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Temperature and Texture Dependent Dielectric Model for Moist Soils at 1.4 GHz

Valery Mironov, Member IEEE, Yann Kerr, Senior Member IEEE, Jean-Pierre Wigneron, Senior Member IEEE, Liudmila Kosolapova, and François Demontoux

Abstract— **In this paper, a monofrequent dielectric model for moist soils taking into account dependences on the temperature and texture is proposed, in the case of electromagnetic frequency equal to 1.4 GHz. The proposed model is deduced from a more general model proposed by Mironov and Fomin (2009) that provides estimations of the complex dielectric constant (CDC) of moist soils as a function of frequency, temperature, moisture and texture of soils. The latter employs the physical laws of Debye, Clausius-Mossotii, and the law of ion conductance to calculate the CDC of water solutions in the soil. The parameters of the respective physical laws were determined by using the CDCs of moist soils measured by Curtis et al. (1995) for a wide ensemble of soil textures (clay content from 0 to 76%), moistures (from drying at 105°C to nearly saturation), temperatures (10 – 40°C), and frequencies (0.3 - 26.5 GHz). This model has standard deviations of calculated CDCs from the measured values equal to 1.9 and 1.3 for the real and imaginary parts of CDC, respectively. In the model proposed in this paper, the respective standard deviations were decreased to the values of 0.87 and 0.26. In addition, the equations to calculate the complex dielectric constant as a function of moisture, temperature, and texture were represented in a simple form of the refractive mixing dielectric model, which is commonly used in the algorithms of radiometric and radar remote sensing to retrieve moisture in the soil.**

I. INTRODUCTION

For retrieving correct soil moisture with the use of the brightness temperature measured by the SMOS at frequency of 1.4 GHz, we need such a dielectric model of moist soils which takes into account the dependence of the complex dielectric constant (CDC) of soil not only on the moisture, but also on temperature and texture. Currently, the algorithm for retrieving soil moisture from the SMOS measurements uses the dielectric model by Dobson [1], which does not account for the temperature dependence. Meanwhile, as follows from the dielectric measurements of [2]-[4], the variations of the real part of the complex dielectric constant can reach 10-15%, with temperature changing in the range from 5 to 40 °C. Except for [5], there are no published dielectric models accounting for temperature dependence at the frequency of 1.4 GHz.

The dielectric model of [5] provides for predictions of the CDC as a function of four variables, namely, wave frequency, moisture and temperature of the soil, as well as the percentage of clay in the soil texture. A physical origin of this model is based on the following. By using the GRMDM [6] and dielectric data measured at different temperatures for an individual type of the soil, there were determined the following parameters and their temperature dependences: 1) CDC of dry soil, 2) maximum fraction of bound water that can be adsorbed by soil (see [6]), 3) the parameters of dielectric relaxation spectrum by Debye, namely, the values of dielectric constant in the low and high frequency limits, time of relaxation, and 4) ohmic conductivity. At that, all the values were derived separately for bound and free water in soil. Further in [5], by using the procedure outlined in [4], [7], the formulas of physical laws by Clausiuss-Mossotii, Debye, and ion conductance were used for regression analyses of the mentioned above parameters as a function of temperature. As a result, for each individual soil, a set of thermodynamic parameters were derived, namely, 1) the volumetric expansion coefficient, 2) energy of activation, 3) entropy of activation. This procedure was applied with respect to the ensemble of soils having different clay percentage in their texture. In [5], for this purpose, the measured in [2] CDC spectra were employed. The ensemble of them covers the temperatures of

10, 20, 30, and 40ºC, contents of clay in soil texture from 0 to 0.76 cm^3/cm^3, and frequencies from 0.03 to 26.5 GHz.

Finally, the totality of parameters in the model of [5] consisted of 1) CDC of dry soil, 2) maximum fraction of bound water, 3) low and high frequency limits of dielectric constant, 4) ohmic conductivities at the temperature of 20 ºC, 5) volumetric expansion coefficients, 6) energies of activation, 7) entropies of activation, and 8) temperature coefficients of ion conductance, as derived separately for the bound and free water in the soil. In [5], all the above mentioned parameters were expressed with the use of polynomial functions as a function of clay content in soil texture. This methodology involves only an implicit consideration of soil mineralogy by a single parameter, namely the content of clay fraction in the soil texture, but within the mineralogical diversity of soils included in the dielectric data base of [2].

The model developed in such a way was validated in [5] by correlating the calculated CDCs with those measured in the whole range of moistures, clay contents, frequencies, and temperatures involved in the measurements of [2]. As shown in [5], [6], in the case of model [5], the standard deviation of calculated and measured CDCs from each other was substantially smaller then that of the model in [1].

According to [9], the dielectric model [5], due to smaller error in CDC predictions, demonstrated a substantially smaller error when modeling the brightness temperature [9], as compared with the dielectric model [1]. Currently, the model of [5] has been implemented in the prototype algorithm of the SMOS mission for remote sensing of soil moisture, and, currently, it undergoes tests in a routine mode. However, as seen from its description above, the model of [5] has a complex structure, which to a certain extent hampers its practical usage.

In this paper, the dielectric model of [5] was converted into a simple form of the refractive mixing dielectric model of moist soils, which provides for the CDC dependence on moisture, temperature and clay content in soil texture at the single frequency of 1.4 GHz. As a result, it has become convenient for practical use, simultaneously retaining the ability of model [5] to account for temperature dependence, which is a substantial advantage over the widely used models [1] and [10]. Moreover, in terms of error of the CDC predictions, it was shown that the proposed model has the same accuracy as the model [5] has.

II. THE MONOFREQUENT TEMPERATURE AND TEXTURE DEPENDENT SOIL DIELECTRIC MODEL

In accordance with the GRMDM proposed in [6], the real part of CDC, ε_s', and imaginary part of CDC, ε_s'', as a function of volumetric moisture, *W*, can be represented in the form of:

$$\varepsilon_s' = n_s^2 - \kappa_s^2, \varepsilon_s'' = 2n_s\kappa_s \tag{1}$$

$$n_s = \begin{cases} n_d + (n_b - 1)W, & W \le W_t \\ n_d + (n_b - 1)W_t + (n_u - 1)(W - W_t), & W \ge W_t \end{cases} \tag{2}$$

$$\kappa_s = \begin{cases} \kappa_d + \kappa_b W, & W \le W_t \\ \kappa_d + \kappa_b W_t + \kappa_u (W - W_t), & W \ge W_t, \end{cases} \tag{3}$$

where n_s, n_d, ,n_b, n_u, *and* κ_s, κ_d, κ_b, κ_u are the values of refractive index and normalized attenuation coefficient for moist soil, dry soil, bound soil water, and free soil water. The normalized attenuation coefficient is understood here as a proportion of the standard attenuation coefficient to the free space propagation constant. W_t is a value of the maximum bound water fraction in a given type of the soil. Using the model proposed in [5], we calculated the GRMDM parameters n_b, κ_b, n_u, κ_u at the frequency of 1.4 GHz as a function of gravimetric clay contents, C, equal to 0, 10, 20, 30, 40, 50, 60, 70 % and temperatures, T, equal to 10, 20, 30 and 40°C. Then, the calculated data were fitted as a function of clay content, with the temperatures being a parameter. For this purpose, second order polynomials $f^{(i)}=A_i(T_j)+B1_i(T_j)C+B2_i(T_j)C^2$, where used. Here, $f^{(i)}$ denotes any of the GRMDM parameters ($f^{(i)}=n_b$, n_u, κ_b, κ_u), and the subscript *i* of the polynomial coefficients takes the respective GRMDM parameter designation, that is, $i= n_b$, n_u, κ_b, κ_u. T_j is a soil temperature. The obtained values of polynomial coefficients $A_i(T_j)$, $B1_i(T_j)$, $B2_i(T_j)$ for all the GRMDM parameters were fitted as a function of temperature by using a first or second order polynomials. Parameters of W_t, n_d and κ_d were assumed to be independent of the temperature, and their dependences on clay content were taken from [5]. As a result, we came up with the following formulas for the GRMDM parameters in equations (1)-(3) as a function of clay content and temperature:

$$W_t=0.0286+0.00307C; \tag{4}$$

$$n_d=1.634-0.00539\,C+2.75\cdot10^{-5}C^2; \tag{5}$$

$$k_d=0.0395-4.038\cdot10^{-4}C; \tag{6}$$

$$n_b=(8.86+0.00321T)+(-0.0644+7.96\cdot10^{-4}T)C+(2.97\cdot10^{-4}-9.6\cdot10^{-6}T)C^2; \tag{7}$$

$$\kappa_b=(0.738-0.00903\,T+8.57\cdot10^{-5}T^2)+(-0.00215+1.47\cdot10^{-4}T)C+(7.36\cdot10^{-5}-$$

$$-1.03\cdot10^{-6}T+1.05\cdot10^{-8}\,T^2)C^2; \tag{8}$$

$$n_u=(10.3-0.0173T)+(6.5\cdot10^{-4}+8.82\cdot10^{-5}T)C+(-6.34\cdot10^{-6}-6.32\cdot10^{-7}T)C^2; \tag{9}$$

$$\kappa_u=(0.7-0.017\,T+1.78\cdot10^{-4}\,T^2)+(0.0161+7.25\cdot10^{-4}T)C+(-1.46\cdot10^{-4}-$$

$$-6.03\cdot10^{-6}T-7.87\cdot10^{-9}T^2)C^2. \tag{10}$$

The ensemble of equations (1)-(10) represents the developed dielectric model, with the input parameters being expressed in the following units: clay content, C, in %, temperature, T, in ºC, and moisture, W, in cm^3/ cm^3.

III. VALIDATION OF THE MONOFREQUENT MODEL PREDICTIONS OVER DIELECTRIC DATA

Using available in the literature [2], [10] dielectric data and the results of our own measurements of the CDCs at 1.4 GHz, we estimated relative to measured data the error of calculations of the CDCs by using the monofrequent model. In addition, we tested the deviations between the CDCs calculated with proposed model, on the one hand, and the ones obtained by using the model of [5] on the other hand. At that, we chose the soils with 1) low clay content, 2) middle clay content, and 3) maximum clay content. In order to supplement the missing in literature data, we carried out own measurements of the CDCs with the soils collected near Bordeaux and Toulouse, France. In terms of texture, the soils measured by the authors were 1) sand (0% clay, 100% sand, and the bulk density of 1.65 g/cm^3), 2) a loamy soil (17% clay, 36% sand, and the bulk density of 1.4 g/cm^3, and 3) a clay loamy soil (34% clay, 29% sand, and the bulk density of 1.3 g/cm^3). Our dielectric measurements were performed using a waveguide technique at the frequency of 1.4 GHz and the temperatures of 22°C ±1°C. The soil samples were placed in a segment of the waveguide, which served as a measuring container. The CDCs of the samples were determined using the Nicolson, Ross and Weir method (NRW) [11], [12] adapted to a rectangular waveguide.

Fig. 1 shows the measured and calculated values of real and imaginary parts of CDC as a function of volumetric moisture at room temperature (20 to 24°C) for the soils with varying clay content. The following soil types are analyzed: (a) sand (SP) light gray (C=0%), sand (SP) white (C=0%), data of [2]; Yuma sand (C=0%), data of [10]; sand (C=0%), data of own measurements; (b) clay (CH) gray (C=34%), data of [2]; clay loamy soil (C=34%), data of own measurements; (c) Miller clay (C=62%), data of [10], clay (CH) light gray (C=76%), data of [2]. As seen from the Fig. 1, the experimental data of different authors correlate well with each other and with the dielectric calculations obtained by using the model of [5] and the proposed monofrequent model. In Fig. 1, the dielectric calculations obtained by using the model of [5] and the monofrequent model are also very close to each other, so that in some cases they are graphically indistinguishable from each other.

Next, we compared with each other dependencies of CDCs on the temperature at fixed moistures, that were calculated by using the proposed monofrequent model and the model of [5], on the one hand, and the ones that were either measured by the authors or taken from [2], on the other hand. In Fig. 2 are shown at fixed moistures the CDCs as a function of temperature (5 to 40°C) for different soil types: 1) sand (SP) white (C=0%), data of [2]; 2) loamy soil (C=17%), data of own measurements; 3) sandy clay loam (C=25%),data of own measurements; and 4) clay (CH) gray (C=34%), data of [2]. As seen from the Fig. 2, the experimental data well correlated with the calculations performed by using the model of [5] or the monofrequent model. In addition, the estimates obtained by using different models deviate from each other of maximum 3%, that occurs only in the case of greater moistures, $W \geq 0.5$.

IV. ERROR ESTIMATION

To estimate an error of the proposed model we correlated the dielectric data taken from [2], [10] as well as the data measured by the authors, with the results of calculations made by using the model of [5] and the proposed model. In this correlation analysis are used only the dielectric data shown in Figs. 1 and 2. In Fig. 3 are shown the calculated CDCs of the analyzed soils as a function of respective measured CDCs. The values of correlation coefficients for the real, $R_{\varepsilon'}$, and imaginary, $R_{\varepsilon''}$, parts of CDC, alongside with their standard deviations, $SD_{\varepsilon'}$ and $SD_{\varepsilon''}$, as well as the equations of linear regression, are given below:

1) model of [5]: $R_{\varepsilon'}=0.996$, $R_{\varepsilon''}=0.993$; $SD_{\varepsilon'}=0.83$, $SD_{\varepsilon''}=0.25$; $\varepsilon'_{cal}= -0.12+0.98\varepsilon'_{meas}$, $\varepsilon''_{cal}= 0.04+0.99\,\varepsilon''_{meas}$;

2) proposed monofrequent model: $R_{\varepsilon'}=0.996$, $R_{\varepsilon''}=0.992$; $SD_{\varepsilon'}=0.87$, $SD_{\varepsilon''}=0.26$; $\varepsilon'_{cal}= -0.24+1.00\varepsilon'_{meas}$, $\varepsilon''_{cal}= 0.07+0.99\,\varepsilon''_{meas}$.

As seen from this analysis, the errors of CDC, in terms of standard deviation, obtained by using the model of [5] or monofrequent model are very close to each other. It is also worth noting that the error of calculated CDCs, relative to the measured ones, are of the same order as the error of dielectric measurements is.

V. CONCLUSION

A simple temperature and texture dependent moist soil dielectric model at the SMOS frequency of 1.4 GHz is proposed based on the model developed in [5]. The proposed model provides for predictions of the real and imaginary parts of CDC of moist soils with error of 0.83 and 0.25, respectively, in terms of their standard deviations with respect to the measured values. As was shown in [13], in the case of using the model of [5], the dielectric model error causes uncertainties in the quantitative determination of soil moisture from the SMOS data which lie in the range ±0.06 cm^3/cm^3, in terms of 95% confidence interval. As was shown in section IV, the errors of the monofrequent model and the model of [5] are equal to each other. Hence the estimate of uncertainties obtained in [13] for sounding moisture is valid for the proposed model.

Concerning the influence of the soils mineralogy, it should be stated that the dielectric data base of [2] consists of the soils containing the following minerals: quartz (from 0 to 100%), smectite clays (from 0 to 80%), K-feldspar (from 0 to 23%), dolomite (from 0 to 21%), as well as the traces of such mineral components as calcite, Na-plagioclase, mica, and cristobalite. Therefore, it is unreasonable to apply the proposed model to calculate the CDCs of the soils containing mineral components other then those comprising the data base of [2], in particular the kaolinites, sulfate hydrates, and zeolites. In addition, it should be noted that the proposed model has not been validated regarding the organic rich and saline soils.

The range of bulk density of soils, for which the proposed monofrequent model can be applied, must correspond to the density of the soils in [2]. Unfortunately, the values of bulk densities are not explicitly given in [2]. Nevertheless, they were estimated to fall in the range from 0.9 g/cm^3 to 1.65 g/cm^3, with using the relationships between the refractive index of dry soil and its bulk density, by the formulas from [14]. For this purpose, were employed the data given in [8] and [15] for refractive indexes of soils and minerals comprising soils. Finally, it should be noted that a simple and clear structure of the formulas in proposed model is its major advantage over the model of [5]. At that, the errors of both models are equal to each other.

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Captions to Figures

Fig. 1. Measured and calculated complex dielectric constant, $\varepsilon=\varepsilon'+i\varepsilon''$, for the soils with different clay content at room temperature (20°C): (a) C=0%, (b) C= 34%, and (c) C= 62 and 76%. Measured data are taken from [2, 10] and obtained by the authors (own meas). Dielectric calculations with the model of [5] and monofrequent model are given with solid and dashed lines, respectively.

Fig. 2. Measured and calculated complex dielectric constant as a function of temperature for soils with different clay content, C, and soil moisture, W: (a) C=0% , (b) C=34%, (c) C= 17% and 25%. Measured data are taken from [2] and obtained by the authors. Dielectric calculations with the model of [5] and monofrequent model are given with solid and dashed lines, respectively.

Fig. 3. Correlation of the measured real part, ε', (a) and imaginary part, ε'', (b) of complex dielectric constant (CDC) with the calculations ones obtained by using the model of [5] and monofrequent model, respectively.

Fig. 1a

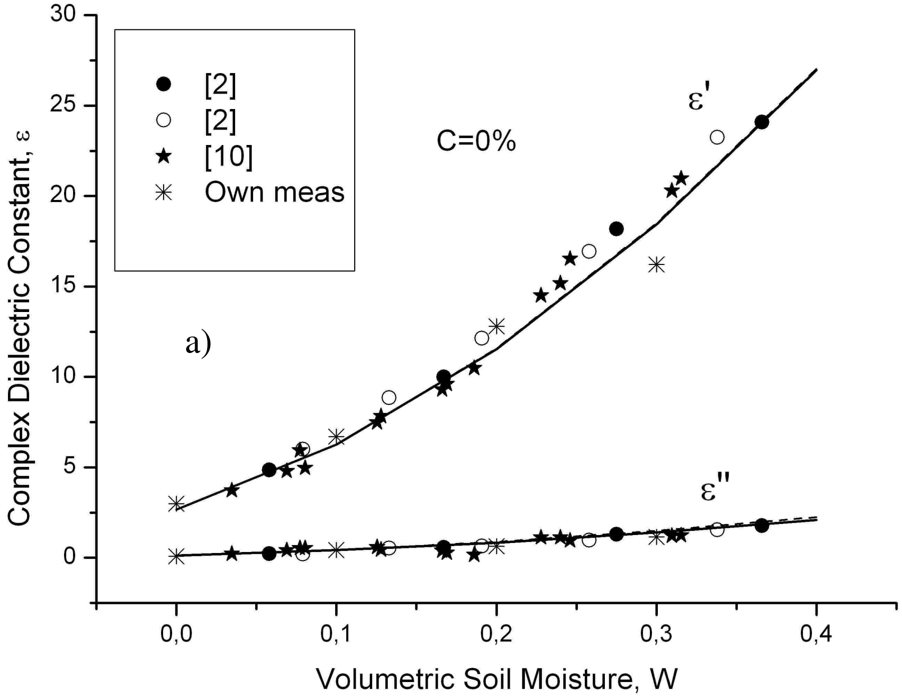

30
25
20
15
10
5
0
Complex Dielectric Constant, ε
● [2]
○ [2]
★ [10]
✳ Own meas
C=0%
a)
ε'
ε''
0,0
0,1
0,2
0,3
0,4
Volumetric Soil Moisture, W

Fig. 1b

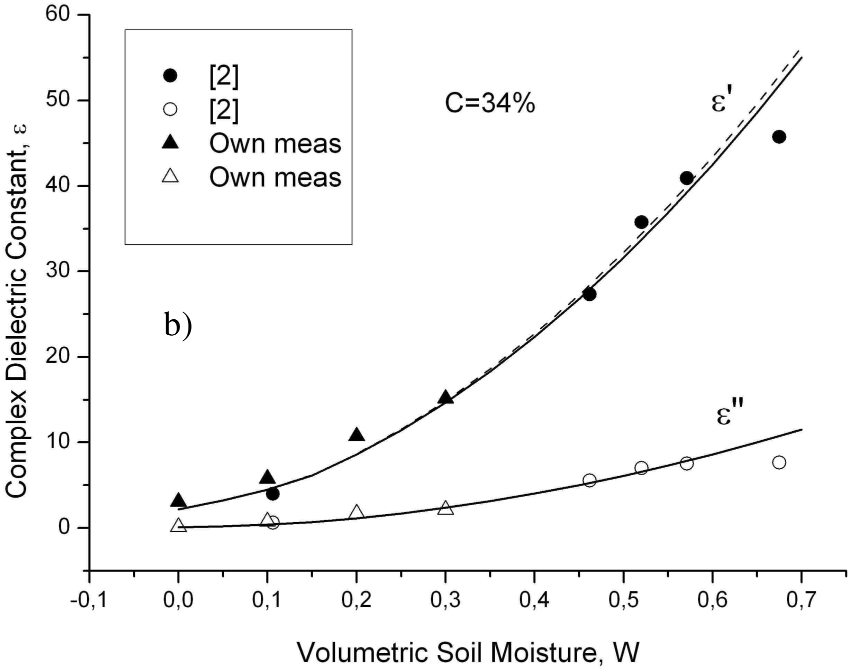

60
50
40
30
20
10
0
Complex Dielectric Constant, ε
● [2]
○ [2]
▲ Own meas
△ Own meas
C=34%
ε'
ε"
b)
-0,1
0,0
0,1
0,2
0,3
0,4
0,5
0,6
0,7
Volumetric Soil Moisture, W

Fig. 1c

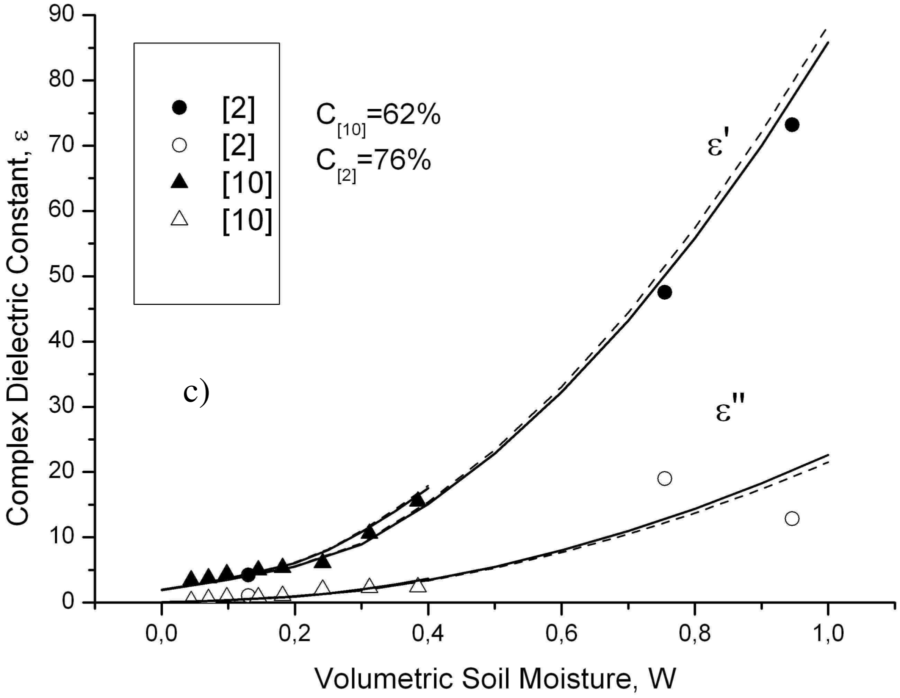

90
80
70
60
50
40
30
20
10
0
Complex Dielectric Constant, ε
● [2]
○ [2]
▲ [10]
△ [10]
$C_{[10]}$=62%
$C_{[2]}$=76%
ε'
ε''
c)
0,0
0,2
0,4
0,6
0,8
1,0
Volumetric Soil Moisture, W

Fig. 2a

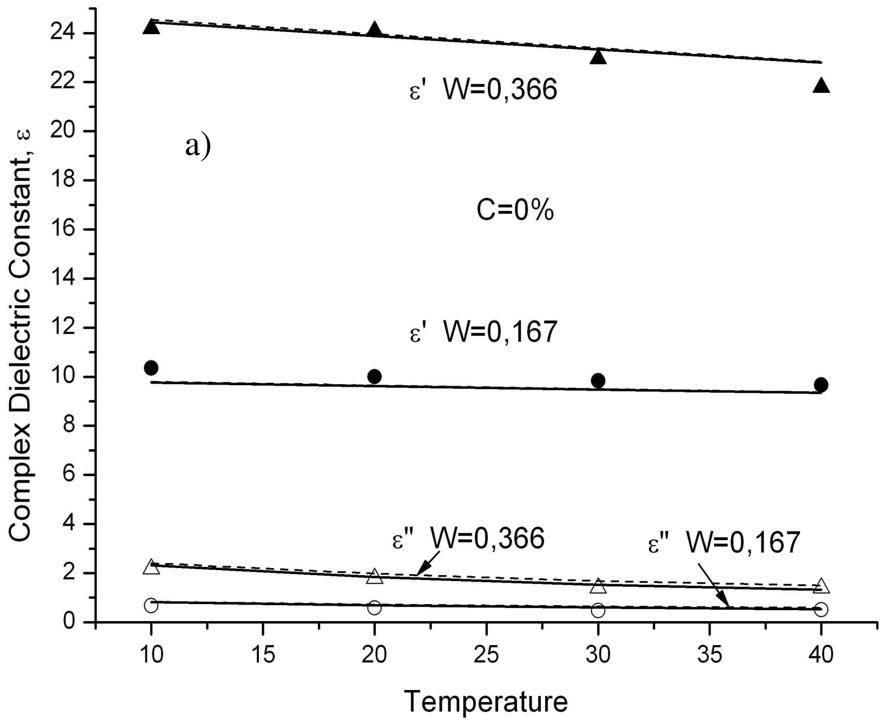

a)
C=0%
ε' W=0,366
ε' W=0,167
ε" W=0,366
ε" W=0,167
Complex Dielectric Constant, ε
Temperature
0
2
4
6
8
10
12
14
16
18
20
22
24
10
15
20
25
30
35
40

Fig. 2b

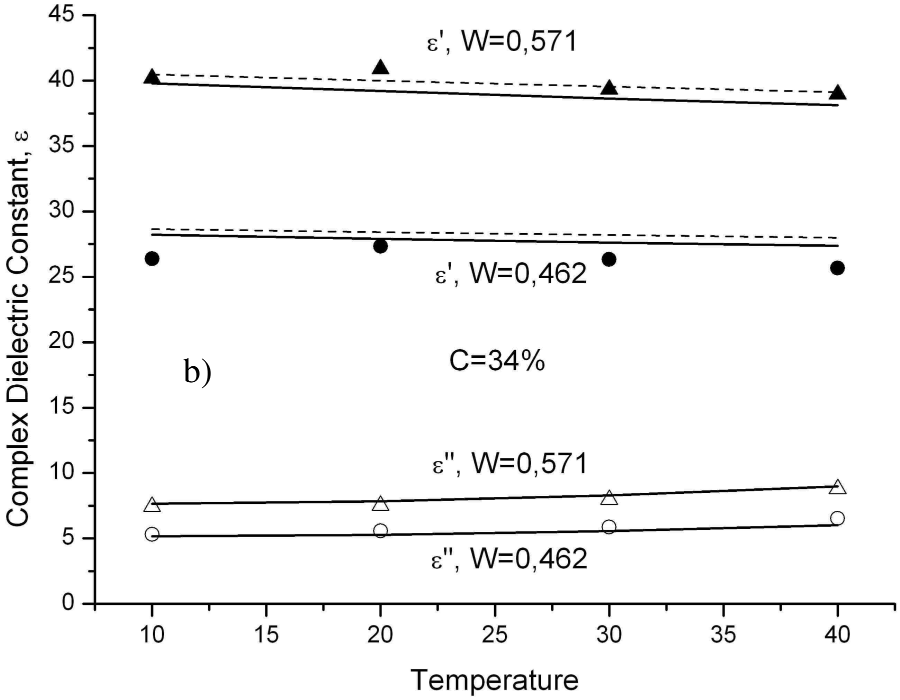

ε', W=0,571
ε', W=0,462
b)
C=34%
ε'', W=0,571
ε'', W=0,462
Complex Dielectric Constant, ε
Temperature
0
5
10
15
20
25
30
35
40
45
10
15
20
25
30
35
40

Fig. 2c

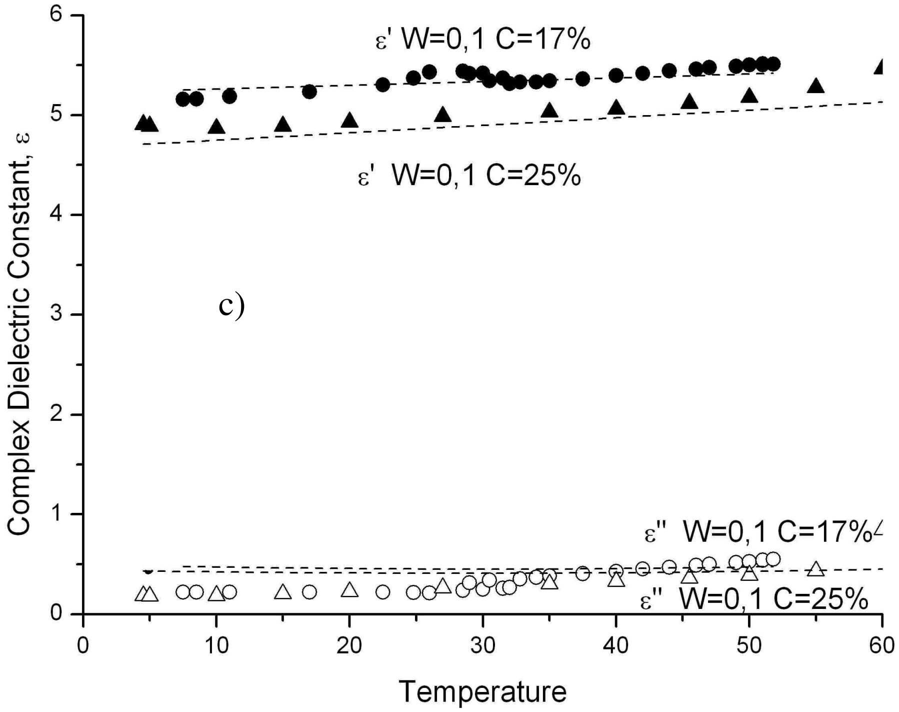

ε' W=0,1 C=17%
ε' W=0,1 C=25%
ε'' W=0,1 C=17%
ε'' W=0,1 C=25%
c)
Complex Dielectric Constant, ε
Temperature
0
1
2
3
4
5
6
0
10
20
30
40
50
60

Fig. 3a

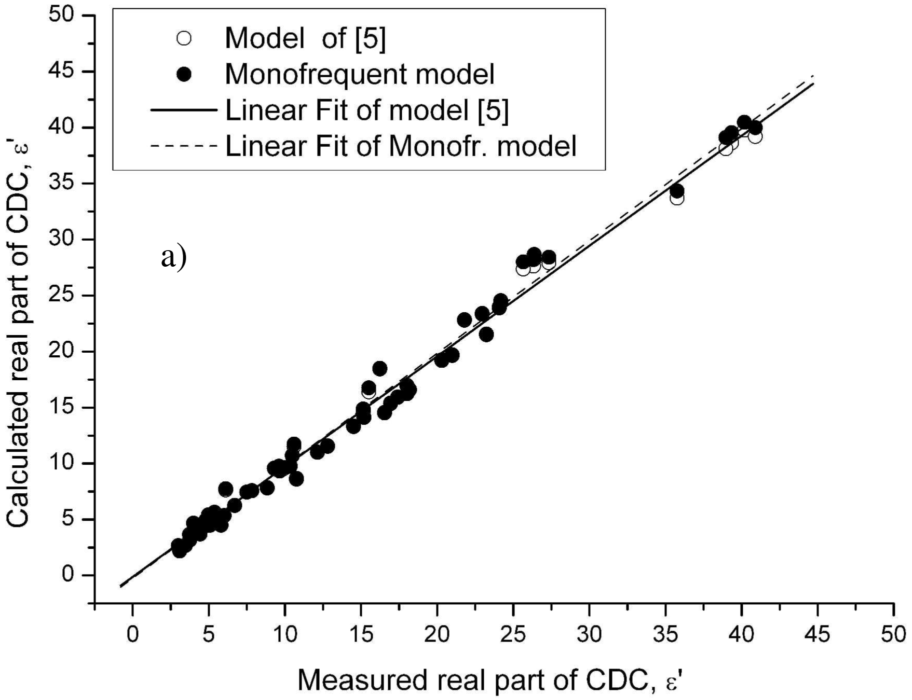
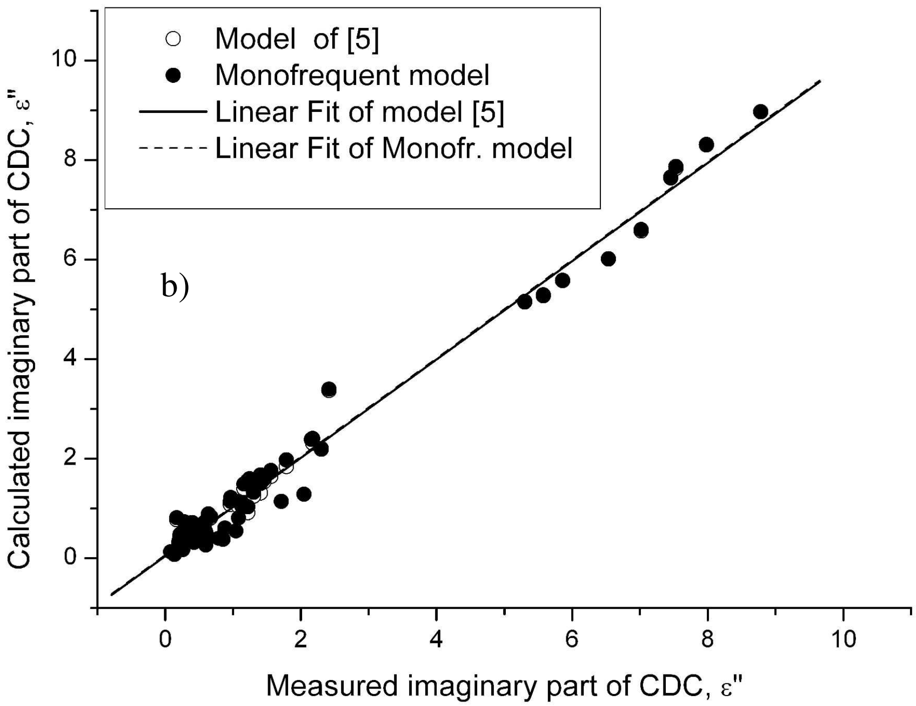

Model of [5]
Monofrequent model
Linear Fit of model [5]
Linear Fit of Monofr. model
a)
Calculated real part of CDC, ε'
Measured real part of CDC, ε'
0
5
10
15
20
25
30
35
40
45
50

Fig. 3b


○ Model of [5]
● Monofrequent model
Linear Fit of model [5]
Linear Fit of Monofr. model
b)
Calculated imaginary part of CDC, ε"
Measured imaginary part of CDC, ε"
0
2
4
6
8
10

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