

Frequency and Time-Domain Dielectric Measurements of Stem Water Content in the Arborescent Palm, *Sabal palmetto*

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ABSTRACT

Two methods for monitoring stem water content in the arborescent palm, *Sabal palmetto* by determining its dielectric constant were compared. The first approach used an oscillating circuit whose frequency (40 to 70 kHz) was determined by a parallel-plate capacitor that sandwiched a portion of the stem. The second technique was based on measurement of the velocity of an electromagnetic pulse (frequency range of 500 kHz and 1 GHz) propagating within a wave-guide embedded in the stem (Time-Domain Reflectometry, TDR). There was basic agreement in the apparent dielectric constant as determined by the two techniques; both resulted in values of approximately 90 when the plant was fully hydrated, falling to values near 50 when water was withheld for one week.

The capacitance technique was non-invasive, but was influenced by temperature fluctuations, and we were unable to calibrate it accurately against stem volumetric water content. Insertion of TDR probes did not lead to tissue damage and determination of an empirical relationship to volumetric water content allowed quantitative estimates of stem water content. Sensitivity of TDR to small changes in stem water content was restricted by the fact that attenuation of the pulse within the stem necessitated the use of short (0.125 m) wave guides. Despite this, during periods of high transpiration ($> 10 \text{ kg plant}^{-1} \text{ d}^{-1}$) bi-hourly changes in stem moisture content were detectable.

Key words: Dielectric constant, *Sabal palmetto*, stem capacitance, time-domain reflectometry, water storage.

INTRODUCTION

Although knowledge of the moisture status of the soil-plant system is essential for the study of plant water relations, techniques for the determination of the water content of both soils and plant tissues continue to be questioned (Gardner, 1987; Kramer, 1987). Measurements of moisture content are criticized for being insensitive, inaccurate, or indirect. What is needed is an inexpensive, readily automated, portable technique that is sensitive to changes in water content while being insensitive to the character of the matrix (Gardner, 1987). In this paper we examine two types of dielectric moisture sensors to monitor the stem water content of arborescent palms.

Stem water contents are difficult to determine because

of high levels of hydration, geometrical constraints, and potentially deleterious effects of intrusions into living tissues. Changes in stem diameter (Hinckley, Lassoie, and Running, 1978), extraction of tissue cores (Waring and Running, 1979; Waring, Whitehead, and Jarvis, 1979), tissue water potential (Goldstein and Meinzer, 1983; Nobel and Jordan, 1983), and gamma ray attenuation (Edwards and Jarvis, 1983; Brough, Jones, and Grace, 1986) have all been used to monitor changes in stem moisture content. Dimensional changes are both easily automated and non-destructive, but are sensitive only to water content changes in the extra-cambial elastic region of the stem. In the case of palms, the existence of a relatively stiff outer layer surrounding the living, elastic

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tissues (Tomlinson, 1961) renders this technique unsatisfactory. Stem tissue, extracted using an increment borer, samples the entire cross-section, but the technique is destructive and may alter the water content of the sample due to tissue compression (Holbrook, 1989). Psychrometers inserted into stems have several disadvantages, including local tissue damage, release of cell contents into the apoplast during insertion, temperature fluctuations, and calibration difficulties. Gamma ray attenuation avoids many of these problems, but its application is complicated by safety considerations.

Another approach to monitoring tissue moisture status is to measure the dielectric constant. The dielectric constant (ϵ) is an intrinsic property of a material and relates to the ability of a material to store electrical energy reversibly. The dielectric constant (ϵ) is defined as,

$$\epsilon = 1 + \chi \quad (1)$$

where χ is the electrical susceptibility—the proportionality constant between the electric field and the degree of polarization (Jackson, 1975). Because of its large dipole moment and ability to form hydrogen bonds, water has an extremely high dielectric constant (78.3 at 25 °C) compared to most solids and liquids (3 to 10, Wheast, 1975). Furthermore, the dielectric properties of pure water are fairly insensitive to temperature (approximately -0.37 °C^{-1} from 10 to 30 °C, Wheast, 1975) and independent of frequency up to 10^{10} Hz (Jackson, 1975). Although solutes affect the dielectric losses (conductivity) of an aqueous medium, at low concentrations and high frequencies this influence is thought to be small (Hasted, 1973). Changes in the apparent dielectric constant of a water-permeated medium, therefore, may result primarily from changes in the moisture content (Sheriff, 1976; Topp, Davis, and Annan, 1980; Pissis, Anagnostopoulou-Konsta, and Apekis, 1987).

Dielectric measurements can be made in both the frequency and time-domain (Hasted, 1973). Both approaches have been used to determine plant and soil moisture with varying degrees of success (Sheriff, 1976; Dalton, 1987; Halbertsma, Przybyla, and Jacobs, 1987; Topp, 1987; Harbinson and Woodward, 1987). In this study the dielectric properties of the stem of the aborescent palm, *Sabal palmetto* (Walt.) Loddiges ex J. A. & J. H. Schultes, were measured with both a capacitance-to-frequency converter operating as a resonator and a time-domain reflectometer.

MATERIALS AND METHODS

Measurements of stem dielectric constant were made on potted individuals of *Sabal palmetto*. Details regarding tree cultivation under greenhouse conditions as well as results of water balance

experiments with these trees were presented by Holbrook and Sinclair (1992). Stem sections used in temperature experiments and calibrating the time-domain reflectometer were obtained from trees growing naturally in a wooded area approximately 20 km southeast of Gainesville, FL.

Frequency-domain measurements

Frequency-domain measurements of stem capacitance were made using a Capacitance-to-Frequency Converter (CFC). The CFC consisted of an oscillating circuit sealed in a water-tight metal case, with a frequency that depended upon the value of a large parallel plate capacitor that surrounded the stem (Fig. 1). The circuit was supplied with a fixed voltage (8 V) and the frequency of the oscillator was allowed to vary so that the circuit remained in resonance (i.e. voltage and current completely out of phase). The heart of the circuit consisted of a timer chip (XRL555) operating in an astable mode (Jung, 1977; Fig. 2). Frequency was measured using a datalogger (Model 21X, Campbell Scientific¹) as a high-frequency pulse counter. Pulses were summed at 1 s intervals and a mean value recorded at 15 or 30 min intervals. Air temperature was measured with a chromel–alumel thermocouple and the voltage from the thermocouple recorded at 15 min intervals by the datalogger.

Oscillator frequency is determined by the time required to charge or discharge a 'timing' capacitor between $1/3$ and $2/3$ of the supply voltage (V_s). The timing capacitor consisted of two copper plates (6.3×30.5 cm, < 0.2 cm thick) mounted vertically on opposite sides of the tree stem (Fig. 1). The sides of the tree were smoothed with a beltsander so that the copper plates would lie flush against the stem. The side of the copper plates adjacent to the stem was coated with Kapton polyimide film (Dupont Company, Wilmington, DE) to prevent any electrochemical interactions between plates and tree. Any change in

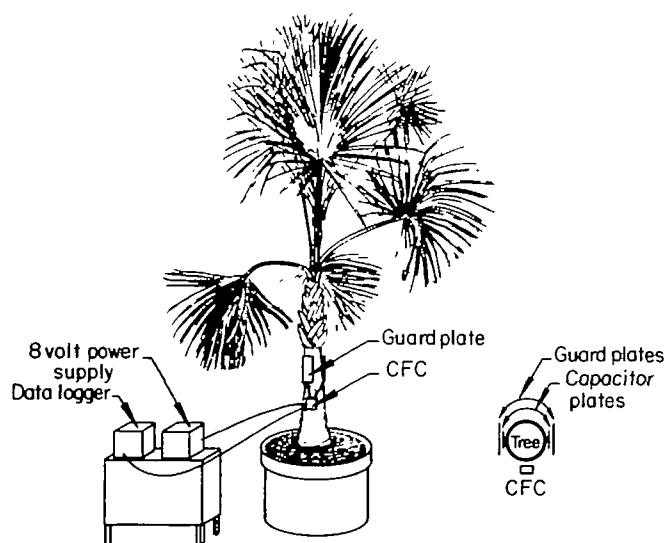


Fig. 1. Schematic drawing of the equipment used to monitor stem capacitance. The paired copper plates are located flush with the exterior of the trunk. The Capacitance-to-Frequency Converter (CFC) box is located just below the bottom edge of the timing plates. An 8 V supply (floating ground) powers the CFC and frequency is recorded using a datalogger. Inset shows a cross-section of the tree stem with capacitor plates drawn to scale.

¹ Mention of company names or commercial products does not imply recommendation or endorsement by the United States Department of Agriculture over others not mentioned.

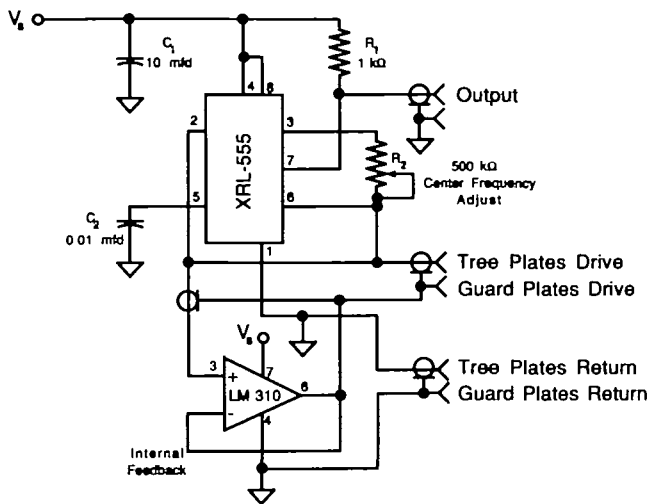


FIG. 2. Diagram of the Capacitance-to-Frequency Converter (CFC) circuit.

the value of the capacitor formed by the copper plates alters the time needed for charge and discharge, and hence alters the resonant frequency. As the capacitance increases, oscillator frequency decreases and vice versa. The circuit was configured to charge and discharge the capacitor through the same resistor (R_2) and, hence, operated with an intrinsic 50% duty cycle (Jung, 1977). Before sealing the water-tight boxes, R_2 was adjusted so that all CFC circuits resonated within 0.1 Hz when connected to the same test capacitor. The output to the pulse counter was a comparator (a transistor to ground) tied high via a 1 k Ω resistor so that output was either at V_+ (when the capacitor was charging) or at 0 V (when discharging).

The ideal relationship between oscillator frequency (ν) and capacitance (C) is:

$$\nu = [R C \ln 4]^{-1}. \quad (2)$$

Because the CFC circuit deviates from equation (2) for frequencies above approximately 40 kHz, the circuit was calibrated from 3 kHz to 120 kHz by placing a series of test capacitors (11 to 1100 pF) across the terminals of the CFC and measuring the frequency. The frequencies for the CFC circuit when placed around a palm stem were in the range of 40 to 70 kHz. For the calibration, oscillator frequency was measured using a high-precision stabilized counter (Model 5385A, Hewlett-Packard, Inc.). The test capacitors were measured with a capacitance meter (Beckman Circuitmate DM25L), accurate to 3%. Interpolation of frequency data into capacitance was performed by fitting the calibration data for the CFC circuits to a log power series:

$$\log_{10}(C) = \sum_{i=0}^n A_i [\log_{10}(\nu)]^i \quad (3)$$

where $n=2$ to 4, $r^2 > 0.999$.

Because of the high input impedance of the timing capacitor (infinite in the real part), it was necessary to guard the circuit to eliminate the capacitance of the coaxial cables (RG-58, 33 pF/ft) as well as any other capacitive couplings of the plates (Horowitz and Hill, 1989). Circuit board traces, coaxial cables leading to and from the tree, and the plates themselves were guarded by surrounding them with a shield of equal potential. The guards consisted physically of (a) external traces on the circuit board; (b) the braided exterior portion of the coaxial

cables to the plates; and (c) a larger capacitor (copper plates 13.3 \times 38.1 cm) located 7.6 cm exterior to the timing plates (Fig. 1). These were held at the same potential as the positive timing plate using an operational amplifier (LM310) configured as a unity gain follower (Horowitz and Hill, 1989). This chip has an extremely high input impedance ($10^{12} \Omega$, 1.5 pF) and thus has little influence on the resonant frequency. The circuit board was configured so that the LM310 input was also guarded, thus eliminating most of the 1.5 pF input capacitance. Low output impedance, on the other hand, allows the LM310 to supply sufficient current to hold the guard at the positive-plate potential.

Absence of fringing fields from the inner plates, a direct consequence of the guard plates, allows the dielectric constant (ϵ) of the material between the timing plates to be calculated to a high degree of accuracy using the ideal parallel plate capacitor formula:

$$\epsilon = C d / A \epsilon_0 \quad (4)$$

where C is the measured capacitance (F), d is the distance between the plates (m), A is the area of the plates (m²), and ϵ_0 is the relative permittivity of free space ($8.85 \times 10^{-12} \text{ F m}^{-1}$). Thus, if water is withdrawn from stem tissues during the day by transpiration, the dielectric constant should decrease causing the value of the timing capacitor to decrease and the oscillator frequency to increase. Recharge of stem tissue during the night as water is drawn from the soil should lead to an increase in the value of the apparent dielectric constant of the stem, resulting in an increase in the value of the timing capacitor and a decrease in the resonant frequency.

To avoid any systematic errors that might occur from differences in placement or orientation of the capacitor plates on the tree (e.g. the degree to which they lie flush against the rough stem surface), measured ϵ was normalized by dividing it by the long-term mean value ($\langle \epsilon \rangle$). In order to compare the relative magnitudes of diurnal fluctuations, the data were expressed as $(\langle \epsilon_{\max} - \epsilon_{\min} \rangle / \langle \epsilon \rangle)$.

Several tests were conducted to determine the CFC sensitivity to changes in stem water content relative to changes in temperature. For these tests the timing capacitor was placed across a glass aquarium in the laboratory and the CFC frequency and water temperature recorded. The dielectric constant of water was determined assuming that the copper plates sandwiched three homogeneous layers (glass-water-glass) and using published values for the dielectric constant of glass (Wheat, 1975). In addition, two water-filled plastic cylinders (1 m tall \times 0.25 m diameter) were used as 'palm stem-analogues' in the greenhouse. These were used to assess the influence of fluctuations in air temperature on the measured dielectric constant of a uniform 'stem' that was not changing in water content. Pure water was chosen because the relationship between temperature and ϵ is well known (Wheat, 1975).

Changes in conductivity within the stem (e.g. resulting from changes in solute concentrations) were not anticipated to influence significantly measurements of stem capacitance, because this circuit, as a result of the internal construction of the XRL555, resonates when the displacement current through the plates is maximum rather than when the charge on the plates is maximum. Such 'kinetic energy' resonances are, unlike amplitude resonances found in mechanical mass-spring resonances (and in fixed frequency capacitance measurements that measure charge), independent of the losses (Marion, 1970). Nevertheless, CFC sensitivity to ion concentrations was tested using distilled water and a saturated salt solution. The 'test cell' consisted of a 5.2 \times 5.0 \times 10.0 cm plastic container that was surrounded by the timing capacitor and filled with either deionized water or a

saturated NaCl solution and the resonant frequency determined. These measurements were made in the laboratory at constant temperature.

A major drawback in using the frequency-domain approach to measure palm stem water content was the difficulty of calibration. Problems arose in attempting to use only sections of stem in the calibration because the sections changed in dimensions as they lost water, altering the spacing between the plates. Larger pieces of stem consisting of the entire stem cross-section did not shrink, but were impossible to dry uniformly. Because of these difficulties, CFC measurements were used only as relative indicators of stem moisture content.

Time-domain measurements

Fellner-Feldegg (1969) proposed that dielectric properties could be measured in the time-domain, and subsequently, Topp *et al.* (1980) proposed time-domain measurements as a means to measure soil moisture content. Time-Domain Reflectometry (TDR) has been recommended because of its relative insensitivity to soil temperature, salinity, and texture (Topp *et al.*, 1980; Topp, 1987). The ability to detect accurately moisture near the soil surface and in pot studies have increased its acceptance (Topp and Davis, 1985; Baker and Lascano, 1989). Use of TDR to measure the water content of plant tissues, however, has only been attempted in one other study (Constanz and Murphy, 1990).

Time-domain measurements of apparent dielectric constant are based on the relation between the speed of propagation of an electromagnetic wave and the dielectric constant of the medium. Specifically, the index of refraction, N , is equal to the speed of light in free space ($3 \times 10^8 \text{ m s}^{-1}$) divided by its velocity in the medium (Jackson, 1975). The index of refraction is also equal to the real part of the square root of the complex dielectric constant. In practice, the measurement can be made using a time-domain reflectometer: an instrument that sends a fast rise-time pulse into a dielectric filled wave guide and measures the flight time of the pulse's leading edge. TDR takes advantage of the reflections that occur at each change in impedance along the path (index of refraction change), which are recorded as changes in the voltage of the returning pulse. Within the medium in question the pulse is constrained by a parallel transmission line or wave guide. The pulse propagates through the material as a transverse wave, reflects off the 'open' at the end of the wave guide, and returns to the TDR unit where its time of flight is measured.

TDR measurements were made using a time-domain reflectometer (Model 1415A, Hewlett-Packard, Inc.) attached to a high-speed sampling oscilloscope (Model 140, Hewlett-Packard, Inc.). This TDR unit has a rise time of less than 150 ps when operating in the reflectometer mode and an output of 0.25 V. The frequency distribution of the TDR pulse ranged from <1 MHz to >1.8 GHz, determined using a spectrum analyser (Model 85698, Hewlett-Packard, Inc., 0.01 to 22 GHz). As the impedance matching transformer has a finite bandwidth, only frequencies between 500 kHz and 1 GHz actually enter the tree. The energy-weighted average frequency within this range was approximately 360 MHz (Fig. 3).

The wave guides were constructed from 3.17 mm diameter \times 125 mm long stainless steel rods. Spacing between the rods was 25 mm. Cabling between the TDR unit and the wave guide consisted of 50 Ω RG-8 cable, a RF-pulse transformer (Model TP-103, Anzac, Inc.) which converts an unbalanced 50 Ω load to a 200 balanced signal, 190 Ω twin lead antenna wire (9090, Belden, Inc.), and two miniature banana plugs. Small (2.38 mm) holes drilled into the ends of the stainless steel rods provided a firm connection for the wire.

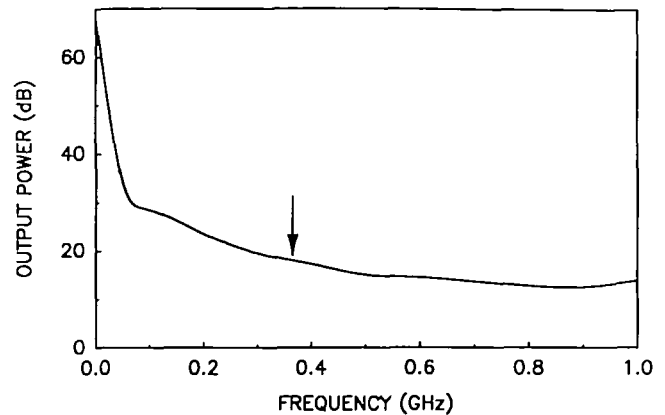


FIG. 3. Output power as a function of frequency for the Hewlett-Packard 1415A time-domain reflectometer. The energy-weighted average frequency in the 500 kHz to 1 GHz range was 360 MHz.

A major assumption in the determination of dielectric constant from TDR measurements is that the imaginary part of the dielectric constant (the conductivity or dielectric loss) is small enough to be ignored. This allows taking the real part of the square root of the dielectric constant to 'commute' with taking the complex square root (i.e. $N = (\epsilon^{0.5})_{\text{real}} \simeq (\epsilon_{\text{real}})^{0.5}$). In this case the apparent dielectric constant (ϵ_a) is equal to,

$$\epsilon_a = (c t / (2L))^2 \quad (5)$$

where c is the velocity of light in free space ($3 \cdot 10^8 \text{ m s}^{-1}$), t is the time of flight (s), and L is the wave guide length (m) which must be doubled since the pulse edge traverses it twice. The term 'apparent dielectric constant' is used to denote that the influence of the loss term has not been explicitly included (Topp *et al.*, 1980). Davis and Annan (1977) and Topp *et al.* (1980) report that, for the wide range of soils they have considered, the dielectric loss is small relative to the real portion and does not significantly alter the measured propagation velocity.

It is also possible to estimate the dielectric loss (conductivity) directly from the TDR reflections by looking at the voltage of the reflected pulse (V_R) relative to the voltage of the pulse that enters the wave guide (V_T , Dalton, Herkelrath, Rawlins, and Rhoades, 1984; Dalton, 1987). Calculation of the conductivity is based on the exponential attenuation of the signal as it propagates a distance $2L$,

$$V_R = V_T e^{(-2\alpha L)} \quad (6)$$

The attenuation coefficient, α , can be approximated as,

$$\alpha = \sigma / 2(\mu \mu_0 / \epsilon \epsilon_0)^{0.5} \quad (7)$$

where σ is the electrical conductivity of the medium, μ and μ_0 are the relative magnetic permeabilities in the medium and in free space, and ϵ and ϵ_0 are the dielectric constants (relative permittivities) in the medium and in free space (Lorrain and Corson, 1970; Dalton *et al.*, 1984). For media containing low magnetic material, $\mu = 1$ and σ can be calculated by substituting equation (7) into (6) and solving for σ (Dalton *et al.*, 1984; Jackson, 1975):

$$\sigma = [\epsilon^{0.5} / (1.2 \times 10^3 \pi L)] \ln(V_T / V_R) \quad (8)$$

Since dielectrics dissipate energy both in polarization and in conductance, measurements at more than one frequency are needed to distinguish the two processes (Lorrain and Corson, 1970). Thus, the σ values presented here are actually σ_{apparent} —to denote that energy dissipation resulting from polarization

has not been distinguished from energy dissipation resulting from charge flow (current). Measurements of σ_{apparent} were made on an intact tree and the effect of disregarding the imaginary part of the dielectric was determined for stem tissue under conditions of maximum and minimum hydration (Holbrook and Sinclair, 1992).

Stem tissue was calibrated for the TDR apparatus using $7 \times 5 \times 15$ cm blocks of stem cut from a recently (<1 d) felled tree. Wave guides were inserted into each block from the exterior of the stem. Initial volume was determined by weighing the block in air and in water and calculating the buoyancy force. TDR readings were made each morning, after which the blocks were placed in front of a fan and their weight loss monitored. Upon reaching the specified moisture loss, the blocks were enclosed in plastic bags and allowed to equilibrate overnight. Stem samples were kept in a refrigerator whenever possible to minimize tissue degradation and microbial activity. A series of successive measurements was made on each block, after which the rods were removed and the stem material dried. Eighteen blocks from two trees were used.

RESULTS AND DISCUSSION

Frequency-domain measurements

CFC measurements of the dielectric constant of water made in the laboratory were close to published values (Wheat, 1975). The dielectric constant of 15 °C water in a glass aquarium (plate separation of 15.5 cm) was calculated to be 80.8 ± 1.5 as compared to the published value of 82.0 (Wheat, 1975). The temperature dependence of these measurements was -0.47 ± 0.017 °C⁻¹, while the published data indicate a decrease in the dielectric constant of pure water of -0.37 °C⁻¹ (Wheat, 1975). Uncertainty in these calculations derive from knowing neither the dielectric constant of the specific glass used in the aquarium, nor its temperature dependence; we thus used the extreme values published for standard glass (6.32 to 6.75; Wheat, 1975).

The dielectric constant of water-filled plastic cylinders in the greenhouse oscillated diurnally. The relative diurnal fluctuations in ϵ ($(\epsilon_{\text{max}} - \epsilon_{\text{min}}) / \langle \epsilon \rangle$) of these 'stem-analogues', however, were always equal to or less than the relative diurnal fluctuation of ϵ_{water} calculated from air temperature. The response to temperature was not the result of a direct effect on the electronics. The manufacturer's specifications for the timer chip and other components indicate a temperature sensitivity for the CFC circuit of less than 75 parts 10^{-6} °C⁻¹, which corresponds to less than 4 Hz °C⁻¹ for a circuit resonating at 50 kHz. This was confirmed by the lack of frequency oscillations when a fixed capacitor was placed across the terminals of the CFC in the greenhouse.

Measurements confirmed that the CFC was relatively insensitive to the presence of dissolved NaCl in pure water (Fig. 4). Resonant frequencies of the two liquids differed most at low water volumes (i.e. when the test cell was only partially full) and converged as the container filled.

The apparent dielectric constants ($\epsilon_{\text{apparent}}$) of palm

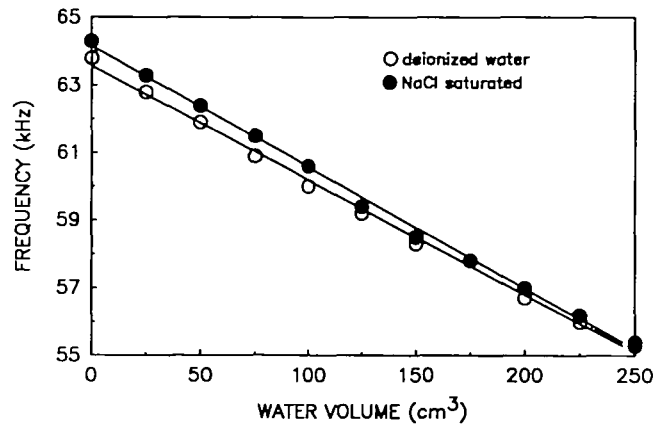


FIG. 4. Oscillator frequency as a function of amount of water contained in a 250 cm³ test cell. Measurements were made with deionized water ($Y = 63.573 - 0.0339 X$, $r^2 = 0.988$) and a saturated NaCl solution ($Y = 64.155 - 0.0359 X$, $r^2 = 0.999$).

stems as measured by the CFC were within the range of values expected for a partially saturated medium (40 to 70, Fig. 5). The $\epsilon_{\text{apparent}}$ of a palm tree from which water was withheld for two successive 7 d periods showed three patterns: (1) a daily oscillation in $\epsilon_{\text{apparent}}$; (2) a decrease in the mean daily value as water was withheld; and (3) a decrease in the amplitude of the diurnal fluctuations as water was withheld. Addition of water to the pot at the end of the 7 d drying period reversed the latter two trends. The apparent dielectric constant of the stem decreased during the daylight hours with daily minima being reached at approximately 19:00 EST and increased throughout the night (maxima at approximately 09:00 EST). These patterns are in accord with the hypothesis that water is extracted from the stem to meet both short (daily) and long-term transpiration-induced deficits.

Daily variations in temperature could also result in diurnal oscillations in $\epsilon_{\text{apparent}}$ (i.e. minima in the after-

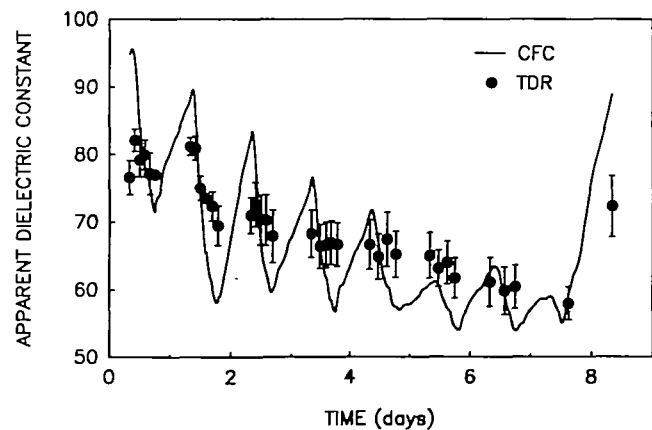


FIG. 5. Apparent dielectric constant of a palm stem as measured by Capacitance-to-Frequency Converter (CFC) and Time-Domain Reflectometry (TDR) techniques. The palm was initially well-watered. Water was withheld until the end of day 7, at which time the plant was liberally watered.

noon, maxima in the morning). Diurnal oscillations in the dielectric constant of pure water calculated from measurements of air temperature, however, were smaller than those of the stem material (Fig. 6). Furthermore, unlike the diurnal fluctuations in $\epsilon_{\text{apparent}}$ of the stem, there was no change in either the range or the amplitude of $\epsilon_{\text{pure water}}$ calculated from air temperature. The relative diurnal fluctuation ($(\epsilon_{\text{max}} - \epsilon_{\text{min}}) / \langle \epsilon \rangle$) of the stem was between 0.30 and 0.35 when the tree was maximally transpiring, while values between 0.13 and 0.18 were characteristic of days later in the drying period. In contrast, the mean relative diurnal fluctuation of $\epsilon_{\text{pure water}}$ calculated from air temperature was 0.058. These data indicate that the patterns of $\epsilon_{\text{apparent}}$ of the stem cannot be fully accounted for by the effects of temperature on the dielectric constant of pure water. They do not, however, rule out an interaction between temperature and $\epsilon_{\text{apparent}}$ of a complex, living tissue (Pethig, 1979).

Water loss from a tree was prevented in one test by enclosing the entire leaf crown in a large bag of aluminized mylar. Diurnal fluctuations in $\epsilon_{\text{apparent}}$ were also observed in this stem which was not losing water by transpiration. Relative diurnal fluctuation in ϵ ($(\epsilon_{\text{max}} - \epsilon_{\text{min}}) / \langle \epsilon \rangle$) of the mylar-enclosed tree was 0.150, while changes in air temperature during these measurements were estimated to result in a relative fluctuation in $\epsilon_{\text{pure water}}$ of 0.068. Cut lengths of stem (1.2 m long) from recently felled trees also exhibited diurnal fluctuations in $\epsilon_{\text{apparent}}$. Stem sections located both within the laboratory and outdoors had relative diurnal oscillations larger than that calculated for pure water tracking the ambient temperature (Table 1). The relative fluctuation in $\epsilon_{\text{apparent}}$ of the stem segment located outdoors was over twice that of the stem segment in the laboratory, while the calculated fluctuations of $\epsilon_{\text{pure water}}$ attributable to temperature variations increased by approximately 3.5 (Table 1).

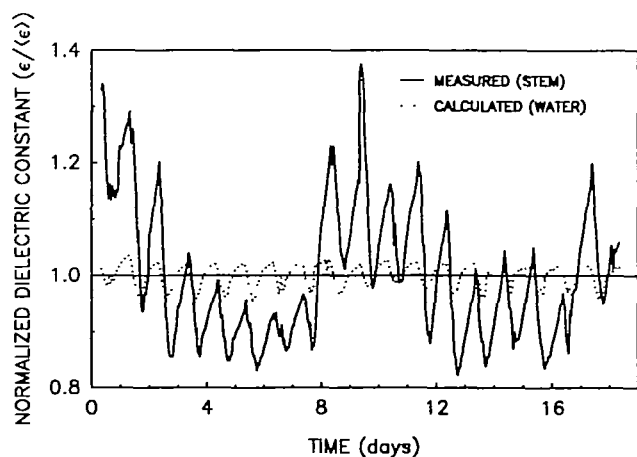


FIG. 6. Measured and calculated values of apparent dielectric constant of palm stems normalized by the mean ($\langle \epsilon \rangle$) to remove any systematic error. The palm was initially well-watered and water was added on days 7, 9, and 16.

Time-domain measurements

TDR measurements of the apparent dielectric constant of excised stem sections in the laboratory were related to the volumetric water content although the variance was high (Fig. 7). Possible sources of error included tissue damage caused by handling and rod insertion, uneven distribution of moisture throughout the tissue as it dried, and changes in tissue volume as it dried. Sectioning of the palm stems did not indicate tissue damage because tissue discoloration was slight and restricted to within 2 mm of the rods. Tissue drying did not result in detectable changes in the spacing of the wave guides, although it influenced calculation of the volumetric water content. A similar dependence of ϵ on the moisture content of tropical vegetation samples was seen by Tan (1981) using microwave measurements at 9.5 GHz.

Apparent dielectric constants calculated for stem material at high water contents exceeded the value for pure water (78.3 at 25 °C, Wheat, 1975). This may be due to: (1) overestimation of $\epsilon_{\text{apparent}}$ resulting from neglecting the dielectric loss (σ); (2) systematic error in determining the point at which the pulse enters the wave guide (i.e. overestimating the time of flight); or (3) protein-water interactions. Dielectric constants up to 100 have been reported for proteins in an aqueous medium (Pethig, 1979), and Pissis *et al.* (1987) reported that little or none of the water in plant stems behaves dielectrically like pure water.

TDR measurements of the $\epsilon_{\text{apparent}}$ of intact palm stems were generally between 50 and 90 depending on the water status of the plant. Values were highest when the plant was well-watered and declined as water was withheld (Fig. 5). In the first days after water was withheld and transpiration rates were high, there was evidence for a net loss of water from the stem during the day, followed by replenishment at night. Later in the week as the stem dehydrated the diurnal oscillations were not observed, suggesting that the fluctuations were not due to temperature.

Conductivity (σ) measurements of intact stem material from TDR data indicated that its influence on the apparent dielectric constant was small. The values of σ were largest at high stem water contents (0.61 S m⁻¹), falling to values of 0.07 S m⁻¹ as water was withheld for one week and the water content of the stem decreased. Estimated error in neglecting the dielectric loss for the stem material was as high as 6% (at high water contents), but typically <1%. The effect of this error would be to overestimate the dielectric constant (i.e. $(\epsilon_{\text{real}})^{0.5} < ((\epsilon_{\text{complex}})^{0.5})_{\text{real}}$). In comparison, soil σ values calculated from TDR measurements made in the potting material during the same period (Holbrook and Sinclair, 1992) ranged from 0.006 S m⁻¹ (when the soil was saturated) to 0.002 S m⁻¹, with the estimated error in neglecting the dielectric loss always being <0.01%.

TABLE 1. CFC measurements of the dielectric constant of stem segments (ϵ_{stem}) located in the laboratory and outdoors

The cut ends of each segment were covered to prevent water loss. Air temperature (T_{air} , °C) was measured in each location and the dielectric constant of pure water at that temperature calculated (ϵ_{water}). Values represent the mean (s.e.) of parameters from three 1 d intervals (\bar{X}). Diurnal fluctuation (DF) refers to the amount each parameter (temperature or measured dielectric constant) varied within a day; relative diurnal fluctuation (RDF) is the normalized fluctuation in the dielectric constant, $(\epsilon_{\text{max}} - \epsilon_{\text{min}})/\langle\epsilon\rangle$.

	Laboratory			Outdoors		
	T_{air}	ϵ_{stem} (measured)	ϵ_{water} (calculated)	T_{air}	ϵ_{stem} (measured)	ϵ_{water} (calculated)
\bar{X}	23.3 (0.28)	57.1 (1.35)	78.9 (0.10)	18.3 (1.85)	64.0 (0.73)	80.8 (0.68)
DF	3.2 (0.16)	3.0 (0.59)	1.2 (0.06)	14.1 (1.18)	9.4 (1.94)	5.2 (0.44)
RDF		0.064 (0.005)	0.015 (0.001)		0.146 (0.029)	0.054 (0.012)

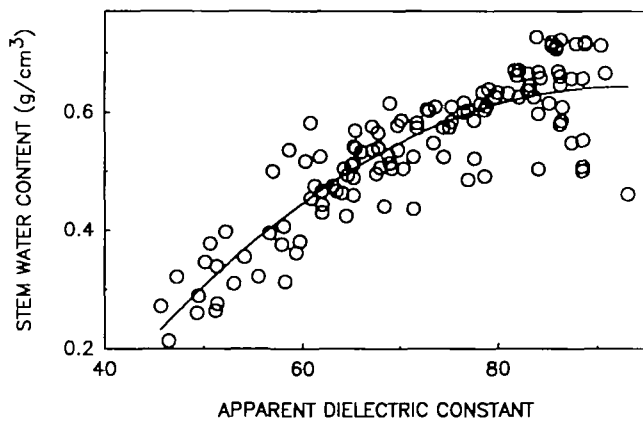


FIG. 7. Calibration data for Time-Domain Reflectometry (TDR) palm stem tissue water content measurements. A second order polynomial, $Y = -0.9567 + 3.4597 \cdot 10^{-2} X - 1.8707 \cdot 10^{-3} X^2$ ($r^2 = 0.881$, $n = 127$) was fitted to the data.

Comparison between frequency and time-domain techniques

Both CFC and TDR techniques were sensitive to changes in stem moisture content; estimates of ϵ declined as water was withheld and returned to their initial values upon watering. Furthermore, the range of values determined by the two techniques was similar. Both methods are relatively inexpensive, portable, and readily automated. Advantages of the CFC technique are that it is non-invasive and that it could be adapted for use on plant structures of various sizes (including quite small ones). Serious drawbacks include temperature effects in the tree and difficulties in obtaining a meaningful calibration with volumetric water content.

TDR, on the other hand, worked well as an estimator of stem water content (Holbrook and Sinclair, 1992). It appeared to be insensitive to temperature fluctuations and an adequate empirical calibration was obtained. Since the travel time of the pulse is measured with TDR, the ability to detect small differences in propagation velocity (and hence moisture content) increases with longer wave

guides. On the other hand, the non-zero conductivity of the palm stem continually attenuates the signal; thus if the path length is too long then the returning edge of the pulse will be undetectable. This latter problem could be alleviated with a higher voltage input or by signal averaging of a large number of pulses to resolve the small return signal. Wave guide length, however, is ultimately limited by the dimensions of the structure being measured. In the case of palm stems, signal attenuation necessitated use of fairly short wave guides. These were approximately equal to the radius of the stem.

Other problems shared by both techniques include the necessity for accurate installation of the sensors (wave guides parallel, capacitor plates parallel and flush against the stem), as ϵ calculations are geometry dependent. Because of the reliance on absolute configuration, use of either technique on materials that undergo large volume changes would have to account for such changes. Finally, both techniques probe the ϵ of only a portion of the stem. Since stems are both structurally heterogeneous and unlikely to have a uniform moisture distribution along their length, a number of probes are needed to gain a more detailed knowledge of the stem moisture profile.

An inherent difference in sensitivity between the frequency and time-domain measurements of dielectric properties arises from the relationship between the measured variable (frequency or time of flight) and the dielectric constant. In the CFC method, the measured variable, frequency, is inversely proportional to the capacitance and thus to the dielectric constant. In TDR, the measured variable, time delay, is proportional to the square root of the dielectric constant. Thus, if all other effects were equal (including instrument resolution), the CFC technique would be more sensitive to small changes in $\epsilon_{\text{apparent}}$. Furthermore, frequency measurements, both in general and with the equipment used in this study, can be made to a much greater resolution than propagation speed along a relatively short wave guide.

As the goal of these measurements was to obtain

estimates of changes in the amount of water stored within the palm stem, obtaining an empirical calibration to volumetric water content was essential. Ideally, calibration of either sensor should be made using intact (rooted) plants. TDR and CFC readings would then be followed immediately by gravimetric determination of the water content of that portion of the stem. This would require a large number of plants that could be sacrificed and temperature effects would have to be considered as well. We were not able to conduct such an extensive calibration in this study with palm trees. Nevertheless, the relationship between volumetric water content and ϵ as determined by TDR was quite strong and provided an estimate of changes in water storage of the stem that basically agreed with other, indirect, estimates of stem water extraction (Holbrook and Sinclair, 1992).

One unexplained difference between the two techniques occurred when the drought-stressed plants were rewatered. The CFC responded immediately to the addition of water and regained the initial value within approximately 12 h (Fig. 5). Even if the water was applied at midday, when transpiration was occurring, the capacitance of the stem as measured by the copper plates began to increase. The TDR probes, on the other hand, responded more slowly, usually regaining their initial status after 2 d, although this could be reduced to 1 d if the rewatering took place during a period of low evaporative demand. Stem capacitance and leaf water potential returned to near their initial values in approximately the same period of time; TDR measurements regained their original (pre-drought) values over approximately the same period of time it took for the stem to return to its initial weight as determined by the difference between water loss from the stem via transpiration and water movement into the stem from the soil (Holbrook and Sinclair, 1992). Differences between CFC and TDR in response time to rewatering of droughted palms may indicate that these two measurement frequencies are sensitive to water in different compartments of the palm stem tissue.

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