Trace 2 shows the saturated soil. In both cases the trace goes up because the impedance of the soil is larger than that of the 50-ohm line. The end of the electromagnetic distance of the probe is determined in the same way as with the 300-ohm type. For the 50-ohm lines the beginning of the probe is situated at the summit of the bump. The calculation of the dielectric constant using (10) is also shown. The electromagnetic trace of an unfrozen dry soil is similar to the electromagnetic trace of a frozen saturated soil. As the soil thaws, the trace of a frozen saturated soil will slowly evolve from trace 1 to trace 2.

### Field Experiments

*Soil.* A field site was selected 10 km north of Fairbanks, Alaska, in a 70-year-old birch-aspen stand on a south facing permafrost-free site. Approximately 10–15 cm of organic material ($A_{00}$, $A_0$ horizons) covered the underlying mineral soil. Fairbanks silt loam was the predominant soil type in this area.

During fall 1980, three plots were instrumented with sets of transmission lines (300-ohm type). A square of about 100 cm × 100 cm was cut out of the organic matter ($A_{00}$, $A_0$ horizons) and removed so that a pit could be excavated to install the probes. It was put back above the backfill after the probes were inserted horizontally through the pit wall into the undisturbed soil. The probes were installed in a manner similar to that described in the calibration curve section. On the control plot the probes were buried horizontally at the following depths from the surface: 5, 15, 20, 25, 30, 35, 40, 50, 60, 75, 90 and 110 cm. On the two treated plots (plot 1 and plot 2) the probes were put at the following depths from ground surface: 5, 15, 20, 30, and 40 cm. On all three plots the first probe was put in the organic matter in the $A_0$ horizon, the rest of the probes were located from the $A_1$ horizon to the $C_2$ horizon. On treated plot 1, 3.8 cm of water was applied to simulate late fall rainfall, while 6.25 cm was applied to treated plot 2. This added water provided a wider range of soil moisture con-

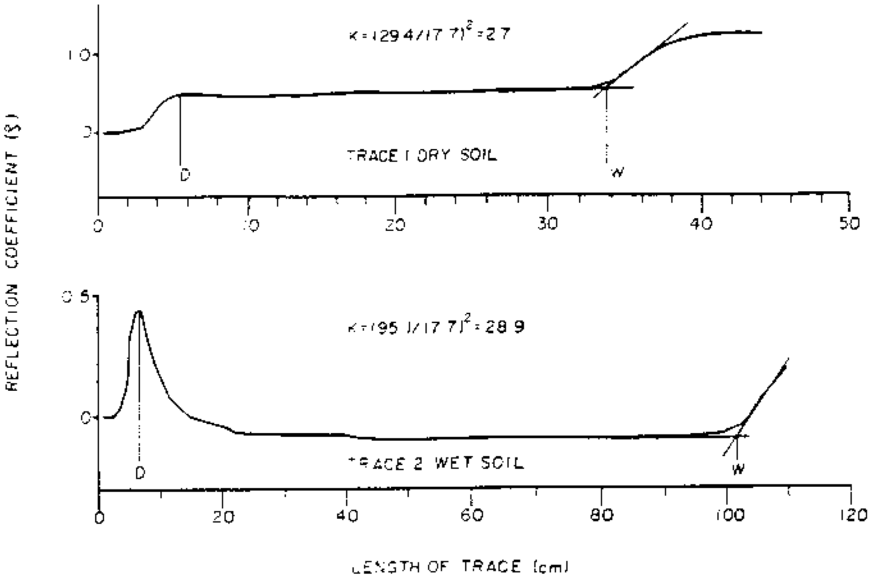

Fig. 2. Electromagnetic traces for the 50-ohm line. $K$ was found by using (10).

ditions. Equal increments of water were added over a 5-day period: 1.25 cm/d for plot 1 and 0.75 cm/d for plot 2. The water was pumped from a holding tank and applied using an oscillating lawn sprinkler. The quantity of water applied was determined from the level of water left in the tank.

The next fall (October 10, 1981) the above sets of probes were all replaced with 50-ohm transmission lines. On the control plot, two gravimetric samples on each side of the old probes were taken at 5-cm intervals from a depth of 12.5 cm below the surface to 42.5 cm and at 10-cm intervals from 42.5 to 92.5 cm. We used a soil corer that takes a 137-$\text{cm}^3$ sample. The volumetric water content was determined from the 300-ohm line data obtained 3 days earlier and compared with the gravimetric results by calculating the means and standard deviations of both methods. On the treated plots, probes were added at the 60- and 110-cm levels. A third treated plot was also added, and the probes were put at the same depths as the other treated plots. On October 1, we applied 3.8 cm of water on plot 1, 2.5 cm on plot 2, and 1.25 cm on plot 3.

*Snow.* Two assemblages of snow probes were installed on the control plot. An assemblage has five sets of snow probes placed horizontally 5 cm apart from a height of 2.5 cm to 22.5 cm above the ground. The height of the styrofoam blocks which support the probes is 25 cm. One assemblage was placed prior to snowfall, and the second one was put on the top of the first one when the snow depth reached the 25-cm level. Thermistors were also installed at the following heights above the surface of the ground: 1, 2.5, 5, 7.5, 10, 15, 20, 25, 30, 35, 45, 50, 55, 60, 65, 70, and 75 cm.

## RESULTS AND DISCUSSION

### *Calibration Curve*

The results of pressure plate extractor were compared with the following equation of *Topp et al.* [1980] for mineral soil (Figure 3):

$$\theta = -5.3 \times 10^{-2} + 2.92 \times 10^{-2}\ \mathrm{K} - 5.5 \times 10^{-4}\ \mathrm{K}^2 - 4.3 \times 10^{-6}\ \mathrm{K}^3 \qquad (11)$$

The solid line in Figure 3 represents the cubic equation, and the dashed lines show the 95% confidence intervals. The moisture content at 45% is accurate to about 5%. Almost all the points are situated in the envelope curves, but most of the data are situated on the lower side of the solid line. Out of 19 cases, 16 values of $K$ were lower when taken with the static suppressor, but from Figure 3, they are not significantly lower.

*Topp et al.* [1980] also develop an equation for organic soil, but they express the equation in terms of the moisture content $\theta$ rather than in terms of $K°$:

$$K = 1.74 - 0.34\ \theta + 135\ \theta^2 - 55.3\ \theta^3 \qquad (12)$$

We applied (12) to generate data points which were used to devise an equation in terms of $K$ using the least squares method. This was done because the dependent variable in our case is the moisture content $\theta$ not $K$. The equation for the organic soil using (12) becomes

$$\theta = -2.52 \times 10^{-2} + 4.15 \times 10^{-2}\ \mathrm{K} - 1.44 \times 10^{-3}\ \mathrm{K}^2 + 2.20 \times 10^{-5}\ \mathrm{K}^3 \qquad (13)$$

The dry density of the organic soil used by *Topp et al.* [1980] is 0.422. In our case it was situated around 0.55 (T. A. Moore, personal communication, 1983). Unlike mineral soil, the density of an organic soil might be an important factor affecting the relationship between the dielectric constant and the moisture content due to the increased presence of air. Therefore (13) might not be accurate for our soil.

### *Determination of the Electromagnetic Length*

*Angle effects.* The results of the two experiments are presented in Table 1. If all the data points at 43% moisture content were plotted on Figure 3, they would be all situated within the envelope curves. For the 0% moisture content case, all the points are within the standard error of estimate of ±0.2 in $K$ as determined for the calibration curve. Therefore we can infer that a probe's position didn't affect significantly the complex dielectric constant, even at large deviations from the desired parallel spacing. So it is not critical that the probes be exactly parallel.

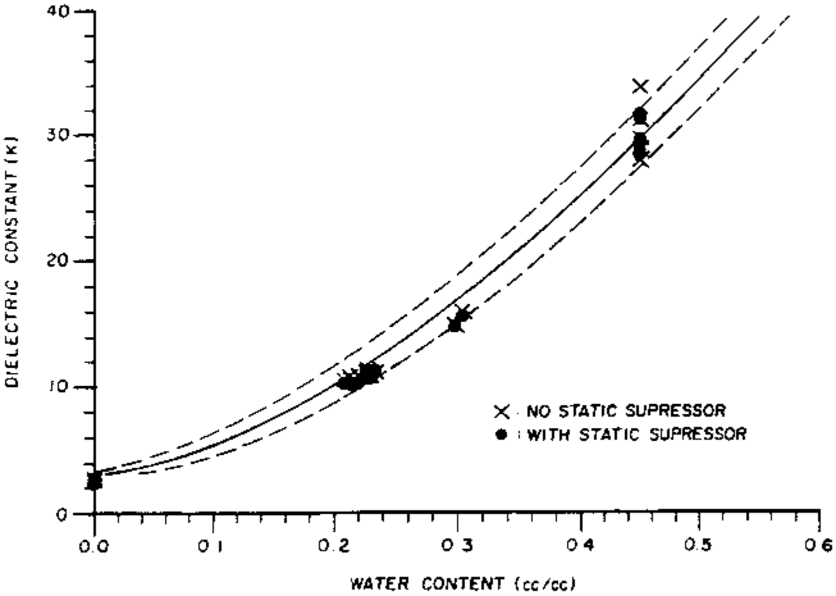

Fig. 3. Variation of soil dielectric constant with water content (adapted from *Topp et al.* [1980]).

*Transition zone.* Each transition zone differs according to the design used and the dielectric material between the probes. In the case of a 300-ohm line in the soil, point *W* lies between C and D most of the time because of the magnitude of power loss in the 300-ohm line (Figure 1). In such cases it is impossible to find the beginning of the probes (i.e., D) through the use of tangents because the curve does not flatten between B and W. Figure 4 is a good example of such a trace. If one assumes that W is as indicated on the figure, then one does not know where to put the tangents to find D because the trace does not flatten between E and V, as in Figure 1.

Another method was needed to determine the electromagnetic length of the probes (D–W) for the bad traces (that behaved like the trace in Figure 4). Assuming that B–D was constant at different moisture contents and that the lowest point on the trace represented the end of the probe, then W could be found using tangents. B–D, determined from ideal traces, could be subtracted from B–W to give D–W. The average B–D length of 16 ideal traces was 15 cm with a standard deviation of ±3.1 cm. This average length could be used to determine the other cases by subtracting B–D from B–W (which is easily determined on the bad traces using tangents). The only problem was that the assumption was wrong, and B–D increased with increasing dielectric constant of the soil. For example, the lowest $K$ (5.5) from our ideal trace had a B–D length of 12 cm and the largest $K$ (23.9) had a B–D of 20 cm. Furthermore, the traces we have had problems with had a $K$ around 3 or less. Therefore our estimation was biased because we were taking a B–D for traces that had a $K$ greater than 5.5. Nevertheless, we used that value, knowing that $K$ would be underestimated at low moisture content ($\theta < 1\%$).

The transition zone for the 50-ohm line was much shorter. For example, the B–D length was 3 cm long instead of 15 cm, as with the 300-ohm line. This was due to the fact that the 300-ohm line had high electrical losses, and this was translated into a longer transition zone.

*Snow.* Tangents could not be used to determine the beginning and the end of the probe, which were actually in the snow. There was no detectable reflected pulse at the styrofoam-air or styrofoam-snow interfaces. This was due to the fact that the dielectric constants of the styrofoam (1.0), air (1.0), and snow (1.2–1.9) are approximately the same. An example of such a trace is given in Figure 5, where the styrofoam block is superimposed on the trace. The dielectric used was air.

Another method had to be found to calibrate the system. Specifically, it was necessary to locate points D and W which represent the beginning and end of the probe, respectively. The distances A–D and W–X were constant because the dielectric was always the same. Therefore any change in the dielectric property between D and W will be directly proportional to A–X. A is the point where the transition zone begins and therefore where the trace begins to rise. X is determined using tangents. To calibrate the system, we used air as the dielectric. The determination of D and W on the electromagnetic trace was done by short-circuiting the probe at those points. The distances A–D and W–X are then subtracted from A–X to obtain the electromagnetic length for the section of interest.

This was done for five probes with air as the dielectric. The average dielectric constant was 0.94 with a standard deviation of ±0.04. The short-circuiting method is not accurate. A correction factor of 0.06 was therefore introduced so that the dielectric constant of air would match the theoretical value of 1.0.

TABLE 1. Relative Complex Dielectric Constant as Measured by the TRD Method of Soil and Air for the 50-ohm Transmission Line for Spaced Probes Differently at Distal Ends.

| | Relative Complex Dielectric Constant | | |
|---|---|---|---|
| | | Fairbanks Silt Loam | |
| Spacing, cm | Air | 0%* | 43%* |
| 1.0 | 1.0 | 1.9 | 27 |
| 2.5 | 1.0 | 1.9 | 24 |
| 4.5 | 1.1 | 1.8 | 25 |
| 6.5 | 1.0 | 2.1 | 26 |
| triangle | 1.1 | 1.8 | 25 |

The probe lengths are 18 cm for the soil and 91 cm for the air.
*Volumetric water content.

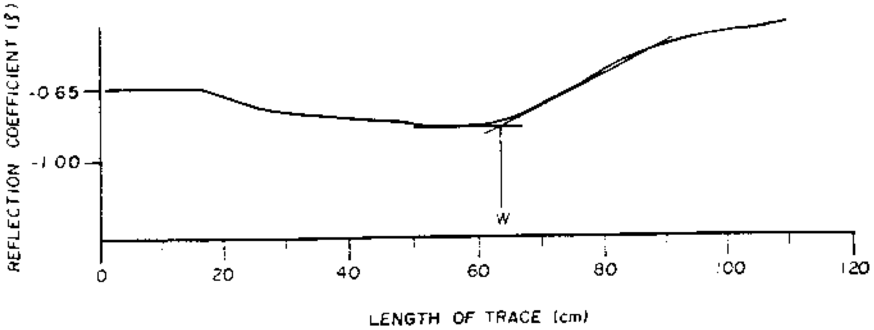

Fig. 4. Electromagnetic trace of a 300-ohm line (plot 2, April 29, 1981, 40 cm deep). As can be seen, the location of the tangents here is highly subjective and inaccurate.

### Field Experiments

*Soil.* Field data are presented here to show how the TDR technique can be used to monitor the unfrozen water content continuously in the field and to monitor snowmelt transmission in the soil. The variation of unfrozen water content at different levels in the soil using the 300-ohm line configuration is shown in Table 2 for three plots. Equations (13) and (11) were utilized for the organic horizon and the mineral soil, respectively. The underlined readings show the position of the wetting front resulting from snowmelt infiltration into the ground. The snowmelt infiltration or thawing at different depths can be easily detected on the control plot. The same effect was observed only at the first two depths in the two experiments plots. Because of the high ice content in the soil pores, snowmelt infiltration was effectively blocked.

The unfrozen water content determined October 10, 1981 by the TDR method (300-ohm line) was compared with gravimetric data taken 3 days after. This experiment was performed because the transition zones of the 300-ohm line were quite large and we wanted to see how accurate the results were. The average volumetric water content of the soil between 15 and 90 cm as determined by the 300-ohm line on October 10 was 15.7% with a standard deviation of ±3.5. The same average water content by gravimetric analysis was 17.9% with a standard deviation of ±3.9. This indicated that even with a bad line configuration, good results could still be obtained at high water contents. The total water content was underestimated by 2%. The TDR results of the 300-ohm line were not as accurate for unfrozen water content below 16% because of the difficulty in estimating $K$. This explains the negative results in Table 2.

Why did the 300-ohm line give bad results? The cable tester was a wide band time domain reflectometer that sends an electromagnetic pulse containing the frequencies between 1 and 1000 MHZ. The magnitude of the attenuation of those frequencies along the line depends on the physical characteristics of the line. The 300-ohm TV line is an unshielded parallel line; therefore the interference due to external sources is quite high and radiation of the electromagnetic wave is much higher. This results in greater attenuation of the signal along the 300-ohm transmission line relative to a 50-ohm coaxial line. This attenuation translates into a power loss and longer transition zones at the beginning and end of the probes. The error in this case could be reduced by using longer probes to decrease the ratio of the length of the transition zones to the total trace length.

For fall 1981 through spring 1982, Figures 6 to 9 illustrate the variation of unfrozen water content with time and depth using the 50-ohm coaxial line (Type 2). Each figure shows the decrease of unfrozen water content from October 31 to March 28 as freezing and cooling of the soil occurs. On April 28 the unfrozen water content starts to increase due to snowmelt infiltration into the seasonally frozen ground. Little thawing of the soil occurs at this time because the ice and infiltration water coexist in equilibrium at 0°C. The readings of May 17, reflect the thawing as well as the infiltration in deeper layers of the soil. The readings of July were done when the soil had completely thawed at the maximum depth of frost penetration. The values of moisture content for the plots were fairly high on July 1, since 3.8 cm of rain fell during the two preceding weeks.

*Snow.* *Smith and Patterson* [1980] plotted data of *Sweeney and Colbeck* [1974] on snow-water mixtures on Topp's curve (equation (11)). The snow data follow the curve but with more variability than the soil data. Figure 10 shows that the snow dielectric constant (a key factor for determining unfrozen water content) is independent of the snow temperature at high

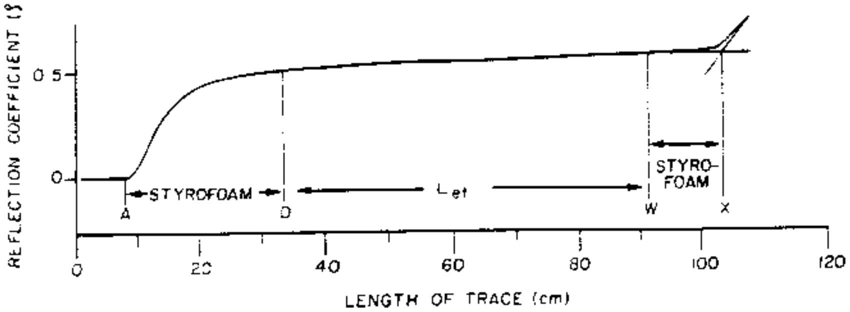

Fig. 5. Electromagnetic trace of a snow probe. Notice the reflected pulse at A and X and the lack of reflected pulse at D and W.

TABLE 2. Volumetric Percentage of Unfrozen Water Content for Various Soil Depths as Measured with the 300-ohm Line

| | Probe Depth Control Plot, cm | | | | | | | Probe Depth Plot 1,* cm | | Probe Depth Plot 2† cm | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Date | 5‡ | 15§ | 20§ | 25§ | 30§ | 35§ | 40§ | 5‡ | 15§ | 5‡ | 15§ | 20§ |
| Jan. 5, 1981 | −1 | 0 | −1 | 0 | 2 | 0 | 0 | 0 | 5 | 4 | 0 | 3 |
| Feb. 20, 1981 | −2 | 2 | 0 | 1 | (m) | 2 | 4 | 2 | 4 | 5 | 1 | 4 |
| March 13, 1981 | −1 | 1 | 1 | −1 | 1 | 0 | 2 | 2 | 6 | 4 | 1 | 1 |
| April 20, 1981 | 1 | 2 | 1 | 0 | 2 | 1 | 3 | 2 | 5 | 7 | 1 | 5 |
| April 21, 1981 | 1 | 2 | 2 | 1 | (m) | 0 | 3 | 34 | 6 | 12 | 0 | 7 |
| April 22, 1981 | 9 | 2 | 2 | 2 | 3 | (m) | 1 | 37 | 7 | 28 | 11 | 6 |
| April 24, 1981 | 22 | 8 | 0 | 1 | 2 | 0 | 2 | 47 | 7 | 34 | 12 | 6 |
| April 25, 1981 | 22 | 18 | 17 | 5 | 2 | 1 | 2 | 49 | 7 | 36 | 12 | 7 |
| April 26, 1981 | 21 | 25 | 25 | 21 | 7 | 1 | 2 | 46 | 9 | 35 | 10 | 5 |
| April 27, 1981 | 16 | 23 | 24 | 23 | 19 | 3 | 4 | 37 | 7 | 36 | 11 | 6 |
| April 28, 1981 | 16 | 25 | 24 | 23 | 25 | 9 | 3 | 39 | 8 | 40 | 10 | 5 |
| April 29, 1981 | 15 | 23 | 24 | 24 | 25 | 20 | 6 | 44 | 7 | 49 | 11 | 6 |
| May 1, 1981 | 14 | 23 | 24 | 24 | 27 | 20 | 7 | 42 | 7 | 50 | 10 | 7 |
| May 7, 1981 | (m) | 5 | 27 | 27 | 28 | 18 | 12 | 31 | (m) | 37 | 33 | 7 |

The (m) indicates a missing value.
*3.8 cm of water added.
†6.25 cm of water added.
‡Organic soil.
§Mineral soil.

snow temperatures (near 0°C). This happens because a large range of moisture contents can exist when the snow is at 0°C during the melting process. This is due to the time history of the snow from a temperature and a liquid content point of view [*Colbeck*, 1982]. Density is another important factor in the determination of unfrozen water content of snow using the TDR technique. We wrongly thought that, like that of a soil, the snow density is not important and by just measuring the dielectric constant of the snow, one could find its unfrozen water content using Topp's relationship. We also expected only one unfrozen water content for each temperature. This might be true for low temperature but not at 0°C. We were led astray because we thought that the data plotted by Smith and Patterson had different snow densities and also had different temperatures. The data of *Sweeney and Colbeck* [1974] reveal that the snow densities were high and situated around 0.68 and the temperature of the experiment was also constant at 0°C. *Ambach and Denoth* [1980] plotted some data expressing the variation of dielectric constant with the dry snow density (Figure 11). From that figure, we could infer that even without water, the snow dielectric constant would have a large variation due to its density only. Furthermore, the dielectric constants of the snow are all below 2.0, which precludes the use of Topp's relationship. Data where we had the snow density available (Fairbanks) were plotted on Figure 11, and they appear to be a good fit to the line. *Ambach and Denoth* [1975] suggested the relationship

$$\theta_{uf} = \alpha[(K' - 1) - 2.22\,\rho] \tag{14}$$

where

$\alpha$ proportionality factor;
$\theta_{uf}$ volumetric water content of snow;

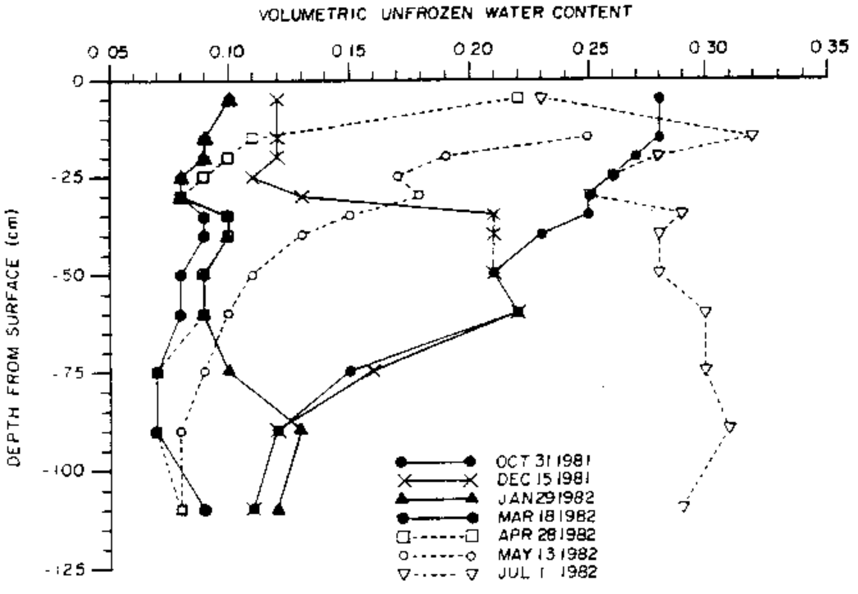

Fig. 6. Water profile of control plot.

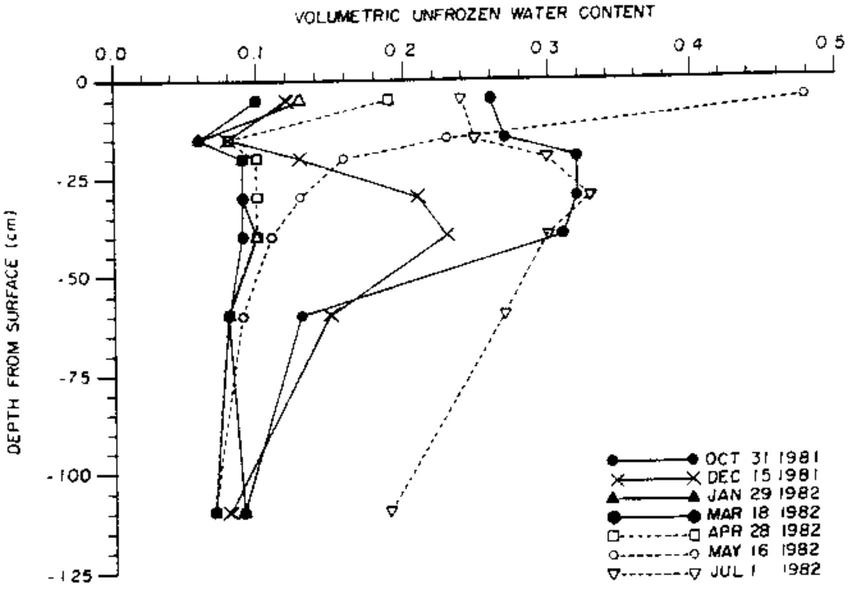

Fig. 7. Water profile of plot 3 (1.25 cm of water).

$K'$ real part of dielectric constant at a frequency higher than 20 MHz;

$\rho$ snow density.

Knowing the proportionality factor and the snow density, the volumetric water content of the snow could be easily determined by measuring $K'$ with time domain reflectometry.

As snowmelt proceeds, Figure 12 shows the increase in the dielectric constant at every level. This increase was probably due to the increase of liquid water content and also from the increase in snow density due to melt metamorphosis. The reference level is the soil surface.

### *Suggestions About Transmission Line Design*

*Spacing of parallel probes.* The maximum spacing between the center of the probes is dependent upon the wavelength of the electromagnetic signal. The spacing should always be smaller than a tenth of the wavelength, otherwise higher than transverse electromagnetic modes will occur [*Davis and Chudobiak*, 1975] and (6) will not be valid. The soil located at twice the spacing between the probes has a negligible effect on $K$ [*Davis and Chudobiak*, 1975]. The volume sampled is approximately equal to the square of the spacing between the probes [*Topp et al.*, 1982*a*]. The shape of volume sampled is probably similar to a flattened cylinder with an ellipsoid cross section.

*Probe length.* Probes as long as 100 cm were used by *Davis and Chudobiak* [1975] and as short as 12.5 cm by *Patterson and Smith* [1980]. If the probes are too short, then the transition zone lengths (A–E and V–Z, Figure 1) are long relative to the trace length for the probes (D–W, Figure 1) and $L_{et}$ is determined less accurately. Longer probes increase sample size, but the attenuation increases too. This may lengthen the transition zone at the end of the probe. We used probes 18 cm long the first year and 46 cm long the second year.

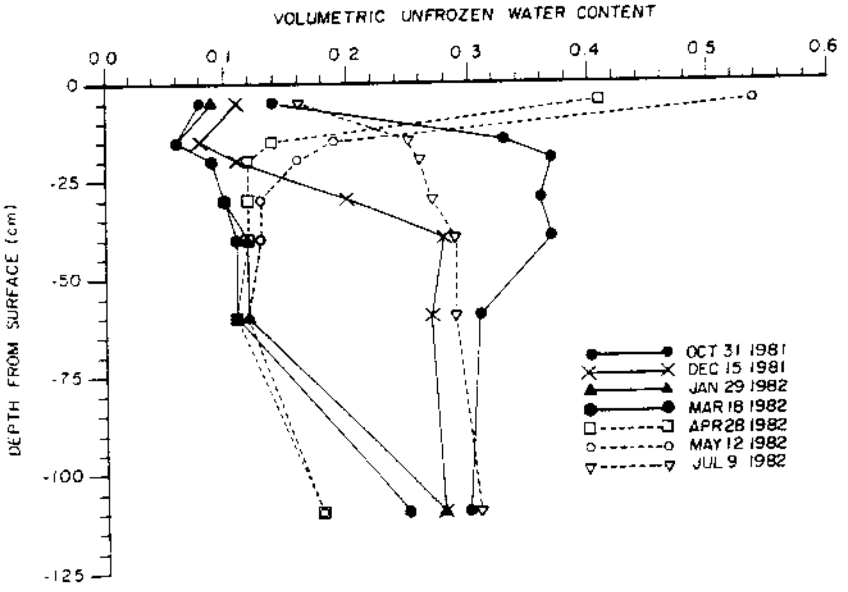

Fig. 8. Water profile of plot 2 (2.5 cm of water).

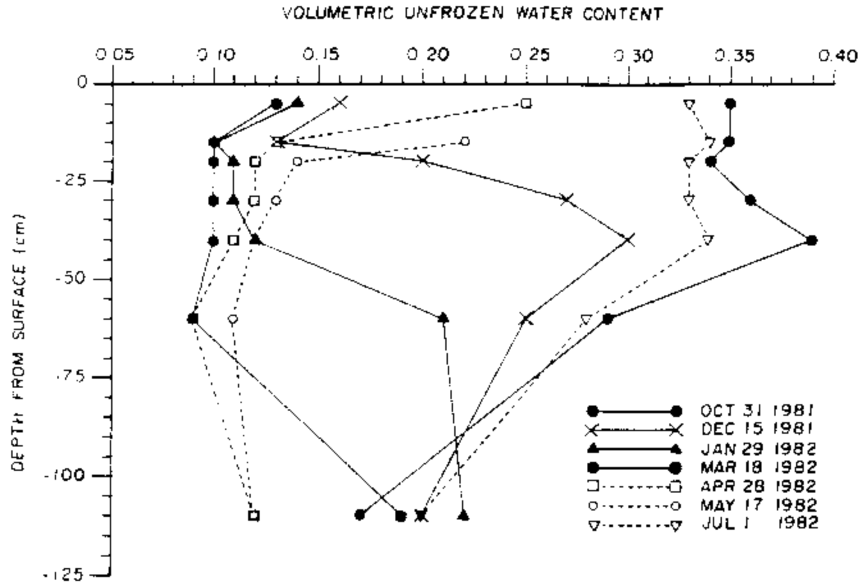

Fig. 9. Water profile of plot 1 (3.8 cm of water).

*Balanced versus unbalanced lines.* *Topp et al.* [1980] used balanced lines. We used unbalanced ones, and the results in Figure 3 seem to be practically the same. The coaxial cable at the junction of the 50-ohm line and the parallel probes was split for 5 cm. After the connection is made, we suggest that some silicone glue or tape be put on the split cable to decrease the influence of water content on that part of the line and also to decrease the chance of short-circuiting the probes.

*Insertion in the ground.* As noted by *Davis et al.* [1977], the probes should be installed with excellent soil contact to avoid lower values in *K* due to the presence of air between the probe and the soil. Holes should be drilled if the soil is rocky. Whether or not pilot holes were used, the soil densities were lower between the probes when the soil was packed around the probes [*Topp et al.*, 1982*a*]. The fact that we used probes having a diameter three times smaller than Topp et al. minimized the problem of increased soil density adjacent to the probes. When the transmission line is connected to the probes for the electrical connection, they should be flush with the beginning of the probes; otherwise it will generate a longer transition zone.

*Horizontal probes versus vertical probes.* For continuous measurement of the dielectric constant year round the probes should be installed horizontally to minimize both thermal and hydraulic disturbances of the soil by the instrumentation. Thermal disturbance is minimized because with the horizontal arrangement the transmission line can be run over a certain distance in the soil and away from the probe before it surfaces to the air. The transmission line can then be warmed up or cooled down by the soil before the heat wave reaches the probes. Hydraulic disturbance is minimized by running the transmission line below the level of the probes for awhile; this permits the water that might flow along the line to percolate downward before it reaches the probes. The horizontal arrangement of the probes has three significant technical advantages over vertical installations. First, the moisture content

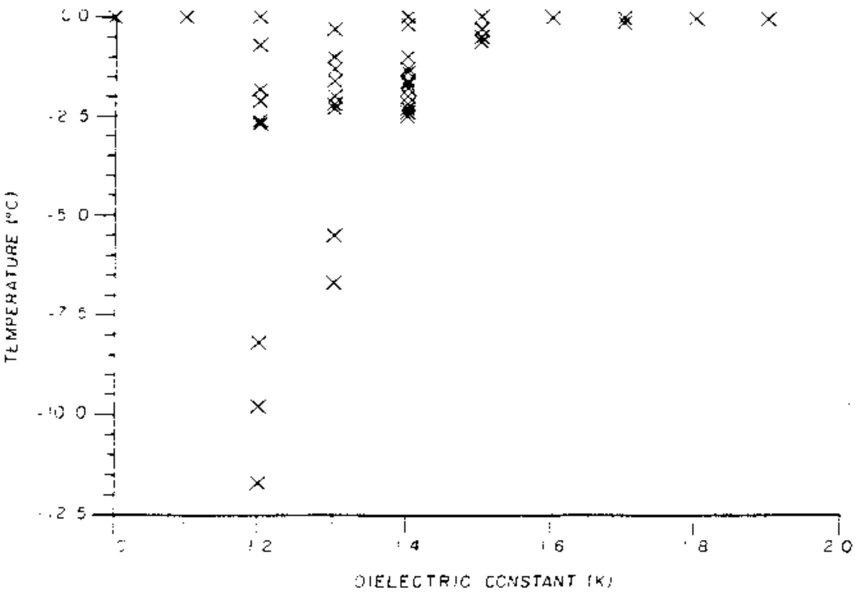

Fig. 10. Variation of snow dielectric constant with snow temperature in degrees Celsius.

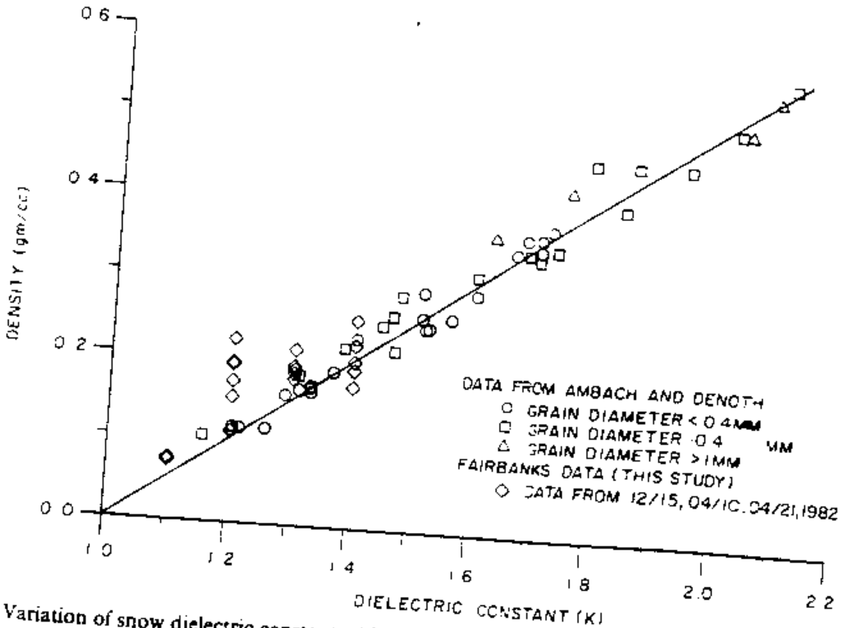

Fig. 11. Variation of snow dielectric constant with snow density (adapted from *Ambach and Denoth* [1975]).

can be determined over a much narrower vertical band of soil. Second, resolution with depth is not sacrificed. Third, the sample size or the length of the probe has no set limits. The method of horizontal installation does require more time for installation. Care should be taken during the back-filling operation of the pit to insure proper compaction and drainage patterns similar to undisturbed areas.

## CONCLUSIONS

From *Smith and Patterson* [1980], we know that Topp's relationship (equation (10)) can be used to obtain a point measurement of unfrozen water content in a frozen soil. It is obvious that if the technique is to be used for continuous measurement, then the probes must be installed horizontally to minimize hydraulic and thermal disturbances. The length of transmission line to be run in the ground to minimize thermal disturbances depends on meteorological conditions, soil thermal characteristics, and also on the snowpack depth. Some experiments could be done to quantify these factors. Also, the horizontal method of probe installation could lead to both more precise and accurate determination of the soil moisture content in a vertical soil profile. The above statements are derived from theoretical considerations. The 50-ohm coaxial transmission line is recommended over the 300-ohm TV line because it resulted in a more accurate measurement of $K$ resulting in a better prediction of the moisture content.

We have successfully applied this technique to the monitoring of snowmelt infiltration into seasonally frozen soils under a variety of soil moisture conditions. This technique could also be used to monitor the unfrozen water content in a snowpack. For soils the relationship between the volumetric water content and dielectric constant is essentially independent of density; this is not true when snow is the dielectric material.

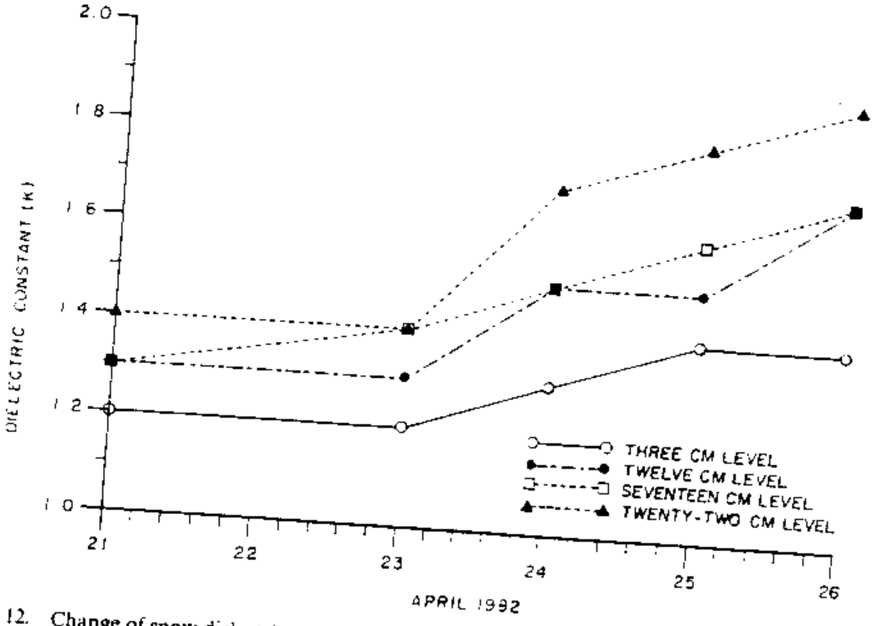

Fig. 12. Change of snow dielectric constant at different levels above soil-snow interface with time.

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# Monitoring the Unfrozen Water Content of Soil and Snow Using Time Domain Reflectometry

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