

# A Study on Measuring Electrical Capacitance to Access the Volumetric Water Content of Simulated Soil

W. S. Rial, Y. J. Han

**Abstract:** Wet porous media representing agronomic soil that contains variable water content with variable electrolyte concentration was measured to study the shape of the curves of the electric double layer capacitance versus frequency from 10 KHz to 10 MHz. This was done in an attempt to find the lowest practical operating frequency for developing low cost dielectric constant soil moisture probes. Cellulose sponge was used as the porous media. A high frequency electronic bridge circuit was developed for measuring the equivalent network parallel resistance and capacitance of porous media. It appears that the effects of the electric double layer component of the total parallel network capacitance essentially disappear at operating frequencies greater than approximately 25 MHz at low electrolyte concentrations but are still important at 50 MHz at higher concentrations. At these frequencies, the double layer capacitance masks the diffusion region capacitance where true water content capacitance values reside. The general shape of the curve of volumetric water content versus porous media dielectric constant is presented, with an empirical equation representing data for this type of curve. It was concluded that the lowest frequency where dielectric constant values which represent true water content information will most likely be found is between 30 and 50 MHz at low electrolyte concentrations but may be above 50 MHz when the total electrolyte concentration is near the upper level required for most mesophyte plant nutrition.

**Keywords:** Electrical Capacitance, Volumetric Water Content, Simulated Soil

## Introduction

A current need in agronomy and horticulture is to have available at the desired depth and at relatively low-cost while using simple technology, real-time values of the volumetric water content ( $\theta v$ ) of the growing media. Only a few technologies are currently available that can measure true  $\theta v$  of water in soil with these constraints. One of these technologies utilizes the real component of the complex dielectric constant which is derived from the complex electrical permittivity of soil. The real component of the dielectric constant of soil contains true water content ( $\theta v$ ) information and  $\theta v$  can be calculated from measurement of the soil electrical capacitance found in the diffusion region. The imaginary component of the complex dielectric constant contains true electrical conductivity ( $\sigma$ ) information and its magnitude can be calculated from measurements of the soil electrical resistance or conductance.

One of the problems encountered for developing low cost dielectric constant instruments or probes is the complicated nature of soil due to its variability. A

second problem is due to the presence of electrolyte in the soil solution. A third problem is associated with the choice of the operating frequency of the instrument.

A reasonably low-cost dielectric constant or capacitance probe is simple in concept but may be difficult to implement at this time with the required electronics. The electronic circuitry needs to independently measure the resistance and capacitance of the equivalent, parallel, electrical resistance and capacitance (R-C) circuit representing wet soil which contains electrolytic material (plant nutrient, fertilizer, salts). The equivalent R-C electrical circuit of wet soil is complicated by the fact that at frequencies below approximately 1 KHz, the capacitance value of the equivalent parallel R-C circuit is huge in value due to electrode polarization (Denaro, 1971; Ferris, 1974). At frequencies above 1 KHz to approximately 25 MHz, the capacitance value is still very large at the lower frequency extreme, decreasing to a much smaller value (which can represent true  $\theta v$ ) at some frequency above approximately 25 MHz. One of the severe measurement problems in trying to measure  $\theta v$  in porous material at frequencies less than approximately 25 MHz is the magnitude of the electric double-layer capacitance (Bockris et al., 1974; Fried, 1973)); this capacitance overwhelms the capacitance value in the diffusion region that represents true  $\theta v$  (Goodisman, 1987).

This paper describes work done to attempt to

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understand the general behavior of the electrical capacitance of porous material representing wet soil for the purpose of predicting the lowest practical operating frequency for making the necessary parallel R-C circuit electrical measurements for assessing  $\theta v$  in practical soils. The literature indicates that it may be impossible to make  $\theta v$  measurements using capacitive or real dielectric constant technology below approximately 1 MHz (Hasted, 1973). One researcher indicated that the lower frequency limit for soil may be approximately 30 MHz (Thomas, 1966).

To study the effects of frequency on the real component of the complex dielectric constant, cellulose sponges were used as the porous material representing soil. These sponges were charged with calibrated amounts of  $\theta v$  and with known concentrations of a common 1:1 binary electrolyte representing ionic plant nutrient or fertilizer. For measurements of the equivalent R-C circuit of wet soil, the sponges were inserted into a precision test cell which was located in one arm of a modified Harris electronic bridge circuit. The capacitance representing  $\theta v$  and the resistance representing the electrical conductivity ( $\sigma$ ) were then measured at frequencies from 10 KHz to 10 MHz in a 1:2:5 frequency sequence, in an attempt to find the lowest practical frequency where the measured capacitance is the capacitance of the diffusion region that represents the true  $\theta v$  of the sponges.

**Objectives**

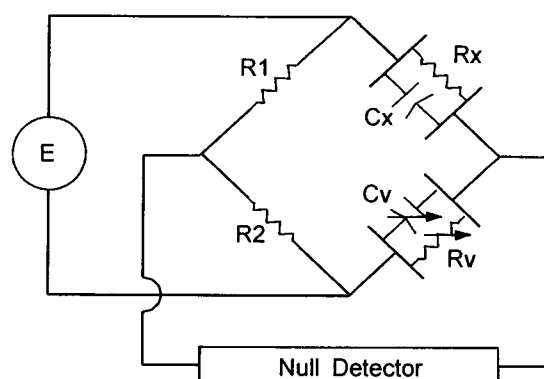
1. To develop a simple, modern equivalent of the electronic balancing bridge circuit for independently measuring the parallel circuit capacitance and resistance of wet, porous material representing soil,
2. To study the general shape of the curve of the electrical double layer capacitance at non-microwave frequencies, and
3. To try to find a lower frequency limit for practical  $\theta v$  measurements.

**Materials and Methods**

**1. Modified Harris Bridge**

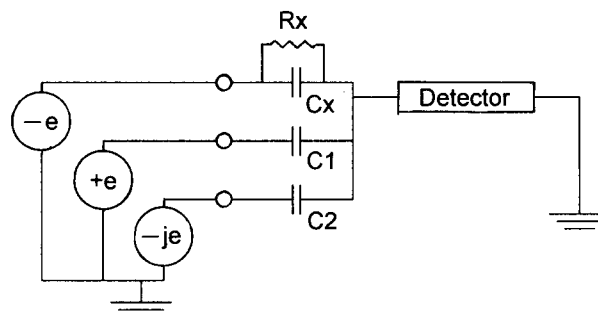
One of the most common circuit topologies used to measure resistance and capacitance in parallel is the alternating current, balancing electronic bridge. This type of circuit can have high sensitivity (can detect an imbalance of  $2.5 \times 10^{-5}$  at low frequencies and  $1.0 \times 10^{-4}$  at high frequencies of a 1 volt peak-to-peak sine wave) due to balance being achieved at a null of the detector output. The standard four-arm bridge circuit for measuring resistance and capacitance in parallel is shown in fig. 1. Another version of the balancing electronic bridge is the Harris bridge configuration (Hill et al., 1969) shown in fig. 2.

One of the special features of the Harris bridge circuit concept is that the alternating-current sine and



where  $R1$  = fixed resistance value,  
 $R2$  =  $R1$ ,  
 $R_x$  = unknown resistance of sample (porous media),  
 $C_x$  = unknown capacitance of sample (porous media),  
 $R_v$  = variable compensating resistance,  
 $C_v$  = variable compensating capacitance, and  
 $E$  = sine-wave voltage source.  
 At balance,  $R_x = R_v$  and  $C_x = C_v$ .

**Fig. 1 Bridge circuit for parallel R and C.**



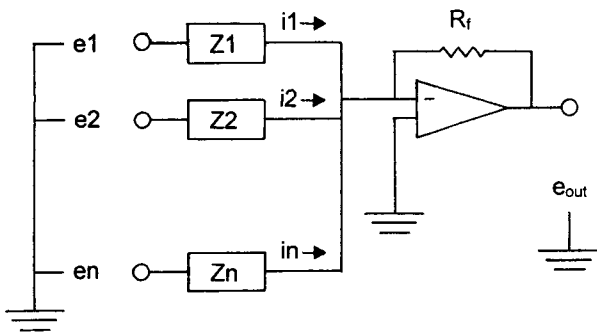
At balance,  $C_1 = C_x$  and the reactance ( $X$ ) of  $C_2 = R_x$ .

**Fig. 2 Basic harris bridge circuit.**

cosine signal sources and one side of the detector can be at circuit ground potential. This reduces stray capacitance or makes it easier to compensate stray capacitance to circuit ground, especially in the detector section of the bridge.

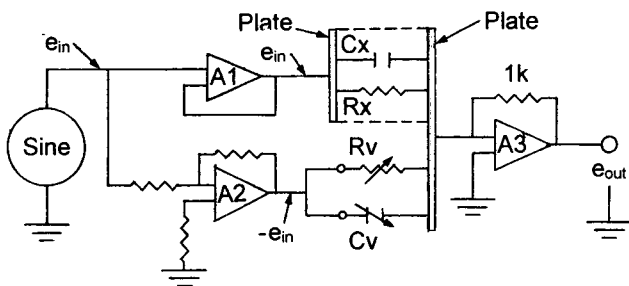
A more modern version of the Harris bridge circuit was developed by Rial (1999) in which the input to the detector is at virtual ground potential, and the detector section algebraically sums the input branch currents. A virtual ground can be achieved at the summing junction of a highly fed-back operational amplifier in the standard current-to-voltage converter circuit configuration as shown in fig. 3. The output voltage of the current-to-voltage converter is a linear function of the input current (which algebraically sums the branch currents).

For this soil instrumentation research, it was



At bance,  $\sum (i_1, i_2, \dots i_N = \text{zero})$

**Fig. 3 Modified harris bridge circuit using a current-to-voltage converter.**



where

- +e<sub>in</sub> = variable frequency and amplitude sine wave source,
  - e<sub>in</sub> = 180° phase reversal of +e<sub>in</sub>,
  - e<sub>out</sub> = voltage output to oscilloscope,
  - A1 = voltage amplifier with gain = +1.000,
  - A2 = voltage amplifier with gain = -1.000,
  - A3 = current-to-voltage converter,
  - C<sub>x</sub> = parallel capacitive component of porous media,
  - R<sub>x</sub> = parallel resistive component of porous media,
  - C<sub>v</sub> = variable compensating capacitance, and
  - R<sub>v</sub> = variable compensating resistance.
- At balance, e<sub>out</sub> = zero

**Fig. 4 Final modified harris bridge circuit configuration.**

necessary to have independent adjustment (compensation) of both the resistive and capacitive components of the equivalent parallel R-C network of the soil. It was found that the resistive and capacitive components of simulated soil samples located between two metallic plate-electrodes could be balanced most easily with a balancing bridge circuit based on the simplified concept of fig. 3, by using the bridge circuit configuration shown in fig. 4.

In order to compensate the unknown components R<sub>x</sub> and C<sub>x</sub> with known components R<sub>v</sub> and C<sub>v</sub> respectively in fig. 4, it was found that an imbalance

appearing as e<sub>out</sub> must be observed with relation to the phase of the e<sub>in</sub> signal used as a reference. This requires that the zero-crossing voltage of e<sub>out</sub> for an imbalance in R must coincide with the zero-crossing of e<sub>in</sub> or -e<sub>in</sub> and that the zero-crossing of e<sub>out</sub> for an imbalance in C must coincide with the peak of e<sub>in</sub> or -e<sub>in</sub> or coincide with the zero-crossing of the first derivative of e<sub>in</sub> or -e<sub>in</sub>. Without reference to these phase relations when using an oscilloscope to obtain bridge balance, null at e<sub>out</sub> was found to be very time-consuming and tedious because a simultaneous imbalance in R and C appears non-sinusoidal at e<sub>out</sub>, making it difficult to ascertain which compensating element (i.e., R or C) needs to be adjusted.

## 2. Precision Capacitor

If the capacitance C<sub>x</sub> in fig. 4 represents only true volumetric water (θv) as found in the diffusion region and does not represent the capacitance of the electric double layer, then a crude estimate of the upper limit of the required compensating capacitance C<sub>v</sub> can be made by assuming a maximum volumetric water content of 0.50 (approximate saturation θv for many common soil textures) and assuming samples will be measured in a test cell with 10.0 cm<sup>2</sup> plate area and 1.0 cm plate separation. By assuming 100% volumetric water has a dielectric constant equal to approximately 80 at 25°C (Malmberg and Maryott, 1956), then 80 × 0.50 equals approximately 40 as a typical dielectric constant near saturation for many common soil textures. The total amount of capacitance required can be calculated by using the standard capacitance equation for parallel plate capacitors with as stated below in Equation 1.

$$C_{pF} = \frac{DC \times \epsilon_o \times A}{d} \quad (1)$$

where

- C<sub>pF</sub> = capacitance in picofarads,
- DC = real dielectric constant of material between plates,
- ε<sub>o</sub> = 8.854 × 10<sup>-2</sup> picofarads/cm for air or vacuum,
- A = area of plates in cm<sup>2</sup> and
- d = separation between plates in cm.

Inserting the typical value 40 into equation 1 reveals that C<sub>v</sub> equals about 35 pF for the above stated test cell dimensions. To accurately measure low values (less than 50 pF) of the capacitance C<sub>x</sub> in fig. 4 by balancing out C<sub>x</sub> with the variable capacitor C<sub>v</sub>, a precision variable capacitor was needed. A precision variable capacitor with a range of about 1 to 50 pF was designed as follows.

The metallic plates of the variable capacitor were made of 1.16 mm (1/16 inch) nominal thickness FR-4

epoxy-glass printed circuit board material containing one ounce copper on one side. All other parts were made of polyvinyl chloride (PVC) plastic to provide high electrical resistivity except for the mounting base which was wood. A mechanical side-view of the 0-50 picofarad variable capacitor is shown in fig. 5.

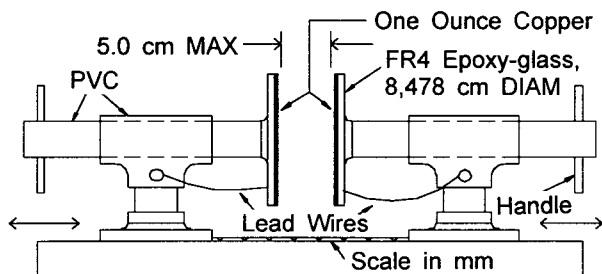


Fig. 5 Precision 1 to 50 picofarad capacitor.

### 3. Sponge Material

To understand the nature of the general electrical circuit of soils, laboratory experiments were made with simulated soil material. A number of porous materials were tried as suitable sample material such as neoprene foam rubber, silicone foam rubber, urethane foam, cellulose foam, and other synthetic porous material. Most of these materials would not "wet", that is, not absorb water into its pore spaces. For this application, only cellulose sponge material appeared satisfactory in that it would "wet" easily, could be easily cut and shaped, was relatively uniform, could be charged with greater than 40% volumetric water-content ( $0.40 \text{ cm}^3/\text{cm}^3$ ) and not leak or drip, was easily obtainable, and easy to rinse out and dry.

Sponges were cut from the cellulose sponge material, providing porous electrically-insulating material that was uniform from sample-to-sample and that could be charged with a specific volume of water containing a known amount of electrolyte. These porous-material samples (sponges) were used to simulate uniform soil for the purpose of measuring the characteristics of the parallel resistance ( $R_x$ ) and capacitance ( $C_x$ ) between two metal plates as shown in fig. 4. Twenty relatively uniform, dry, right cylinder samples were prepared, each close to  $10 \text{ cm}^2$  in top area and 1.1 cm thick and they were weighed and numbered.

### 4. Test Cell

To hold the sponges, a precision test cell was designed and built that would have low inherent "fringe" or extraneous residual capacitance and be able to be used in one arm of a high-frequency, modified Harris bridge measuring instrument. The test cell was designed with two parallel, metallic plates (electrodes) spaced 1.0 cm apart as shown in fig. 6. One of the plates is circular with an area of  $10.0 \text{ cm}^2$ . The other electrode is a square plate with an area of

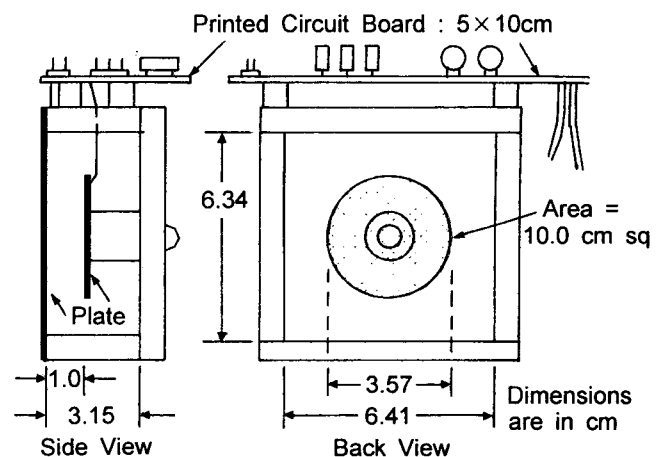


Fig. 6 Test cell.

approximately  $36 \text{ cm}^2$ . Low capacity electrical circuit connections were provided from each plate to the modified Harris bridge circuitry. The square plate was removable, allowing the 1.1 cm thick cylindrical sponges (porous media) to be located almost exactly concentric with the round plate. Then the square plate was replaced, compressing the sponge to exactly 1.0 cm thickness. This made a capacitor with parallel conducting plates whose dielectric was the sponge material. The enclosed volume ( $10.0 \text{ cm}^3$ ) between plates is the basis of these volumetric water content ( $\theta_v$ ) measurements. To vary conditions, sponges could be charged with a known volume of pure water or water containing KCl, manipulated to ensure uniform wetting and distribution of the solution, and placed and compressed to occupy the space between the plates within the  $10 \text{ cm}^3$  chamber in the test-cell.

Because of the corrosive nature of electrolytic material (soil solution) on metals, a material for the conductive plates had to be researched. Saline solutions and body fluids are similar in chemical composition and one of the best materials in this respect is type 316L stainless steel for general saline solutions and type 316LM for medical implants (Peckner and Bernstein, 1977; de Renzo, 1985). The type 316L in 16 gauge (USA), 1.57 mm nominal (0.062 inch) thickness was available locally, and was used for making the test-cell's, electrically conductive plates. The side walls and back of the test cell were made of nominal 6.3 mm thick methyl methacrylate (Lucite) and the insulating "stand-off" to support the round plate was made of nylon material.

The capacitance between the plates per the standard parallel-plate capacitor (equation 1) with air as the dielectric in the empty cell (with all electrostatic field lines being perpendicular to the conductive plates and excluding any "fringe" capacitance) was calculated to be 0.885 picofarads. From Walker (1990) can be found that for this test cell configuration, there is also a "fringe" capacitance of approximately 1.0 picofarad.

The overall inherent residual capacitance in the empty test cell then equals approximately  $0.885 + 1.0$  which equals approximately 1.9 picofarads. The mechanical drawing of the final configuration of the test cell is shown in fig. 6.

The dry dielectric constant of the cellulose sponge samples was constant in value at approximately 2.2 and the conductive component of the wet sponges was controllable with KCl solutions. With a test specimen (wet sponge) in place between the conductive plates, calculations of dielectric constant derived from the standard parallel plate capacitance equation could be made. The bridge measurement frequency was controllable over a frequency range of 10 KHz to 10 MHz sinusoidal but useful measurements above 5 MHz were not obtainable because of the lack of expertise for developing precision electronic bridge circuitry above this frequency.

### 5. Instrumentation

The complete instrumentation for sponge measurements was composed of the following items.

- (1) Variable-frequency sine-wave generator from 1 KHz to 1 MHz with 2 volt peak-to-peak output (Hewlett-Packard model 3311A Function Generator),
- (2) Fixed-frequency sine-wave oscillators of 2, 5, and 10 MHz,
- (3) Bridge circuitry as shown in fig. 4,
- (4) +15.0 and -15.0 volt DC power-supplies for the electronics,
- (5) Frequency counter (Hewlett-Packard model 5308 A Timer/Counter),
- (6) Digital Multimeter (Fluke model 8000A Digital Multimeter),
- (7) Several capacitor decade-boxes (for variable capacitance),
- (8) Several resistor decade-boxes (for variable resistance),
- (9) Precision 0-50 pF variable capacitor described previously,
- (10) Platform to assemble the instrumentation,
- (11) The test cell described previously,
- (12) Various cables and test-leads for interconnecting, and
- (13) Oscilloscope (not shown: Hewlett-Packard model 1740a).

The resistor decade-boxes, the capacitor decade-boxes, and the 1-50 picofarad precision capacitor were used as  $R_v$  and  $C_v$  for measuring  $R_x$  and  $C_x$  of fig. 4.

A photograph of the complete test set-up is shown in fig. 7.

### 6. Experimental Design

1.0 liter quantities of distilled and de-ionized water were prepared containing KCl in 0.001 and 0.01 molar

concentrations to be used to represent electrolytic material in soil water. Experiments were performed using cellulose sponges in the test cell with the following test conditions.

- nominal  $\theta_v$  : 0, 0.10, 0.20, 0.30, 0.40
- KCl molarity : 0.001, 0.01
- KHz frequency : 10, 20, 50, 100, 200, 500

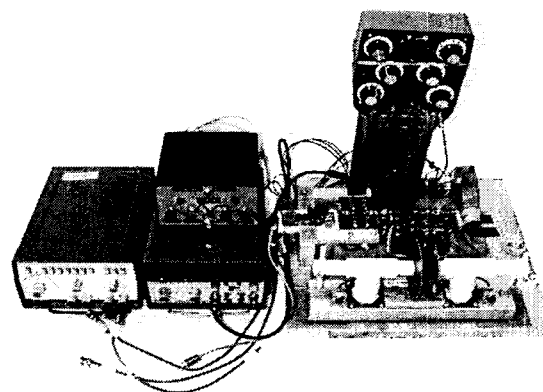


Fig. 7 Photograph of the complete test set-up for measuring sponges.

MHz: frequency: 1, 2, 5

At each step change in actual  $\theta_v$ , molarity, and frequency, the modified Harris bridge was balanced (nulled) and the equivalent resistance and capacitance balancing values recorded. All experiments at about 22 °C ambient temperature measured different sponge samples with at least 3 replications at each step in actual charge of  $\theta_v$ , molarity, and frequency. Measurements with the combination of 0.001 M and 10 KHz were not used.

### Results and Discussion

Plots of the results of measurements of parallel R and C versus molarity versus frequency for a constant molarity of 0.001 for KCl at actual values of  $\theta_v$  equaling 0, 0.10, 0.20, 0.30, and 0.40, are shown with solid lines in Fig. 8. What these curves show is the general behavior of the measured, electrical capacitance versus frequency from above the electrode polarization frequency limit (1 KHz) to 5 MHz, where 5 MHz is approaching the limit of frequency for this particular instrumentation (10 MHz). The curves also show extrapolated values of capacitance values between 5 and 50 MHz.

The plots at 0.001 molar KCl in fig. 8 show that the electric double-layer capacitance dominates the equivalent, parallel, resistance-capacitance circuit less and less as frequency increases and as an asymptote in

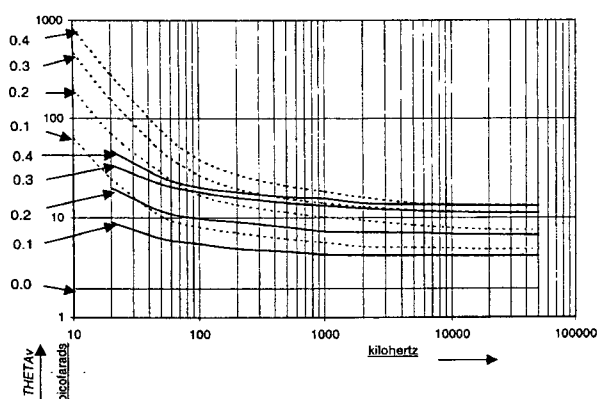


Fig. 8 Capacitance versus frequency at 0.001 (solid) and 0.01 (dashed) molar KCl.

capacitance is approached beyond approximately 10 MHz (Rial, 1999). Apparently in fig. 8 at 0.001 molar KCl, there is still some small remnant of the electric double-layer capacitance at 10 MHz at  $\theta v$  equals 0.3 and 0.4. The lowest frequency where the slope has become approximately zero indicates that the diffusion region of electronic charge has been entered (Fried, 1973; Galster, 1991; Gileadi et al., 1975). The asymptotic value (where the slope is zero) of the measured capacitance in the diffusion region can be used to calculate the true dielectric constant  $DC_{real}$  of water (only) which reflects the true value of volumetric water content ( $\theta v$ ) of water contained in the samples for these conditions.

The previous experiment at 0.001 M was repeated with a KCl concentration of 0.01 molar. These results at 0.01 M are also plotted in fig. 8 with dotted lines, concurrently with the 0.001 M data with solid lines. Values above about 5 MHz are extrapolated to approximately 50 MHz.

In spite of the difficulty to achieve good bridge balance for both R and C at frequencies above about 1 MHz, fig. 8 shows that an apparent asymptote is being approached beyond about 10 MHz for both the 0.001 M and 0.01 M curves. It further appears that there is more remnant non-zero slope at 10 MHz of the 0.01 M (dotted) curves than of the 0.001 M (solid) curves. This suggests that for higher values of electrolyte concentration in porous materials (note: in agronomic and horticultural soils, 0.01 M total electrolyte concentration would be a large value of required mesophyte nutrition), a true asymptote may not be achieved even at 50 MHz and may require bridge operation at frequencies approaching 100 MHz or possibly greater. Further work between 10 MHz and 100 MHz with an electrolyte concentration near 0.01 M may be needed to ascertain the lowest practical operating frequency at very high total molar concentration of mesophyte nutrients.

### An Example of the Usefulness of the Data and Plots

In a parallel-plate capacitor like that used in the test cell (fig. 6) and shown in the circuit of fig. 4, dielectric constant can be calculated from capacitance measurements by rearranging the standard, parallel-plate capacitance equation 1 as shown in equation 2 as follows:

$$DC = \frac{\text{capacitance } e \text{ in picofarads} \times d}{8.854 \times 10^{-2} \times A} \quad (2)$$

For the test cell of fig. 6,

$$DC = 1.13 \times C_{pF} \quad (3)$$

where  $C_{pF}$  = measured capacitance in picofarads.

The extrapolated values of capacitance from fig. 8 at 50 MHz and 0.001 molar concentration and their corresponding dielectric constant values for these sponges are shown in table 1. The values of  $\theta v$  shown are actual (charged) values of volumetric content.

Table 1 Extrapolated capacitance and calculated dielectric constant (DC) at 50 MHz and 0.001 M KCl

$\theta v$	0	0.1	0.2	0.3	0.4
Cpf	1.95	4.00	6.73	11.00	13.49
$DC_{real}$	2.20	4.52	7.61	12.43	15.24

From values of calculated  $DC_{real}$  can be calculated approximate volumetric water content  $\theta v$  by using an empirical equation similar to equation 4 (Von Seggern, 1993) which is very representative of the shape of the curve of  $\theta v$  versus  $DC_{real}$  for typical soil used for mesophyte plant culture (Rial, 1999):

$$\theta v = s \times (DC_{real}^2 - DC_{dry}^2)^m \quad (4)$$

where

$s$  = scale factor,  
 $DC_{real}$  = real component of the dielectric constant,  
 $DC_{dry}$  = dielectric constant of dry porous media, and  
 $m$  = shape factor.

The general shape of the curve for an equation represented by equation 4 is shown in fig. 9.

It can be seen in fig. 9 that the shape of the curve is not linear at lower values of  $\theta v$  due to the retention of water in very small capillary spaces

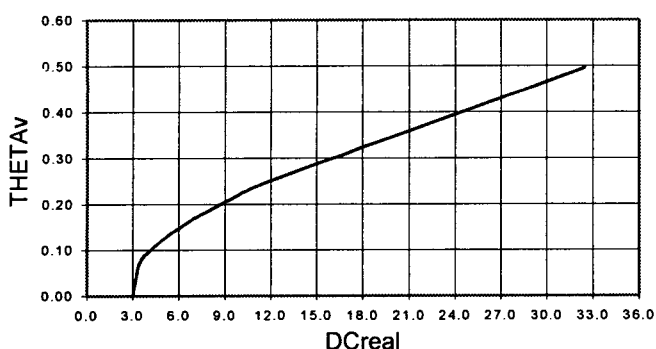


Fig. 9 Representative plot of  $\theta v$  versus  $DC_{real}$  for wet porous material and agronomic soil.

(Hillel, 1980). Also, the intercept will occur at the value of dielectric constant for dry, typical agronomic soil which equals approximately 3.0 (Topp et al., 1980; Wang and Schmugge, 1978), but equals approximately 2.2 for the cellulose sponge material used for these experiments.

For the values of calculated  $DC_{real}$  from table 1, an empirical equation based on the general form of equation 4 which is specific to these sponges at 50 MHz (extrapolated) and molarity of KCl of 0.001 was found to be as follows in equation 5:

$$\theta v = 0.029 \times (DC_{real}^2 - 2.2^2)^{0.48} \quad (5)$$

Calculated values of  $\theta v$  using Equation 5 from  $DC_{real}$  values from table 1, compared to the actual values of  $\theta v$  are shown in table 2 and plotted in fig. 10 with a coefficient of determination ( $R^2$ ) of 0.9947. Again, the actual values of  $\theta v$  for these sponge measurements was the actual volumetric water content ( $\theta v$ ) imposed at each step.

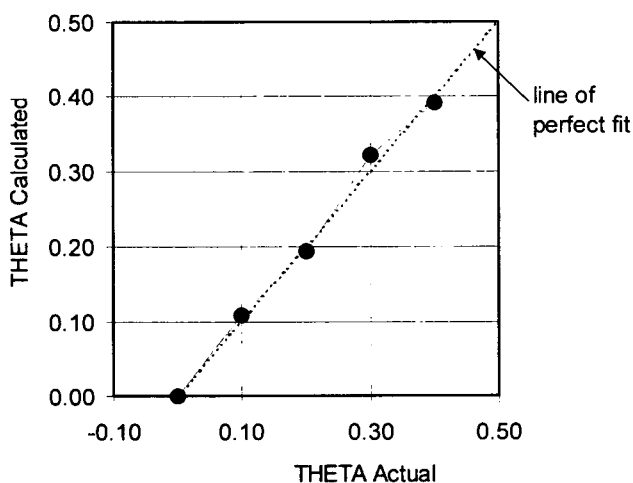


Fig. 10 Plot of  $\theta v$  calculated versus  $\theta v$  actual at 0.001 molar KCl.  $R^2 = 0.9947$ .

Table 2 shows that it is possible to calculate  $\theta v$

Table 2 Actual and calculated values of  $\theta v$  using extrapolated  $DC_{real}$  at 0.001 M

Actual $\theta v$	Calculated $\theta v$ (eq. 4)	Difference Actual-calculated
0.0	0.00	0.00
0.10	0.108	-0.008
0.20	0.195	+0.005
0.30	0.321	-0.021
0.40	0.392	+0.008

At balance,  $R_x = R_v$  and  $C_x = C_v$ .

from representative  $DC_{real}$  values derived from measured capacitance values with error equal to or less than approximately  $0.02 \text{ cm}^3/\text{cm}^3$  absolute for some porous media when using extrapolated values of capacitance at 50 MHz and 0.001 molar KCl under similar conditions.

### Conclusions

Several conclusions were drawn as follows.

1. A modified Harris electronic bridge circuit using operational amplifier integrated circuits can be implemented for high frequency applications.
2. The capacitance of the equivalent resistance-capacitance parallel circuit for wet porous media can be measured with suitable electronic circuitry at the appropriate frequency.
3. The measured capacitance representing water in wet porous media can be converted to dielectric constant values by using one of the standard capacitance equations.
4. It was observed that the diffusion region wherein resides true water content capacitance information is between 30 MHz and 50 MHz when the total ionic concentration is 0.001 molar for a type 1:1 electrolyte. The diffusion region where true water content information can be found for total 0.01 molar concentration for a type 1:1 electrolyte may be above 50 MHz and possibly as high as 100 MHz.
5. An empirical equation for  $\theta v$  versus  $DC_{real}$  can be found by trial-and-error curve fitting, which can result in relatively small (equal to approximately 2.0% absolute or less) error between actual and calculated values of  $\theta v$  from zero to approximately 0.40 with a total concentration of approximately 0.001 molar for a type 1:1 electrolyte.
6. Results from these experiments with wet sponges can be the basis for developing low-cost capacitive probe instrumentation that calculates values of  $\theta v$  from calculated values of  $DC_{real}$ , by measuring diffusion region capacitance in agronomic and horticultural soil.

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