Model for Dielectric Constant of Seawater based on L-band Measurements with Conductivity by Definition

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***Abstract*—This manuscript reports an improvement in the model for the dielectric constant of seawater used to fit laboratory measurements of the dielectric constant at L-band. The new model (dielectric constant as a function of salinity, temperature and frequency) is based on the response of a polar molecule proposed by Debye and fits the same measurement as reported in earlier work, but uses a functional form for conductivity, σ(S,T), that is given by the definition of salinity. The new version of this model fits the data well and has the advantages that the relaxation time constant is allowed to be a function of temperature and salinity and is well behaved when extrapolated to high salinities.**

***Index Terms*—Dielectric Constant, L-band, Microwave Remote Sensing; Ocean Salinity.**

I. Introduction

An accurate model for the dielectric constant of sea water as a function of salinity and temperature is an essential element in remote sensing of parameters of the ocean surface such as sea surface salinity (SSS) and sea surface temperature (SST). An accurate model at L-band is particularly important for remote sensing of SSS which is done at 1.4 GHz [1]. A major milestone at this frequency was the development of a model for saltwater by Klein and Swift [2] based on laboratory measurements at L- and S-band [3,4] and employing a functional dependence on frequency based on the response of polar molecules to an applied electric field [5,6]. It wasn't until the development of sensors to measure sea surface salinity from space, such as SMOS [7,8] and Aquarius [9] became a reality that new measurements were made at L-band [10,11]. The accuracy of these modern measurements is well documented [10] and the approach addresses an error due to heating of the sample potentially present in the earlier measurements. The range of these measurements was extended, using the same equipment, to include cold water and lower salinity by Zhou et al [11]. (Measurements were also made using the transmission line method by [12] but only the model fit was reported and it is inconsistent with other models [13]).

In previous work, a model based on the new L-band measurements [10,11] was reported using the Debye frequency dependence [11]. This is a functional form motivated by theory and generally accepted for models in this frequency range [6,13]. In this model, it was assumed that the relaxation constant in the Debye resonance was independent of salinity (the value determined from measurements on freshwater was used) and conductivity was a free parameter determined as part of the fit to the data. However, the modern definition of salinity is now given in terms of conductivity [14] and it is possible to invert this relationship to obtain conductivity as a function of salinity and temperature [15]. The inversion is now recognized by the oceanographic community [16] and essentially gives conductivity as a function of temperature and salinity by definition.

The expression for conductivity obtained in the earlier work [11] is close to this definition (see Appendix I.A in [13]) and the model fits the data well. However, by adopting the definition for conductivity as a function of SSS and SST, additional degrees of freedom are available to fit the data and it is possible to remove the previous assumption on the relaxation time. In addition, allowing the relaxation time to be a function of SSS solves a problem of unrealistic behavior at high salinity present in the previous model and also occurring in other models [17]. This manuscript documents this new fit to the data and model for the dielectric constant.

II. Background

The starting point for building a model the dielectric constant for seawater is the dielectric constant of pure water. Applying theory for the polarization of an ideal polar molecule in the presence of an electromagnetic field as originally derived by [5] leads to the following form for the dielectric constant [6]:

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$$\varepsilon_{dw}(T) = \varepsilon_\infty + \frac{\varepsilon_{s0}(T) - \varepsilon_\infty}{1 + j\omega\tau_0(T)} \quad (1)$$

where ω is frequency, ε_∞ is the dielectric constant in the high frequency limit, τ_o is the relaxation time and ε_{so} is the static (i.e. $\omega = 0$) dielectric constant of pure water (no salinity).

Experimental evidence supports this functional form for pure water near L-band with a relaxation time of about 0.01 ns corresponding to about 15 GHz. For higher frequencies, the evidence suggests additional "resonances" are needed [15] and for very high frequencies a series of resonances has been suggested [18]. However, the next resonance is near 120 GHz and for applications at L-band (1.4 GHz) where remote sensing of ocean salinity is done, these higher order terms are not significant.

Equation (1) is applicable to fresh water and "bound" charge (i.e., due to orientation and stretching of the molecule). It does not include the effect of ions which are present when salt is added to the water. To obtain the dielectric constant of seawater, another term must be added to account for the current created by the motion of ions:

$$\varepsilon_{sw} = \varepsilon_\infty(S,T) + \frac{\varepsilon_s(S,T) - \varepsilon_\infty(S,T)}{1 + j\omega\tau_{sw}(S,T)} - \frac{j\sigma(S,T)}{\omega\varepsilon_0} \quad (2)$$

where σ is the conductivity of the water and ε_o is the permittivity of free space. The parameters ε_∞, ε_s and τ have the same roles as before but now are functions of both salinity and temperature whereas in (1) they were only functions of temperature. These are parameters of the model to be determined based on observation (i.e., measurements of the dielectric constant at the frequencies of interest). This will be done here at 1.4 GHz using the measurements documented in [10,11].

Fitting the model in (2) to the data is impacted by the large number of unknowns when polynomials in S and T are used to represent the unknown parameters with sufficient order to match the data as done in [10]. However, there is additional information that can be applied to reduce the unknowns:

1. The parameter, ε_∞, is the value of the dielectric constant in the limit of infinite frequency. In the previous work [11] the constant value $\varepsilon_\infty = 4.9$ was used as suggested by [2] and [15] and used in their models. All the models used in the context of remote sensing of salinity have a value close to this [13]. However, conclusive evidence for the value of this parameter does not exist and modelers have treated it as a free parameter to be adjusted, including some with a temperature dependence and one with a weak dependence on salinity (see Appendix I.D in [13]). In the absence of solid evidence for the value of the parameter, the assumption $\varepsilon_\infty = 4.9$ will be made as before.

2. When S = 0, the static term, ε_s, must reduce to the freshwater value; hence, $\varepsilon_s(S,T)$ should have the following form [6]:

$$\varepsilon_s(S,T) = \varepsilon_{s0}(T)[1 - S \cdot \alpha(S,T)] \quad (3)$$

Similarly, the relaxation time should converge to the relaxation time of fresh water when S = 0, giving:

$$\tau_{sw}(S,T) = \tau_0(T)[1 - S \cdot \beta(S,T)] \quad (4)$$

The parameters $\alpha(S,T)$ and $\beta(S,T)$ are to be determined from the measurements, and for convenience in writing equations later we let:

$$R_s(S,T) = 1 - S \cdot \alpha(S,T) \quad (5a)$$
$$R_\tau(S,T) = 1 - S \cdot \beta(S,T) \quad (5b)$$

3. In the late 1970's, the definition of salinity (practical salinity) was tied to conductivity and defined as a ratio of measured conductivity to a reference value of conductivity and temperature [14]. Experiments led to an equation that defined salinity in terms of the ratio of measured conductivity to the reference value together with a polynomial in temperature [14]. An inversion of this relationship gives conductivity as a function of salinity and temperature [15] and a version of this inversion adopted by international agreement is available for salinity 0 < S < 42 psu and -2 < T < 35 ºC from [16].

Employing the three assumptions above, the dielectric constant of seawater can be written in the form:

$$\varepsilon_{sw}(S,T) = \varepsilon_\infty + \frac{\varepsilon_{s0}(T)R_s(S,T) - \varepsilon_\infty}{1 + j\omega\tau_0(T) \cdot R_\tau(S,T)} - \frac{j\sigma_{MB}(S,T)}{\omega\varepsilon_0} \quad (6)$$

where the parameters ε_{so}, τ_o, R_s and R_τ are to be determined based on the measurements at 1.4 GHz on fresh and seawater.

In previous work by the authors fitting (6) to the laboratory measurements [11], conductivity was included as one of the unknown parameters and the relaxation time was assumed to be independent of salinity and equal to the value for pure water, τ_o. In the work reported here the conductivity $\sigma(S,T)$ will be given as obtained from the definition of salinity as given by [16] and denoted as σ_{SM}. The additional freedom this permits will be used to determine the relaxation coefficient: i.e., the polynomial $\beta(S,T)$ in $R_\tau(S,T)$.

III. Model Development

The procedure followed by [11] for fitting (6) to the measurements will be adopted here. The data used in the fit is given in Table V of [10] and Tables I-III of [11]. The data is also available with additional details at [19].

The first step is to use the measurements of the dielectric constant of distilled water to determine $\tau_o(T)$ and $\varepsilon_{s0}(T)$ by fitting (2) to the measurements. The procedure and results (Section III.A of [11]) are not changed here. These two parameters are expressed as third order polynomials in T and the results of the best fit are as given in (4) and (5) in [11]:

$$\tau_o(T) = 1.75030\text{E-}11 - 6.12993\text{E-}13\ T + 1.24504\text{E-}14\ T^2 - 1.14927\text{E-}16\ T^3 \quad (7a)$$

$$\varepsilon_{s0}(T) = 8.80516\text{E+}01 - 4.01796\text{E-}01 \cdot T - 5.10271\text{E-}05 \cdot T^2 + 2.55892\text{E-}05 \cdot T^3 \quad (7b)$$

The next step is to fit the model to the measurements of seawater to determine the remaining unknown parameters, $\alpha(S,T)$ and $\beta(S,T)$. The measurements consist of values for the real and imaginary part of the dielectric constant and to fit the model to the data, (6) is separated into its real and imaginary parts:

$$\varepsilon_{sw}(S,T) = \varepsilon_{sw}^{'}(S,T) - j\varepsilon_{sw}^{''}(S,T) \quad (8)$$

where:

$$\varepsilon_{sw}^{'}(S,T) = \varepsilon_\infty + \frac{\varepsilon_{s0}(T)R_s(S,T)-\varepsilon_\infty}{1+\omega^2\tau_0^2(T)R_\tau^2(S,T)} \quad (9a)$$

$$\varepsilon_{sw}^{''}(S,T) = \frac{\omega\tau_0(T)R_\tau(S,T)[\varepsilon_{s0}(T)R_s(S,T)-\varepsilon_\infty]}{1+\omega^2\tau_0^2(T)R_\tau^2(S,T)} + \frac{\sigma_{MB}(S,T)}{\omega\varepsilon_0} \quad (9b)$$

and $R_s(S,T)$ and $R_\tau(S,T)$ are given by (5). Rearranging (9a-b), one obtains:

$$R_\tau(S,T) = \frac{\varepsilon_{sw}^{''}(S,T) - \frac{\sigma_{MB}(S,T)}{\omega\varepsilon_0}}{\omega\tau_0(T)\cdot[\varepsilon_{sw}^{'}(S,T)-\varepsilon_\infty]} \quad (10)$$

where $\varepsilon_{sw}^{'}(S,T)$ and $\varepsilon_{sw}^{''}(S,T)$ are the measured values, $\tau_0(T)$ is given in (7a) and $\sigma_{MB}(S,T)$ is given by the definition of salinity [16]. $R_s(S,T)$ can be obtained by rearranging (9a), which gives:

$$R_s(S,T) = \frac{[\varepsilon_{sw}^{'}(S,T)-\varepsilon_\infty][1+\omega^2\tau_0^2(T)R_\tau^2(S,T)]+\varepsilon_\infty}{\varepsilon_{s0}(T)} \quad (11)$$

which is determined using the measured value, $\varepsilon_{sw}^{'}(S,T)$, and $R_\tau(S,T)$ from (10).

The unknowns $R_\tau(S,T)$ and $R_s(S,T)$ in (10)-(11) will be modelled as polynomials in *S* and *T*. This makes the fitting a linear process, which guarantees its reliability and robustness. Several polynomial structures have been tested and a second order polynomial fit the data with minimum error and produced a smooth curve. Another issue of concern in the choice of the polynomials is that the two expressions be of the same order in S. This assumption is made to bound the ratio $R_\tau(S,T)$ / $R_s(S,T)$ in the case of very high salinity which, if not done, can result in unrealistic values of the brightness temperature for water bodies such as the Great Salt Lake in Utah [17]. Thus, the choice for the polynomials in $R_\tau(S,T)$ and $R_s(S,T)$ are:

$$R_\tau(S,T) = 1 - S\cdot(p_1 + p_2T + p_3T^2 + p_4ST) \quad (12a)$$
$$R_s(S,T) = 1 - S\cdot(q_1 + q_2T + q_3T^2 + q_4ST) \quad (12b)$$

The coefficients obtained after fitting to the data are:

$$\begin{bmatrix} p_1 \\ p_2 \\ p_3 \\ p_4 \end{bmatrix} = \begin{bmatrix} 2.36697\text{e-}04 \\ -3.13370\text{e-}04 \\ 4.11494\text{e-}06 \\ 6.45673\text{e-}06 \end{bmatrix} \quad \text{and} \quad \begin{bmatrix} q_1 \\ q_2 \\ q_3 \\ q_4 \end{bmatrix} = \begin{bmatrix} 3.03525\text{e-}03 \\ -2.66520\text{e-}06 \\ 1.59915\text{e-}07 \\ -4.19071\text{e-}07 \end{bmatrix} \quad (13)$$

IV. Discussion

In the discussion to follow, the model defined by (5)-(7), (12) and (13) will be called GW2022 and the previous model which used the freshwater value for the relaxation constant and a fitted value for conductivity [11] will be called GW2020. Both models are fitted to the same laboratory measurements and used the same methodology for fitting, and as expected, the quality of the fit is about the same for the two models. This is illustrated in Table I which reports the mean difference and standard deviation (STD) of the fit and data for the two models. The fits are comparable, but the new model has the advantages that the functional form for conductivity is consistent with the definition of salinity, and that the model for the relaxation time allows for a dependence on salinity in seawater. In addition, the dielectric constant in the new GW2022 model is well behaved for large values of salinity.

Table I
Comparison with Data

Model	Real Part		Imaginary Part	
	Mean	STD	Mean	STD
GW2020	0.0009	0.1093	-0.0116	0.2929
GW2022	0.0056	0.1142	-0.0130	0.2753

A. Conductivity

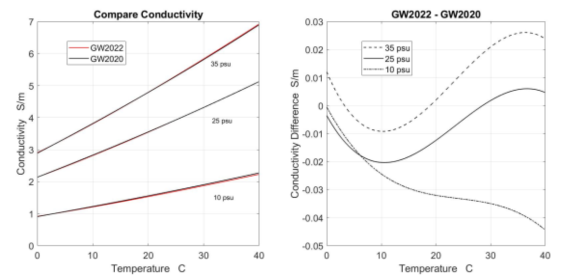

Fig 1. Conductivity as a function of temperature (left) for both models and difference between models (right) for S = 10, 25 and 35 psu..

The original GW2020 model was a good fit to the data and the expression for conductivity in that model (a polynomial with coefficients determined as part of the fit to the data) was close to the definition. This is illustrated in Fig.1. On the left is the conductivity from the polynomial fit in GW2020 and the conductivity from the definition (used in GW2022) is plotted as a function of temperature for S = 10, 25, 35 psu. On this scale it is hard to distinguish the fitted value from the definition given by [16]. The panel on the right shows the difference between the conductivity for two models as a function of temperature for several values of salinity. The difference is less than 0.04 S/m over the full range of salinity and temperature. To put this in context, the difference at T = 25 ºC and S = 35 psu is 0.01 S/m which corresponds to a difference in salinity of about 0.075 psu and almost twice this for very cold water (e.g., SST = 1 ºC)

B. Relaxation Time

One of the advantages of the new model is that it was possible to determine the relaxation time from the measurements and include a dependence on salinity in the case of seawater. The new relaxation time (4) is shown in Fig. 2 as a function of temperature in the left panel and as a function of salinity on the right. The relaxation time used in the GW2020 model is the dash-dot curve in the panel on the left (i.e., the curve for S = 0 psu). The dependence on salinity is weak (curves in the left panel are close together and the curves in the right panel are relatively flat) while the dependence on temperature is greater. To provide an idea of the magnitude of the change in the model

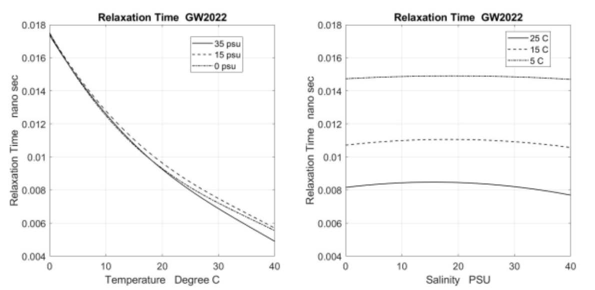

Fig 2. Left: Relaxation time $\tau_{sw}(S,T)$ as a function of T for S = 0, 15,35 psu; Right: Relaxation time as a function of S for T = 5, 15, 25 ºC.

for the relaxation time, the ratio between the relaxation time of seawater and fresh water, $R_\tau(S,T)$, is plotted in Fig. 3 as a function of temperature for several values of salinity. The ratio is close to unity (within 8%) but increases or decreases depending on temperature and salinity. The difference is smallest for cold water with the greatest difference at high temperatures and high salinity.

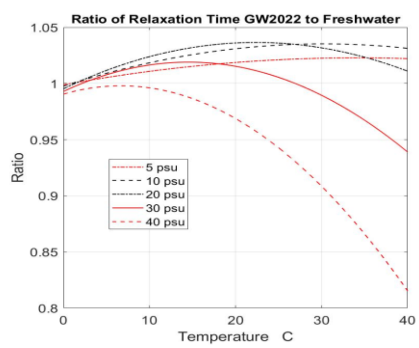

Fig 3. Ratio, $R_\tau(S,T)$, as a function of SST for several values of salinity.

C. Brightness Temperature

Although both models are good fits to the measurements at 1.4 GHz, they do predict differences in brightness temperature. This is illustrated in Fig. 4 which reports the difference in brightness temperature, ΔTb = TbGW2022 – TbGW2020, predicted by the two models as a function of temperature for several values of salinity for nadir incidence. For values of salinity and temperature likely to be encountered in the open ocean (e.g., 25 < S < 38 psu and 10 < T < 30 ºC) the differences in Tb are relatively small (│ΔTb│ < 0.5 K). But the difference can be larger and strongly temperature dependent for smaller values of salinity (black dashed and dash-dot curves in Fig. 4). The small changes in Tb predicted by the two models are not necessarily evidence of the quality of the model in the context of retrieving salinity. This is because each model is a nearly identical fit to the data and the error in the retrieval of salinity using these models, all else being ideal and equal, should reflect this accuracy. But if the goal is to develop a model which best represents understanding of the physical world, then the new model has some advantages: a more realistic model for the relaxation constant and better behavior at high salinity.

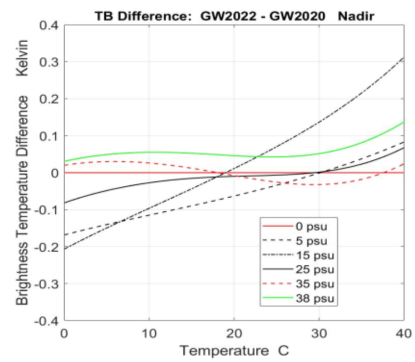

Fig. 4. Difference in Brightness temperature at nadir between GW2022 and GW2020 as a function of temperature for several values of salinity. The two models are identical for freshwater (S = 0).

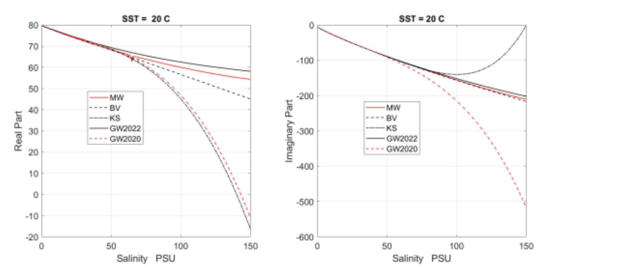

Fig 5. Behavior of several models at high values of salinity. Real part (left) and imaginary part (right) of the modelled dielectric constant.

D. High Salinity

More important than the small differences in predicted Tb, are the structural differences in the revised model. These include the use of conductivity consistent with the definition of salinity and a relaxation time that allows for a dependence on salinity. Equally important is the choice of the polynomials used to represent the $R_s(S,T)$ and $R_\tau(S,T)$ which have been selected to keep the ratio of these terms bounded in the limit of large salinity in (6). The consequence of these changes is illustrated in Fig. 5 which shows the real and imaginary parts of the dielectric constant as a function of salinity for T = 20 ºC. The behavior of several other models which are being used for remote sensing of salinity are also shown: KS = The model of Klein-Swift [2] used in the processing of SMOS data; BV = the recent model of Boutin et al [20]; MW = the model of Meissner-Wentz [21, 22] used in the retrieval of salinity from SMAP and Aquarius; and GW2020 = the original model [11]. Two of the models, KS and GW2020, have much different behavior with increasing salinity than the others. The real part (left panel) of these models decreases with increasing salinity and eventually changes sign. The imaginary part of the KS model increases with increasing salinity and eventually changes sign (not realistic as it indicates waves with growing amplitude). The real and imaginary parts of the dielectric constant for the other three models, BV, GW2022 and MW, are similar with a roughly linear dependence on salinity. In part this is because they all use the same model for conductivity, σ(S,T): BV and GW2022 use the definition [16] and MW uses the version of this inversion given by [15] which is nearly identical. The curves in Fig. 5 are temperature dependent, but the relative behavior at different temperature is the same.

V. Conclusions

A new model has been developed for the dielectric constant of seawater at L-band. The unknown parameters in the model have been determined by fitting the model to laboratory measurements at 1.4 GHz. This model is an improvement of an earlier model [11] based on the same laboratory measurements. The two models are both good fits to the data, but the new model has the advantages that the functional form for conductivity, σ(S,T), is consistent with the definition of salinity; that the new expression for the relaxation time constant is based on the measurements and both fits the measured value for freshwater (S = 0) and also the measurements with salt water; and that the new model for the dielectric constant is well behaved for large values of salinity.

These advantages are important for work currently underway to improve remote sensing of sea surface salinity. The future of remote sensing of salinity is likely to include measurements outside the limited protected band at 1.4 GHz [23] and especially likely to include lower frequencies where the sensitivity to salinity is largest [24]. In fact, measurements of the dielectric constant are currently underway at 700 MHz [25]. A model with conductivity based on the definition and independent of the measurements and frequency will make it easier to build a model for the dielectric constant that covers the expanded frequency range. Another area where research is underway is to extend the model to water bodies with very high salinity. Examples are Salt Lake in Utah and Lake Assal in Djibouti. This is an issue because existing models at L-band are based on data in the range 0 < S < 40 psu and the polynomials used to fit the data are not necessarily well behave outside of this regime as illustrated in Fig. 5. Although the new model has not been fitted to measurements at large values of salinity, it has been constructed to behave well in the limit of large salinity. Measurements by the authors are currently in the beginning stage to extend the data to high salinity.

VI. References

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