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Measuring the dielectric permittivity of a plant canopy and its response to changes in plant water status: An application of Impulse Time Domain Transmission

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Abstract

Impulse Time Domain Transmission (ITDT) has been used to measure the complex dielectric permittivity of media such as ethanol, water and variably saturated sand. This paper applies ITDT to measurements of the complex dielectric permittivity of a vegetation canopy. The dielectric permittivity of a vegetation canopy is very close to that of air and only very small changes in its value will occur with changes in plant water status. This paper presents preliminary results demonstrating that ITDT can make repeatable measurements of the complex components of the dielectric permittivity of a plant canopy. Furthermore, ITDT is shown to be highly sensitive to the very small changes in dielectric that occur as a result of changes in plant water status. Based on these preliminary results, there are potential applications foreseen for ITDT in microwave remote sensing, irrigation scheduling, plant physiological ecology, and fire susceptibility.

Abbreviations: ITDT – impulse time domain transmission; TDR – time domain reflectometry; VNA – vector network analyzer.

Introduction

The water status of vegetation has a strong correlation with the influence exerted by vegetation on carbon, energy and water vapor exchange between land surfaces and the atmosphere. It also provides an interface between hydrological and ecological systems. Knowledge of plant water status is useful for studies of plant physiological processes (Chaves et al., 2002; Parry et al., 2002); agricultural production (Wanjura and Upchurch, 2002; Muchow et al., 1986); microwave remote sensing applications (Jackson and Schmugge, 1991; de Roo et al., 2001); and fire susceptibility (Serrano et al., 2000; Pyne et al., 1996).

The application of direct measurements of leaf- and stem- water content to individual plants and canopies requires extensive and time-consuming sampling to represent variation in wood and leaves at various states. Other available methods of monitoring whole-plant water dynamics include measurements of sap flow (Smith and Allen, 1996); trunk diameter fluctuations (Moriana et al., 2000); canopy temperature (Wanjura et al., 1995); the Crop Water Stress Index (Jackson et al., 1981); carbon and water fluxes (Goulden et al., 1996); and microwave transmission properties using transmitting and receiving horn antennae (Ulaby and Jedlicka, 1984; Brunfeldt and Ulaby, 1983). However, these measurements all represent indirect measures of the plant water status. Remotely sensed data, in both the visible and microwave wavebands, have the potential to provide information on plant water status at these larger scales (Wigneron et al., 2000, Schepers et al., 1996, Zarco-Tejada et al., 2003). However, at present, and for the near future,

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their utility is limited both spatially and temporally. This paper introduces a novel, non-destructive electromagnetic technique that has the potential to directly and continuously monitor changes in plant water status at scales ranging from the individual to whole canopies. This technique is an extension of Time Domain Reflectometry, one of the most widely used methods for measuring in situ soil moisture at the point scale.

Time Domain Reflectometry (TDR – Topp et al., 1980) is a maturing electromagnetic technique for measuring the dielectric permittivity of soils, which is directly related to the soil water content. TDR measures the two-way travel time of an electromagnetic wave along a probe inserted into the soil relative to its travel time when the probe is in air. In addition to soils, TDR techniques have also been applied to measure the dielectric permittivity in plants by inserting the TDR probe into the stem (Constantz and Murphy, 1990; Holbrook et al., 1992; Wullschleger et al., 1997; Irvine and Grace, 1997, Sparks et al., 2001). An alternative technique uses a co-axial dielectric probe (Franchois et al., 1998; Salas et al., 1994; McDonald et al., 1999, 2002). Experiment-specific calibration curves can then be constructed relating the dielectric permittivity and stem water content. However, the insertion of probes into the stem causes damage and impacts the water distribution around the probes. In addition, problems can arise resulting from incomplete or inconsistent contact between the dielectric probe and the stem itself. The probes used in all the above experiments are necessarily short and will only sample a very localized area. To date, attempts to measure the dielectric of a vegetation canopy have concentrated on measuring the attenuation coefficient, i.e., the parameter that describes the damping effect of the vegetation on the microwave interaction with the soil. Either the power transmitted through the canopy is measured by a receiver placed on the opposite sides of the canopy to the emitter (Ulaby and Jedlicka, 1984), or the power reflected by a wide-beam standard target placed below the canopy is measured (Brunfeldt and Ulaby, 1983). These measurements were found to be of limited value because of the large standard deviations relative to the measured means.

The Impulse Time Domain Transmission (ITDT) electromagnetic measurement technique developed and tested on substances such as water and variably saturated sand by Harlow et al. (2003a, b) is similar to TDR. However, unlike TDR, ITDT measures the one-way travel time along the probe and requires instrumentation to be connected at both ends. For applications involving soils this is a less practical approach than TDR, where the instrumentation is connected at only one end. However, within a sparse vegetation canopy this is simple to implement. A main advantage of ITDT over TDR is that ITDT waveforms are significantly easier to analyze than TDR waveforms because the first-arriving energy is readily separated from multiple reflected and interfering secondary arrivals using a gating function. The application of ITDT to measure the dielectric permittivity of a vegetation canopy has many potential advantages over existing methods of determining plant water status. ITDT is a non-destructive, non-contact method that does not impact evapotranspiration and has the potential to be totally automated. It can be applied at both the single plant level and the patch scale, resulting in canopy average measurements of the dielectric permittivity as well as plant specific measurements. This scaling ability provides a valuable link between *in situ* and remotely sensed measurements. This paper presents preliminary results demonstrating the ability of ITDT to make repeatable measurements of the dielectric permittivity of a sparse and heterogeneous plant canopy and to monitor changes in plant water status.

Dielectric permittivity

The response of a medium to a time-dependent electric field is determined by the complex dielectric permittivity, an intrinsic property of the medium:

$$\varepsilon = \varepsilon_r' + i\varepsilon''. \tag{1}$$

Here ε_r' is the real part of the permittivity, and ε'' is the imaginary part of the permittivity (or the dielectric loss) of the medium (Ulaby et al., 1986). Stated simply the dielectric constant is a measure of the ability of a media to redistribute its charges so as to oppose an applied electric field. It is dependent on the frequency of the applied field. Of the substances present within plants, water has the highest dielectric permittivity (of the order: $80+5i$), and air has a dielectric permittivity of $(1+0i)$. Therefore small changes in water content lead to significant changes in the canopy-average dielectric. The presence of salts changes the conductivity of water which results in an increase of the dielectric loss and hence changes the dielectric permittivity of a medium. The magnitude of the dielectric permittivity (ε_{mag}) provides information on changes in water content of the plant canopy. It is given by the Pythagorean Theorem:

$$\varepsilon_{\text{mag}} = \sqrt{(\varepsilon_r')^2 + (\varepsilon'')^2}. \tag{2}$$

The loss tangent (T_l) is a measure of the relative strength of the losses to the real part of the dielectric:

$$T_l = \varepsilon''/\varepsilon_r'. \tag{3}$$

Hence it will show changes in the conductivity of the pore water in the plant, which might occur as a result of changes in its environment.

ITDT measurement technique

A Vector Network Analyzer (VNA) is used to measure the transmission and reflection properties of a transmission line or any other network. In this study, the time domain response of an impulse transmitted along a twin rod transmission line is analyzed. The response contains information about both the first arrival (that part of the signal transmitted along the line only once) and secondary reflections resulting from impedance mismatches within the apparatus. If the experimental apparatus is designed in such a way that the secondary reflections are well separated in time from the first arrival, the secondary reflections can be filtered from the first arrival using a time domain gate. This gated time domain response is then converted to the frequency domain using a Fast Fourier Transform. The transmitted and incident signals are then used to determine the frequency dependent complex dielectric permittivity.

The phase and magnitude of the complex transmission coefficient measured with the rods embedded in the sample relative to those measured with the rods in air are used to calculate the phase per unit length (β) and the attenuation per unit length (α) (Ida, 2000):

$$\alpha = \left[\ln\left(T_{\text{air}}/T_{\text{sample}}\right)\right]/L, \tag{4}$$

$$\beta = \frac{\omega t}{L}, \tag{5}$$

where T_{air} and T_{sample} are the magnitudes of the transmission coefficient measured in air and in the sample, respectively; L is the length of the sample in m; ω is the angular frequency in Hz; and t is the travel time of the impulse through the medium in seconds. The travel time is related to other transmission properties as:

$$t = \frac{\phi'(\omega)}{\omega} + \frac{L}{c}, \tag{6}$$

where ϕ' is the difference between the phase of a pulse transmitted through air and that through the medium; and c is the speed of light in a vacuum in m s^{-1} (see Harlow et al. (2003a) for more details).

The real part of the permittivity (ε_r') can be found by (Ida, 2000):

$$\varepsilon_r' = c^2\left[\left(\frac{\beta}{\omega}\right)^2 - \left(\frac{\alpha}{\omega}\right)^2\right]. \tag{7}$$

The magnitude of the permittivity (ε_{mag}) can be calculated as (Ida, 2000):

$$\varepsilon_{\text{mag}} = c^2\left[\left(\frac{\beta}{\omega}\right)^2 + \left(\frac{\alpha}{\omega}\right)^2\right]. \tag{8}$$

The imaginary part is calculated using the real part and the magnitude of the permittivity and the Pythagorean theorem for complex numbers (Equation 2).

Materials and methods

Experimental setup and initial testing

The ability of ITDT to detect canopy water status in a repeatable fashion was tested within a laboratory setting. Figure 1 shows a schematic of the general experimental setup. The transmission line comprised two steel rods 3 mm in diameter, 97 cm long and separated by 2.2 cm. These rods were supported horizontally using clamps and stands. The rods were inserted through the canopy and hence each rod was surrounded by sparse vegetation. This method of probe insertion has minimal impact on the behavior of the plant: it is non-invasive and non-destructive. The cross section of the sampling volume of the rods is approximately twice the separation of the rods in the plane of the rods and approximately the separation of the rods perpendicular to the plane of the rods. Since the measurement represents a difference between vegetation and air, any proportion of the length of the rods can be surrounded by the canopy.

Each end of the transmission line was connected to the Vector Network Analyzer (VNA) via coaxial connecting cables and terminal blocks. The VNA used in this study (HP 8752C Network Analyzer – Hewlett-Packard, Santa Rosa, CA) was set up to measure at 401 equally spaced points in the frequency range of 300 kHz to 1.5 GHz. Measurements were made in transmission. To synthesize a time domain impulse input, the frequency components were weighted appropriately and transformed into the time domain

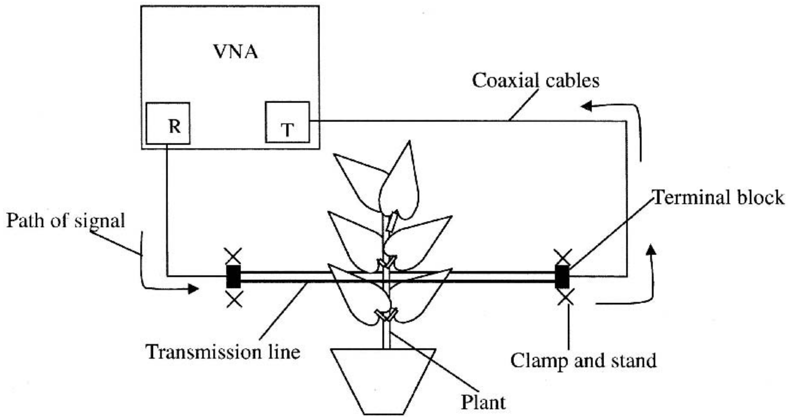

Figure 1. Schematic of the experimental setup. R and T are Reflection and Transmission ports of the VNA, respectively.

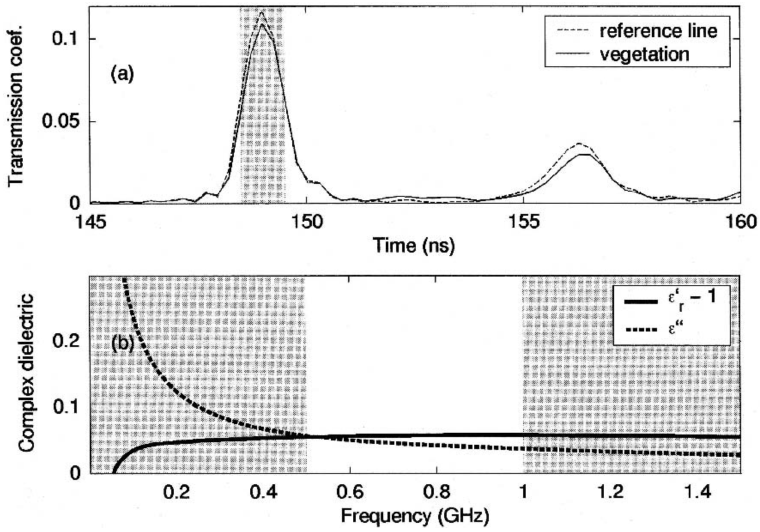

Figure 2. (a) Time domain response of rods in air (reference line) and within a rosemary canopy. The shaded area represents the region over which the gate is applied. (b) Frequency domain components of the complex dielectric permittivity of the rosemary canopy. The non-shaded area represents the frequency range over which the measurement of the complex dielectric permittivity is valid.

using an inverse Fast Fourier Transform (Harlow et al., 2003a).

The applicability of this experimental setup to measure the frequency dependent dielectric permittivity of vegetation canopies was initially explored using a rosemary canopy (*Rosmarinus officinalis*) approximately 20 cm in diameter which was placed centrally along the rods. In particular, this experiment was used to test the conditions under which the time separation between the primary and any secondary arrivals is large enough to separate these two signals with the time domain gate.

Repeatability of the measurement technique

The first set of experiments was designed to test the repeatability of measurements for sparse and heterogeneous vegetation canopies with a complex dielectric permittivity very similar to that of air. In particular, to address the following questions: What impact does the location of the plant along the rod have on the measurements? Does changing the gate width change the value of the complex dielectric permittivity? Are the measurements sufficiently repeatable? These questions were addressed by exploring the impact of the location of a single plant and the impact of increasing the canopy size.

The impact of the location of a single plant with respect to the length of the rods was tested using two contrasting plants. The first plant was the rosemary canopy (*Rosmarinus officinalis*) approximately 20 cm in diameter and the second plant was a tomato plant (*Lycopersicon esculentum* L.) approximately 25 cm in diameter. In each case, the plant was moved from end to end along the rods three times in 5 cm increments.

Repeatability of the ITDT measurement technique was further tested by a stepwise increase of the canopy size. Twelve small, similar herbaceous plants each 5 cm wide were systematically inserted along the 97 cm rods one plant at a time. The first plant was located at the center of the rods and each subsequent plant added from alternate ends of the rods.

Monitoring plant water status

One potential application of the ITDT measurement technique is to monitor the changes in dielectric permittivity related to changes in plant water status. Two complementary experiments were designed to demonstrate the sensitivity of ITDT to changes in plant water status and highlight the potential of this method to improve understanding of plant physiological processes.

The first experiment monitors the complex dielectric permittivity as a function of the relative water content of drying vegetation. A Japanese boxwood plant was cut apart, and the resulting pieces of vegetation canopy were put into a cylindrical PVC pipe that had a 26 cm twin rod transmission line installed vertically along its axis. Measurements of the mass of the system (cylinder plus contents) and the dielectric permittivity of the drying vegetation were made at periodic intervals. The changes in dielectric in this experiment will be larger than might be expected when vegetation moves from an unstressed to a stressed state.

The second experiment was used to explore the response of the tomato plant (used in the repeatability experiments) when subject to drought. In this case the 97 cm long rods were inserted low in the canopy, straddling the main stem. The mass of the soil plant system was monitored periodically as it dried from saturation. This experiment was carried out in very controlled conditions: in a room with no windows and constant lighting and temperature.

Results

Applicability of ITDT method to vegetation canopies

The ability of ITDT and the proposed experimental design to measure the dielectric permittivity of a vegetation canopy was initially assessed using the rosemary plant. Figure 2a shows the time domain transmission coefficient with the rods (1) embedded in air (reference line) and (2) surrounded by the rosemary. There is very little visible difference between the two measurements because the canopy average dielectric constant is very similar to that of air. The high peaks at time = 149 ns represent the energy that passes directly through the system with no internal reflections. This first arriving energy travels along a direct path through the apparatus and, therefore, is of interest for the measurement of the complex dielectric permittivity. All subsequent, smaller peaks arrive noticeably later than this first arrival and are due to longer travel paths resulting from multiple reflections within the apparatus. These subsequent reflections may contain relevant information about the medium under test; however, this information depends on the geometric distribution of dielectric in the sample as well as the impedance mismatches that occur at the ends of the transmission lines. Since this information may not be known prior to the measurement, the secondary reflections are removed from the signal before analysis. The time separation between the first and subsequent arrivals is such that they can be easily separated by a time domain gate (Figure 2a – shaded region). Within the time domain gate (shaded region) the gate maintains the shape of the time domain response. Any other signal outside this region is set to zero. The gate width in this example is 1.0 ns. Figure 2b shows the frequency dependent dielectric permittivity of the rosemary plant. It should be noted that, as a result of the gating, the complex dielectric permittivity is only accurately determined over the non-shaded frequency range shown in Figure 2b (Harlow et al., 2003a).

Repeatability of the measurement technique

The repeatability of the measurements made for both the tomato plant and the rosemary was explored as a function of the location of the center of each plant on the rods. Figure 3 shows the magnitude of the measured dielectric permittivity at a frequency of 0.75 GHz. For the central 37 cm, the magnitude of the dielectric permittivity is relatively constant and is 1.0991 ± 0.0004 for the rosemary plant (Figure 3a)

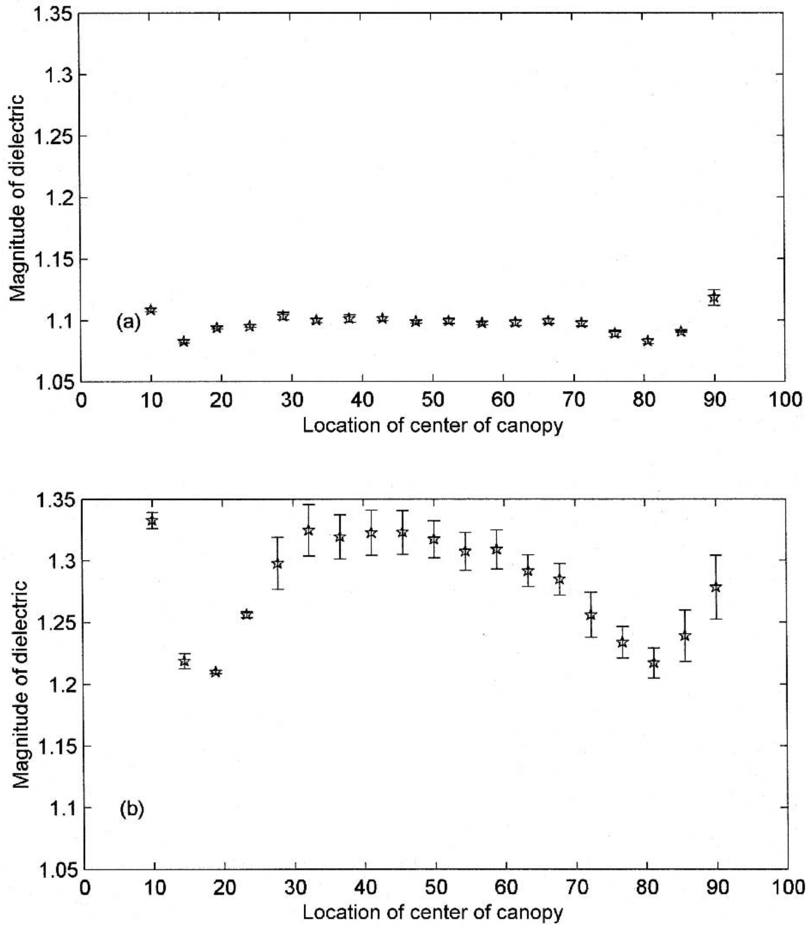

Figure 3. Magnitude of the complex dielectric permittivity of (a) a rosemary canopy and (b) a tomato canopy at 0.75 GHz frequency using an applied gate width of 2.8 ns as a function of distance of the center of the canopy from one end of the rods. Error bars are based on the standard deviation of three measurements; where the plant was moved after each measurement.

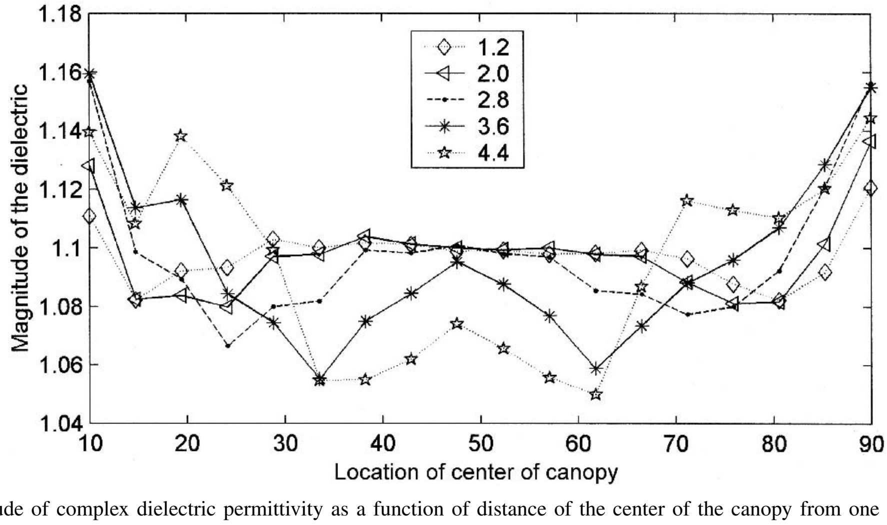

Figure 4. Magnitude of complex dielectric permittivity as a function of distance of the center of the canopy from one end of the rods for different gate widths.

and 1.3110 ± 0.0015 for the tomato plant (Figure 3b). At the outer 30 cm ends of the rods, the magnitude of the measured dielectric permittivity is a strong function of location. This dependence on the location of the plant is a result of reflections from the canopy itself. When the plant is located at the center of the rods, the reflections are well separated in time from the primary peak and the measurement of the dielectric permittivity more accurate. However, nearer the ends of the rods the secondary arrivals are so close in time to the primary arrivals that the gating is not able to remove all of the information contained in these secondary arrivals. The function is not symmetrical about the center of the rods because the canopy is not uniform and the coaxial cables and connectors are not identical at either end of the rods.

Figure 4 shows similar results to Figure 3, but, in this case, demonstrates the sensitivity of the magnitude of the dielectric permittivity to the applied gate width. The width of the central plateau is a function of gate width. At the smaller gate widths (<2.8 ns), despite not all of the first arrival being included in the analysis, the dielectric permittivity is independent of location along the majority of the rods. Although this loss of information does not affect the magnitude at 0.75 GHz, it results in a narrower frequency range over which the measurement of the dielectric is accurate (Harlow et al., 2003a). At the larger gate widths (>2.8 ns), the width of the central plateau decreases because more information is included from secondary reflections for smaller deviations in plant position. This results in errors in the magnitude of the measured dielectric permittivity even when the plant is at the mid-point of the rods. A gate width of 1 ns was used for this study because errors were found to be a minimum (Harlow et al., 2003). This outweighs the fact that the applicable frequency range is reduced.

Repeatability of the ITDT measurement technique is further demonstrated for increasing canopy size using a series of small herbaceous plants (5 cm wide), each with a volume fraction of 0.0453 ± 0.005 and a gravimetric water content of 0.927 ± 0.002 g^{-3} cm^{-3}. Figure 5 shows the difference between the measured complex dielectric permittivity and that of air (1 + 0i), as a function of the width of the canopy at 0.75 GHz. When there are no plants on the rods this difference is 0 + 0i. The average complex dielectric permittivity per unit length of the canopy, found from the fitted relationship, is (0.0055 + 0.0014i) cm^{-1} with a standard error of 0.0007 cm^{-1} in the real component and 0.0003 cm^{-1} in the imaginary component. Some of the variability results from inter-plant differences in water content, structure and density. In the presence of greater than ∼8 plants, the dielectric permittivity is impacted by the ends of the rods as in Figure 3. Despite this, R^2 is greater than 99% for both the real and imaginary components and a high degree of linearity demonstrates the repeatability of the measurements.

Monitoring plant water status

The ITDT measurement technique is shown to be highly repeatable. The next question to be addressed is whether it can detect the, possibly very small, changes in dielectric permittivity with changes in plant water status. Figure 6a presents the complex dielectric permittivity at 0.75 GHz for the drying harvested boxwood plant. The water content of the boxwood is defined relative to its value immediately before harvesting, which is not necessarily the maximum possible water content of the plant. Clearly, there is a measurable relationship between the relative water content and the dielectric permittivity of the vegetation. The slope of the relationship changes with relative water content – the complex components of the dielectric permittivity decreasing more slowly at the higher relative water contents than at the lower relative water contents. The dielectric permittivity is a mixture of the proportions of free water (real part ∼80), bound water (real part ∼4) and plant dry matter (real part ∼8). Therefore these results suggest that the plant might be losing a greater proportion of bound water at the beginning of the drying and a lower proportion near the end. Figure 6b shows the loss tangent (imaginary component divided by real component). The loss tangent contains information about the effects of dielectric relaxation of rotating molecules or effects of ohmic loss due to changing ionic strength in the plant cells. A linear fit between the loss tangent and the relative water content less than 0.4 has an R^2 value of 99.7%. The relationship between either of the complex components of the dielectric and the relative water content is more variable below a relative water content of 0.4 (Figure 6a). These results imply that the loss tangent either has a smaller error associated with it than the complex components themselves or that the complex components change in more complicated ways but are constrained by the condition that the loss tangent changes linearly.

The second example shows the complex dielectric permittivity of the tomato plant subject to drought. The mass of the soil plant system was quantified in terms

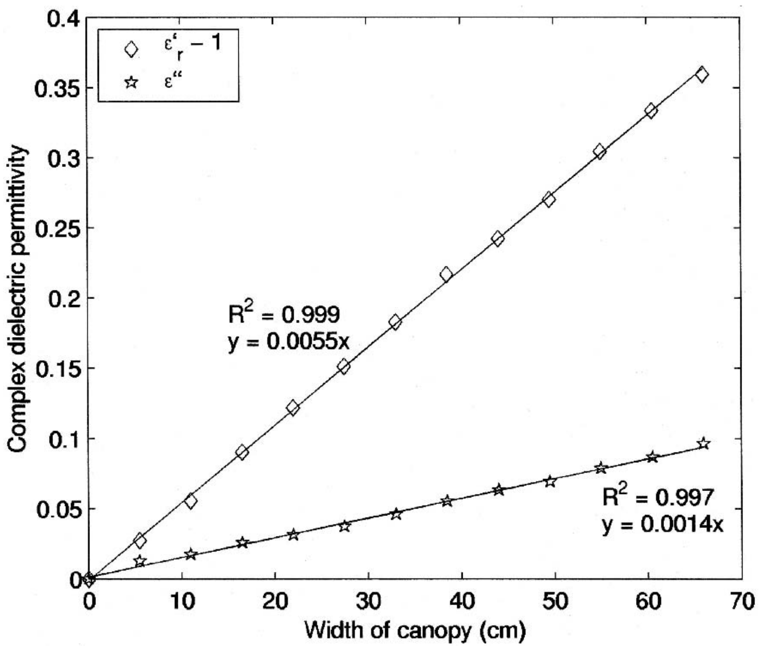

Figure 5. Complex dielectric permittivity of bedding plants systematically added to the center of the rods at 0.75 GHz as a function of proportion of rod covered. The slope of these relationships gives the average value of the dielectric permittivity per unit length (cm) of canopy.

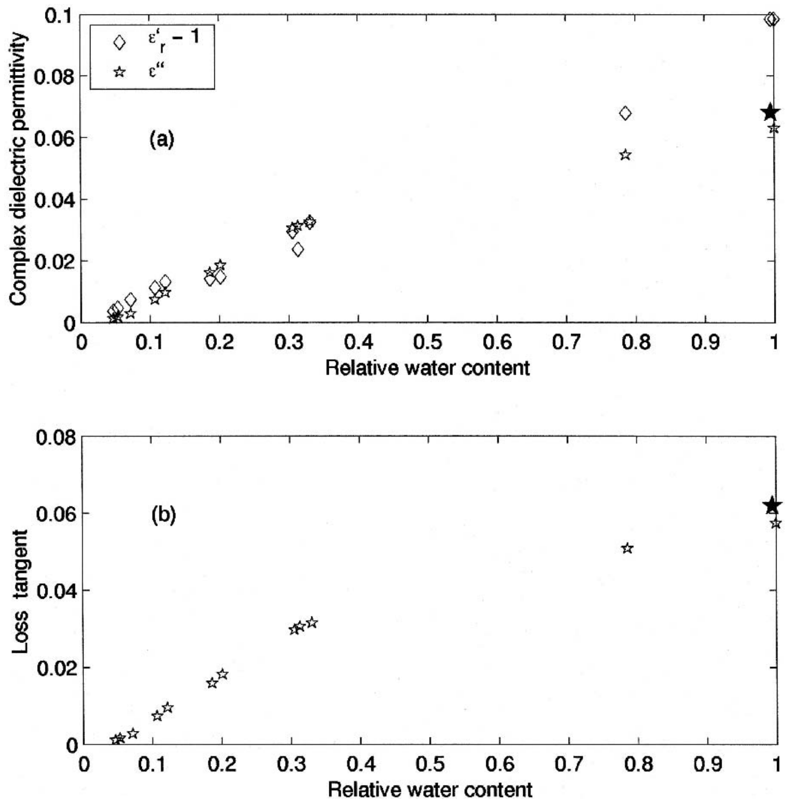

Figure 6. (a) Complex dielectric permittivity and (b) loss tangent at 0.75 GHz of a drying, harvested plant relative to that of air as a function of relative water content.

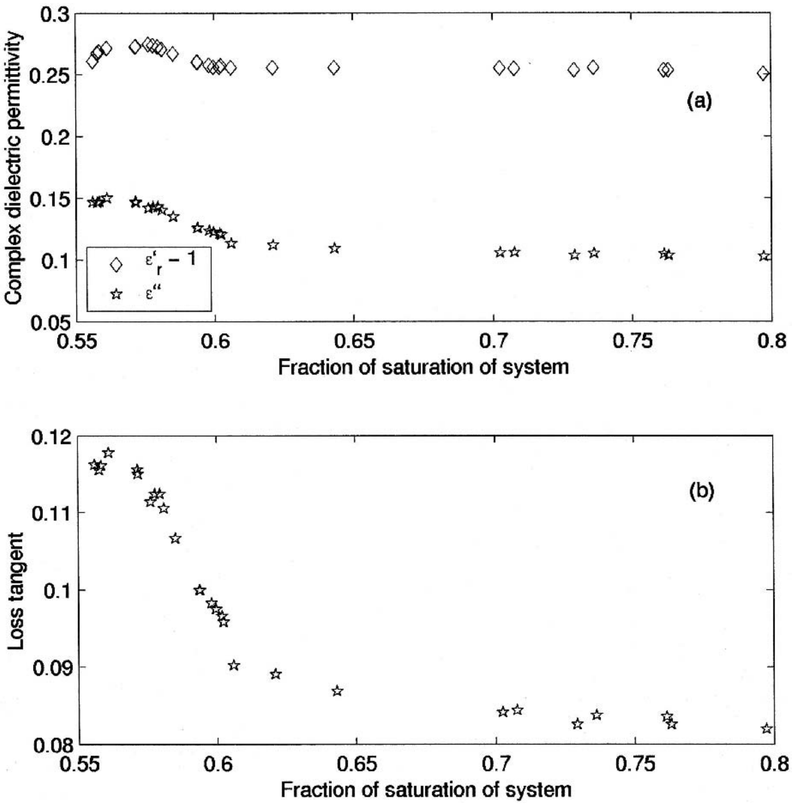

Figure 7. (a) Complex dielectric permittivity and (b) loss tangent as a function of fraction of saturation the tomato plant.

of fraction of saturation; given by the mass of the system over the mass of the system at the start of the experiment (fraction of saturation = 1 at the start of day 1). Therefore the soil water content dominates the value of the fraction of saturation. Figure 7a shows the components of the dielectric permittivity as a function of the relative saturation of the soil-plant system. The complex dielectric permittivity is relatively constant between 0.8 and 0.6. There is an increase in both the real and imaginary component of the dielectric permittivity at about 0.6 (day 10), followed by a decrease below 0.57 (day 13). This demonstrates a response of the ITDT measurement of the complex dielectric permittivity to drought stress. This increase in both complex components of the permittivity and the loss tangent began approximately 3 days before any visible signs of wilting. Figure 7b shows the loss tangent. There is a sharp increase in the loss tangent at the onset of stress (relative water content of 0.6).

The filled measurement in Figure 6 (with a relative water content just less than 1) has a greater complex dielectric permittivity and loss tangent than the measurement with relative water content of 1, taken immediately after harvesting. This is a comparable increase to the gradual increase in the complex dielectric permittivity at the onset of drought stress in Figure 7 at 0.6 fraction of saturation. The decrease in the complex components of the dielectric permittivity at 0.57 fraction of saturation in Figure 7 is comparable to the decrease seen in Figure 6. For practical reasons, measurements in Figure 7 ceased once the plant started to wilt; however, it is expected that the complex dielectric would continue to decrease and provide a response similar to that seen in Figure 6 if the dry down had continued.

Discussion

Results of the repeatability experiments demonstrate that, despite disturbing the measurement system in between each measurement, the measurements are highly repeatable when the canopy is located near the middle of the rods. Three contrasting canopies were measured: rosemary which has several woody stems and small leaves; tomato which has a single dominant green stem and fewer larger leaves; and a series of small herbaceous plants with several green stems and mid-sized leaves. The measurements made within the tomato plant have greater variability because they are sensitive to the location of the single large stem relative to the cross section of the rods. The measurements made with the rosemary canopy are averaged over several similar stems and hence are less sensitive to the location of each stem. The small herbaceous plants present a relatively uniform dense canopy, and measurements over this canopy show very little variability, despite the fact that the plants are not identical. In general, the differences in both the magnitude of the dielectric permittivity and its error are associated with the canopy structure, density, and relative homogeneity.

Two canopies, each undergoing different stages of drought were monitored using ITDT. The harvested boxwood canopy was instantaneously put under severe drought stress by harvesting, whereas the tomato plant was gradually put under drought stress and recovered after the end of the experiment. There are, however, indications that both of the plants respond in a similar fashion with an increase in the complex dielectric permittivity and the loss tangent at the onset of stress and a decrease when stress is fully established. The increase in dielectric permittivity at the onset of stress might indicate an increase in the volumetric water content of plant components, possibly resulting from closure of the stomatal guard cells. However, the imaginary component increases significantly faster than the real component; as is clearly shown through the loss tangent in Figure 7b. This increase could be related to changes in the relative proportions of bound and free water in combination with a shift in cell osmotic potential. Further studies in which ancillary variables are measured such as leaf water content and potential and transpiration will be necessary to understand the reason for this response.

Whilst ITDT shows distinct promise as a tool for making continuous, non-invasive measurements of changes in plant water status the applicability of making these measurements in the field has yet to be proven. Since the canopy average dielectric is sensitive to the position of the plants with respect to the rods, it is likely that atmospheric turbulence will also impact the results. In addition, at such low values of dielectric permittivity, changes in relative humidity of the atmosphere may also be a factor. As it stands the method will work best for small scales, vegetation such as crop canopies or grasses and in the laboratory or greenhouse. The rod separation can be increased if there is sufficient amplification of the transmitted signal. The rod length can also be increased, however this becomes impractical at rod lengths $> \sim 3$–5 m. However, the use of a transmission radar or horn antennas instead of a transmission line will enable measurements over significantly larger scales and more woody vegetation. At these scales atmospheric turbulence may also become less significant.

This paper discusses the sensitivity of the ITDT measurement to changes in water content. Given this sensitivity, one obvious potential application of ITDT is in the continuous monitoring of plant water status for irrigation scheduling and fire susceptibility. Rigorous experiments to determine how measurements made with this technique relate to more classical measurements of plant water status would lead to other potential applications within the fields of remote sensing, agriculture and plant physiology.

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