TDR 2006
Purdue University

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Ref.: Jones, Scott B., Robinson, David A. and Friedman, Schmulik P., "Development of a Subsurface Open-Ended TDR Probe for On-the-Go Mapping of Water Content", Proc. TDR 2006, Purdue University, West Lafayette, USA, Sept. 2006, Paper ID 17, 15 p., https://engineering.purdue.edu/TDR/Papers

Development of a Subsurface Open-Ended TDR Probe for On-the-Go Mapping of Water Content

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Abstract

Reliable and rapid measurement of soil water content at the field-scale could greatly enhance many agronomic as well as environmental activities such as development of reclamation strategies, reducing fertilizer application and characterizing hydrologic and geophysical properties. This capability suggests the need for improvements in sensor design, signal analysis and novel application of the technology before real-time field-scale measurements for precision agriculture are readily available. With the long term goal to develop a system that provides depth-dependent soil characteristics such as water content, electrical conductivity and temperature, we have designed and tested a flange-type open-ended TDR probe. We considered different geometrical configurations of the open-ended probe design compatible with either a single-sided near-surface probe or double-sided probes embedded within a subsurface blade. The fringing field associated with the sensing volume was modeled and a network analyzer was used to measure and compare attenuation among different open-ended probes, with a dielectric probe as reference. The use of multiple sensing heads for multi-depth measurements required a dedicated TDR for each head to obtain waveforms at a sufficient rate for mapping purposes using existing technology. Waveforms were collected in static and on-the-go field conditions and compared to determine the influence of travel speed on the resulting waveform. Deviations from the mean of 9 consecutive waveforms collected in moist soil traveling at 5 kmph were only double the RMSE of the same probes at rest in water, demonstrating the stability and accuracy of on-the-go measurements. At the maximum waveform collection rate of 3 seconds, 4 m grid spacings were achievable at a travel speed of 5 kmph. Faster waveform collection (and future analysis) will provide higher resolution water content maps. waveform analysis approaches are being considered for inclusion into analysis software providing field-scale mapped water content with the ultimate goal of real-time measurements.

Keywords: TDR, on-the-go, open-ended probe, mapping soil moisture

Introduction

There is tremendous interest and growing capability to 'probe' soil properties on-the-go in the process of transient and mobile activities involving agriculture, environment and industry. Soil and plant properties such as electrical conductivity, surface reflection, plant canopy temperature and others are useful in assessing qualitative features and monitoring temporal and spatial changes in properties of interest. Systems have been developed with multiple sensing capabilities that provide realtime decision making capabilities in addition to more complex data collection requiring post processing. Patents or patent applications exist that describe subsurface water content measurement systems [1, 2] but with little information on the accuracy of measurement. Stop and go systems requiring TDR probes to be inserted and removed at each location have been developed and evaluated [3, 4]. Little however has appeared in the scientific literature regarding reliable and accurate water content sensing capability for on-the-go mapping.

Among the many methods for water content determination, oven-drying (gravimetric) is the only direct method, and only some of the electromagnetic-based methods being used are highly accurate with little influence from secondary effects such as temperature and salinity[5, 6]. Time domain reflectometry (TDR) has been one of the most reliable and accurate methods for soil moisture determination since the seminal work of Topp, Davis and Annan [7]. This method relies on a transmission line measurement of travel time, which is dependent upon the porous medium dielectric through which the signal propagates. A number of hurdles stand in the way of implementing on-the-go electromagnetic-based water content measurement. The first is the need for development of rapid and potentially simultaneous measurements from probes at multiple soil depths with GPS reference. The difficulties of implementing an on-the-go TDR measurement in the subsurface using conventional 2- or 3-rod TDR probes include electrode support interference (e.g., embedded electrodes), minimum length requirements (i.e., > 8 cm) that create probe clogging, probe-soil contact issues and other problems that relate to specific measurement protocols (e.g., required measurement time vs. vehicle speed). Probe configuration and geometry determines in large part the volume of soil that can be sensed and the distribution of the electromagnetic field within the sample also impacts the effective water content that results from such measurements.

In order to overcome the difficulties of making measurements in saline soils and to minimize friction resistance of probes traveling through soil we have taken the approach to adapt TDR open-ended or short probe designs and interpretation algorithms [8-11]. Open-ended probes have been widely used in physics and chemistry for permittivity measurements in liquids and biological tissue [12]. The TDR waveform is obtained from an incident voltage signal directed towards the sample being measured and the reflected signal includes information about the electrical characteristics of the unknown sample. To simplify data processing, the signals are transformed to the frequency domain using Fourier (short probe) or Laplace (open-ended probe using bilinear analysis) transforms. The bilinear function [9, 11] computes admittance values of the unknown sample, the cell and the characteristic admittance of the coaxial line. The reflection coefficient is related to the complex permittivity and to the complex bilinear coefficients that depend on the choice of reference dielectric, admittance of the transmission line, connectors, etc. They are calibrated with measurements in three standards: short circuit, open circuit and 50 Ω termination or the use of three dielectric samples with known permittivities.

Due to their small sampling volume and associated complex signal analysis, these open-ended probes have not been extensively used in agriculture but have excellent potential for subsurface on-the-go measurements. A major advantage is the minimal path length and subsequent low attenuation from electrical conduction. In soils with appreciable salinity, conventional time domain analysis with longer probes becomes progressively inaccurate due to signal attenuation to the point of failure. Jones and Or [13] demonstrated that permittivity, which is inextricable using TDR travel-time analysis in saline soils, could be extracted using frequency domain techniques and shorter TDR probes that reduce signal attenuation. The permittivity determination capability demonstrated in sand and silt loam soil, with EC_w values of up to 40 dS m^{-1}, is well beyond the normal requirements for determining water content in saline agricultural soils. We propose parallel development and automation of the methodologies associated with open-ended and short TDR probes for on-the-go measurements of volumetric water content and apparent electrical conductivity. These could be linked with TDR analysis software (e.g., WinTDR 6.0, [14] for testing under field conditions and eventually linked with the field mapping system for saline and non-saline environments. The overall goal of enhancing precision agricultural practices is illustrated in Fig. 1 where the invasive open-ended TDR probe provides water content, electrical conductivity, and temperature measurements linked to a GIS mapping and analysis system that could potentially link with other information systems such as non-invasive instrumentation (e.g., electromagnetic induction).

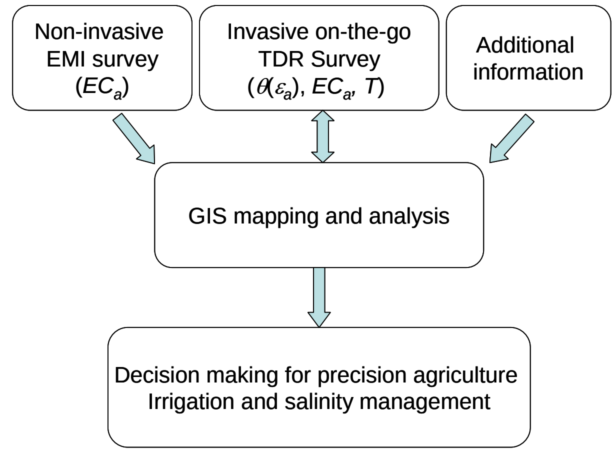

Figure 1. Outline of the process for integration of a complete mapping package for development of a water content and salinity assessment and management tool.

Objectives

The objectives of the proposed study are based on our longer-term goals of understanding and accurately describing the status and behavior of water and salinity in agricultural and environmental ecosystems. This requires development of novel measurement and analysis techniques accompanied by appropriate models relating water content and soil solution electrical conductivity for enhancing precision agricultural practice and salinity management. Within this context, the specific objectives of this study were to 1) design, construct and test novel time-domain reflectometry-based electromagnetic sensors capable of assessing subsurface soil moisture in an on-the-go mode of transport and 2) to develop waveform analysis capabilities for extracting frequency-dependent soil permittivity for water content determination.

Theoretical considerations

When employing TDR with an open-ended probe, an incident voltage signal, $V_0(t)$, is directed towards a sample being measured and the reflected signal, R(t), includes information about the electrical characteristics of the unknown sample. To simplify data processing, the signals are transformed to the frequency domain using the Laplace transform.

$$F(s) = L[f(t)] = \int_0^\infty e^{-st} f(t)dt \qquad (1)$$

Here lower case letters indicate time domain (i.e., v_0, r) and upper case refer to frequency domain parameters (e.g., V_0, R) where F(t) is the signal in time domain, F(s) the transformed signal in the frequency domain, where s = σ + $i\omega$, for i = √-1 and ω being the radial frequency. The bilinear function is defined as:

$$\frac{Y_x}{G_c} - \frac{Y_r}{G_c} = \frac{A^*(\omega)\rho_x^{\ *}(\omega) + C^*(\omega)}{1 - B^*(\omega)\rho_x^{\ *}(\omega)} \qquad (2)$$

Where Y_x and Y_r are the admittances of the unknown sample and the reference respectively and G_c is the characteristic admittance of the coaxial line.

$$\frac{Y_x}{G_c} = \frac{(V_0(\omega) - R_x(\omega))}{(V_0(\omega) + R_x(\omega))} \qquad (3)$$

$$\frac{Y_r}{G_c} = \frac{(V_0(\omega) - R_r(\omega))}{(V_0(\omega) + R_r(\omega))} \qquad (4)$$

The reflection coefficient, $\rho^*{}_x$, is related to the complex permittivity by

$$\rho_x^{\ *}(\omega) = \frac{i\omega\gamma d\varepsilon_x^*}{c}\frac{\tan(z_x^*)}{z_x^*} \qquad (5)$$

where γ is the ratio of air line admittance to the characteristic line admittance, d is the thickness of the dielectric, c is the speed of light, ε_x^* is the complex permittivity and

$$z_x^* = \frac{\omega d}{c}\sqrt{\varepsilon_x^*} \qquad (6)$$

Parameters A^*, B^*, C^* are the complex bilinear coefficients that depend in a complex manner on the choice of reference dielectric, admittance of the transmission line, connectors, etc. These parameters are computed by calibration with three standards: A short circuit, open circuit and 50 Ω termination or by the use of three dielectric samples with known permittivities (e.g., liquids within the permittivity range of interest). For an ideal short circuit $B^*(\omega) = 0$ and C is within experimental error in the range $0<C<1$. Using the standards will give linear equations which can be solved through iterative algorithms such as the Newton-Raphson method. The resulting complex permittivity provides frequency-dependent characterization of the medium of interest (i.e., moist soil). Significant progress using such an approach for short coaxial probes has been made at Montana State University by Castiglione and Wraith (personal communication).

Materials and Methods

Two different open-ended coaxial probes were constructed to provide both near-surface and subsurface waveforms for subsequent analysis of volumetric water content. Because of the inherent difficulties in designing and constructing high quality transmission line fixtures, prototype probes were created using off the shelf coaxial adaptors with BNC x N-type connectors. The N-type connector was machined down to a flat surface at the base of the connector forming an open-ended probe having low loss characteristics (Fig. 2, Probe 1). A 1.5 m RG-58 coaxial cable was used to connect the cable tester and probe. The probe was embedded in a Lexan plate using epoxy. The plate was configured for a sand-filled rain gutter and drug across at a range of speeds in dry and saturated sand. The plate was later attached to the bottom of a crow's foot furrowing implement for creation of a shallow channel for the probe in field testing.

A second probe was custom made using a 0.66 cm diameter stainless steel rod epoxied inside a 1.55 cm diameter hole drilled through a carbon steel blade (Fig 2, Probe 2). The inner and outer conductors were connected to an RG-174 coaxial cable run down the back and through a hole in the centerline of the blade with inner conductor attached to the inner cylinder and the outer conductor soldered to the blade. The T-like geometry provided simultaneous reflections from both halves of the probe. The idea being that the blade cuts through the soil separating the two halves and sensing the fringing field that extends into the soil. Measurements in probes 1 and 2

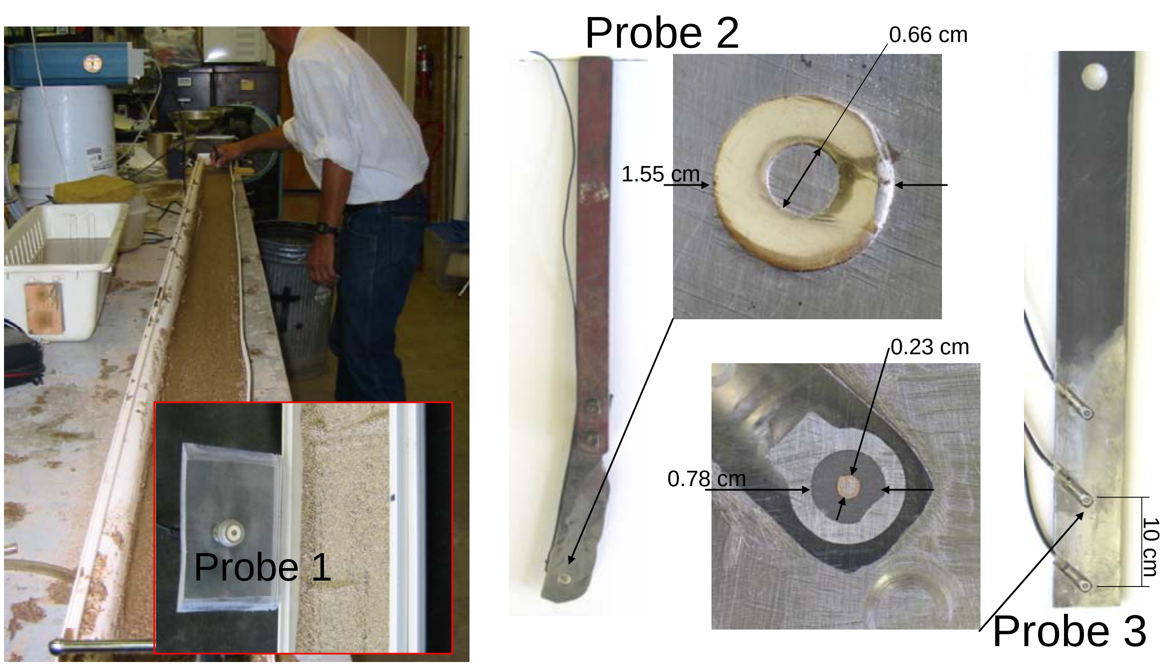

Figure 2. Prototype open-ended coaxial probes developed for subsurface measurement of water content. Probe 1 is a one-sided probe for near surface measurements and was tested in a sand-filled tray at different speeds under dry and saturated conditions. Probe 2 is double-sided for subsurface interrogation and has a single measurement depth where the outer conductor is the blade body while Probe 3 has three measurement depths with inner and outer conductors isolated from the blade. Here the BNC tee was epoxied inside the blade and milled flush with the blade on both sides exposing the tee cross-section.

were made with a Tektronix TDR cable tester (Tektronix Inc., Beaverton, OR; 1502B Metallic Cable Tester). Waveforms were captured with WinTDR 6.1 waveform analysis software [15] from the Tektronix cable tester.

Expanding this design, a third probe (Probe 3, Fig. 2) was developed for simultaneous measurements at multiple depths. In this case the probes were isolated from the blade to avoid electrical interference. The design employed BNC – type coaxial T's that were epoxied into three slots of a steel blade and milled flush with the blade surface. One Campbell Scientific TDR-100 was connected to each probe (3-TDR's total) to provide the fastest possible simultaneous measurements in an on-the-go mode. Each Campbell Scientific datalogger (1-CR23x and 2-CR10x) was synchronized and collected waveforms from the 3 TDR's at the rate of every 3 seconds.

Prototype probes were tested in the field to determine the effects of travel speed on the resulting waveforms. The soil in the field plot where measurements were made is Millville Silt Loam (Coarse-silty, carbonatic, mesic Typic Haploxeroll). Probes 1 and 2 were tested in the summer of 2005 where the volumetric water content was near 0.17 cm^3 cm^{-3} and a section of the measurement transect was wetted to field capacity (0.24 cm^3 cm^{-3}) to provide contrast. Probe 3 was tested in the spring of 2006 where the approximate volumetric water content in the subsurface of the bare soil was uniform at around 0.2 cm^3 cm^{-3}.

The fringing field of the open-ended probe was simulated to demonstrate the relative measurement volume. This volume of influence was determined from transmission line modeling using the Arbitrary Transmission Line Calculator-ATLC ([16]; available at: http://atlc.sourceforge.net/ verified 18 May 2006) [6]. The permittivity values used in the simulation were 3 for plastic insulation between conductors and 30 for soil, a contrast ratio of 1:10.

Results

One of the first questions we asked in looking to apply open-ended TDR measurements in an on-the-go mode was what the sampling volume would be that is dictated by the fringing field that develops at the end of the probe. The other question was how a given probe might compare to an open-ended dielectric probe that is typically used with a network analyzer. In this case, we were interested in the power loss over a range of frequencies (1 MHz to 1 GHz). Perhaps the real test would be whether or not the probe movement across the soil would impact the waveform. In other words, waveform repeatability in a homogeneous system (e.g., sand) should be evaluated. For this we constructed a tray (Fig. 2, Probe 1) that the probe could travel along the top of. Waveforms were collected with the probe being moved at different speeds first through dry sand followed by water-saturated sand. Partially saturated conditions were problematic for this setup due to the sand cohesion forces and resulting tearing of the sand surface. The preliminary results were promising enough to develop a blade for field testing with a single probe embedded in the blade (Fig. 2, Probe 2) and this was followed with a third prototype probe having multiple sensors that was constructed and tested (Fig. 2, Probe 3). Finally we considered on-the-go limitations given the currently available TDR/multiplexer/analysis systems on the market. We summarize with a description of the mapping system used and some possible additions.

Open-ended probe sampling volume

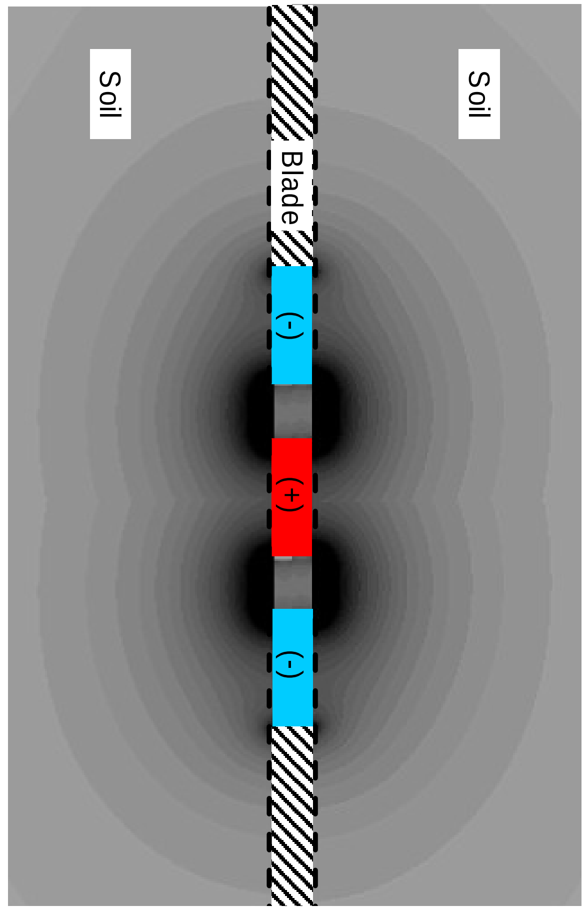

Figure 3. Modeled energy density (shaded regions) showing the preference or weighting placed on material closest to the electrodes of a 'blade-like' open-ended TDR probe designed to be pulled through the soil (ε = 30).

The open-ended probe geometry provides a flat surface ideal for sliding past the soil with minimal disturbance. The electromagnetic field fringes into the soil around the termination of the open-ended probe. The depth of penetration is a function of the dielectric of the soil and probe insulator as well as the dimensions of the electrodes. We used EM-field modeling software for describing the spatial energy density surrounding the transmission line as a means of designing the probe geometry, in this case to portray the EM field of an open-ended probe configured as a blade (Fig. 3). This modeling is also useful for estimating the sampling volume of the probe and how the measurement is impacted by the compaction of the dielectric (soil). For this example, the inner conductor radius is approximately half that of the outer conductor 'inner' radius. The resulting image shows more than 90 percent of the resulting field extending to a distance approximately equal to the outer conductor's inner edge radius. There is also more weight given to the permittivity of soil adjacent to the probe surface and between inner and out conductors. The resulting energy density distribution could be superimposed (as a first order approximation) on the resulting bulk density near the probe to determine correction factors for soil compaction effects on permittivity. To this point in our research, no compaction effects have been considered, but this will be an important consideration for future development.

Signal Loss Analysis

A common measurement for characterizing liquid dielectric permittivities is to use the frequency-dependent output of a network analyzer coupled with a dielectric probe (open-ended measurement). These systems comprised of very costly instrumentation provide precise and accurate measurements of permittivity in addition to system analysis capabilities. We used the analyzer's ability to measure attenuation of the signal in the frequency domain to evaluate the quality of our different cable/probe configurations. We compared the frequency-dependent attenuation of the network analyzer signal traveling through the air-line/dielectric probe to those of our different cable/probe systems shown in Fig. 4. The straight line in the center indicates no attenuation. The line ending in a white dot is the attenuation of the air line/dielectric probe shown in each output image. Interestingly, Probe 1, which was made from a coaxial adapter (N-type x UHF) combined with a 40 cm high quality cable shows less attenuation than the airline (70 cm)/dielectric probe combination. The high quality cable that came with the network analyzer may not be a feasible option for real world applications and higher attenuations should

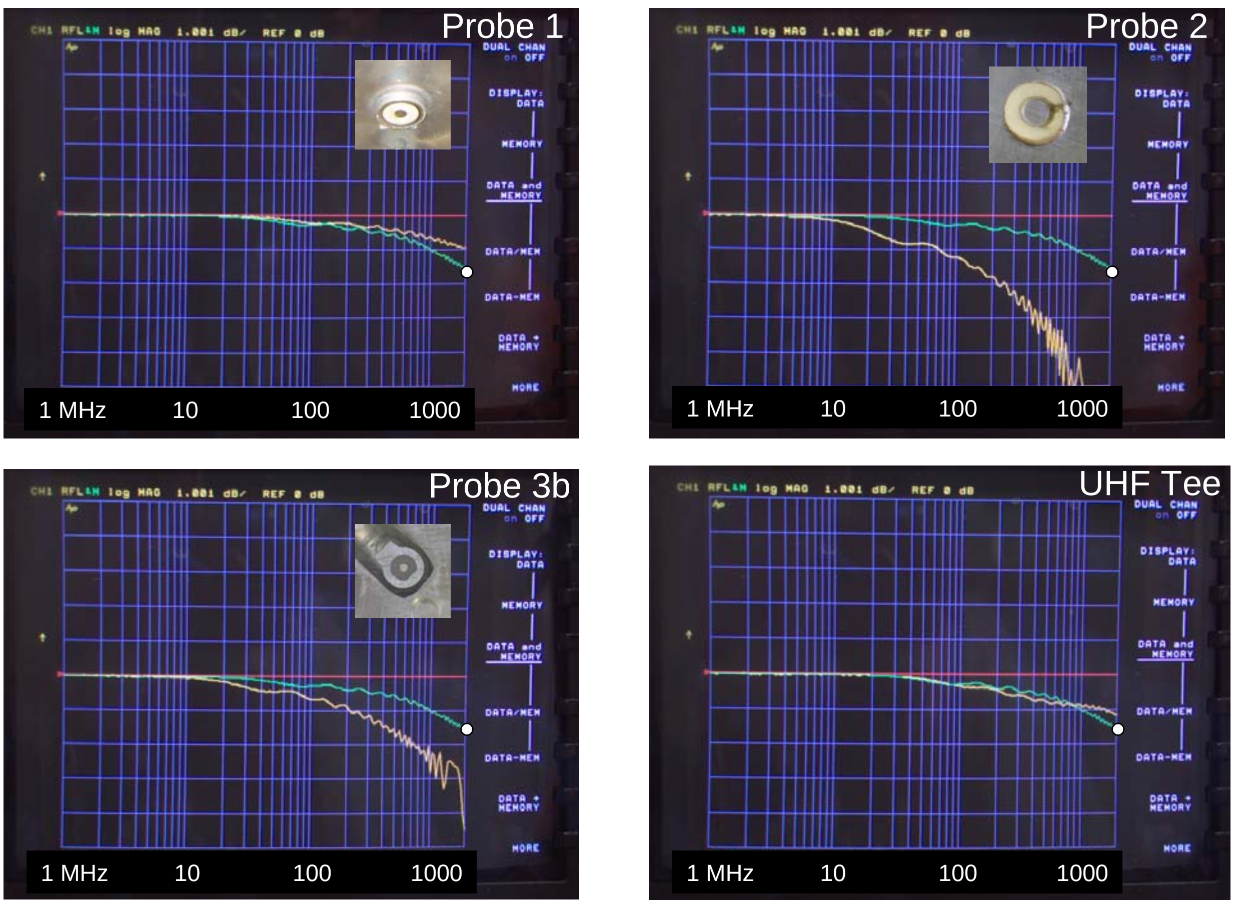

Figure 4. Frequency-dependent losses measured by a network analyzer where each tick on the y-axis represents 1 decibel and the centerline is 0 loss. The line ending in a white dot (same in each figure) represents the loss in the high quality dielectric probe designed for the network analyzer. The unique lines represent combined losses of each of four different probe/cable systems. Probe 1 is a single sided reflection, while probe 2, probe 3b (bottom) and the UHF Tee are double sided reflections. Note that in Probe 1 and the UHF Tee, the accompanying cable was much higher quality and the UHF fittings are higher quality and larger than Probe 2 and Probe 3b, respectively.

be expected for more affordable cables (e.g., RG8). Probe 2 shows significant signal degradation which comes from the combination of the RG-174 cable and the custom-made probe. The advantage of the RG-174 cable is in its small, 3 mm, diameter which facilitates a thinner blade and less cable wear and tear. Probe 3b is the bottom probe in the 3-probe blade (Fig. 2, Probe 3), which shows less attenuation than Probe 2, but significantly more than the reference system. Here an RG-58 coaxial cable and multiple connectors contribute significantly to the losses. The BNC-type tee used in the blade as the sensor, itself, shows very little attenuation (e.g. tee without cable). This fitting/cable combination was the largest diameter system we could fit in the one half inch (13 mm) blade thickness we used for Probe 3. The tradeoff again is in providing minimal disturbance to the soil (thin blade) while maintaining the necessary strength to pull the blade through the soil without blade failure (bending). The final comparison shown is using an UHF tee with the high quality cable. In this case, the loses are again on the order of those from the reference system. In order to implement this system, a thicker (20 – 25 mm) blade would be required. Each probe could be evaluated more thoroughly as to its permittivity measurement capability using liquids to characterize and calibrate in both non-dispersive and dispersive dielectric liquids [5, 6].

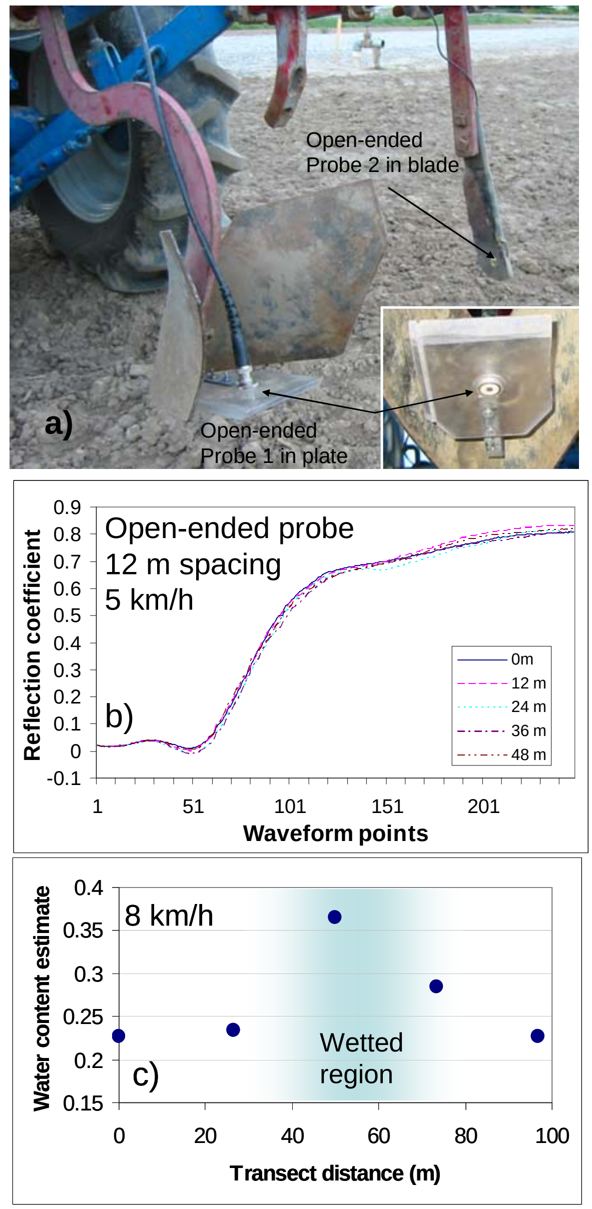

Figure 4. a) Picture of ‘blade-’ and ‘sled-configured’ prototype open-ended TDR probes. b) Waveforms measured with the blade probe in the field at uniform water content (i.e., Millville silt loam) along a 50 m transect. c) Water content interpreted from the blade open-ended probe reading in a non-uniformly wetted transect in the same field.

Waveform repeatability

The preliminary laboratory measurements used to determine the influence of travel speed on waveform consistency and repeatability used conventional travel-time analysis with a 15 cm parallel-plate TDR probe mounted to a Lexan sled. An open-ended probe (Fig. 2, Probe 1) was tested in a similar manner, considering only waveform output. Results of the Tektronix TDR measurements at speeds up to 8 km/h (5 mi/h) in dry and water-saturated sand, respectively, revealed no significant differences between static and dynamic permittivity measurements. Prototype probes were constructed for field testing (Fig. 4a), and travel-time analysis was adopted as an approximate means of water content determination using an apparent probe length of 5 mm. Because travel time analysis accuracy diminishes with probe length, this technique was only used as a convenience for preliminary assessment. The two different prototype open-ended probes shown in Fig. 4a were connected to the Tektronix TDR with waveform analysis and collection carried out on an 'as fast as possible' basis (about 9 seconds). A 50 m transect on bare Milville silt loam soil was used to initially observe variations in waveform output. Fig. 4b shows 5 different waveforms collected using Probe 2 in a 50 m transect of uniform soil whose water content was approximately half of field capacity. In a 100 m transect of the same soil, a wetted strip was brought to field capacity near the 50 m mark for contrast. The resulting approximate travel-time analysis shows water content along the transect in Fig. 4c. Movies were made of the tractor pulling the blade through the soil (http://soilphysics.usu.edu/locked/onthegomapping.htm).

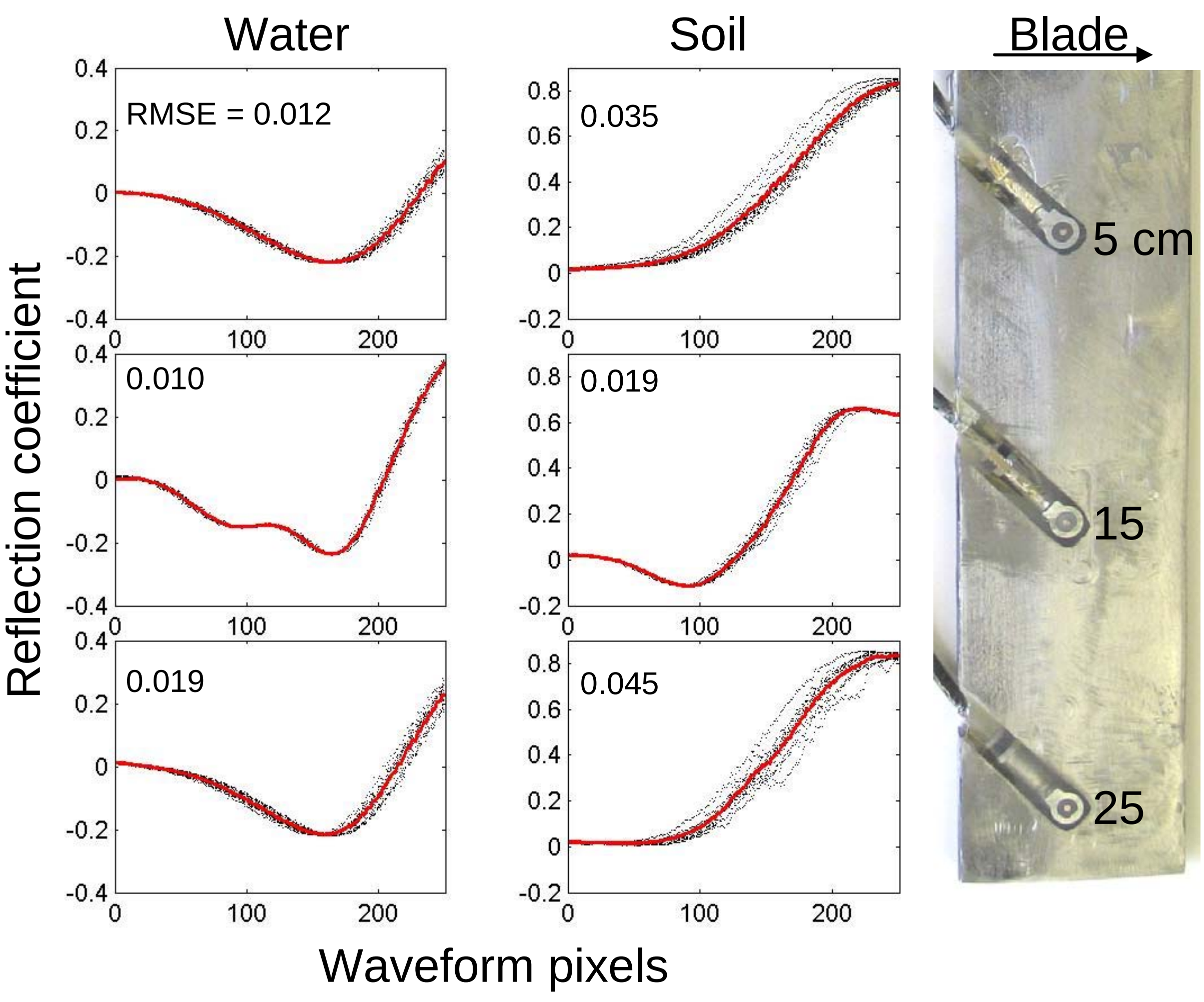

Figure 5. Waveforms obtained in water and in Milville silt loam soil near field capacity (~ 0.2 cm^3 cm^{-3}), showing 9 replicated waveforms with the solid line representing the average and root mean squared errors (RMSE) listed for each. The three probes shown at right were measuring at 5, 15, and 25 cm below the soil surface traveling at 3.2 kmph (0.9 m/s).

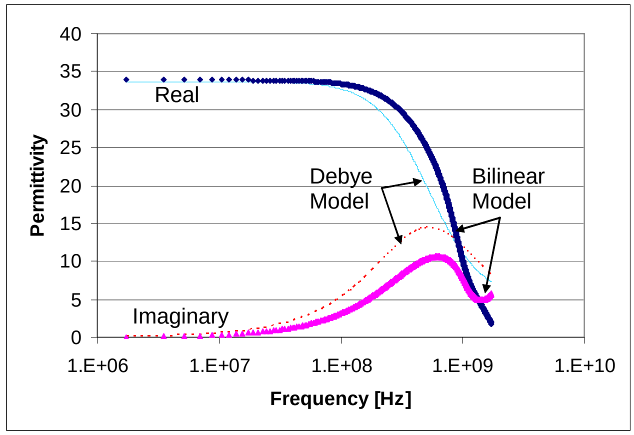

Figure 6. Bilinear analysis example showing a comparison to Debye modeled real and imaginary permittivities of glycerin.

For multiple depth sensing, the blade pictured in Fig. 5 (see Fig. 2, Probe 3) was mounted on a tool bar and pulled through the same field plot in the spring time with near field capacity soil moisture. Three different depths were set, in the first run the bottom blade was set at 5 cm below the surface. The next run had the bottom at 15 cm and the middle at 5 cm depths. The third run had all three sensors at the depths shown in Fig. 5. The tractor speed in each case was 3.2 kmph (0.9 m/s) and the length of each transect was approximately 25 m (2.7 m grid spacing). For comparison purposes, we measured 9 consecutive waveforms for each of the three probes while stationary in water. We compare these to 9 waveforms from the final run having all three probes traveling through the soil. The line in each case represents the average of the 9 waveforms and data points exhibit variations from this mean. The root mean squared errors were computed referencing the average waveform and are shown for each sensor and medium type. An approximate doubling in the RMSE value is shown for all three probes when measurements are taken in soil on-the-go. Given the spatial variability of soil properties in general, this result suggests high accuracy water content determinations are possible for mapping subsurface soil moisture using open-ended probes.

Bilinear analysis example

The bilinear analysis technique is useful for waveform analysis and interpretation of the complex permittivity for short and open-ended reflection measurements [8-11]. We followed the procedures outlined in the literature and with significant difficulty (i.e., due to errors in manuscripts) arrived at an approximate solution. Our initial results illustrated in Fig. 6 show reasonable comparison to debye parameter fitting to the measured real and imaginary permittivities of glycerin. In the process of our development we began collaborating with others developing similar approaches for short TDR probes and determined their progress and results were far superior to ours (Castiglione and Wraith, personal communication) and hence we determined not to pursue further development of this technique, rather we chose to focus on the hardware development.

Limitations of existing technology

Changes in soil water content occurring in natural systems are on the order of hours to days and therefore monitoring activities have not required rapid acquisition from soil moisture sensors. As a result, limitations in TDR acquisition time depend on the instrument characteristics, data transfer and waveform analysis time. For open-ended probe measurements where minimum grid spacing and maximum travel speed is the objective, only the waveform collection is critical. The analysis for either water content or EC could be post processed to avoid slowing down the acquisition time as illustrated in Table 1. With this in mind, Figure 5 illustrates the tradeoff between acquisition time and desired grid spacing where for a minimum waveform acquisition time of 3 seconds, and minimum grid spacing of 4 m, the maximum travel speed is 5 kilometers per hour (1.35 m/s). Some of the limitations in acquisition time related to decades-old technology where transfer rates (e.g., 1200 baud rate) remain a bottle neck for data collection. Either limiting the amount of data passed back and forth or using advanced communications could conceivably reduce acquisition frequencies to less than 1 second allowing faster speeds and finer grid spacings for field mapping of water content and electrical conductivity.

Table 1. Collection times (seconds) for single and multiplexed probes where water content (WC) and electrical conductivity (EC) are determined and a waveform (WF) is collected. The Tektronix utilized WinTDR waveform analysis software and the Campbell Sci. CR23X/TDR100 system performs the storage and analysis.

	Tektronix w/WINTDR				**Campbell Sci. CR23X/TDR-100**			
	WC (s)	EC (s)	WF (s)	Total (s)	WC (s)	EC (s)	WF (s)	Total (s)
1 probe	0.01	7	8	15	1.2	0.9	3	5.3
multiplexer	0.05	0.05	0.05	0.05	0.01	0.01	0.01	0.01
2 probes	0.02	14	16	30	2.4	1.8	6	10.6
3 probes	0.03	15	24	45	3.6	2.7	9	15.9

The other significant limitation is analysis of the waveform using TDR. Limitations suggested by the WINTDR travel-time analysis software indicate the waveform acquisition from a Tektronix cable tester requires about 50 percent of the total time while the travel time analysis requires on 10 ms. The electrical conductivity analysis requires about 7 seconds (essentially another waveform acquisition required), so between waveform transfer and analysis the total ‘real time’ capability is between 8 and 16 seconds with this system. For a open-ended probe the analysis technique is not fully developed and will require some software development to be fully implemented for quasi-real time measurement of water content.

Other challenges relate to the abrasion resistance of the probe and its accompanying insulating materials. Materials that are softer than the steel used in the blade or other housings will wear faster resulting in probe and measurement degradation. The use of coaxial adaptors is convenient for research purposes, but is not a long term viable solution. Stainless steel conductors are a likely choice, though this material will be more expensive and difficult to machine. The insulating material (e.g., Teflon, polypropylene, etc.) is the most likely place

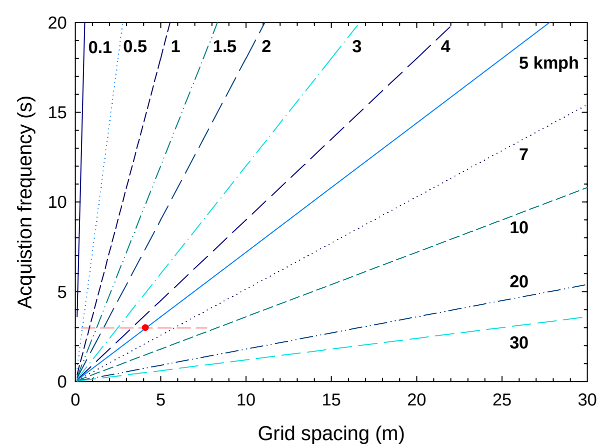

Figure 7. Example maximum speed for a desired grid spacing of 4 m and maximum waveform collection interval (see Table 1) of 3 seconds. For this configuration, the maximum travel speed is 5 kilometers per hour (kmph, 1.35 m/s). Faster acquisition frequencies facilitate higher vehicle speeds.

where wear will show soonest. High abrasion resistant materials such as Kevlar may be worthy of consideration. Additional considerations include a free-floating system to avoid blade bending during lateral tractor/implement movement. This was a problem we encountered using Probe 3 at the deepest depth where the blade bent at the end of the run. Improvements in strengthening the blade using thicker steel and an improved design for introducing the cable into the blade.

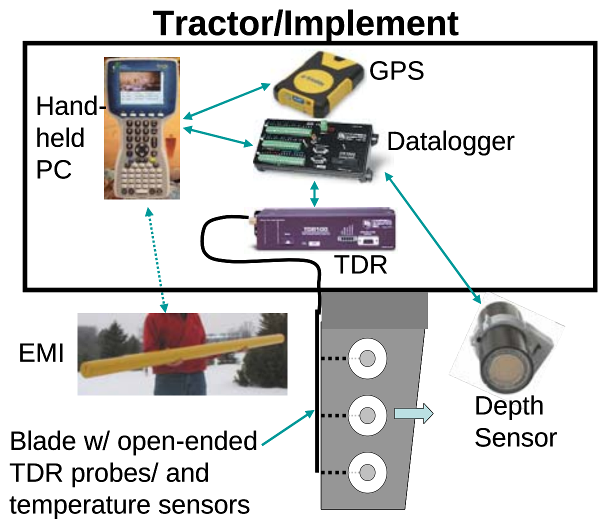

Figure 8. Proposed on-the-go measurement system with integrated components including the datalogger, TDR, depth sensor and invasive TDR probe with potential for non-invasive electromagnetic induction (EMI) sensor.

Summary

Invasive open-ended TDR probes designs have been developed and tested in near-surface (1-5 cm) and subsurface (5-30 cm) applications. The probes were evaluated to determine the effect of travel speed on the resulting waveform, with little effect shown compared to static measurements. Using existing technologies, grid spacing and data acquisition times limited the rate of travel to 5 kmph for a 3 second acquisition at a 4 meter sampling grid. Speeds up to 12 kmph were tested with little change in waveform quality. Faster acquisition times are needed to accommodate such high rate of travel and are possible with improvements in communications and processing capabilities. A network analyzer demonstrated power losses associated with different probe designs, where larger UHF style connectors provided the lowest loss probes tested and which were equivalent or lower loss than the commercial dielectric probe used for comparison. The fringing field at the end of the probe impacts the reflection contained in the waveform and is dependent upon the dielectric permittivity of the soil. The hypothetical system envisioned for mapping of soil moisture (and electrical conductivity) includes a hand-held PC, GPS, datalogger, TDR, depth sensor, subsurface probe(s) and other associated measurement devices (e.g., electromagnetic induction sensor, see Figure 8). Sensor depth determination would be incorporated in the datalogging system using either ultrasonic or linear displacement sensors that could potentially control and adjust sensor reading depth. There is certainly value in measuring at multiple rather than at a single depth, but with a considerable trade-off in power requirements and 'blade' design thickness. Factors impacting the travel speed include data acquisition capability and frequency and impact on parameter measurement accuracy. Waveform analysis techniques are being developed to derive frequency-dependent relationships for water content and electrical conductivity of the soil. Using GPS referenced measurements, we envision field-scale water content and electrical conductivity maps referencing multiple soil depths that compliment conventional and developing on-the-go precision agricultural measurements.

Acknowledgements

We acknowledge financial support from a New Faculty Research Grant at Utah State University and technical support from Hiruy Abdu, Zijun Zhang, Bill Mace and Kelly Lewis.

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