



# Estimation of sea water salinity from dielectric measurements: Effect of temperature

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Dielectric measurements have been carried out for distilled water and saline water solutions of salinities 10000, 20000, 30000, 40000 ppm, as well as sea water of Diu beach area, using Anritsu Shockline Vector Network Analyzer (VNA, model no: MS46322A) in the frequency range from 1 GHz to 20 GHz, over the temperatures of 20°, 30° and 40 °C. From the measured values of dielectric constant and dielectric loss, the values of  $\tan\delta$ , conductivity and emissivity of water solutions have been calculated. The variation in dielectric properties of water with salinity and temperature of measurement is compared with values calculated using Stogryn equations as well as Klein and Swift model and results are found to be in good agreement with corresponding values. From the dielectric loss values and the emissivity values of distilled water and saline water solutions at certain fixed frequencies, the salinity of sea water collected from Diu beach has been estimated to be 36,327 ppm which agrees very well with the physicochemical analysis report of laboratory.

**Keywords:** Salinity, Pure water, Dielectric constant, Dielectric loss,  $\tan\delta$ , Conductivity, Emissivity

## 1 Introduction

Previously the complex permittivity  $\epsilon^* = \epsilon' - j \epsilon''$  of distilled water and NaCl solutions of concentrations varying from 5,000 to 35,000 ppm have been investigated<sup>1</sup> over the frequency range from 200 MHz to 1.4 GHz using a Vector Network Analyzer, and from the measurements the salinity of the Kanyakumari beach sea water was estimated to be 34,000 ppm. Lang *et al.*<sup>2</sup> measured the complex dielectric constant of sea water with different salinities at 1.413 GHz over the temperature range from 5 °C to 35 °C.

Midi *et al.*<sup>3</sup> measured dielectric properties of pure water, tap water and saline water solutions of different conductivities up to 5 S/m, over the frequency range from 40 Hz to 50 GHz at a fixed temperature of 22 °C. It has been observed that the static dielectric constant of water sample decreases with increase in salinity, and hence with increase in DC conductivity, and is dependent on the frequency of measurement. Further it has been observed<sup>3</sup> that the conductivity of pure water increases significantly at frequencies higher than 10 MHz, and for saline water solution of 5 S/m it increased significantly for frequencies higher than 1 GHz.

Previously it has been observed<sup>4</sup> have shown that distilled water and saline water shows effects on soil properties which is directly relevant with land fertility. It has been observed that salinity of water has profound

effect on the dielectric loss of moist soils, over the frequency range from 300 kHz to 1.5 GHz and at 5.65 GHz<sup>5</sup>. Such type of study also provides useful data for remote sensing applications of oceans, salinity estimation of different reservoirs and for the estimation of the effect of salinity on dielectric properties of soils.

Ellison *et al.*<sup>6</sup> measured the permittivity of natural seawater, synthetic seawater, and aqueous NaCl solutions over the frequency range from 3 GHz to 20 GHz over the temperature range from -2° to 30 °C; as well as at spot frequencies of 23.8 GHz, 36.5 GHz and 89 GHz at selected temperatures in the range of -2° to 30 °C. It was observed that the permittivity of synthetic sea water agrees very well with natural seawater as compared to the NaCl solutions.

The aim of present work is to study the effect of temperature on dielectric properties of distilled water, saline water solutions with different salinities and sea water of Diu beach, over the frequency range from 1 GHz to 20 GHz, at temperatures of 20°, 30° and 40 °C. Experimental data of dielectric constant, dielectric loss,  $\tan \delta$ , conductivity and emissivity are compared with Stogryn equations<sup>7</sup> and Klein-Swift model<sup>8</sup> for further verification.

The salinity of sea water approaches up to about 40,000 ppm at temperatures up to 40 °C<sup>9</sup>. Further the salinity of enclosed seas reaches higher values, such as Arabian Gulf water near sea shore of Kuwait and Saudi Arabia reach up to 50,000 ppm, whereas that of Australian Shark Bay have salinity up to about 70,000

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ppm<sup>9</sup>. The salinity of sea water can be estimated from the known values of dielectric loss or emissivity of saline water solutions at microwave frequencies.

## 2 Materials and Methods

### 2.1 Sample preparation

The Saline water solutions of different salinities varying from 10,000 ppm to 40,000 ppm were prepared with an addition of NaCl (AR grade, procured from Finar Limited) in distilled water. Saline water solutions were carefully prepared in volumes of 100 ml, using the Eq. (1):

Salinity of water solution (in ppm)

$$\frac{\text{NaCl powder (ingm)}}{\text{Distilled water (in l)}} \dots (1)$$

Physicochemical properties of seawater collected from Diu beach were obtained from the Vishal Analytic Laboratory, Ahmedabad, and are listed in Table 1.

### 2.2 Experimental method

The experimental methodology used in this work is similar to the one employed in our previous paper<sup>10</sup>. Measurements of complex permittivity of all samples were carried out over the frequency range from 1 GHz to 20 GHz by using Anritsu Shockline Vector Network Analyzer (VNA, model no: MS46322A) (Fig. 1) and dielectric assessment kit provided from

Table 1 — Physicochemical properties of seawater collected from Diu beach.

No.	Physicochemical properties	Estimated values from laboratory
1	Electrical Conductivity at 25 °C	63600millimho/cm
2	pH at 25 °C	7.39
3	Total Dissolved Solids	36720mg/l
4	Total Hardness (as CaCO <sub>3</sub> )	7750mg/l
5	Total Alkanity (as CaCO <sub>3</sub> )	610mg/l

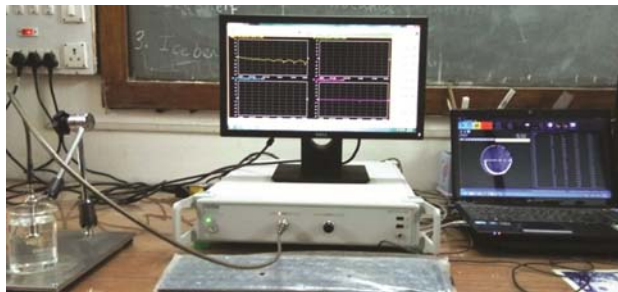


Fig. 1 — Anritsu Shockline Vector Network Analyzer (Model-MS46322A).

SPEAG along with DAK 3.5 probe. Before the measurement, the calibration process was carried out using the open, short and two liquids (HPLC water and Methanol) as two standard load materials.

After the proper calibration, the measurements of complex permittivity were carried out for the samples at temperatures of 20°, 30° and 40 °C.

After the completion of measurement of each sample, the sample was removed and the probe (DAK-3.5) was thoroughly cleaned with distilled water and then Acetone, before the measurement of next sample. For temperature variation, constant temperature bath was used.

## 3 Results and Discussion

Figure 2 shows variation of dielectric constant ( $\epsilon'$ ) of pure water at different temperatures over the frequency range from 1 GHz to 20 GHz. It can be observed from the Fig. 2 that, with the increase in frequency from 1 GHz to 20 GHz, the dielectric constant of pure water and saline water solutions decreases. Further, for pure water, at given fixed frequency the dielectric constant decreases with increase in temperature over the frequency range from 1 GHz to ~7.4 GHz. This phenomenon inverts its nature approximately after a critical frequency of ~7.4 GHz in which the dielectric constant increases with increase in temperature at given fixed frequency. This critical frequency increases with increase in the salinity of water. The molecules of NaCl dissolved in water form Hydrogen bonding with water molecules which increases the inertia of molecules. It causes decrease in dielectric constant ( $\epsilon'$ ) as salinity in water increases<sup>11</sup>.

The experimental values of dielectric constant ( $\epsilon'$ ) are also compared with the values calculated using the Stogryn equations in Fig. 2. It can be observed from Fig. 2 that the experimental values of dielectric constant ( $\epsilon'$ ) below 7.4 GHz are slightly higher than the calculated values. After 7.4 GHz the experimental values of dielectric constant ( $\epsilon'$ ) are slightly lower than the values calculated using the Stogryn equations<sup>8</sup>.

Figure 3 shows the variation of dielectric loss ( $\epsilon''$ ) of pure water with frequency, as well as with temperature. At given frequency, as temperature increases the dielectric loss decreases. Dielectric loss ( $\epsilon''$ ) of pure water increases with the increase in frequency at all temperatures, reaching a peak value near 20 GHz.

The experimental values of dielectric loss are compared with values calculated using the Stogryn

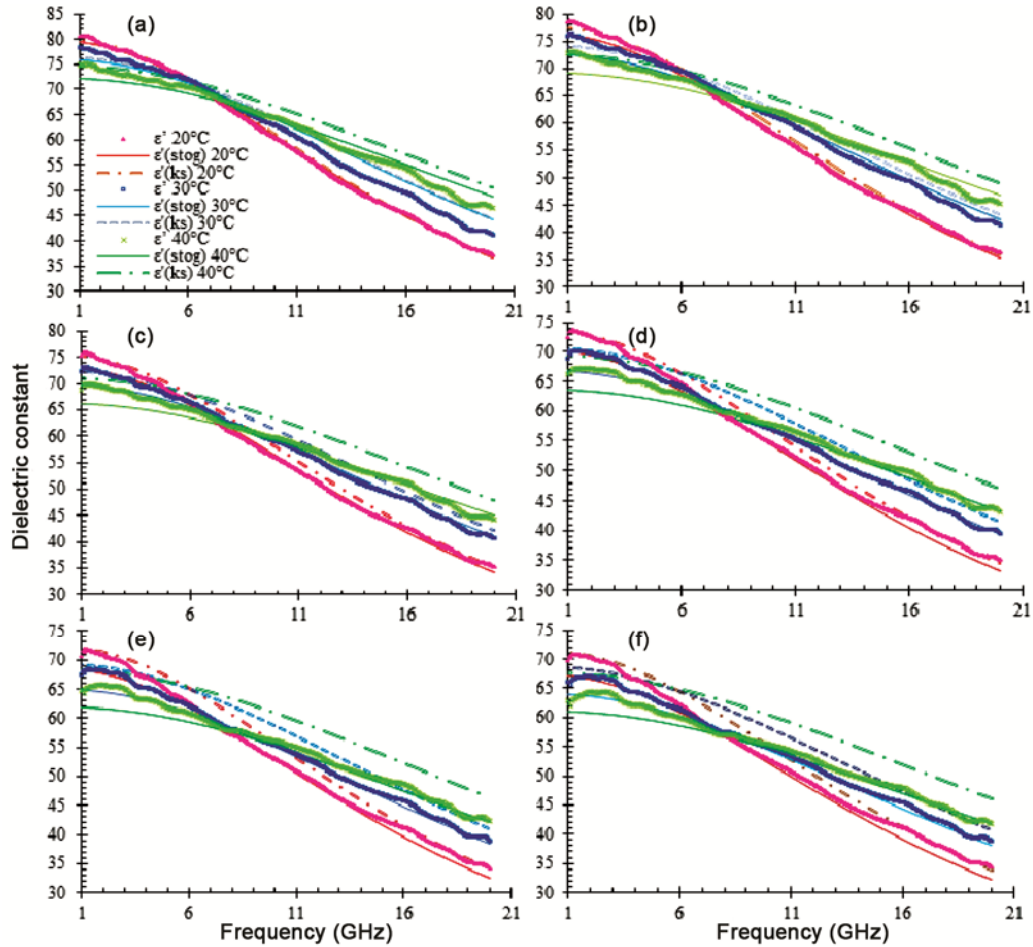


Fig. 2 — Variation of dielectric constant ( $\epsilon'$ ) with frequency (in GHz) at temperatures of 20 °C, 30 °C and 40 °C for (a) pure water, and Saline water solutions of (b) 10,000 ppm, (c) 20,000 ppm, (d) 30,000 ppm, (e) Sea water collected from Diu and (f) Saline water solution of 40,000 ppm compared with the values calculated using Stogryn equations and Klein-Swift model.

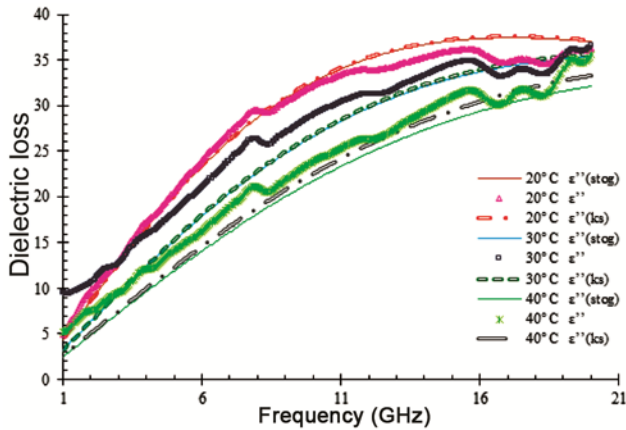


Fig. 3 — Variation of dielectric loss ( $\epsilon''$ ) with frequency (in GHz) at temperatures of 20°, 30° and 40 °C for pure water, compared with the values calculated using Stogryn equations and Klein-Swift model.

equations and Klein and Swift model. At 20 °C experimental values are in good agreement with calculated values up to approximately 10 GHz after

which the experimental values are lower than calculated values using the Stogryn equations and Klein and Swift model. At 30 °C and 40 °C temperatures, the experimental values of  $\epsilon''$  are slightly higher than the calculated values up to 16.35 GHz after which these values are lower than the calculated values.

From Fig. 4 it can be observed that, the dielectric loss of saline water solutions increases with increase in salinity. The dielectric loss of saline water solutions increases with increase in temperature up to certain transition frequency after which it starts to decrease with increase in temperature, at given fixed frequency. This transition frequency increases with increase in Salinity, i.e., for 10,000, 20,000, 30,000 and 40,000 ppm these values of the transition frequency are 4.1, 6.35, 7.45 and 8.1 GHz, respectively. Experimental values of dielectric loss are compared with values calculated using the

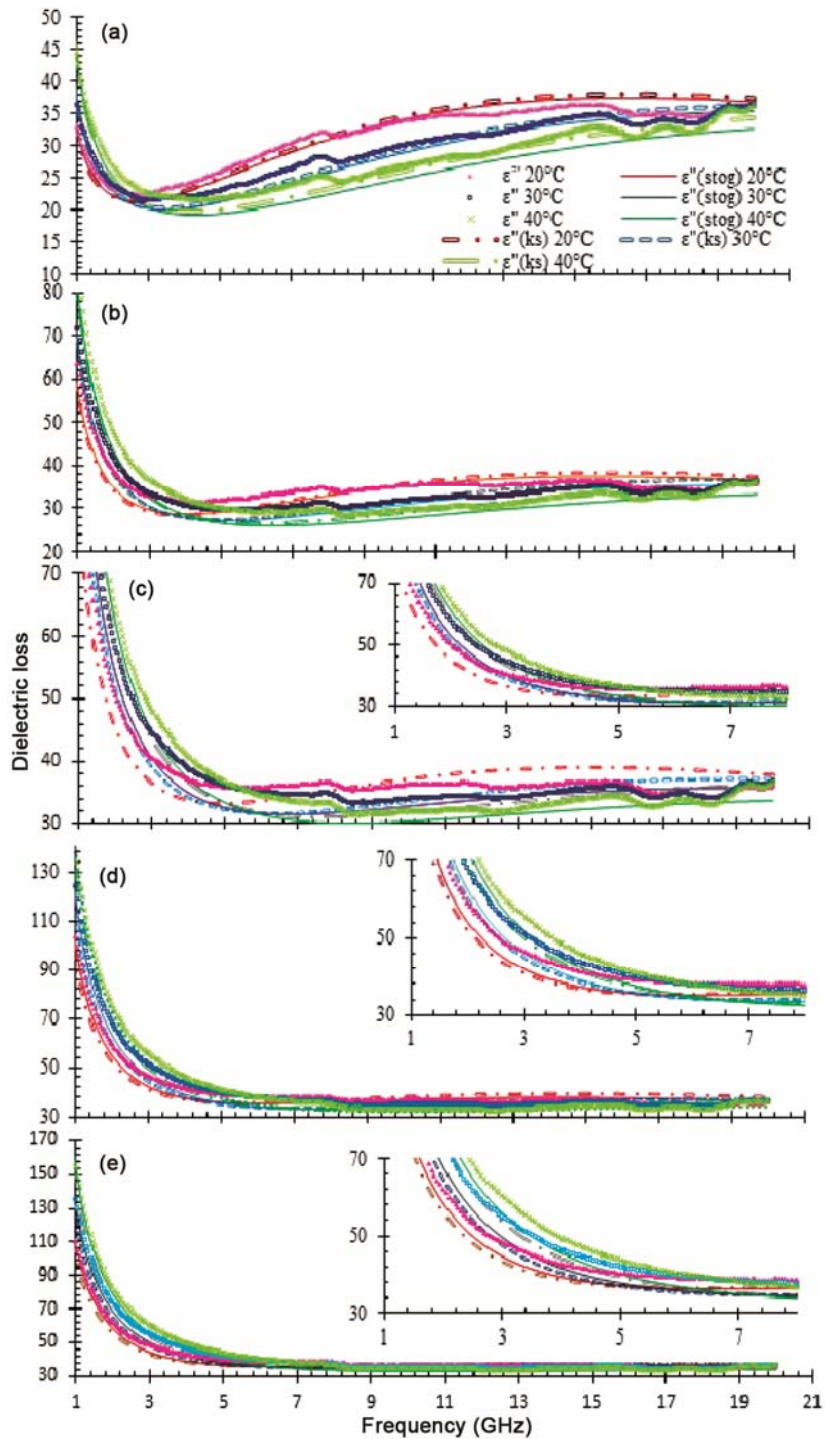


Fig. 4 — Variation of dielectric loss ( $\epsilon''$ ) with frequency (in GHz) at temperatures 20 °C, 30 °C and 40 °C for Saline water solution of a) 10,000 ppm, b) 20,000 ppm, c) 30,000 ppm, d) Sea water collected from Diu and e) Saline water solution of 40,000 ppm.

Stogryn equations and Klein and Swift model. Effect of salinity is more prominent in dielectric loss as compare to dielectric constant, at frequencies below  $\sim 6$  GHz<sup>12</sup>.

The  $\tan\delta$  is a quantity which represents energy loss per cycle to energy stored per cycle<sup>13</sup>. Figure 5

represents variation in  $\tan\delta$  with frequency, for pure water at different temperatures of 20°, 30° and 40 °C. The values of  $\tan\delta$  decrease with increase in temperature. It can be observed from the Fig. that  $\tan\delta$  calculated using the Stogryn equations and

Klein and Swift model are lower than the estimated values at 30° and 40 °C, whereas at 20 °C the calculated values agree very well with the estimated values up to about 11 GHz after which the calculated values are higher than the estimated values.

Figure 6 shows the variation of  $\tan\delta$  for saline water solutions of salinities 10000, 20000, 30000 and 40000 ppm, and Diu sea water, over the 1 GHz to 20 GHz frequency range. It can be observed from Fig. 6 that, at a given frequency, the value of  $\tan\delta$  increases with increase in salinity of water at all temperatures. As salinity increases the number of NaCl molecules bound with free water molecules increases, increasing the dielectric loss, which in turn increases the value of  $\tan\delta$ . Further it can be observed from the Fig. 6 that, for water solution of given salinity, the value of  $\tan\delta$  decreases with increase in frequency, reaches minimum at particular frequency depending on temperature and salinity of water sample, after which it increases slowly with increase in frequency. At lower frequency range the value of  $\tan\delta$  is higher at higher temperatures, for given saline water sample; but at higher frequencies the value of  $\tan\delta$  is higher at lower temperature. As salinity increases, the frequency at which the minimum of  $\tan\delta$  occurs, is found to shift towards higher frequency.

Figure 7 represents variation of conductivity with frequency from 1 to 20 GHz at various temperatures, for the distilled water, for the saline water solutions, and for seawater sample collected from the Diu sea bank. Conductivity of Pure water and the saline water solutions increases with increase in the frequency, and with temperature. As the NaCl molecules bound with water molecules are more conductive than free water molecules the conductivity increases with increase in salinity of water. The increase in conductivity of saline water with increase in temperature is due to the increase in mobility of bound water molecules. The number of free ions present in saline water is directly proportional to the salinity, hence the conductivity of water increases with increase in the salinity of water<sup>5</sup>.

The emissivity of water was calculated for normal incidence using the measured values of complex permittivity  $\epsilon^* = \epsilon' - j\epsilon''$ , using the equation<sup>1,14</sup> :

$$e = 1 - \left| \frac{1 - \sqrt{\epsilon}}{1 + \sqrt{\epsilon}} \right|^2 \quad \dots (2)$$

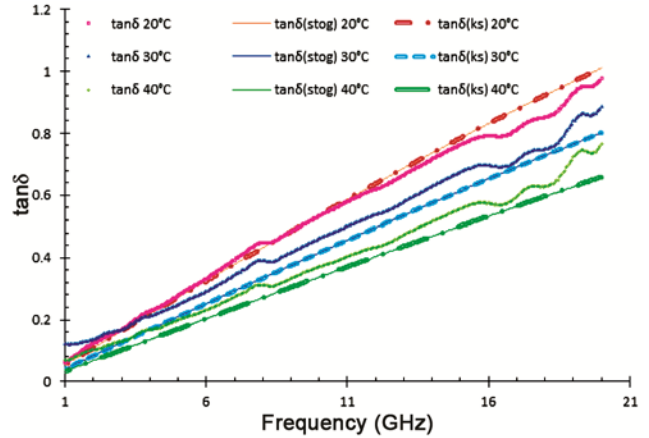


Fig. 5 — Variation of  $\tan\delta$  with frequency (in GHz) for Pure water at 20°C, 30 °C and 40 °C

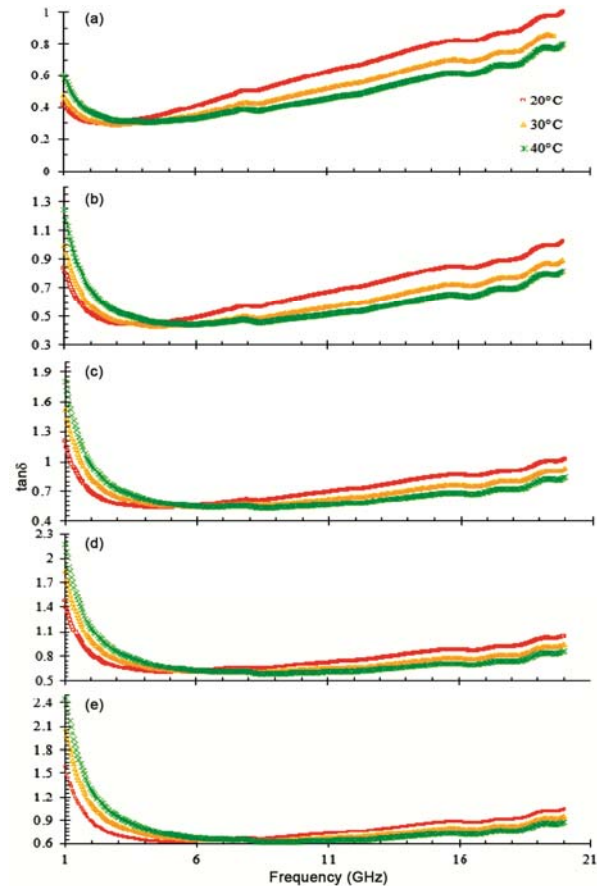


Fig. 6 — Variation of  $\tan\delta$  with frequency (in GHz) at 20 °C, 30 °C and 40 °C temperatures, for Saline water solution of a) 10,000 ppm, b) 20,000 ppm, c) 30,000 ppm, d) Sea water collected from Diu and e) Saline water solution of 40,000 ppm.

where, the second term in above equation is the Fresnel reflection coefficient<sup>8</sup> and  $\epsilon$  is magnitude of complex permittivity.

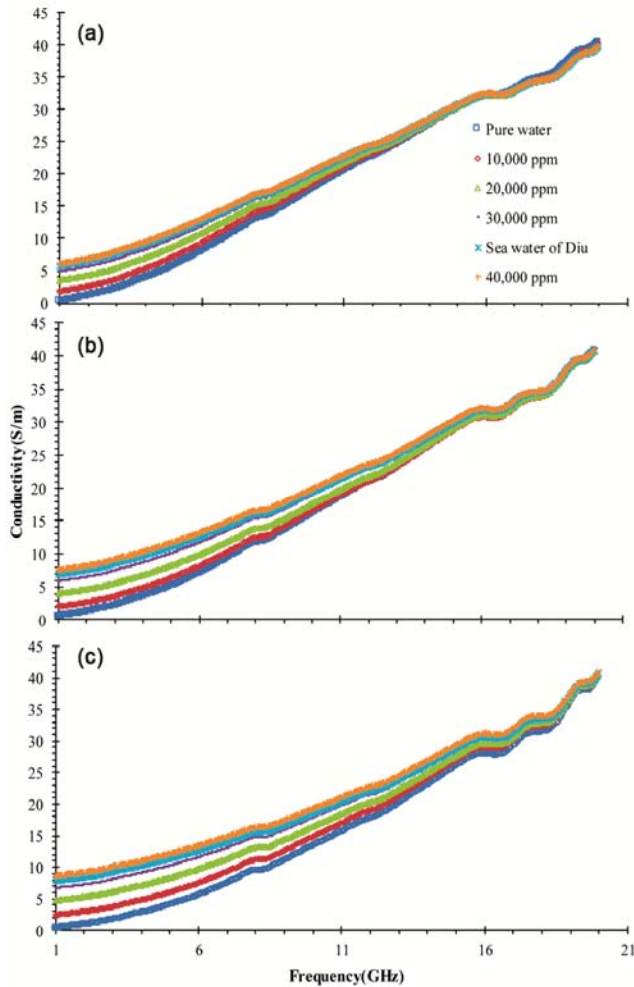


Fig. 7 — Variation of conductivity with frequency (in GHz) for pure water, sea water sample collected from Diu, and the saline water solutions of various salinities at a) 20 °C, b) 30 °C and c) 40 °C temperatures.

Figure 8 shows variation of emissivity of pure water and the saline water solutions with frequency from 1 to 20 GHz, at 20 °C, 30 °C and 40 °C temperatures. It can be observed that the emissivity of distilled (pure) water increases linearly with increase in frequency at 20 °C, 30 °C and 40 °C. The emissivity of saline water solutions decreases rapidly with decrease in frequency, below about 4 GHz - 5.5 GHz depending on temperature and salinity. At certain transition point frequency ranging from 4 GHz to 5.5 GHz depending on temperature, the emissivity of distilled water and saline water solutions become

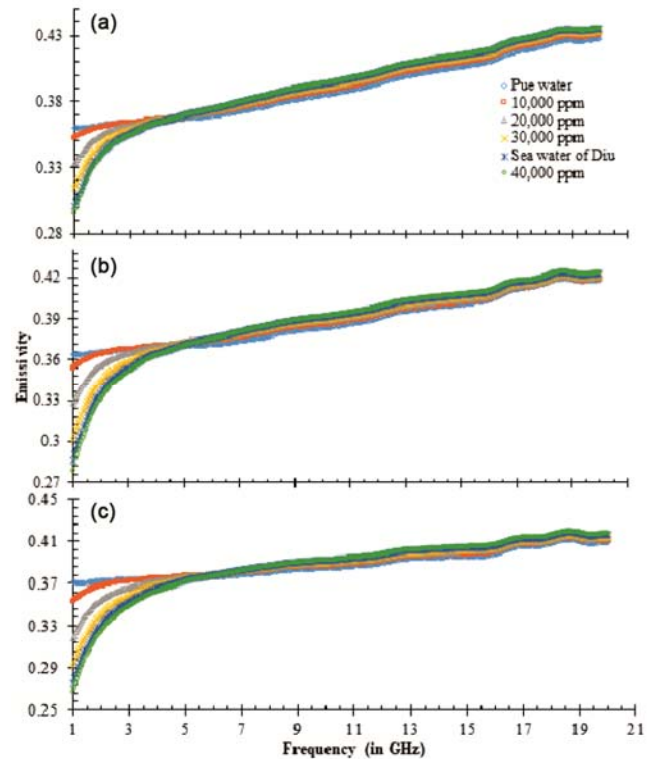


Fig. 8 — Variation of emissivity with frequency (in GHz) for pure water, Sea water sample collected from Diu, and the saline water solutions of various salinities at a) 20 °C, b) 30 °C and c) 40 °C temperatures.

almost same, after which the emissivity of the water samples slightly increases with increase in salinity. Also, after this transition point frequency, the emissivity of saline water solutions increases slowly and linearly with increase in frequency. The rate of increase in emissivity of saline water solutions with frequency is visible in lower frequency range below the transition point frequency, after which this difference becomes very small at higher frequencies. Hence we believe that, to estimate salinity of water from emissivity, the most suitable frequency range over this temperature range is below the transition point frequency dependent on temperature.

### 3.1 Estimation of sea water salinity

The salinity of water collected from Diu sea bank was estimated by comparing the dielectric loss and emissivity of the saline water of Diu sea beach with that of water solutions of known salinities.

Figure 9 shows variation of dielectric loss of water solutions with salinity at 1.4 GHz, 2.65 GHz, 5.35 GHz and 9.6 GHz microwave frequencies. It can be observed from the graph that the dielectric loss of saline water increases with increase in salinity up to 5.35 GHz, after which it does not vary appreciably with salinity. Table 2 lists the relationship between dielectric loss and salinity (S in ppm) in terms of

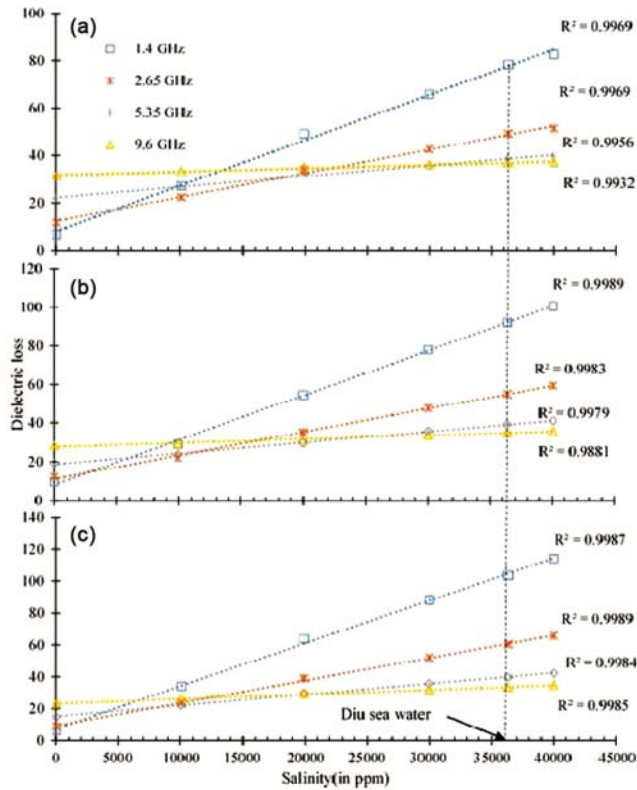


Fig. 9 — Variation of dielectric loss with Salinity (ppm) of water at temperatures (a) 20°, (b) 30° and (c) 40 °C at fixed frequencies

linear equations at specific frequencies at different temperatures. It should be noted that, while drawing trend lines and getting the equations relating the dielectric loss with salinity of water solutions in ppm, we excluded the markings of dielectric loss of sea water of Diu. From these linear trend equations, the salinity of Diu sea water was calculated by putting the values of dielectric loss of Diu sea water at given frequencies at given temperature, and are reported in the table.

Figure 10 shows variation of emissivity of water solutions with salinity, along with that of Diu sea bank water at 1.4 GHz, 2.65 GHz, 9.6 GHz, and 12

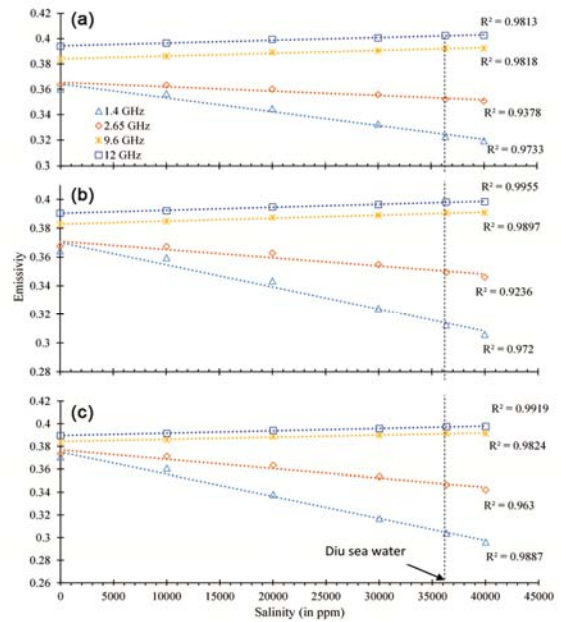


Fig. 10 — Variation of Emissivity versus Salinity at temperatures a) 20°, b) 30° and c) 40 °C at 1.4 GHz, 2.65 GHz, 9.6 GHz and 12 GHz

Table 2 — Equations obtained from figure (9) representing the linear trend lines of Dielectric loss against Salinity (S in ppm) for Pure water and saline water solutions at 20°, 30° and 40° C temperatures.

Frequency (GHz)	Temperature	Linear trend equation of dielectric loss ( $\epsilon''$ ) versus salinity (S in ppm)	$\sim R^2$ value	Experimental value of dielectric loss	Estimated salinity of Diu sea water (ppm)	Percentage deviation from Physio-chemical Lab. report
1.4GHz	20 °C	$\epsilon'' = 0.0019 S + 8.3266$	0.9964	78.32	36839	0.9%
	30 °C	$\epsilon'' = 0.0023 S + 8.205$	0.9986	92.11	36480	0.1%
	40 °C	$\epsilon'' = 0.0027 S + 7.3068$	0.9987	103.61	35666	2.3%
2.65GHz	20 °C	$\epsilon'' = 0.0010 S + 12.613$	0.9964	49.23	36618	0.3%
	30 °C	$\epsilon'' = 0.0012 S + 11.289$	0.998	55.14	36544	0.1%
	40 °C	$\epsilon'' = 0.0014 S + 9.4694$	0.9989	60.33	36327	0.5%
5.35 GHz	20 °C	$\epsilon'' = 0.0004 S + 22.34$	0.9947	38.78	41092	12.6%
	30 °C	$\epsilon'' = 0.0006 S + 18.76$	0.9974	39.10	33907	7.1%
	40 °C	$\epsilon'' = 0.0007 S + 15.231$	0.9983	39.77	35057	4.0%
9.6 GHz	20 °C	$\epsilon'' = 0.0001 S + 31.732$	0.9918	36.79	50585	38.6%
	30 °C	$\epsilon'' = 0.0002 S + 27.725$	0.9854	34.91	35904	1.6%
	40 °C	$\epsilon'' = 0.0003 S + 23.261$	0.999	33.41	33833	7.3%

Table 3 — Equations obtained from figure (9) representing the linear trend lines of Emissivity for Pure water and saline water solutions with salinity (S in ppm) for temperatures of 20 °C, 30 °C and 40 °C.

Frequency (GHz)	temperature	Linear trend equation of Emissivity (e) versus salinity (S in ppm)	$\sim R^2$ value	Experimental value of Emissivity	Estimated salinity of Diu sea water (in ppm)	Percentage deviation from Physio-chemical Lab. report
1.4GHz	20 °C	$e = -1 \times 10^{-6}S + 0.3639$	0.9702	0.33	38310	5.0%
	30 °C	$e = -2 \times 10^{-6}S + 0.3699$	0.9662	0.31	28725	21.3%
	40 °C	$e = -2 \times 10^{-6}S + 0.3751$	0.9863	0.31	35555	2.6%
2.65GHz	20 °C	$e = -3 \times 10^{-7}S + 0.3654$	0.9269	0.36	31700	13.2%
	30 °C	$e = -6 \times 10^{-7}S + 0.3708$	0.9068	0.35	35777	2.0%
	40 °C	$e = -8 \times 10^{-7}S + 0.377$	0.9549	0.35	37981	4.1%
9.6 GHz	20 °C	$e = 2 \times 10^{-7}S + 0.3841$	0.9793	0.39	31300	14.2%
	30 °C	$e = 2 \times 10^{-7}S + 0.3829$	0.9893	0.39	38930	6.7%
	40 °C	$e = 2 \times 10^{-7}S + 0.3844$	0.9816	0.39	35450	2.9%
12 GHz	20 °C	$e = 2 \times 10^{-7}S + 0.3943$	0.9789	0.40	31450	13.8%
	30 °C	$e = 2 \times 10^{-7}S + 0.3904$	0.9966	0.40	38810	6.3%
	40 °C	$e = 2 \times 10^{-7}S + 0.3896$	0.9923	0.40	39005	6.9%

GHz microwave frequencies. It can be observed from the graph that the emissivity of saline water decreases with increase in salinity below at 1.4 GHz and at 2.65 GHz, where as it slightly increases with increase in salinity at 9.6 GHz and 12 GHz. From experimental data of emissivity against salinity S (in ppm), at given spot frequencies, at temperatures 20°, 30° and 40° C (Fig. 10), the linear trend line equations relating the emissivity with salinity S (in ppm) were obtained, for Pure water and saline water solutions of salinity 10000 to 40000 ppm (excluding the data of Diu sea water). It should be noted that, while drawing trend lines and getting the equations relating the emissivity with salinity of water solutions in ppm, we excluded the markings of emissivity of sea water of Diu. Table 3 lists the relationship between emissivity (e) and salinity (S) in terms of linear equations at specific frequencies at different temperatures. From these linear trend equations, the salinity of Diu sea water was calculated by putting the values of emissivity of Diu sea water at given frequencies at given temperature, and are reported in the table.

The average salinity calculated from Table 2 and Table 3 comes out to be 36327 ppm. The estimated dielectric loss and emissivity values of Diu sea beach water at the selected frequencies were marked against the average value of calculated salinity 36327 ppm in Fig. 9 and Fig. 10, at all temperatures. It can be observed from Fig. 9 and Fig. 10 that the marks placed on the trend lines agree very well with the nature of trend lines with  $R^2$  values very close to 0.99. Further the estimated value of salinity of Diu sea water, as 36327 ppm, agrees very well with the

physico-chemical analysis report obtained from laboratory as 36720 ppm, with deviation of only 1.07 %. This suggests that by knowing the values of dielectric loss or emissivity of saline water solutions, the salinity of sea water can be estimated. We selected the frequencies of 1.4 GHz, 2.65GHz, 5.35GHz, 9.6GHz and 12 GHz for the estimation of salinity of Diu sea water in terms of its dielectric loss and emissivity, as these are the frequencies used by remote sensing satellites. This data can be useful for estimation of salinity of sea water at these temperatures using remote sensing applications.

#### 4 Conclusions

Dielectric constant and dielectric loss of distilled water and saline water solutions have been estimated over the frequency range from 1 GHz to 20 GHz. The estimated values are compared with the Stogryn equations as well as with the Klein and Swift model and found to be in good agreement with the calculated values. The dielectric loss of saline water solutions increases with increase in salinity. The dielectric loss of saline water solutions increases with the increase in temperature, up to certain transition frequency dependent on temperature, after which it decreases with increase in temperature. At lower frequencies below 4 GHz to 5.5 GHz depending on temperature, the emissivity of water decreases rapidly with decrease in frequency and increase in salinity. The salinity of Diu sea bank water estimated from the trend line equations relating dielectric loss with salinity of saline water solutions, as well as the trend line equations relating emissivity of saline water solutions with salinity in ppm is about 36,327 ppm,



which agrees very well with the value obtained from the chemical analysis of the water as 36,720 ppm.

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