Published September 26, 2014



# Measurement of Soil Water Content with Dielectric Dispersion Frequency

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**Frequency domain reflectometry (FDR) is an inexpensive and attractive methodology for repeated measurements of soil water content (θ). Although there are some known measurement limitations for dry soil and sand, a fixed-frequency method is commonly used with commercially available FDR probes. The purpose of our study was to determine if the soil dielectric spectrum could be used to measure changes in θ. A multifrequency FDR probe was constructed with a 6-mm diameter, and a soil dielectric spectrum was obtained. Using the dielectric spectrum, the dielectric dispersion frequency ($f_d$) was determined. It was discovered that changes in $f_d$ were highly correlated with changes in θ, and a third-order polynomial equation ($R^2$ = 0.96) was developed describing the relationship. The effectiveness of $f_d$ for θ measurement was evaluated for three soils and a sand across a range of θ. The effects of soil temperature and soil salinity were also evaluated. Accurate measurements of θ were obtained even in dry soil and sand. The root mean square error of the θ estimated by the $f_d$ measurement was 0.021. The soil temperature and soil salinity had no measureable effects on θ determination. The use of $f_d$ for θ determination should be an effective and accurate methodology, especially when dry soils, soil temperature, and/or soil salinity could potentially cause problems with the θ measurements.**

Abbreviations: FDR, frequency domain reflectometry.

Accurate measurements of soil water content (θ) are critically important for determining effective irrigation management and understanding soil processes. Many recent scientific research efforts have addressed the development of durable θ measurement systems that are accurate, offer fast response times, are nondestructive, and are relatively low cost (Noborio, 2001; Robinson et al., 2003; Xu et al., 2012).

Time domain reflectometry (TDR), frequency domain reflectometry (FDR), and capacitance are the three main ways to measure the soil water content based on soil dielectric properties. According to probe circuit principles, if a probe works in the time domain, it is called a TDR probe. If a probe has a controlled operating frequency, it is called an FDR probe because it depends on the permittivity properties in the frequency domain. If a probe circuit covers a frequency range, it should be called a capacitance probe because the circuit functions as an inductance capacitance oscillator.

Dielectric methods have the added advantage that data can be collected nearly continuously and either stored on site or transmitted to a computer. Dielectric methods have gained wide acceptance for delivering fast, in situ, nondestructive, and reliable θ measurements with reliable precision (Topp and Ferré, 2002; Topp et al., 2000).

Soil Sci. Soc. Am. J. 78:1500–1506
doi:10.2136/sssaj2013.10.0429
Received 5 Oct. 2013.
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Frequency domain reflectometry is used to measure differences in the dielectric spectra of soil within different ranges of the frequency base that are sensitive to different physical and chemical soil properties. Several studies have been performed on measured soil dielectric properties for a range of frequencies. Campbell (1990) studied soil dielectric properties and the influence of electrical conductivity in the 1 to 50 MHz range. Wensink (1993) studied the dielectric properties of wet soils in the 1 MHz to 3 GHz range. Heimovaara et al. (1996) compared TDR and FDR measurements of dielectric permittivity in the 0 to 1 GHz range. Skierucha and Wilczek (2010) measured soil permittivity in the 10 to 500 MHz range (Delta-T Devices, 1999; Kelleners et al., 2005; Logsdon et al., 2010; Seyfried et al., 2005).

The accuracy of FDR is influenced by soil type, probe geometry, soil salinity, and soil temperature (Baumhardt et al., 2000; Chandler et al., 2004; Kelleners et al., 2005). Although we can determine an operating frequency at which the measurement accuracy does not change with changes in soil temperature and salinity for most soils, the measurement frequency will not be applicable for use in all soils, for example in sand or saline soil. An important research area is to determine how to design FDR probes so that the measurement technique is applicable for a broader range of soils and soil properties at different soil temperatures and salinity levels. One promising approach may be through the study of the soil dielectric dispersion frequency. The dielectric dispersion frequency is an electromagnetic frequency after which the dielectric permittivity approaches zero. Shang et al. (1999) stated that the observed dispersion frequency is related to the velocities and travel times of electromagnetic waves through a soil sample and air in the sample holder. They presented a relationship between soil volumetric water content and a maximum loss factor (the peak of the imaginary trace). Shang et al. (1999) suggested that the dispersion frequency may be used to represent the intrinsic properties of the soil. The relationship between the soil volumetric water content and the dielectric dispersion frequency should be further considered because both properties are closely related to the maximum loss factor. The objectives of this study were to: (i) evaluate the relationship between the soil dielectric dispersion frequency and θ for different soil types, temperatures, and salt concentrations; and (ii) evaluate the potential of using changes in the dielectric dispersion frequency as an accurate method of measuring θ.

## MATERIALS AND METHODS

Four different soils, representing a range of clay and sand contents, were used in this experiment (Table 1). The sand used was a pure sand with no clay or silt contents and was washed with water before use. The three soils used were from the Ida series (fine silty, mixed, superactive, calcareous, mesic Typic Udorthents), the Nicollet series (fine-loamy, mixed, superactive, mesic Aquic Hapludolls), and the Webster series (fine-loamy, mixed, superactive, mesic Typic Endoaquolls) (Soil Survey Staff, 2014). The soils were air dried, sieved through a 1.0-mm (no.18) sieve, and oven dried at 105°C for 24 h. For the relationship of soil water content and dispersion frequency, the dried soils were thoroughly mixed with deionized water at five different water contents covering a range of water contents from moist to dry. Soil at each water content was packed into polyvinyl chloride (PVC) columns (80-mm height, 60-mm diameter). Soil samples sat in the PVC columns for at least 24 h before the start of measurements. The soil temperature was controlled by a water bath to determine temperature effects on the soil dielectric spectra. The effect of soil salinity on the soil dielectric spectra was determined by using KCl solutions of 0.02, 0.04, 0.06, 0.08, and 0.1 mol/L to mix with the dried soils when obtaining the desired θ.

The soil dielectric spectra were measured with a vector network analyzer (VNA, Hewlett-Packard 8753ES, Agilent Technologies). One port (S11, scattering parameter) was used during the measurements and the results recorded with a Smith-chart format chart recorder. The measurement frequency range was set from 1 to 3000 MHz on a logarithmic scale. The number of data points was set to 801. The power level was set to 0 dBm (1 mW) with a dynamic range of at least −40 dBm (100 nW). The phase-preserving cable (low loss for electromagnetic wave propagation) was connected to Port 1 of the VNA with an open, short, and load at a resistance of 50 Ω. Calibration was performed in accordance with the manufacturer's specifications using suitable calibration standards (Maury Microwave 85050B BNC calibration kit). After calibration, the broad-band 50 Ω standard load produced a dot trace located in the middle of the Smith chart at 50 Ω with a phase angle equal to 0°. The short standard produced a dot trace at 0 Ω with a phase angle of 180°. The open standard produced an open trace on the Smith chart. We started measurements of the soil 2 h after the VNA was powered on to ensure the stability of the instruments (Xu et al., 2012). The scattering parameter ($S_{11}$) was obtained from the VNA and converted to permittivity using the procedure of Logsdon and Laird (2002), who based their procedure on that of Campbell (1990) and Kraft (1987). Matlab codes were used for performing the calculations that transform the $S_{11}$ into the dielectric permittivity (Logsdon, 2005). After a study of the dielectric dispersion frequency, we determined the relationship between the dielectric dispersion frequency and the soil water content. The dielectric dispersion frequency was determined from the intersection of the tangent of the flat line before the graphic point displaying the dielectric dispersion frequency and the tangent of the dropping line.

Frequency domain reflectometry probes having a 6-mm radius were constructed for use in this study (Fig. 1). The probe needles were seven stainless steel tubes (i.e., hypodermic needles) having a 28-mm length equipped with a BNC-type connector

**Table 1. The particle sizes and densities of the soils used in the study.**

| Soil | Clay | Silt | Sand | Packed bulk density |
|---|---|---|---|---|
| | | kg/kg | | $Mg/m^3$ |
| Sand | 0 | 0 | 1 | 1.60 |
| Nicollet | 0.235 | 0.325 | 0.440 | 1.12 |
| Ida | 0.250 | 0.701 | 0.049 | 1.17 |
| Webster | 0.336 | 0.341 | 0.323 | 1.17 |

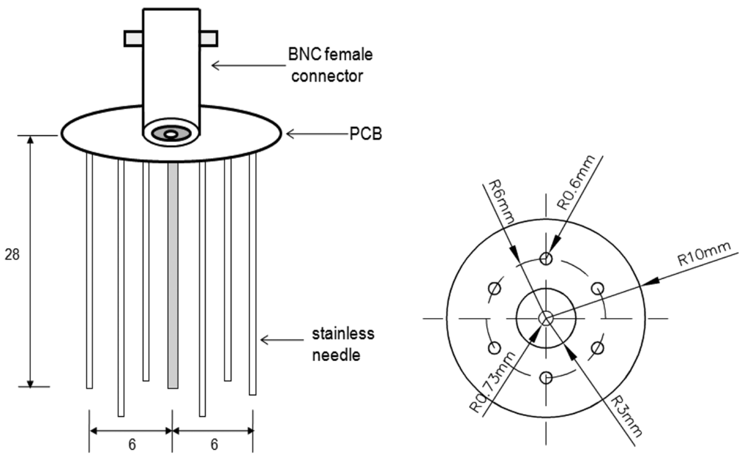


**Fig. 1. Schematic view of the constructed multifrequency frequency domain reflectometry probe (6-mm diameter), with dimensions in millimeters (PCB is printed circuit board).**

(female jack BNC, 50 Ω).The diameter of the outer rods was 1.2 mm and the middle rod diameter was 1.46 mm. The spacing between the two external rods was 6 mm.

## THEORY

When an alternating electrical field is applied to a dielectric medium, some charges are bound, yet these positive and negative charges can move locally relative to each other and result in a polarized medium. The polarization is quantitatively described by the equivalent relative permittivity ($\varepsilon^*$), which is a complex dimensionless parameter (Logsdon, 2005):

$$\varepsilon_r{}^* = \varepsilon_r - j\varepsilon_i \qquad [1]$$

where $\varepsilon_r$ is the real part of the complex permittivity that represents the ability of a material to store electrical energy, $j$ is $\sqrt{(-1)}$, and $\varepsilon_i$ is the imaginary part or loss factor of the complex permittivity that describes the loss of electrical field energy in the material (Logsdon, 2005; Shang et al., 1999). The imaginary part of the complex permittivity is the result of electrical conduction and molecular relaxation (Robinson et al., 2003; Seyfried et al., 2005; Topp et al., 2000), which are related to $\varepsilon_i$ as

$$\varepsilon_i = \varepsilon_{ird} + \frac{\sigma_{dc}}{2\pi f \varepsilon_0} \qquad [2]$$

where $\varepsilon_{ird}$ is the loss factor due to dielectric losses, $\varepsilon_0$ is the absolute dielectric of a vacuum ($8.854 \times 10^{-12}$ F/m), $f$ (Hz) is the measurement frequency, and $\sigma_{dc}$ (S/m) is the direct current electrical conductivity (Logsdon, 2005; Seyfried et al., 2005).

There are three main types of polarization mechanisms in pure materials: electronic polarization, ionic polarization, and orientational polarization (i.e., the rotation of dipolar or polarized molecules) (Baker-Jarvis, 2000). The polarization displays one of two characteristic spectra such as resonance or relaxation at characteristic frequencies and influences the shape of the permittivity as a function of the frequency (Al-Mattarneh et al., 2008). The mechanism of dipoles relaxing is called *dielectric relaxation*. Debye (1929) and Cole and Cole (1941) gave a model for the ideal dipoles (Logsdon, 2005):

$$\varepsilon^*(f) = \varepsilon_\infty + \frac{\varepsilon_S - \varepsilon_\infty}{1+\left(jf/f_r\right)^{1-\alpha}} \qquad [3]$$

where $\varepsilon_S$ is the low frequency and $\varepsilon_\infty$ is the high frequency of $\varepsilon_r$, $f$ (Hz) is the measurement frequency, $f_r$ is the relaxation frequency, and $\alpha$ is an exponent that describes the spread of the relaxation peak. If the relaxation is Debye, then $\alpha = 0$ and the spread is small.

Soil is a lossy dielectric material. Soil permittivity is a measurement of the extent to which the electrical charge distributed in the soil can be polarized by the application of an electrical field. The soil dielectric spectrum captures the complex polarization mechanisms. In addition to electronic polarization, ionic polarization, and orientational polarization, there is also interfacial polarization or Maxwell–Wagner polarization (which occurs in the kilohertz range) and is a multiphase phenomenon (Chen and Or, 2006). Bound water relaxation can also affect the representation of the permittivity spectrum in wet soil.

## RESULTS AND DISCUSSION

Figure 2 presents the real and imaginary permittivities of two of the soils across a range of volumetric water contents. The real and imaginary permittivities decreased with increasing frequency. The large values in the low-frequency range are attributed to polarization and conduction of the electrical double layers, which are the signature characteristics of aqueous colloidal materials including wet soils (Shang et al., 1999). For frequencies between 1 and 30 MHz, the real and imaginary permittivity sharply decreased. For frequencies >30 MHz, the real dielectric permittivity showed some increase before declining near 1 GHz. The imaginary dielectric permittivity decreased with increasing frequencies and had a rapid rise at a frequency of 1 GHz. The frequency at which the real dielectric permittivity rapidly declined is the dispersion frequency, $f_d$ (Shang et al., 1999). The frequency between 30 MHz and the dispersion frequency should be used for measuring the soil water content. In this frequency region, the real dielectric curve is flatter and thus more ideal for measuring the soil water content. The dispersion frequency, shown in Fig. 2a, changes for different values of soil water content.

The real and imaginary dielectric permittivities were affected by differences in the texture and temperature of the soil. From the complex permittivity spectra of the soils, we can determine the ideal measurement frequency at which the apparent permittivity of the four soils was relatively constant for a range of texture and temperatures. Xu et al. (2012) reported that 70 MHz was the best measurement frequency at which the apparent permittivity of four select soils did not change for a range of temperatures and salinities. It should be noted that fixed-frequency methods have limitations for soil water content measurements

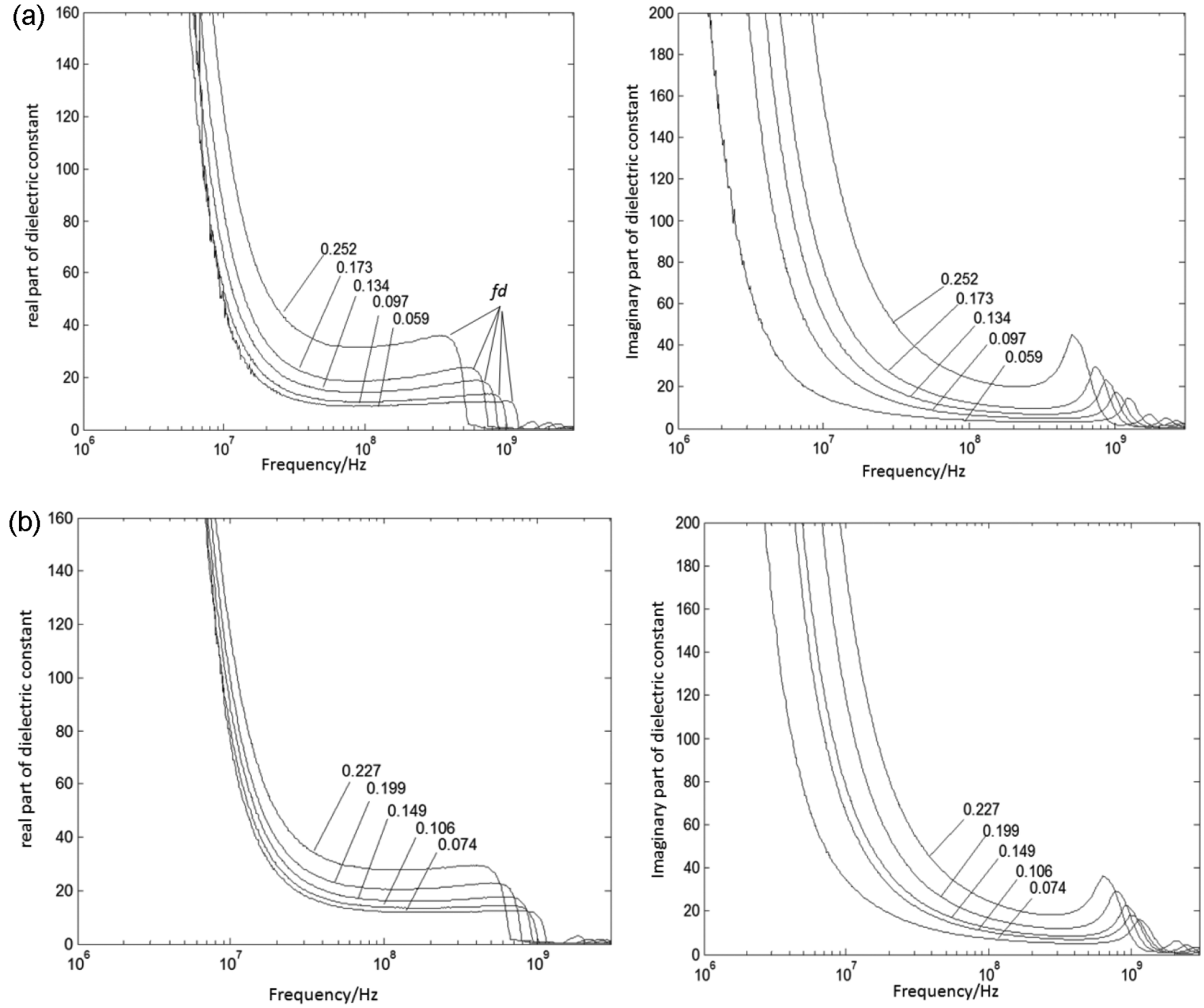


**Fig. 2. The complex permittivity spectra of soils: (a) Ida soil; (b) Webster soil.**

because the optimal frequency for all types has not been found and most commercial probes have limits on measurements in sand and saline soils.

Figure 3 presents the real and imaginary permittivities of four air-dry soil samples. A large amount of permittivity noise was produced in the frequency range of 10 MHz to 1.18 GHz because of the Maxwell–Wagner relaxation, which occurs in the kilohertz range for dry soils. It was not easy to determine the dielectric spectra for the four soils using the information presented in Fig. 3. Compared with fixed-frequency meth-

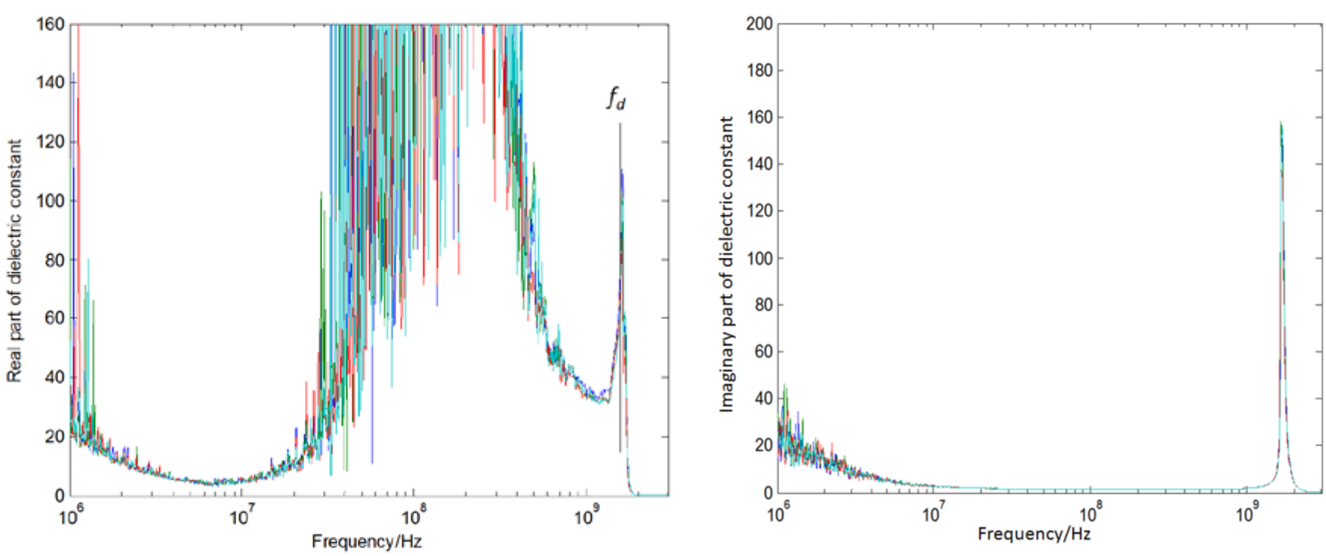


**Fig. 3. Four air-dry soil dielectric spectra, showing the dielectric dispersion frequency ($f_d$).**

ods, a multifrequency determination in the frequency range of 40 MHz to 1.18 GHz would not be appropriate for measuring the soil water content of dry soils, and a different approach is necessary if a multifrequency method is to be used. However, Fig. 3 does indicate that the soil dispersion frequencies are similar for the four air-dried soils. Compared with Fig. 2, the dispersion frequency increased as the soil water content decreased, indicating a relationship between the dispersion frequency and the soil water content.

The real and imaginary dielectric permittivities are affected by temperature because the molecular relaxation and electrical conductivity are sensitive to material temperatures. Seyfried and Grant (2007) reported that temperature responses were both positive and negative for different soils. Figure 4 shows the permittivity traces at soil temperatures of 10 to 50°C for the Ida soil at a constant water content of 0.30 $m^3/m^3$. The real part of the dielectric permittivity in the lower 40 MHz increases as the temperatures increase, but it decreases at values >152 MHz as the temperatures increase. In contrast, except for some measurement error, the dispersion frequency displayed only negligible changes as the temperature changed. Other soils are expected to behave in a similar pattern.

Topp et al. (1980) reported that soil salinity can affect measurements of the soil dielectric permittivity. Figure 5 shows the dielectric spectra of Webster soils for different salt concentrations when the soil water content was constant at 0.30 $m^3/m^3$. The real dielectric permittivity for the Webster soil was almost unchanged across the different salt concentrations because changes in the real permittivity seemed to occur only in response to changes in the soil water content. The imaginary part of the permittivity changes with the salt concentrations because the imaginary part describes the loss of electrical field energy in the material. Figure 5 indicates that the dispersion frequency did not respond to differences in the salt content of the soil.

Figure 6 displays the results of measurements at different temperatures and/or different water contents. A strong rela-

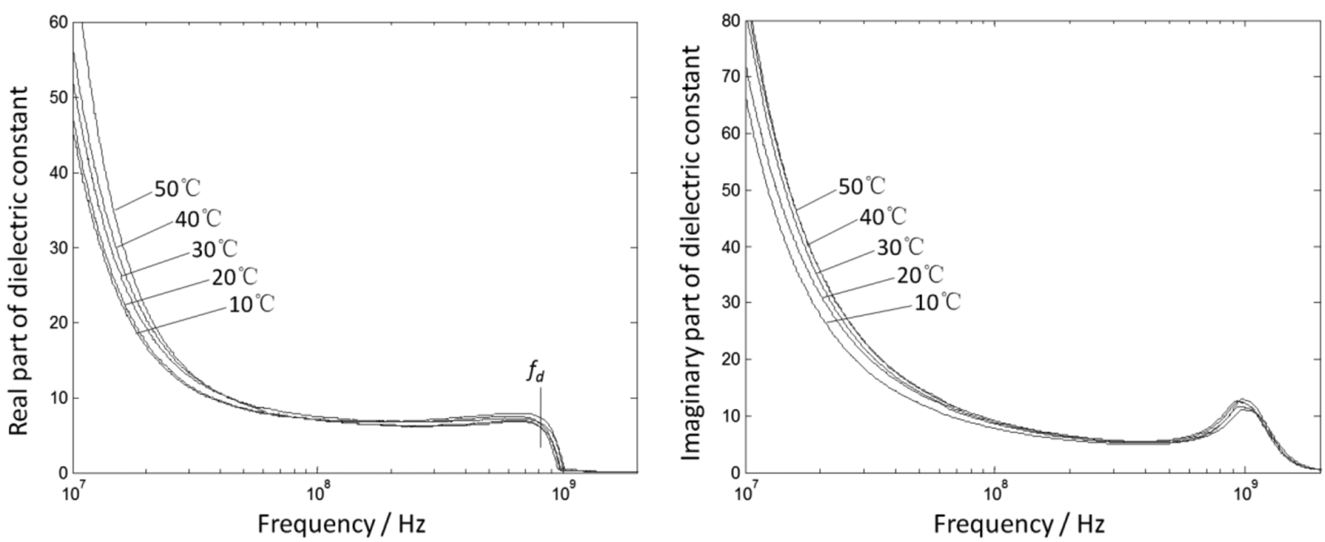


**Fig. 4. The dielectric spectra of Ida soils at different temperatures, showing the dielectric dispersion frequency ($f_d$).**

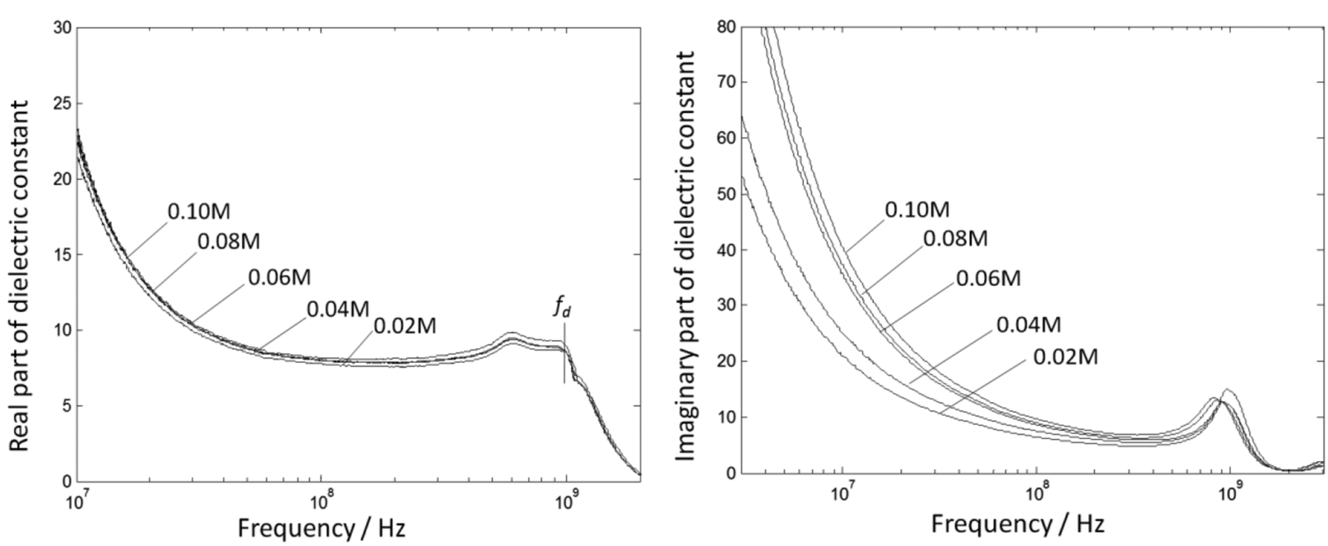


**Fig. 5. The dielectric spectra of Webster soils at different salt concentrations (0.30 $m^3/m^3$) , showing the dielectric dispersion frequency ($f_d$).**

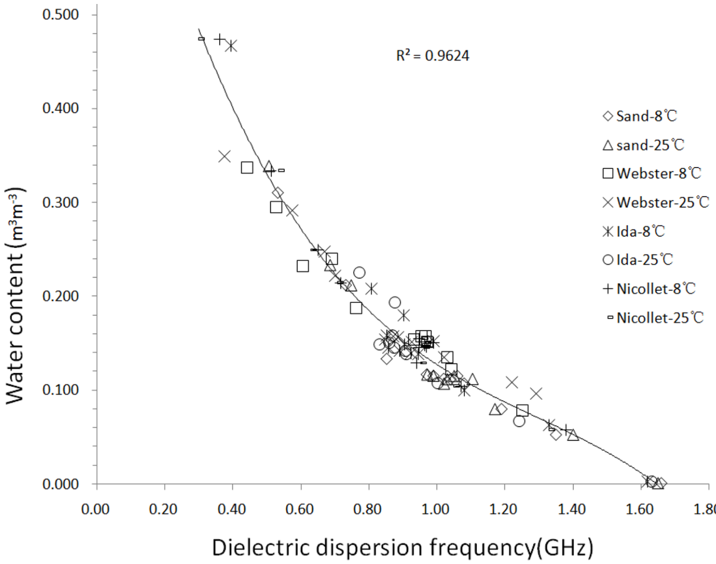


**Fig. 6. The relationship of water content and the dielectric dispersion frequency.**

tionship between the dielectric dispersion frequency and the soil water content was indicated, with a coefficient of determination of 0.96. A third-order polynomial equation fit the data well:

$$\theta = -0.3209 f_d^3 + 1.2004 f_d^2 - 1.6577 f_d + 0.9055 \qquad [4]$$

indicating that the dielectric dispersion frequency may be used to estimate soil water contents for different soils at different temperatures. The root mean square error (RMSE) of the θ estimated by the $f_d$ measurement is 0.021, which is better than 0.027, the RMSE of θ estimated at 70 MHz(Xu et al., 2012) and better than the RMSE of $f_d$ = 0.0288, which is estimated by the Topp equation.

## CONCLUSIONS

An FDR probe was constructed that allows the measurement of the soil dielectric spectrum. Using the soil dielectric spectrum data, the soil dielectric dispersion frequency was determined. The dielectric dispersion frequency is a useful frequency within the soil dielectric spectrum because it displays a strong relationship with the soil water content even in dry soils and sand. It was also determined that soil temperature and salt content had negligible effects on the dielectric dispersion frequency. The relationship between the dielectric dispersion frequency and the soil water content was determined for a range of water contents in three different soils and a sand. A third-order polynomial equation was developed to determine the soil water content based on changes in the dielectric dispersion frequency. The use of the dielectric dispersion frequency methodology to determine soil water content offers an alternative means to measure soil water content that is accurate regardless of soil temperature or soil salinity. Although its accuracy in field soils needs further examination, with further refinement the use of the soil dielectric dispersion frequency for soil water content measurement offers a new technology that may provide benefits over currently used fixed-frequency FDR methods.


## ACKNOWLEDGMENTS

We express our appreciation to Gavin Simmons, Robert Hill, Dedrick Davis, Jiming Song, Brian Hornbuckle, and Robert Weber for providing valuable advice and assistance. This work was supported by the Natural Science Foundation of China (51309193, 51279167), the U.S. National Science Foundation under Grant 1215864, and by Hatch Act and State of Iowa funds. The work was also supported by the 111 Project of Chinese Education Ministry (no. B12007).


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