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A manually controlled TDR soil moisture meter operating with 300 ps rise-time needle pulse*

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Summary. The principle of operation of a simple, manually controlled Time-Domain Reflectometer (TDR meter) for soil moisture measurements, which operates with a needle pulse of 300 ps rise-time, is described. A block diagram and constructions are also given. Construction of a switchless multiple sensor probe, having an inherent delay reference, is presented. Results of measurements of the soil dielectric constant as related to water content, for soils having different bulk densities, textures and humus content show a high correlation. The results agree closely with other investigators measurements with different, more expensive, TDR instruments. The general principle of microprocessor-controlled TDR-operated soil moisture meter is considered.

Recent advances in fast rise-time pulse technics have allowed the extension of application of Time-Domain Reflectometers (also called cable radars) beyond testing telecommunication lines. The increase of the resolution of a transmission line impedance discontinuity location made it possible to apply TDR for dielectric constant measurements, using a suitably short waveguide segment as probe (Fellner-Feldegg 1969). A coaxial transmission line method was first applied by Davis and Chudobiak (1975) for soil moisture investigations. Chudobiak et al. (1979) applied an open end parallel transmission line for investigations of moisture dynamics on curing concrete. This has become essentially the base for the rapid development of the TDR techniques for the soil water regime investigations. The sampling oscilloscope (TEKTRONIX) provided with a TDR plug-in cable tester module (Topp et al. 1982; Dasberg and Dalton 1985) as well as a portable commercial cable tester (TEKTRONIX) have been used (Hayhoe and Bailey 1985; Topp and Davis 1985; Ryden 1986). Both instruments operate with step voltage pulse of 45 ps and 140 ps rise-time respectively.

The TDR technique, as related to the electromagnetic wave propagation phenomenon, is not burdened by the interfacial processes inherent for the Frequency-Domain electrocapacitance measurements, therefore its implementation for investigations on

* Patent pending

the soil water regime seems promising. However, the TDR instrumentation needs a fast rise-time step pulse, of about 100 ps (during 100 ps, light in free space covers the distance of 3.3 cm). This makes it difficult to design such instruments and causes the relatively high price of commercially offered devices (the IRAMS model 6000 TDR soil moisture meter is probably the only one available for soil science measurements at present).

However, to use the TDR method for reading the capillary-porous materials dielectric constant, the pulse does not have to be step-shaped. As explained below, this shape of the pulse does not seem the best choice in such an application. Also the fidelity of the pulse shape reproduction, one of the crucial parameters of commercial TDR cable testers, is not important. Therefore a TDR based device for measuring soil moisture need not be sophisticated or expensive. Based on these concepts, such an instrument has been developed. It is the purpose of this paper to share experience with those who are interested in more complete understanding of TDR-based device operation as well as in designing such instrumentation, tailored to their particular needs.

TDR system background

The principles of TDR can be easily found in any textbook on telecommunications as well as in many recently published articles concerning its application for the soil moisture measurements. Thus we will limit our review to the extent necessary to make this paper convenient to read without referring to the sources.

The TDR, as applied to dielectric constant measurements, is based on the relationship between the velocity of electromagnetic wave propagation and dielectric constant of the medium the wave propagates in. For nonmagnetic materials, having low dielectric loss, this relation can be simplified to:

$$V=\frac{c}{\sqrt{K}}, \tag{1}$$

where: V – electromagnetic wave propagation velocity, c – velocity of electromagnetic wave (light) propagation in free space, K – relative apparent dielectric constant of the medium the wave propagates in.

The probe, built from two parallel rods forming an open parallel line (waveguide), is embedded into the soil (Fig. 1). A feeder (coaxial cable waveguide) provides the probe with a needle voltage pulse. On instant t_1, when the pulse reaches the probe input, part of its energy is reflected back from the discontinuity in the line electrical impedance at the feeder-probe interface. The reflection coefficient, r, determines the phase and magnitude of the reflected pulse as compared to the incident one, which, in terms of electrical impedance, is expressed as:

$$r=\frac{Z_p-Z_0}{Z_p+Z_0}, \tag{2}$$

Where Z_0 is the characteristic impedance of the feeder and Z_p is the probe impedance. The rest of the pulse energy enters the probe and runs forward. On instant t_2, when the pulse remainder reaches the end of the probe, another part of its energy is reflected backward. These reflections returning toward the source can be projected to an oscilloscope screen if it is connected to a 'Y' connection in the feeder. The result, as seen on the oscilloscope screen, is shown in the lower part of Fig. 1. The time interval $t=t_2-t_1$ can be measured and K can be then calculated according to Eq. (1) as:

$$K=K(\theta)=\left(\frac{c\cdot t}{2\cdot l}\right)^2, \tag{3}$$

where l is the probe length and θ is soil moisture. The $K=f(\theta)$ relationship can be determined by fitting an empirical curve, such as a polynomial of optional degree, to the $K(\theta)$ experimental data.

Materials and methods

Principle of the TDR read-out operation

The principle of the apparatus operation is shown in Fig. 2. A free running square wave generator, G_f, (frequency of about 1 kHz) triggers the action of a sampling head and two identical pulse generators G, G_s which produce 6000 mV high needle pulses U_1, U_2 of 300 ps rise-time and half-height width. Electrical pulses occurring within such a short time cannot be processed in real time using commonly available electronic devices. For this reason, the sampling technique, as described below, is used.

The leading edge of the free running generator pulse resets the capacitances C_s in the sampling head (Fig. 3) and C in the delay circuit (Fig. 4) respectively and triggers both needle-pulse generators, G and G_s. The triggering action of one of these generators, G_s, referred to as the strobe, can be delayed by a voltage-controlled delay circuit. The pulses feed the probe through the coaxial feeder and undergo the above described reflections.

Sampling head

Both the initial and reflected pulses converge at the sampling head. The sampling head input (Fig. 3) is provided with a voltage gate consisting of a diode, D, reverse biased by a threshold voltage, V_{tr}, set at the level slightly more positive than the highest magnitude among all the appearing here voltage pulses (the initial and the reflected ones) taken separately.

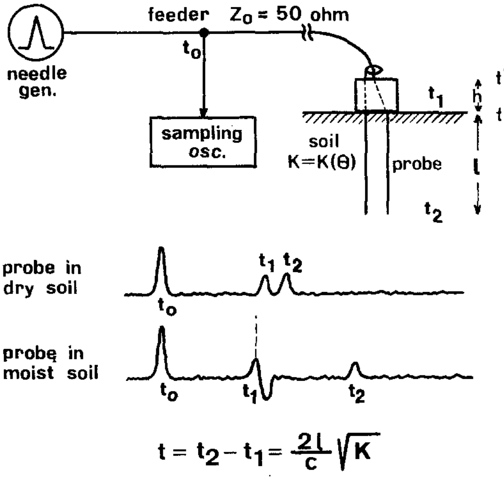

Fig. 1. Principle of TDR-based measurement of the soil dielectric constant. Disturbance of the incident pulse phase, t_1, coming from the interference of the subreflections generated at the instants t' and t'', due to the impedance sub-interfaces contributed by the rods support, can be noticed

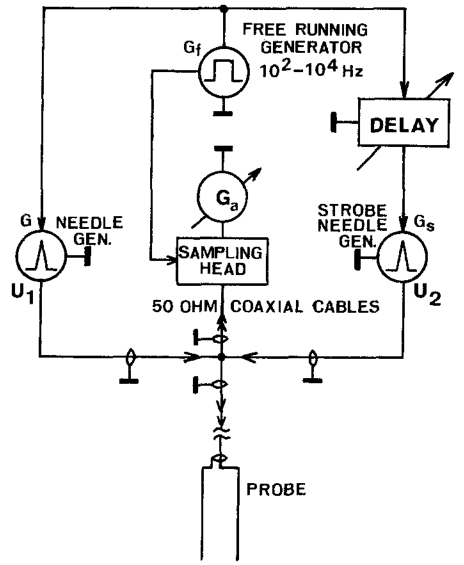

Fig. 2. Principle of TDR-operating soil moisture meter read-out

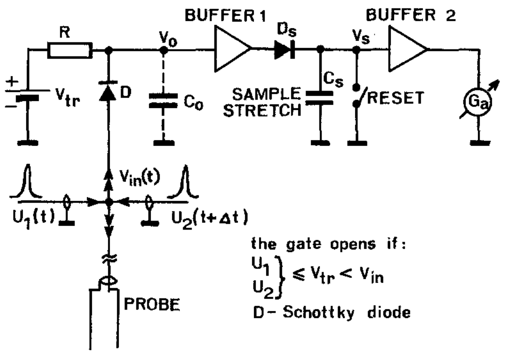

Fig. 3. Principle of sampling head operation

The Schottky diode, D, the fastest among all electronic gates, can be understood as a fast, self-acting valve, which opens or closes respectively to the diode forward or reverse bias. Varying the strobing pulse phase (delay) causes the superposition of the analyzing pulse and the strobing one. The resultant voltage, V_{in}, coming from the pulses superposition, overgrows the gate threshold, V_{tr}, the diode, D, becomes forward biased and the gate opens. Once the gate is opened the input voltage, V_{in} charges up the capacitance C_0 with the charge directly proportional to its magnitude (time of its occurrence is related to that of the strobing half-height, which is constant). When V_{in} falls below V_{tr} the diode becomes reverse biased and the capacitance C_0 discharges through R. The rate of its discharge is inversely proportional to the $C_0 \cdot R$ time constant.

Voltage V_0 developed across the capacitance C_0 is inversely proportional to its value, therefore, due to relatively small charges captured by the gate, C_0 must be small to develop a reasonable magnitude of V_0. In practice, the scattered capacitance of the head input wiring is sufficient. Because C_0 discharge occurs relatively slowly, there is enough time to charge up the capacitance C_s by the buffer 1. The diode D_s and buffer 2 do not allow C_s to discharge, therefore the voltage V_s, which is directly proportional to the peak magnitude of the input voltage V_{in}, remains practically unchanged during the time long enough to process it further. Because the action is repetitive (about 1000 actions per second), tuning the rheostat R_d (Fig. 4), which is

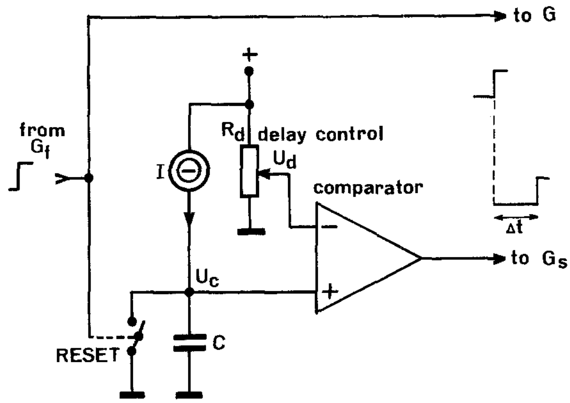

Fig. 4. Principle of the delay circuit operation

responsible for the phase delay the sample is to be taken with, makes it possible to collect many, sequentially phase-delayed samples from many particular single runs, and then, following their time sequence, reproduce the whole single run.

When phases of the manually delay-tuned sampling (strobing) pulse and of the free running analyzing pulse, which is being sampled, agree, the voltage indicated by the galvanometer G_a reaches maximum. Two such maxima are taken into account: first – due to the pulse reflected from a marker and second – due to the pulse reflected from the probe open end.

The measurement consists in reading the delay controlling voltage U_d difference related to these two maxima occurrence as indicated by the galvanometer G_a. Because the delay is directly proportional to the controlling voltage U_d, time necessary for the pulse round trip along the probe length can be directly read from the rheostat, R_d, dial. Once the time t is known, the relative dielectric constant of the soil, K, can be computed, and then the soil volumetric moisture can be found based on a polynomial approximation of the $K = f(\theta)$ relationship.

Delay circuit

Principle of the delay circuit operation is shown in Fig. 4. Current source, I, charges condenser C with constant current. This causes a linear increase of voltage U_c to develop. As U_c reaches the level of U_d, set by the rheostat R_d, the comparator regenerates the leading edge of the triggering pulse with the delay linearly related to the control voltage U_d.

Pulse generators

Both the pulse generators are identical. Fig. 5 depicts their principle of operation. The leading edge of the triggering pulse from the generator G_f (or delay) causes avalanche discharge of the energy stored in a section of an opened 50 Ω transmission line, the length of which determines the resulting pulse half-height width. The R–C in-series bypass improves the pulse shape.

Probes

Single sensor probe. The TDR probe was composed of two 8 cm long parallel steel rods, each 3 mm in diameter, placed 1 cm apart. Prior to the measurements it was found that the probe sphere of influence is a flattened cylinder the height of which is equal to the probe length and with a diameter of about three times as much as the distance between the rods. The rods were fixed to a rectangular bar-shaped lucite support. Because of the support finite thickness, h, the pulse undergoes reflections from the two impedance interfaces it creates with the feeder and the soil surface as is shown in Fig. 1. If the support thickness, h, is not greater than a certain critical value, phase t_1 of the incident pulse reflection is burdened by an error coming from t' and t'' reflections interference. Time t_1 may shift forward or backward dependently on the probe im-

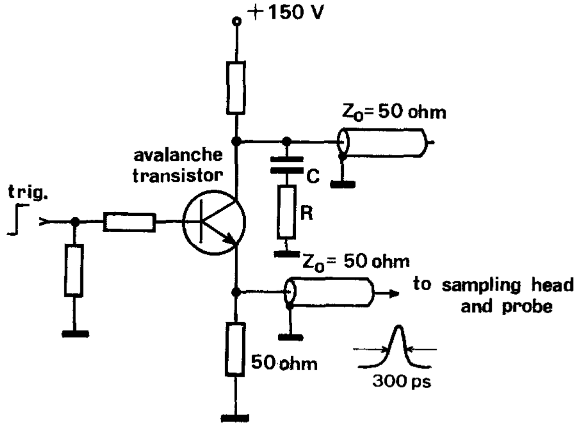

Fig. 5. Principle of operation of the 300 ps rise-time needle pulse generator

pedance as compared to the feeder one. The low-loss parallel line impedance, Z, is expressed as:

$$Z = \frac{120}{\sqrt{K}} \ln\left(\frac{s}{d} + \sqrt{\left(\frac{s}{d}\right)^2 - 1}\right), \tag{4}$$

where K is the soil relative dielectric constant ranging from 2.3 up to about 30 (or more) for dry and moist conditions respectively, d is the diameter of the rod and s is the separation of the rods. For moist conditions the probe impedance is lower than 50 Ω for which the reflection at the instant t'' is in opposite phase to the incident pulse. Then the phase t_1 of the resultant pulse reflected from the feeder-probe interface shifts backward, dependently on the ratio of their magnitudes. Similarly, for dry conditions the probe impedance is larger than that of the feeder and the resultant t_1 pulse phase is shifted forward. To make the phase t_1 well fixed, the $t'' - t'$ interval should not be less than $2 \cdot Tr$, where Tr is the pulse rise-time. Since K for lucite is 2.5 it can be computed, from Eq. (3), that the support thickness, h, should not be less than about 6 cm. To avoid problems with the support, a phase marker was fixed 5 cm apart from the 2 cm thick support. A coaxial 50 Ω cable fed the probe. Its final, 6 cm long, segment connected directly to the probe rods, was substituted by a segment of another, 75 Ω coaxial cable. The impedance interface between these two cables was the marker.

Because of the presence of the isolating support as well as of the 6 cm segment of the 75 Ω transmission line between the marker and the soil surface, the sensor "dead time", t_d, due to round trip along this setup has to be accounted for. It can be determined from the interreflection time measurement carried out on a low-loss liquid of known dielectric constant. Following Eq. (3) the dead time, t_d can be computed from:

$$t = t_d + \frac{2 \cdot l}{c} \sqrt{K}, \tag{5}$$

where K is dielectric constant of the applied dielectric liquid taken from tables.

Multiple sensor probe. Figure 6 shows the multiple sensor probe. Feeders of several sensors, similar to the above described one, meet in the knot Kn. The particular feeder lengths must successively increase. In order to provide the feeders with proper round trip time relations the following condition must be obeyed:

$$t_n = t_{n-1} + t_d + \frac{18}{c} l_{n-1}, \tag{6}$$

where t_n is the time necessary for the pulse to make the knot-marker round trip distance, L_n, for the next longer feeder, t_{n-1} is the time the pulse takes to make the knot-marker distance, L_{n-1},

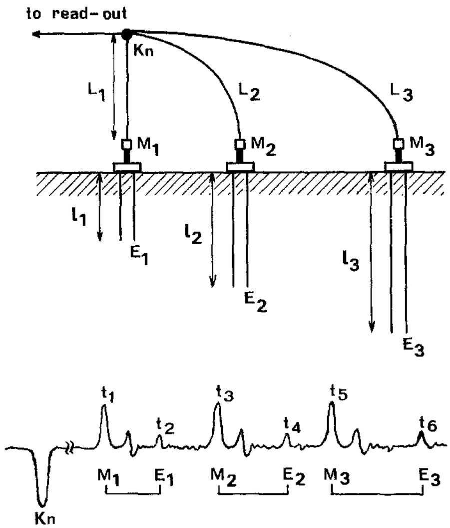

Fig. 6. Principle of the multiple sensor probe operation. Reflections from phase markers, M_n, and sensors endings, E_n, are accounted for. Time intervals t_3-t_1 and/or t_5-t_3 make the inherent delay reference

for the preceding feeder, and l_{n-1} is the length of the preceding sensor. The value of 18 comes from $2 \cdot \sqrt{K_{water}}$.

The bottom part of Fig. 6 shows the sequence of reflections coming from the probe as it is seen on a sampling oscilloscope screen. The average dielectric constant of a particular soil layer can be computed from the reflections time-succession analysis.

Inherent delay reference

Time differences relating to reflections from two chosen markers, M_n, can be utilized as the delay time references to compute corrections for the error coming from the delay circuit drift. Fixing the respective feeders length difference and knowing the specific delay (in ns/m) of the applied line the feeders are made of, it is easy to compute appropriate corrections or adjust the delay control, R_d, dial prior to measurements being taken.

Materials

Reliability of the device as applied for dielectric constant measurements was verified using several media of known dielectric constants. These were: benzene, acetone, water and air. Then, investigations on the moisture – dielectric constant for soils differing in texture and humus content were carried out. Samples of the soils were moistened with tap water and compacted in a glass container. The soil moisture and bulk density for each particular sample were determined. Dielectric constant of samples was measured using the single sensor probe described above, provided with the phase marker and the delay reference established by an appropriate length open end coaxial line, branched at the knot.

Results and discussion

The device proved reliable as applied for non-lossy media dielectric constant measurements. The table below illustrates comparison between the tabulated media and results of the measurements carried out in room temperature.

size class / soil	sand 1.0 – 0.1 mm	silt 0.1 – 0.002 mm	clay 0.002> mm	humus %
o	8	34	58	0.42
□	2	63	35	0.84
+	0	57	43	1.30
•	40	54	6	3.30
Δ	86	11	3	0.00
----	86	5	9	0.16

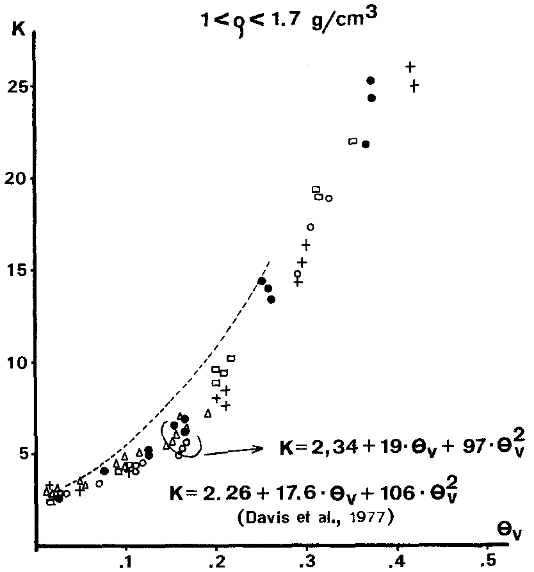

Fig. 7. Dielectric constant versus volumetric water content for the mineral soils investigated

medium	K meas.	K tab.
acetone	20.7	21.4
air	0.96	1.0
benzene	2.21	2.29
water	83.8	81.0

Figure 7 illustrates the relative dielectric constant-soil moisture relationships for the soils investigated taken under laboratory conditions (18–20 °C). The soil texture, humus content and scatter of the samples bulk density are shown in its upper part.

A second degree polynomial was fitted to the data, excluding the soil marked with dashed line. It can be seen that the results are close to those obtained by Davis et al. (1977). The reason for the departure of the dashed line marked soil $K(\theta v)$, as compared to the other relationships, remains unclear (its magnetic properties were not investigated).

A manually controlled TDR moisture meter, like the one described above, cannot be utilized for automatized data aquisition systems (such as data loggers), where microprocessor controlled devices are preferable. The sampling techniques are particularly suited for CPU-controlled implementation for the inherent sample-and-hold mode of its operation. The general principle of operation of such a TDR-operated soil moisture meter implementation is described below.

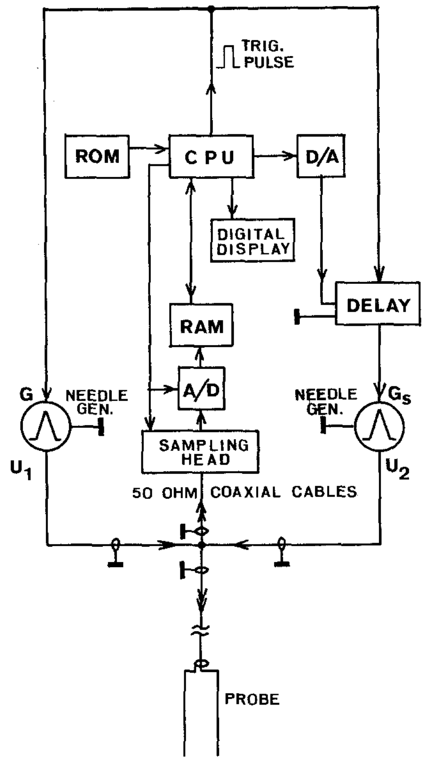

Fig. 8. Principle of operation of microprocessor-controlled TDR moisture meter

Figure 8 presents the principle of operation of the microprocessor, CPU, controlled TDR moisture meter. During each repetitive sampling cycle each particular voltage sample captured by the sampling head is converted into its binary coded equivalent by the analog-digital converter, A/D, and then stored in the random access memory, RAM. When the cycle is over the CPU increments the delay-controlling voltage, thus delaying each sampling by about 20 ps. This is performed by the D/A converter. After the whole single run has been sampled, the voltage sample file stored in RAM is processed in order to find, with reference to the subsequent markers, the time departure between the first and third voltage maxima, as well as the maxima between the respective markers (Fig. 6). The soil moisture content is then calculated as described above and the result is displayed. The controlling program is permanently stored in the read-only memory, ROM. The device can be developed to perform the functions of a data logger by adding a real time clock and a control keypad. The computed results as well as time and depth related to them are then stored in RAM.

The delay unit is the only critical component (with regard to its long-term voltage-delay calibration drift) of a TDR-operated moisture meter. Autocorrections of computations due to the delay drift can be accounted for by utilization of the inherent delay reference as described above. Thermal drift of the reference was found negligible as compared to the shortest time window occurring during measurements on dry soils (the applied 50 Ω coaxial cable delay thermal drift was found equal to 1.5 ps/m/deg whereas the shortest time window was of the order of a nanosecond). It is to be emphasized that the utilization of such a simple and inexpensive delay circuit solution, compared to the commercial TDR units, was made possible by the inclusion of the delay reference measurement as the inherent stage of the procedure.

Data from the literature as well as from the results presented proved that the individual calibration of the TDR based devices for each particular soil is unnecessary for soils developed from similar parent material if a relative error of about 6% is allowable. However, if the demanded accuracy is higher or if there appears to be a large departure between individual soils moisture-dielectric constant relationships, then individual calibration can be performed. This can be done in the laboratory on disturbed samples, using any probe.

The particular application of the TDR apparatus described, as limited to dielectric constant measurements, limits it necessary features exclusively to the time location of the impedance discontinuities. This greatly reduces the demands of the meter when compared with the TDR cable tester. The cable tester has a wider application because it was designed for reflection coefficient measurements as well as for the recognition of the transmission line damage impedance type (capacitive, resistive, or inductive) from the shape of the reflected signal. Therefore a TDR-operated soil moisture meter can be much less sophisticated and much less expensive.

The needle-pulse technique is not only sufficient but may be a better choice, because the reflected, needle-shaped, signals are easy to interpret and are not referenced to the incident signal amplitude but, measured from zero volts, are relatively large.

The multiple sensor probe described seems to produce better determined reflections than the notched probe (Chudobiak 1979; Topp and Davis 1985). The improvement comes because it is not necessary to share the pulse energy sequentially due to the sequential intermediate impedance interfaces of the notched probe.

Conclusions

Application of a needle pulse instead of a step pulse seems to be a better choice for use in TDR-operated soil moisture meters. It is possible to read moisture from several TDR sensors simultaneously without the necessity of switching. This can be done by matching the sensor feeder lengths and connecting them to a common junction.

TDR soil moisture probes should be provided with a well defined phase reference such as a phase-marking pulse coming from a discontinuity purposly introduced in the feeder impedance.

Because soils are very complex capillary-porous media, all conclusions concerning their moisture TDR-based measurements should also be valid for other simpler porous media such as grain, hay and many other agricultural and food industry products.

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