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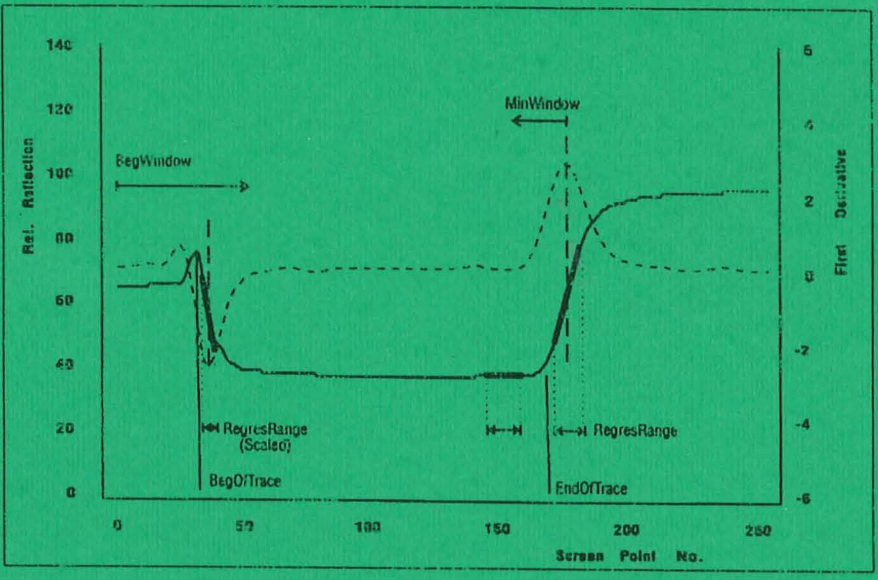

MSc Thesis (Examensarbete)
Supervisors (Handledare) **: Per-Erik Jansson & Manfred Stähli**

Institutionen för markvetenskap
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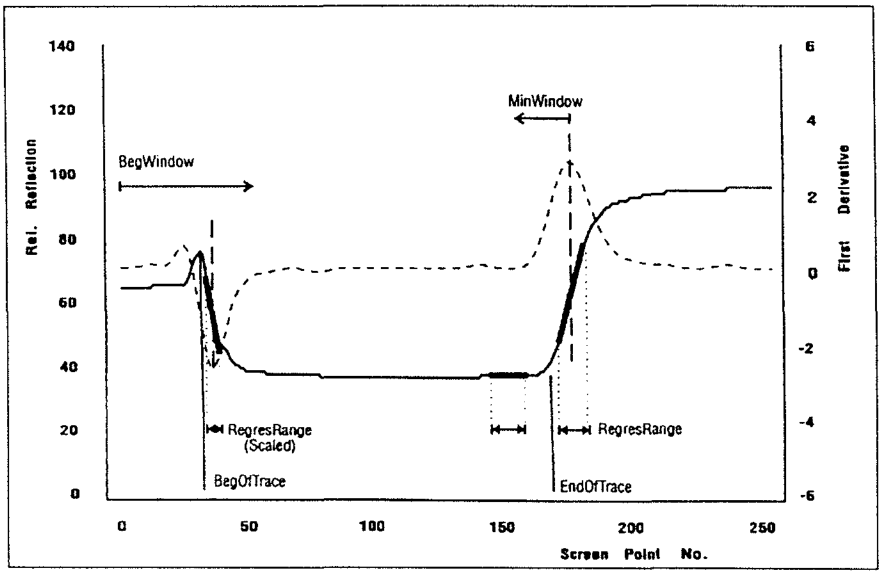

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PREFACE

This is the report of my diploma work of a master degree in soil science at the Swedish University of Agricultural Sciences (SUAS). The work was mainly conducted at the Division of Environmental Physics during twenty weeks, in summer -96 and during the following winter. During this time a system for measurement of soil moisture, a technique known as Time-Domain Reflectometry, was tested, in laboratory as well as in field with respect to sources of errors. A few of the components of the systems tested had earlier been used by researchers at the Department of Soil Science while other components were newly purchased. I hope that this work can give some help to recognize and avoid some sources of errors that occur in TDR soil moisture measurements.

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ABSTRACT

In the monitoring of soil water Time-Domain Reflectometry (TDR) has gained widespread use. TDR has proved to be useful both in determination of soil water content and soil bulk electrical conductivity. These measurements are, however, complex and there are many sources of errors to consider. The purpose of this investigation is therefore to identify errors, the causes of these errors and to suggest improvements. This was achieved by a literature study as well as by two experiments, one conducted in the field and one conducted in the laboratory. Four TDR-systems were tested.

The results show that errors can be classified in two groups, errors which is influencing the determination of the dielectric constant, K_a, and errors affecting the conversion of K_a to volumetric water content, θ_v. The former type can be further divided into errors which concern the quality of the trace and errors influencing the evaluation of the trace. Unbalanced probes and long cables were identified as contributing to uncertainties. Errors from conversion of K_a to θ_v were considered when the systems were calibrated. One of the programs tested allows convenient one-point calibration with a trace offset parameter. The advantage of re-evaluation of measurements with individual settings also permits increased accuracy of measurements.

REFERAT (in Swedish)

Time-Domain Reflectometry (TDR) har vid markvattenmätningar fått en omfattande användning. TDR har visat sig användbart både i vattenhaltsbestämningar och för mätning av markvattnets elektriska konduktivitet. Mätningar med TDR är dock komplexa och det finns mänga felkällor att beakta. Syftet med den här undersökningen är att identifiera fel, felkällor samt att föreslå förbättringar i systemens design för att undvika felkällor. Detta gjordes dels genom en litteraturstudie och dels genom två experiment, ett i fält och ett i laboratorium. Sammanlagt undersöktes fyra TDR-system.

Resultaten visar att fel kan klassificeras i två grupper, fel som påverkar bestämningen av permitivitetskonstanten, K_a, och fel som påverkar konverteringen av K_a till volumetriskt vatteninnehåll, θ_v. Den förra gruppen kan vidare delas in i fel som rör kvalitén på mätsignalen och fel som påverkar utvärderingen av denna signal. Obalanserade givare och långa kablar var indentifierade till att bidra till osäkerheter i mätningar. Felkällor när K_a omvandlades till θ_v diskuterades när systemen kalibrerades. Ett av utvärderingsprogrammen som användes har en "trace off-set" parameter för enkel enpunktskalibrering av mätsystemet. Möjligheten att analysera mätsignalen i efterhand med individuellt satta parametrar ökar också nogrannheten i mätningarna.

INTRODUCTION

Water is essential for human existence. Vital human activities carried out for a long time such as agriculture, forestry and drinking-water supply depend completely on the availability of water. Late in human history industrial activities have also started to consume large amounts of water. These activities have, together with the urban structure of building areas and roads, the use of artificial fertilisers and pesticides in agriculture influenced the availability and the quality of water. Water, and particularly clean water, has become a scarce resource in many parts of the world. Water is, furthermore, both an outstanding solvent and a transport medium for nutrients and other potential pollutants. The monitoring of water has therefore gained increasing interest.

Soil water is of special interest due to the storage of water available for plants and as the stage in the water cycle where the chemical composition changes due to interactions with soil before reaching groundwater, streams, lakes and seas (Figure 1).

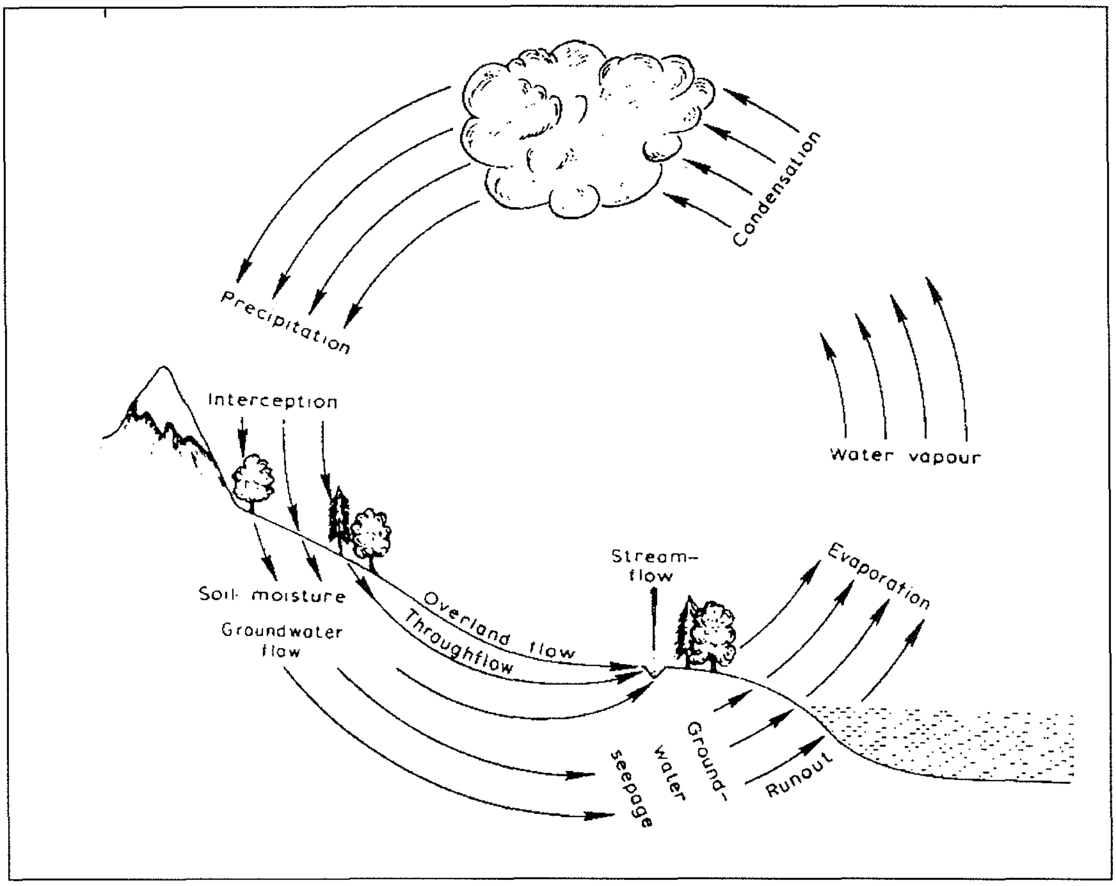

Figure 1. The water cycle (from Ward and Robinson, 1990).

The capacity of soils to store water is also determined by the composition of the soil (i.e. texture and structure) and by processes which control the movement of water through the soil such as drainage, evaporation and transpiration. These processes take place at different depths in the soil and this is important to consider when soil water content is to be estimated. The rates of these processes are then influenced by different factors such as climate, topography and vegetation.

The major change in chemical composition of water in the hydrological cycle also takes place in the soil. This is a result of the fact that soil water in the root zone dissolves carbon dioxide that is released from the respiration of plant roots. In other words, the soil water is acidified. This increases the weathering of minerals and results in an increasing content of dissolved ions in the soil water. On arable land, the application of fertilisers and pesticides also further increases the concentration of solutes in soil.

Many methods to determine soil water content are both labour-intensive and time - consuming. Sampling of soil cores for gravimetric determination of soil water content requires both a lot of digging and when the samples are taken the site is ruined for further sampling. The method is therefore destructive. The neutron probe method is, in contrast, a less demanding but on-site calibration is needed and the radiation from the instrument poses a health risk. Remote radar sensing techniques are also convenient and cover large areas, but do not account for the deeper parts of the soil (Kutilek, 1994).

A preferable method to measure both soil water content and soil bulk electrical conductivity should be continuous and non-destructive. It should also measure at many depths ranging from the surface to the groundwater level. This can be achieved by measurements of the dielectric property of soil (Davis and Annan, 1977). The dielectric property is primarily a function of soil water content (Topp et al., 1980). It has also shown to be a useful estimator of soil bulk electrical conductivity (Giese and Tiemann, 1975). Techniques that are based on measurements of the dielectric property of soil are traditionally called capacitance methods. Time-Domain Reflectometry (from here on referred to as TDR) is a method that has gained widespread use and is both suitable to determine the water content and the electric conductivity of the soil water (Topp et al., 1980; Heimovaara, 1992).

There are several advantages of TDR in measurements of soil water content and soil bulk electrical conductivity compared to other methods:

- direct measurements of a soil property that is primarily a function of water content and electrical conductivity of soil water
- non-destructive
- high spatial and temporal resolution
- continuous measurements through automated systems
- allows flexible system design

The practical use of TDR for monitoring of soil water is also considerable. TDR is used in estimation of water storage for crops in yield analysis, flood control, monitoring of water fluxes, detection of pollutant solute transport, determination of salt influences in soils including arable land and in the monitoring of leaching from landfills and landslide activities (Topp et al., 1980); (Mallants et al., 1994); (Aimone-Martin and Oravecz, 1994). Nevertheless, TDR measurements are complex and in order to operate successfully there are many sources of errors that must be considered.

The aim of this study is therefore to clarify the sources of uncertainties in measurements by classification of errors and by examining how different components contribute to these errors. Suggestions on how to improve the measurements are also given. Two experiments with four different TDR-systems were conducted. In one of these experiments, two software programs were used in the evaluation of the measurements.

Three questions were asked:

1. What type of errors give uncertainties in the systems examined?

2. What components in the systems contribute to these errors in the measurements of soil water content?

3. Which of the software programme used gives the most reliable and easiest evaluation of the soil water content measurements?

BACKGROUND

The following paragraph is concerned with the development of the TDR-technique as well as some examples of the use of TDR measurements at the Department of Soil Science at the Swedish University of Agricultural Sciences (SLU). The latter also includes a discussion of some problems to operate that led to this study.

History of dielectric measurements of soil water

Measurements of dielectric properties to estimate water content in soils is not a new idea. This was suggested, in literature, already in 1939 (Patterson and Smith, 1980). During the 1960's and the 1970's many attempts were made to use dielectric properties for estimation of water content in soils (Davis and Annan, 1977). The instruments used, however, were originally designed to test electric cables and was operating in frequency ranges where the dielectric property is frequency dependant. Consequently, accurate measurement of soil water content, θ_v, was prevented (Topp et al., 1980). However, in 1980 instruments that operated on a lower frequency range (1-1000 MHz) where the dielectric property of soil is not strongly frequency dependant began to be used (Topp et al, 1980). The technique operated was referred to as TDR and is, in principle, similar to a well-known technique, RADAR. A difference between traditional capacitance methods used to measure dielectric properties and TDR is that while the former operates on a single frequency, the latter uses a wide spectrum of frequencies. This also decreases the influence of frequency dependants of the dielectric property which provide more accurate measurements in soils of various water contents (Patterson and Smith, 1980).

The dielectric property, furthermore, had earlier been described as a complex constant, composed of a real part and an imaginary part where the imaginary part corresponds to dielectric losses (Davis and Annan, 1977). For materials with low losses, such as soil, the imaginary part was also shown to be negligible and the real part can be approximated to a measurable apparent dielectric constant, K_a (Topp et al., 1980).

The relationship between K_a and θ_v

General equations

An empirical relationship between the apparent dielectric constant, K_a, and the volumetric soil water content, θ_v, was given by Topp et al. (1980). Four soils, a sandy loam, two clay loams and a heavy clay was examined. The TDR measurements conducted were correlated with gravimetrical soil core samples. The relationship gained is useful in general for most soils (Topp et al., 1980).

$$\theta_v = -0.053 + 0.0292K_a - 0.00055K_a^2 + 0.000043K_a^3 \qquad \text{eq. (1)}$$

where θ_v is the volumetric water content (-)
and K_a is the apparent dielectric constant (-)

The validity of TDR as a method for measuring soil water content in non-uniform soils with steep gradients were also examined by Topp et al. (1982a). Three cases were examined, a two-layer model, a general water content gradient with a more stratified and continuous gradient and the detection of a water-front in an infiltration event. For all cases TDR was shown to be a useful method for measuring soil water content.

TDR is, as the name suggests, built on the principle that a brief electromagnetic pulse is sent along a transmission line and reflected. The measurements are then conducted in the time-domain. Ledieu et al. (1986) determined the soil water content directly from the transit time of the electrical pulse and discovered a simpler relationship.

$$\theta_V = 5.69t - 17.58 \qquad \text{eq. (2)}$$

where t is the travel time for the pulse along the probe (ns)

The relationship is further improved when soil bulk density is considered. An change of 0.1 g/cm3 in bulk density was shown to give a change in soil water content of 0.34 %. (Ledieu et al.,1986)

$$\theta_v = 5.688t - 3.38\delta - 15.29 \qquad \text{eq. (3)}$$

where δ is the soil bulk density (g cm^{-3})

The dielectric constant, K_a, is primarily determined by the dominant material in the soil. A general relationship between K_a and soil water content was derived by Roth et al. (1992) from this starting point. The dielectric constant for organic soils was concluded to be lower than that of mineral soils at a corresponding soil water content. In other words, bulk density is a significant factor to be considered when K_a is estimated. A third degree polynomial relationship was found for 11 mineral soils and another similar equation was calculated for 7 organic soils.

Among the mineral soils, furthermore, special attention was given to a Ferralsol in order to examine whether magnetic properties influence TDR measurements or not. It was shown that magnetic properties from minerals, i.e. magnetite and maghemtite, hardly influence the measurements because of the very brief travel time of the TDR pulse.

To summarize: A general relationship between K_a and θ_v is useful for most soils. The dominant material of the soil, however, determines K_a and consideration of soil bulk density improves the relationship, especially for organic soils.

Mixing models

Dirksen et al. (1993) proposed, with a similar starting point as Roth, that tightly bound water is a factor to consider when a relationship between K_a and soil water content is determined. The tightly bound water was estimated to have a much lower dielectric constant, in the same range as ice, other than free water. Tightly bound water was considered by using two four-component mixing models. One of the mixing models was empirical and the other was theoretical. Both were compared with equation 1 for 11 soils including loess as well as bentonite (Figure 2). The theoretical mixing model gave a better calibration function than equation 1 at lower values of soil bulk density and for fine textured soils that hold tightly bound water. The empirical model gave unpredictable values and did not seem to be useful even when fitted data was used.

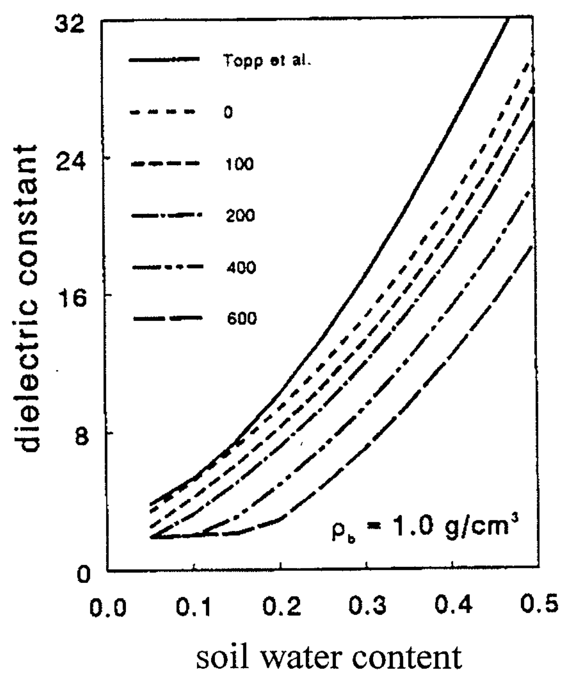

Figure 2. Influence of tightly bound water as specific surface vs. soil water content according to the theoretical mixing model used by Dirksen and Dasberg. The soil bulk density was set to 1.0 g cm^{-3} and the specific surface, S = 0, 100, 200, 400, 600 m^2 g^{-1}. Equation 1 is also shown, referred to as Topp's equation, in the figure (from Dirksen and Dasberg, 1993).

Jacobsen and Schönning (1993) compared different calibration functions, including physical mixing models, for five soils from coarse sandy soil to sandy clay loam. From this one set of data it was also shown that the most suitable third-order polynomial equation gave more accurate soil water contents than any of the mixing models. For precise measurements for individual soils, however, one theoretical mixing model was better than any of the third-degree polynomial equations.

Nevertheless, a calibration function that included the effect of soil bulk density did not improve the fit compared with earlier relationships presented by Jacobsen et al. (1993). The calibration, however, was conducted for field plots at three locations and was shown to be better than equation 1. It was also shown that the variation of the measurements increased with increasing clay content.

Hook et al. (1995) investigated temperature effects on the dielectric electric constant. Four soils: peat, sand and two loams were compared considering the soil water content using a mixing model. The model was calibrated by measurements on distilled water. The temperature dependency was shown to increase with increasing water content in soils. It is also at high water contents where changes in temperature can cause the largest errors. The influence of temperature was however smaller for free water than for tightly bound water. A temperature correction coefficient was also suggested (see Hook et al., 1995 for details).

To summarize: The dielectric constant, K_a, is influenced by soil properties such as temperature, bulk density, tightly bound water and soil bulk electrical conductivity. The influence of these soil properties has been considered as single parameters in empirical equations and by several variables in so called mixing models. Mixing models have in some cases been shown to improve calibration functions. When absolute values of θ_v are needed, calibration for individual soil-types is required.

Soil bulk electrical conductivity

Measurements of electrical conductivity in soil water by TDR have also gained widespread use. Dalton et al. (1984) was among the first to use TDR to measure soil bulk electric conductivity but did not take multi-reflections caused by discontuintues in cables used into account. Topp et al. (1988) concluded that the approach of Giese and Tiemann (1975) gave the most satisfying results.

Measurements of solute breakthrough curves were conducted by Mallants et al. (1994). Horizontally installed TDR probes which measured bulk soil electrical conductivity in saturated soil columns in a laboratory were used and shown to be useful. However, it was concluded that many TDR probes are necessary, especially for structured soils, to follow the breakthrough event accurately. This is because of the fact that the probes measure a rather small area and the risk of excluding a macropore with high transport velocity is obvious.

That the same TDR-system simultaneously can measure both soil water content and electrical conductivity was also shown by Nadler et al. (1991). The measurement of electrical conductivity was also considered less sensitive than water content determination since the contact between the probe and the medium is not crucial in the former case.

TDR in frozen soil

TDR has also shown to be useful in frozen soil and snow to detect unfrozen water (Patterson and Smith 1980; Stein and Kane 1983). The apparent dielectric constant, K_a, for ice is 3.2, which is very similar to that of dry soil but significantly lower than that of unfrozen water (82 at 20°C). K_a has also been shown to be a good indicator of the relationship between unfrozen and frozen water in the soil at temperatures below 0 °C. Patterson and Smith (1980) showed that the unfrozen soil water content corresponded well when the soil water content obtained by equation (1) was compared with the result gained from another method, dilatomery.

Salt distribution in a freezing soil was examined by Stadler and Stähli (1997). This was accomplished by exposing two columns, one sand and one loam, to a freezing and thawing event. The flow of water was directed towards both ends of the columns during the freezing event but was opposed by diffusion towards the middle where the salt concentration increased. In the frozen part of the soils, the low content of salt was also only just detectable by TDR. The concentration of solutes in frozen soils was moreover said to be determined by this diffusion with the appearance of high concentration gradients and in addition the content of unfrozen water.

The salt concentration was calculated as a function of temperature, soil bulk electric conductivity and the unfrozen soil water content according to the model of van Loon et al. (1991). The function was also shown to be useful for low salt concentrations of unknown ions, a situation which is similar to that expected in most field conditions.

Development of components

The components of the TDR-system have, of course, been modified and improved during the evolution of the TDR-system. This concerns especially the system's sensing device, the probe. Furthermore, automated systems with multiplexed connections from the main component of the system, the cable tester, allowed the use of many probes. Software programs to co-ordinate these automated measurements and to evaluate the measurements have also been developed.

Probes and probe-design

The two most common probe-types are the two-wired and the three-wired. The probe is connected to the rest of the system by a coaxial cable, a cable with two leads. In a three-wired probe the centre cord of coaxial cable is connected to the middle of the three rods and the outer conductor is divided between the other two rods. This configuration makes the electromagnetic field symmetrical and the probe is said to be balanced. Signals from three-wired probes are in general clearer and easier to interpret than signals from unbalanced two-wired probes (Nadler et al., 1991). A device that balances two-wired probes is the balun, which will be further discussed in the paragraph instrumentation.

The probe length is one aspect of system-design that determines the soil volume measured. In other words, the soil water content is determined as an average of the probe length. In combination with long cables, which give a more significant signal attenuation, the use of short probes results in signals which are difficult to interpret. Heimovaara (1993) tested the maximum cable length for different probe lengths. For probes longer than 0.2 m, 24 m cables could be used. For probes shorter than 0.1 m the maximum cable length which gave an acceptable quality of the signal was 15 m. Stein and Kane (1983) explained the uncertainties occurring when short probes lengths were used with the fact that the transmission zone (where the change in electrical properties from the cable to the probe-wire take place) between the cable and the probe becomes long relative to the probe length. As a consequence, K_a is determined less accurately.

The electrical field that is created between the rods determines the volume of soil measured. Baker&Lascano (1989) found the cross-area, which primarily influences the measurements, to be rectangular with elliptical corners and of about 1000 mm^2. Ledieu et al. (1986) found that accurate measurement of soil moisture was possible with two-wired probes with 2,5 cm between the rods, in layers of 4-5 cm thickness. The maximum distance between the probe-wires is also dependent on the wavelength of the electromagnetic signal and should be smaller than a tenth of this wavelength. This prevents transverse electromagnetic modes that would interfere with the propagation velocity's relationship to K_a. (Stein and Kane, 1983). The volume sampled is nearly the square of the distance between the rods (Topp et al., 1982a). The shape of this volume is furthermore likely to be an ellipse-shaped cylinder.

The diameter of the rods also influences the robustness of the probe. This, of course, is a practical aspect when probes are to be installed and when for example a hammer is used to push the rods in to the soil. However, if probes with a thick rod diameter are used, there is a risk of increasing soil density around the rod. Topp et al. (1982b) obtained a lower soil density when the soil was packed around the probes than when probes were pushed in to the soil.

Another aspect which has to be considered is the angle effect that can be expected when the separate rods of the probe are not installed parallel. This would theoretically influence the measured soil volume and therefore K_a. According to results from Stein and Kane (1983) it is not, however, very important that the rods are installed exactly parallel. In soils with high soil water content (θ_v = 40 %) no difference in measured K_a due to angle effects was detected. Nevertheless, when very dry soil (θ_v = 0 %) was examined K_a differed slightly ($\pm$ 0.2).

Installation of probes in the soil needs to be done in a way that ensures good soil contact to prevent air between the probe and the soil lowering the K_a-values. Pre-drilled holes can in this context be a risk but are in some soils (e.g. rocky soils) inevitable. Probes can also be installed at any angle in the soil. Most common are horizontally and vertically installed probes. Vertically installed probes are inserted from the surface and are therefore more convenient. Horizontally installed probes, however, give smaller thermal and hydraulic disturbances than vertically installed probes (Stein and Kane, 1984).

Interpretation of a trace is easier and more accurately carried out if the probe is designed in a way that gives sharp changes in impedance. The beginning and the end of the trace are characterised by transmission zones where a gradual change in the reflection coefficient take place due to: power losses, imperfect connections between conductors and rods and a non-ideal open circuit at the end of the probe (Stein and Kane, 1983). The transmission between the conductors in the cable and the rods are usually sieved. This gave a more distinct transmission zone probably due to lower losses by multi-reflections (Thomsen, 1997). Another way to obtain a clearer signal is to connect the two transmission lines, at the same place, by using two diodes (Ledieu et al. 1986).

The probe head should to consist of a material in which no reflections are created which disturb the signal such as resin or epoxy cement for use in electrical devices. The head is, furthermore, often made of materials such as POM (polyacetal-Acetal plastic) which is a material with suitable electrical properties and high resistance to changes due to temperature fluctuations and UV exposure (Thomsen, 1997).

System considerations

Hook et al. (1992) hooked up diodes between the conductors and designed a low-loss probe that allowed measurements with clear signals to be conducted with a cable length up to 100 m. Different cables were compared concerning rise time of the pulse by Hook and Livingstone (1995). A coaxial cable of 75 ohm was shown to have a better rise time than the one often used 50 ohm cable (RG58). In addition, it has a thinner diameter and costs less than the latter. Measurements in a strongly layered media were also carried out with excellent accuracy with three-diode probes.

Propagation velocity errors were identified and quantified by Hook and Livingstone (1995a) using a newly developed TDR-technique including remotely switched diodes and differential wave form detectors. They concluded that dissolved ions and the use of long cables are the most significant sources of errors.

Errors in converting TDR measurements of propagation velocity to estimates of soil water content were examined by Hook and Livingstone (1995b). By using a simple physically-based model, the linear relationship between T/T_{air}, the ratio of the travel time for the pulse in soil over the travel time in air, versus θ_v, was examined. In some cases, the deviations from linearity corresponded to the delay in travel time. It was shown that the main component contributing to errors of conversion in agricultural soils (except clays) was the measurement of the transition time. The transition time is a function of θ_v. A value of the T/T_{air} - θ_v slope was also presented.

Automated systems

Systems to measure large numbers of probes automatically have been developed (Heimovaara, 1996). Campbell (1991) described a system with a logger and a maximum of three levels of multiplexers which allow measurements of up to 512 probes. A PC-based system that measures 49 probes was described by Thomsen (1994). Automated systems are made up of components that need to be co-ordinated in time for successful measurements. This is done by a software computer program. The software program is in turn operated from either a logger or a PC. An interface i.e. a device which handles the communication between logger/PC and cable tester is also required for automated measurements.

TDR measurements at the Department of Soil Sciences, SLU

Stähli and Fryklund (1995) used TDR to observe infiltration in washed sands used in biological water treatment systems. Different equations such as Topp (1980) and Ledieu (1986) were compered with gravimetric core samples. Topp was shown to have a better fit at low water contents in the examined sands. Andersson (1994) used TDR to determine if the time of sowing influences water uptake for barley. Two different TDR techniques and a neutron probe were compared. A stationary TDR system was found to work better than a portable system and both were considered more reliable and user-friendly than the neutron probe. Conversion of dielectric constant to soil water content with equation (1) gave significantly lower water contents than expected. It was concluded that calibration was necessary for reliable estimation of absolute values of soil water content.

Stähli (1995) also used TDR to follow infiltration events in frozen soils. Two sandy soils have been monitored by TDR and measurements have been conducted since 1994 (Stähli, 1997). These set-up's were the same as used in experiment 1 in this paper. The measurements were, however, subjected to a number of errors and problems. The evaluation of the data from the automated system, described as system A, in the chapter 'Material and methods', was unreliable on some occasions. Time-consuming manual evaluation was then required. The idea of this study was therefore to investigate what the causes of these uncertainties were and to identify other sources of errors that occur in TDR-measurements which concerns several researchers at the department. Components for a laboratory set up had, furthermore, been purchased to design a TDR-system for precise measurements for soils used in teaching. The intention to use these components in a laboratory set-up for determination of physical properties of different soils at the Department of Soil Sciences led to a study trip to, Foulum Research Centre in Denmark where a new software program for evaluation of TDR-measurements was demonstrated. This software program was then compared with a program used for several years in an experiment.

METHODS AND MATERIAL

TDR-measurements are as mentioned rather complex. In this paragraph the theory of the measurements is described. This includes the principle of TDR as well as capacitance theory and TDR-theory (the relationships used directly in the measurements). Instrumentation is also discussed when the function of different components is explained. The experimental set-ups are also described.

Theory

Principles of Time-domain reflectometry

Time-domain reflectometry belongs to the capacitance methods for measuring soil water content. The method measures continuously and non-destructively a change in voltage over a brief period of time on permanent soil-installed wave guides or probes. This is accomplished by the transmission, the reflection and the detection of a brief electrical pulse.

First, the electromagnetic pulse is produced by a pulse generator in the cable tester, the main component of a TDR-system. Then the signal travels through a transmission line and reach the probe (Figure 6). At the transmission point between the cable and the probe the electrical properties of the media surrounding the conductor changes. As a consequence a part of the electrical pulse is dissipated in the soil and another part of the pulse is reflected back along the transmission line. The proportion dissipated to the soil is related to the electrical conductivity while the travel time of the pulse along the probe is a function of the water content of the soil.

Finally, the reflected signal travels back and is detected on an oscilloscope on the cable tester. The event is recorded as a time -voltage plot on the oscilloscope. K_a is interpreted from the travel time of the pulse along the probe while the electric conductivity is determined from the difference in voltage between the cable and the end of the probe.

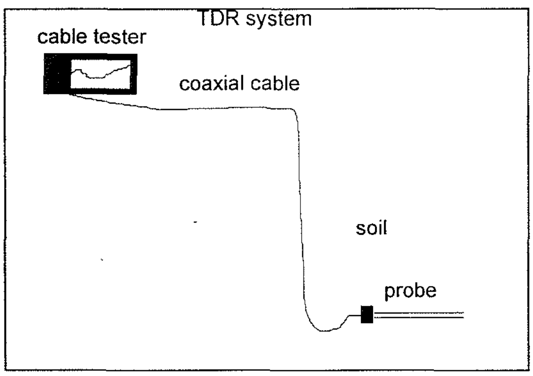

Figure 3. Schematic figure on a TDR-system.

The dielectric constant

The dielectric property can be described as a complex constant (Davis and Annan, 1977):

$$K^* = K' + j(K'' + \frac{\sigma dc}{we_o}) \qquad \text{eq. (4)}$$

where K^* is the complex dielectric constant (-)
and K' is the real part of the dielectric constant (-)
and K'' is the imaginary part of the dielectric constant (-)
and σdc is the zero-frequency conductivity (m s^{-1})
and w is the angular frequency (rad s^{-1})
and e_o is the free space permittivity (m s^{-1})
and j is the imaginary number, $(-1)^{1/2}$

The complex dielectric constant is not really a constant since the imaginary part varies for most materials. The real part, K', is also known as a material's electrical permittivity while the imaginary part, K'' describes the electrical losses. An electrical loss term, *tan y*, is defined as:

$$\tan y = \frac{K'' + \frac{\sigma dc}{we_0}}{K'} \qquad \text{eq. (5)}$$

All the characters defined as above.

Certain soils such as clays have a larger loss term than sands. The losses also increase with water content and salt concentration (Patterson and Smith, 1980).

For low loss materials, such as soil in the frequency range of 1-1000 MHz is K'' considerably less than K' and can be neglected.

$$K' \approx K^* \qquad \text{eq. (6)}$$

In TDR measurements the dielectric property is expressed as the apparent dielectric constant, K_a. Soils are low loss materials and in general K_a can be approximated as:

$$K_a \approx K' \qquad \text{eq. (7)}$$

Figure 4 shows the dependency of the complex dielectric constant, K^*, of the electrical loss term, *tan y*, and real dielectric constant, K'. Below frequencies of 1000 MHz is *tan y* small and can usually be neglected.

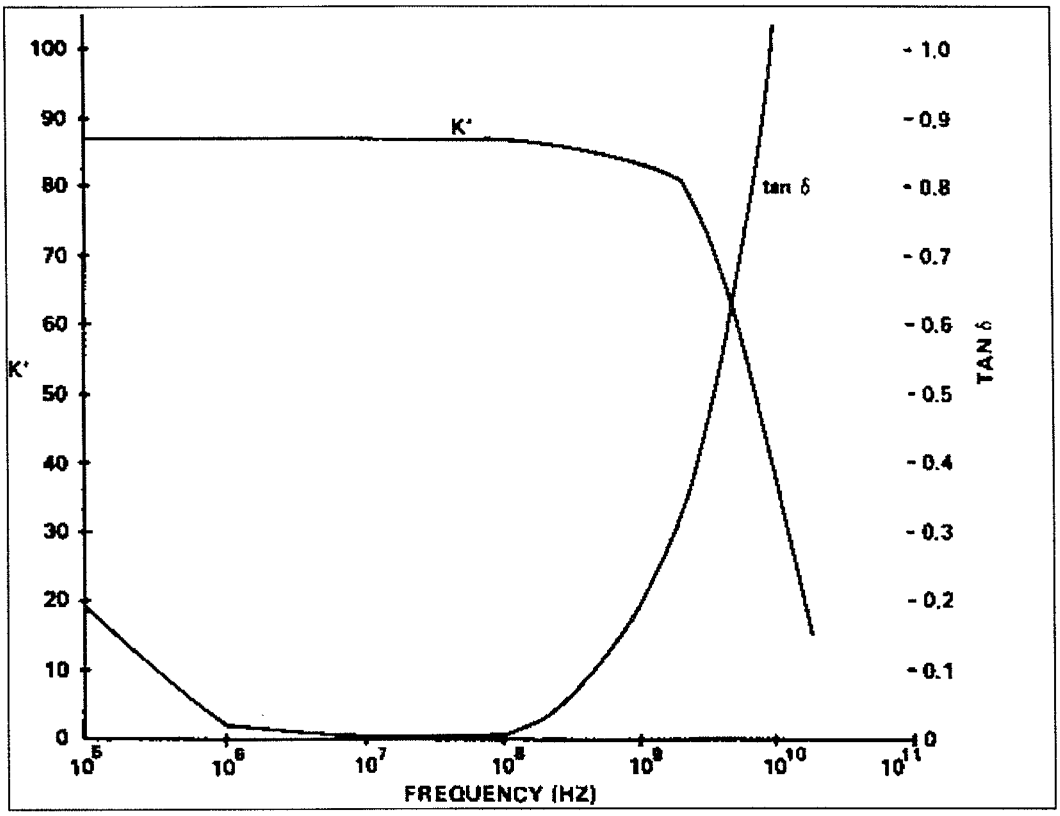

Figure 4. Dependency of the real dielectric constant, *K'* and the loss factor, *tan y* for water at 20°C (from Patterson and Smith, 1980).

Capacitance theory

Since most of the users of the TDR-technique are not likely to be electronic specialists, some capacitance theory follows. Firstly, the nature of the electromagnetic pulse, the concept of permittivity and the wave's propagation velocity is discussed. Then capacitance and the use of impedance in TDR is explained. Finally, the dielectric constant for different materials is shown.

The electrical pulse can be seen as a brief generation of electromagnetic waves; electromagnetic waves actually consist of a magnetic and an electrical field. The vectors of these fields have propagation directions at an angle of 90° to each other and also to the propagation direction of the electromagnetic wave. The electromagnetic wave transports energy and requires new generation of waves to continue. The frequency of the waves on the one hand is set by the source that generates the wave. The propagation velocity of the wave on the other hand is determined by the permittivity of material which transports this energy. The propagation velocity is related to the permittivity constant (Sears et al., 1982):

$$v = \frac{1}{(eu)^{1/2}} \qquad \text{eq. (8)}$$

where v is the propagation velocity of the electromagnetic wave (m s^{-1})
and e is the permittivity constant (s m^{-1})
and u is the magnetic permeability (s m^{-1})

For relatively isolating materials, such as soil, the influence of the magnetic permittivity on the propagation velocity can be neglected. In other words, the permittivity constant becomes a characteristic of the propagation velocity for these materials.

$$v = \sqrt{(\frac{1}{e})} \qquad \text{eq. (9)}$$

As mentioned earlier TDR belongs to the capacitance methods for measuring soil water content but the recorded change in voltage is in fact a change in impedance. Impedance is the total opposition to the electrical current and may be divided into a frequency independent part known as resistance and a frequency dependent part called reactance. In the frequency range of 1MHz to 1GHz (where TDR-signals are operating) the reactance is not very dependent for a relatively isolating material which makes impedance measurements useful when soil water content is to be determined. Reactance is, furthermore, made up of capacitance and inductance. This also implies that capacitance corresponds to changes in impedance. Capacitance can also be viewed as a conductor's ability to store energy in the isolating layers between the leads and is specific for different materials, depending on the permittivity of the material (Tektronix, 1989):

$$C = e(\frac{A}{l}) \qquad \text{eq. (10)}$$

where C is the capacitance (F)
and e is permittivity constant (-)
and A is the area of the lead (m^2)
and l is the length of the lead (m)

Similarly, the use of voltage measurements in a capacitance method can be explained by the following: two parallel electrodes surrounded by soil make up a capacitor, as any two conductors separated by an isolator would do. Another name for an isolator or non-conductance material is a dielectric. The capacitor then induces an electromagnetic field surrounding the conductants. The capacitance depends on the charge of the field and on the difference in potential. The electrical charge is unaffected by the addition of an isolator. This is showed by placing an isolator between the leads which causes the potential to rise. When the isolator is then removed, the potential will return to the original value (Sears et al., 1982):

$$C = \frac{Q}{V_{ab}}$$ eq. (11)

where C is the capacitance (F)
and Q is the electrical charge (C)
and V_{ab} is the change in voltage (V)

Different materials are, of course, influenced by the electrical field differently. Dipole molecules will under the influence of the field polarize. As a consequence elements built up of polar molecules, such as water, will therefore conduct an electrical pulse better than elements that consist of less polar molecules, such as air or solid soil. This electrical conductance for different materials can be expressed as a dielectric constant, K, which is 1 for air ,4-8 for solid soil and 82 for water at 20 °C (Kutílek, 1994; see Table 1). The significantly larger value for water makes the measurement of the dielectric constant useful when soil water content is to be estimated. The dielectric constant is expressed as the ratio between the conductance of the dielectric and the conductance in a vacuum (Sears et al., 1977):

$$K = \frac{C}{C_0}$$ eq. (12)

where K is the dielectric constant (-)
and C is the capacitance of capacitor with dielectric (F)
C_0 is the capacitance of capacitor in vacuum (F)

Table 1. The dielectric electric constant, K, at 20°C (except for ice) for different materials (after Kutílek, 1994)

Material	K
Vacuum	1
Air (1 atm)	1.00059
Polyethylene	2.25
Ice	3.2
Soil	4-8
Water	82

The propagation velocity is, moreover, related to K_a by:

$$v = \frac{c}{\sqrt{K_a}}$$ eq. (13)

where v is the propagation velocity (m s^{-1})
c is the speed of light ($\approx 3.8\ 10^9$ m s^{-1})
K_a is the apparent dielectric constant (-)

TDR-theory

The propagation velocity is not measured directly in TDR but is deduced from the length of the transmission line and the travel time of the wave. Instead the travel time of the pulse, or the transit time, is measured when the pulse travels along the probe. The propagation velocity, v_p, is then determined from this. v_p can be described by the equation:

$$v = \frac{2L}{t} \qquad \text{eq. (14)}$$

where v is the propagation velocity (m/s)
and L is the length of transmission line in soil (m)
and t is the transit time for electrical pulse (ns)

The factor 2 in equation (14) is explained by the fact that the wave is reflected and has to travel twice the length of the transmission line to the detector. If equation (14) is substituted in equation (13) then the following relationship is gained:

$$K_a = (\frac{ct}{2L})^2 = (\frac{L_a}{L})^2 \qquad \text{eq. (15)}$$

where L_a is the apparent length in soil (m)
and L is the apparent length in air (m)

Soil bulk electric conductivity

The principle of measuring soil bulk electric conductivity with TDR is that the impedance decreases with increasing ion solvents. This is detected by the difference in amplitude of the wave signal, in the time-voltage plot, between the minimum value at the trough of the curve and a maximum value after the gradual rise of the signal.

At low frequencies, the impedance is equal to the total resistance (Giese and Tiemann, 1975).

$$R = Z\frac{(1+p)}{(1-p)} \qquad \text{eq. (16)}$$

where R is the total resistance (ohm)
and Z is the impedance of cable tester (ohm)
and p is the reflection coefficient at infinite times (-)

A problem related to the measurement of the impedance is multiple reflections interference which originates from irregularities in the cable caused by discontinuities (Heimovaara, 1996). When soil bulk conductivity is measured the interest is focused on the difference in voltage level between the signal from the cable and the part reflected passing through the probes. The determination of the beginning and the end of the trace for travel time is fundamental for measuring soil water content but becomes unimportant when soil bulk conductivity is determined. On the contrary to soil water content measurements where the use of long transmission lines means loss of energy and arduous detectable trace this set-up could be beneficial for soil bulk conductivity measurements. A more accurate value of the impedance at infinite time is obtained since interference of the reflection coefficient becomes less significant than in a short cable. The reflection constant is then calculated from the voltage wave:

$$p = \frac{V_\infty - V}{V} \qquad \text{eq. (17)}$$

where V_∞ is the infinite value of voltage (V)
and V is the voltage (V)

The bulk electrical conductivity, EC, for low frequencies can also be expressed as (Nadler et al.,1991):

$$EC = kfZ = kfR \qquad \text{eq. (18)}$$

where k is the cell constant of TDR probe (m^{-1})
and f is the temperature correction coefficient (-)
and R is the resistance of the soil (ohm)

The cell constant is usually determined from calibrations with solutions of known concentration. This is also the normal procedure by which the internal resistance of the cable and the cable tester is determined. The bulk soil electrical conductivity is temperature-dependent and the temperature coefficient, f, can be obtained through the relationship:

$$f = \frac{1}{1 + 0.019(T - 25)} \qquad \text{eq. (19)}$$

where T is the temperature at which the electrical conductivity is measured

The resistance of the soil, R_s, can then be calculated as the difference between the total resistance, R_{tot}, and the resistance of the cable, R_{cable}:

$$R_s = R_{tot} - R_{cable} \qquad \text{eq. (20)}$$

Heimovaara et. al. (1996) calculated a linear relationship for R_{cable} for a specific device by calibrations in solutions with known soil bulk conductivity. It was also possible to determine the cell constant, k, by this procedure. The reflection coefficient can be calculated as in equation (17). The soil bulk electric conductivity can then be calculated as in equation (18).

Instrumentation

TDR-systems consist of several different components. The function of these components will briefly be described here (for details see instruction manuals).
The instruments and components used in the experiments conducted are as follows:

Hardware:

- Metallic Cable testers 1502B, 1502C (Tektronix)
- Coaxial cables (RG58) and Communication cable (Tektronix 6549)
- Probes: two-wired; (Campbell, PB 30), 25 cm (modified PB 30), 10 cm; three-wired; 15 cm (Figure 8.)
- Baluns (Campbell)
- Multiplexer (Campbell, SDMX50)
- Data-logger (Campbell, CR10)
- PC lap top

Software:

- AutoTDR software program (Thomsen, 1994)
- PI 100 (Campbell, 1995)

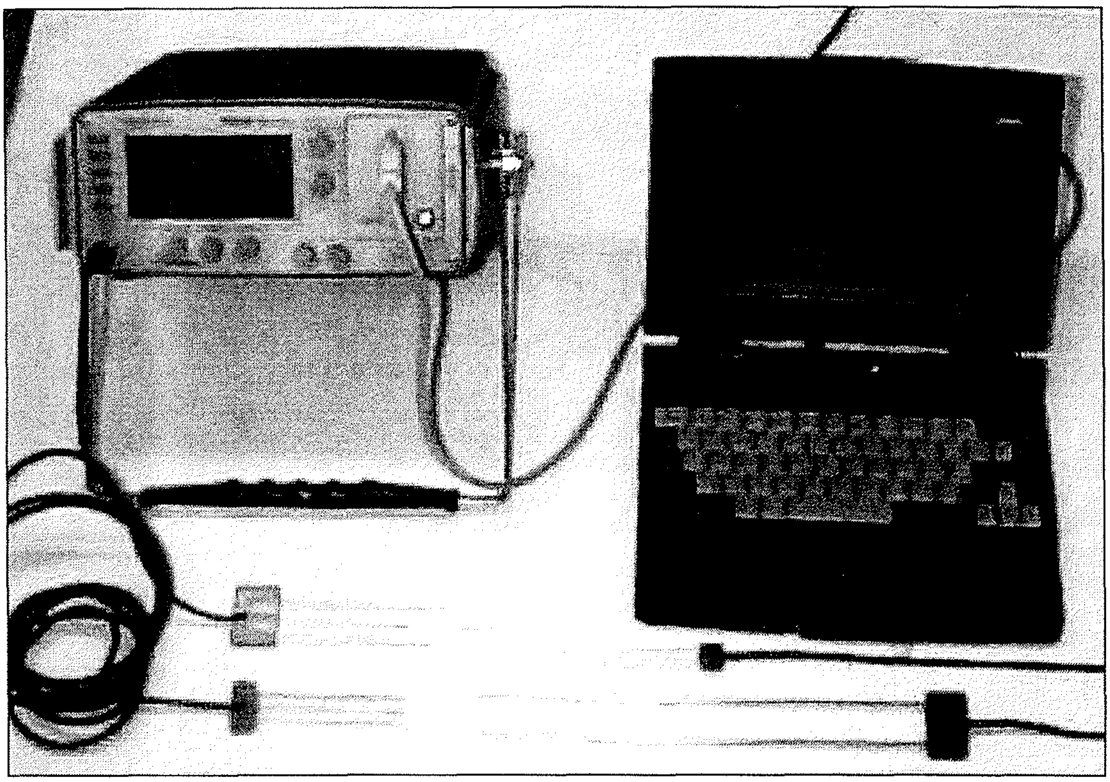

Figure 5. A TDR-system, similar to system D, with cable tester, cables, two and three-wired probes and a PC (From: http://tal.agsci.usu.edu/, Utah State University, Department of Soil Physics).

Cable tester

The cable tester is constructed to locate defects in metal cables. The instrument works by tracking reflections caused by discontinuities in the cable from an emitted brief pulse. These discontinuities can be caused by foreign substances in the cable (such as water). Reflections occur due to changes in impedance since the dielectric constant varies for different materials and is displayed as a wave form that shows change in voltage over time on the oscilloscope of the cable tester. Smaller changes in impedance occur in any cable and are referred to as noise. Under some circumstances, (e.g. when long cables are used) signal attenuation can make noise more significant which results in a signal that is harder to interpret.

An important property of the measurements which is set at the instrument is the propagation velocity, v_p , the velocity with which the pulse travels through the cable. The propagation velocity varies for different materials and is expressed as a fraction of the velocity in a vacuum. The propagation velocity for the common cable (RG58) used in this study is, for example, 0.66, i.e. 2/3 of the propagation velocity for the electromagnetic wave in vacuum. This value corresponds to the v_p of the electromagnetic pulse travelling in the cable and is used when the length of the transmission line is calculated and K_a is determined (eq.14). A menu at the display of the cable tester gives information about v_p-values for cables of different materials (Tektronix, 1995). Two typical traces on the voltage-time display are the short-cut that is shown by a downward pulse and the open circuit that can be viewed as an upward pulse (Tektronix, 1995).

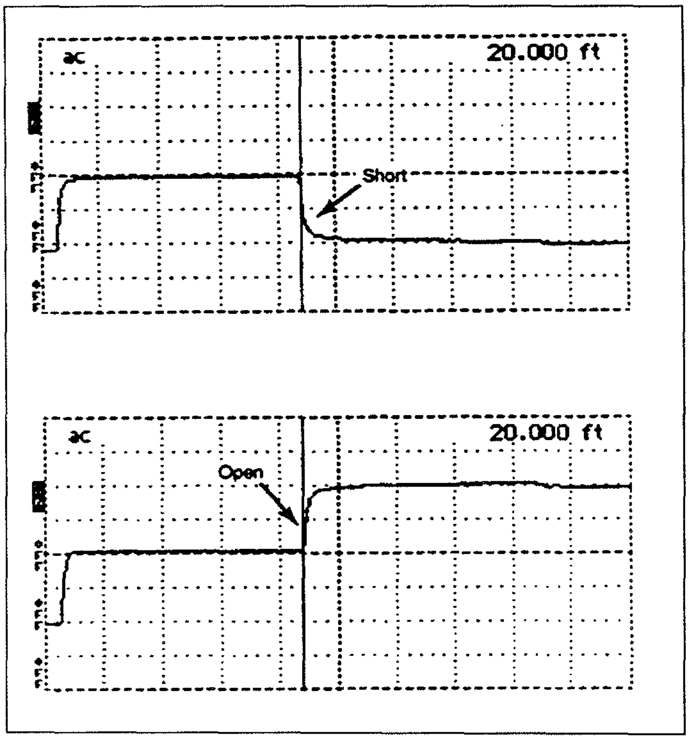

Figure 6. Schematic figure of typical traces, short circuit and open circuit, found on the cable tester's oscilloscope (From Tektronix, 1995).

Probes

Probes are sensing devices indicating the change in impedance between the coaxial cable and the soil, acting as an extended wave guide leading the pulse along the rods of the wire. The probe length and the propagation velocity is then used to determine the travel time of the pulse that corresponds to K_a (equation 15).

The probe consists of two or more parallel metal rods often connected to the coaxial cable in an enclosed head (Figure 6) . In two wired probes the inner conductant of the cable goes to one of the rods and the outer conductor to the other rod. A coaxial cable consists of two conductors, an inner conductor and an outer conductor. In a two-wired probe one of the conductors is connected to each wire. The pulse transported through the coaxial cable is however not equally divided between the two conductors. One of the probe wires receives a larger part of the pulse, which makes the field surrounding the probes asymmetrical. The probe is said to be unbalanced. The fact that measurements are still performed with accuracy can be explained by the fact that the electrical field surrounding the wires is divided as the signal travels along the probe.

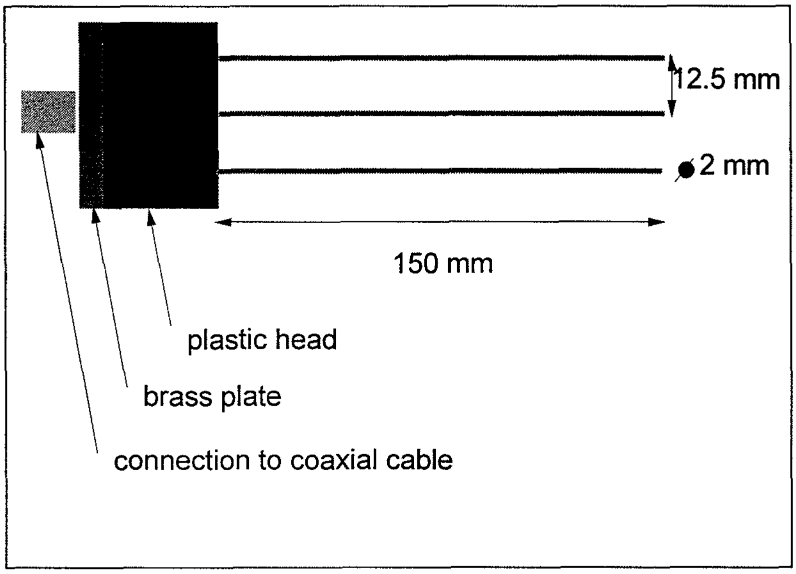

Figure 7. The three-wired probe used in experiment 2.

Cables

Cables are designed to transport energy in a certain range of frequencies with the smallest losses. As a consequence, the cable impedance does not change very much. Changes in impedance cause, as mentioned, reflections and energy loss which is really the principle of TDR-measurements. Although cables are designed to minimise energy losses, losses still occur and become significant when long cables are used. In practical measurements with automated systems both cables and multiplexers give significant energy losses and signal attenuation. Each level of multiplexers correspond to a signal attenuation loss equivalent to an additional 5 m of cable (Campbell, 1995).

Multiplexers

Multiplexed connections or relay scanners allow simultaneous measurements of many probes using only one cable tester. The analogue signal from the cable tester is switched over with a position jumper that directs the signals of the cables from the different probes. Several multiplexers can be connected in up to three levels, with coaxial cables in between, for the use of up to 512 probes in the system (Campbell, 1995). Each multiplexer has 8 connections and is controlled by a software PC program through a logger or a PC that co-ordinates the probes with the cable tester. A five conductant cable is also needed for communication between the logger, the cable tester and the multiplexer. The cable tester in automated systems is supplied with an interface that handles the communication between the logger or the PC and the cable tester.

In a system where more than one multiplexer is used the addresses of the multiplexers are important to co-ordinate the measurements. The addresses of the different multiplexers are set in the program but is also set mechanically at the multiplexers. On the panel of the multiplexers two different addressing positions is therefore to be set, MSD (most significant digit) and LSD (least significant digit). When a system of more than 8 channels are used several multiplexers are required. The multiplexers then needs to be divided in to a superior, level 1, and slaves, level 2. These addresses are as mentioned set mechanically to the right at the panel of the multiplexer (see Campbell, 1990 for further instructions). The interface has four address switches which are also set manually.

Baluns

One problem that often occurs in field measurements when long cables have to be used, is energy losses which make the signal more difficult to interpret due to disturbances or noise. A device that could makes energy losses less significant for the TDR-system especially when using long cables is the balun. The balun is used for two purposes: to match different impedance's and to balance a cable. The balanced cable with a balun divides the energy between the inner and the outer conductor which results in a clearer signal. Baluns can also be used to match cables with different impedance without energy losses. A 50 ohm coaxial cable from the cable tester, for example, can be matched with a 200 ohm twinax cable to make measurements with longer cables possible since the noise in a cable with higher impedance becomes less significant. Baluns are often made from ferrite, a ceramic composed of ferric and other metal oxides, that concentrates the magnetic field and prevent a large electrical flow in the ferrite due to high electrical resistance (Spaans and Baker, 1993).

Software for evaluation of data

Automated TDR measurements and evaluation of data are usually carried out with computer programs. The software is programmed for two main purposes: to control the measurements and to evaluate the data obtained. The first of these two purposes includes settings of parameters, such as probe type, probe length, cable length, etc. It also deals with the co-ordination of measurement signals that are directed between the computer and the cable tester. For example, when several probes are used in an automated system, the software addresses the signal through the different channels of the multiplexer to the cable tester.

The second purpose for a TDR software program can be approached with two different philosophies: to store raw data for later analysis or to store automatically converted the data of soil water content or soil bulk conductivity. The former strategy of storing raw data refers to that the whole trace which occurs on the display of the cable tester is saved. The raw data is in other words a photo-copy of the cable tester's display. The advantage of this strategy is that evaluation can be made later and that re-evaluation is possible. The storage of these raw data demands, however, significantly more space in the memory of the storage facility. The smaller capacity of a logger allows therefore only briefer time periods of saved raw-data while a PC could store raw-data for a very long time.

The evaluation of data is also controlled by parameters to interpret the trace. These parameters are, for instance, instructions to define the beginning and the end of the trace, individual offsets for traces deviating from the usual shape. The trace is then analysed with an algorithm. (Figure 8)

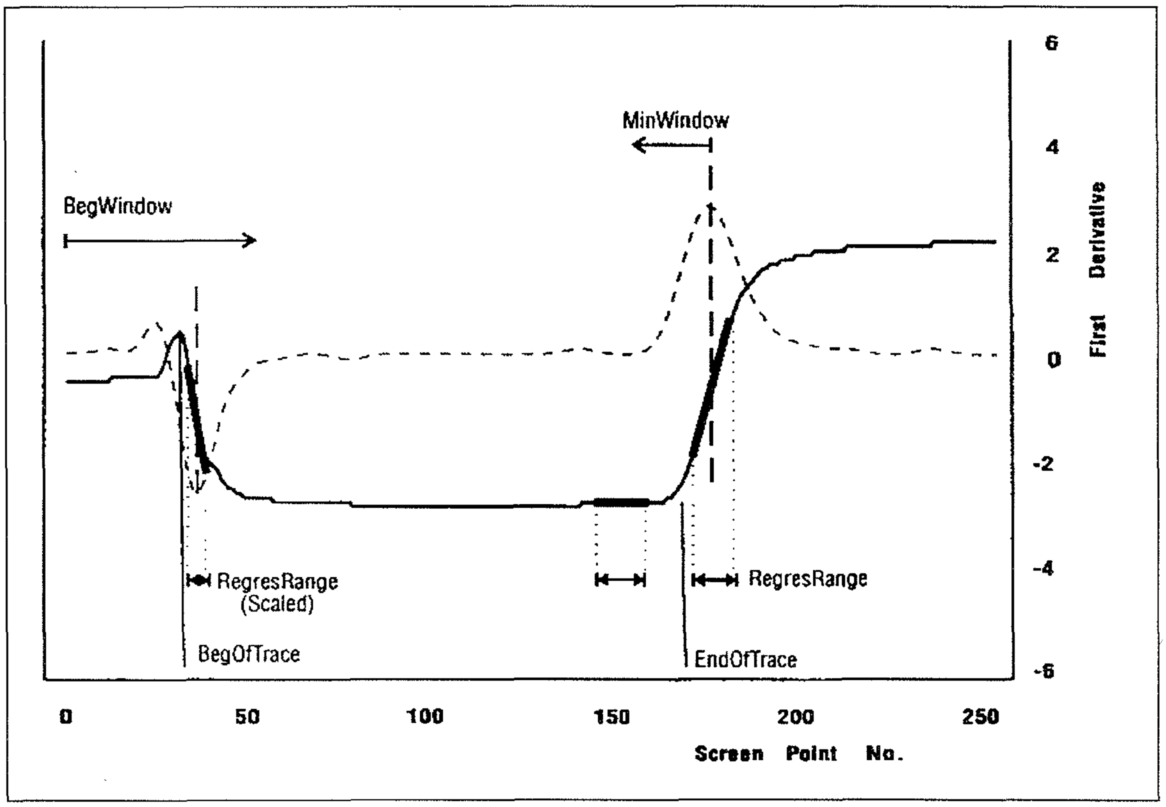

Figure 8. A trace produced by AutoTDR with some of the parameters used in the evaluation (from Thomsen, 1994).

The different tasks operated by the software are often divided into smaller programme units. These units could be, for example, programs for communication with the cable tester, serial communication with the multiplexers and analysis of the trace. In order to make parameter setting easier and to present the result in a visual way graphic programs and a screen menu may be included. A number of parameters are given and options are given to specify different properties of the system.

The Campbell Programming Instruction 100 (from now on referred to as PI 100) can be used to design programmes of different purposes. The program uses parameters all set in the program list found by codes and set by flags (Figure 9). AutoTDR, the other software in this comparison has a main menu including a sub menu for the setting of parameters and is more user friendly in the sense that the parameters are set in the menu and not in the listing of the program as is the case in the P.I 100. Parameters such as probe length, cable length and equation for conversion to water content are essential information requested in both of the two software program.

AutoTDR stores raw data and although PI 100 has the same option, the size of the storage capacity makes it more common to store only K_a values and soil water contents.

TABLE 4-1 Instruction 100 Parameters

PAR. NO.	DATA TYPE	DESCRIPTION
01:	2	SDM1502 address
02:	2	Output option 0 Water content 1 Raw data 98 Manual step through 99 SDM1502 signature
03:	FP	Probe length, metres
04:	FP	Cable length, metres; enter 0 for auto search
05:	4	Multiplexer channel/Reps A B C D A Chan. of 1st Mux, 0 if none B Chan. of 2nd Mux, 0 if none C Chan. of 3rd Mux, 0 if none D No. of Probes to scan
06:	4	Input location
07:	FP	Multiplier
08:	FP	Offset

Input Locations altered:
Water content 1 per probe scanned
Raw data 256 per probe scanned

Intermediate Locations required:
531 the first time Instruction 100 is used
16 intermediate locations for each Instruction 100 thereafter.

Figure 9. Parameter setting in Campbell software programme PI 100 (From Campbell, 1995).

Experimental set-up

Two experiments were conducted in sandy soils, a washed sand referred to as Baskarp and a natural sandy soil referred to as Nåntuna. Sandy soils have, of course, a simpler structure than clays which makes water fluxes easier to explain. Furthermore, sandy soils do not absorb a lot of tightly-bound water which is the case for clays. This tightly-bound water is not detectable by TDR and would make a comparison between different sources of errors more difficult. In the first experiment, conducted in the field, errors from probes and cables were examined. In the second, performed in the laboratory, the role of software program evaluation in measurements was examined. In a third experiment manual measurements of electrical conductivity were conducted.

The TDR-systems used in the different set-ups were similar in the following respects: The automated systems were all programmed by Campbell Programme Instruction 100 and a data-logger (Campbell CR10) was used to process and store information. Multiplexers (Tektronix SDMX50) and a 5 conductor communication cable (Tektronix 6549) to alternate the connection between the probes and the cable tester were also used in these automated systems. Other similar components used in all of the set-ups were, furthermore, a Metallic Cable Tester (Tektronix 1502B or 1502C) which was supplied with an interface (Tektronix SP 232) and coaxial cables (RG 58, 50 ohm).

Experiment 1 - in field

In this experiment, errors from probes and cables were examined. The conversion of K_a to θ_v was also examined as calibration functions for the two sands were determined. The experiment was conducted in four field plots (Figure 10). The plots were equal in pairs, two plots with Baskarp sand and two plots with Nåntuna sand. Each plot was supplied with two separate automated TDR-systems. The systems were different in probe type only. The first system installed (October -95), system A, had two-wired unbalanced probes 15 cm long and long (24 m) cables. The second system, system B, installed in June -96 was supplied with balanced 30 cm two-wired probes (Campbell PB 30) and 19 m cables at corresponding depth. Measurements were conducted of 10 min intervals, except during a drainage event when the water content was measured every 2 min.

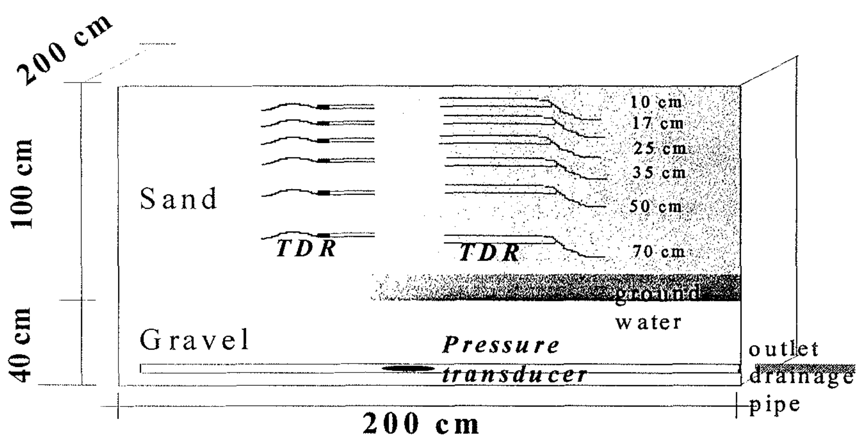

Figure 10. Schematic figure on the experimental set up in field used for systems A and B.

Experiment 2- in laboratory

In the second experiment two plastic cylinders, 50 cm of height and 29,5 cm in diameter, were filled again with Nåntuna sand and Baskarp sand for studies in laboratory. Both sands were dried when filled and placed upon a 5 cm gravel layer. Each of the two cylinders was provided with two sets of TDR probes, six two-wired and five three-wired (Figure 11) in two separate systems. A water container and an electrical pump were used to apply water to the cylinders and an arrangement of hosts controlled an artificial ground water level. After the two soils had been saturated during a wetting event the containers were drained as the ground water level was drained in steps (to avoid trapped air). Later an electrical fan of 250 watts was used to dry the soils. The system with two-wired probes, system C was automated (PI 100) while manual measurements were conducted in the system with three-wired probes, system D (Figure 11). These manual measurements were evaluated with the software AutoTDR. The automated measurements were conducted every 5 minutes while manual measurements were conducted at different water contents ranging from dry water conditions to near saturated conditions. This was accomplished to test the software's evaluation of the trace and to see how the different parameter settings influence the interpretation.

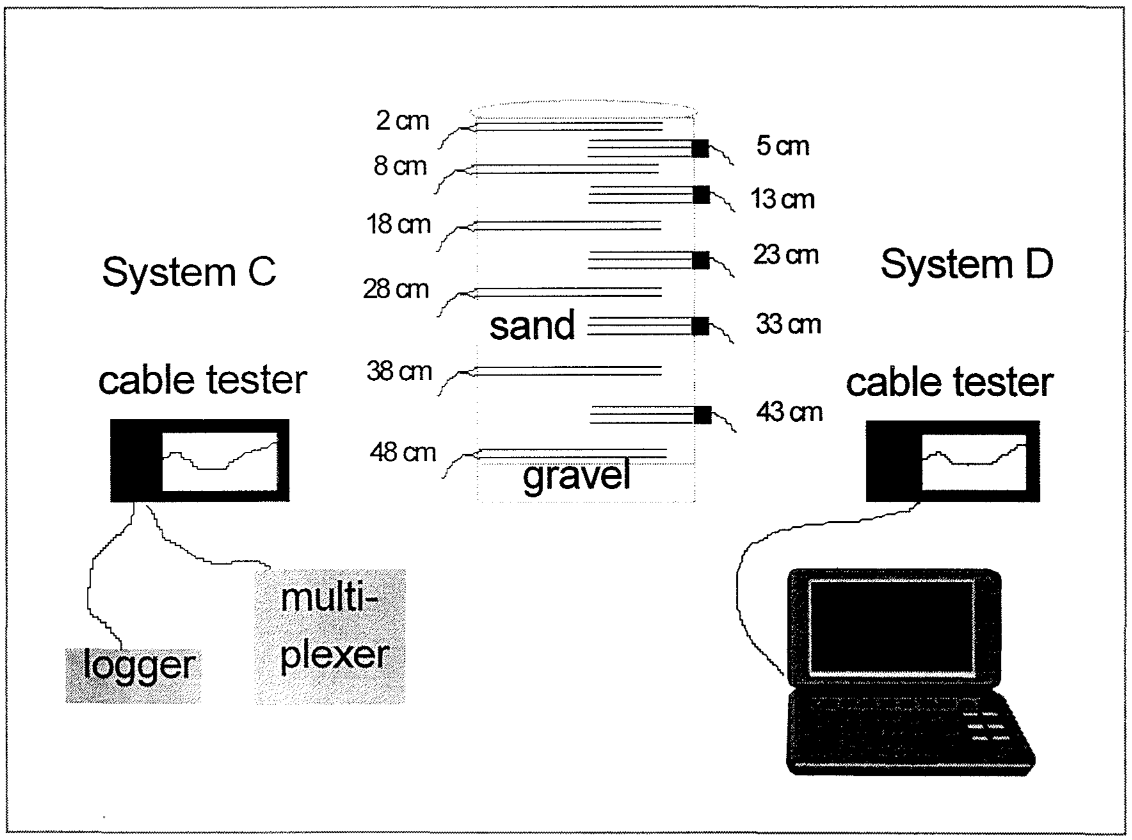

Figure 11. Schematic figure on the laboratory set up. Two systems, C and D measure on probes installed in a cylinder of sand.

RESULTS

Experiment 1

Trace performance

While system A gave unrealistic K_a values and water contents, system B gave reasonable data (Figure 12). System A, with long cables and short unbalanced probes gave, on one hand, a trace heavily disturbed by noise. Measurements with system B also consisting of long cables but with long balanced probes gave, on the other hand, an acceptable quality of the signal.

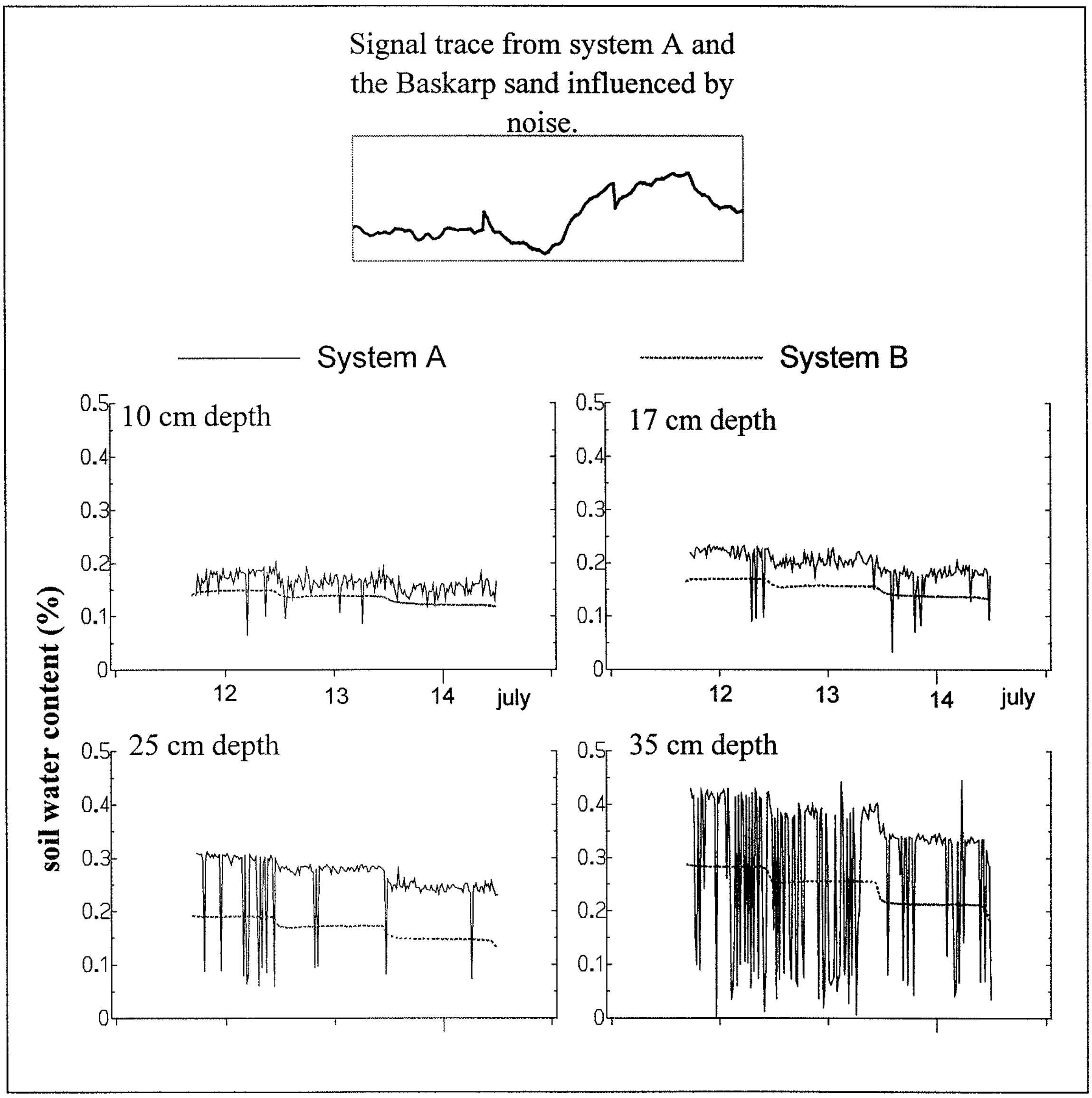

Figure 12. Traces disturbed by noise. Above: An example of a trace from system A influenced by noise before the electrical ground of the power supply was disconnected. Below: Time series of traces from system A and system B at four depths.

The quality of the signal from system A was later improved when the electrical ground in the system was given attention. The ground had earlier been supplied from the power net but this had apparently disturbed the signal. The noise was also reduced simply by disconnecting the ground of the power-supply. A point close by the plots was instead used as ground to have a similar potential as the soil in which the probes where installed.

Another phenomenon that occurred at water contents near saturation in the Nåntuna sand was an incorrect interpretation of the trace. The end of the trace become under these conditions very flat. PI 100 then failed to detect the last inflexion point of the trace (Figure 7) which made the apparent probe-length longer. As a consequence K_a became unreasonably large and unrealistic water contents of 80-100 % were recorded.

Gravimetric calibration

An acceptable calibration function was not found for system A, as a consequence of the poor quality of the trace.

The accuracy of data from system B was further improved when the system was calibrated against small core samples. The calibration functions found for the two sands and system B were:

For Baskarp: $\theta_v = -0.000206 + 0.070K_a + 0.002088K_a^2$ eq. (21)

For Nåntuna: $\theta_v = 0.00005 + 0.03330K_a + 0.007245K_a^2$ eq. (22)

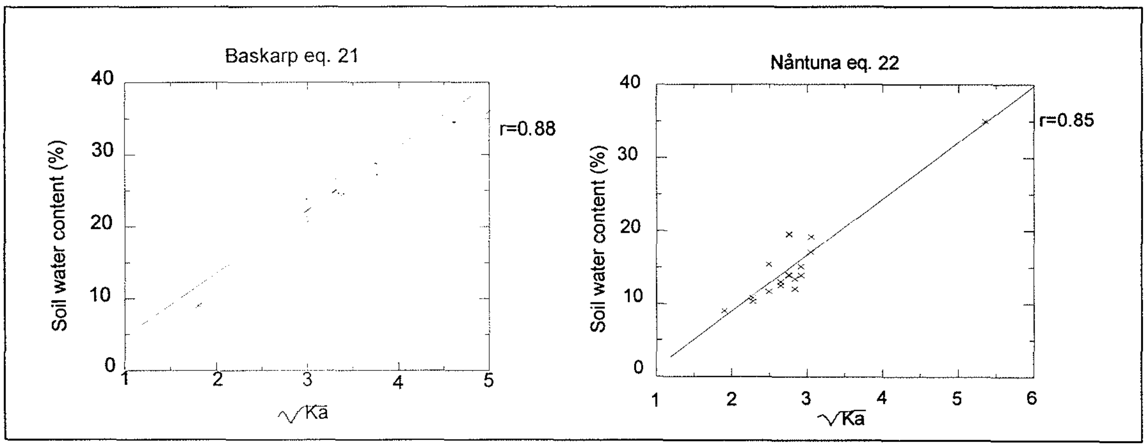

Figure 13. Calibration curves for Baskarp sand and Nåntuna sand obtained from gravimetrical sampling of small cores.

The calibration functions were constructed with measuring points from one occasion when soil cores where taken. This resulted in a somewhat small distribution in data with respect to water content. The data also occurred at different water content ranges in the two sands, between 20-37 % for Baskarp and between 9-20 % for Nåntuna. Each curve was therefore complimented with a constructed point in the range were points were lacking. These values were obtained with the pressure outflow method in which the water contents of core samples were determined at different pressures. These data are presented in figure 15 below.

Drainage event

A drainage event was then recorded by system B in order to compare equations (21) and (22) with the commonly used Topp equation (eq. 1). The groundwater level of the field plots was lowered with approximately 10 cm each day for three days. During this time the plots were also covered to prevent evaporation. The volume of drained water was measured with tipping buckets. System A was also used to record changes in water content at different depths. The accumulated outflow was measured with tipping buckets but was also calculated from TDR measurements. This is shown in figure 14. The calculations were conducted for layers defined by the depth of the probes.

Figure 14 shows, on one hand, that both eq. 1 and eq. 21 underestimate the absolute soil water content significantly in the Baskarp sand. For Nåntuna, on the other hand, eq. 1 overestimates the drained volumes. Relative differences in water content are, however, very well described by the TDR measurements in both sands. For the Nåntuna sand Eq. 22 gives volumes that corresponds well with the volumes measured by tipping buckets.

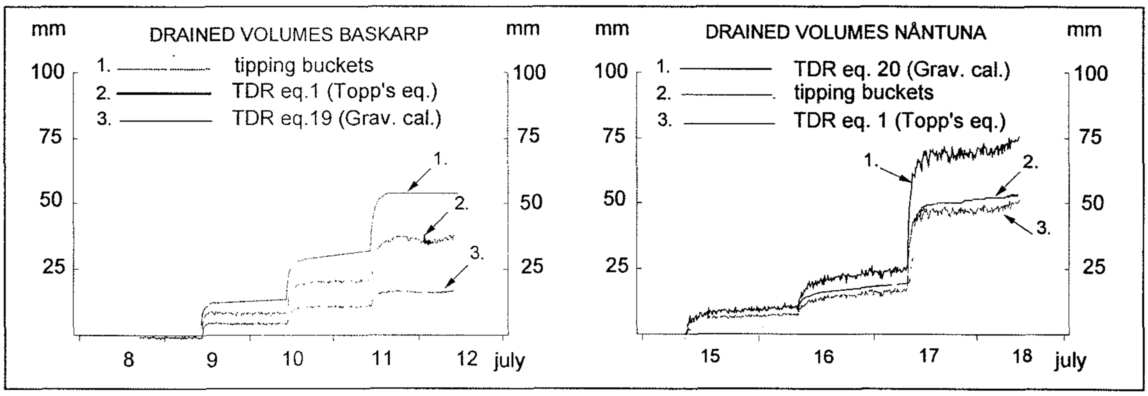

Figure 14. Drained volumes from the Baskarp sand and the Nåntuna sand, measured with tipping buckets and TDR, when the groundwater level was lowered by 10 cm each day for three days.

Experiment 2

Calibration- trace set-off parameter

In order to determine the water content of two calibration points for system D the water content was estimated both at saturated conditions and at dry conditions. The water content at saturated conditions was determined by a relationship between the porosity and the water content determined gravimetrically with soil cores. The porosity was calculated to 47% for the Baskarp sand and 44% for Nåntuna. Five soil cores were sampled from each sand. The porosity was then determined using a relationship between the specific weight and the bulk density. The result was compared with similar data obtained from the field set-up in experiment 1, where a relationship between the porosity and saturated soil water content had been calculated also by gravimetric soil core sampling. The ratio between the porosity and the saturated water content was used when a saturated water content was calculated. This resulted in a saturated soil water content, θ_{sat}, of 38% for Baskarp and 40.5% for Nåntuna.

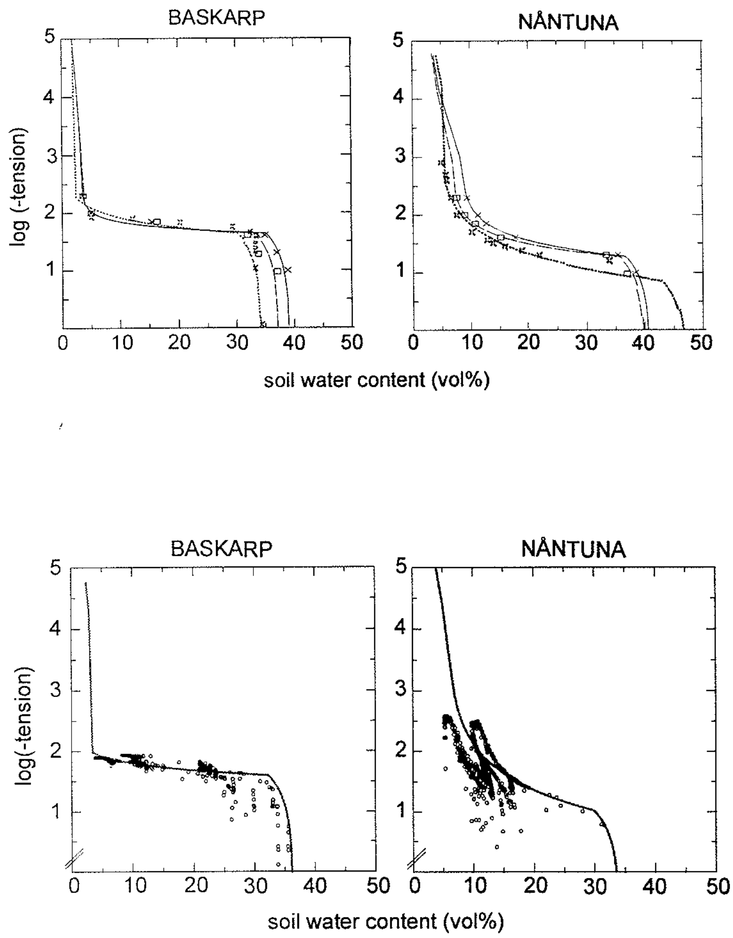

Figure 15. pF-curves. Above: Curves based on data from soil cores and the pressure outflow method at different depths. Below: Curves from field measurements with TDR and tensiometers.

The water content at 100 cm water column, θ_{100}, was estimated to be 9% for Baskarp and 7% for Nåntuna. This was obtained from pF-curves established with data from soil cores using the pressure outflow method.

The possibility of re-evaluation of traces in AutoTDR and system D was then used to calibrate the measurements against the two values of saturated water content and the water content at the tension 100 m water column. This was accomplished by adjusting a trace off-set parameter until the measured values corresponded to the calculated values. These off-set values were determined to be -0.02 for the Baskarp sand and 0.025 for the Nåntuna sand. This gave θ_{100} and θ_{sat} 8.9 % and 37.7 % for Baskarp and 7.4 % and 40.8 % for Nåntuna.

Comparison between the two systems

The logger-based system, system C, showed significantly lower values of soil water content. When the PC based system, system D, predicted a soil water content of 8,9% for Baskarp and 7,0 % for Nåntuna at the tension 100 m water column, the logger system displayed a corresponding water contents of 3.5 % and 5.0 %. In conditions near saturation, system C recorded 33% and 39 % while system D gave 37.7 % and 40.8 %.

Software evaluation of different probe types

The two systems C and D also run with different probes and software evaluation programs. The results are shown in table 2.

Table 2. K_a values measured and evaluated with a combination of the components in system C and system D at near saturated conditions in a sandy soil.

probe nr.	PI 100 two-wired probe	AutoTDR two-wired probe	PI 100 three-wired probe	AutoTDR three-wired probe
1	20.52	19.80	17.47	19.28
2	19.80	18.83	17.72	19.29
3	17.30	16.17	18.49	20.28
4	20.70	19.61	17.30	19.16
5	19.71	18.93	17.89	19.35
6	21.16	20.43	-	-

Table 2 shows that PI 100 evaluates measurements conducted with the three-wired probe resulting in K_a-values in average about 9 % lower than when evaluated by AutoTDR. When the two-wired probe was used, on the contrary, AutoTDR evaluates the measurements about 5 % lower than PI 100. AutoTDR was used with a trace off set value determined according to the user's manual for both probe-types. The trace off values used were 0.172 for the two-wired probe and 0.128 for the three-wired probe. These trace off values, however, deviated significantly from the calibrated values because they were determined according to the instruction manual (Thomsen, 1994). It is also important to remember that the two probe types were installed at different depths in the cylinder which means that the values from the same rows in the table can only be compared between similar probes.

The systematic deviation of two-wired probe nr. 3 (Table 2) together with an inspection of the probe set-up resulted in an additional investigation of how the length of the probe actually in contact with soil influences the measurements. In other words, the installation of the probes from the outside of the cylinder-wall does not allow the whole probe to be buried in the soil. The sensitivity of K_a to the fraction of the sensor not in contact with the soil was examined. This was achieved by setting a shorter probe length, corresponding more with the part of the probe in contact with the soil using a parameter in AutoTDR. The K_a values obtained were compared with the value obtained using the total probe length in the parameter setting. For the two-wired probe-type in system C, a setting 1 cm shorter than the total length of the probe gave a 8% higher value. For 2 or 3 cm the corresponding values were 18 % or 29 %. For most probes in the set up, 2 or 3 cm of the rods were not in contact with soil. For the three-wired probes of system D, the set up is, on one hand, made in a way that a shorter length of the rods is in contact with soil. On the other hand, this probe-type is shorter which made the deviations even greater: 1 cm of non-soil contact gives an increased K_a of 16% while 2 cm which is more reasonable gave 30 %.

Software parameter setting

The parameter setting in AutoTDR can be reduced to set probe type and probe length when using a default function. For other probe types than a standard probe (Thomsen, 1994) a more accurate interpretation of the trace could, however, be accomplished by abandoning the default function and to set parameters manually and individually.

Differences in parameter setting in AutoTDR were examined by altering two parameters, RegressRange and SmoothWindow. RegressRange sets the length of the segment used, when regression lines are drawn, to define the beginning and the end of the trace (Figure 6). This is expressed as horizontal co-ordinate points on the trace plot. SmoothWindow is a filter that averages the values of the trace. How the settings effect the measurements at water contents near saturated conditions is presented in table 3.

Table 3. K_a-values when the parameter setting is altered in AutoTDR.

Settings	**SmoothW 5**	**10**	**15**	**20**
RegRess 5	17.87	20.56	20.52	20.43
10	18.13	20.16	19.96	20.20
15	17.94	19.89	20.05	19.91
20	17.65	20.17	19.87	19.30
25	17.50	19.93	19.69	19.03

DISCUSSION

TDR-systems consist of several components that can contribute to errors in soil moisture measurements. There are two major groups of errors: those that influences the determination of K_a and those that occurs when K_a is converted to soil water content (figure 16). The first of these errors which belong to the type found on the left side in the figure, can then be further divided into those that influence the signal as it appears on the cable testers oscilloscope and others that affect the interpretation of the trace.

The type of errors discovered in the two experiments described above can be summarised and classified as follows:

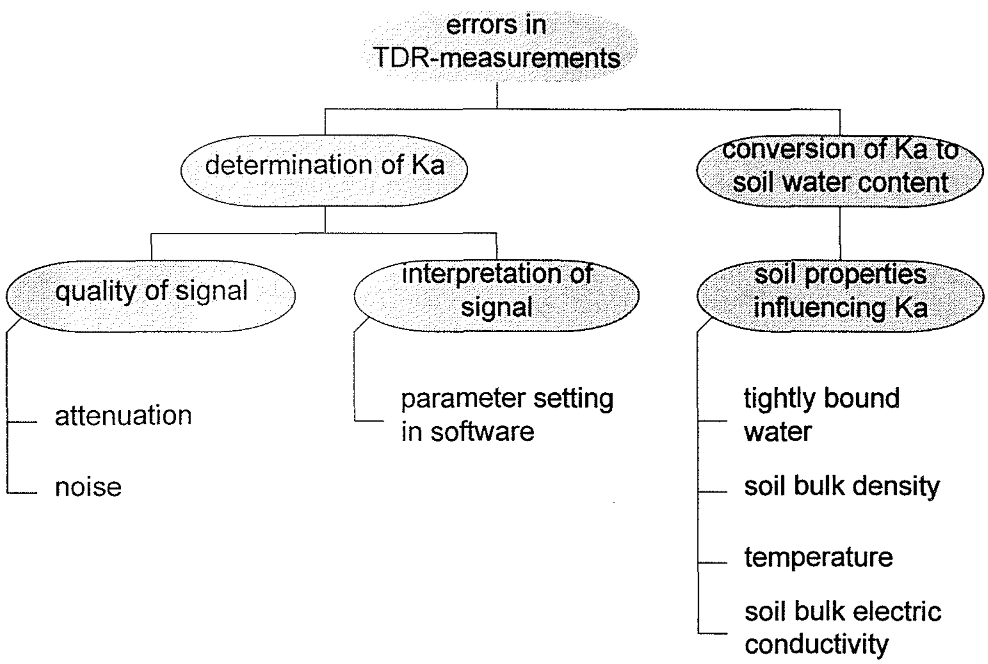

Figure 16. Classification of some errors occurring in TDR-systems. The errors primarily focused on in this study are found on the left side, related to determination of the apparent dielectric constant, K_a in soils. The soil properties, on the right side in the figure, influencing the conversion of K_a to θ_v are considered when calibration functions are determined.

Errors which affect the quality of the signal

The first group of errors, found to the left in figure 16, can be exemplified by observations made in field, such as: noise due to improper grounding, signal attenuation due to long cables and noise due to the use of long cables in combination with short unbalanced probes (Figure11).

Power supply and electrical grounding

Noise and signal fluctuation can affect the possibilities of a proper evaluation of the trace. A trace affected by an improper grounding is characterised by a fluctuating trace which pattern reminds of sinus curves. As a consequence the software program that interprets the trace does it in an unreasonable way or even fails to interpret the trace. This problem can be overcome simply by disconnecting the ground wire of the cable that supports the cable tester with power. This is not, however, a satisfying solution since electrical systems require a ground connection for safty. Besides a stationary system requires a grounding as protection of the euqipment from thunderstorms. Instead, a grounding point near the site where the probes are installed should be chosen.

The stationary system A, for example, was heavily disturbed by noise until the electrical grounding was re-arranged. The grounding from the power-supply was disconnected and the grounding was taken from a pole which was put up next to the measured plots. Thus, it is of importance that the electrical ground-point is selected near the installation of the probes to ensure that the potential of the soil does not differ much from the electrical ground used in the power-supply.

Signal attenuation

A problem that often occurs when long cables are used is signal attenuation. Loss of energy makes noise more significant and the trace becomes difficult to interpret. This is even more likely to be the case when short probes are used since the shorter probe length gives a shorter trace which can, due to the relative long transmission zones, easily be interpreted incorrectly. In practical measurements in the field, however, long cables are often required. One way to avoid signal attenuation is then to use cables with a higher impedance. Noise, which is always present during any measurement, will then be less significant. Cables with a higher impedance can be matched with cables with lower impedance using a balun. A 50 ohm cable from the cable tester connects, in this way, a longer 200 ohm twinax cable which improves the quality of the signal (Thomsen, 1994).

System considerations

The errors described above are in general caused by improper instrumentation. One strength of the TDR-system is the flexibility in design which makes it possible to adjust the system to different soil types, conditions and to the demands of the users . Nevertheless, this flexibility can also be a weakness if the user does not have the knowledge to correctly adjust the system to different conditions. Even a widespread system, such as system B (Campbell), where the different components are designed to be used together, has been subject to significant changes. (Campbell, 1995).

The difference in nature of soils are for example between a sand and a clay requires attention and consideration when similar systems are used for both types of soil. This has not been examined in this study but similar systems like those operated in the experiments described in this paper have been used in clays. Andersson (1994) may be correct when she concludes that the contact between the probe and the soil was the explanation to underestimated water contents in a clay soil.

The cables and probes used in system C are connected by screws. The result is a signal where the beginning of the trace is difficult to define. The peak indicating the beginning of the trace becomes fairly large. The connection was also modified to allow quicker installation, which further decreased the distinctiveness of the transmission zone. The material used in the modified connection also had different isolating properties than the cable and is also fragile. It is not surprising that a connection between the probe and the cable with this design contribute to uncertainties in measurements. A connection between the cable and the rods with a more distinct transmission zone is preferable.

In the second experiment, K_a, changed significantly when the actual probe length was changed in system C. Apparently, the part of the probe in contact with the soil is shorter than the probe length due to the arrangement of the probes. A shorter probe length reflecting the length of the probe in contact with the soil was set and the obtained K_a was compared with the value gained with the full probe length. That this significantly influences K_a is easy to understand if equation (15) is considered. The size of the deviations is, however, surprising. For the two-wired probe type in system C, a setting 1 cm shorter in the probe length parameter setting gave a 7 % lower value than a setting with the total probe length. Corresponding values for 2 and 3 cm were 15 % and 20 % and these values seems reasonable for the probes in this set up. The three-wired probe type in system D is, on one hand, made in a way such that a shorter length of the rods looses soil contact. On the other hand, the probe is shorter which make deviations even greater. Assuming 1 cm of non-soil contact gives a K_a value 16 % lower than a parameter value using the total length of the probe.

In the latter case these deviations were compensated by calibration with a trace off-value. in addition, the bending of the cylinder wall influences the probe set up in a way that the outer rods get a slightly shorter contact with the soil than the middle rod. Another effect of the wall in a experiment design of this type, furthermore, may be influences of the distribution of soil moisture.

Errors caused when the signal is interpreted

The second type of error which influences the determination of K_a concerns the interpretation of the trace. Interpretations are conducted with software programs controlled by parameter settings. Both software programs used in this paper, PI 100 and AutoTDR interpret the trace by locating inflection points at the trace which determine the beginning and the end of the trace by regression lines and interception points (Figure 7).

A phenomenon that occurred in system B during the measurements in the Nåntuna sand was improper interpretation of the trace. At nearly saturated water contents the software PI 100 was not able to recognise the inflexion point at the end of the trace as the trace under these conditions became very flat. The result is unreasonable high values of K_a and soil water content. This type of error has also been observed by Campbell (1995) in other soil types. A solution to this problem would be to use cables with a shorter rise time. Ledieu et al. (1985) are correct when they suggest a cable of 75 ohm impedance and with shorter rise time as a solution to this type of problem.

In PI 100 it is not, furthermore, possible to set any parameter which influences the way the trace is interpreted. In AutoTDR, however, two parameters, SmoothWindow and RegressRange influence the way the trace is evaluated. The result of the settings can be conveniently and quickly evaluated by eye as the trace is displayed.

SmoothW has a critical value where the interpretation changes significantly. This is the value of the settings when deviating points of the trace are excluded by the filter function. In other words, small changes on the trace which were earlier identified as inflection points are smoothed through the filter function and the inflection points are moved. The desired value of SmoothW is obtained when the filter function excludes noise interference near the beginning and end of the trace but where the real beginning and end of these points are not moved. In the case examined, this value is apparently situated somewhere between (5) and (10) because of the significant difference in the resulting K_a-value for these two settings. This also corresponds rather well with the value (8) obtained when the default function was used.

RegressR is theoretically correct when the smallest possible value (5) is chosen. This is when the regression line's slope corresponds best to the slope close to the inflection point. However, if the inflection points have been moved when SmoothW filtered the trace then a larger value of RegressR could give a more accurate interpretation. The two parameters have to be matched for an optimal interpretation of the trace.

It is also important to remember that these tests were conducted with few probes and also with only five measurements on each probe. The results above are therefore to be seen as an indication on how the two software programs evaluate the two types of probes. An extensive statistical analysis of this is, unfortunately, out of the scope of this study.

Comparison of software

The advantage of using a PC and AutoTDR compered to a logger and PI 100 is considerable. First the evaluation of the trace could be made by eye, on the computer screen where the trace is graphically displayed, immediately after the measurement. This saves time during for example, an installation of a system. Secondly, re-evaluation is possible in a direct and convenient way. Lastly, TDR measurements are conceptually difficult to comprehend and immediate interpretation of the graphical trace is educational.

Another observation when PI 100 was used concerns the propagation velocity. The velocity is set in PI 100. If the setting on the cable tester doesn't correspond to the

value in the programme, then the apparent cable length will change. As a consequence the programme will start to search for the trace in the wrong place. This is displayed on the oscilloscope of the cable testers as a brief glimpse of the trace followed by a long search for the trace. In the end when the trace is not located an enlargement of a discontinuity somewhere along the cable is shown. The values of K_a are then typically small (Ka<1). In AutoTDR this error will not occur since the programme reads the settings on the cable tester through an interface.
In general, system D with the three-wired probe and PC for storage of data evaluated by the software AutoTDR, seems to be more reliable and robust than any of the other systems. This is because of a high reproducibility and the possibility to re-evaluate the trace which can increase the precision of the measurements. The software interpreted the traces measured in different water regimes without any failure of the type occurring when PI 100 evaluated the Nåntuna sand under near-saturated conditions. Sometimes, however, the program fails to recognise the beginning of the trace, followed by a message to move the trace on the cable tester's oscilloscope. This is probably due to the fact that the first peak of the trace, in some cases, is fairly large. The running of the program is also sometimes interrupted if the wrong probe type is given in the parameter setting. Then the programme has to be started up again and the parameter setting has to be given once more. An error message would be preferable.

Re-evaluation of trace by AutoTDR also allows calibration against a single calibration-point by the use of a trace off value. The single point can be chosen most conveniently either at the saturated water content or at the residual water content.

Suggestion on system design

By using a system similar to system D, with the possibility of re-evaluating the trace by adjusting the parameter settings, precise measurements can be conducted. It could be especially convenient in soils where data of saturated water content or the residual water content are known since no separate calibration method nor calculation of specific calibration functions are then required. Further measurements in different soils such as clays and organic soils are required before it is possible to say anything about AutoTDR's usefulness in all types of soils. It would also be desirable to test the system during a longer period with an automated version of the system.

Conversion of K_a to θ_v

The calibration function (eq.22) found for system B and the Nåntuna sand showed a better fit than equation (1). For Baskarp, however, the function (eq.21) gave lower values than obtained both from the tipping buckets and calculated values of equation (1). This is a consequence of the constructed points of the two curves. The constructed point of the Nåntuna sand is situated near saturated conditions and is well estimated. It is also this range of the curve that holds the largest volumes of water, the significant part when accumulated volumes are measured. In the Baskarp sand the very low soil water contents are represented by a constructed point. The water content is here overestimated which results in a curve with a too flat slope and too low volumes of drained water.

The different characteristics of the two sands could also contribute to uncertainties. The Baskarp sand transports water very fast during a filling event and air could also easily get trapped in this condition. The water content near saturation may vary and might not be well described by a single calibration curve. Nåntuna, on the contrary will fill up more slowly, preventing air from getting trapped. During the installation of the probes, however, pockets with drier material were observed in the Nåntuna sand.

Soil properties influencing K_a

The choice of two sandy soils to conduct the TDR measurements in, decreased the influence of soil properties such as tightly bound water, soil bulk density and salt concentration on K_a. A widely used relationship (equation 1), however, did not describe the absolute soil water contents in these two sands as well as expected. Instead, new calibration functions for the two sands were determined and one of them was shown to describe the relationship better than equation (1).

Development in TDR-technology

Finally, a few words about the development of the TDR-technology. A trend in TDR-systems design is that the cable tester is replaced by smaller units. A portable version of TDR is TRASE that allows measurements without a separate calibration method but with lower accuracy than permanent systems (Soil Moisture Company, 1997). Two other systems of pocket size are Soil content reflectometer CS 615 (Campbell, 1997) and TRIME (IMKO,1997). The former is designed to be used in combination with a logger and the latter can either be operated together with a logger or a PC. The manufacturers promise deviations less than about 2% from the actual water content. This is still not near the accuracy of less than 1% gained in many permanently installed systems (Topp et al., 1980; Ledieu et al., 1985) but may be sufficient for many purposes. These types of portable systems are specially well suited to sporadic measurements on probes installed over a large area.

Another trend in system-design is the development of highly automatic permanent systems. These systems are computer-based and can be monitored remotely by for example, a mobile phone and a modem. The data from the measurements can then be collected as the station is called up and transferred using internet. This, of course, saves time when TDR measurements are conducted at remote sites. TDR has also been used as a calibration method for remote sensing techniques conducted from aeroplanes or satellites. These techniques have previously been limited by shallow resolution depths but measurements to a depth of one meter have to date been conducted.

CONCLUSIONS

- Errors in TDR-measurements can be divided into two groups: Errors influencing the determination of the dielectric constant, K_a and errors which occur when K_a is converted to soil water content, θ_v. The first type is often caused by improper instrumentation while the latter type often occur when the influence of soil properties on K_a is neglected.

- Long cables, multiplexer-devises and probes with long transmission zones that causes relative large energy losses of the system all contribute to errors in the measurement of K_a. The implementation of general equations in very dry conditions or in conditions near saturated contribute to another source of error when θ_v is considered.

- Probes with a distinct transmissionzone and cables of 75 ohm decreases relative energy losses which increases the accuracy of the determination of K_a. The accuracy of measurements in very dry conditions or at conditions near saturation is improved when an apropirate equation is choosen.

- When accurate values of absolute soil water content are required a specific calibration of the system is needed. If values of relative changes in water content to describe the dynamics of soil moisture are more important then a general equation such as Topp's equation can be used without further calibration.

- Flexible system design is a strength of TDR but the different components must be matched to function together for accurate measurements in a certain type of soil. This advantage of flexibility can, however, also be a weakness if the knowledge on proper system design are lacking. One important property of a system is a probe type with a distinct transmission zone that allows accurate interpretation of the trace by software.

- Re-evaluation of traces can improve the interpretation. Individual parameter settings can improve the accuracy of the measurements compared with using default functions. In AutoTDR this evaluation is conveniently done by eye directly on the computer-screen. A trace off-set parameter allows easy calibration at conditions where a good fit of the general equations can not be expected.

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I. APPENDIX: TERMS AND SYMBOLS

A = area (m^2)
c = speed of light ($3\ 10^8\ ms^{-1}$)
C = electric capacitance (F)
e = electric permittivity constant (-)
EC = soil bulk electrical conductivity (sm^{-1})
f = temperature coefficient (-)
j = the imaginary number $(-1)^{1/2}$
k = cell constant (m^{-1})
K = dielectric constant (-)
l = length (m)
p = reflection coefficient (-)
Q = electrical charge (C)
R = total resistance (ohm)
S = specific surface (m^2g^{-1})
t = travel time (ns)
$tan\ y$ = dielectric loss(-)
T = temperature (°C)
u = magnetic permeability
v = velocity propagation (nm/s)
V = voltage (-)
w = angular frequency (-)
Z = impedance (ohm)
θ_V = volumetric water content ($cm^3\ cm^{-3}$)
σdc = zero frequency conductivity
δ = soil bulk density ($g\ cm^{-3}$)

II. Appendix: TROUBLESHOOTING

The display cable tester's shows us possible mismatch of the system. Below some symptoms that occurred during the experiments are given causes and solutions.

Symptoms Causes Solutions

"Noisy" signal

electrical losses due to long cables, short probes, several levels of multiplexers

shorten cables, change to cables with an higher impedance e g 75ohm instead of 50 ohm. Longer probes.

that is fluctuating

check grounding of system, interferences on coax-cables from extern cables- install an external ground (other than the power-supply) on site, shield coax-cables

Clear signal

Ka too low after long search -setting of cable length/ vp wrong

air-spalting (clays) –reinstall, if not OK change probetype

Ka too high failure of the evaluation program to recognise the end of trace- occure in near saturated conditions

θ_v unreasonable

at very dry conditions or at conditions near saturated – check the equation converting K_a to θ_v, change equation-calibrate the system with an individual equation or use trace-off value if possible. Test the probe by shortcutting it, using for example a screwdriver, near the probe head. If the change in impedance (voltage is shown) that occures on the cable testers osilloscope is gradual and not steep the design of the probe itself contribute to energy-losses which lowers the precison of the measurements.

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Sveriges Lantbruksuniversitet
Institutionen för markvetenskap
Avdelningen för lantbrukets hydroteknik
Box 7014
750 07 UPPSALA

Tel. 018-67 11 85, 67 11 86

Swedish University of Agricultural Sciences
Department of Soil Sciences
Division of Agricultural Hydrotechnics
P.O. Box 7014
S-750 07 UPPSALA, SWEDEN

Tel. +46-(18) 67 11 85, +46-(18) 67 11 86