Standardizing Characterization of Electromagnetic Water Content Sensors:

Part I. Methodology

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ABSTRACT

Performance differences in the growing number of electromagnetic (EM) sensors designed to estimate soil water content from a variety of indirect measurements (e.g., from measured travel time, capacitance, frequency shift, etc.), suggests the need for a standardized sensor characterization methodology. We suggest that characterization and evaluation of EM sensors, which currently lack referenceable standards, be carried out in a homogeneous fluid of known permittivity rather than in a porous medium of unknown permittivity. Our objectives were to i) develop a methodology for evaluating EM sensor measurement attributes referencing sensor-specific characteristics and targeted soil properties and ii) suggest standards for characterization and comparison of sensors. Criteria for qualitative assessment of sensors include determination of effective measurement frequency, susceptibility to variations in salinity, dielectric relaxation and temperature and a look at spatial variation in sensor sampling area. Measurement frequencies for broadband sensors can be inferred from correlated network analyzer and sensor measurements or from manufacturer suggestions. Fluids were selected to provide surrogate soil-related effects such as relaxation occurring both within and outside of the effective measurement frequency range of common sensors. Test conditions included dielectrically relaxing (R) and non-relaxing (NR) as well as electrically conducting (C) and non-conducting (NC) liquids and combinations thereof (e.g., NR-C). No suitable combination of relaxing and conducting (R-C) dielectric fluid was found in this study, but remains a goal of future work because it represents the more difficult and often common condition for EM sensor

1   measurements in soils containing contributors to relaxation (e.g., clays, organic matter).

2   Standards are based on fluids of known (based on Cole-Cole parameters) or measurable (using a

3   Network Analyzer) frequency-dependent permittivity that provide a reproducible homogenous

4   system for immersion of EM sensors. The methodology described here was applied using seven

5   different EM sensing systems and results are given in Blonquist et al. (this issue).

6

7   **INTRODUCTION**

8   Electromagnetic (EM) sensors determine volumetric water content, θ_v, and in some cases

9   bulk electrical conductivity, σ_b, by measuring EM sensor response in the medium under

10   consideration. The strong dependence of EM signal properties on volumetric water content, θ_v

11   ($m^3\ m^{-3}$), stems from the high permittivity of free water ($\varepsilon_{fw} \approx 80$). Electromagnetic estimates of

12   soil θ_v and σ_b have gained popularity as technology has improved. These sensors, including

13   TDR, TDT, frequency domain and capacitance devices, are valuable water, and in some cases

14   salinity, monitoring tools in both the field and the laboratory. However, it is sometimes the case

15   that a new sensor is promoted and distributed only to be disapproved of years later due to poor

16   measurement performance. The cost to users in unreliable experimental results or reduced

17   productivity for growers ultimately comes back on the company in the form of a damaged

18   reputation. These costs could be minimized or avoided by appropriate assessment of sensors and

19   dissemination of standardized performance criteria. Studies evaluating EM sensor performance

20   have typically evaluated permittivity determinations in a number of soils over a range of water

21   contents (Evett et al., 2002; Leib et al., 2003; Seyfried and Murdock, 2004). These studies are

22   useful in demonstrating the general water content measurement capability in specific soils.

23   However, these results are often misleading and conflicting due to confounding effects arising

1   from bound water or salinity that can be disguised by soil-specific calibrations showing

2   improved apparent sensor performance. The question we ask is, "does the sensor provide a

3   unique and therefore reliable permittivity response (e.g., voltage, travel time, etc.) from water

4   content changes when temperature, salinity and even soil type are also varied. Establishing

5   standards for testing and characterization of EM sensors will provide users with a reference by

6   which to judge sensor measurement capability and perhaps categorize sensors according to key

7   criteria affecting permittivity determinations.

8   **Permittivity vs. Water Content Calibration of EM Sensors**

9   It is important to note that almost all EM sensors infer permittivity from indirect

10   measurements of travel-time, impedance, capacitance, resonant frequency, frequency shift and

11   other indirect means. For θ_v determination, permittivity assessment is often an intermediate step

12   that is bypassed by sensors whose output (e.g., voltge, time, etc.) does not lead directly to a

13   calculation of permittivity. Such sensors can provide accurate water content determination based

14   on empirical and often soil-specific calibrations. However, permittivity is the physical property

15   giving rise to θ_v determination and it is much easier to provide a known permittivity in which to

16   measure (e.g., using dielectric liquids) than to provide a known water content in soil (i.e., due to

17   soil heterogeneity, and hydrostatic water distribution). We therefore suggest assessment of

18   sensor quality should refer to accurate permittivity determination. Liquids serve as 'ideal'

19   dielectric media owing to their well-defined dielectric properties such as temperature dependence

20   (Wohlfarth, 2004), sample homogeneity, consistency and ease of acquisition. Liquids also avoid

21   complications associated with soil such as air gaps near conductors and density variations.

22   Dielectric fluids such as air and distilled water have been used for calibration of EM sensors and

23   verification of accurate permittivity determinations (Kaatze et al., 1996; Robinson et al., 2003b).

1   These two extreme values of permittivity form bounds around most of the permittivities one

2   expects to find in nature. Beyond permittivity calibration there is the need for calibration for θ_v

3   determination. Where the soil is coarse or medium textured in nature, the empirical relationship

4   of Topp et al. (1980) is commonly employed to infer θ_v from permittivity determinations. A

5   physically-based approach may also be taken using dielectric mixing models to derive the

6   permittivity – θ_v relationship (Friedman, 1998; Jones and Friedman, 2000). However, EM

7   sensors that do not measure permittivity directly or that employ modifications such as rod

8   coatings require additional soil-dependent permittivity calibrations due to their non-linear output.

9   For end users the investment in time and resources to generate new soil-specific calibrations can

10   be unappealing and difficult. Numerous references addressing the permittivity – θ_v relationship

11   and related factors affecting this relationship have been identified (Ferre et al., 1996;

12   Heimovaara et al., 1996; Hilhorst, 1998; Jones et al., 2002; Or and Wraith, 1999; Robinson et al.,

13   2003a; Topp et al., 1980). We will focus our presentation on characterization and calibration of

14   sensors used for permittivity determination, avoiding further discussion regarding water content

15   determination.

16   **Sensor Permittivity Calibration**

17   **Travel-time measurement:** Permittivity can be derived from measurement of the travel

18   time of an EM signal propagating along a transmission line embedded in a medium. The

19   propagation velocity (v_p) of the signal transmitted by the sensing system is a function of the EM

20   properties of the medium according to:

21
$$v_p = \frac{c}{\sqrt{\varepsilon\mu}}$$
                                                                              [1]

1   where c is the speed of light in free space ($3 \cdot 10^8$ m s^{-1}), and ε and μ are the dielectric permittivity

2   and magnetic permeability of the medium relative to free space. Most soil are non-magnetic, thus

3   μ is equal to one and ε determines v_p. We distinguish between the apparent sensor determined

4   permittivity, K_a, and the permittivity of the medium of interest, ε. By rearranging Eq. [1] we

5   solve for ε, which is assumed equal to K_a in soil that do not exhibit dielectric loss (i.e. lossless

6   media). In Eq. [1] $v_p = L_e / t$ where t is travel time in the sample [s], and L_e is the electrical length

7   of the probe (i.e. length of conductor 'seen' by the EM signal).

8   Travel time sensing systems require accurate determination of L_e, which should be

9   calibrated with de-ionized water and air because these two media bound the entire soil

10   permittivity range (e.g., $2 < K_a < 60$) in which measurements will take place. For travel time

11   sensors this can be accomplished using the method of Heimovaara (1993) and Robinson et al.

12   (2003b). This method involves deriving a signal travel time correction factor (t_0), accounting for

13   signal travel in the sensor head, and L_e from measurements in air and water. The following pair

14   of equations (Robinson et al., 2003b) is solved for the unknown t_0 and L_e values:

15

16
$$t_p = t_0 + t_s = t_0 + L_e \sqrt{\varepsilon_{air}} / c \qquad\qquad [2]$$

17
$$t_p = t_0 + t_s = t_0 + L_e \sqrt{\varepsilon_{fw}} / c \qquad\qquad [3]$$

18

19   where t_p is the total travel time [s] of the signal and is a combination of t_0 and travel time in the

20   sample (t_s), ε_{air} is 1 for air permittivity and ε_{fw} is temperature dependent free water permittivity

21   calculated by the following equation (Weast, 1986):

22

1
$$\varepsilon_{fw}(T) = 78.54[1 - 4.579 \times 10^{-3}(T - 25) + 1.19 \times 10^{-5}(T - 25)^2 - 2.8 \times 10^{-8}(T - 25)^3] \qquad [4]$$

2

3 where T is temperature measured in °C. Subsequent K_a measurements are made by rearranging

4 Eq. [2] to solve for K_a (replacing ε_{air}) of the medium being measured and using the determined

5 electrical length and measured travel time ($t_s = t_p - t_0$) in the sample according to the following

6 (Heimovaara and Bouten, 1990):

7
$$K_a = \left[\frac{t_s c}{2 L_e}\right]^2 \qquad [5]$$

8

9 Here the 2 accounts for a 'reflection' measurement as in time domain reflectometry (TDR), and

10 is omitted for one-way travel measurements used in time domain transmissometry (TDT). For

11 consideration of the effect of dielectric loss Robinson et al. (2003a) suggested the following

12 relation:

13
$$K_a = \frac{\mu\varepsilon'}{2}\left(1 + \sqrt{1 + \left\{\left[\varepsilon''_{rel} + \left(\frac{\sigma_{dc}}{2\pi f \varepsilon_0}\right)\right]/\varepsilon'\right\}^2}\right) \qquad [6]$$

14 where ε' is the relative real part of the permittivity, ε''_{rel} is the imaginary part of the permittivity

15 caused by relaxation losses, σ_{dc} is the dc frequency electrical conductivity [S m^{-1}], f is frequency

16 [Hz] and ε_0 is the permittivity of free space (8.854·10^{-12} F m^{-1}).

17   **Other sensors:** Theoretically, for impedance or capacitance sensors permittivity is

18 derived from measurement of the impedance (Z) of the probe embedded in a medium (Campbell,

19 1990):

20
$$Z = \cotanh \frac{\left(2\pi f L_e \sqrt{\varepsilon\mu}\right)}{c} j \qquad [7]$$

1   or the capacitance (*C*) of a circuit which uses the medium surrounding the probe as the dielectric

2   material (Kelleners et al., 2005):

3    $$C = g \cdot \varepsilon \cdot \varepsilon_0 \qquad\qquad\qquad [8]$$

4   where $j = (-1)^{1/2}$, *g* is a geometric factor [m] associated with probe configuration and the other

5   variables are as described. Generally, impedance and capacitance sensors measure oscillation

6   frequency or frequency shift, which is related to signal resistance, impedance and capacitance.

7   For this type of sensor, measurement output should be correlated with independently measured

8   permittivity owing to the output response varying and being sensor-dependent. Additional effects

9   on permittivity determination include salinity and temperature. These effects would not be

10   evident when performing soil-specific water content calibrations unless σ_b and temperature were

11   included in the measurement.

12   **Frequency-dependence of permittivity determination**

13   Recent research has focused on frequency-dependent permittivity determinations (e.g.,

14   using network analyzer) for greater information retrieval and improved θ_v determination (Hook

15   et al., 2004; Huisman et al., 2004; Logsdon and Laird, 2004; Starr et al., 2000). High end

16   instruments such as network- or impedance-analyzers can be used to accurately determine

17   frequency-dependent complex permittivity of homogeneous systems such as liquids and

18   powders. Dielectric probes having geometries that allow high frequency signal passage interface

19   with network analyzers to measure intrinsic electrical properties of these materials and relate

20   them to complex permittivity and loss tangent. However, the instruments are expensive, have

21   limited measurement frequency ranges and often require precision probe geometries for

22   permittivity determinations. The need for frequency-dependent permittivity determinations is

23   illustrated in Figure 1 using bentonite clay, quartz sand and talc at different water contents. The

1   wet bentonite clay exhibits strong dielectric relaxation revealed in the large change in

2   permittivity as a function of network analyzer measured frequency. This relaxation is related to a

3   reduction in the apparent energy storage capacity of the system as sources of this energy storage

4   such as molecular rotation and ion migration (e.g., Maxwell-Wagner effect) are unable to

5   respond to the faster cycling of the electrical field, resulting in reduced permittivity at higher

6   frequency. Very little relaxation is exhibited by most dry materials and even by some wet

7   materials with low surface area such as the sand and talc. This suggests that sensors measuring at

8   different frequencies in dispersive porous media may predict vastly different θ_v assuming a

9   standard calibration equation relating permittivity to θ_v (Topp et al., 1980).

10   There are a number of factors which also influence the bulk permittivity determination

11   that are worthy of consideration. The geometry and spacing of the electrodes along which the

12   signal travels in the medium dictate the resulting electric field from which the permittivity

13   determination is derived. Sensor design including probe geometry can have a significant impact

14   on the permittivity determination (Pettinellia et al., 2002). Other effects include the influence of

15   temperature and electrical conductivity on both the medium's permittivity and on the sensor

16   output.

17   **Temperature dependence of permittivity determination**

18   Temperature effects arise both from the temperature dependence of the medium (e.g.,

19   water, soil etc.) and from the temperature-dependent response of the sensor itself. The

20   temperature effect on sensor performance can be characterized and potentially included in

21   calibrations to account for soil temperature fluctuations. These effects can be significant under

22   field conditions where daily diurnal temperatures fluctuate significantly with maximum changes

23   occurring near the surface and decreasing with depth. These effects should ideally be separated

1   but the physical connection between conductors and sensor circuitry in many instances makes

2   this a difficult task. Information on sensor measurement accuracy and effective measurement

3   frequency coupled with the frequency-dependence of the medium being measured add to the

4   difficulty of separating these two temperature effects.

5   **Soil-Specific Factors Affecting Permittivity Determination**

6   In many cases, poor sensor performance can be attributed to a sensor's inability to

7   provide a unique permittivity - θ_v relationship response (e.g., salinity or temperature changes

8   modify this relationship or cause measurement frequency shifts) in soils that are often also

9   poorly correlated to Topp et al.'s (1980) K_a - θ_v relation, which many users assume as a default

10   calibration. Properties of the soil such as surface area, particle shape and constituent

11   configuration (layering) (Jones and Friedman, 2000; Jones and Or, 2002; Robinson and

12   Friedman, 2001; Robinson et al., 2002) contribute to permittivity determination errors and

13   ultimately erroneous θ_v determination. Electrical conductivity of the soil solution can modify the

14   permittivity, especially when measured at frequencies in the tens of Megahertz range or less, due

15   to Maxwell-Wagner effects associated with charge migration and build up at interfaces (Hilhorst,

16   1998). These effects can be amplified or even disguised by changes in temperature due to the

17   temperature dependence of electrical conductivity and to the permittivity of the various forms of

18   water (Or and Wraith, 1999). These confounding effects associated with soil, including gaps

19   around sensor rods and other heterogeneities, should ideally be avoided when evaluating the

20   sensor performance. Ultimately, the quality of EM sensor $\theta_v(K_a)$ predictions is largely dependent

21   on the sensor's ability to accurately determine water content (based on permittivity) and this

22   ability should be quantified using a standard approach for the benefit of users.

1   The objectives of this research were to i) develop a methodology for evaluating EM

2   sensor measurement attributes based on sensor-specific characteristics (e.g., frequency-and

3   temperature-dependence) and targeted soil properties (i.e., related to losses) and ii) suggest

4   standards for evaluation of sensor measurement performance. Four specific measurement

5   conditions are suggested to be representative of most soils addressing the frequency band where

6   many EM sensors operate and including effects of electrical conductivity, which when large

7   enough can completely attenuate the measurement signal. The four target conditions created

8   from dielectric liquids with the following designations are proposed: 1) NR-NC for non-relaxing

9   and non-conducting (e.g., sandy soil) conditions would provide unambiguous testing of sensors

10   where permittivity is independent of frequency, 2) R-NC for dielectrically relaxing and non-

11   electrically conducting conditions (e.g., low conductivity clayey and organic soils) to evaluate

12   effects of dielectric relaxation on permittivity determination, 3) NR-C for dielectrically non-

13   relaxing and electrically conducting conditions (e.g., saline sand) for evaluating effects of

14   electrical conductivity on permittivity determination, and 4) R-C for dielectrically relaxing and

15   electrically conducting conditions (e.g., many fine-textured soils) for evaluating these combined

16   effects which are commonly found in natural soils.

17

18   **THEORETICAL AND EXPERIMENTAL CONSIDERATIONS**

19   **Measurement and modeling of frequency-dependent permittivity**

20   Frequency-dependent permittivities can be determined using network or impedance

21   analyzers (e.g., Hewlett Packard, Beaverton, OR, model 8752C) and dielectric probes (e.g.,

22   Hewlett Packard, Beaverton, OR, model 85070B). Temperature-dependent permittivities of

1   liquids may be measured in a non-metallic (e.g., glass) container surrounded by a circulating

2   water-filled radiator where temperature of the circulating water is adjustable.

3   For dielectrics exhibiting relaxation within the effective measurement frequency of the

4   sensor, the Cole and Cole (1941) model describes the real and imaginary permittivity response of

5   fluids with permanent electric dipole moments (Sihvola, 1999). The Cole-Cole model can be

6   fitted to the frequency-dependent permittivity data obtained with a network analyzer, providing

7   complex permittivity parameters describing liquids and some porous materials. Fitting

8   algorithms are common in mathematical software and in spreadsheets using optimization of

9   model parameters (Weerts et al., 2001; Wraith and Or, 1998). The Cole-Cole model (Hasted,

10   1973; Heimovaara et al., 1994) can also be used to describe frequency-dependent real (ε') and

11   imaginary components (ε'') of permittivity from the complex expression:

12

$$\varepsilon^* = \left[\varepsilon_\infty + \frac{(\varepsilon_s - \varepsilon_\infty)}{1 + \left(\dfrac{j \cdot f}{f_{rel}} \right)^{1-\alpha}} \right] + \frac{j \cdot \sigma_{dc}}{2\pi \cdot f \cdot \varepsilon_0} \qquad [9]$$

14

15   where ε_s is the static permittivity, ε_∞ is the infinite (i.e. high frequency) permittivity, f is

16   frequency [Hz], f_{rel} is the relaxation frequency [Hz], and α is a parameter that corresponds to the

17   dispersion in the relaxation frequency range. Permittivity is described as a complex number

18   containing both real and imaginary parts. The real component (ε') of complex permittivity (ε^*) is

19   dependent on dielectric material energy storage, and the imaginary component (ε'') of complex

20   permittivity is dependent on energy loss arising from electrical conductivity and heat dissipation

21   arising from dielectric relaxation phenomena (Robinson et al., 2003a):

1
$$\varepsilon^* = \varepsilon' - j\varepsilon'' = \varepsilon' - j\left(\varepsilon''_{rel} + \frac{\sigma_{dc}}{2\pi f \varepsilon_0}\right)$$
[10]

2   where the term in parenthesis is the combined imaginary component (ε''). The permittivity

3   estimated by EM sensors, K_a, is some combination of ε' and ε'', the magnitude of each being

4   dependent upon the sensor circuit design. Figure 1b illustrates network analyzer measured ε' and

5   ε'' in bentonite clay at 30 percent volumetric water content and modeled ε^*, ε' and ε'' results. In

6   this case the imaginary losses (ε''_{rel} and σ_{dc}) are significant. For lossless media (ε'' negligible),

7   we assume K_a approximates ε'. For this condition, the Cole-Cole model is fit to measured

8   network analyzer data in order to facilitate determination of what we refer to as the maximum

9   passable frequency, f_{max}. The modeling reduces noise in the network analyzer measurements and

10   describes these data as a continuous function. The determination of f_{max} is achieved by

11   correlating the frequency associated with the intersection of K_a on the ε' curve described by the

12   Cole-Cole model, described in the following.

13   **Maximum passable frequency (f_{max}) determination**

14   Evaluation of sensor permittivity determination performance is based on the dielectrically

15   relaxing or electrically conducting conditions described in the introduction. Determining sensor

16   effective measurement frequency is critical to understanding and characterizing the permittivity

17   determination performance, especially in frequency-dependent dielectrics. For the non-relaxing

18   and non-conducting condition (i.e., $K_a = \varepsilon'$), the effective measurement frequency for TDR has

19   been suggested to correspond to the intersection of the TDR measured K_a and the network

20   analyzer measured real permittivity ($\varepsilon'(f)$) as illustrated in Figure 2 (Or and Rasmussen, 1999;

21   Robinson et al., 2003a). Robinson et al. (2003a) termed this the maximum passable frequency

1   (f_{max}) related to the highest 'unfiltered' frequency being reflected back to the TDR. This

2   approach is only applicable to non-relaxing media because relaxation effects tend to shift the

3   effective frequency to reduced values associated more with the signal group velocity (Robinson

4   et al., 2005). For travel-time measurements (TDR, TDT), the mean maximum passable frequency

5   can be derived from averaging multiple determinations of f_{max} in non-relaxing, non-conducting

6   liquids of varied permittivity. The coefficient of variation of f_{max} is the standard deviation divided

7   by the average frequency.

8   **Test conditions**

9   Sensor evaluation criteria are related to the four soil-related effects discussed previously,

10   that are associated with relaxation and electrical conductivity. Liquids that were evaluated and

11   tested are listed under each of the four conditions shown here:

12   **NR-NC.** 2-Isopropoxyethanol (99%, Aldrich Chemical, St. Louis, MO) and de-ionized water

13   solutions can be used to ascertain sensor performance in NR-NC media. The solutions are

14   prepared by measuring the desired volumes of each liquid and thoroughly mixing them together

15   before permittivity determinations are conducted (frequent mixing is required to avoid

16   separation). For further detail concerning the described solutions the reader is referred to Kaatze

17   et al. (1996).

18   **NR-C.** Sodium Chloride (100%) was mixed with different solutions listed in Table 1 to

19   generate electrically conductive mixtures, both non-relaxing and relaxing. The amounts were

20   varied depending on the solution where lower dielectric solutions exhibited reduced NaCl

21   solubility. Periodic mixing was found to be important to assure spatially uniform concentrations.

22   For the NR-C condition, 2-isopropoxyethanol and de-ionized water solutions and pure de-ionized

23   water were mixed with NaCl according to Table 2. Linear regression was used to obtain the

1	following two equations describing the amount of NaCl required to obtain solution electrical

2	conductivity, σ_b, (Orion conductivity meter model 150A and Conductivity Cell 013005D) in a

3	60% 2-isopropoxyethanol:water solution

4	$$\sigma_b = 0.260 \cdot C_{NaCl} + 0.00327, \; r^2 = 1.00,$$	[11]

5	and in de-ionized water

6	$$\sigma_b = 1.71 \cdot C_{NaCl} + 0.00385, \; r^2 = 0.999,$$	[12]

7	where C_{NaCl} is grams of sodium chloride in 1 Liter of solution.

8	**R-NC.** Network analyzer measured and Cole-Cole modeled permittivities were derived for

9	Glycerol (100%, Mallinckrodt Baker Inc., Paris, KY), Brasso® (Reckitt Brenckiser Inc., Wayne,

10	NJ), 1-propanol (Class 1B, HPCL grade, Fisher Scientific, Fair Lawn, NJ), castor oil

11	(Cumberland Swan, Smyrna, TN) and Carbowax (Polyethylene Glycol 300) (Dow Chemical

12	Company, Midland, MI), which were initially selected as candidate liquids to ascertain sensor

13	performance in R-NC media.

14	**R-C.** A number of the relaxing fluids (i.e., Glycerol, 1-propanol) and mixtures containing

15	suspended solids (Brasso®) were evaluated by attempting to dissolve NaCl for increased

16	electrical conductivity up to 2 dS m^{-1} to obtain an R-C system. Clay suspensions have potential

17	to provide both relaxing and conductive conditions, but obtaining a standard reference would be

18	questionable, and suspensions tend to exhibit multiple relaxation phenomena including Maxwell-

19	Wagner effects which show relaxation at relatively low frequencies (e.g., 1 MHz, (Dudley et al.,

20	2003; Ishida et al., 2000)).

21	**Temperature variation**

22	Using controlled fluid temperature and knowing or measuring (with network analyzer) the

23	temperature dependence of the fluid permittivity allows examination of the sensor's temperature

1   dependence. Temperature-dependent Cole-Cole (1941) parameters (ε_s) were fit to network

2   analyzer measurements in two permittivity ranges. Permittivity values near 80 (water) and 40 (a

3   0.6 volume fraction mixture of 2-isopropoxyethanol in water) were chosen to represent two

4   upper values found in solution and in soil, respectively. Using these reference permittivity

5   determinations in non-relaxing solutions, the static permittivity is taken as reference against

6   which sensor measured permittivities are compared.

7
8   **Modeling Sensor Sampling Volume**

9   The sample volume in which the electromagnetic energy is most dense will contribute the

10   greatest weight to the permittivity determination (Ferre et al., 1998). Knight (1992) related the

11   EM energy storage density distribution surrounding TDR Probes to the sampling volume in a

12   homogeneous isotropic dielectric medium. The EM energy storage density distribution can be

13   calculated using finite difference modeling to infer the sampling volume and measurement

14   weighting of a given sensor. The Arbitrary Transmission Line Calculator (ATLC) (Kirkby, 1996)

15   is a computer software program that employs a finite difference approach to calculate

16   characteristic impedances of prescribed geometries assumed to function as transmission lines

17   (Kirkby, 2003). ATLC uses transmission line theory to calculate EM parameters (i.e. EM energy

18   density, electric field intensity, and voltage distributions based on conductor geometry) from the

19   impedance data. Robinson et al. (2003a) described the theoretical basis for relating the porous

20   medium sample permittivity to the electric potential (ϕ), electric field intensity ($\nabla\phi$) and energy

21   storage density (($\nabla\phi)^2$). The computation of energy storage density for a coaxial cell geometry of

22   radius r, includes the electric charge per unit length, Q, and permittivity of material in the cell, ε.

23
$$\left(\nabla\phi\right)^2 = \left(\frac{Q}{2\pi \cdot \varepsilon \cdot r}\right)^2 \qquad\qquad [13]$$

1   The binary ATLC output data was normalized and converted to numerical output using a

2   Matlab® function (Humphries, 2004). The function also calculates the cross-sectional area

3   within a specified minimum EM energy density contour (i.e., the sample area that contains all the

4   EM energy density values within the specified minimum value). The mean and standard

5   deviation $(\nabla\phi)^2$ values within the specified minimum area are also computed. The sampling

6   volume is calculated by multiplying the cross-sectional area within the specified area by the

7   physical probe length. Technically, the sampling volume should include the volume beyond the

8   end of the probes that influences the measurement, but owing to the difficulties inherent in

9   determining the distance that the signal reaches beyond the probe's end, the physical length is

10   used. The coefficient of variation (*CV*) within the specified area is calculated by dividing the

11    $(\nabla\phi)^2$ standard deviation by the mean.

12   **RESULTS**

13   **Network Analyzer Measured Permittivity of Reference Fluids**

14   For generation of permittivity standards between those of water and air, the 2-

15   isopropoxyethanol:water mixture used by Kaatze et al. (1996) provides fluids with a wide

16   permittivity range between 10 and 80 whose relaxation occurs at frequencies greater than 1 GHz.

17   (Debye, 1929) or Cole-Cole (1941) model parameters describing isopropoxyethanol (Kaatze et

18   al., 1996) and other liquids (Bao et al., 1996; Friel and Or, 1999) are available in the literature

19   where access to a network analyzer is unavailable. We used a dozen different 2-

20   isopropoxyethanol:water fluid combinations for network analyzer measurements and fit the

21   Cole-Cole model to these data generating the parameters listed in Table 1. Other liquids were

22   examined relative to their reduced relaxation frequency, which was targeted to lie between 1 and

23   1000 MHz, with permittivities between 5 and 40. Table 1 also lists the Cole-Cole model

1   parameters fit to these measured data with lower relaxation liquids, including glycerol, Brasso®,

2   1-propanol, 300C Carbowax and caster oil.

3   **Non-relaxing – non-conducting condition (NR-NC)**

4   A comparison of our Cole-Cole fitted static permittivities for the 'non-relaxing and non-

5   conducting' 2-isopropoxyethanol:water mixture and those of Kaatze et al. (1996) are plotted in

6   Figure 3, given as a function of volume fraction of 2-isopropoxyethanol, X_{iso}. A second order

7   polynomial equation was fit as a function of X_{iso} to the static permittivities given in Table 1 (24.2

8   $\pm 0.5\ {}^{o}C$).

9                    $$\varepsilon_s = -13.8 \cdot X_{iso}{}^2 - 51.9 \cdot X_{iso} + 77.9 \quad \text{RMSE=0.698}$$ [14]

10

11 The relaxation occurring beyond 1 GHz in the 2-isopropoxyethanol:water mixture is illustrated

12 in Figure 4a and b showing Cole-Cole modeled real and imaginary permittivities as a function of

13 frequency. The relaxation frequency migrates gradually from that of water at around 18 GHz to

14 pure 2-isopropoxyethanol with a relaxation frequency of around 3 GHz. These mixtures provide

15 reliable lossless frequency-dependent permittivity data for calibration and probe characterization

16 between 1 and 1000 MHz. Neither of these liquids show significant dielectric relaxation below a

17 frequency of $\approx$ 2 GHz, which is the approximate upper frequency limit of many transmission line

18 EM sensors. While the frequency range of a sensor can be characterized (e.g., Heimovaara

19 (1994) reported a Tektronix TDR frequency band between 20 kHz and 1.5 GHz) it is much more

20 difficult to characterize the effective measurement frequency range which can vary with

21 dielectric. The difference between the network analyzer ε' at the sensor's average maximum

22 passable frequency and the sensor measured K_a value represents the residual permittivity of the

1   sensor. If several measurements are made over a given permittivity range as suggested here, then

2   the residual permittivity values can be used to calculate the root mean squared error (RMSE) as

3   follows:

4   $$RMSE = \sqrt{\frac{1}{n}\sum_{1}^{n}(m_r - m_s)^2}$$ [15]

5   where n is the number of measurements, m_r is the reference permittivity determination (i.e.,

6   network analyzer) and m_s is the sensor permittivity determination. The RMSE value indicates

7   the total deviation from the network analyzer, which serves as the permittivity reference. The

8   NR-NC solution is the proposed condition for manufacturer testing and calibration of EM sensor

9   batch variability. Drawbacks of the use of volatile fluids include the potential for permittivity

10 variation over time from evaporative loss of fluid mass, and the potential for alcohols to absorb

11 water, with a resulting increase in permittivity.

12 **Relaxing – non-conducting condition (R-NC)**

13 Standards for probe characterization using R-NC conditions were considered using a

14 number of different liquids in which effects of relaxation are observed. As with the

15 measurements in NR-NC media, a RMSE value can be calculated for the sensor measurements in

16 R-NC media where again, the network analyzer measurements are used as the reference. Where

17 dielectric relaxation occurs within the sensor measurement range, it tends to reduce the effective

18 measurement frequency for broadband sensors as illustrated in Figure 2 (Robinson et al., 2005).

19 This frequency shift is also tied to the impedance mismatch that results from changes in the

20 permittivity of the dielectric medium reduced by relaxation. The dielectric relaxation provides

21 greater contrast for estimating the approximate effective measurement frequency from network

22 analyzer data than do NR-NC liquids. This condition is further restricted to cases where the

1 sensor-measured permittivity lies within the frequency-dependent permittivity range of the

2 network analyzer or other reference being used.

3 Relaxation peaks may be useful for emphasizing relaxation loss effects within a given

4 sensor's frequency response or to mimic a soil's relaxation. For example the relaxation exhibited

5 by Glycerol occurs in the 100 MHz frequency range that is common to some EM sensors (Figure

6 4c and d). Relaxations of Brasso and Carbowax (i.e., polyethyleneglycol) are spread over a wider

7 frequency band than the pure molecular liquids due to their having suspended solids and long-

8 chain molecular structure of varied length, respectively. For standardized testing and

9 repeatability, we recommend pure molecular liquids (glycerol, 1-propanol) rather than liquids

10 that often vary among manufacturers and from lot to lot in composition and purity (Brasso,

11 polyethyleneglycols, oils).

12 **Non-relaxing –conducting condition (NR-C)**

13 Measurements in NR-C media can be made in de-ionized water and in mixtures of 2-

14 isopropoxyethanol and de-ionized water with increasing amounts of salt added to increase

15 electrical conductivity. De-ionized water and mixtures of 2-isopropoxyethanol and de-ionized

16 water were used because neither shows significant dielectric relaxation below ≈ 1 GHz, and

17 significant amounts of salt can be dissolved in both. The same solution covering a range of

18 electrical conductivity values should be used in order to ascertain the effects of electrical

19 conductivity on the permittivity determination. The electrical conductivity range evaluated

20 should equal a known range or determine the range of the sensor being considered if unknown.

21 The amount of salt (e.g., NaCl) required for approximating these electrical conductivities is listed

22 in Table 2 for the two solutions described. It should be noted that other volume fractions of de-

23 ionized water and 2-isopropoxyethanol could be used, but as the permittivity of the solution gets

1 lower it becomes more difficult to dissolve the desired amount of salt (i.e., six times more NaCl

2 for a solution with one half the permittivity).

3   The Cole-Cole model (Eq. [9]) describes real and imaginary permittivities of non-

4 conducting solutions and in theory small additions of ions to a solution have little effect on the

5 permittivity within the range of σ_b typical of non-saline and even moderately saline conditions.

6 However, at extremely high electrical conductivity ion presence has a marked effect on ε'

7 (Hasted, 1973). In our measurements of conducting solutions only minor differences in ε' were

8 noted among network analyzer measurements in different levels of conductivity, but substantial

9 differences in ε" were observed at lower frequencies for increasing σ_w (Figure 5). Because of the

10 difficulty in relating measurements of ε' and ε" to sensor determination of K_a, we did not fit

11 Cole-Cole model parameters to conducting solutions nor use network analyzer measurements of

12 complex permittivity as a reference for NR-C conditions. The modest range of electrical

13 conductivities where EM sensors operate (i.e., $0 - 2$ dS m^{-1}) can lead to substantial changes in

14 sensor measured permittivity and are worthy of consideration and characterization. We propose

15 to use each sensor's measurement in solution at 0.0 dS m^{-1} as the reference from which to track

16 effects of conductivity on sensor measurements followed by estimation of the RMSE for NR-C

17 media.

Relaxing – conducting condition (R-C)

18

19   Probably the most common test condition relative to natural soils is one where an element

20 of relaxation and electrical conductivity is present as in clay soils. Unfortunately, this condition

21 is also the most difficult to generate using liquids. As stated previously, the solubility of salts in

22 dielectric liquids is proportional to the magnitude of permittivity. Upper bounds on solution

23 electrical conductivity are limited by the reduced solubility in the lowest dielectric fluid. For the

1   NR-C condition using 0.6 - 2-isopropoxyethanol:water mixture where ε_s = 40.0, the low

2   solubility of the 2-isopropoxyethanol limited the maximum value of electrical conductivity.

3   Attempts were made to synthesize a relaxing and conducting medium via dissolving NaCl in the

4   R-NC solutions described above. Each attempt failed due to the inability to dissolve a significant

5   amount of NaCl. For Brasso® and 1-propanol the failure was likely due to the low static

6   permittivity values (28.0 and 22.8, respectively) of the solutions. Using 10 percent water and 1-

7   propanol, a maximum electrical conductivity of only 0.25 dS m^{-1} was obtained. For glycerol and

8   10 percent water, the maximum electrical conductivity reached was 0.35 dS m^{-1}. This failure

9   underscores the difficulty of obtaining an R-C system providing electrical conductivities

10   sufficient to test sensor performance (i.e., σ_{dc} > 0.5 dS m^{-1}). We anticipate there are other liquids

11   not tested here that may provide a more suitable R-C system that would provide electrical

12   conductivities on the order of 2 dS m^{-1}, which we propose as a test solution in our sensor

13   evaluation and characterization protocol.

14   **Temperature**

15   Temperature-dependent standards provide a reference for comparing sensor-related

16   temperature effects and potentially calibrating against these effects for the case where sensors

17   measure temperature. The two proposed NR-NC liquids, water and a mixture of water and 2-

18   isopropoxyethanol, both exhibit well-defined ε(T) relationships (Figure 6). The 0.6 2-

19   isopropoxyethanol:water mixture is described by the linear equation, ε(T) = -0.083T + 41.765

20   (R^2 = 0.999). Complete immersion of sensors in liquid and adequate time for sensor electronics

21   to come to temperature equilibrium is required. By varying liquid temperature using an external

22   heating/cooling source or circulating water bath, the effects of temperature on sensor

1   performance and potential corrections for instrument offset should lead to improved permittivity

2   determination.

3   **Modeling probe sampling volume**

4   The method for determining probe sampling volume using the ALTC program and

5   Matlab code was described previously. For the example shown in Figure 7a, the dielectric of the

6   background was set to a value of 1 and the simulation was rerun using a background of 10,

7   yielding the same distribution of the field regardless of the background permittivity value for the

8   homogeneous case. For a layered background with permittivity contrast, the resulting field varies

9   depending on the contrast (Ferre et al., 1998; Ferre et al., 2001; Robinson et al., 2003a). In

10   Figure 7b, the horizontal layering case is shown consisting of a background permittivity above

11   the conductors of 10 and a value of 1 below. This order-of-magnitude contrast results in greater

12   field penetration within the higher permittivity region which significantly modifies the electric

13   field density and therefore the probe sampling volume.

14   Evaluations of sampling volume should focus on the homogeneous background case for

15   consistency. The cross-sectional area of the region multiplied by the probe length yields the

16   approximate sampling volume of the probe (i.e., volume containing 90% of the maximum EM

17   energy used here). The coefficient of variation of the EM energy density (CV_ρ) values within this

18   area provides a statistic indicating the uniformity of the EM energy density distribution within

19   the approximated sampling area and volume. Probe geometries exhibiting lower CV_ρ values

20   theoretically provide a more uniform weighting or representative measure of the average

21   permittivity (water content) within the sampling volume.

22

23

1 **CONCLUSIONS**

2 Electromagnetic sensor evaluation and characterization criteria have been developed for

3 the purpose of giving users and manufacturers a much needed standard approach for comparison,

4 testing and calibration. The primary consideration should be specification of or determination of

5 the sensor effective measurement frequency, which is not always specified or readily

6 determinable. The effective measurement frequency is a key factor in permittivity determination

7 due to the frequency-dependence of many dielectrics (e.g., soil) and this frequency can shift

8 when using broadband EM sensors, especially where losses due to dielectric and conductive loss

9 mechanisms cause filtering of higher frequencies. Sensor permittivity determination comparisons

10 based on network analyzer referenced permittivity spectra provide a standard for determination

11 of effective sensor measurement frequency (i.e., maximum passable frequency for travel-time-

12 based sensors). Even without a network analyzer, Cole-Cole model parameters, presented here

13 and elsewhere, describe the complex fluid dielectric character and can be used for sensor

14 calibration and evaluation. Other sensor evaluation criteria include examining effects of

15 dielectric relaxation within or outside of the sensor's effective measurement frequency as well as

16 electrically conducting and non-conducting conditions. The lossless conditions, non-relaxing

17 (NR) and non-conducting (NC), are useful for evaluating the sensor's permittivity determination

18 range capability as well as permittivity determination calibration. The relaxing (R) and

19 conducting (C) conditions (i.e., R-NC, NR-C and R-C) apply to measurements in soil exhibiting

20 dielectric or electrically conductive losses and a combination thereof. These effects are perhaps

21 the most important to consider given the difficulties of determining water content in clayey and

22 saline soils. Effects of temperature on sensor measurement performance can also be evaluated

23 using dielectric liquids of known permittivity described here. The influence of sensor conductor

1   geometry relative to permittivity determination sampling volume can be modeled using the

2   ATLC program or other EM modeling software. In this study no suitable combination of

3   relaxing and sufficiently conducting ($\sigma_{dc} > 0.35$ dS m^{-1}) solution was found due to lower salt

4   solubility associated with a reduced dielectric constant. Application of these performance criteria

5   are presented in a companion paper by (Blonquist et al., 2005).

6   **ACKNOWLEDGEMENTS**

14

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1 **Table 1.** Cole-Cole parameters (Eq. (9) fitted to network analyzer measurements in non-relaxing

2 mixtures of 2-isopropoxyethanol:water and in relaxing dielectric liquids shown. Model

3 parameters are ε_s, the static permittivity; ε_∞, the high frequency permittivity; f_{rel}, the relaxation

4 frequency [Hz]; σ_b, the bulk electrical conductivity [S m^{-1}]; ε_0, the permittivity of free space

5 ($8.854 \cdot 10^{-12}$ F m^{-1}) and α is a parameter ranging from 0 to 1 that corresponds to the dispersion in

6 the relaxation frequency range.

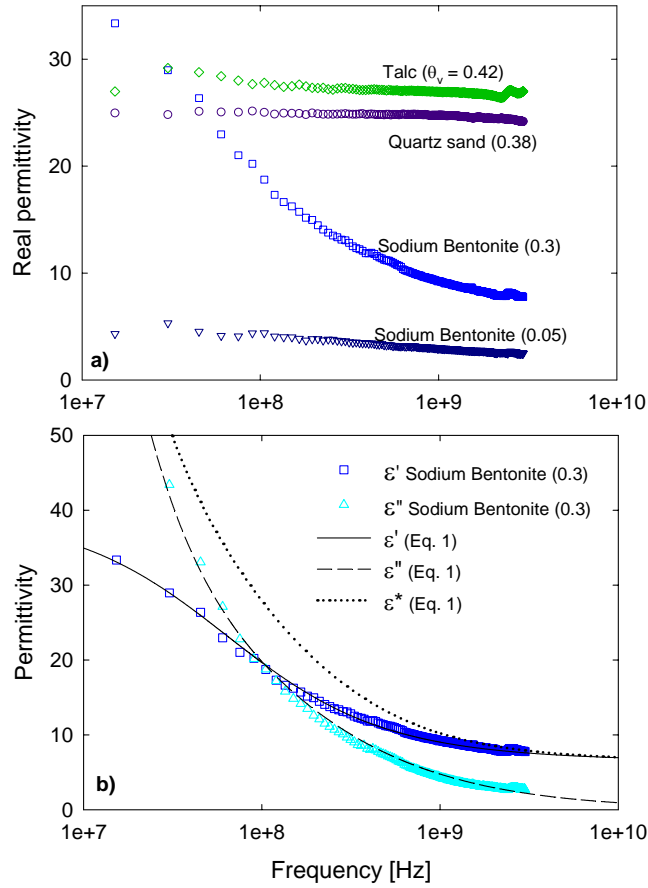|	$\varepsilon_s^{\S}$	ε_∞	σ_b [dS m^{-1}]	f_{rel} [GHz]	α	RMSE (ε')	RMSE (ε'')
Non-relaxing							
1.000*	12.70	3.50	0.00	3.25	0.12	0.142	0.163
0.920	17.65	3.50	0.00	2.87	0.11	0.115	0.183
0.855	23.70	3.50	0.00	2.89	0.10	0.240	0.189
0.800	28.00	3.50	0.00	3.03	0.10	0.213	0.146
0.760	30.50	3.50	0.00	3.12	0.10	0.112	0.170
0.727	32.00	3.50	0.00	3.28	0.10	0.142	0.180
0.680	36.35	3.60	0.00	3.70	0.08	0.0972	0.155
0.580	43.50	3.60	0.00	4.55	0.08	0.260	0.178
0.430	53.15	3.60	0.00	6.12	0.06	0.179	0.263
0.290	62.75	3.60	0.00	8.38	0.05	0.215	0.179
0.150	68.15	3.60	0.00	12.7	0.03	0.275	0.249
di-water	78.50	4.50	0.00	18.7	0.00	0.0842	0.184
0.600†	40.00	3.60	0.00	4.36	0.08	0.420	0.831
Relaxing							
Glycerol	46.50	5.25	0.00	0.127	0.20	0.257	0.416
Brasso®¶	28.00	3.00	0.00	0.0354	0.40	0.200	0.129
1-propanol	22.75	4.25	0.00	0.475	0.04	0.258	0.489
300C Carbowax¶	16.75	3.80	0.00	1.27	0.22	0.171	0.287
Castor Oil¶	3.75	2.60	0.00	1.06	0.50	0.0859	0.299

7
8 * Denotes the volume fraction of 2-isopropoxyethanol mixed into de-ionized water.
9 † NR-NC liquid that was mixed with NaCl to generate the NR-C medium.
10 § ε_s and ε_∞ are static and high frequency permittivities, σ_b is the dc electrical conductivity [S/m], f_{rel} is the relaxation
11 frequency [Hz], and α is a relaxation width parameter.
12 ¶Not recommended as standards due to the likelihood of permittivity variation from different sources and lots.

1 **Table 2.** Mass of NaCl [g] dissolved in 1L of solution for approximate bulk electrical
2 conductivities, σ_b, [dS m^{-1}] shown.
3

Approximate σ_b	**De-ionized water**		**60% 2-iso/40% de-ionized water**	
	NaCl	Measured σ_b	NaCl	Measured σ_b
[dS m-1]	[g L-1]	[dS m-1]	[g L-1]	[dS m-1]
0	0	0.0064	0	0.0013
0.5	0.29	0.53	1.90	0.50
1	0.58	1.00	3.83	1.00
2	1.17	2.01	7.67	2.00
4	2.34	3.98	15.3	3.94

4

Figure 1. Frequency-dependent permittivities from a) network analyzer measurements of different soil minerals demonstrating mild and strong relaxation as a function of the volumetric moisture contents indicated in parenthesis, and b) real (ε'), imaginary (ε'') and complex (ε^*) permittivities fit to measured real and imaginary permittivities of Sodium Bentonite using Eq. (9). Model parameters are $\varepsilon_s = 40.0$, $\varepsilon_\infty = 6.50$, $\sigma_{dc} = 0.055$ S m^{-1}, $\alpha = 0.3$ and $f_{rel} = 6.37 \times 10^7$ Hz.
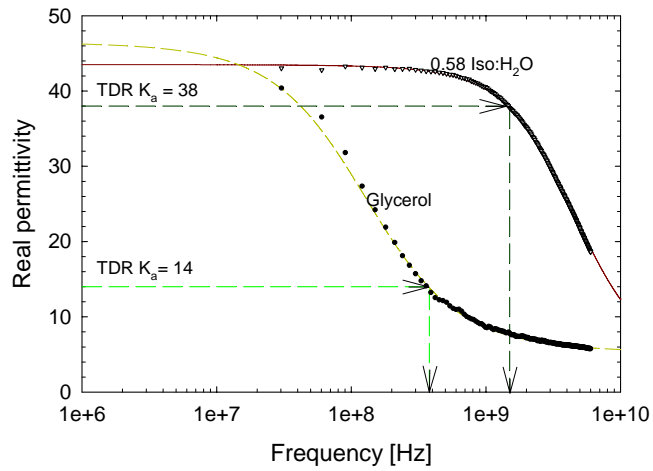
1

2   Figure 2. Example of sensor measurement frequency determination by relating TDR measured

3   permittivity (K_a) to the Cole-Cole modeled network analyzer data (symbols), yielding what is

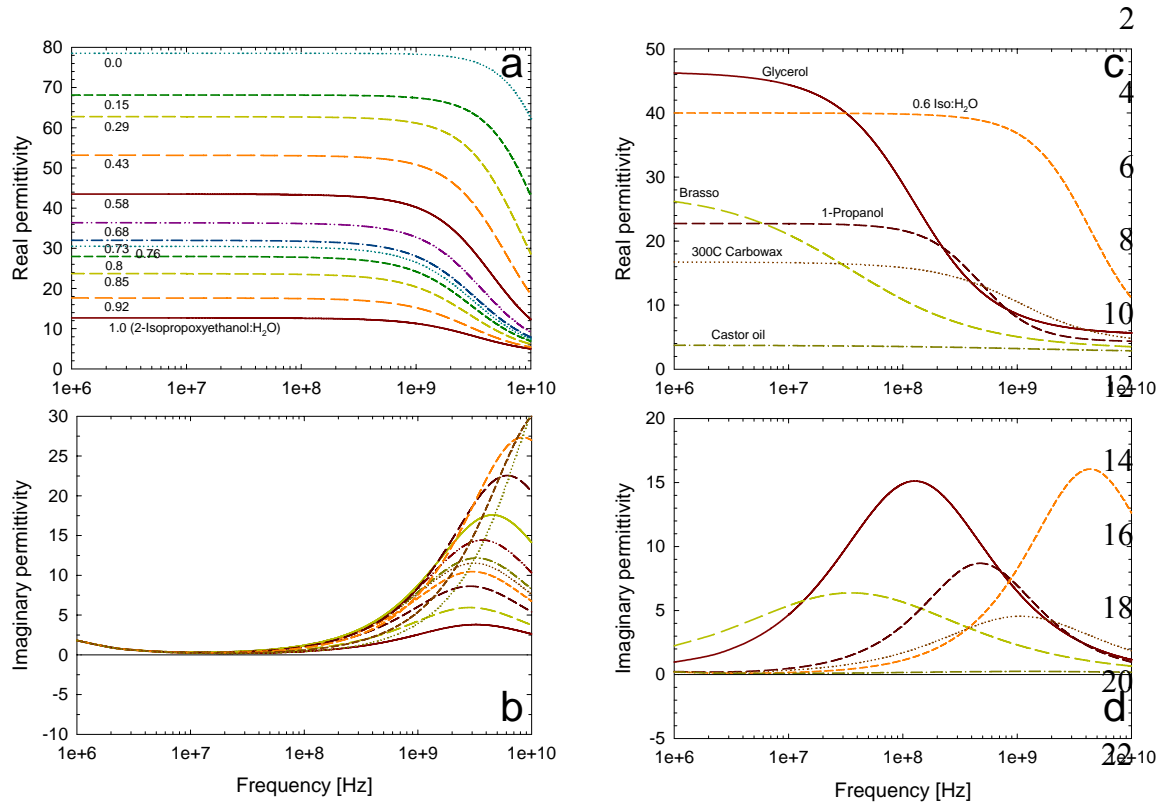4   termed the maximum passable frequency for travel-time instruments.

5
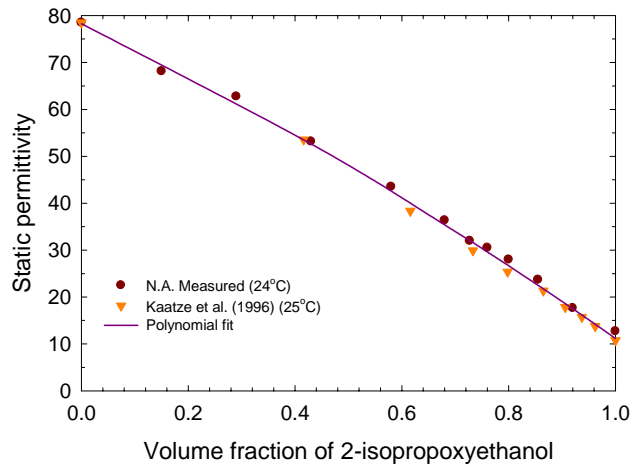
Figure 3. Measured and fitted static permittivity (obtained from ε_s in Eq. [9]) of water - 2-isopropoxyethanol mixtures as a function of volume fraction of the latter. Data from Kaatze et al, (1996) are compared with our network analyzer (NA) measurements. A polynomial equation was fit to the network analyzer (N.A. Measured) data and is presented in the text as Eq. [14].
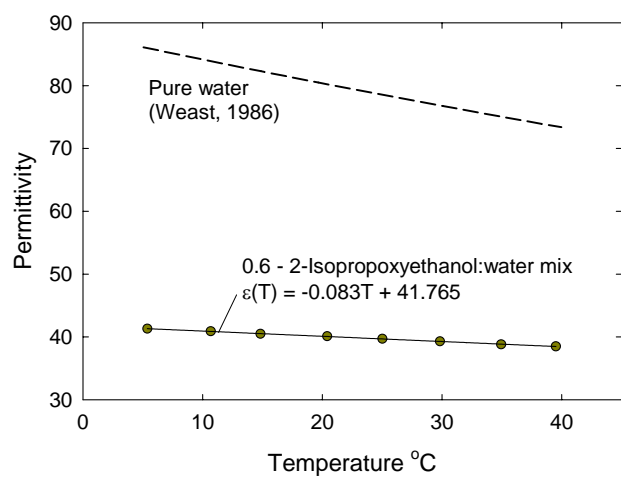
Figure 4. Modeled (eq. (9)) real and imaginary permittivities of various dielectric liquids and mixtures thereof (numbers in 'a' indicate volume fraction of 2-isopropoxyethanol:water). In a) (real) and b) (imaginary), relaxation occurs beyond 1 GHz, outside the frequency range of many EM sensors. In c) and d) relaxations occur within the MHz frequency range where EM sensors operate. The broader relaxation spectrum of 'Brasso' (polishing compound) is due to its complex liquid makeup and mixture of fine suspended solids.
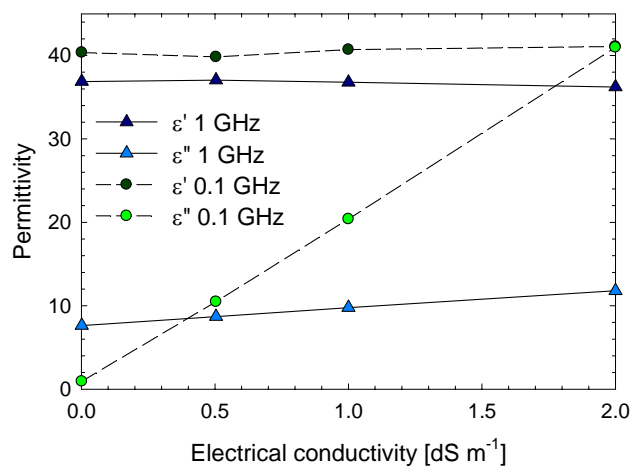
Figure 5. Network analyzer measured real and imaginary permittivities measured in a 0.6

fraction mixture of 2-Isopropoxyethanol:water as a function of solution electrical conductivity.

The effect of salinity on the imaginary component is two to three times greater at 0.1 GHz as

compared to data at 1 GHz.

The chart shows Permittivity versus Temperature °C. A dashed line labeled "Pure water (Weast, 1986)" decreases from about 86 to 73. A solid line with data points labeled "0.6 - 2-Isopropoxyethanol:water mix" with equation $\varepsilon(T) = -0.083T + 41.765$.

1

2   Figure 6. Temperature dependent permittivities of pure water and a 0.6 mixture of 2-

3   Isopropoxyethanol and water. A linear equation was fit to the measured mixture permittivities

4   shown.
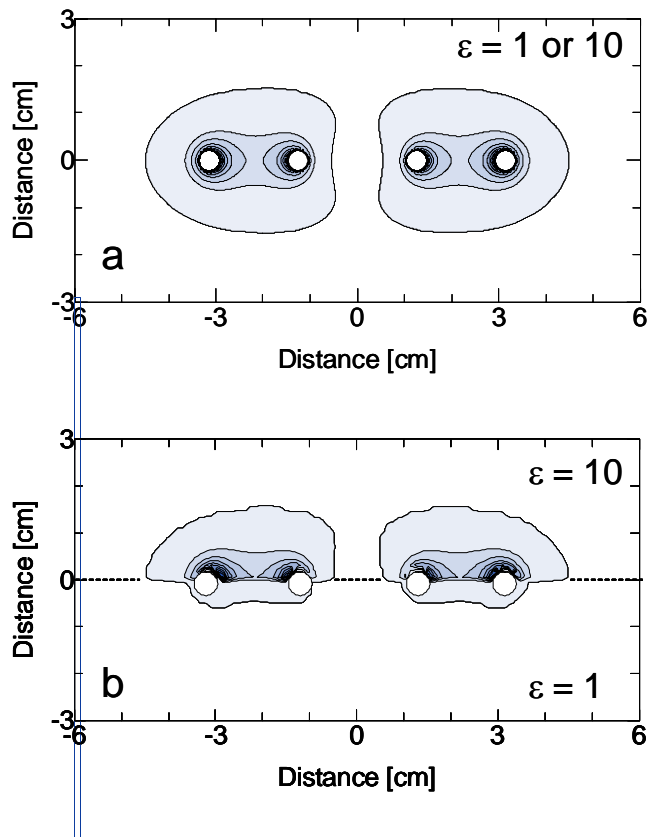
1

2   Figure 7. Cross-section of the modeled sampling area of a 2-conductor, looped TDT sensor

3   (Acclima TDT, Blonquist et al., this issue). The electromagnetic energy storage density was

4   modeled using the ATLC model of Kirkby (1996) with normalized contour lines ranging from 0

5   to 1 at increments of 0.1. The two center rods are connected and the two outer rods form a

6   separate connection. In a) the energy storage density is independent of background permittivity,

7   while in b) there is an order of magnitude difference between the background permittivity of the

8   top and bottom half of the cross-section resulting in a significantly different distribution.