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# Facilitating Soil- and Plant-Water Research Through the Use of TDR

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**Abstract**

The development of TDR for measurement of soil water content and electrical conductivity has resulted in a large shift in measurement methods for a breadth of soil and hydrological characterization efforts. TDR has also opened new possibilities for soil and plant research. Five examples show how TDR has enhanced our ability to conduct our soil- and plant-water research. (i) Oxygen is necessary for healthy root growth and plant development but quantitative evaluation of the factors controlling oxygen supply in soil depends on knowledge of the soil water content by TDR. With water content information we have modeled successfully some impact of tillage methods on oxygen supply to roots and their growth response. (ii) For field assessment of soil mechanical properties influencing crop growth, water content capability was added to two portable soil strength measuring devices; (a) A TDT (Time Domain Transmittivity)-equipped soil cone penetrometer was used to evaluate seasonal soil strength-water content relationships. In conventional tillage systems the relationships are dynamic and achieve the more stable no-tillage relationships only relatively late in each growing season; (b) A small TDR transmission line was added to a modified sheargraph that allowed shear strength and water content to be measured simultaneously on the same sample. In addition, the conventional graphing procedure for data acquisition was converted to datalogging using strain gauges. Data acquisition rate was improved by more than a factor of three with improved data quality. (iii) How do drought tolerant plants maintain leaf water content? Non-destructive measurement of TDR water content using a flat serpentine triple wire transmission line replaces more lengthy procedures of measuring relative water content. Two challenges remain: drought-stressed leaves alter salt content, changing electrical conductivity, and drought induced changes in leaf morphology affect TDR measurements. (iv) Remote radar signals are reflected from within the first 2 cm of soil. Appropriate calibration of radar imaging for soil water content can be achieved by a parallel pair of blades separated by 8 cm, reaching 1.7 cm into soil and forming a 20 cm TDR transmission line. The correlation between apparent relative permittivity from TDR and synthetic aperture radar (SAR) backscatter coefficient was 0.57 from an airborne flyover. These five examples highlight the diversity in the application of TDR in soil and plant research.

**Key Words**: TDR, time domain reflectometry, time domain transmissivity (TDT), soil water, soil and plant water, soil physical behavior, oxygen diffusion, roots, field soil strength, cone penetration resistance, remote sensing

## Introduction

Over the 25 years since time domain reflectometery (TDR) was introduced to soil science (Topp et al., 1980)[1] there have been innovative developments of the TDR technique which have focused primarily on the measurement of soil water content and electrical conductivity. In parallel, and starting somewhat later there have also been a diversity of advances in TDR applications in geomechanics and hydrology. In a review of the TDR state-of-the-art Robinson et al. (2003)[2] indicated the power and flexibility of the technique for wide use. In soil science, however, literature indicates emphases on improving the understanding of the physical basis of electromagnetic wave propagation and how such knowledge improves and diversifies the application of the TDR technique (Heimovaara (2004)[3] and references therein). Topp and Reynolds (1998)[4] described how TDR for in situ, nondestructive measurement of water and ionic solutes has revolutionized the study and management of the transfer and storage of mass and energy within the soil profile. TDR-measured water content has been applied successfully to water balance studies over a range of scales - from kilometers as in small watersheds to millimetres of the root-soil interface. The combined water content - solute mass measurement capability has made this technique a very powerful tool for characterizing solute leaching and for evaluating theories and models in solute transport.

This paper presents some examples that focus on how the capability for *in situ* water content measurement has advanced or enhanced soil and plant water studies. The development of roots and other soil biology depends on a balance between both water and oxygen supply. Studies of critical aeration levels and oxygen transport have been severely hampered by lack of soil water content information during dynamic plant growth periods. Although oxygen cathodes for measuring oxygen concentration in the root zone were developed and refined over 30 years ago (Willey, 1974)[5] few valuable measurements of soil oxygen limits have been possible because of the dynamic interaction of water content and air-filled porosity. Recently Cook and Knight (2003)[6] have considerably advanced the modeling of oxygen transport in soil with root and microbial consumption of oxygen along the diffusion path from the atmosphere. The advances in modeling can only be assessed through accurate measurement of oxygen and water content in the rooting zone. With simultaneous measurement of water content and oxygen concentration, we have attempted to assess the impact of varying soil tillage on oxygen and water supply to maize roots (Topp et al., 2000)[7]. Here we show the modeled seasonal patterns of oxygen availability based on TDR measured water content and temperature and the general effect of tillage and trafficking on oxygen supply.

For a given soil and condition, its strength varies with water content, yet field methods for estimation of soil strength, such as using a cone penetrometer or a portable sheargraph, have, until recently, commonly relied on independent estimation of gravimetric soil water content. Consequently interpretations of field soil strength and characterization of soils based on the interaction between strength and simultaneous measurement of water content is lacking. Topp et al. (2001)[8] used TDT (Time Domain Transmissivity), similar in principle and performance to TDR, to modify a cone penetrometer for simultaneous water content measurement and presented calibration results. Modifications included the addition of a helical wrapped transmission line on the penetrometer shaft and just above the cone force sensor. This paper presents results from the combination penetrometer used to investigate the relationship between water content and cone resistance for a clay loam soil and the impact of tillage on the relationship, based on a study by Lapen et al. (2004a)[9].

Field measurement of soil shear strength using the Cohron sheargraph (1963)[10] has been poorly developed since its introduction. The sheargraph had two major limitations that hindered its widespread use. Firstly the graphing approach was tedious and cumbersome, and secondly the water content had to be determined independently. In recent modifications to this instrument, we have converted the sheargraph to a shearlogger and added a TDR transmission line to the shear head allowing more automatic recording of both shear strength and water content as shown in Figures 5 and 6 below.

The penetration depth in soil for remote-sensing radar waves is approximately 10 to 30 mm. Until relatively recently ground-truthing estimates of soil water content used to calibrate radar backscatter were restricted to gravimetric sampling or using TDR probes not designed to measure at shallow depths (McNairn et al., 2002)[11]. This paper presents a TDR probe that can be used in shallow (< 30 mm) soil surface layers to validate water contents obtained from airborne or satellite radar estimates (Lapen et al, 2004b)[12].

In plants, relative water content (RWC) is a useful indicator of the water status of a leaf and a plant's ability to tolerate drought (Sinclair and Ludlow, 1985)[13]. RWC is a comparison of the amount of water in a leaf at any given time to a similar leaf that is turgid (Barrs and Weatherly, 1962)[14]. It is a time and labor consuming measurement.. In an attempt to correct this shortfall we have devised a serpentine TDR transmission line held in a clamping mechanism, so that the water content of growing leaves can be measured non-destructively and *in situ.* This device has the potential to be used in the selection for drought tolerance by plant breeders.

The experiments introduced above are detailed in the following sections to illustrate the versatility and potential use of the TDR in wide-ranging and diverse applications.

## Improving Capabilities for Understanding Soil Aeration Limitations

In this experiment oxygen ($O_2$) supply to roots was modeled using field measurements of water content and oxygen concentration in combination with other model parameters. The supply of $O_2$ to roots occurs by diffusion in the air-filled porosity from the atmospheric source. Roots and other biological (microbial) material consume $O_2$ by respiration along the diffusion path. Macroscopically $O_2$ diffusion is often represented by:

$$D_a \frac{d^2C}{dz^2} = q_r + q_m \qquad (1)$$

where $D_a$ is the diffusion coefficient for $O_2$ in soil air ($m^2\ s^{-1}$), $C$ ($kg\ m^{-3}$) is $O_2$ concentration in air, $z$ (m) is depth in soil, $q_r$ is the rate of root respiration ($kg\ s^{-1}\ m^{-3}$) and $q_m$ is the microbial respiration rate ($kg\ s^{-1}\ m^{-3}$) (Cook and Knight, 2003)[6]. Oxygen can also be transported by advection via a number of mechanisms (Topp et al., 1997)[15], but diffusion has been shown to be the dominant process for oxygen transport in soils (Kirkham, 1994)[16]. From the solution to Equation (1) given by Cook and Knight (2003) [6] we have developed a model using the ModelMaker software which incorporates data from a field trial (Fig. 1) used to study the growth of maize under different tillage and trafficking treatments.

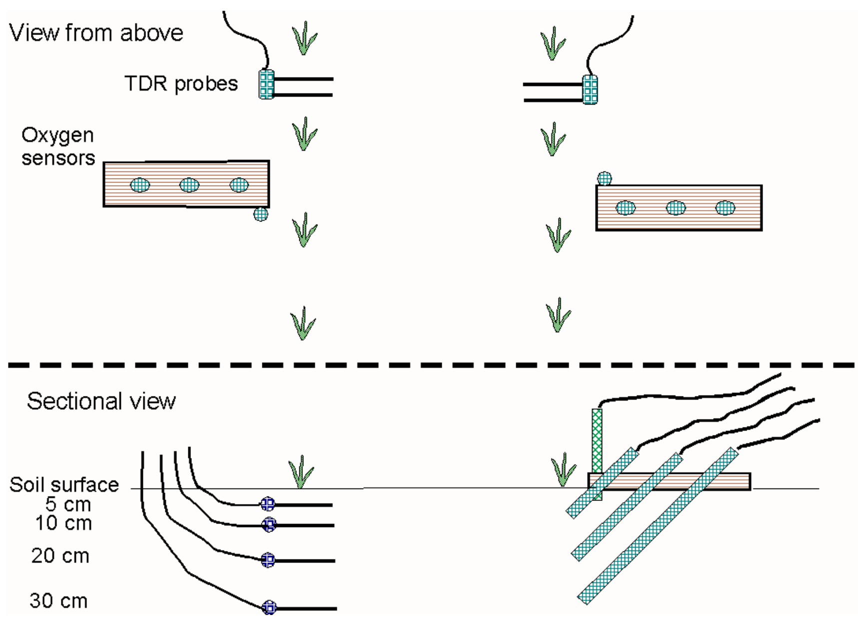


Fig. 1: Field layout of TDR probes and oxygen sensors for the measurement of water content and oxygen concentration in the field plots.

The aim of the field trial was to assess the effect tillage and trafficking on $O_2$ supply to maize roots in a clay loam. Two tillage treatments: No Till (NT) and Conventional Till (CT), were incorporated into two trafficking treatments: “Best”(B) carried out only as required at optimal timing to minimize soil compaction, and “Worst”(W) i.e. additional tractor coverage when soil was wet (above liquid/plastic condition). Thus there were four treatments – BNT, WNT, BCT and WCT. Each treatment was duplicated giving rise to a trial consisting of eight plots. TDR probes ( 20 cm long parallel pair) (Environmental Sensors, Inc.) to measure soil water content and $O_2$ cathode sensors (Jensen Instruments and Qubit) to measure $O_2$ concentration were set up as depicted in Figure 1. The TDR probes were horizontally placed at depths of 5, 10, 20 and 30 cm in each plot. At the same depths copper-constantan thermocouples (not shown in Fig 1) were also inserted for the measurement of soil temperature. $O_2$ sensors were installed in angled access tubes to allow periodic removal and calibration of the sensors with minimal site disruption. TDR, thermocouple and $O_2$ sensors were installed directly in the maize row and in close proximity (50 cm apart) to each other along the row. The sensor arrangement was duplicated in an adjacent growing row (Figure 1). As only sixteen $O_2$ sensors with data logging capability were available, the sensors were moved around twice weekly to allow measurement at all locations 1/3 of the time in each 10-day period. Field installation and measurement commenced as soon as maize plants had emerged and measurements continued until crop maturity. $O_2$ and soil temperature were recorded using data loggers (Campbell Scientific). The TDR water content was measured manually three times a week.

***Results of Oxygen Measurement and Modeling***

During the 2001 growing season there was less than average rainfall leading to growing conditions in which both water and/or oxygen could have been crop-limiting factors. At depths of 5, 10 and 20 cm it was not possible to identify and separate effects of inadequate water from those of limiting oxygen (Lapen et al., 2004a)[9]. At 30 cm depth the measured $O_2$ concentration indicated restricted $O_2$ levels especially early in the season, and at this depth a treatment effect was also seen. In Fig. 2 the model-predicted $O_2$ levels at 30 cm decreased during the early season for all treatments. Over the first 90 days after planting when the crop had the most active growth, the excess trafficking with no-till (WNT) caused the greatest reduction in $O_2$ followed by optimal trafficking with no-till (BNT). Over the same period conventional tillage had greater $O_2$ supply but did not eliminate fully the excess trafficking until 70 days into the growing period. In the last 40 days of the growing season when the soil was much drier and had greater air-filled porosity, all treatments had similar $O_2$ concentrations indicating more favorable conditions for gas diffusion despite the treatment differences.

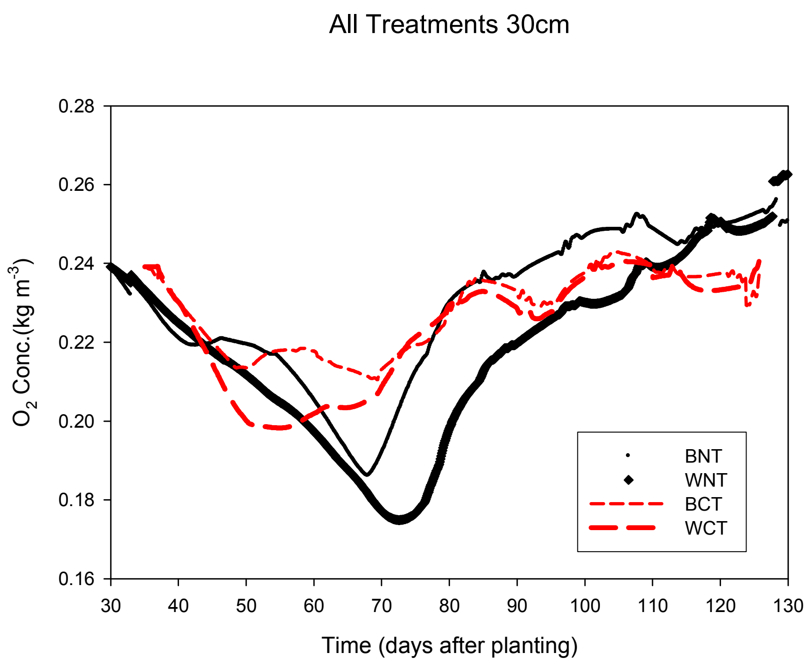


Fig. 2: Model predicted soil $O_2$ concentrations during 2001 growing season, at 30 cm depth on maize plots subjected to four trafficking and tillage treatments.

In modeling $O_2$ transport, water content is critical as this determines the air-filled porosity. Soil water content is a soil property that changes rapidly as a result of weather and crop extraction. Hence frequent measurement of soil water content is vital to model the dynamics involved in oxygen flow. In this experiment, the use of TDR and the data logging capability made it possible to measure water content at specific depths in the soil on a time sensitive basis, without which this experiment would not have been possible.

The following example of a pre-TDR study (Dwyer et al., 1996)[17] is presented to highlight the importance of being able to acquire soil water content data in order to fully understand the interaction between root growth and soil aeration. Dwyer et al.[15] presented a detailed study of the effects of tillage and weather on rooting patterns of maize over the years 1987, 1988 and 1989, but no soil water content information was recorded in the study. Cook et al. (2007)[18], on the other hand, predicted that rooting patterns in soil will be determined by oxygen supply, resulting in a negative correlation between root length density at the soil surface ($R_0$) and the soil depth ($Z_r$) over which respiration occurred. Using the data from Dwyer et al.[15], Cook et al.[18] showed that there was a strong negative correlation between $R_0$ and $Z_r$ (Table 1). At mid-season growth, the means for $R_0$ and $Z_r$ for the three years, shown in Table 1 indicate significant differences between 1987 and the other two years. In 1987 the soil was much wetter immediately after planting compared to the subsequent two seasons, as indicated by rainfall data which was equal to or exceeded potential evapotranspiration. The corresponding impedance to oxygen transfer from the atmosphere into the soil when the soil was wetter may have restricted rooting depth (Dwyer et al.[17]) and changed the vertical root distribution with greater concentration near the surface. Crop yield data for 1987 showed that it was a different but not an entirely unfavourable growing season. TDR measurements in association with the Dwyer et al. study may have provided a more comprehensive explanation of how maize recovered from the early growth restriction to make the 1987 growing season not entirely unfavourable.

Table 1. Mean $R_0$ and $Z_r$ values for the 18 leaf stage of a maize crop grown for three consecutive seasons. The tillage experiments are described by Dwyer et al. (1996) [17]. Data from all trials and sites have been aggregated together to demonstrate year to year variation. Standard deviation of means is in brackets. The numbers of data points were; 26 in 1987, 48 in 1988 and 52 in 1989.

| Year | $R_0$ (kg m$^{-3}$) | $Z_r$ (m) |
|---|---|---|
| 1987 | 173 (72) | 0.026 (0.006) |
| 1988 | 5 (4) | 0.126 (0.248) |
| 1989 | 8 (8) | 0.136 (0.106) |

**Combination Soil Cone Penetrometry**

Topp et al. (2001[8], 2003[19]) have described the calibration and preliminary use of the portable, motor-driven soil cone penetrometer for the simultaneous measurement of cone resistance and soil water content. The sensors for the penetrometer are the load cell immediately above the cone and the helical wrapped parallel pair transmission line (Fig 3). The penetrometer used TDT (time domain transmission) as the signal carrier for the water content determinations. In a more complete description of the combination penetrometer Topp et al. [8], [19] have given standard error for water content determination as ± 0.02 $m^3$ $m^{-3}$ and for cone resistance as ± 0.04 MPa. The depth of electromagnetic field penetration into the soil at which the water content sensor was inserted has been estimated to be 3 mm.

***Results with the Combination Penetrometer***

Using the penetrometer for soil strength measurements in the tillage trial briefly described above, Lapen et al.[9] found a negative linear relationship between water content and cone resistance that was temporally stable for surface soils in the No-till treatments. For the surface soils of conventional tillage treatments, however, Lapen et al.[9] found that the cone resistance vs. soil water content relationships were dynamic (and not always firmly negative) approximately for the first 90 days after planting, after which time a more stable negative relationship was obtained. After 90 days the linear regression parameters were statistically similar within the no-till and tillage treatments.

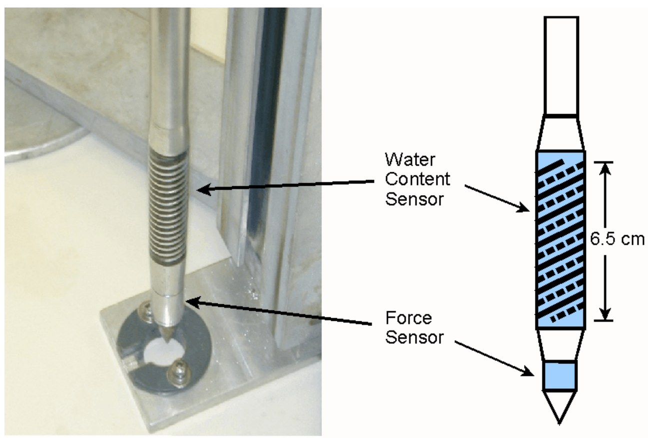


Fig. 3: Cone penetrometer indicating the location of the water content and force sensors.

In addition, comparison between no-till surface soil, at 10 cm depth, and the subsoil (i.e. soil that has not been subject to tillage for over 10 years), 21 cm depth, indicated that water content vs. cone resistance relationship was similar (Fig. 4) at water contents wetter than 0.2 $cm^3$ $cm^{-3}$. The regression parameters indicate that for the 21 cm depth the intercept is 5% higher than that at 10 cm depth while the slopes are the same. Although there is insufficient data to be statistically conclusive, an increase in penetration resistance at 0.2 $cm^3$ $cm^{-3}$ water content in the subsoil (21 cm depth), possibly indicates a coarser structured soil at this depth compared to the surface layer. The ability to obtain water contents readily during cone penetration measurement on a soil provides a ready means of separating the effect of water content and soil structure on penetration resistance. The quality of data collection using the combination cone penetrometer system has great potential for documenting important crop limiting soil structural changes that occur over a growing season.

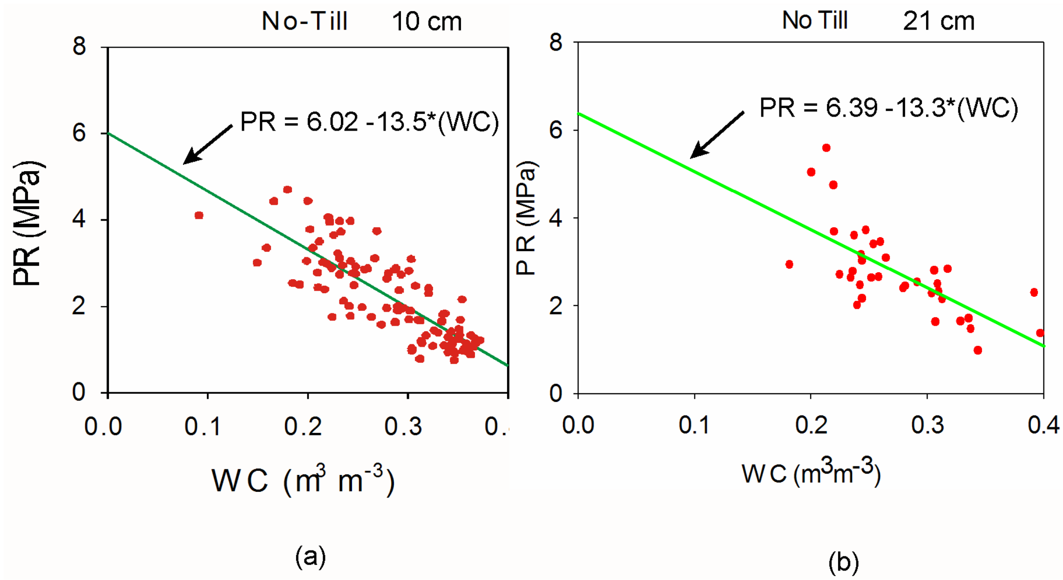


Fig. 4: Cone resistance vs. water content relationships determined with the combination cone penetrometer for the no-till treatment (a) at 10 cm depth, (b) at 21 cm depth.

The ability to characterize intensively the effect of water content on cone resistance as shown here (Fig 4) and in Lapen et al. [9] has been a desire of soil tillage and compaction specialists for years. The dynamic capability offered by TDR and TDT and the flexibility of design of the transmission line has the potential of being a valuable tool in assessing the effects of soil management practices in studies related to soil tillage and cultivation.

**A TDR Enhanced Soil Shearlogger**

Soil shear strength, or shear resistance, arises from two characteristics of the soil body: soil cohesion and internal friction. The relationship between shear resistance, τ kPa, and normal stress, $\sigma_n$, kPa is represented by the Mohr-Coulomb equation:

$$\tau = c + \sigma_n \tan\varphi \qquad (2)$$

where *c* (kPa) is cohesion and tan *φ,* the coefficient of friction, is the tangent of the angle of friction, *φ* (Lambe and Whitman, 1979)[20]. The Cohron sheargraph is a torsional shear device used to measure soil strength *in situ* (Cohron[10]). In the sheargraph a coil spring acts as a transducer and the applied normal stress and the measured shear stress are graphically represented by the X and Y axes on a graphing drum, and soil water content is measured independently. We modified the conventional sheargraph to a shearlogger by incorporating strain gauges for more automated data collection, and more importantly attached a TDR TX line so that *in situ* water content can also be measured at the time of shear (Topp and Lapen, 2007) [21].

For use with a TDR, a TX line was added to the shear head as a pair of cylindrical concentric blades of similar depth to the grouser blades (Fig. 5a). The blades of radii 10 and 20 mm are held in place by a 3 mm thick layer of epoxy resin. Fig. 5a shows slots in the resin plastic through which the grouser blades of the shear head (Fig. 5b) are inserted for shear measurements. TDR measurements have been made using TRASE model instruments (Soilmoisture Equipment Corp., USA) by the authors but other TDR instruments can also be used. For automatic recording of stresses, two strain gauge load cells, one to record normal stress and another to record shear stress, were located between the shear head and the spring assembly (Fig. 6). Although the load cell modification minimised the need for the original coil spring, the spring was retained to facilitate an estimation of applied stress(es) by the operator. The voltage signals from the load cells were recorded by a CR510 datalogger (Campbell Scientific, Inc., Canada). More construction detail and measurement procedures for the shearlogger were given by Topp and Lapen[20] .

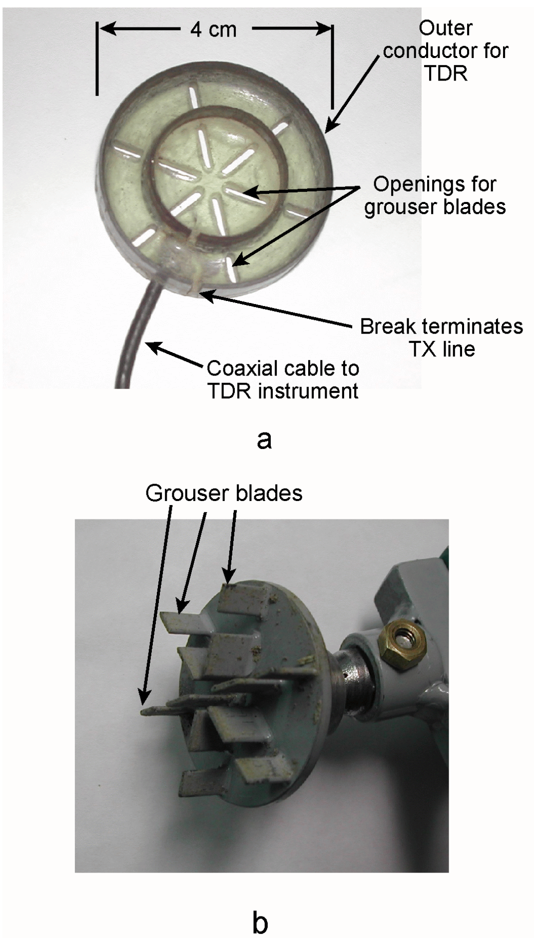


Fig 5: a) TDR water content sensor, viewed from below, b) and shear head and grouser blades which insert through WC sensor.

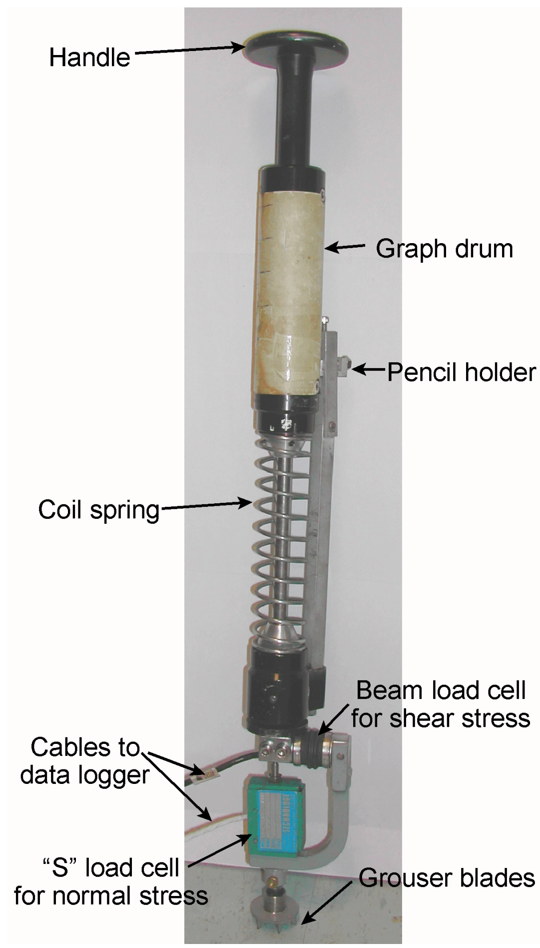


Fig 6: Fully assembled shearlogger, including redundant sheargraph components.

The calibration of the TDR-linked water content sensor (WC sensor) on the shearlogger was compared with triplicated measurements from a conventional three-pronged 15 cm "buriable" TRASE probe inserteded into a set of hand-packed columns (PVC (polyvinyl chloride) cylinders of 12.5 cm diameter and 20 cm high) of a clay loam soil at a uniform bulk density of 1.2 Mg $m^{-3}$.

The soil columns were slowly wet by incremental additions of tap water so that a set columns with a range of water contents ranging from 0.05 (air dry) to 0.32 $m^3 m^{-3}$ were obtained.

During measurement at a desired depth in the soil profile, the TX line is pressed into a 50 x 50 mm area of levelled soil surface that has been gently cleared of vegetation to minimise soil disruption. Water content using the TDR is measured first. The grouser blades on the shear head are then pressed into the soil through the matching slots in the plastic (resin) cap for measurement of shear strength (Figure 5(a) and 5(b)). For each soil depth, measurement of the maximum shear stress for a series of three to five applied normal stress are obtained and a linear graph of shear stress against the corresponding applied normal stresses plotted from which soil cohesion and the coefficient of friction are obtained from the intercept and slope respectively. These parameters may then be related to average water content. The series of measurements should be replicated three to five times at each soil depth.

***Results of Measurements using TDR Enhanced Shear Logger***

The calibration data comparing the WC sensor with the TDR probe are shown in Fig 7. There was a strong linear relationship ($r^2 = 0.97$) with a slope close to 1 (within 1.5%) and a small y-intercept of 0.031 $m^3 m^{-3}$. This translational offset, though unexpected, was taken into account in all subsequent shear head sensor measurements by adding 0.031 $m^3 m^{-3}$ to all readings. The magnitude and consistent nature of the offset value will have minimal influence on comparative studies of shear strength.

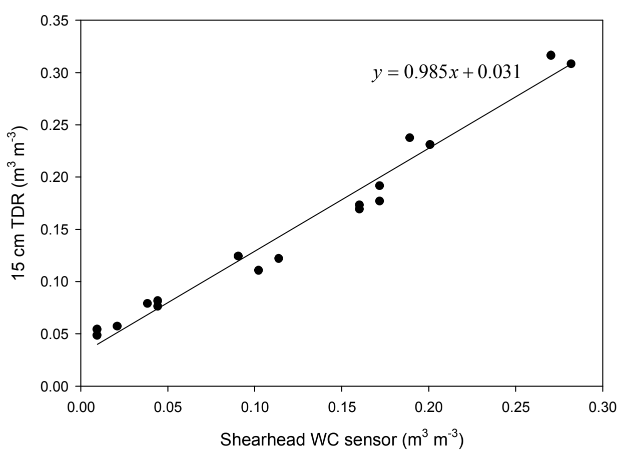


Figure 7: Shearhead WC sensor data from the surface (1 cm deep) of packed soil columns compared with 15 cm TDR measurements.

The shearlogger presents a convenient and efficient field tool for the collection of soil mechanical parameters including soil cohesion, angle of friction and how they vary with ambient water content (Table 2). Shearlogger data can be used to detect and measure both brittle and plastic shear failure (Topp and Lapen[21]). Although the conventional sheargraph (Cohron[10]) has been used for studies in soil shear strength (Ayers 1987[22]; Kirby and Ayers 1993[23]; Topp and Lapen[21]) it has not gained wide use over the last 40 years. Additions of the TDR water content capability and digital data collection from force sensors has provided much needed consistency in water content measurement and removed considerable tedium and operator variance from measurement. The rate of data collection has also been increased by about four times. Although the data quality appears to have been maintained, an independent full-scale evaluation of the shearlogger has yet to be carried out.

Table 2. Shear strength parameters cohesion ($c$) and angle of friction ($\varphi$) for a clay loam soil at two TDR water contents (WC) with standard deviation (SD).

| $c$ (kPa) | $\varphi$ (°) | $R^2$ | WC ($m^3\ m^{-3}$) | SD |
|---|---|---|---|---|
| 24.5 | 6.7 | 0.496 | 0.140 | 0.017 |
| 16.3 | 18.4 | 0.846 | 0.207 | 0.018 |

**A Convenient TDR Probe used for "Ground-Truthing" Radar Backscatter Data**

The essential feature that was necessary for ground-truthing soil water content using TDR was that the probe had a geometric configuration which confined the wave to a relatively well-defined rectangular volume (75 mm wide x 200 mm long x 20 mm deep) on the soil surface. The TDR probe consisted of two rectangular stainless steel (SS) blades (knives), each of dimensions 0.7 mm x 22 mm x 200 mm (Fig 8) that were clamped along the 200 mm side of a PVC block (200 mm x 75 mm x 30 mm) in such a way that the blades extended 15 mm beyond the PVC and lay parallel to each other 75 mm apart. The exposed edges of the blades were sharpened so that the blade arrangement could be easily pushed into the soil/residue surface to the fullest extent of the blade extensions, a depth of 15 mm. Robinson *et al.* [2] suggest the sampling volume of this probe geometry as being primarily confined to the region between the blades, with some fringing of the signal field below the bottom edge of the blades. It is estimated that the fringing extends effectively only 5 mm below the lower edge of the blades giving a sampling depth of 20 mm. A narrower spacing between the blades (<75 mm) may decrease the fringing effect but will at the same time decrease sampling area. The desire for radar ground-truthing is for increased spatial coverage per sample; hence the 75 mm separation was chosen arbitrarily to provide a compromise between coverage area and fringing effects.

A 1 m wooden handle with a "D"-shaped hand-hold on the opposite end was attached to the side of the PVC block opposite to that of the SS blades. The arrangement of probe and handle allowed probe insertion into the soil from a standing position with the convenience of carrying the TDR instrument in a back-pack. Each TDR reading could be obtained in less than one minute using this arrangement.

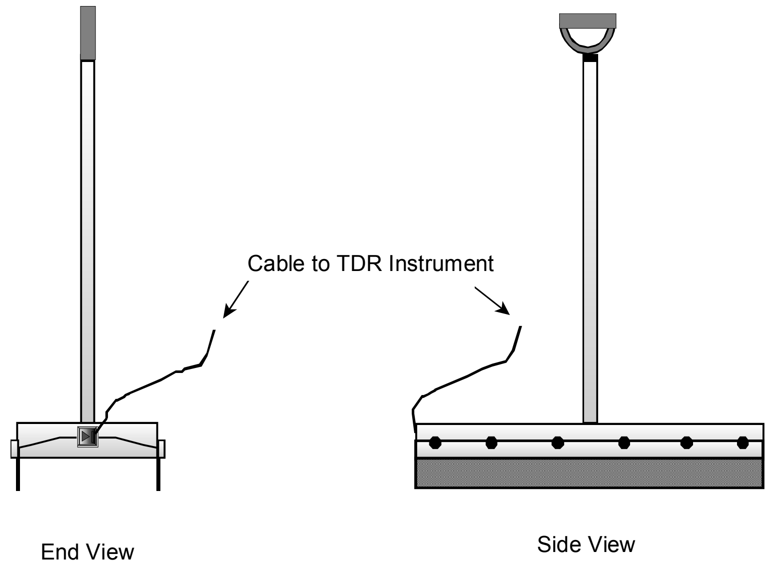


Figure 8: Schematic drawing of the TDR probe.

In this study, the probe was connected to an MP917 TDR instrument (ESI, Environmental Sensors Inc.) using an appropriate PIN diode connected between the SS blades and a 1.5 m length 50 ohm coaxial cable with BNC termination at the opposite end. In common practice, Synthetic Aperture Radar (SAR) reflectance is correlated with dielectric permittivity in remote sensing. In this case the MP917 parameters were set to convert the measured dielectric permittivity directly to water content using the Topp *et al.*(1980)[1] calibration equation converted to linear form by Topp and Reynolds (1998)[4]. The direct conversion to water content provided better visualization of the field conditions during the experiment detailed below.

The experimental field site was approximately 16.5 ha. and the soil texture over the area ranged from sandy loam to clay loam. Twenty eight days prior to commencement of the experiment the field was planted to maize in the east-west direction (30$^{o}$ N of E x 30$^{o}$ S of W) and at commencement maize plants were approximately 0.15 m in height. The micro topography of the soil surface reflected the cultivation/planting operations which created ridges and hollows parallel to the rows of maize. Row heights ranged between 0.05 and 0.15 m, with 0.2 to 0.3 m horizontal separation, which created a roughly sinusoidal wavy ground surface with wave amplitude of 0.08 m and wavelength of 0.50 m. Forty-eight primary sampling sites were geo-referenced over the field. Within each of the sampling sites six micro-sites were chosen for TDR water content measurements. The micro sites consisted of cultivation induced ridge/hollow micro-topography (measurements were triplicated for ridge and hollows respectively). Ancillary data such as soil surface roughness, plant density and plant water content were also measured at each primary site.

The C-band (5.6 cm) polarimetric airborne SAR data used in this analysis were acquired using the Convair-580, operated by Canada Centre for Remote Sensing, Ottawa, Ontario. Three images of the field site were acquired on 25 June 2002 at the following angles of incidence: 47.2°, 49.1° and 50.5°. The first and last images were both acquired with the antenna facing north. In this paper data acquired for the first image (47.2°) from east to west, will only be reported. Image quality and calibration were evaluated using single look complex (SLC) images and locational accuracy was assessed using geocoded, terrain corrected images (4m, WGS84, DEM at 1:250,000). These images met all quality assessment criteria which included location accuracy of less than one pixel (4 m x 4 m), radiometric accuracy of 0.8 dB within scene and 1 dB between scenes (Bugden *et al*., 2004[24]; Hawkins *et al*., 1999[25]). Linear HH polarization images (in power domain) were synthesized from the geocoded, terrain-corrected data. For this paper analysis was focused on the linear HH images from the first flight path since HH is the polarization that corresponds most closely to relative permittivity.

### *Results of the Spatial Pattern of Soil Water Content*

The basic performance of the soil surface TDR probe was found to be satisfactory from measurements in air and water and was compatible with the MP917 TDR instrument (Environmental Sensors, Inc.) Following these initial results, we have constructed similar probes with the PIN diode replaced by a 5 pf capacitor making the probe compatible with TRASE or Mini-TRASE TDR instruments (Soilmoisture Equipment Corp.) which operate with hand-held controls with the instrument back-packed.

The surface soil water content varied as a result of the regular roughness caused by the tillage/planting operations. The TDR measurements (Table 3) showed that ridges and hollows over the field had an average water content of 0.10 (±0.04 $m^3\ m^{-3}$) and 0.15 (±0.05 m3 $m^{-3}$) respectively. The coefficient of variation was consistent between the ridge and hollow data across the field, but within-site variability was almost as large as that across the whole field. The overall water content recorded by TDR ranged from 0.06 to 0.30 $m^3\ m^{-3}$.

Table 3: Summary statistics for TDR and SAR data

| | Max. | Min. | Mean | St. Dev. | CV (%) |
|---|---|---|---|---|---|
| | Soil water content by TDR measurement ($m^3\ m^{-3}$) | | | | |
| Ridges | 0.227 | 0.055 | 0.103 | 0.036 | 35 |
| Hollows | 0.302 | 0.057 | 0.147 | 0.048 | 32 |
| Site Average | 0.264 | 0.057 | 0.125 | 0.041 | 32 |
| | $\varepsilon_{ra}$, relative permittivity (dielectric constant) from TDR | | | | |
| Ridges | 12.3 | 4 | 6 | 1.6 | 27 |
| Hollows | 17.2 | 4.1 | 8.1 | 2.4 | 30 |
| Site Average | 14.7 | 4.1 | 7 | 2 | 29 |
| | $\sigma^0$, Backscatter data from SAR | | | | |
| 48 site pixels | 0.052 | 0.009 | 0.027 | 0.01 | 37 |
| 5-pixel averages | 0.049 | 0.011 | 0.027 | 0.009 | 33 |
| Field | 0.104 | 0.007 | 0.03 | 0.01 | 33 |

***Comparison between SAR and TDR***.

The coordinates of the SAR data did not directly coincide with those of the TDR and adjustment was made based on knowledge of the field site and field boundaries. The 48 SAR pixels that coincided in location with the 48 primary TDR measurement sites were selected and compared directly with the relative dielectric permittivity determined using TDR. The size of the measured zone at the primary TDR sites was less than the 4 m x 4 m pixel separation of the SAR. Due to the uncertainty of how well the measurement locations coincided with each other, it was thought that incorporating additional SAR pixels would relate better to the TDR data. Thus four additional SAR pixels adjacent to those already selected as coincident were included to obtain a five-pixel average of SAR data for comparison with the averaged TDR data for each primary site. Table 3 presents the summary statistics for TDR apparent relative permittivity ($\varepsilon_{ra}$) and for SAR backscatter reflection ($\sigma^0$). The $\sigma^0$ data from pixels of the TDR sites are representative of the field in general having very similar means and standard deviations. The range of $\sigma^0$ for the field is larger than that for the 48 sites. However the TDR sites appear to have provided field-representative $\sigma^0$ data for correlation with the $\varepsilon_{ra}$ from TDR. A limited geostatistical analysis (Lapen et al. [12]) of the two data sets suggests that the TDR sampling was also spatially representative of the SAR data.

The $\varepsilon_{ra}$ results (Table 3) show that the range of values in the ridges were about 30% lower than those in the hollows and may be attributed to lower water content on the ridges. The coefficient of variation of about 30% for both the ridges and hollows is similar to that found in $\sigma^0$. Anticipating a linear relationship between $\sigma^0$ and $\varepsilon_{ra}$ we carried out a number of linear regressions, the results of which have been summarized in Table 4. Surprisingly, it was found that $\sigma^0$ from single SAR pixels indicated a linear correlation with $\varepsilon_{ra}$. The correlation coefficient of 0.48 ($r^2$ = 0.23) that was obtained was deemed to be strong given the many complicating factors associated with ground-truthing remotely sensed data and image processing. Some of the complicating factors include soil surface roughness scattering, sample size differences between TDR and SAR and possible lack of geo-coincidence between TDR, SAR and incidence angle. Averaging four additional SAR pixel values with the single values improved the correlation coefficient to 0.56 ($r^2$ = 0.32) but the slope and intercept coefficients remained essentially unchanged by increasing the average area sampled for $\sigma^0$ (Table 4). McNairn *et al*.[11] reported correlation coefficients of comparable magnitude using a simple linear regression, such as 0.50 for vegetated soil and 0.68 for stubble covered soil. Lower correlations resulted, relative to site average TDR data, by taking either the ridge or the hollow TDR data separately. This finding indicated that more representative TDR data, in terms of SAR information, could be obtained via accounting for microscale spatial variability in soil water contents. That the values for hollows (higher water content) were more highly correlated (0.51 vs 0.40) with $\sigma^0$ relative to the ridge values is an indication that higher water contents influence radar back scatter to a greater extent than lower values. It is probable that the ridges also played a greater role in scattering radar waves away from the receiving sensor, relative to hollows.

Table 4: Regression summary for $\sigma^0 = A (\varepsilon_{ra}) + B$

| $\sigma^0$ | $\varepsilon_{ra}$ | A | B | $R^2$ | SEE |
|---|---|---|---|---|---|
| 48 site pixels | site average | 0.00248 | 0.01 | 0.228 | 0.009 |
| 5-pixel averages | site average | 0.00247 | 0.0095 | 0.319 | 0.007 |
| 5-pixel averages | hollows | 0.00182 | 0.012 | 0.264 | 0.007 |
| 5-pixel averages | ridges | 0.00208 | 0.0143 | 0.157 | 0.008 |

Plant water content and density were measured at each TDR site and converted to volumetric water content assuming even distribution of plant water in the 0.15 m height above the soil surface. When plant water was treated as another dependent variable in the data analysis the correlation coefficient was only slightly increased (< 1 %), indicating that the water content of short (< 0.15 m tall) maize plants did not influence significantly the radar backscatter. On the other hand the geometric scattering from the plants may have been a significant contributor to variance but this was not tested in this experiment. The plant row and tillage ridges were 30° from parallel to flight direction of the SAR and would therefore augment the potential for scattering the return signal. In addition, in drier soil of the ridges the incident wave will penetrate more deeply than in the hollows. Thus in the hollows the 20 mm TDR measurements may not have measured the deeper, wetter soil detected by the SAR.

This leads to the question - was the TDR probe used accessing enough depth for adequate referencing of the SAR back scatter estimates? A simple and definitive answer cannot be given based on a limited data set such as from the experiment reported here. However there is some indication that 20 mm depth is a useful depth for referencing. The first indication of depth adequacy relates to the correlation coefficient of 0.56 discussed above. To a first approximation 66% of back scattered energy arises from the first wavelength depth in the soil. The wavelength in soil is estimated by dividing the wavelength in air (56 mm) by the square root of the relative permittivity of the soil. Using the mean value of the $\varepsilon_{ra}$ (7) (Table 3) we found the wave length to be 21 mm, i.e. within the depth range covered by this TDR probe. A similar estimate based on the minimum water content measured on the ridges gave a wave length in the dry soil of 30 mm. Even in this case almost 50 % of backscatter would arise from within the depth of soil measured by TDR. This very simplified analysis concurs with another first approximation approach for depth of penetration presented by Ulaby *et al*. (1996) [26]. Thus it can be concluded that a TDR probe measuring to a depth of 20 mm with high precision (± 5 mm) would give a reliable measure of the relative permittivity of the soil giving rise to C-band backscatter for water contents above 0.01 $m^3\ m^{-3}$. This relatively simple experiment indicates that a more comprehensive research project would be valuable to advance comparability between TDR and SAR data. Such research should encompass a broader range of soil and field conditions and utilise two TDR probes each reaching to different depths and used concurrently.

**TDR for Determination of Leaf Water Content**

For leaf water content measurement it was necessary to construct a TDR transmission line to measure a sample <2 mm thick. A three wire parallel transmission line (TX) was machined onto a 35 x 65 mm rectangular copper-clad circuit board (Fig 9a). The TX line was laid out in a serpentine pattern on the board with five segments connected by four semi-circular loops. The TX conductor dimensions were: outside conductors, 1 mm wide; center conductor, 0.5 mm wide; with separation between center and outside conductors being 0.5 mm. Separation between adjacent sections of the TX line was 1 mm. The active area of the TX line was approximately 30 x 45 mm. The total linear length of the TX line was approximately 180 mm. The input end of the TX line was adapted for automatic reading by TRASE model (Soilmoisture Equipment Corp.) TDR instruments by connecting a 5 pf capacitor between center and outer conductors. Similarly attached to the TX line was a coaxial line for connection to the TDR instrument. The TX circuit board was mounted on one of the self-adjusting plates of a spring-loaded hand clamp (Fig 9b). On the other plate of the spring clamp was mounted a 30 x 65 x 4 mm aluminium plate on which a 3 mm layer of closed pore polyethylene foam was bonded. For measurement the leaf is held firmly against the TX line by the clamp spring and supported on the opposite side by the foam layer (Fig. 9b).

To test the leaf TDR filter paper (0.2mm thick) was cut in the shape of the active area of the TX board (45 x 30 mm). Cut papers were weighed dry and after saturating in distilled water. The wet papers were allowed to dry in air and at intervals of three to four minutes during drying, each paper "leaf" was reweighed and water content measured with the leaf TDR probe. Measurements were made on triplicated "leaves". The gravimetric water content of the filter papers was calculated using the standard formula. The TRASE TDR was set to a 10 ns capture window and the travel time in the TX line was recovered manually from the recorded TDR traces. To test the effect of salt concentration on the sensor a 1.0 M KCl solution was used instead of distilled water in the above procedure. The total travel times were plotted against volumetric water content, where the gravimetric water content was converted to volume basis using the bulk density of the filter paper "leaves" in the initial dry condition.

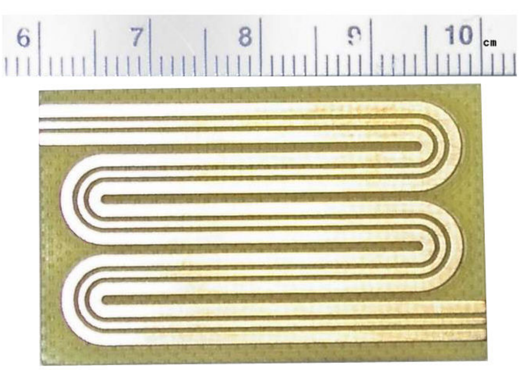

Figure 9a. The circuit board with the TX line machined into the surface and electroplated.

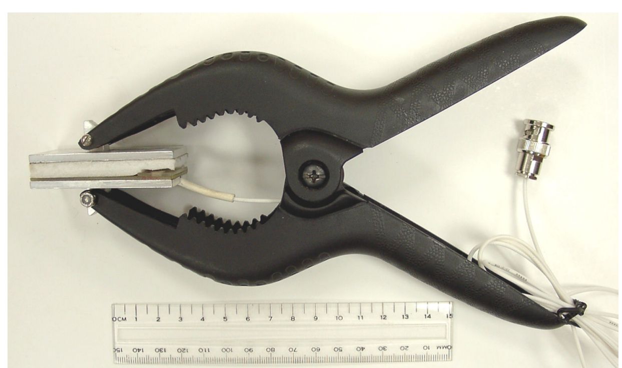

Figure 9b. Spring loaded clamp housing the circuit board TX line.

After calibration using the filter paper "leaves", soybean (*Glycine max* L. Merr.) leaves from well watered plants growing in a growth chamber were sampled *in situ* with the leaf TDR. The leaves were removed from the plants, weighed and floated on distilled water in petri dishes for 12 hours before they were reweighed and measured with the leaf TDR. The leaves were then dried for 48 hours at 105°C and reweighed. The RWC was calculated as: (fresh wt – dry wt) / (turgid wt – dry wt) (Barrs and Weatherly[14]). Leaf thickness was measured on representative leaves while fresh and after drying.

***Results and Discussion from Leaf TDR Sensor***

The tests with the filter paper were initially encouraging. There was a significant relationship between gravimetric water content and the total travel time recorded for the leaf probe. After conversion to volumetric water content the relationship with travel time was not as linear as was anticipated (Fig. 10). Salt concentration does not appear to influence the signal as the travel time to water content relationships for water and salt solution were indistinguishable. Thus the water and salt solution data were combined in an attempt to use the filter paper data to characterize the electrical behavior of the TDR leaf probe. The travel time offset estimated as the time axis intercept in Fig. 10 was 0.9 ns. The electrical length of the probe can be derived from the slope of the travel time versus volumetric water content relationship, such as that in Fig. 10. To attempt to get the probe electrical length from Fig. 10 would indicate that probe electrical length or the calibration would be water content dependent, which cannot be the case for a useful sensor. On a positive note, the sensor does not appear to be influenced by salt concentration at the levels used in this study, therefore, the natural changes in salt concentrations in leaves, may not greatly influence TDR water content measurements.

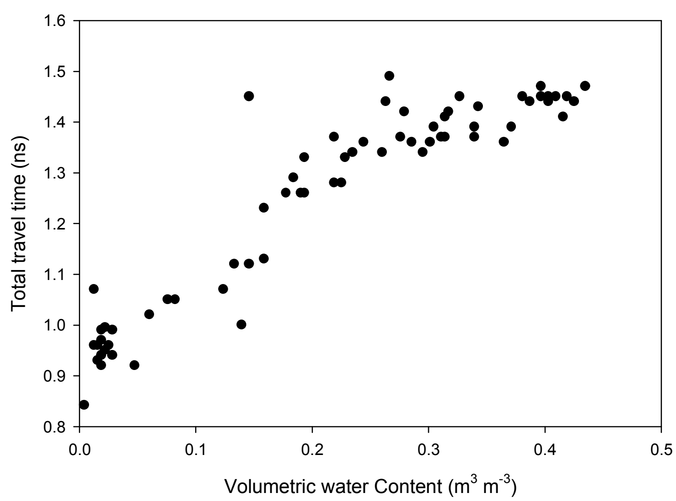


Fig 10. Travel time versus water content relationship for the TDR leaf sensor using filter paper "leaves" to simulate plant leaves.

The experiment with the leaves was less successful than with the filter paper. While the internal water content of the soybean leaves increased by an average of 12 % gravimetrically by soaking over night in water, the leaf TDR sensor did not register a corresponding increase in travel time (i.e. increase was only from 1.36 to 1.38). The RWC of the leaves was well within the limits for well watered plants (0.87). The leaf TDR sensor does not appear to be "seeing" the water content of the leaves.

Although this study has not provided an adequate data set to validate the use of the leaf TDR probe, the results from the filter paper and the soybean leaves has shown the potential for future development and use of such a probe to characterize leaf morphology with drying. As early as 1987, El-Rayes and Ulaby (1987)[27] demonstrated the feasibility of using EM waves for leaf water content but did not go to a specific method. To our knowledge no one else has been able to make sufficiently quantitative measurements and it seems possible that others have reached the same point as we have where volume change causes problems. The leaf thickness decreased from 0.34 to 0.21 mm (>60%) during drying indicating that leaf volume changes with water content change. Leaf thickness after soaking would have been greater than 0.34 mm. Presumably, water content changes in both filter paper and leaves are accompanied by changes in bulk density, causing the nonlinearity in Fig. [10]. Thickness changes were more apparent in the leaves than the filter paper, perhaps due to a less uniform structure or more air filled spaces. The use of fringing electromagnetic (EM) field in the design of this transmission line may be a factor which affected measurement. The EM field in which the leaf or filter paper sits "fringes" out from one copper conductor and returns back to the other two. The intensity of this field decreases with distance out from the surface. If the leaf or filter paper decreases in thickness with decreasing water content, the remaining water experiences a more intense EM field causing greater loss of EM field beyond the thickness of leaf or paper. This would be indicated as a changing sensitivity of travel time with water content, a feature that is clearly evident from the changing slope in Fig. [10].The apparent interaction of leaf thickness change and the fringing EM field have given much more effect than we anticipated. The experience derived from this study has provided valuable information for redesign of the leaf TDR transmission line.

## General Discussion and Conclusion

Five specific applications of TDR show differing aspects of enhancing research and development. In soil aeration studies the TDR water content can be measured on a time sensitive basis to recover the dynamic changes of water content in time. In addition, measurements at different depths in the soil profile offer the advantage of having depth-related profiles of water and air contents to inform the gaseous diffusion processes. As a consequence of the TDR technology we are in a position to separate quantitatively the impact on crop growth of shortage of either water or air, a major step forward in plant and soil research.

Both of the soil mechanical applications involved TDR transmission line design and fabrication. For the combination penetrometer the helical wrapped TX was devised to work in combination with the cone penetrometer to obtain water content data both coincident and collocated with the cone to improve the ability to establish data relationships between cone resistance and water content. In the shearlogger the TX line had to accommodate the operation of the shearhead, measure water content of the soil before it was sheared and not cause disturbance of the soil prior to shear measurement. Another important consideration was the need to remove the tedium of manual measurements embodied in the sheargraph approach. In these cases we believe we have demonstrated successful achievement of the requirements. Others must conduct independent measurements to validate (or otherwise) our claim.

For the remote sensing application we have modified a TDR TX line to confine the volume of measurement to approximate more closely the volume of soil from which the radar backscatter was actually occurring. The ergonomic considerations for both the probe and the TDR instrument allowing them to be conveniently portable during operation were important for efficacious use of this system for "ground-truth" sampling.

The measurement of leaf water content is greatly desired by plant physiologists but it remains a major challenge for TDR application. We have shown how the mode of leaf drying with volume change overcame the capabilities of our specifically designed serpentine parallel TX line. Although some optimistic observations were made we must redesign our TX line.

Our overall achievements involved collaborations among scientist of widely varied backgrounds and needs. These collaborations have demonstrated once more the diversity of possibilities to apply TDR for the enhancement of research.

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