Debye Parameters of Humidity-Varying Soils for Induction Logging Techniques

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Abstract ─ This paper focuses on the tabulation of calculated Debye coefficients for a wide range of soils for source waves ranging from 300 MHz to 2 GHz. Debye coefficients of different soils will produce accurate FDTD dispersive simulations for wireline logging purposes. The FDTD dispersion analysis is based on an Auxiliary Differential Equation (ADE) method which depends on the Debye coefficients. A complex set of soil data is acquired and used in a two-step numerical solver to calculate the Debye coefficients. For a wide range of soils, Debye coefficients were developed for one, two, and three pole expansions. Most fits for one pole fits were highly inaccurate, so the coefficients generated were disregarded. Coefficients for two and three term expansions were accurate and were generated and tabulated here.

Index Terms ─ Complex media, Debye, dispersion analysis, FDTD method, induction logging, moisture content, soils.

I. INTRODUCTION

The finite-difference time-domain (FDTD) method has been proven to efficiently simulate the propagation of waves in dispersive media [1]-[4]. With the aid of the FDTD method as well as post-processing techniques, an accurate model for oil and gas exploration can be performed [1]-[2]. It is essential to consider the electrical properties of soils in FDTD simulations to ensure an accurate model of propagating waves in them is developed. Methods to determine electrical properties of soils surrounding a borehole are known as induction logging techniques. Induction logging techniques have been developed and improved in the past years and have helped to extract natural resources [5].

Soils are characterized as dispersive media, and if the electrical properties of a particular soil are known, proper analysis and simulations can be performed [6],[7]. When adapting a cylindrical model, the comparison between the results produced by the simulation and the results obtained via wireline logging can indicate pockets of natural resources. Multi-pole models have been used in FDTD formulations to adapt dispersive wave propagation. Such multi-pole models include the Cole-Cole and Debye models [8]-[9]. Due to the nature of soils, propagating waves experience a dampening force that can be best described by a linear, first order differential equation on the polarization state of the particles within the soil [10]. This differential equation gives rise to the Debye electrical permittivity model, which can be easily implemented in an FDTD algorithm. Although the Debye model is a special case of the Cole-Cole model, using a Cole-Cole model will complicate greatly a dispersive FDTD algorithm. This is in addition to it being a model that does not accurately describe the linear dampening nature that the propagating waves experience in soils. The Debye model describes the dispersion relation for waves within the soil experiencing this relaxation. Papers like [11],[12] perform permittivity fits to determine the Debye coefficients for a variety of human tissues for frequencies up to 20 GHz, since human tissues behave in a similar manner to soils [4]. Thus, a similar analysis to the one presented in [11] can be used in this paper. In induction logging applications, low frequencies are desired to extend the distance that the wave will propagate through the soil. Therefore, the focus in this paper will be on frequencies up to 2 GHz.

Given that soils are dispersive and their permittivities change as a function of frequency of the source wave, the electric field response will be different depending on the frequency content of said source wave. In the FDTD analysis, the Debye model is used to simplify the inclusion of dispersive soils by means of an auxiliary differential equation (ADE) [4]. The ADE will have an order equal to the number of desired terms in the Debye model. Since discretizing the ADE is required, keeping a low number of terms for the Debye fit will be computationally efficient. A model is adapted where the soils are dispersive and isotropic, so their electrical properties will change with frequency, but will not change as a function of the coordinate's direction at each point in the soil. The calculation of Debye coefficients can be used in any coordinate system since the assumed medium is isotropic.

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Via a 2-step numerical solver, Debye coefficients for a range of soils containing different amounts of water content are calculated and tabulated in this paper. The accuracy of the fits presented by the Debye coefficients is shown for all soil types for two and three term expansions. On a practical application, soils have a noticeable water content, so soils with a 0% moisture content were disregarded.

This paper is an extension of [7], as the method outlined in it has been improved to produce more accurate fits. Modifications on this developed method provide fits where having a higher number of poles becomes more relevant due to the higher accuracy produced.

II. BACKGROUND ON THE DEBYE MODEL

Soils change the dispersion relation of the waves propagating through them, which in turn alters their phase and group velocities. When entering soils, the dispersion model to be adapted is the Debye Model [11],[12]. This is due to how particles inside them experience a first order relaxation dampening force [10]. Much like it was performed in [11],[12], all analysis methods in this paper follow the same structure shown in them. The method adapted in this paper will also deal with the usage of attenuation values from a source wave.

We initially begin with a relaxation differential equation describing the polarization of the arranged particles within the material [13]:

$$\tau\dot{\mathbf{P}}+\mathbf{P}=\epsilon_0(\epsilon_s-\epsilon_\infty)\mathbf{E}\,, \qquad (1)$$

where τ is the relaxation time coefficient, ε_∞ is the relative permittivity at high frequencies, and ε_s is the static permittivity. In (1), the time derivative term corresponds to the polarization rate of change of the particles.

When dealing with waves entering the material, the response of the material is described by a non-linear polarization of the molecules containing different k^{th}-order susceptibility terms $\chi^{(k)}$ the form of a Taylor expansion [10]:

$$\begin{aligned}\mathbf{P}_s&=\epsilon_o\left(\chi^{(1)}\mathbf{E}+\chi^{(2)}\mathbf{E}^2+\chi^{(3)}\mathbf{E}^3+...\right)\\ \mathbf{P}_s&=\gamma^{(1)}\mathbf{P}+\gamma^{(2)}\mathbf{P}^2+\gamma^{(3)}\mathbf{P}^3+...\end{aligned} \qquad (2)$$

Similarly, the electric field will adapt an expansion form similar to that in (2). Each higher order magnitude will have an associated different magnitude and is denoted by $\gamma^{(k)}$. To solve for the polarization state **P**, each polarization term will be associated with the corresponding electric field term having the same order. Therefore, inserting (2) into (1) and transforming to frequency domain, it is seen that the solution for each higher order term adapts the same form. A weighting coefficient A_k will rise from the nature of the Taylor coefficients as well as different relaxation terms τ_k for each term. Thus, the polarization state in frequency domain is given by:

$$\mathbf{P}(\omega)=\sum_{k=1}^{\infty}\frac{A_k\epsilon_o(\epsilon_s-\epsilon_\infty)}{1+j\omega\tau_k}\eta^{(k)}\mathbf{E}^k\,. \qquad (3)$$

With the use of the auxiliary $D(\omega)$ field, one can extract the relative permittivity of the medium in frequency domain. Thus, introducing now a pole weight given by $\Delta\epsilon_k=A_k\eta^{(k)}(\epsilon_s-\epsilon_\infty)$, the Debye permittivity model is introduced as:

$$\epsilon_r(\omega)=\epsilon_\infty+\sum_{k=1}^{N}\frac{\Delta\epsilon_k}{1+j\omega\tau_k}\,. \qquad (4)$$

When being compared to a non-dispersive medium, the Debye model differs by the following terms:

- N : Number of terms in Debye model,
- ε_∞ : Permittivity at high frequencies,
- $\Delta\varepsilon_k$: Pole weight,
- τ_k : Relaxation time.

III. FORMULATION AND TABULATION OF DEBYE COEFFICIENTS

To properly tabulate the Debye coefficients for a given medium, dielectric measurements are needed. That is, one needs the real and imaginary components of the electrical permittivity of the soils as functions of frequency. These values will be used on a two-step algorithm that will generate an algebraic expression as a function of frequency for the relative permittivity. The coefficients within said algebraic expression will correspond to the Debye coefficients.

A. Formulation

For each associated frequency of an incoming source wave, a complex function of the permittivity is given by:

$$\epsilon_r(\omega)=\epsilon'-j\epsilon''\,. \qquad (5)$$

By having the set of permittivity values at each associated frequency, the MATLAB function *invfreqs* can make a rational expression for the set of permittivity values, given by:

$$\begin{aligned}\epsilon_r(j\omega)&=\frac{\sum_{k=1}^{N}b_{k-1}(j\omega)^{k-1}}{\sum_{k=1}^{N+1}a_{k-1}(j\omega)^{k-1}}\,,\\ &=\frac{b_0+b_1(j\omega)+b_2(j\omega)^2+...+b_{N-1}(j\omega)^{N-1}}{a_0+a_1(j\omega)+a_2(j\omega)^2+...+a_N(j\omega)^N}\,.\end{aligned} \qquad (6)$$

The MATLAB *residues* function will decompose (6) as a multi-pole form similar to the form of (4), resulting in:

$$\begin{aligned}\epsilon_r(j\omega)=R&+\frac{(-r_N/p_N)}{1+j\omega(-1/p_N)}+\frac{(-r_{N-1}/p_{N-1})}{1+j\omega(-1/p_{N-1})}+...\\ &+\frac{(-r_1/p_1)}{1+j\omega(-1/p_1)}\,.\end{aligned} \qquad (7)$$

The permittivity form shown in (7) will make R be ε_∞, the $-r_k/p_k$ terms be $\Delta\varepsilon_k$, and the $-1/p_k$ be the τ_k terms, when compared with (4).

B. Data processing for fitting algorithm

Electromagnetic measurements of soils are obtained from [14], where the attenuation α and relative permittivity ε' are measured for select values of frequencies. Two samples of soils are shown in Table 1.

Table 1: Electromagnetic measurements of soils at various humidity moisture contents [14]

Clay Loam 6% Moisture		
Frequency (MHz)	**Relative Dielectric Constant ε'**	**Attenuation (dB/cm) α**
300	5.667	0.283
500	5.108	0.387
1000	4.649	0.568
2000	4.151	0.761
4000	4.024	1.14
9300	3.826	2.31
Sand 8% Moisture		
Frequency (MHz)	**Relative Dielectric Constant ε'**	**Attenuation (dB/cm) α**
300	6.957	0.249
500	6.792	0.278
1000	6.708	0.335
2000	6.533	0.535
4000	6.425	1.27
9300	5.854	2.86

Within a lossy medium, there is an associated loss factor α that can be derived from Maxwell's equations [10]. This attenuation factor depends on the imaginary term of the permittivity ε'':

$$\alpha = \omega\sqrt{\frac{\mu_0\epsilon_0\epsilon'}{2}\left(\sqrt{1+\left(\frac{\epsilon''}{\epsilon'}\right)^2}-1\right)}\ , \tag{8}$$

where after some algebraic manipulations, the imaginary term of the permittivity can be evaluated as:

$$\epsilon'' = \epsilon'\sqrt{\left(\frac{2\alpha^2}{\mu_0\epsilon_0\epsilon'\omega^2}+1\right)^2-1}, \tag{9}$$

where ε' is the relative permittivity, and ω is the angular frequency. Table 1 shows how there are six data points for each associated soil. Fits were first performed using a polynomial interpolation on the data points but resulted in larger errors on 2 pole fits than 3 pole fits. This problem was no longer present when there was no interpolation performed on the original data points. The processing of the attenuation values in Table 1 made possible the creation of the frequency-dependent values described in (5). Similar fits for the remaining soil samples were produced to obtain a larger set of complex permittivity values.

C. Results and determination of Debye coefficients

A MATLAB algorithm was developed based off of the formulation described from (4)-(7). Fits were produced for one, two, and three terms for the soils used. Papers like [11] and [12] demonstrated the validity of using this range of terms for dispersive media following the Debye model. The fits shown in Figs. 1 and 2 were produced by the current algorithm for the soils shown in Table 1.

Although all data ranged from 300 MHz - 9.3 GHz, all data was trimmed and fitted for 300 MHz - 2 GHz, since it is our range of interest for the application to be developed in the FDTD algorithm.

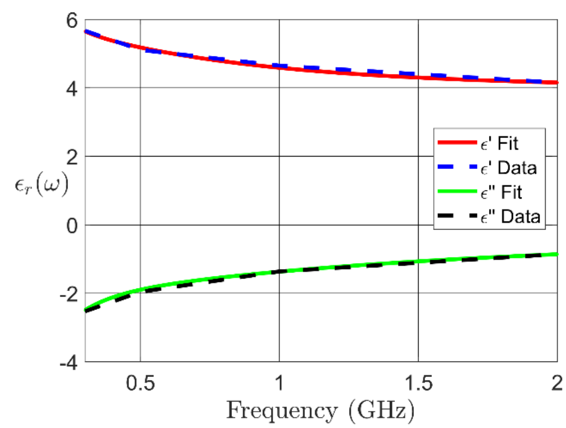

Fig. 1. 2 pole Debye fit vs. interpolated data for clay loam 6%.

Table 2: Two term Debye coefficients for clay loam 6% humidity

ε_∞	$\Delta\varepsilon_1$	$\Delta\varepsilon_2$	τ_1 (ns)	τ_2 (ns)
3.911	1.485	10.336	0.183	2.590

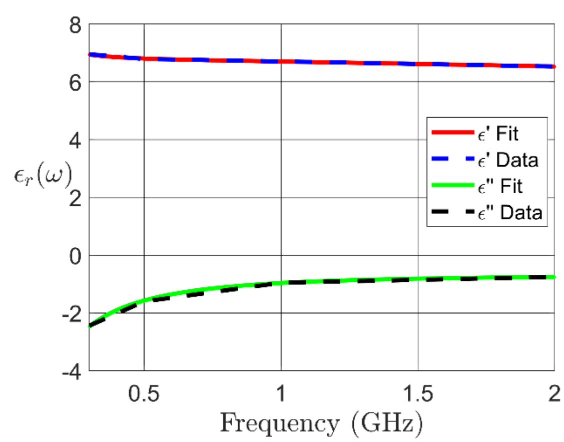

Fig. 2. 2 pole Debye fit vs. interpolated data for sand 8%.

Table 3: Two term Debye coefficients for sand 8% humidity

ε_∞	$\Delta\varepsilon_1$	$\Delta\varepsilon_2$	τ_1 (ns)	τ_2 (ns)
5.863	0.895	29.667	0.047	6.531

D. Tabulation of Debye coefficients for humidity-varying soils

The data for different types of soils was computed for one term, two terms, and three terms in the Debye expansion. Although it is desired to have fits for two poles to reduce the complexity of the ADE, it is necessary to compute fits with a higher number of poles to reduce the difference error as much as possible. Tables 4 and 5 display the computed coefficients for various soils along with their respective maximum error differences in the complex permittivity. The difference errors were computed as:

$$\%\text{ Error} = \left|\frac{\epsilon_f^{(\chi_i)} - \epsilon_d^{(\chi_i)}}{\epsilon_d^{(\chi_i)}}\right| * 100\%\,. \tag{10}$$

Where $\varepsilon_f^{(\chi i)}$ is the permittivity value from the fit points for either the real or imaginary part, and $\varepsilon_d^{(\chi i)}$ is the permittivity value from the data points for either the real or imaginary part. Here, (χ_i) denotes which part of the permittivity is used, either the real or imaginary part. One pole fits produced maximum errors of 31%, so they were disregarded.

Two pole fits produced errors ranging from 0.23% to 19%. While the latter percentage may seem troublesome, this error generated was a singularity in the entire frequency range. That is, the fit produced accurate results except at one point. To testify the accuracy of the fit, the root-mean-square error (RMSE) was calculated for all fits. For instance, the fit producing a 19% error in ε" also has an RMSE of 0.054, which is marginally low. The RMSE values obtained for all soil fits ranged from 0.008 to 0.087 in both ε' and ε", respectively, thus showing that the 2 pole fits were accurate. As expected, three pole fits produced more accurate fits, as is seen in Table 5.

Few values of Debye coefficients in both Tables 4 and 5 are large or negative. While this may seem concerning, they are acceptable parameters to use on the FDTD algorithm. Large valued Debye coefficients were also seen in [11],[12],[15].

Some fits for three pole expansions produced complex coefficients. For every complex coefficient produced, there was a complex conjugate coefficient associated. That is, from Table 5, whenever $\Delta\varepsilon_2$ and τ_2 are complex, $\Delta\varepsilon_3 = \Delta\varepsilon_3^*$ and $\tau_3 = \tau_3^*$. There is the case when this also holds true for Δε1 and $\Delta\varepsilon_2$ as well as τ_1 and τ_2. Although it may seem troublesome to have complex coefficients for the FDTD implementation, it is safe to use them because the ADE will be purely real once these coefficients are substituted in the corresponding updating equation. This is due to the linearity of the ADE produced by the Debye model and the complex conjugate pairs cancelling all imaginary components within the ADE.

IV. CONCLUSION AND FUTURE REMARKS

The Debye model is adapted to produce permittivity fits of humidity-varying soils. Adapting dielectric measurements as data to construct a set of complex permittivity values, fits were produced for the frequency range of 300 MHz - 2 GHz. Numerical fits were produced for one, two, and three poles, finding that two and three poles produced accurate fits. It was concluded that while producing a fit with a higher number of poles, there is a trade off by having a more complicated ADE to develop. A proper tabulation of the Debye coefficients for all soils encountered was produced for those seeking to use such coefficients.

Table 4: Debye fit for humidity-varying soils (2-poles fit) [300 MHz - 2 GHz]

Soil Type	ε_∞	$\Delta\varepsilon_1$	$\Delta\varepsilon_2$	τ_1 **(ns)**	τ_2 **(ns)**	**Max % Error in ε'**	**Max % Error in ε"**
Sand 1%	2.958	0.155	1.080	0.112	1.544	0.376	9.562
Sand 2%	2.915	-0.159	0.672	-0.295	0.600	0.534	11.677
Sand 4%	3.854	0.240	15.966	0.110	6.400	0.755	3.358
Sand 8%	5.863	0.895	29.667	0.047	6.531	0.227	2.831
Sandy Loam 1.5%	3.168	0.989	-0.719	0.259	-0.559	4.339	15.930
Sandy Loam 3%	3.154	0.802	-45.642	0.188	-30.193	2.572	6.393
Sandy Loam 6%	4.172	1.638	31.021	0.196	5.013	1.275	2.189
Silt Loam 2.5%	2.660	0.436	23.667	0.190	21.708	2.445	7.663
Silt Loam 5%	3.243	1.286	52.499	0.221	22.123	1.909	1.925
Clay Loam 1%	2.990	0.595	-0.262	0.352	-0.369	1.165	19.196
Clay Loam 3%	2.700	0.389	2.166	0.124	1.221	0.522	4.859
Clay Loam 6%	3.911	1.485	10.336	0.183	2.590	1.334	3.635
Clay 1%	2.683	0.301	14.247	0.162	16.212	2.108	9.735
Clay 3.5%	3.201	0.949	-3.378	0.264	-2.213	2.536	3.250
Clay 7%	4.017	3.403	230.460	0.329	113.882	7.473	16.126

Table 5: Debye fit for humidity-varying soils (3-poles fit) [300 MHz - 2 GHz]

Soil Type	ε_∞	$\Delta\varepsilon_1$	$\Delta\varepsilon_2$	$\Delta\varepsilon_3$	τ_1 **(ns)**	τ_2 **(ns)**	τ_3 **(ns)**	**Max % Error in ε'**	**Max % Error in ε"**
Sand 1%	2.963	0.119	-0.035	0.673	0.094	-0.237	0.879	0.118	0.572
Sand 2%	2.897	0.058	-0.079	1.105	0.098	-0.210	1.155	0.181	1.591
Sand 4%	3.852	0.211	-0.422	5.267	0.097	-0.947	2.401	0.574	1.596
Sand 8%	5.863	0.902	5.57+3.19i	5.57-3.19j	0.047	1.69+2.08j	1.69-2.08j	0.308	3.194
Sandy Loam 1.5%	3.226	-0.174	0.437	1.955	-0.094	0.167	1.152	0.148	1.417
Sandy Loam 3%	3.161	0.607	-0.167	1.954	0.163	-0.337	1.156	0.440	0.455
Sandy Loam 6%	4.175	4.871	2.97-5.08j	2.97+5.08j	0.292	0.56+0.45j	0.56-0.450j	2.024	7.677
Silt Loam 2.5%	2.679	-0.068	0.274	1.490	-0.149	0.155	1.116	0.196	1.274
Silt Loam 5%	3.246	1.514	1.40+0.92j	1.40-0.92j	0.239	0.32+1.31j	0.32-1.31j	4.362	4.657
Clay Loam 1%	2.977	0.133	-0.089	1.045	0.112	-0.142	0.948	0.181	1.488
Clay Loam 3%	2.677	0.227	0.669	4.060	0.075	0.390	4.377	0.291	0.601
Clay Loam 6%	3.915	6.626	-0.45-2.50j	-0.45+2.50j	0.322	0.34+0.33j	0.34-0.33j	3.048	10.252
Clay 1%	2.692	0.178	-0.064	1.074	0.116	-0.178	0.996	0.150	0.895
Clay 3.5%	3.202	1.213	0.81+0.58j	0.81-0.58j	0.294	-0.055+1.10j	-0.055-1.10j	7.010	2.661
Clay 7%	4.098	0.14 +0.22j	0.14-0.22j	8.062	0.059 +0.16j	0.059-0.16j	0.998	2.882	9.492

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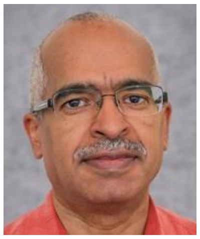

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