International Journal of Classified Research Techniques & Advances (IJCRTA)
Multidisciplinary Peer-Reviewed Online Open Access Journal Impact Factor: 5.455
Volume 3, Issue 2, April-June 2023 ID: IJCRTA000072 ISSN: 2583-1801
Email: ijcrta@gmail.com Website: www.ijcrta.org

A Review: Methods of Calculation of Dielectric Properties

Amit L. Shinde[*1], Sarthak V. Khedekar[*2], Satish B. Kamble[*3], Rahul B. Bhakte[*4]

Author Affiliation:
[*1]Department of Physics, J.E.S. College Jalna, Maharashtra, India.
[*2]Department of Physics, J.E.S. College Jalna, Maharashtra, India.
[*3]Department of Chemistry, J.E.S. College Jalna, Maharashtra, India.
[*4]Department of Chemistry, Shri. Madhavrao Patilcollege, Murum (M.S.), India.

Citation of Article: Shinde A, L., Khandekar, S, V., Kamble S, B., & Bhakte R, B (2023). A Review: Methods of Calculation of Dielectric Properties International Journal of Classified Research Techniques & Advances (IJCRTA) ISSN: 2583-1801, 3(2), 13-25. ijcrta.org

Abstract:

Radar and other electromagnetic sensors can be used to locate hidden bombs and ground mines. To function well, the sensors need adequate soil characteristics, such as how much water is in the soil. People frequently use math to estimate how much water is in the ground in order to predict how well electromagnetic sensors will function. Because there are so many different varieties to choose from, each with their unique qualities, it can be challenging to select the best model for various circumstances. This essay discusses many models and approaches for understanding how materials conduct electricity. Some of these involve creating models based on how the substance appears or on earlier findings.

Keywords: Electromagnetic sensor, Characteristics, Models, Etc.

Introduction:

There are many countries where there are dangerous land mines and explosives still lying around. Land mines and UXO on the ground are very dangerous and make the land dangerous too. So we need to clean it up to keep people safe. Lots of ways to find buried landmines and unexploded ordnance (UXO) use electrical signals. The characteristics of the material that surrounds an object we want to study are very important. It helps us see the object better by making it stand out from the surrounding material. The way a material can stop or slow down electromagnetic waves affects how those waves travel and bounce back. The way a material works when electricity passes through it depends on things like how it feels, how tightly it's packed, what kind of rocks or minerals it has, how much natural material it has, and how often the electricity is passing through. But water content is most important. In the past, people found out that changes in space and time can affect the soil system. The reason why landmines and UXOs look different is because the soil around them is different in different places and at different times. The amount of water in soil can be different in different places, even if they are very close together. This is true in many different types of environments. Variations in soil water content can affect sensor performance differently over small areas. We can guess how well a sensor will work in certain types of soil by knowing how the soil and the sensor interact. To guess how well electromagnetic sensors will work, experts often use models to guess what the ground is made of. Different models have been suggested to describe the properties of soil, but none cover all the different aspects. It can be difficult to choose the right model for every situation.

There are different ways to measure things in soil. These methods can be sorted into four groups: guessing based on what we already know (like the Cole-Cole or Debye method), measuring how much space the soil takes up, using past experience to make a guess (like the pedotransfer method), and using math to figure out an average or overall measurement. The method called effective medium approach or composite spheres model is only good for simple shapes and it's hard to use for things that have different materials mixed together. We think this way of doing things is not helpful in finding landmines and bombs, so we won't talk about it in this paper. We wrote an article that looks at different ways of predicting how well electricity flows through soil in fields. This review tries to explain the main ways people approach things. We talk about the most important leaders and papers of every method. We will talk about what each method is like, how it can be used, and its good and bad points. Lastly, we will talk about the different ways and give suggestions on how to make the current models better.

Theory:

The way electromagnetic energy affects things depends on what that thing is made of and how fast the energy is moving. The ability of a material to hold an electrical charge can differ depending on the frequency of the electrical signal. This can cause some energy to be lost due to different ways the charge moves in the material. Different types of small-scale vibrations called resonance cause relaxation. In a mixture of soil, there are different ways that the material can loosen up. This can happen because of the solid parts, the water inside the soil, or how these two things interact with each other. This picture shows different ways that make wet soil relax. There are tools that can find hidden things underground. These tools use frequencies between 0.1 and 10 GHz. They mainly look for resonance caused by bound water relaxation.

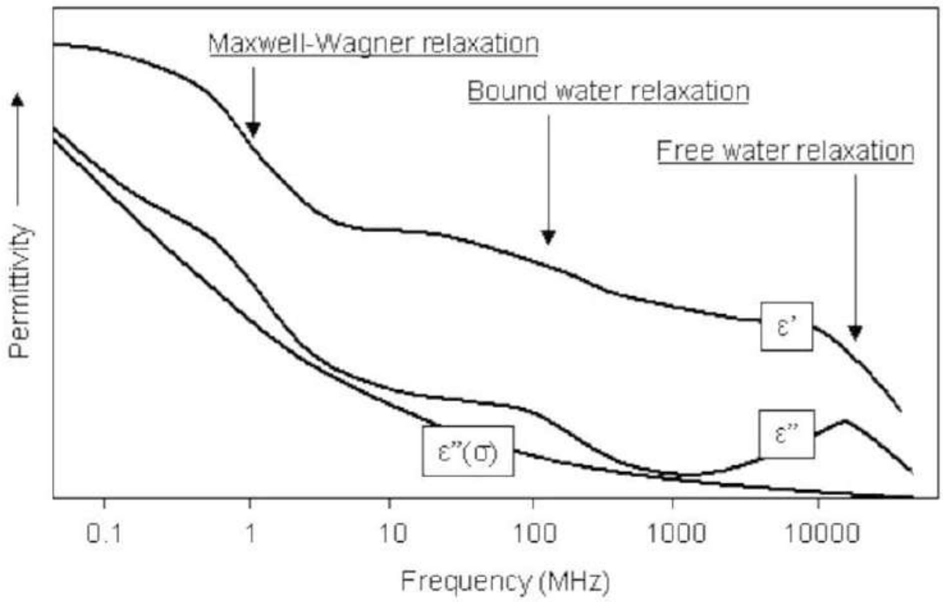

Fig. Graph showing frequency-dependent dielectric properties and major relaxation phenomena of wet soils. ε' and ε" refer to the real and imaginary parts of the relative permittivity, respectively, while ε" (σ) represents the dc conductivity.

Dielectric permittivity (ε*) is a complex function with real and imaginary components and is defined as $\varepsilon = \varepsilon' - \varepsilon'' * j$

Where j is the square root of -1.

The real part (ε') is often expressed as the relative permittivity (εr), which is the ratio of the electric-field storage capacity to that of free space11. The relative permittivity is a frequency dependent variable and decreases with increasing frequency15. The imaginary part (ε") of the dielectric permittivity is usually expressed in terms of dielectric losses, which include dispersive losses, as well as free-water relaxation and bound-water relaxation losses (Fig.). At frequencies below 1 to 1.5 GHz ε* is only weakly frequency dependent16 and dielectric losses are generally low17. However, at these low frequencies ε' and ε" are very sensitive to changes in soil water conductivity above about 10 mS/m. At frequencies below around 50 MHz ε* depends strongly on soil type. At frequencies above about 1 to 1.5 GHz the dielectric losses increase with increasing water content, even for low conductivity values. Several studies document measurements of frequency dependent dielectric soil properties (Table). The results from these measurements show that is difficult to describe the relationship between textural characteristics and the frequency dependent complex dielectric properties of soils using one single model.

Table 1. Characteristics of some studies that document measurements of frequency dependent dielectric soil properties.

Name and reference	Frequency range (GHz)	Input	# of [soils] & samples	Soil types
Wensink Knoll Heimovaara Curtis Nguyen	0.001-3 0.0001, 0.001, 0.01 0.001-0.15 0.45-26.5 1-0.75	θ V_a θ θ T_w θ θ	11 11 3 [12] 30[c] 1	Clay, Silt, Peat artificial mixtures of sand and Clay USDA[b] : SiL, LSa, SiClL USDA[b] : Sa, SaL, Si, SiCl, SiClL,Cl Sand

θ: volumetric water content, V_a: volume air fraction in soil,
T_w: soil water temperature. USDA texture classification
J.O. Curtis, personal communication.

Literature Review:

1. Phenomenological models:

Phenomenological models, like Cole-Cole and Debye, show how a material behaves at different frequencies based on how long it takes to relax. These models help to check how well materials conduct electricity at certain frequencies. The Cole-Cole relaxation model explains how things can become polarized when they are exposed to different frequencies. The complex dielectric permittivity is a measurement that describes how well a material can store electric charge.

$$\varepsilon^*(f) = \left[\varepsilon_\infty + \frac{\varepsilon_s - \varepsilon_\infty}{1 + (jf/f_{rel})^{1-\beta}}\right] - \frac{j\sigma_{dc}}{2\pi f \varepsilon_0}.$$

Where εs and ε∞ are the static value of the dielectric permittivity and the high-frequency limit of the real dielectric permittivity, respectively. For H2O εs and ε∞ equal 80 and 4.22, respectively, depending on temperature. ε_o is the dielectric permittivity of free space (8.854·10-12 F/m) 22. frel is the dielectric relaxation frequency of the material (17.1 GHz for water),

σdcis the electrical conductivity and β is an empirical parameter to describe the spread in relaxation frequencies, which increases with the complexity of the mixture. For distilled water, or other pure liquids with a single relaxation frequency, β is zero, resulting in the original Debye model. For tap water and moist sandy soils β is 0.0125 and 0.3 according to Heimovaara and Roth et al. respectively. Some other values for β are reported in literature.

According to the Cole-Cole model the complex resistivity or impedance can be expressed as,

$$R^{*}(\omega) = R_0\left\{1 - m\left(1 - \frac{1}{(1 + j\omega\tau)^{c}}\right)\right\},$$

Where R_o is the dc resistivity, m is a variable (0.1-1.0) depending on the mineral content, ω is the (radial) frequency, τ (range 10-4-104) is the time constant, and c is a variable (0.2-0.6) depending on the grain size distribution. Roth et al. report a value of 8 for τ in moist sandy soils. T values for different materials have been reported in the literature

As seen from the formulations above phenomenological models need recalibration for each specific material. Therefore, it is difficult to use these models to describe the dielectric differences between varying soil types.

2. Volumetric models:

"Volumetric models explain how much electricity can pass through different parts of soil based on what they're made of and how they react to electricity." All models need information about solid matter, pore space, and how much water is in the space. Depending on the type of model used, adding information about the amount of organic matter and bound water in the system may help to improve the accuracy of certain predictions. Normally, we don't consider how frequency affects things. The models have been calibrated, for example, by time-domain reflectometry. Over the years different volumetric mixing models have been proposed that can be grouped in different types such as Arithmetic Average, Harmonic Average, Liechtenecker-Rother, and Time-Propagation. The Complex Refractive Index (CRI) model or exponential model, which is based on the Liechtenecker-Rother model, is one of the most popular methods. The CRI model for a material with n components can be written as:

$$\varepsilon_m^{\alpha} = \sum_{i=1}^{n} v_i \varepsilon_i^{\alpha}$$

Where VI is the volume fraction of the ith soil constituent, and α is an empirical variable (0.5 according to some authorse.g. The scaling factor α gives CRI and other volumetric mixing models a semi-empirical nature. The α parameter can theoretically vary from –1 to +1 but for multiphase mixtures such as soils values between 0.4 and 0.8 have been found. Other values for α reported in the literature are 0.33, 0.46 for three-phase systems and 0.65 for four phase systems including bound water. Several attempts have been made to give a more physical basis to the scaling factor. It has been shown that the value of α also (inversely) correlates with the measurement frequency.

Another volumetric mixing model is the Maxwell-De Loor model, which assumes disc-shape inclusions with random distribution and orientation. This model has been used to describe dielectric properties of four-phase mixtures (εm) using

$$\varepsilon_m = \varepsilon_h + \sum_{i=1}^{3} \frac{v_i}{3} (\varepsilon_i - \varepsilon_h) \sum_{j=1}^{3} \left(\frac{1}{1 + A_j \varepsilon_i / \varepsilon_b - 1} \right).$$

Here, εh, εi, and εb are the dielectric permittivity of the host medium (solids), the permittivity of the inclusions, and the effective permittivity near boundaries, respectively, VI represents the volume fraction of the inclusions, and Aj refers to the depolarization ellipsoid factors. Recently, a new volumetric mixing equation based purely on the depolarization factors of different soil constituents has been introduced

This model has a strong theoretical basis and tries to overcome some problems that exist in other volumetric mixing models. In this approach the measured dielectric permittivity is related to the volume-weighted sum of the permittivities of the individual material constituents. A depolarization factor (S) is introduced to account for electric-field refractions at the material interfaces. In this mixing equation:

$$(\varepsilon - 1) = \sum_{i=1}^{n} (\varepsilon_i - 1) S_i v_i$$

Where VI is the volume fraction of the ith soil constituent, S is related to the electric field refraction in soil, which is in turn a function of the shape and surface roughness of the grains. Theoretically, the depolarization factor can be calculated for all materials but currently this is only possible for homogeneous materials with regular-shaped grains.

3. (Semi-) Empirical models:

Empirical models are mathematical descriptions of the relationship between dielectric properties and other characteristics of a medium, especially volumetric water content and texture information. There is not necessarily a physical basis for the mathematical description. Therefore, an empirical model may only be valid for the data that were used to develop the relationship. Many empirical models have originated in the field of time-domain reflectometry (TDR), and were originally used to predict the soil water content from the velocity of electromagnetic signals along TDR probes in the soil.

The classic Topp-model16 uses a third order polynomial to describe the relation between soil volumetric water content (θ) and bulk or apparent relative permittivity (Ka) for measurements taken below the relaxation frequency of water:

$$K_a = 3.03 + 9.3\theta + 146\theta^2 - 76.7\theta^3$$

The regression is an average of TDR measurements integrated over a frequency range of 1 MHz to 1 GHz for several soils and has proved very successful for a wide range of different soils and soil moisture conditions. Ledieu et al. propose a linear relationship between soil water content and Ka, which can be used to expand the Topp-model for higher water contents. The model functions especially good for frequencies around 100 MHz. At higher frequencies and moisture contents close to saturation (θ~0.4) the Topp-model over-predicts the bulk relative permittivity by up to 20%v At very low water contents the Topp-model does not perform well, especially for soils with a large clay content. There exist various empirical models similar to equation that are suitable for specific soil conditions. The bulk density has a profound effect on the relation between θ and Ka . Soils high in organic matter usually have a lower bulk density. Conversion functions have been proposed to account for the bulk density and porosity variations between organic and mineral soils. Dielectric measurements of samples high in organic matter content show that may under-predict θ by about 30%. An alternative function has been proposed to account for this effect. Clay content can have a significant effect on the relation between

The presence of aligned ellipsoidal particles, for example in bedding planes of sedimentary deposits, also has an effect on the effective permittivity. Brisco et al. present results for measurements with a field portable dielectric probe (PDP) at different frequencies ranging from 0.45 to 9.3 GHz. The measurement variability is rather large and the number of soils studied is small. As a result, the third-order polynomial functions that are presented for each frequency may contain a significant error. At frequencies below around 50 MHz the dielectric permittivity depends strongly on soil type. Based on measurements of 6 soils at 1, 5, and 50 MHz it is shown that at the lower frequencies the soil type has a strong impact on both ε' and ε" Third-order polynomial functions for the data measured at 1 MHz and 50 MHz are given. Also data are presented that show the effects of changes in volumetric water content and soil water temperature on the relationships between frequency (1-50 MHz) and ε*. Artificial Neural Networks (ANN's) provide an alternative means of determining the relationship between water content and bulk relative permittivity of soil empirically, either directly or indirectly. Using 10 samples (sand, loamy sand, sandy loam, sandy clay loam) from 5 different soils in Denmark Person et al. demonstrate that ANN's can improve the accuracy of predicting this relationship

ANN's do not produce a universal predictive model and need to be recalibrated for each new sample set. Semi-empirical models are powerful and useful hybrids between empirical models and volumetric models. These models often use a volumetric mixing model as their base and have been calibrated for a specific set of soils. The models include information of physical background of dielectric behavior. They are sometimes able to describe frequency dependent behavior, but may only be valid for the data that were used to develop the relationship. The models by Dobson and

Peplinski use input of the percentage of clay and sand in a soil, as well as the volumetric water content and bulk density to calculate the complex frequency dependent properties of field soils. The model by Hilhorst uses Debye relaxation parameters, the soil matric pressure, which is related to textural characteristics, and a semi-empirical parameter (S, see equation) to calculate the complex frequency dependent soil properties.

SUMMARY

The model chosen depends on how much detail is needed. This table shows different ways to mix materials that work as insulators. Most methods of mixing and predicting things only need a small amount of information to work. We can figure out some things about the way soil holds electricity in an area just by looking at information about the soil and weather. We can use simple models to help us do this. Semi-empirical models are like the ones made by Dobson and other researchers. Peplinski and other authors. Hilhorst can give more information on how soil properties change with different frequencies, but sometimes the information they need is not in databases. When we need more details about how water flows through soil in different areas or at different times, It is concluded that simple three- and four-phase CRI mixing models are adequate to describe mineral soils4 For organic soils (definition: http://www.soils.org/sssagloss/) only four-phase mixing models and the Maxwell-De Loor model provide good results.

Conclusion:

We looked at different ways to know more about how soil holds electricity. We divided the methods into three groups: phenomenological, volumetric, and empirical. We described the main features of each group. The models by Dobson et al. are very detailed but also simple to use. Peplinski and his/her team. Their ideas come from testing many samples of soil and using a scientific process to figure out how it changes depending on sound. This is a big problem because a lot of devices used to find things underground rely on this frequency range. We recommend taking more measurements at this frequency range. This will help us better understand how soil properties change with frequency.

Acknowledgments:

The work at New Mexico Tech has been funded by a grant from the Army Research Office (DAAD19-02-1-027). We thank Dr. Marcel Schaap of the U.S. Salinity Laboratory for several useful suggestions.

Table 2. Overview of dielectric mixing models.

Name and reference	Type[a]	Input[b]: f range (GHz)	Input[b]: Texture	Input[b]: Other	Output[b]	Calibrated for: f range (GHz)	Calibrated for: # of soils	Calibrated for: # of samples	Calibrated for: soil types[c]
Debye[27]	1	∞	-	ε_s, ε_∞, ε_0, f_{rel}	ε', ε'', σ_{eff}	∞	-	-	-
Cole-Cole[26]	1	∞	-	ε_s, ε_∞, ε_0, f_{rel}, β	ε', ε'', σ_{eff}	∞	-	-	-
Birchack 3C[37]	2	-	v_a, v_s	θ, α, ε_i	K_a	4-6	0	2	Crushed Limestone, Bentonite Clay
Wang 4C[40]	2	?	v_a, v_s	v_{fw}, v_{bw}, ε_i	ε', ε''	1.4-5	?	?	
Dobson-De Loor[39]	2	1.4-18	v_a, v_s	v_{fw}, v_{bw}, ε_i	ε', ε''	1.4-18	5	5	USDA: SaL, L, SiL, SiL, SiCl
Roth 3C[20]	2	-	v_a, v_s	T_w, θ	K_a	TDR range	10	13	USDA: SaL, ClL, L, SiL, SiCl, LSa, Peat
Bohl, 3C, 4C[42]	2	-	v_a, v_s	v_{fw}, v_{bw}, ε_i, α	K_a	TDR range	17	34	USDA: SaL, Sa, ClL, L, SiL, SaClL, SiClL, SiCl, LSa, OS[d]
Bohl-De Loor[42]	2	-	v_a, v_s	v_{fw}, v_{bw}, ε_i, α	K_a	TDR range	17	34	USDA: SaL, Sa, ClL, L, SiL, SaClL, SiClL, SiCl, LSa, OS
Hillhorst[6]	2	∞	v_i	v_i, S, ε_i	ε^*	-	-	-	
Topp classic[16]	3a	-	-	θ	K_a	0.001-1	2	4	USDA: SaL, ClL, Cl
Hallikainen[24]	3a	1.4-18 (9 incr.)	Cl, Sa	θ	ε', ε''	1.4-18	5	5	USDA: SaL, L, SiL, SiL, SiCl
Ledieu linear[45]	3a	-	-	θ	K_a	TDR range	?	?	
Brisco PDP[57]	3a	0.45, 1.25 5.3, 9.3	-	θ	K_a	0.45, 1.25, 5.3, 9.3	3	3	USDA: SaL, ClL, SiCl
Herkelrath Om[55]	3a	-	-	θ	K_a	TDR range	1	5	OS
Roth Om[52]	3a	-	-	θ	K_a	TDR range	9	18	USDA: Sa, SaL, LSa, SaClL, Cl, ClL, L, SiL, SiCl, OS
Campbell[58]	3a	0.001, 0.05	-	θ	K_a	0.001-0.05	6	6	Sand, Silt, Clay
Malicki BD[54]	3a	-	-	θ, ρ_b	K_a	TDR range	18	34	USDA: Sa, SaL, SaClL, Cl, ClL, L, SiL, SiClL, SiCl, OS
Curtis[50]	3a	0.1, 0.5, 1	-	θ	K_a	0.1-1	50-75	200-250[e]	
Persson ANN[59]	3a	-	Cl, Si, Sa	θ, ρ_b, Om	K_a	TDR range	5	10	USDA: Sa, LSa, SaL, SaClL
Dobson semi-emp[39]	3b	1.4-18	Cl, Sa	θ, ρ	ε', ε'', σ_{eff}	1.4-18	5	5	USDA: SaL, L, SiL, SiCl
Peplinski semi-emp[6]	3b	0.3-1.3	Cl, Sa	θ, ρ_b, ρ_s	ε', ε'', σ_{eff}	0.3-1.3	4	4	artificial mixtures of Sand, Silt, Clay
Hilhorst semi-emp[48]	3b	0.001-100	v_a, v_s	ε_∞, ε_w, v_{fw}, f_{rel}, p_m, S_i	ε', ε''	0.02, FD sensor and 0.01-1	7	11	USDA: SiL, SaL, Cl, SiClL, ClL, SiCl + pure Sand (1) and Clay (3)

[a]Model types refer to (1) phenomenological, (2) volumetric, (3a) empirical, and (3b) semi-empirical.

[b]Symbols mean Cl: clay %, Sa: sand %, Si: silt %, Om: organic matter %, K_a: apparent relative permittivity, ρ_b: dry bulk density, ρ_s: bulk density of solids, θ: volumetric water content, T_w: temperature of soil water, v_a: volume air fraction in soil, v_{bw}: volume bound water fraction in soil, v_{fw}: volume free water fraction in soil, v_s: volume solid fraction in soil, α: empirical variable, β: spread in relaxation frequencies, ε_i: dielectric permittivity of i[th] soil component, ε': real part of dielectric permittivity, ε'': imaginary part of dielectric permittivity, ε^*: complex dielectric permittivity, ε_s: static dielectric permittivity, ε_∞: dielectric permittivity at infinite frequency, σ_{eff}: effective dielectric conductivity, p_m: matric pressure, S_i: depolarization factor of i[th] soil component.

[c]USDA texture classification[25], Sa: sand, SaL: Sandy Loam, SaClL: Sandy Clay Loam, Cl: Clay, ClL: Clay Loam, L: Loam, SiCl: Silty Clay, SiClL: Silty Clay Loam, SiL: Silt Loam.

[d]OS: organic soil.

References:

1. Hendrickx, J.M.H., R.L. Van Dam, B. Borchers, J.O. Curtis, H.A. Lensen, and R.S. Harmon. Worldwide distribution of soil dielectric and thermal properties. In Detection and Remediation Technologies for Mines and Minelike Targets VIII. Orlando: SPIE 2003.

2. Bauters, T.W.J., T.S. Steenhuis, D.A. DiCarlo, J.L. Nieber, L.W. Dekker, C.J. Ritsema, J.Y. Parlange, and R. Haverkamp, Physics of water repellent soils. Journal of Hydrology. 231: p. 233-243, 2000.

3. Hendrickx, J.M.H., B. Borchers, J. Woolslayer, L.W. Dekker, C. Ritsema, and S. Paton. Spatial variability of dielectric properties in field soils. In Detection and Remediation Technologies for Mines and Minelike Targets VI. Orlando: SPIE 2001.

4. Wilson, D.J., A.W. Western, R.B. Grayson, A.A. Berg, M.S. Lear, M. Rodell, J.S. Famiglietti, R.A. Woods, and T.A. McMahon, Spatial distribution of soil moisture over 6 and 30 cm depth, Mahurangi river catchment, New Zealand. Journal of Hydrology. 276(1-4): p. 254-274, 2003.

5. Jackson, T.J., Effects of soil properties on microwave dielectric constants. Transportation Research Board. p. 126-131 1987.

6. Hilhorst, M.A., C. Dirksen, F.W.H. Kampers, and R.A. Feddes, New dielectric mixture equation for porous materials based on depolarization factors. Soil Science Society of America Journal. 64: p. 1581-1587, 2000.

7. Miyamoto, T., T. Annaka, and J. Chikushi, Extended dual composite sphere model for determining dielectric permittivity of andisols. Soil Science Society of America Journal. 69: p. 23-29, 2005.

8. Maxwell-Garnett, J.C., Color in metal glasses and metal films. Trans. R. Soc. London. 203(Ser. A): p. 385-420, 1904.

9. Sen, P.N., C. Scala, and M.H. Cohen, A self-similar model for sedimentary rocks with application to the dielectric constant of fused glass beads. Geophysics. 46: p. 781-795, 1981.

10. Friedman, S.P., A saturation degree-dependent composite spheres model for describing the effective dielectric constant of unsaturated porous media. Water Resources Research. 34(11): p. 2949-2961, 1998.

11. Martinez, A. and A.P. Byrnes, Modeling dielectric-constant values of geologic materials: an aid to ground penetrating radar data collection and interpretation, in Current Research in Earth Sciences. Kansas Geological Survey. p. 16 2001.

12. Nguyen, B., A.M. Geels, J. Bruining, and E.C. Slob, Calibration measurements of dielectric properties of porous media, in SPE Annual Technical Conference and Exhibition, A.C. Dubey, et al., Editors. Society of Petroleum Engineers: San Antonio, TX. p. 930-941 1997.

13. Santamarina, J.C. and M. Fam, Dielectric permittivity of soils mixed with organic and inorganic fluids (0.02 GHz to 1.30 GHz). Journal of Environmental and Engineering Geophysics. 2(1): p. 37-52, 1997.

14. Hilhorst, M.A. and C. Dirksen. Dielectric water content sensors: time domain versus frequency domain. In Time Domain Reflectometry in environmental, infrastructure and mining applications. Evanston, Illinois: United States Department of Interior Bureau of Mines 1994.

15. Powers, M.H., Modeling frequency-dependent GPR. The Leading Edge. 16(11): p. 1657-1662, 1997.
16. Topp, G.C., J.L. Davis, and A.P. Annan, Electromagnetic determination of soil water content: measurements in coaxial transmission lines. Water Resources Research. 16(3): p. 574-582, 1980.
17. Davis, J.L. and A.P. Annan, Ground-penetrating radar for high resolution mapping of soil and rock stratigraphy. Geophysical Prospecting. 37: p. 531-551, 1989.
18. Wensink, W.A., Dielectric properties of wet soils in the frequency range 1-3000 MHz. Geophysical Prospecting. 41: p. 671-696, 1993.
19. Knoll, M.D. and R. Knight. Relationships between dielectric and hydrogeologic properties of sand-clay mixtures. in 5th International Conference on Ground Penetrating Radar. Kitchener, Ontario, Canada: Waterloo Centre for Groundwater Research 1994.
20. Roth, K., R. Schulin, H. Flühler, and W. Attinger, Calibration of time domain reflectometry for water content measurement using a composite dielectric approach. Water Resources Research. 26(10): p. 2267-2273, 1990.
21. Smith-Rose, R.L., The electric properties of soil at frequencies up to 100 MHz. Proceedings Physical Society London. 47: p. 923, 1935.
22. Heimovaara, T.J., W. Bouten, and J.M. Verstraten, Frequency domain analysis of time domain reflectometry waveforms 2. A four-component complex dielectric mixing model for soils. Water Resources Research. 30(2): p. 201-209, 1994.
23. Curtis, J.O., C.A. Weiss Jr., and J.B. Everett, Effect of soil composition on complex dielectric properties. U.S. Army Corps of Engineers, Waterways Experiment Station: Vicksburg, MS. p. 59 1995.
24. Hallikainen, M.T., F.T. Ulaby, M.C. Dobson, M.A. El-Rayes, and L. Wu, Microwave dielectric behavior of wet soil - Part I: empirical models and experimental observations. IEEE Transactions on Geoscience and Remote Sensing. GE-23(1): p.
25- 34, 1985. 25. Staff, S.S., Soil taxonomy: A basic system of soil classification for making and interpreting soil surveys. SCSUSDA, U.S. Gov. Print. Office: Washington, DC 1994.
26. Cole, K.S. and R.H. Cole, Dispersion and adsorption in dielectrics! alternating current characteristics. Journal of Chemical Physics. 9: p. 341-351, 1941.
27. Debye, P., Polar Molecules. New York: Dover Publ., 1929.
28. Jones, S.B. and D. Or, Frequency domain analysis for extending time domain reflectometry water content measurement in highly saline soils. Soil Science Society of America Journal. 68: p. 1568–1577, 2004.
29. Hasted, J.B., Aqueous dielectrics. London: Chapman and Hall. 302, 1973.
30. Heimovaara, T.J., Frequency domain analysis of time domain reflectometry waveforms 1. Measurement of the complex dielectric permittivity of soils. Water Resources Research.
30(2): p. 189-199, 1994.
31. Roth, F., P. van Genderen, and M. Verhaegen. Analysis of the Influence of Mine and Soil Properties on Features extracted from GPR Data. in Detection and Remediation Technologies for Mines and Minelike Targets VI. Orlando, FL: SPIE 2001.

32. Sheriff, R.E., Encyclopedic Dictionary of Applied Geophysics. 429 ed, ed. E.F. Scherrer. Tulsa, OK: Society of Exploration Geophysicists, 2002.

33. Piggott, S.D., J.D. Redman, and A.L. Endres. Frequency dependence in the complex resistivity of Ottawa sand containing water-air and water-NAPL mixtures. in Symposium on the application of geophysics to engineering and environmental problems. Arlington, VA: Environmental and Engineering Geophysical Society 2000.

34. Iben, I.E.T., W.A. Edelstein, and P.B. Roemer, Dielectric properties of soil: application to radio frequency ground heating. General Electric Company. p. 33 1996.

35. Olhoeft, G.R. and S.S. Smith III. Automatic processing and modeling of GPR data for pavement thickness and properties. in GPR2000, 8th International Conference on Ground Penetrating Radar. Gold Coast, Australia: SPIE 2000.

36. Stillman, D.E. and G.R. Olhoeft. EM Properties of Magnetic Minerals at RADAR Frequencies. in Workshop on radar investigations. Houston, TX 2005.

37. Birchak, J.R., C.G. Gardner, J.E. Hipp, and J.M. Victor, High dielectric constant microwave probes for sensing soil moisture. Proceedings of the Institute of Electrical and Electronics Engineers. 62: p. 93-98, 1974.

38. De Loor, G.P., Dielectric properties of heterogeneous mixtures containing water. Journal of Microwave Power. 3(2): p. 67-73, 1968.

39. Dobson, M.C., F.T. Ulaby, M.T. Hallikainen, and M.A. El-Rayes, Microwave dielectric behavior of wet soil - Part II: dielectric mixing models. IEEE Transactions on Geoscience and Remote Sensing. GE-23(1): p. 35-46, 1985.

40. Wang, J.R. and T.J. Schmugge, An empirical model for the complex dielectric permittivity of soils as a function of water content. IEEE Transactions on Geoscience and Remote Sensing. GE-18: p. 288-295, 1980.

41. Tinga, W.R., W.A.G. Voss, and D.F. Blossey, Generalized approach to multiphase dielectric mixture theory. Journal of Applied Physics. 44: p. 3897-3902, 1973.

42. Bohl, H. and K. Roth. Evaluation of dielectric mixing models to describe the θ(ε)-relation. in Time Domain Reflectometry in environmental, infrastructure and mining applications. Evanston, Illinois: United States Department of Interior Bureau of Mines 1994.

43. Heimovaara, T.J., Time domain reflectometry in soil science: theoretical backgrounds, measurements and models, in Physical Geography. Universiteit van Amsterdam: Amsterdam. p. 169 1993.

44. Jacobsen, O.H. and P. Schjonning. Comparison of TDR calibration functions for soil water determination. in Time-Domain Reflectometry Applications in Soil Science, Proceedings of the Symposium. Tjele, Denmark 1995.

45. Zegelin, S.J. and I. White. Calibration of TDR for applications in mining, grains and fruit storage and handling. in Time Domain Reflectometry in environmental, infrastructure and mining applications. Evanston, Illinois: United States Department of Interior Bureau of Mines 1994.

46. Landau, E.D. and E.M. Lifshitz, Electrodynamics of continuous media. New York: Peergamon, 1960.

47. Zakri, T., J. Laurent, and M. Vauclin, Theoretical evidence for Lichteneckers mixture formulae based on the effective medium theory. J. Phys. D: Appl. Phys. 31: p. 15891594, 1998.
48. Hilhorst, M.A., Dielectric characterisation of soil. Wageningen Agricultural University: Wageningen. p. 141 1998.
49. Ledieu, J., P. De Ridder, P. De Clerck, and S. Dautrebande, A method of measuring soil moisture by timedomain reflectometry. Journal of Hydrology. 88: p. 319-328, 1986.
50. Curtis, J.O., Moisture effects on the dielectric properties of soils. IEEE transactions on geoscience and remote sensing. 39(1): p. 125-128, 2001.
51. Dirksen, C. and S. Dasberg, Improved calibration of time domain reflectometry for soil water content measurements. Soil Science Society of America Journal. 57: p. 660-667, 1993.
52. Roth, C.H., M.A. Malicki, and R. Plagge, Empirical evaluation of the relationship between soil dielectric constant and volumetric water content as the basis for calibrating soil moisture measurements by TDR. Journal of Soil Science. 43: p. 1-13, 1992.
53. Curtis, J. and R. Narayanan, Effects of laboratory procedures on soil electrical property measurements. IEEE transactions on instrumentation and measurement. 47(6): p. 1474-1480, 1998.
54. Malicki, M.A., R. Plagge, and C.H. Roth, Improving the calibration of dielectric TDR soil moisture determination taking into account the solid soil. European Journal of Soil Science. 47: p. 357-366, 1996.
55. Herkelrath, W.N., S.P. Hamburg, and F. Murphy, Automatic, real-time monitoring of soil moisture in a remote field area with time domain reflectometry. Water Resources Research. 27(5): p. 857-864, 1991.
56. Jones, S.B. and S.P. Friedman, Particle shape effects on the effective permittivity of anisotropic or isotropic media consisting of aligned or randomly oriented ellipsoidal particles. Water Resources Research. 36(10): p. 2821-2833, 2000.
57. Brisco, B., T.J. Pultz, R.J. Brown, G.C. Topp, M.A. Hares, and W.D. Zebchuck, Soil moisture measurement using portable dielectric probes and time domain reflectometry. Water Resources Research. 28(5): p. 1339- 1346, 1992.
58. Campbell, J.E., Dielectric properties and influence of conductivity in soils at one to fifty megahertz. Soil Science Society of America Journal. 54: p. 332-341, 1990.
59. Persson, M., B. Sivakumar, R. Berndtsson, O.H. Jacobsen, and P. Schjønning, Predicting the dielectric constant - water relationship using artificial neural networks. Soil Science Society of America Journal. 66: p. 1424- 1429, 2002.
60. Van Dam, R.L., E.H. Van Den Berg, M.G. Schaap, L.H. Broekema, and W. Schlager, Radar reflections from sedimentary structures in the vadose zone, in Ground Penetrating Radar in Sediments, C.S. Bristow and H.M. Jol, Editors. Geological Society: London. p. 257-273, 2003.
61. Peplinski, N.R., F.T. Ulaby, and M.C. Dobson, Dielectric properties of soils in the 0.3-1.3 GHz range. IEEE Transactions on Geoscience and Remote Sensing. 33: p. 803-807, 1995.
62. Koorevaar, P., G. Menelik, and C. Dirksen, Elements of soil physics. Developments in soil science, ed. A.E. Hartemink and A. McBratney. Vol. 13: Elsevier. 242, 1983.
63. Miller, T.W., B. Borchers, J.M.H. Hendrickx, S. Hong, L.W. Dekker, and C. Ritsema. Effects of soil physical properties on GPR for landmine detection. In Fifth International Symposium on Technology and the Mine Problem 2002.