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AN AUTOMATIC TIME DOMAIN REFLECTOMETRY DEVICE TO MEASURE AND STORE SOIL MOISTURE CONTENTS FOR STAND-ALONE FIELD USE

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A b s t r a c t. A field setup was developed to measure soil moisture content on ten different positions using the Time Domain Reflectometry (TDR) technique. The setup has been designed to meet specific field demands, such as a complete independency of an external power source, a low power consumption, long-term use without the need for maintenance, and compact dimensions. The system consists of a microprocessor driven TDR instrument connected to a palmtop computer through a serial RS232 communications line. The system is controlled from the palmtop computer incorporated in the design. Type of measurement, such as water content, dielectric constant or pulse travel time can be chosen. Also, the measuring interval can be selected between one minute and twenty-four hours in one minute intervals. Data retrieval from the system is reduced to simply exchanging the PCMCIA memory-card from the palmtop computer. The system is powered by a 12V battery/solar panel system. During the first tests a number of errors in the software were found and a problem with the power supply was detected and was subsequently put right.

K e y w o r d s. Time Domain Reflectometry, TDR field device, data logging, soil moisture content

INTRODUCTION

Since the introduction of Time Domain Reflectometry (TDR) techniques for soil moisture measurement applications [9], great progress has been made in the development and the perfection of this technique concerning accuracy and automation. The first TDR systems, used for measuring soil moisture, were based upon analogue and later on digital models of the Tektronix cable tester [3,9-11] and were operated manually. Later automatic systems based upon Tektronix cable testers were presented. Baker and Allmaras [1] introduced two systems. (i) An analogue system consisting of a Tektronix 1502 cable tester, a 12-position multiplexer and a Campbell CR21X data logger to control the system and to store the data, and (ii) a system built around a digital Tektronix model 1502B cable tester, using a 12-position multiplexer and a PC to control the setup and to store the data. Both systems needed an electricity main connection.

Wraith and Baker [12] presented a modified system that was similar to the analogue system of Baker and Allmaras. However, this system was working on two 12 V batteries instead of a main connection. Henkelrath *et al.* [5] also used a battery powered system based upon a Tektronix cable tester, a 12-position multiplexer and a Campbell 21X data logger writing the measured digitized TDR reflections to a magnetic tape. Heimovaara and Bouten [4] built a 36-channel TDR system that was especially intended for use on a remote forest location. They used a Tektronix 1502B cable tester, a laptop computer and a set of Joslyn RF coaxial switches to multiplex the

TDR signals. The data coming from the cable tester were written to a floppy disk inside the laptop computer, which also controlled the system. The system was powered by a 12 V battery that was exchanged regularly. In a later system the laptop PC was replaced by a custom microprocessor board with a floppy disk drive (Heimovaara, personal communication). Malicki and Skierucha [6] introduced a manually controlled TDR device that was based upon a pulse shaped signal instead of a step pulse used in all the Tektronix systems. Later this device was developed into a computerized system intended for laboratory use [7]. A further development of this system into a field system is described in this paper[1].

The ideal TDR device for use in the field would be a device that (i) uses very little energy and is independent of any main electricity connection, (ii) can store almost an infinite amount of data, (iii) needs no maintenance, (iv) is small in its dimensions, and (v) has the property that measured data can be retrieved from the system very quickly. The devices, which are listed in the short overview given here, lack in one or more of these points for application on remote field sites. The most important bottlenecks are power supply/power consumption and data storage. Power consumption is very often a problem with battery-powered TDR equipment because of the relatively large amount of energy needed to generate the pulse signals. Also, the multiplexing system often consumes relatively much more power. The longer it takes to do a single measurement, the more power the system will consume. So, the duration of one measurement, or the speed of the device, is important. Data storage can be a problem if the calculated water content is not stored, but the TDR reflectogram has to be stored thus much data space for every measurement is needed. The disadvantage of the early Tektronix-based systems was that they had to store the complete reflectograms that were then processed in the laboratory. Later, this processing was done on the PC that was part of the system, so that water contents could be retrieved immediately.

It was our purpose to build a TDR system for use in the field that has improvements compared to already existing equipment. We tried to concentrate mainly on two items; power consumption of the system, and data storage. These were the points that attention was especially paid to when designing the system.

Although the emphasis of this paper lies more on the technique of the system, its purpose is not only to inform developers of TDR-systems. Also people who use TDR for their research are addressed by informing them about developments in TDR-technique. Because this is a description of the TDR-system that we developed, and not a paper about some scientific hypothesis, a measurement series is shown as an illustration and not to draw any kind of scientific conclusion.

DESCRIPTION OF THE TDR SYSTEM

The TDR system presented in this paper can be divided into three main parts: the TDR instrument itself, the computer and the power supply, as can be seen in Fig. 1. These three parts will be discussed separately. Technical details about the main components used, can be found in Table 1.

The TDR instrument

The system that was designed is based upon an improved TDR instrument developed for use in the laboratory [6]. The instrument can be operated by an RS232 serial interface line of a PC or a terminal and reacts to commands sent over this serial line as a string of ASCII characters. So, by connecting the device to a PC an automatic setup can be realised

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1 A development in another direction was followed by commercial companies who developed custom TDR equipment not consisting of different sub-systems but devices that combined this equipment in a single device [2,8].

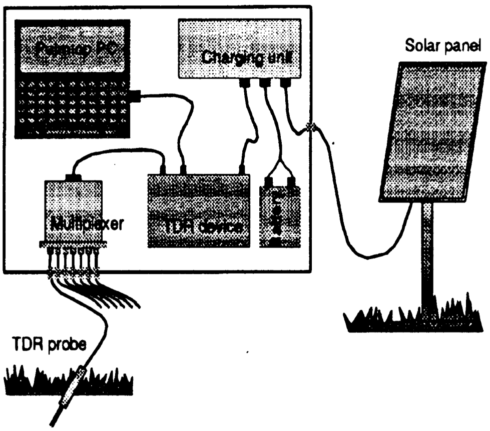

Fig. 1. A schematic overview of the system. The TDR device, palmtop computer, power supply and the multiplexer are housed inside a steel cabinet. The solar panel is attached outside the cabinet.

to do volumetric water content measurements. Because the instrument can operate only one TDR sensor simultaneously, a ten-position multiplexer is added to be able to connect ten sensors to the system. The fast needle shaped pulses used, contains harmonic components into the gigahertz region. This is the reason we used a special high frequency coaxial type to multiplex the signals with the least possible distortion. Using a latching model reduces the power consumption of the system. A 100 mA pulse of only 10-ms duration is needed to set the switch in the right position.

In the prototype of our design ten sensors were connected. The electronic circuits inside the TDR instrument are built in this way so that it is possible to connect up to 255 different sensors when coaxial switches are added. When more than ten sensors are being used, second level multiplexers have to be connected to the first level multiplexer. The quality of the switches is such that this is possible to 'chain' more levels of devices without quality loss of the signal. Special attention should be paid on the quality of coaxial connectors and the precision of their installation on cables connecting first and second level multiplexers. This also counts for the connectors attached to the end of the TDR probe cables. The coaxial cables used, should have low attenuation, especially when the probes are located at long distances from the TDR device.

The sensors were of the two-rod type that were introduced earlier [6]. The rods were 10 cm long, made of 2 mm thick stainless steel, set 15 mm apart and were moulded into a PVC tube. The length of these tubes varied from 15 cm to 3 m. This made it possible to choose the desired length for vertical (through the surface) or horizontal (buried) installation. The cables of the sensors had a length of 4 m. A reference 'sensor' was added to the system to compensate temperature effects on the electronics of the instrument and the temperature effect on the sensor cables. This reference 'sensor' consisted of a piece of cable with an accurately known characteristic. Every time when a series of measurements was done this cable was also measured and these results

Table 1. The main components of the TDR-system and their technical specifications

Component	Technical details
HP95LX palmtop computer	Fully compatible 'IBM'-PC computer. Dimensions: 16x8.5x2.5 cm. Power consumption: 60 mA @ 9V battery voltage. Memory cards: HP 512 KB. Manufacturer: Hewlett-Packard
TDR - device	Needle-pulse operating TDR device. Power consumption: 450 mA @ 12V while measuring. Measuring time per probe: 18 s
Multiplexer	10-position coaxial switch. Connections: SMA connectors. Bandwith: 18 GHz. Uses BCD coded signal for switching. Power consumption: 100 mA pulse @ 12V (10 ms, latching). Type number: K&L, 10-MP-12-F-SMA-I-BCD. Manufacturer: K&L, USA
Solar system	Solar panel connected to a 12V battery via a chrging regulator. Solar panel: Siemens M24, 24W panel. Regulator: Siemens LR/07 EK. Battery: general type 12V, 6.5 Ah battery
Housing	Steel, 38x30x21 cm cabinet. Manufacturer: Rittal, type AE1031

were used for compensation of the measurements of the 'real' sensors.

Because the TDR instrument consumed a lot of energy (450 mA at a supply voltage of 12V) it could not be left switched on when no measurements were done. To deal with this problem a special mechanism was designed. A small low power circuit reacted to the presence of characters on the serial line going to the TDR instrument by switching on the power supply of the TDR unit. When the instrument is 'awake', the computer can send commands to it to do measurements. The multiplexer was driven directly by the microprocessor inside the TDR instrument. The desired position of the switch was coded through the measuring command coming from the PC. After doing the measurement the power supply of the TDR instrument could be switched off by issuing a special command from the PC.

The computer

The computer in the system has the function of controlling the system, initiating the measurements and storing the data. For this purpose a Hewlett Packard HP95LX palmtop computer was used. The computer has built-in software that can be used to put it into a kind of low power 'sleep'-mode. While in this 'sleep'-mode the computer uses practically no power. A built-in timer can activate the computer at a programmed time and continue program execution.

In short it works as follow: the timer inside the computer activates the computer and the control program starts running. This control program wakes up the TDR instrument by sending a message over the serial line. The TDR instrument sends back a message to confirm that it is active. After this, the computer can start sending measuring commands to which the TDR instrument responds by returning measurement results. The computer receives these values over the serial line and stores them in a data file on the PCMCIA memory-card (credit-card-size memory-card). When all desired measurements are done the computer puts the TDR instrument to sleep by sending the corresponding command. Next the program sets its internal wake-up timer and switches off its own power.

The measured data were written to the PCMCIA memory-card of the computer together with the Julian day number and the measuring time as a fraction of the twenty-four-hour cycle (for instance 35.99653 for the time 23:55 on 4th February). When a 512-kbyte RAM-card is used, this card would have enough capacity to store 6900 measurement values, which is equivalent for measuring one cycle of nine measurements every two hours during 568 days (1.5 year).

The configuration of the experiment can be stored in two separate files. In the first file the calibration data of all connected sensors are entered. Also, the channel to which the reference cable is connected and its length is entered. In the second file is entered: the name of the file to which the data has to be written, the interval between two measurement cycles, which can vary between 1 and 1440 min (24 h), the number of repetitions that have to be taken over which an average will be calculated per measurement, the type of measurement that has to be stored in the data file (vol. % water in m^3m^{-3}, dielectric constant (-) or travel time of the needle shaped pulse (ps) along the sensor rods) and data about what sensor number is connected to what multiplexer port. The program uses these data files to control the setup.

Because the data are written to a PCMCIA memory-card, the collection of the data is reduced to simply exchanging this memory-card with an empty one. After returning from the field the data file on this card can be transferred to a PC by means of another HP95LX, memory-card reader or a PC having a PCMCIA disk drive. Because the data is written in ASCII format, importing the file in a spreadsheet or a text processor to process is very easy. It can also be convenient because the data file is readable.

Power supply

Because of the often moist conditions in the field, working with voltages that are not dangerous is safer, for example voltages lower than 42 V. In our case the TDR instrument was powered with 12 V, and the computer was powered with 9 V. Because the complete system uses only 2 Ah every twenty-four hours when measuring ten sensors every half hour, it becomes possible to power the setup with a solar panel/battery system. This would be practically impossible for a system with a large power consumption. For the battery we used a type that supplyed the system with energy for three days without any charge from the solar panel. To recharge the battery we used a solar panel with a solar charging regulator. The charging regulator was necessary to regulate the charging of the battery, so it would not be overcharged. It also switched off the system when the battery was drained below 8 V, to prevent the battery from being damaged. The panel/regulator combination was designed to be able to charge a fully discharged battery within one day of sunshine, (under conditions in the Netherlands). Even with a completely overcast sky the solar panel would still give some energy to slowly charge the battery.

Fig. 2. Inside view of the device where the TDR device (top), and the palmtop computer can be seen. The equipment is housed in a steel cabinet and is mounted on a steel rack with the solar panel on top.

Housing

The whole system (Fig. 2) is housed in a steel cabinet mounted on a stainless steel rack. On top of this rack the solar panel is mounted. The solar panel screens the cabinet from direct sunshine to prevent the inside from heating up too much. The solar panel can be tilted in the direction of the solar orbit to collect the maximum amount of sunshine. The cabinet itself has to be placed with its back heading south. The sensor cables are led into the cabinet through a PVC plate in the bottom of the cabinet, using cable glands.

TEST OF THE TDR DEVICE

A prototype of the instrument was tested continuously during a two-month period. The cabinet was installed with its back facing south. Eight sensors were installed vertically into the heavy clay soil, under a 30-degree angle from vertical to prevent rainwater from running along the sensor rod into the sensor hole. The sensors were installed at depths varying from 10 to 60 cm close to the cabinet. This was first intended to test the reliability of the system. The system worked well over the whole period, except a few software bugs that turned up during these months. The retrieval of measured data, by means of exchange of PCMCIA RAM-cards, turned out to be ideal. It took less than a minute to retrieve the data measured during a period of weeks. We noticed that during a period of two months the battery voltage never dropped below 12.5 V in the period of June-August 1993. In one period the sky was overcast during a whole week. At the end of this week the solar panel had not charged the battery enough to keep its voltage and the system stopped. After this incident we had to conclude that the battery did not have capacity enough to last a long period without direct sun. This means that we will have to increase the battery capacity.

After this first test we decided to do a second test on the DLO Winand Staring Centre experimental field station. Because we did not calibrate the sensors to the soil that was present on the test site, the absolute accuracy of the measurements is limited to about 6 to 7 % [6]. The system was installed to monitor the soil water behaviour for a longer period (Fig. 3). In Fig. 4 the soil moisture content is plotted against time for a period of eight days. Three sensor values are shown at depths of 10, one at 30 and one at 50 cm below the surface. The second and third trace at 30 and 50 cm below the surface are left out for clarity. As can be seen in the 10 cm traces, the accuracy of the automatic measurements laid well in the 6 to 7% range of the manual measurements. The plot where the sensors were installed was surrounded by a small embankment that was subsequently flooded with water. The graphs

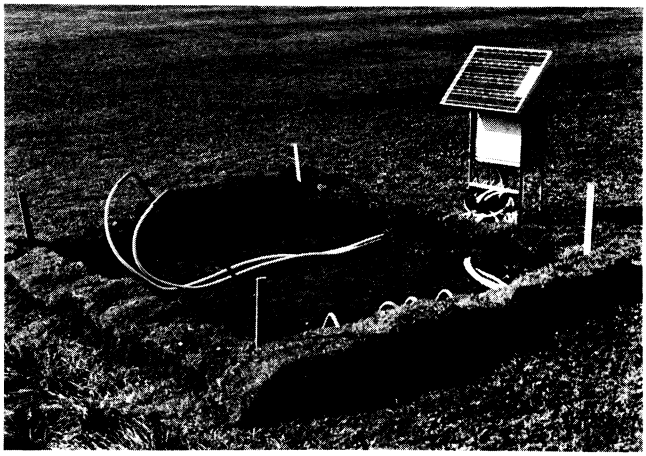

Fig. 3. Installation of the TDR system at the experimental field station. The grass was taken away from the experimental plot and was surrounded by a small embankment that was subsequently flooded with water.

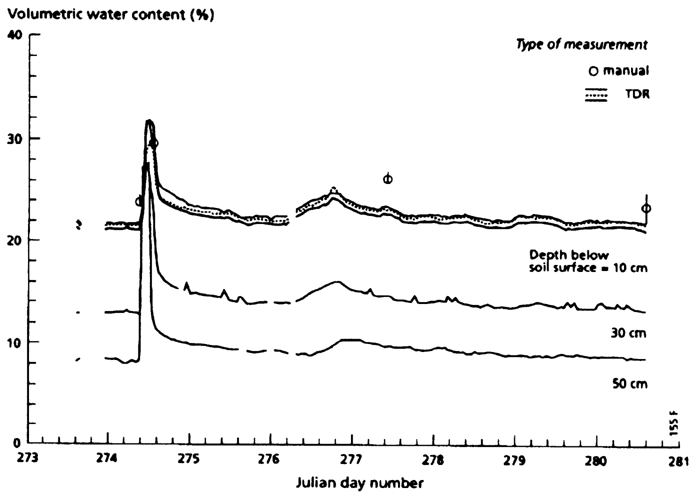

Fig. 4. Three sensor values at depth of 10, one at 30 and one at 50 cm below the surface during an eight-day period. The individual points, shown as circles, show measurements taken from 10 cm depth. They have been determined using the thermo-gravimetric method. The error bars through the circles show the variation of three different samples.

show a sharp increase in volumetric water content that also quickly disappears again due to transport to deeper layers. At the end of day 276 an increase in water content can also be observed. This is due to rainfall during this day. Note the time delay in the measurements of the deeper sensors.

One multiplexer channel gave some strange results, probably due to malfunctioning of the multiplexer relay. These errors can be seen as gaps in one of the measurement curves (-30 cm). We think that the corresponding multiplexer position had a bad electrical contact, because none of the other channels showed this effect. A software (timing) error caused a gap in all five graphs during day 276.

CONCLUSIONS

During the experiments a few problems occurred. We found some bugs in the software that had to be corrected. Further on we discovered that the battery capacity was too small. This problem can be easily solved by using a battery with a larger capacity. In this way we could probably bridge a longer period without direct sunshine. A third problem was caused by a malfunctioning multiplexer relay. We assume that this is caused by a manufacturing fault since it only appeared on one channel, and the rest of the channels did not cause any problem. We experienced that the means of data retrieval was very convenient. Also, the fact that large amounts of data can be stored onto a very small medium was convenient. Because of the solar panel/battery power-system the device can be installed quickly, also at remote sites, without having to worry about power supply facilities. Because the TDR device itself is controlled from a computer by means of the serial communications line, this provides the possibility to expand the system with other devices that also have this option. With this a flexible and very compact measuring system can be built for measuring various parameters in the field.

REFERENCES

1. **Baker J.M., Allmaras R.R.:** System for automating and multiplexing soil moisture measurements by time-domain reflectometry. Soil Sci. Soc. Am. J., 54, 1-6, 1990.
2. **Dalton F.N.:** Development of time-domain reflectometry for measuring soil water content and bulk soil electrical conductivity. In: Advances in Measurement of Soil Physical Properties: Bringing Theory into Practice (Eds G.C. Topp, W.D. Reynolds, R.E. Green). SSSA, Spec. Publ. No. 30, Soil Sci. Soc. Am. Inc., Madison, USA, 143-167, 1992.
3. **Dasberg S., Dalton F.N.:** Time domain reflectometry field measurements of soil water content and electrical conductivity. Soil Sci. Soc. Am. J., 49, 293-297, 1985.
4. **Heimovaara T.J., Bouten W.:** A computer controlled 36-channel Time Domain Reflectometry system for monitoring soil water contents. Water Resour. Res., 26, 2311-2316, 1990.
5. **Henkelrath W.N., Hamburg S.P., Murphy F.:** Automatic, real-time monitoring of soil moisture in a remote field area with time domain reflectometry. Water Resour. Res. 27(5), 857-864, 1991.
6. **Malicki M.A., Skierucha W.M.:** A manually controlled TDR soil moisture meter operating with a 300 ps rise-time needle pulse. Irrig. Sci., 10, 153-163, 1989.
7. **Malicki M.A., Plagge R., Renger M., Walczak R.T.:** Application of time-domain reflectometry (TDR) soil moisture miniprobe for the determination of unsaturated soil water characteristics from undisturbed soil cores. Irrig. Sci., 13, 65-72, 1992.
8. **Skaling W.:** TRASE: a product history. In: Advances in Measurement of Soil Physical Properties: Bringing Theory into Practice (Eds G.C. Topp, W.D. Reynolds, R.E. Green). SSSA Spec. Publ. No. 30, Soil Sci. Soc. Am. Inc., Madison, USA, 169-185, 1992.
9. **Topp G.C., Davis J.L. , Annan A.P.:** Electromagnetical determination of soil water content: Measurement in coaxial transmission lines. Water Resour. Res., 16, 579-582, 1980.
10. **Topp G.C., Davis J.L., Annan A.P.:** Electromagnetical determination of soil water content using TDR. I. Application to wetting fronts and steep gradients. Soil Sci. Soc. Am. J., 46, 672-678, 1982.
11. **Topp G.C., Davis J.L.:** Measurement of soil water content using time-domain reflectometry (TDR). A field evaluation. Soil Sci. Soc. Am. J., 49, 19-24, 1985.
12. **Wraith J.M., Baker J.M.:** High-resolution measurement of root water uptake using automated time-domain reflectometry. Soil Sci. Soc. Am. J., 55, 928-932, 1991.