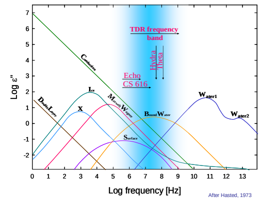
Standardizing Characterization and Calibration of Electromagnetic Sensors for Dielectric Measurement

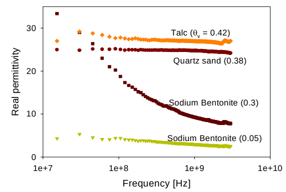
Scott B. Jones[1], J. Mark Blonquist[1], David A. Robinson[1], V. Philip Rasmussen[1] and Dani Or[2]

[1]Utah State University (scott.jones@usu.edu); [2]University of Connecticut

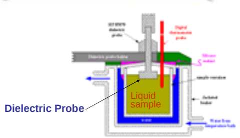
Introduction

- Performance differences in the growing number of electromagnetic (EM) sensors designed to predict soil and porous media water content from dielectric (ε) measurements, suggest a need for standardizing the characterization and calibration of sensors.
- EM sensor measurement frequencies generally lie within the MHz frequency range.
- Frequency-dependent dielectric and electrical loss factors illustrated at right influence ε measurements and are associated with a number of soil and environmental factors.
- We suggest that sensor characterization and evaluation be carried out using a homogeneous liquid dielectric rather than in the often confounding and frequency-dependent dielectric of soils and porous media.
- Our objectives were to:
  1) develop a methodology for evaluating EM sensor measurement attributes referencing sensor-specific characteristics and targeted porous medium properties,
  2) and to suggest standards for calibration and comparison of sensors.





Network Analyzer

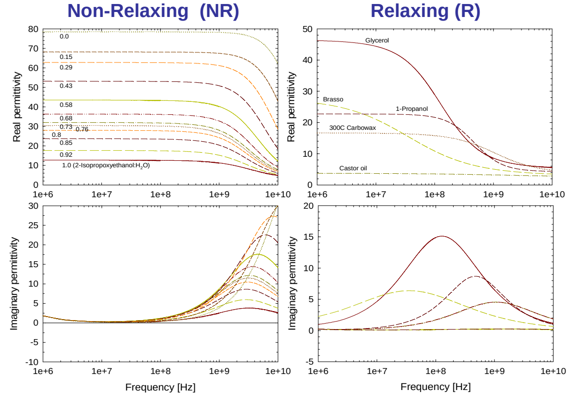


Measured and Modeled Frequency-Dependent Dielectric Reference

- The frequency-dependent dielectric of candidate reference liquids were measured using a network analyzer and dielectric probe.
- Using an HP 8572C network analyzer permittivity measurements are made in the frequency range between 10 and 6000 MHz.
- Temperature dependent liquid permittivities were obtained using a circulating water bath to change and maintain liquid temperature.
- The Cole-Cole (1941) model was used to model these network analyzer measured complex permittivities as a function of frequency.

Relaxing and Non-Relaxing Liquids

- Sensor response to dielectric relaxation is observed using fluids whose relaxation frequency lies within the typical EM sensor (MHz) frequency range.
- Mixtures of distilled water and Iso-propoxyethanol (Kaatz et al., 1996) were used as non-relaxing fluids that provided a range of dielectric values from 10 to 80.
- A number of other liquids (glycerol, brasso, propanol, Carbowax, caster oil) were evaluated, most of which showed MHz relaxation frequencies.
- Test conditions included dielectrically relaxing (R) and non-relaxing (NR) as well as electrically conductive (C) and non-conductive (NC) liquids and combinations thereof.

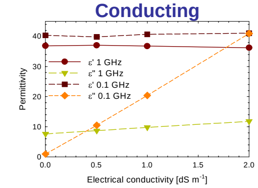


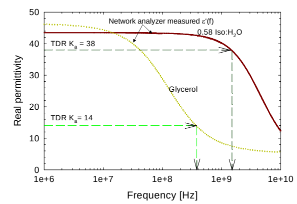
Conductive (C) and Non-Conductive (NC) Liquids

- NaCl was mixed with candidate dielectric liquids to obtain conductive mixtures to test the effects of conductivity on dielectric measurements.
- The solubility of salt is proportional to the magnitude of the fluid dielectric and only 'non-relaxing' liquids (Iso-propoxyethanol:water mixtures) with higher permittivities yielded electrical conductivities above 0.5 dS m^{-1}.

Probe Immersion

Conducting





Maximum Passable Frequency (MPF) Determination

- Travel-time analysis of reflection or transmission measurements, K_a, are a function of the 'maximum passable frequency' of the TDR or TDT device (Robinson et al., 2003).
- Intersecting K_a with Frequency-dependent network analyzer measured permittivities (Or and Rassmussen, 1999) yielded the MPF of the sensor.
- For NR-NC measurements an average MPF was determined for TDR and TDT measurements in the range 12 < K_a < 62 shown in Table 1.
- For R-NC measurements MPF varied among test media 1-propanol, Brasso and glycerol and were reduced 3 to 4 times below

Suggested Standards

- Network Analyzer is reference for ε(f).
- NR-NC media provide lossless frequency-dependent 10 < K_a < 80 measurements.
- R-NC media provide relaxing 'modified' frequency-dependent K_a measurements.
- NR-C media provide conductively lossy K_a measurements referencing K_a at 0 dS m^{-1}.
- R-C media providing EC values > 0.5 dS m^{-1} were not found among candidate liquids.
- Temperature effects are referenced to K_a(25ºC) in NR-NC liquid where ε_s = 40.

Probes Evaluated

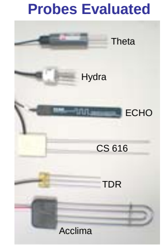


Table 1. Sensor maximum deviation from reference dielectric based on sensor measurement frequency and root mean square error (RMSE).

	Tektronix TDR	CSI TDR100	Acclima Digital TDT	CSI CS616	Hydra Probe	Theta Probe	ECH_2O Probe
MPF (MHz)	1640	1450	1230	varies	50	100	varies
NR-NC media							
Max. deviation	±1.95	±2.94	±2.76		±5.09	±1.92	
RMSE	0.0389	0.0318	0.0485		0.126	0.0809	
R-NC media							
Max. deviation	±0.206‡	±0.279‡	±0.511‡		±5.70	±3.28	
RMSE	0.0155	0.0204	0.0259		0.179	0.139	
NR-C media							
ε_s=40.0							
Max. deviation	±1.86	±2.69	±1.70	±23.7	±3.09	±9.65	±111
RMSE	0.0302	0.0393	0.0270	0.300	0.0544	0.167	1.62
Temperature							
ε_s=40.0 at 25°C							
Max. deviation	±1.47	±2.56	±1.75	±3.73	±9.91	±1.98	±3.88
RMSE	0.0246	0.0375	0.0309	0.0526	0.110	0.0323	0.0606
ΣRMSE	0.1092	0.1290	0.1323	0.3526	0.4694	0.4192	1.6806

† ε_s values were determined with the temperature dependent water permittivity equation given in Weast (1986).
‡ Maximum passable frequency reduced by relaxation losses.

Summary and Conclusions

- Evaluation and characterization criteria presented here provide users and manufacturers a standardized and quantifiable approach for comparison, testing and calibration of electromagnetic sensors.
- Standards include Network Analyzer frequency-dependent dielectric measurements in fluids exhibiting or not exhibiting sources of loss from combinations of dielectric relaxation (R, NR) and from electrical conductivity (C, NC).
- Temperature effects on sensor performance can also be well characterized using non-relaxing and non-conductive fluids.
- This methodology was applied to 7 sensors showing improved performance of higher measurement frequency sensors, which exhibit reduced error (lower RMSE) for the standards used in this study (Blonquist et al., 2005, in review in VZJ).

Acknowledgements

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