Study of seawater permittivity models and laboratory validation at 5 GHz

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(Received: March 16, 2012; in final form September 11, 2012)

Abstract: Microwave remote sensing of ocean relies on one of the important parameters known as complex permittivity, with dielectric constant ε' as real and dielectric loss ε" as imaginary part. In the present work, four seawater permittivity models were studied. These models were proposed by Klein and Swift (1977), Strogryn (1995), Ellison et al. (1998) and Meissner and Wentz (2004). These models provide relative dielectric properties and conductivity of seawater at any frequency as function of the salinity and temperature. These models are based upon experimental data, performed by the respective authors as well as the laboratory data of others. The experimental data are fitted to empirical and theoretical calculation of relative dielectric properties of seawater. The Klein and Swift (1977) and Ellison et al. (1998) models fitted data using single Debye function while Strogyrn (1995) and Meissner and Wentz (2004) used double Debye fit. Computation of dielectric constant ε' and dielectric loss ε" for single Debye fit models for frequencies 1-40 GHz for various salinities and temperatures are graphically represented. Considering the remote sensing applications for Indian Ocean, the salinity values are chosen in the range of 20-35, for temperatures between 20 °C to 30 °C. The theoretical database of permittivity is experimentally validated at 5 GHz for Arabian seawater samples of various salinity and at 30 °C. The Von Hippel method is used for laboratory measurement and least square fitting technique to calculate the dielectric constant ε' and dielectric loss ε".

Keywords: Permittivity Models, Arabian Sea, 1GHz-40 GHz, Dielectric constant, Dielectric loss

1. Introduction

Ocean salinity and temperature varies geographically as well as temporally and are vital parameters for oceanographers and meteorologists in studying surface circulation, climate dynamics, atmosphere modeling, environment modeling etc. Fresh water influx occurs at sea surface by rivers reduces salinity and salinity increases due to evaporation. Equatorial surface waters temperature is higher since it receives more solar radiation than polar surface (Lynne D Talley 2002). Microwave remote sensors can monitor variations in salinity and temperature, by calculating radiance (brightness temperature). The ocean brightness temperature depends upon absolute thermodynamic temperature and emissivity. The emissivity is complex function of dielectric constant of seawater. The dielectric constant is in turn governed by electrical conductivity and microwave frequency under consideration. Conductivity is function of salinity and temperature (Smyth, 1955; Hasted, 1973).

Permittivity models for the static permittivity of aqueous saline solutions and seawater given by Klein and Swift (1977), Stogryn (1995), Ellison et al. (1998) and Meissner and Wentz (2004) were studied. These models provide the relative permittivity and conductivity of seawater at particular microwave frequency as a function of the salinity and temperature. These models are based upon experimental data, performed by respective authors as well as the laboratory data of others. The experimental data were fitted to empirical and theoretical expressions for calculation of relative permittivity of seawater for any frequency, salinity and temperature value desired. Exercise of computing dielectric constant ε' and dielectric loss ε" for single Debye fit models for frequencies 1-40 GHz. Considering the remote sensing applications for Indian Ocean, the salinity values are chosen in the range of 20-35, for temperatures between 20 °C to 30 °C. The theoretical database of permittivity is experimental verified at 5 GHz for Arabian seawater samples of various salinity and at 30 °C. The Von Hippel method is used for laboratory measurement and least square fitting technique to calculate the dielectric constant ε' and dielectric loss ε".

2. Material and methods

2.1 Seawater permittivity models

The dielectric coefficient of seawater at microwave frequencies below 40 GHz can be represented by a simple Debye relaxation expression, given by

$$\varepsilon^*(f,T,S)=\varepsilon_\infty+\frac{\varepsilon_s-\varepsilon_\infty}{1-j2\pi\tau f}+j\frac{\sigma}{2\pi\varepsilon_0 f}$$

$$=\varepsilon^1-j\varepsilon^{ii} \qquad \text{......} 1$$

Where ε_s and ε_∞ are, respectively, the static and high frequency dielectric coefficients of the seawater, ε_0 is the permittivity of free space (=8.85*10-12 F/m), τ is relaxation time in seconds, σ is the ionic conductivity of the dissolved salts in mho/m, and f is the frequency in Hertz. The real and imaginary parts of the permittivity are ε' and ε", respectively.

The parameters ε_s, ε_∞, τ and σ are all functions of the temperature T and salinity S of the seawater.

a) Klein-Swift model: The Klein-Swift Model (1977) uses a simple Debye expression for the seawater dielectric over a limited frequency range ($f < 10$ GHz) and polynomial fits for the static dielectric coefficient, the ionic conductivity and the relaxation time as a function of temperature and salinity. The seawater dielectric coefficient in this model was derived from dielectric measurements of seawater and aqueous NaCl solutions conducted at 1.43 and 2.65 GHz for salinities in the range in between 4 and 35. Their derivation is based on the assumption that ε_∞ has a constant value from 4.9 to 8.5 for salinity values between 23 and 39 and temperatures of 0-30 °C.

This model is widely used for seawater dielectric coefficients, although the authors recommend care when using their model at frequencies above 10 GHz. The respective authors say that possible inaccuracies in ε^* might occur at higher frequencies (above 10 GHz) because of uncertainties in τ and ε_∞.

b) Stogryn model: Liebe *et al*. (1991) introduced a modified form of the traditional Debye model to improve the prediction of the dielectric properties of freshwater at frequencies beyond 100 GHz, called the double Debye model. The model incorporates two relaxation constants (τ_1 and τ_2) and is expressed as

$$\varepsilon^* = \varepsilon_\infty + \frac{\varepsilon_s - \varepsilon_1}{1\text{-}j2\pi\tau_1 f} + \frac{\varepsilon_1 - \varepsilon_\infty}{1\text{-}j2\pi\tau_2 f} \qquad .....2$$

where ε_1 is an intermediate dielectric constant. The primary ($\gamma_1 = [2\pi\tau_1]^{-1}$) and secondary ($\gamma_2 = [2\pi\tau_2]^{-1}$) relaxation frequencies are functions of temperature. For T=274K, γ_1 and γ_2 are 9.15 and 364 GHz respectively. The fact that two relaxation constants were required to optimally fit the model to the experimental data suggests that a second relaxation process exists, though its mechanism is not clearly understood.

Stogryn et al. (1995) provided a double Debye fit for both fresh and seawater in salinity range between 0 to 38. They used their own laboratory measurement in frequency range 7 GHz to 14 GHz, which they supplemented with existing measurement. Their model has same form as equation 2 including ion conductivity term.

$$\varepsilon^* = \varepsilon_\infty + \left(\frac{\varepsilon_s - \varepsilon_1}{1+j2\pi f\tau_1} + \frac{\varepsilon_1 - \varepsilon_\infty}{1+j2\pi f\tau_2} + j\frac{\sigma}{2\pi\varepsilon_0 f}\right) \qquad .....3$$

Stogryn et al. (1995), with experimental studies, found that first relaxation time in double Debye equation showed a definite decreasing tendency as the salinity increased at fixed temperature, as it should. This result marked contrast with Klein and Swift and emphasizes the fact that good estimation for relaxation time requires sufficiently higher frequencies. Analysis of data showed well-defined trends at lower temperature, but the random fluctuations as a function of salinity at the higher temperature. Hence, they suggest for more laboratory readings at higher temperature t >15°C should be taken to remove uncertainties.

c) Ellison et al. model: Ellison et al. (1996; 1998) developed a model of the dielectric constant of seawater based on their own measurements. They calculated permittivity in two frequencies ranges, for lower ranges3GHz ≤ f ≤ 20GHz; a simple Debye parameter range are used and for higher ranges 20GHz ≤ f ≤ 40GHz in temperature ranges –2°c ≤ t ≤ 30°c and salinity 20% ≤ S ≤ 40%. They also compared the permittivity data of natural seawater, artificially prepared seawater and aqueous NaCl.

Ellison et al. They found that there is significant difference in permittivity measurement between natural seawater, artificial seawater and aqueous NaCl solutions of same salinity up to 3 GHz. Their model is more precise and more adapted to real seawater but is limited down to 3 GHz. They also found that organic and particulate content of natural seawater plays little role in the permittivity measurements of seawater (any variations due to organic content is less than 0.5%). Although, they found that the permittivity predicted by their model are consistent up to about 10 GHz with the Klein and Swift model, their model for $\varepsilon_{sw}\infty$ (T, S) is notably dissimilar from the one of Klein and Swift (1977) since this parameter is found to decrease with increasing temperature up ~15°C and then to increase with increasing temperature. However, the respective authors found that this does not have a critical influence upon low permittivity values.

d) Meissner and Wentz model: The model (Meissner and Wentz 2004) provided a fit using two Debye relaxation frequencies. For pure water, the fit is based on laboratory measurements in the temperature range between −20 °C and +40 °C including supercooled water and for frequencies up to 500 GHz. For seawater, the fit is valid for temperatures between −2 °C and +29 °C and for frequencies up to at least 90 GHz. At low frequencies, the model is a modified version of the Klein-Swift model. Validation of their model using analysis of 4 SSM/I-V_{pol} channel gives pretty good results.

2.2 Dielectric constant and dielectric loss using permittivity models

Theoretical computation of the dielectric constant ε' and dielectric loss ε'' for frequencies 1-40 GHz, salinity values in the range of 20-35 and for temperatures between 20 °C to 30 °C are done using single Debye models i.e. the Klein and Swift Model and Ellison et al. model. Debye equations and fitting parameters are referred in respective research papers (Klein, and Swift, 1977; Ellison et al., 1998). Graphically represented are the computed values under results and conclusions section.

2.3 Laboratory Validification of dielectric properties at 5 GHz

The theoretical obtained dielectric properties by using models are experimentally validated for 5 GHz for seawater samples collected form Arabian Sea.

2.3.1 Seawater sampling

By participating in ORV Sagar Kanya scientific cruise SK-259, organized by NCAOR in May-June 2009 that is summer monsoon period, seawater samples were collected from Arabian Sea (Figure 1). Surface seawater at different locations were drawn through bucket thermometer and two bottles of the samples were preserved around 4°C by adopting standard procedure. Out of two bottles, one of the samples was used to determine the salinity parameter at that location using an Autosalinometer 8400B in the laboratory onboard Sagar Kanya vessel and the other sample of the same location was brought to the Microwave Research Lab, J.E.S. College, Jalna, Maharashtra for dielectric measurement.

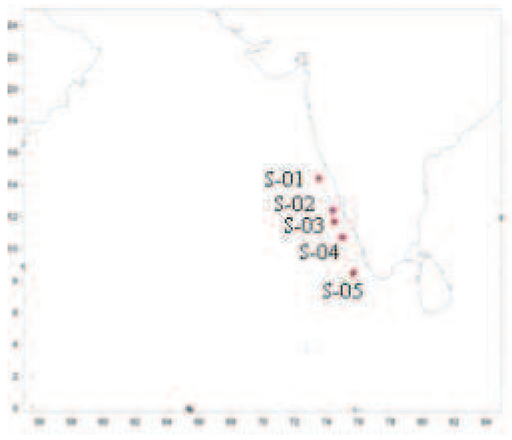

Figure 1: Arabian seawater sample locations

2.3.2 Temperature and salinity measurement

The bucket thermometer is used to measure the temperature of surface seawater. Salinity measurements of seawater samples were done using 8400B AUTOSAL onboard ORV Sagar Kanya laboratory. This instrument is semi-portable, semi-automatic and is used in the land based or sea-borne laboratory to determine salinity levels of saline seawater samples and standard seawater sample by measuring their equivalent conductivity. The instrument reading is displayed in terms of conductivity ratio. Inputting the conductivity ratio to the software available in the computer lab, salinity value of the sample is calculated. The software calculates salinity using the following formula. The equation is based on the definitions and the algorithm of practical salinity formulated and adopted by UNESCO/ICES/SCOR/IAPSO Joint Panel on oceanographic tables and standards, Sidney, B.C., Canada, 1980 (Lewis, 1978; 1980).

$$s = \begin{pmatrix} a_0 + a_1 R_{15}^{1/2} + a_2 R_{15}^{1} + a_3 R_{15}^{3/2} \\ + a_4 R_{15}^{2} + a_5 R_{15}^{5/2} + \Delta S \end{pmatrix} \qquad \text{.... 4}$$

$$\Delta S = \left[\frac{(T-15)}{(1+0.0162(T-15))} \right] * \begin{pmatrix} b_0 + b_1 R_{15}^{1/2} + b_2 R_{15}^{1} + b_3 R_{15}^{3/2} \\ + b_4 R_{15}^{2} + b_5 R_{15}^{5/2} \end{pmatrix} \qquad \text{.... 5}$$

Where $\Sigma a_i = 35.0000, \Sigma b_i = 0.0000.$

For, $2 \le S \le 42$, and

for $-2^{\circ}C \le T \le 35^{\circ}C$.

Table 1: Values of coefficients: a and b

i	a	b
0	0.0080	0.0005
1	-0.1692	-0.0056
2	25.3851	-0.0066
3	14.0941	-0.0375
4	-7.0261	0.0636
5	2.7081	-0.0144

2.3.3 Measurement of dielectric properties

There are several methods of dielectric measurement of liquid (Udo Kaatze, 2010). The Von Hippel method consists of reflecting microwaves at normal incidence in TE mode from the sample placed against a perfectly reflecting sample. This reflection sets up standing waves in the space in front of the sample. The separation of the first minimum from the face of the sample depends upon the wavelength of the electromagnetic wave in the sample and on the thickness of the sample. The change in wavelength causes shift in the minima. The minima of the standing wave pattern occur at intervals of one-half wavelengths from the short circuit when the sample is absent. When the sample is inserted in the cell in front of the short circuit the minima shifts towards the short circuits and in turn, causes a change in wavelength in half power width of the standing wave pattern.

In present work, the dielectric properties of seawater samples are measured using Von Hippel Method (Von Hippel, 1954) for which automated C-Band microwave bench, as shown in Figure 2, is used. The Microwave bench consists of a low power tunable narrow band VTO-8490 solid-state microwave source; having frequency range of 4.3-5.8 GHz. Tuning voltage is kept at 7 volts throughout the experiment, which corresponds to 5 GHz frequency. The other components of the bench setup are an isolator, coaxial to waveguide adapter, attenuator, SS tuner, slotted line and the liquid dielectric cell.

Microwave generated by the VTO propagate through the

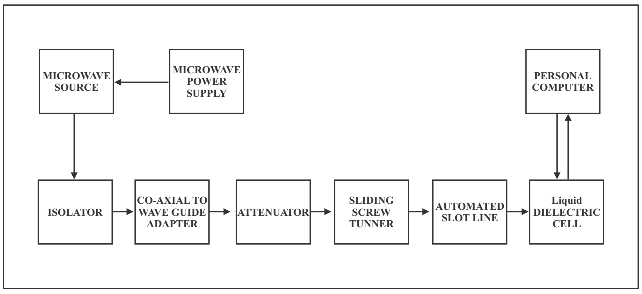

Figure 2: Block diagram of a C-band microwave bench

rectangular waveguide to the liquid cell. A desired power level in the line is adjusted with the attenuator. A slotted section with a tunable probe is used to measure the power along the slot line. The crystal detector (1N23) in the probe is connected to a microammeter and to the PC to read, acquire and store the data. The empty liquid dielectric cell is connected at the output end of the bench. The bench is tuned to get symmetrical standing wave pattern in the slot line. The positions of minima are noted from the pattern from which wavelength λg of the wave-guide can be calculated. The probe position on the slot line is kept constant at the first minima of the standing wave pattern in the slot line. The liquid dielectric cell is then filled with the sample under consideration. The plunger of the liquid cell is initially set in a position such that the thickness of the liquid column below the plunger is zero. By moving the plunger away from this position, data of microwave power is recorded for different plunger positions. The data of plunger positions and the corresponding power are acquired and stored in a file, which is further used to calculate dielectric constant ε' and dielectric loss ε'' using the least square fit program. The parameters α, β, P_0, δ are used as the fitting parameters, where α= attenuation factor, β=propagation constant, P_0=maximum power, and δ= phase factor. The computer program also takes care of calculating error in dielectric constant $\Delta\varepsilon'$ and error in dielectric loss $\Delta\varepsilon''$.

The dielectric properties of seawater samples can be calculated using the relations

$$\varepsilon' = \lambda_0^2\left(\frac{1}{\lambda_0^2} + \frac{(\alpha^2 - \beta^2)}{4\pi^2}\right) \quad \text{.... 6}$$

and

$$\varepsilon'' = \frac{\lambda_0^2 \alpha\beta}{2\pi^2} \quad \text{.... 7}$$

Where λ_0^1 is the free space wavelength, which can be calculated using the formula

$$\frac{1}{\lambda_0^2} = \frac{1}{\lambda_g^2} + \frac{1}{\lambda_c^2} \quad \text{.... 8}$$

Where $\lambda_c = 2a = 2 * 4.73$ cm = 9.46 cm, 'a' being the broader side of the C-band rectangular wave-guide.

3. Results and discussions

In viewpoint of remote sensing applications, computation of dielectric constant ε' and dielectric loss ε'' for single relaxation Debye model fit i.e. Klein and Swift Model and Ellison et al. Model is done for salinity range 20-35 and temperature range 20°C to 30°C as these are the conditions prevailing over the Indian Ocean.

Figure 3 (a-d) shows variation of dielectric constant and dielectric loss with microwave frequencies (1GHz -40 GHz) for temperature 20 and salinities 20, 25, 30 and 35 respectively.

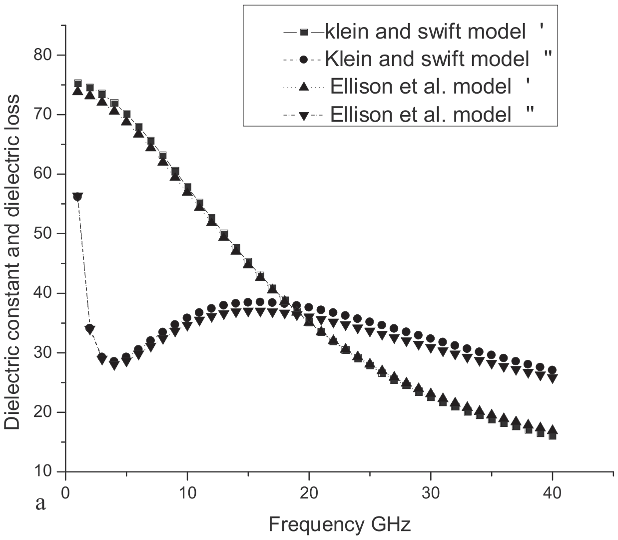

Figure 3: (a) Dielectric constant ε' and dielectric loss ε'' calculated for frequencies 1- 40 GHz by Klein and Swift model and Ellison et al. model for salinity=20 , temperature= 20 °C

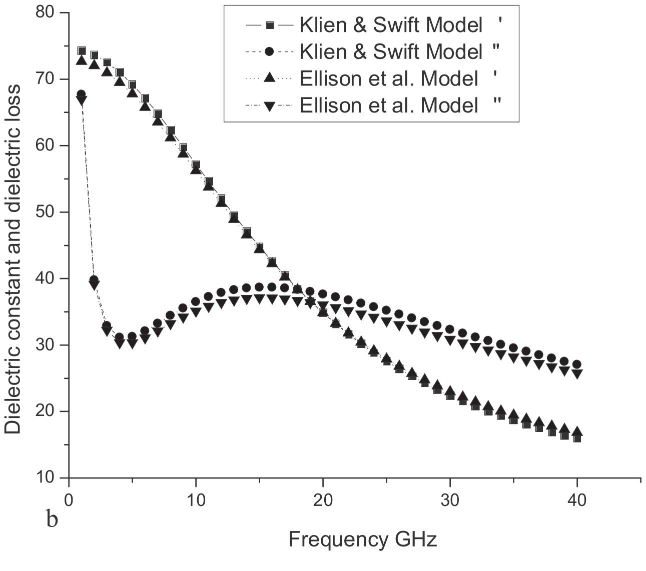

Figure 3: b) Dielectric constant ε' and dielectric loss ε'' calculated for frequencies 1- 40 GHz by Klein and Swift model and Ellison et al. model for salinity=25, temperature= 20 °C

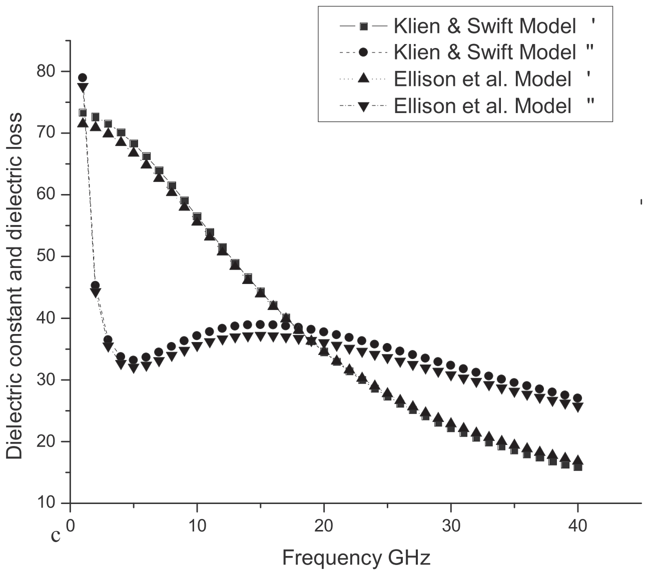

Figure 3: (c) Dielectric constant ε' and dielectric loss ε'' calculated for frequencies 1- 40 GHz by Klein and Swift model and Ellison et al. model for salinity=30, temperature= 20 °C

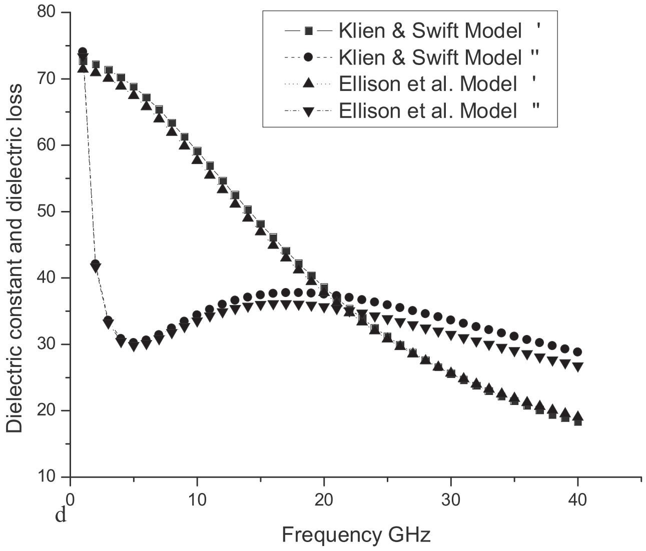

Figure 3: (d) Dielectric constant ε' and dielectric loss ε'' calculated for frequencies 1- 40 GHz by Klein and Swift model and Ellison et al. model for salinity=35, temperature= 20 °C

Figure 4 (a-d) shows variation of dielectric constant and dielectric loss with microwave frequencies (1GHz – 40 GHz) for temperature 25 and salinities 20,25,30,35 respectively.

Figure 5 (a-d) shows variation of dielectric constant and dielectric loss with microwave frequencies (1GHz – 40 GHz) for temperature 30 and salinities 20, 25, 30 and 35 respectively.

These plots provide dielectric constant ε' and dielectric loss ε'' for different grouping of salinities and temperatures for wide range of frequencies calculated by Klein and Swift model and Ellison et al. model.

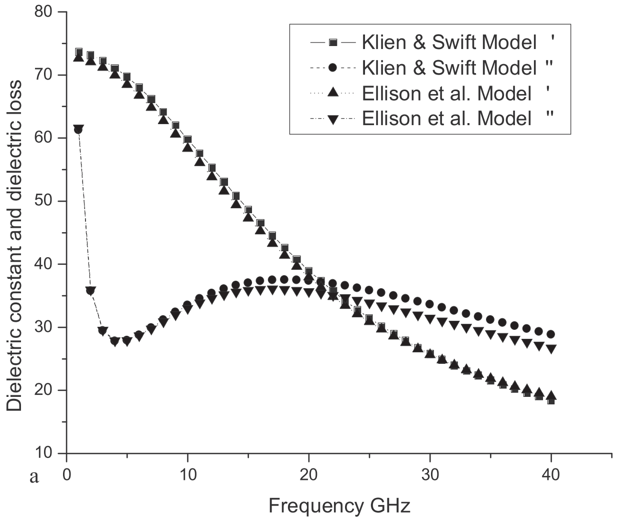

Figure 4: (a) Dielectric constant ε' and dielectric loss ε'' calculated for frequencies 1- 40 GHz by Klein and Swift model and Ellison et. al. model for salinity=20, temperature= 25 °C

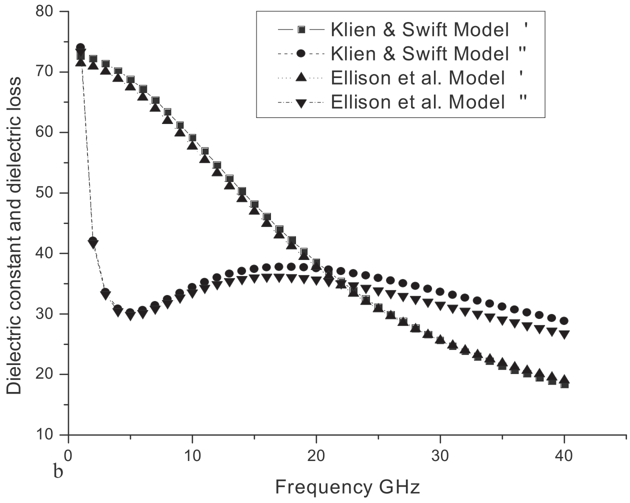

Figure 4: (b) Dielectric constant ε' and dielectric loss ε'' calculated for frequencies 1- 40 GHz by Klein and Swift model and Ellison et. al. model for salinity=25, temperature= 25 °C

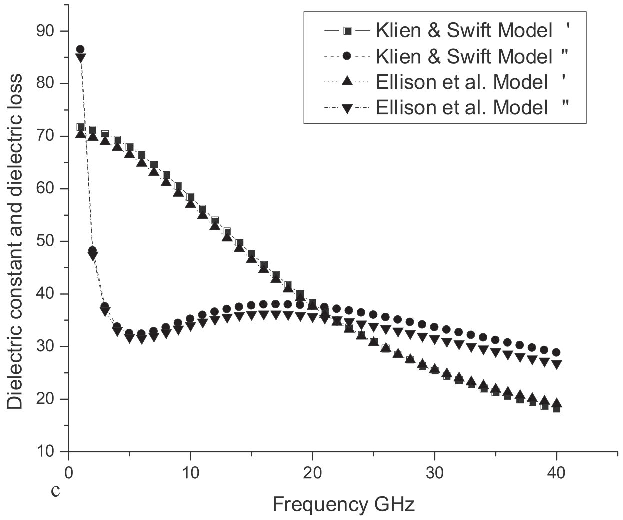

Figure 4: (c) Dielectric constant ε' and dielectric loss ε'' calculated for frequencies 1- 40 GHz by Klein and Swift model and Ellison et. al. model for salinity=30, temperature= 25 °C

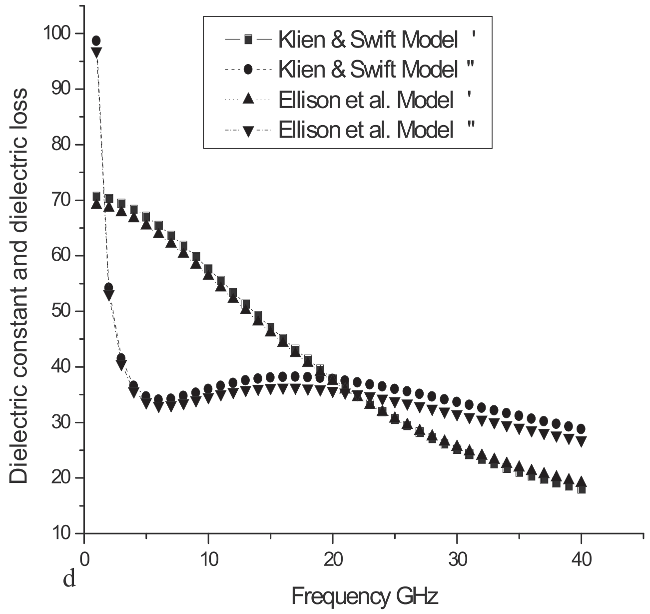

Figure 4: (d) Dielectric constant ε' and dielectric loss ε" calculated for frequencies 1- 40 GHz by Klein and Swift model and Ellison et. al. model for salinity=35 , temperature= 25 °C

It is observed from figure 3 (a-d), figure 4 (a-d) and figure 5 (a-d) that at a given temperature, with increase in salinity values the dielectric constant decreases and dielectric loss increases. However, typical change is seen at L-band (1-2GHz), S-band (2-4GHz), C-band (4-8GHz) frequencies. The dielectric loss decreases with increase in frequency up to 5 GHz, and then gradually increases and remains almost steady up to 15 GHz, and slowly decreases up to 40 GHz.

The dielectric constant ε' value calculated by Ellison et al. model is lower within 2 % than those of Klein and Swift model. The difference in ε' value calculated from two models is very small up to 20 GHz and it is almost negligible at higher frequencies. The variation in dielectric loss ε" factor is within 2 % for frequencies up to 15 GHz. However, the differences increases to about 8% with increase in temperatures and frequencies up to 40 GHz, the loss factor of Ellison et al. model is being lower.

For a given salinity value but with increasing temperature, the difference in dielectric loss ε" values of two models increases for higher frequencies, which is depleted in plots figure 3a, 4a, 5a figure 3b, 4b, 5b figure 3c, 4c, 5c and figure 3d, 4d, 5d.

The theoretically calculated dielectric constant ε' and dielectric loss ε" is experimentally validated at 5 GHz and 30 °C, for seawater samples of varying salinity collected from Arabian Sea. The theoretically calculated dielectric constant ε' and loss ε" values using Klein and Swift model and Ellison et al. model is shown in Table 2. The experimentally measured dielectric constant ε' and dielectric loss ε" is shown in Table 3. The error in measurements of dielectric constant Δε' and dielectric loss Δε" is of the order of magnitude 7 and 2 respectively. It is found that the dielectric constant values are well in agreement with both the models; however the experimental measured value of dielectric loss factor is higher by a of magnitude 20. The difference in the loss factor may be due to combined effect of the lossy nature of seawater as well as instrumental error.

Table 2: The theoretical calculated values of dielectric constant ε', dielectric loss ε", by Klein swift model and Ellison et al. model for seawater samples at 5 Ghz

Sample	**Latitude**	**Longitude**	**Salinity**	**Klein and swift model**		**Ellison et al. model**	
				ε'	**ε''**	**ε'**	**ε''**
S 01	N 14^0 46’	E 73^0 34’	35.88	66.45	35.14	64.70	34.24
S 02	N 12^0 25’	E 74^0 22’	35.29	66.56	34.86	64.82	33.99
S 03	N 10^0 41’	E 74^0 56’	35.17	66.58	34.80	64.85	33.93
S 04	N 08^0 06’	E 78^0 31’	34.64	66.67	34.54	64.95	33.70
S 05	N 07^0 39’	E 78^0 38’	34.98	66.61	34.70	64.89	33.85

Table 3: The experimental measured values of dielectric constant ε', dielectric loss ε" of all seawater samples at 5 Ghz.

Sample	**Latitude**	**Longitude**	**Salinity**	**ε'**	**ε''**
S 01	N $14^0$46’	E $73^0$34’	35.88	66.21	53.73
S 02	N $12^0$25’	E $74^0$22’	35.29	66.35	57.12
S 03	N $10^0$41’	E $74^0$56’	35.17	66.40	53.92
S 04	N $08^0$06’	E $78^0$31’	34.64	66.78	53.93
S 05	N $07^0$39’	E $78^0$38’	34.98	66.59	53.87

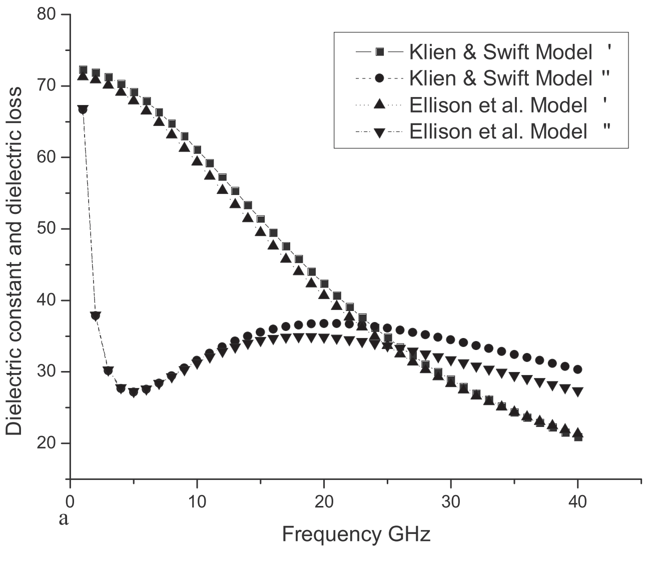

Figure 5: (a) Dielectric constant ε' and dielectric loss ε" calculated for frequencies 1- 40 GHz by Klein and Swift model and Ellison et. al. model for salinity=20 , temperature= 30 °C

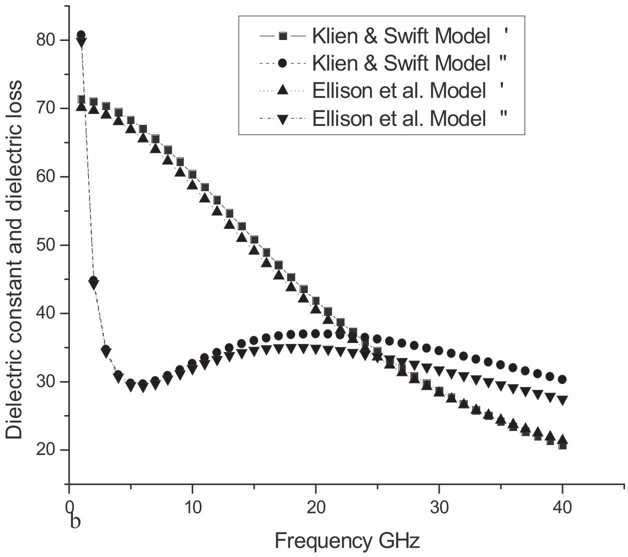

Figure 5: (b) Dielectric constant ε' and dielectric loss ε" calculated for frequencies 1- 40 GHz by Klein and Swift model and Ellison et. al. model for salinity=25 , temperature= 30 °C

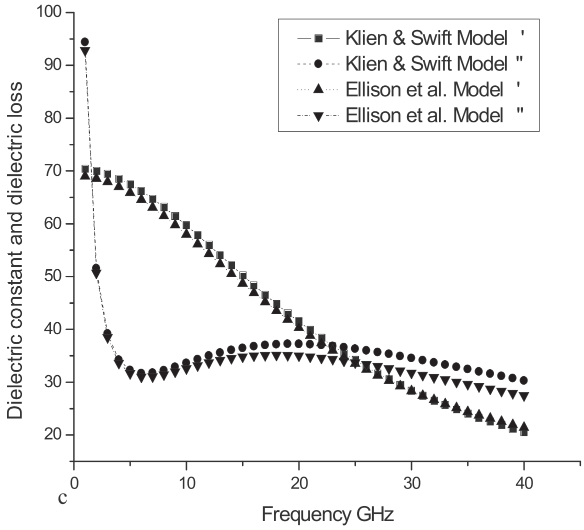

Figure 5: (c) Dielectric constant ε' and dielectric loss ε" calculated for frequencies 1- 40 GHz by Klein and Swift model and Ellison et al. model for salinity=30 , temperature= 30 °C

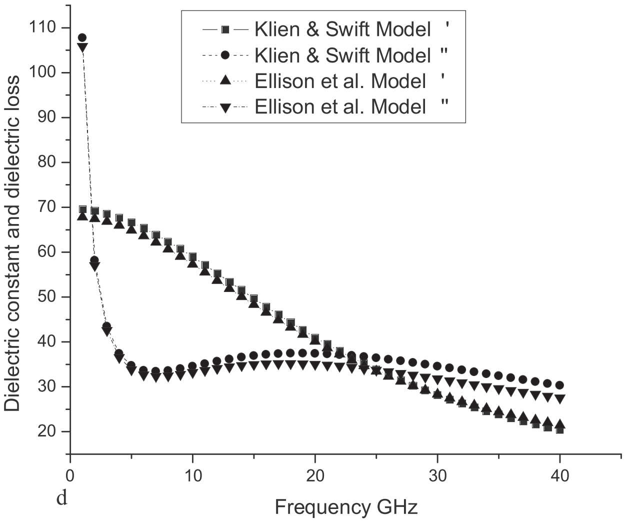

Figure 5: (d) Dielectric constant ε' and dielectric loss ε" calculated for frequencies 1- 40 GHz by Klein and Swift model and Ellison et al. model for salinity=35 , temperature= 30 °C

4. Conclusions

The emissivity and back scattering co-efficient of seawater are significant for microwave remote sensing application of Physical Oceanography. These factors are calculated from the dielectric properties ε' and ε". Variation in these properties are analyzed in detailed for frequency 1-40 GHz and salinity range 20-25 for temperature between 20 °C to 30 °C using Klein and Swift model and Ellison et al. model. The database of theoretically calculated permittivity of seawater is significant in calculating the emissivity and back-scattering coefficient at a given frequency, salinity and temperature value.

The theoretically computed database is laboratory validated at 5 GHz frequency using C-Band microwave bench setup. From the results, it is found that with increase in salinity dielectric constant ε' decreases. It is also found that permittivity measurements using Bench setup gives accurate dielectric constant ε', however the experimental loss factor is higher than the theoretical values.

The laboratory study of dielectric properties of seawater samples from Arabian Sea and Bay of Bengal Sea with varying microwave frequencies will be incorporated in further studies.

Acknowledgements

We are thankful to ISRO for providing the C-Band Microwave Bench Setup under RESPOND project of Dr. M.L. Kurtadikar. Special thanks to NCAOR, Goa, for allowing participation in SK-259 for seawater sample collection. We gratefully acknowledge useful suggestions from the reviewers.

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