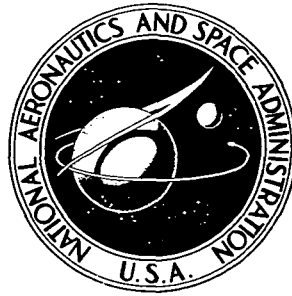


**NASA CONTRACTOR  
REPORT**



**NASA CR-2458**

**NASA CR-2458**

**CAS  
COPY FILE**

**MEASUREMENTS OF THE DIELECTRIC  
PROPERTIES OF SEA WATER AT 1.43 GHz**

*by W. W. Ho, A. W. Love, and M. J. Van Melle*

*Prepared by*  
**ROCKWELL INTERNATIONAL CORPORATION**  
Downey, Calif. 90241  
*for Langley Research Center*



**NATIONAL AERONAUTICS AND SPACE ADMINISTRATION • WASHINGTON, D. C. • DECEMBER 1974**

1. Report No. NASA CR-2458		2. Government Accession No.		3. Recipient's Catalog No.	
4. Title and Subtitle MEASUREMENTS OF THE DIELECTRIC PROPERTIES OF SEA WATER AT 1.43 GHz				5. Report Date December 1974	
				6. Performing Organization Code	
7. Author(s) W. W. Ho, A. W. Love, and M. J. Van Melle				8. Performing Organization Report No.	
				10. Work Unit No.	
9. Performing Organization Name and Address Rockwell International Corporation Science Center Space Division				11. Contract or Grant No. NAS 1-10691	
				13. Type of Report and Period Covered Contractor Report	
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, D.C. 20546				14. Sponsoring Agency Code	
15. Supplementary Notes This report describes the data reduction basis for future remote salinity measurement with an L and S-Band radiometer system. Final Report					
16. Abstract For the remote determination of salinity and temperature of water surfaces of estuaries and bay regions to accuracies of 1 ppt salinity and 0.3 kelvin surface temperature, the combination of L-band (1.4 GHz) and S-Band (2.65 GHz) radiometers as brightness temperature detectors is obtained since the brightness temperature of 1.4 GHz depends mainly on the salinity and at 2.65 GHz mainly on the surface temperature. The determination of the brightness temperature versus surface temperature with salinity as a parameter for 2.65 GHz was performed earlier and is described in contract report NASA CR-1960.  The complimentary determination of the brightness temperature versus salinity with the water surface temperature as a parameter for 1.4 GHz is performed with a capillary tube inserted into a resonance cavity.  The detailed analysis of the results indicates that the measured values are accurate to better than 0.2 percent in the electric property $\epsilon'$ and 0.4 percent in $\epsilon''$ . This implies that the calculated brightness temperature as a function of temperature and salinity is better than 0.2 kelvin. This in turn gives the possibility to reduce the measured data obtained with the two-frequency radiometer system with 1 ppt accuracy to values in the salinity range 5 to 40 ppt.					
17. Key Words (Suggested by Author(s)) Salinity L-Band radiometer S-Band radiometer Dielectric properties of radar surfaces Sea surface temperature			18. Distribution Statement  Unclassified - Unlimited  STAR Category: 13		
19. Security Classif. (of this report) Unclassified		20. Security Classif. (of this page) Unclassified		21. No. of Pages 41	22. Price* \$3.75

## CONTENTS

Section		Page
1.0	INTRODUCTION . . . . .	1
2.0	EXPERIMENTAL TECHNIQUE AND APPARATUS . . . . .	3
3.0	RESULTS . . . . .	9
3.1	Sample Preparation and Analysis . . . . .	9
3.2	Empty Cavity Measurements . . . . .	9
3.3	Distilled Water Measurements . . . . .	11
3.4	$\epsilon'$ Measurements for NaCl Solutions and Sea Water . . . . .	14
3.5	$\epsilon''$ Measurements for NaCl Solutions and Sea Water . . . . .	21
4.0	EMISSIVITY AND BRIGHTNESS TEMPERATURE CALCULATIONS . . . . .	27
5.0	REFERENCES . . . . .	35

**Page intentionally left blank**

## ILLUSTRATIONS

Figure		Page
1	Cross-Sectional Diagram of 1.43 GHz Cavity . . . . .	4
2	Pictorial Views of L-Band Cavity . . . . .	6
3	Block Diagram of Microwave and Electronic Components . . . . .	7
4	Conductivity Setup . . . . .	12
5	Measured Values of $\epsilon'$ for Distilled Water . . . . .	15
6	Measured Values of $\epsilon''$ for Distilled Water . . . . .	16
7	Dielectric Constant $\epsilon'$ of NaCl Solutions and Sea Water Samples at T = 5 C . . . . .	17
8	Dielectric Constant $\epsilon'$ of NaCl Solutions and Sea Water Samples at T = 10 C . . . . .	18
9	Dielectric Constant $\epsilon'$ of NaCl Solutions and Sea Water Samples at T = 20 C . . . . .	19
10	Dielectric Constant $\epsilon'$ of Sea Water Samples at T = 30 C . . . . .	20
11	Coefficient $a_1$ as a Function of Temperature . . . . .	22
12	Dielectric Loss $\epsilon''$ of NaCl Solutions and Sea Water Samples at T = 5 C and T = 20 C . . . . .	24
13	Dielectric Loss $\epsilon''$ of NaCl Solutions and Sea Water Samples at T = 10 C and T = 30 C . . . . .	25
14	Coefficients $c_0$ and $c_1$ as Functions of Temperature . . . . .	26
15	Emissivity Versus Sea Temperature with Salinity as a Parameter . . . . .	31
16	Brightness Temperature Versus Sea Temperature with Salinity as a Parameter . . . . .	32
17	Brightness Temperature Versus Salinity with Sea Temperature as a Parameter . . . . .	33

**Page intentionally left blank**

## TABLES

Table		Page
1	Comparison of Chlorinity Values . . . . .	10
2	$\epsilon'$ and $\epsilon''$ for Distilled Water as a Function of Temperature . . . . .	14
3	Values for the Coefficients $a_0$ and $a_1$ as Functions of Temperature . . . . .	21
4	Coefficients $c_0$ and $c_1$ as Functions of Temperature . . . . .	23
5	Relationship of Brightness Temperature and Emissivity to Salinity at 1.43 GHz . . . . .	29-30

MEASUREMENTS OF THE DIELECTRIC PROPERTIES  
OF SEA WATER AT 1.43 GHz

by

W. W. Ho, A. W. Love and M. J. Van Melle

Members of the Technical Staff  
Rockwell International Corporation

1.0 INTRODUCTION

It has been shown in previous work that one of the necessary criteria for absolute measurement of ocean surface properties by microwave radiometry is that the dielectric properties of sea water be accurately known at the frequency of observation [1]. The results of an in-depth study carried out in the past [2], which involved all aspects of the problem concerning the remote sensing of surface temperature of the world's oceans with an S-band microwave radiometer, have shown that in the absence of severe sea surface state conditions, measurements can be made which are accurate to 0.1 K in brightness temperature or 0.3 K in molecular temperature. It is the purpose of this study to extend the measurements of dielectric properties of sea water samples to L-band frequencies and to apply the laboratory experimental results to calculate ocean surface emissivities as a function of chlorinity and temperature. In this frequency region it is expected that the brightness temperature will be more sensitive to surface chlorinity than to the molecular temperature of the sea surface over fairly wide ranges of chlorinity and temperature values. For this reason, the results are also interpreted in light of possible application for the remote measurements of sea surface chlorinity.



All measurements were carried out at a frequency of 1.43 GHz, and over the temperature range of 5 C to 30 C. Since the variation in the dielectric properties of sea water can be related uniquely to the sodium chloride concentration alone and is independent of geographical location, the samples used were collected only at limited locations where the chlorinity varied from 2 o/oo to 20 o/oo. For purposes of comparison, and also to provide a check on the absolute accuracy of the measurements, the dielectric properties of distilled water and of pure sodium chloride solutions whose concentration varied from 0.3N to 0.7N, were also measured over the same temperature range.

A detailed analysis of the results indicates that the measured values are accurate to better than 0.2% in  $\epsilon'$  and 0.4% in  $\epsilon''$  which in turn implies that the calculated brightness temperatures as a function of temperature and chlorinity are accurate to better than 0.2 K.

## 2.0 EXPERIMENTAL TECHNIQUE AND APPARATUS

The method used to measure the real and imaginary parts of the dielectric constants ( $\epsilon'$  and  $\epsilon''$ ) of the samples was similar to that employed previously for the S-band measurements. A sample of known volume is introduced into a high Q  $TM_{010}$  resonant cavity by means of a capillary tube. The dielectric constants  $\epsilon'$  and  $\epsilon''$  are measured by determining respectively the shift in the cavity resonant frequency and the change in the quality factor, Q, of the cavity. Since a detailed description has been reported elsewhere [1], this report merely summarizes some of the pertinent expressions and indicates those necessary modifications made in the apparatus for working at 1.43 GHz.

The expressions relating the dielectric constants to the measured parameters of a  $TM_{010}$  cavity, for a sample introduced along the axis of the cavity in a lossless cylindrical sample tube, are given by

$$\delta = [v_o/2J_1^2(\chi_o)](\epsilon_s' - 1)(r_1/r_3)^2,$$

$$\Delta(1/Q_o) = [J_1^2(\chi_o)]^{-1} [\epsilon_s'' (r_1/r_3)^2],$$

and

$$\epsilon_s''/(\epsilon_s' - 1) = (v_o/2\delta)\Delta(1/Q_o),$$

where  $v_o$  is the resonant frequency of the cavity with the empty sample tube in place,  $\delta$  is the frequency shift due to the sample,  $\epsilon_s'$  and  $\epsilon_s''$  are the dielectric constants of the sample material,  $r_1$  and  $r_3$  are respectively the radius of the sample and the radius of the cavity,  $\Delta(1/Q_o)$  is the change in the unloaded quality factor,  $Q_o$ , of the cavity, and  $J_1(\chi_o)$  is the value of the Bessel function  $J_1(\chi)$  at the first zero of  $J_o(\chi)$ .

As was the case for the previous work at S-band, all measurements were made relative to distilled water. Aside from the obvious advantage that all systematic errors tend to cancel, there is the additional factor that at 1.43 GHz, the dielectric loss in distilled water is relatively small so that much larger sample tubes, whose volume can be measured to higher accuracy, can be used. This in turn implies that higher precision can be achieved in the absolute measurements of the dielectric constants.

An assembly drawing of the cavity is shown in Figure 1. The main body was constructed of oxygen-free copper and a water jacket was soldered to the outside of the cavity for precision temperature control. Coupling to the cavity was achieved via a coaxial loop whose location and approximate

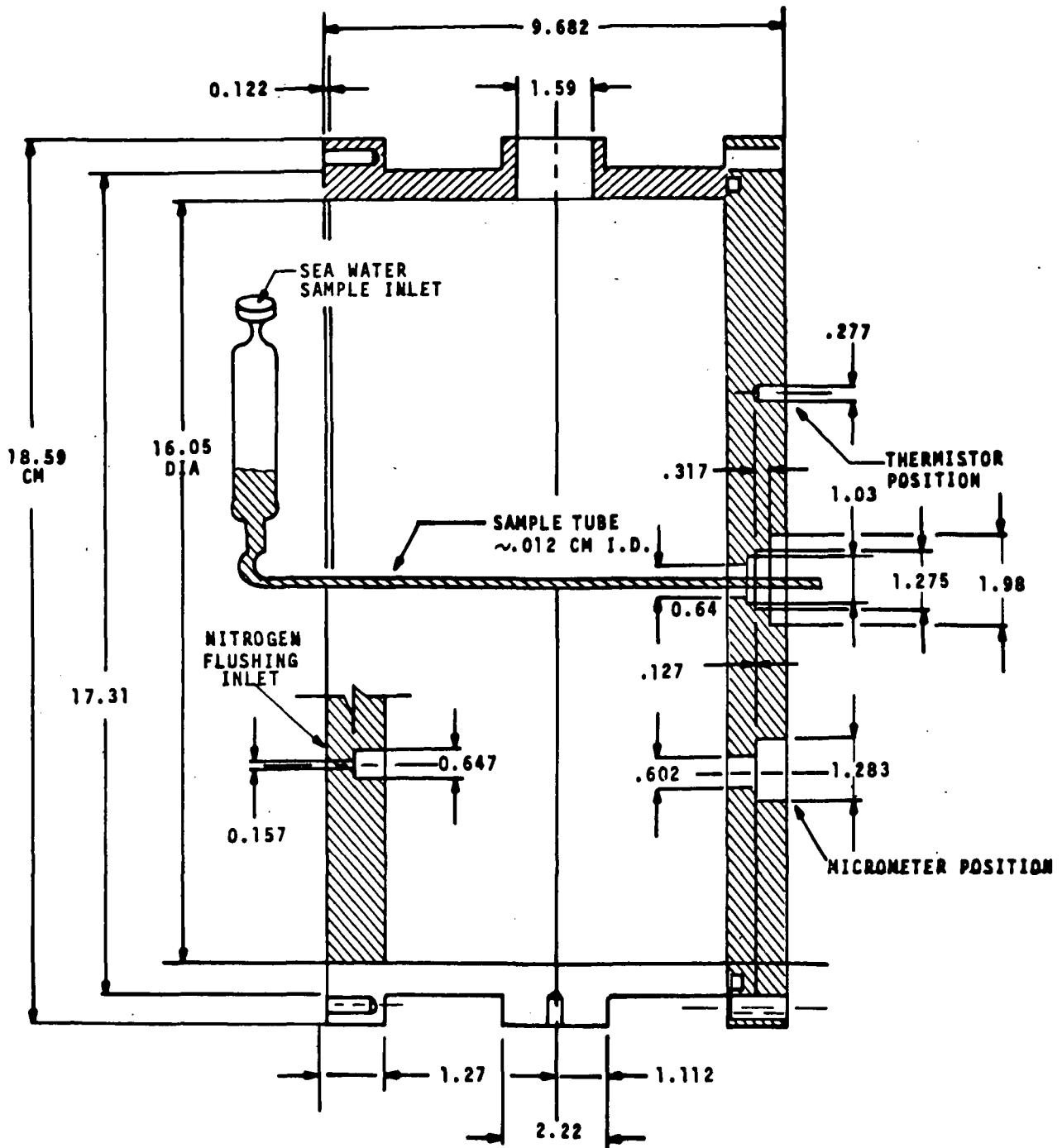
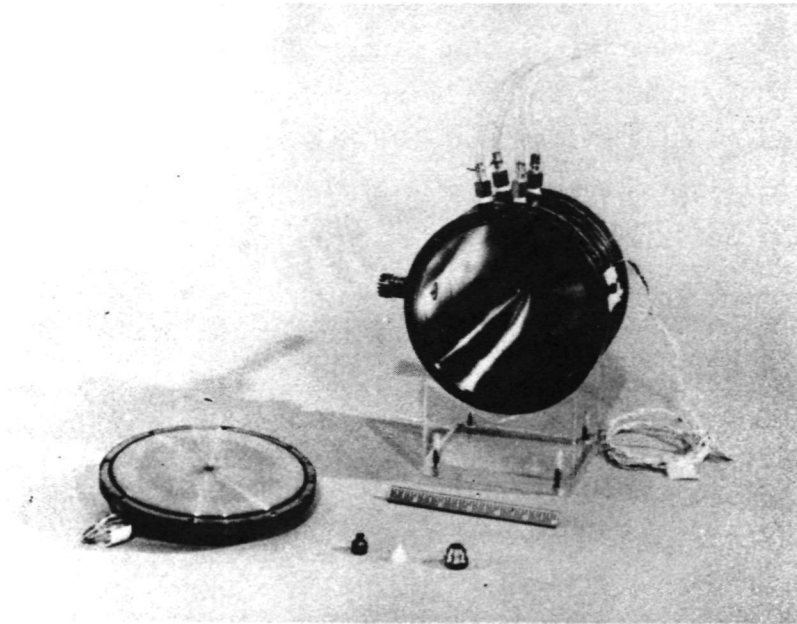


Figure 1 Cross-Sectional Diagram of 1.43 GHz Cavity

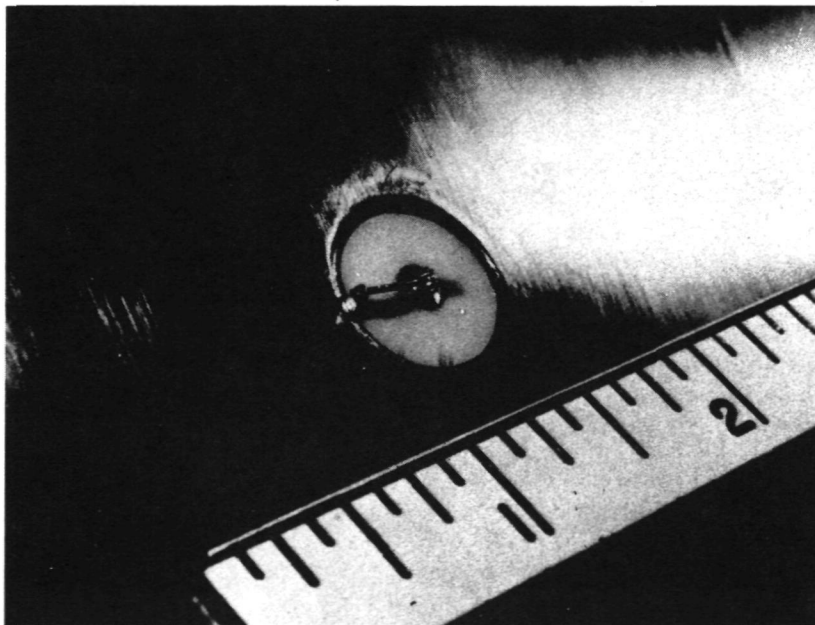
dimensions are shown in Figure 2. The loop size was adjusted so that a coupling coefficient of better than 99% was achieved for the empty cavity. The quartz sample tubes were centered along the axis of the cavity by means of a set of precision-machined teflon plugs. Provision was made to tune the resonant frequency of the cavity by means of a micrometer screw with a 2.5 cm total travel. Since it was required that measurements be made at temperatures below ambient, all joints were either sealed with rubber O-rings or with press-fit teflon plugs, and the cavity was always flushed with dry nitrogen through the small opening shown in Figure 1 before each set of measurements in order to prevent water vapor condensation. The cavity was placed in a foamed, insulated enclosure and the temperature of the assembly was controlled with circulating water from an external constant-temperature water bath. The cavity temperature was monitored with a set of thermistors embedded in the cavity body. These measurements indicated stability to be better than 0.03 C.

The sample tube was fixed in position as shown in Figure 1, and water samples were introduced and removed from the capillary section within the cavity by applying compressed dry nitrogen at the inlet. The tube was flushed with distilled water several times after each measurement and then dried with nitrogen to insure that no contamination of the sample could take place due to residues from the previous run. Typical change in the resonant frequency for dry tube measurements during the course of a few hours is of the order of 1 kHz, or 7 parts in  $10^7$ , indicating excellent repeatability and stability. This is only slightly larger than the change due to typical observed systematic temperature drift over the same time period. Measurements carried out for the same sample, while repeating the sample handling procedure outlined above, agree to within  $\pm 0.3$  kHz, corresponding to a measurement accuracy of better than 0.1% in  $\epsilon'$  for most cases.

A complete schematic diagram of the electronic equipment and microwave components used in the measurements is shown in Figure 3. Since at L-band, the transmission characteristics of coaxial components approach those of waveguide devices, for convenience coaxial components were used throughout. The frequency generation and power-leveling scheme is similar to that used in previous work at S-band, as are the basic modulation and phase-locking techniques.



2a. VIEW OF L-BAND CAVITY WITH END PLATE REMOVED



2b. CLOSE-UP OF LOOP COUPLING

Figure 2 Pictorial Views of L-Band Cavity

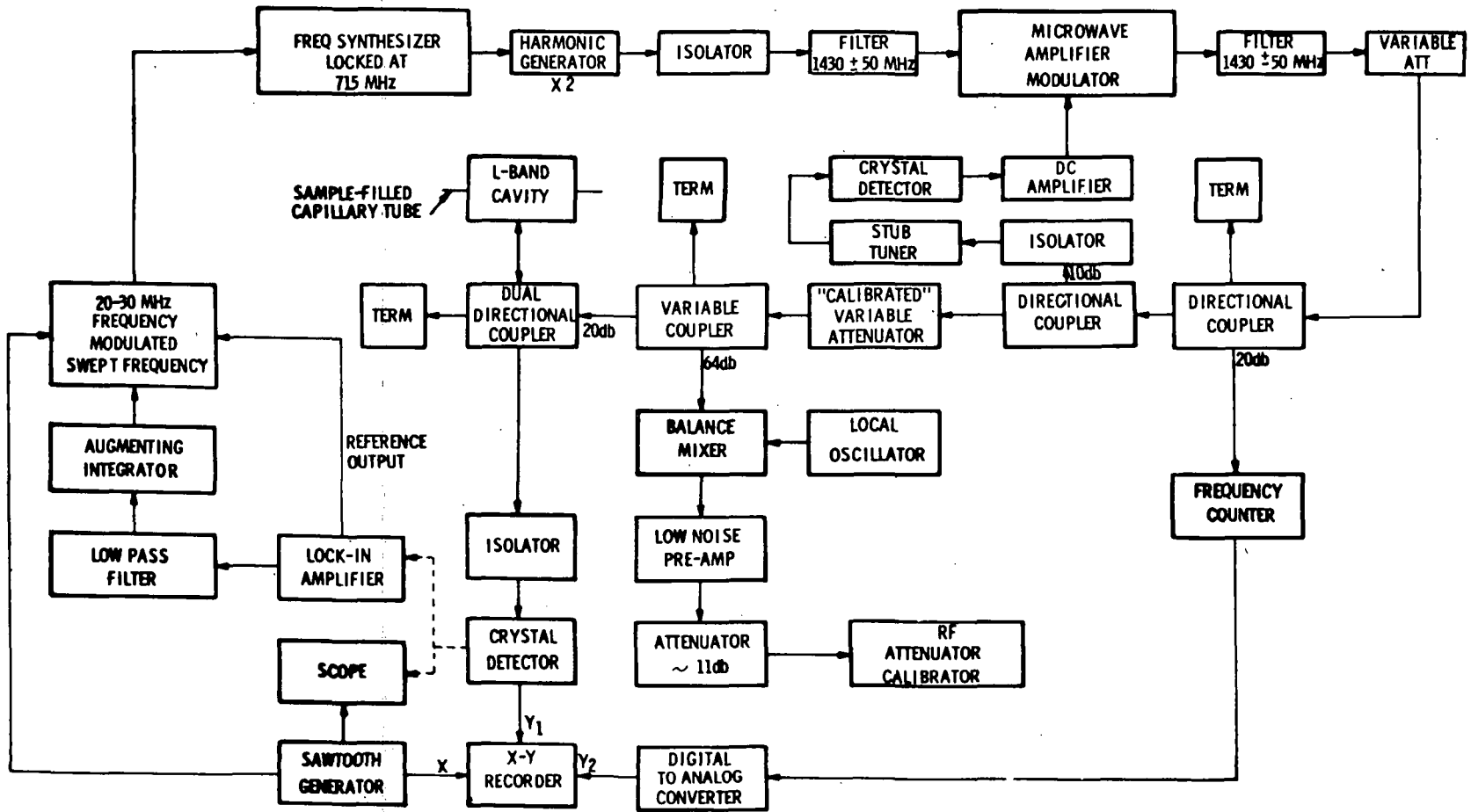


Figure 3 Block Diagram of Microwave and Electronic Components

For resonant frequency measurements, the frequency-modulated microwave power reflected from the cavity is detected by the crystal diode and the modulation-component of the output is measured with a lock-in detector/amplifier. When the modulation is small compared to the width of the cavity resonance, the signal is proportional to the derivative of the resonance curve and the output at the resonant frequency is zero. The output of the lock-in amplifier is then used to control the frequency of the microwave oscillator in a feedback loop so that the oscillator is always at the resonant frequency of the cavity. This output is directly measured with a frequency counter. The measurements were found to be accurate to  $\pm 100$  Hz.

For attenuation measurements, the variable attenuator was calibrated at the end of each series of measurements with a substitution-type RF attenuation calibrator. The variable directional coupler was set at 64 db and the signal from the coupled port was mixed with the output of a local oscillator whose frequency was set to give a difference frequency equal to the IF frequency of the Attenuator Calibrator (30.44 MHz). The difference signal is then amplified by a low noise linear preamplifier and applied to the input of the attenuation calibrator. A 11 db attenuator pad was found necessary to prevent saturation and non-linearity. The microwave variable attenuator was initially set at a convenient reference setting and the calibrator was nulled by inserting a known IF attenuation. An increase or decrease in the microwave variable attenuator setting is then directly measured by resetting the calibrator for null indication. The repeatability of the setting was found to be  $\pm 0.02$  db, and the calibration for the microwave attenuator over a period of weeks changed by at most 0.04 db.

## 3.0 RESULTS

### 3.1 Sample Preparation and Analysis

Sea water samples, and sodium chloride solutions from 0.3N to 0.7N prepared with distilled water, were analyzed to an accuracy of 0.3% with a silver nitrate titration method. Sea water samples of low chlorinity were obtained from various locations in the Chesapeake Bay area. High chlorinity samples were obtained from the coastal waters of southern California. The Chesapeake Bay samples were also analyzed for salinity with a conductivity bridge method by Old Dominion University. The results of the two methods of analysis are compared in Table 1. As can be seen, the average difference between the two sets of results is of the order of 0.5%, with the conductivity method giving consistently lower values of chlorinity. This discrepancy is possibly due to the difference in experimental method, or perhaps to sample evaporation with time, since, due to shipping from the east coast, the titration measurements were carried out several weeks after the conductivity measurements. For consistency, the titration values were used in the subsequent data analysis since all dielectric measurements were performed nearly concurrently with the titration of the samples.

### 3.2 Empty Cavity Measurements

Measurements were performed on the resonant frequency and the Q factor of the empty cavity as a function of temperature. At 20 C, the resonant frequency was found to be 1430.677 MHz which corresponds to an effective diameter of 16.04036 cm. The diameter of the cavity as measured by a caliper was  $16.048 \pm .003$  cm, indicating agreement to within 0.05%. The fractional change in resonant frequency with temperature was found to be approximately  $1.55 \times 10^{-5}$  per degree centigrade and is linear over the range of measurements. This value is consistent with the thermal expansion coefficient of oxygen-free copper.

The Q of the empty cavity, measured by the standard method previously reported, [1], was found to be 20,435 at 5 C, 20,367 at 10 C, 20,000 at 20 C, and 19,858 at 30 C. The repeatability of the measurements was found to be better than 0.2%. The theoretical Q of the cavity is calculated to be 24,000 at 20 C or 20% higher than the actual measured Q. This agreement is good by microwave standards since microscopic surface irregularities



Table 1 Comparison of Chlorinity Values

Sample No.	Chlorinity from titration (‰)	Chlorinity from Conductivity (‰)	‰ Difference
1	13.94	13.84	0.72
2	13.23	13.22	0.08
3	12.99	12.91	0.62
4	11.97	11.89	0.67
5	11.08	10.97	1.00
6	9.93	9.886	0.44
7	8.30	8.256	0.53
8	7.87	7.856	0.18
9	6.99	6.973	0.24
10	4.57	4.523	1.00
11	2.27	2.266	0.18
12	0.224	0.667	*
13	18.72	not measured	
14	19.25	not measured	
15	19.50	not measured	

\*Large error in measurement due to low chlorinity.

never allow attainment of surface conductivities as high as those calculated from the DC conductivity of the metal. The decrease of Q corresponds well with the decrease of conductivity with increasing temperature.

### 3.3 Distilled Water Measurements

The frequency shift and the change in Q of the cavity were measured for distilled water at 5 C, 10 C, 20 C, and 30 C with a variety of different size sample tubes. Both triple-distilled water and de-ionized water were used with no measurable difference in the results. For the shift measurements, the data obtained for different sample tubes agreed very well with each other, i.e. the ratio of the frequency shift at each temperature for two different size sample tubes was a constant to within 0.05%, the constant being the ratio of the volumes of the two sample tubes. For optimal sensitivity, the sample tube size was chosen such that the frequency shifts were of the order of 1.2 MHz with a corresponding decrease in Q by about a factor of 4 ( $\sim 5000$ ). The Q of the cavity was measured to an accuracy of  $\pm 0.15\%$ .

The volume of the sample was measured by two different methods. After a full set of data was obtained, the sample tube was removed from the cavity and cut at the exact positions corresponding to the inner boundary walls of the cavity. The tube was then mounted in a constant temperature ice/water bath fixture as shown in Figure 4. The sample tube was then filled with a standard 1N KCl solution whose conductivity is accurately known, and the resistance of the KCl solution contained in the sample tube was measured with an A.C. bridge. For the sample tube diameter and length in question the resistance was of the order of  $100K\Omega$ . The resistance of the empty tube, as measured by trapping a section of air in the capillary sample tube was of the order of 1000 megohms and stray effects occurring between the ends of the capillary tube and the platinum electrodes were found to be negligible (less than  $10\ \Omega$ ). The length of the tube was measured with a travelling microscope to better than 0.05% and the resistance values were measured to better than 1 part in  $10^4$ .

For a uniform cross-sectional area tube of length  $l$  filled with a conductor of conductance K, the volume of the sample is related to its total resistance R by,

$$V = \frac{l^2}{KR} .$$

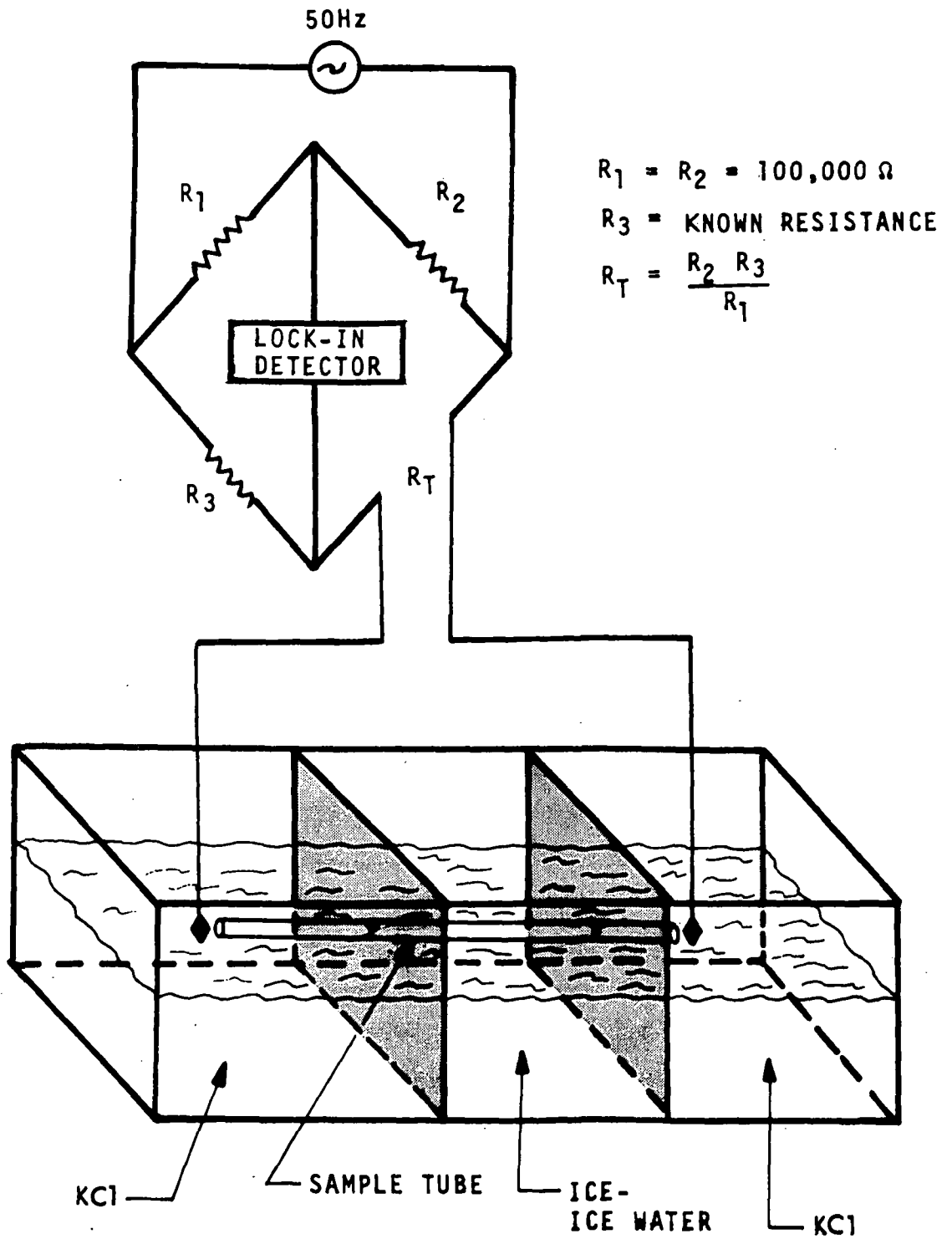


Figure 4. Conductivity Setup

For extremely non-uniform tubes, the above method breaks down in determining the volume of the sample since the result will more heavily weight the smaller cross-sectional areas, and the volume measured will be smaller than the true volume of the sample. It can be shown, for a sample tube of uniform taper whose cross-sectional area varies as  $A = A_0 + A_1 \ell$ , that the measured volume  $V_m$  is related to the true volume  $V_o$  by the expression

$$V_o/V_m = 1 + \frac{1}{12} (x^2 - x^3 + \dots)$$

where  $x = (A_1 \ell_o)/A_o$ , and  $\ell_o$  is the length of the tube.

For  $x = 0.05$ , i.e. a 5% taper in the tube, the error introduced is of the order of only 0.02% whereas for a 10% taper, the error is of the order 0.08%.

Since for the present application, the sample tubes used were chosen for non-uniformity of less than 5%, the above method is well-suited to the measurements and the probable error introduced should be at least less than 0.05%.

After the above measurement was performed on the sample tube, the tube diameter was measured directly by potting the tube in epoxy and sectioning it into approximately 10 pieces. Each end was photographed and a certified scale was used to compute the magnification factor. The photographs were measured and an average value was computed for the cross-sectional area.

The two results, when compared, agreed to within 0.05% which is approximately the uncertainty expected for the second method. For the calculation of the absolute values of  $\epsilon'$  and  $\epsilon''$ , an average value from the results of the two measurements was used.

The results for  $\epsilon'$  and  $\epsilon''$  are tabulated in Table 2 and plotted in Figures 5 and 6. They are consistent with previous measurements by other workers as well as being in good agreement with the values calculated from the data deduced by Hasted with a "constraint filtering program" which utilizes all the available data on water at all frequencies [3]. The agreement in  $\epsilon'$  is within 0.2%, while the value of  $\epsilon''$  is slightly lower (about 2%) than the calculated values. This is not very surprising since the calculated value for  $\epsilon''$  is, to first order, linear in the relaxation time which is only determined to 2nd place accuracy by Hasted's method.

The dashed-dot line in Figure 5 is the static, or DC value, for the dielectric constant of distilled water.

### 3.4 $\epsilon'$ Measurements for NaCl Solutions and Sea Water

The real part of the dielectric constant was determined by measuring the frequency shift due to the sample in a given sample tube and then comparing it to the shift produced by distilled water in the same tube. Different size tubes were used for different samples, depending on the chlorinity of the sample. The results of these relative measurements are shown in Figures 7, 8, 9, and 10. As was found to be the case at S-band, the data can be fitted accurately over the entire range of chlorinity\* with a straight line, with the sea water data shifted slightly from that for NaCl solutions.

The data were least-square fitted to expressions of the form,

$$(\epsilon'_w - 1)/(\epsilon'_s - 1) = a_0 + a_1 x$$

where  $x$  is the chlorinity in  $^{\circ}/\text{oo}$ ,  $\epsilon'_w$  is the dielectric constant for distilled water and  $\epsilon'_s$  that for the sample.

Table 2  $\epsilon'$  and  $\epsilon''$  for Distilled Water as a Function of Temperature

Temperature	$\epsilon'$	$\epsilon''$
5 C	84.54	10.742
10 C	82.96	8.888
20 C	79.56	6.285
30 C	76.14	4.783

\*Sea water is usually characterized, not by chlorinity, but by salinity, defined by, Salinity in  $^{\circ}/\text{oo} = 0.03 + 1.805$  (Chlorinity in  $^{\circ}/\text{oo}$ ).

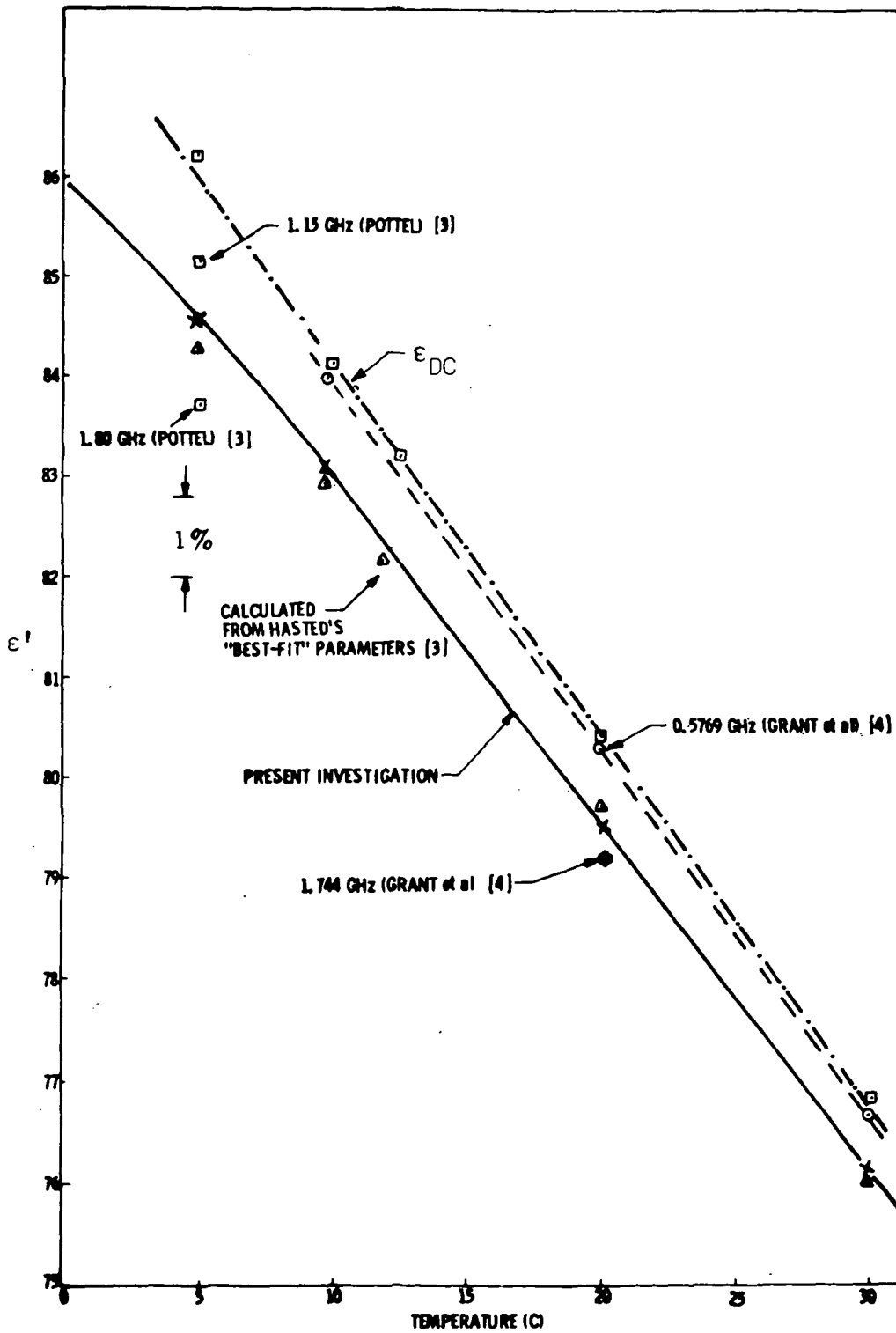


Figure 5 Measured Values of  $\epsilon'$  for Distilled Water

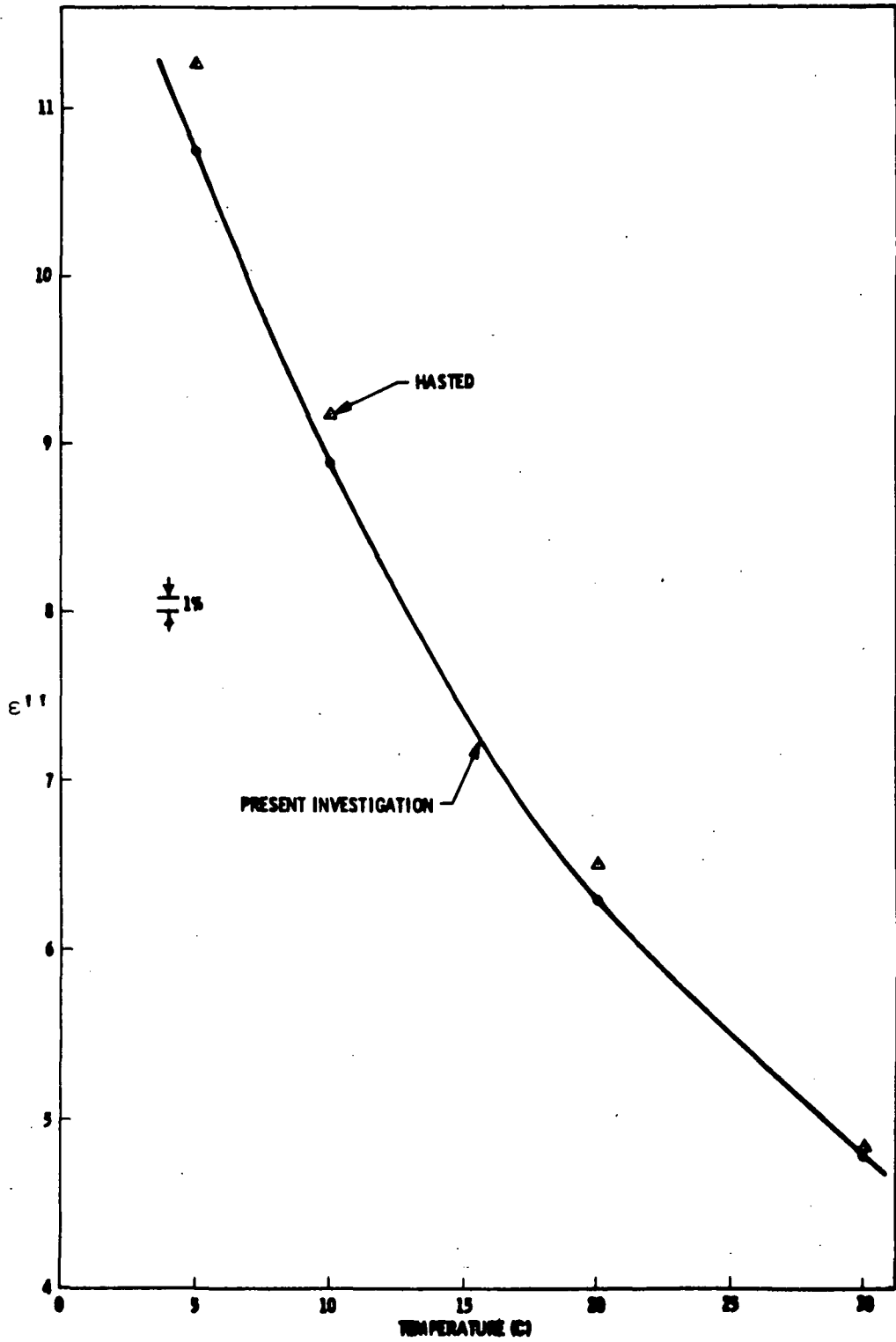


Figure 6 Measured Values of  $\epsilon''$  for Distilled Water

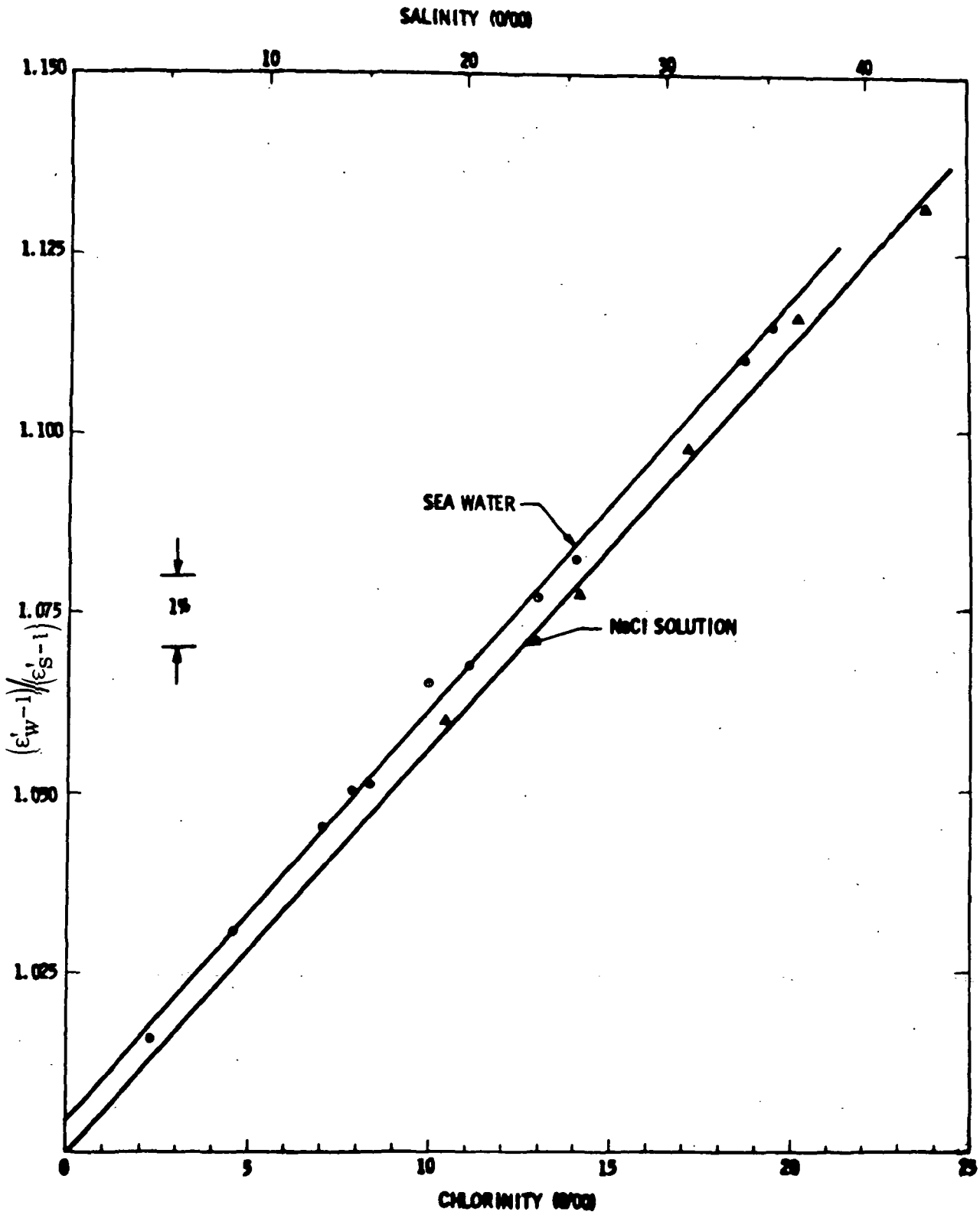


Figure 7 Dielectric Constant  $\epsilon'$  of NaCl Solution and Sea Water Samples at  $T = 5^\circ\text{C}$



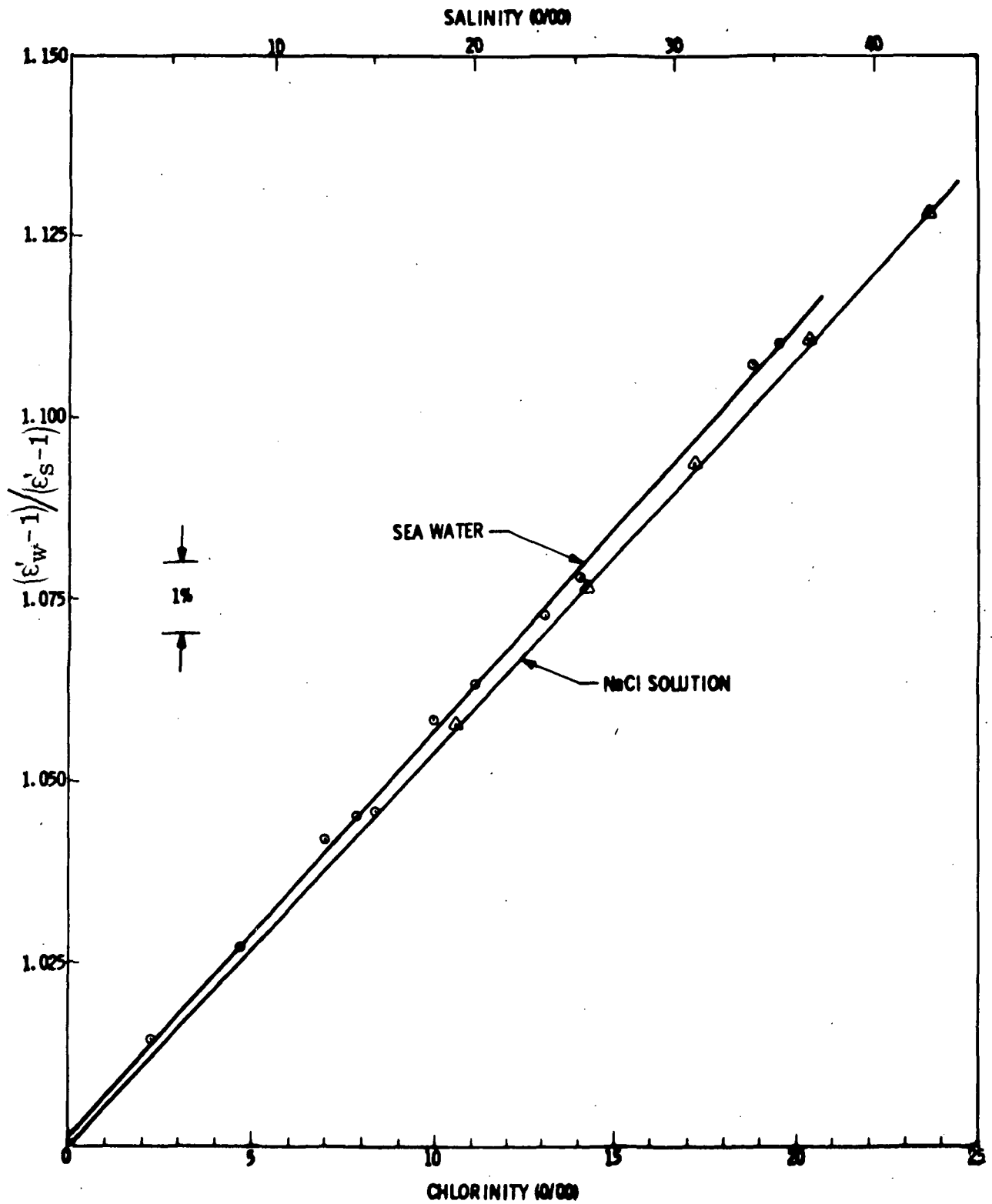


Figure 8 Dielectric Constant  $\epsilon'$  of NaCl Solutions and Sea Water Samples at  $T = 10\text{ C}$

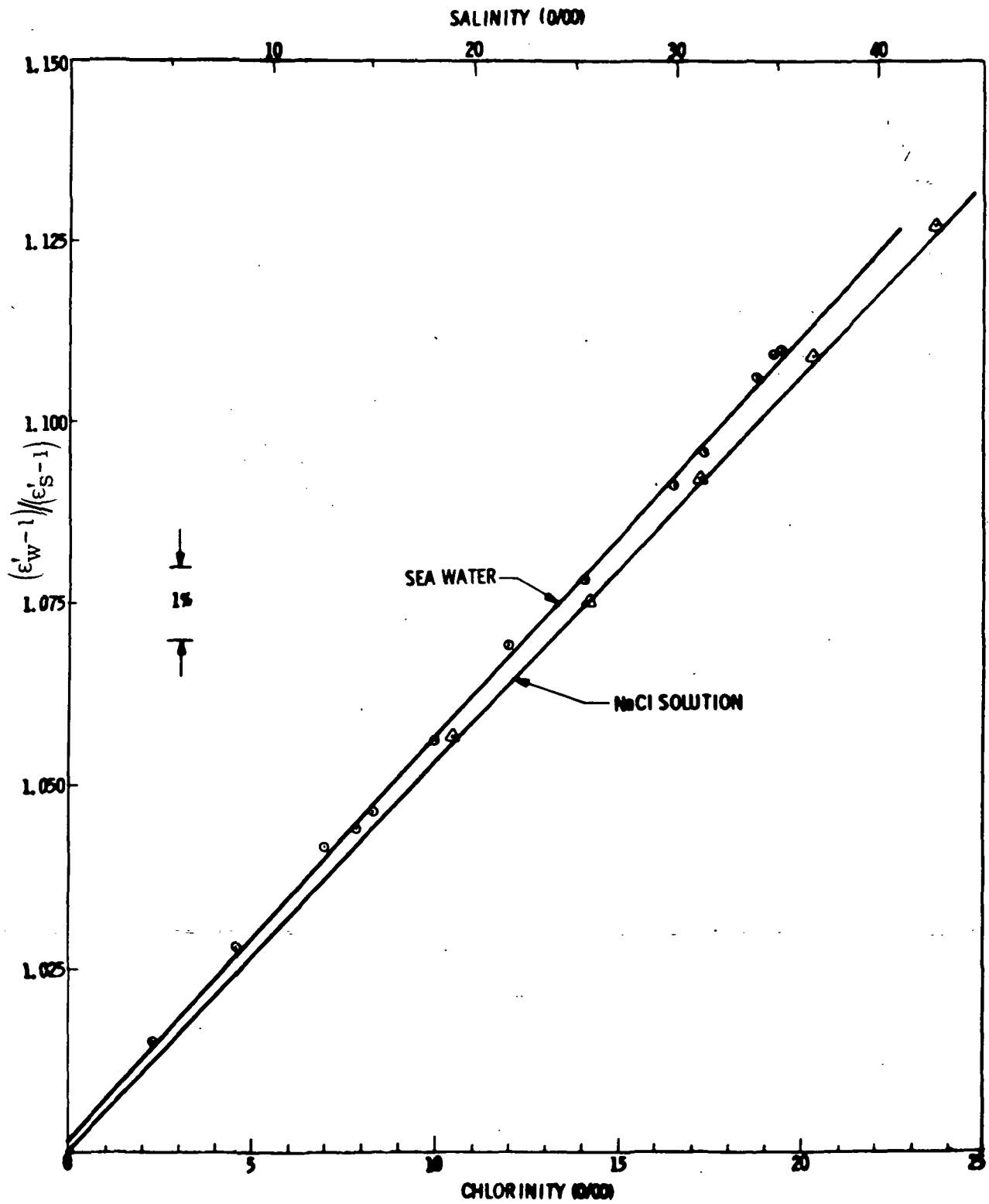


Figure 9 Dielectric Constant  $\epsilon'$  of NaCl Solutions and Sea Water Samples at  $T = 20\text{ C}$

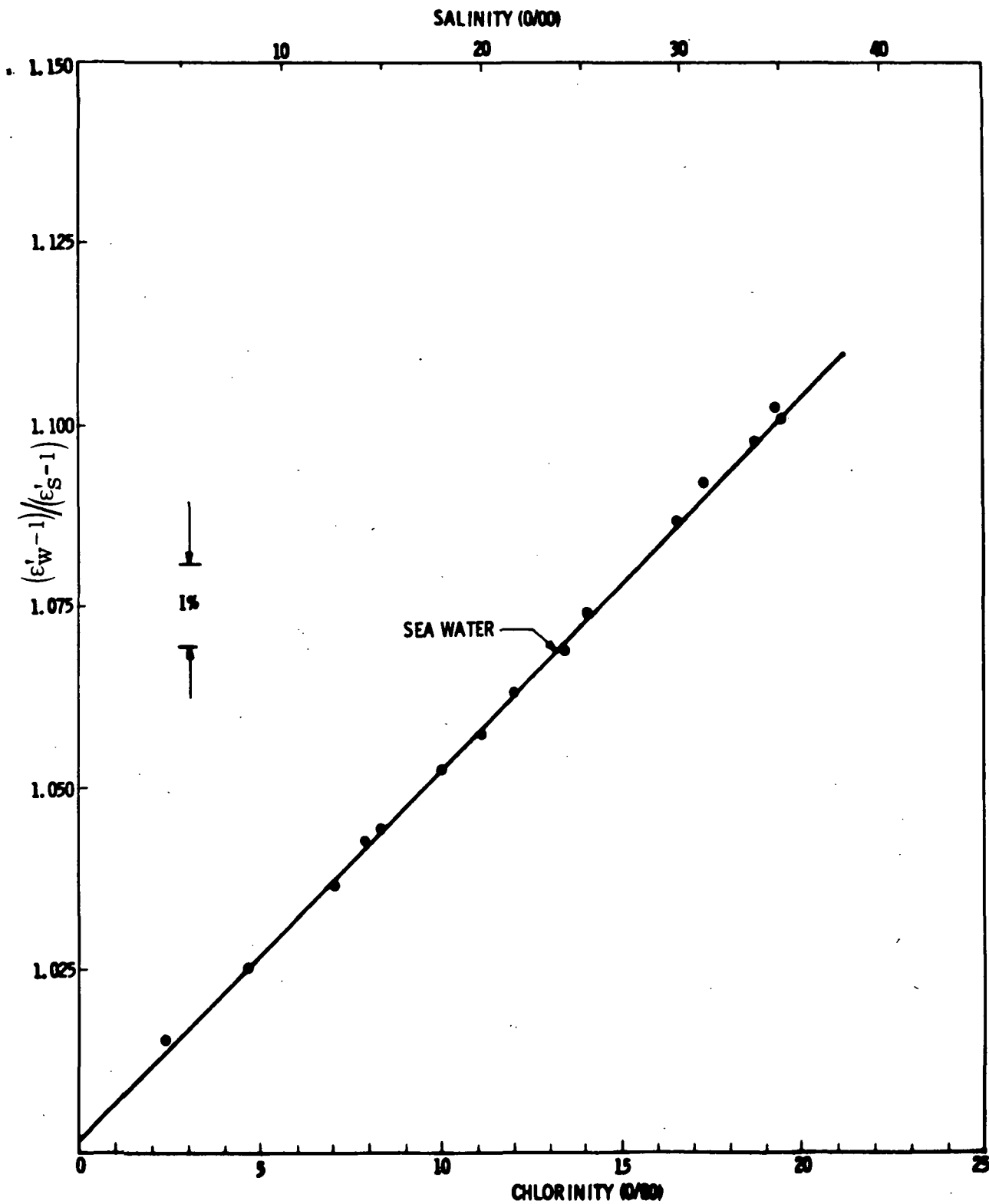


Figure 10 Dielectric Constant  $\epsilon'$  of Sea Water Samples at  $T = 30\text{ C}$

Table 3 Values for the Coefficients  $a_0$  and  $a_1$  as  
Functions of Temperature

Temp.	$a_0$	$\Delta a_0$	$a_1$	$\Delta a_1$	RMS deviation of data points from best fit value
5 C	1.0040	0.0007	$5.67 \times 10^{-3}$	$5 \times 10^{-5}$	0.0009
10 C	1.0015	0.0008	$5.56 \times 10^{-3}$	$7 \times 10^{-5}$	0.0010
20 C	1.0017	0.0007	$5.50 \times 10^{-3}$	$6 \times 10^{-5}$	0.0010
30 C	1.0016	0.0007	$5.14 \times 10^{-3}$	$6 \times 10^{-5}$	0.0010

The results for  $a_0$  and  $a_1$  at each of the four temperatures under consideration are tabulated in Table 3 together with the estimated errors. As can be seen, the rms deviation of the data points from the values computed from the best-fit expressions are of the order of 0.1%. The temperature dependence of  $a_1$  is shown in Figure 11.

It is interesting to note that the values of  $\epsilon'$  do not reduce to the value obtained for distilled water when extrapolated to zero chlorinity, i.e. the  $a_0$  coefficients are not exactly equal to unity. This is most probably due to the fact that the samples used were, for the most part, obtained from brackish water rather than by diluting sea water with distilled water. It is well known that the relative concentration of the various ions in coastal water regions near rivers does not stay constant as is the case for the open ocean. In particular, the sulfate and nitrate concentration tends to increase in relation to the chloride ions.

A similar effect was noticed for brackish water samples in the S-band work.

### 3.5 $\epsilon''$ Measurements for NaCl Solutions and Sea Water

The dielectric losses were measured by observing the changes in  $Q$  of the cavity from that for the empty cavity. The sample size was chosen such that the measured  $Q$  was in the range from 3000 to 7000. The results were then used, in conjunction with the observed frequency shift obtained for each sample while using the same sample tube, to calculate the quantity  $\epsilon''_s / (\epsilon'_s - 1)$ .

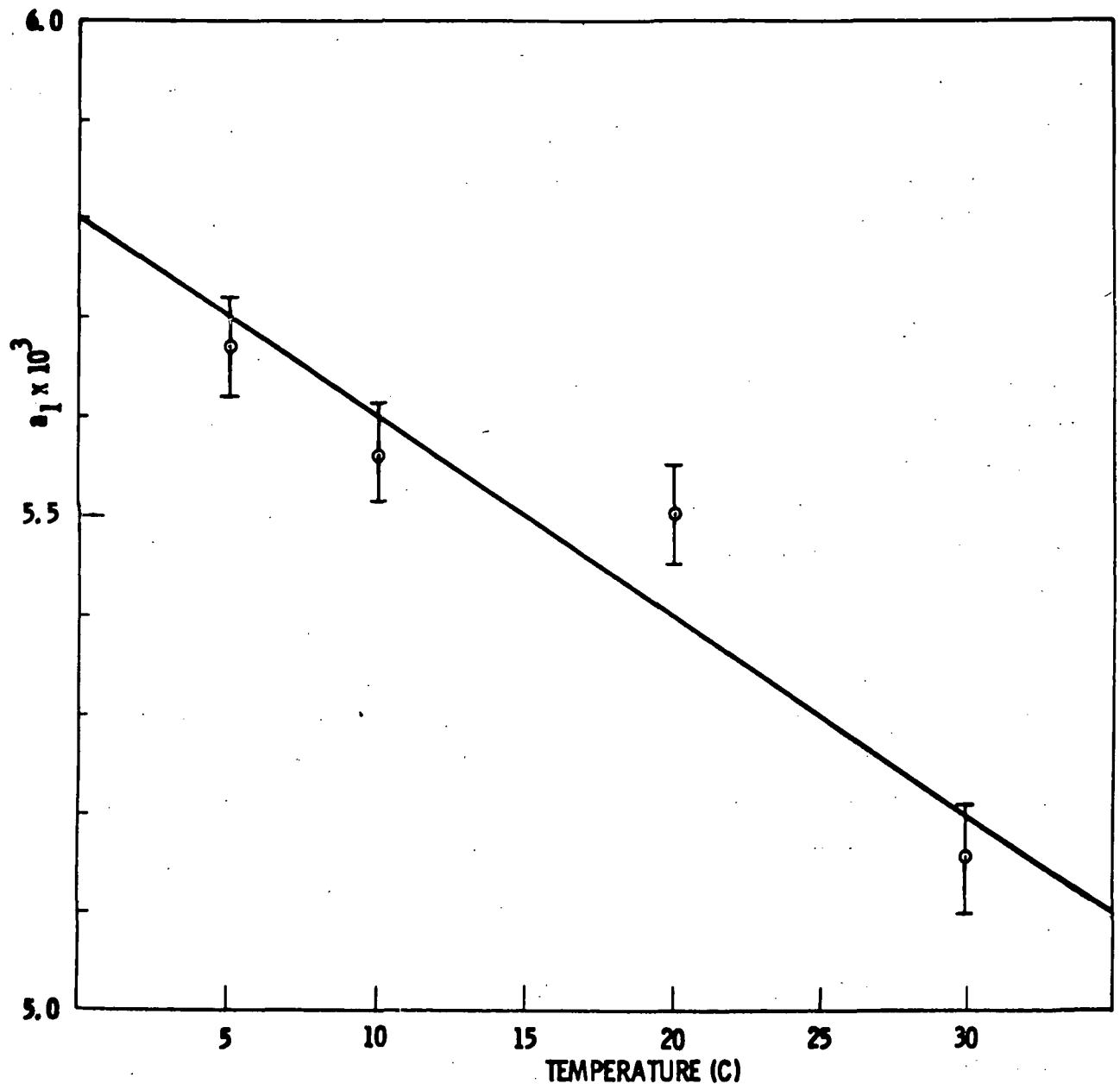


Figure 11 Coefficient  $a_1$  as a Function of Temperature

As the conductivity contribution to the dielectric loss varies inversely with frequency, the values for  $\epsilon''$  at 1.43 GHz are quite large and, in cases of high chlorinity, exceed those for  $\epsilon'$ . This condition imposes conflicting requirements in the measurements since the sample tube size cannot always be chosen such that the accuracy for both the frequency shift and Q measurements are simultaneously maximized. Consequently, the uncertainty in the measured dielectric losses is somewhat larger than that for  $\epsilon'$ .

The results of these measurements are shown in Figures 12 and 13, and the relatively larger scatter in the data points reflects the above mentioned difficulty.

As can be seen from the graphs, good linear fit in chlorinity is again obtained, with the sea water data showing slightly more dielectric loss than that for NaCl solutions of equivalent chlorinity.

A least square fit was made to an expression of the form,

$$\epsilon''_s / (\epsilon'_s - 1) = c_0 + c_1 x,$$

The results for  $c_0$  and  $c_1$  together with their error estimates are given in Table 4.

The temperature dependence of the coefficient  $c_0$  and  $c_1$  are shown in Figure 14, together with the corresponding values of  $c_0$  obtained for distilled water. As in the case for  $\epsilon'$ , it can be seen that the sea water samples at zero chlorinity give a slightly larger dielectric loss than those for distilled water.

Table 4 Coefficients  $c_0$  and  $c_1$  as Functions of Temperature

Temp.	$c_0$	$\Delta c_0$	$c_1$	$\Delta c_1$	RMS deviation of data points from best fit value
5 C	0.1368	0.0041	0.02765	$3.4 \times 10^{-4}$	$5.4 \times 10^{-3}$
10 C	0.1178	0.0035	0.03282	$3.2 \times 10^{-4}$	$5.9 \times 10^{-3}$
20 C	0.0864	0.0033	0.04391	$2.8 \times 10^{-4}$	$5.1 \times 10^{-3}$
30 C	0.0653	0.0052	0.05809	$4.5 \times 10^{-4}$	$9.2 \times 10^{-3}$

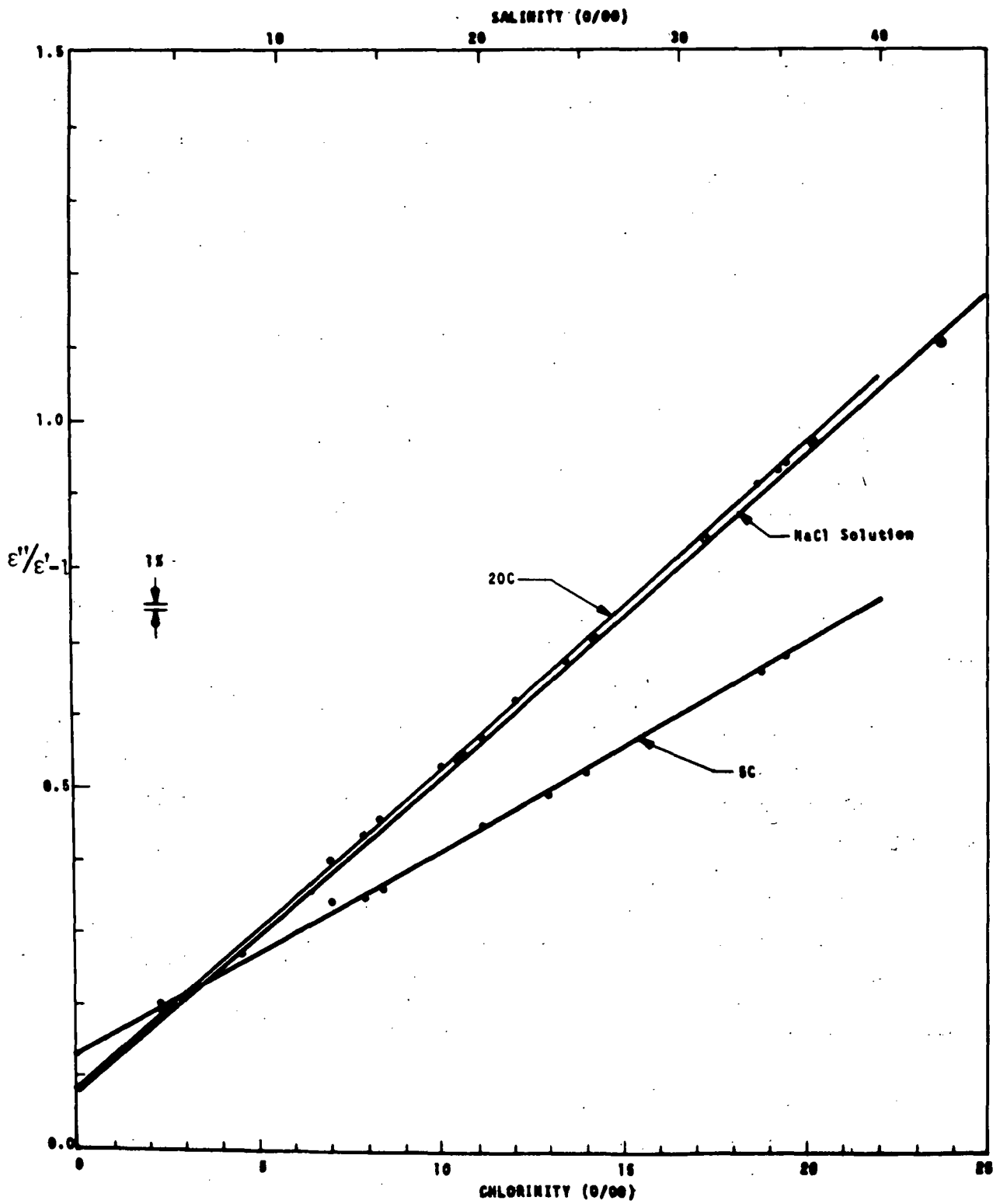


Figure 12 Dielectric Loss  $\epsilon''$  of NaCl Solutions and Sea Water Samples at T = 5 C and T = 20 C

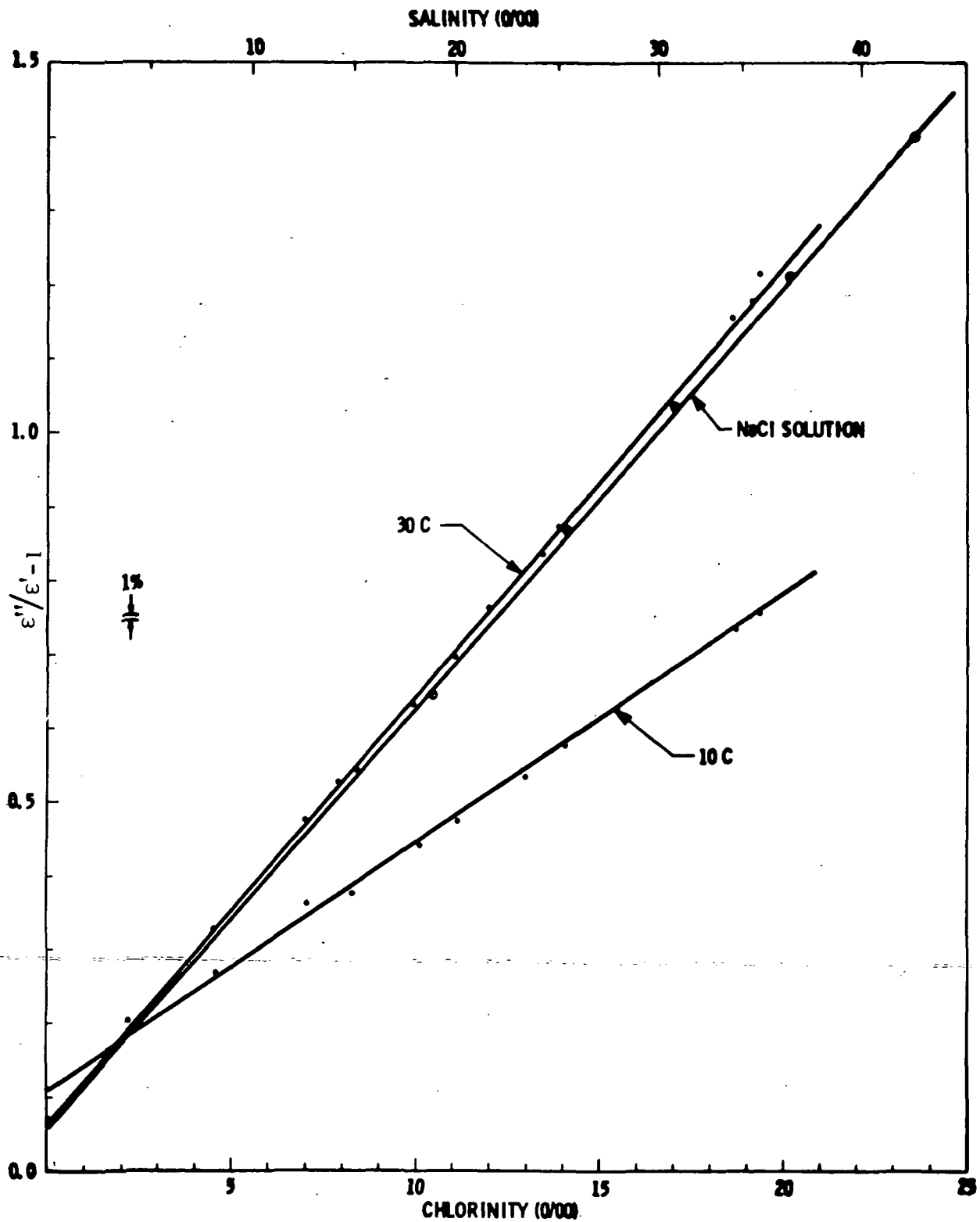


Figure 13 Dielectric Loss  $\epsilon''$  of NaCl Solutions and Sea Water Samples at T = 10 C and T = 30 C



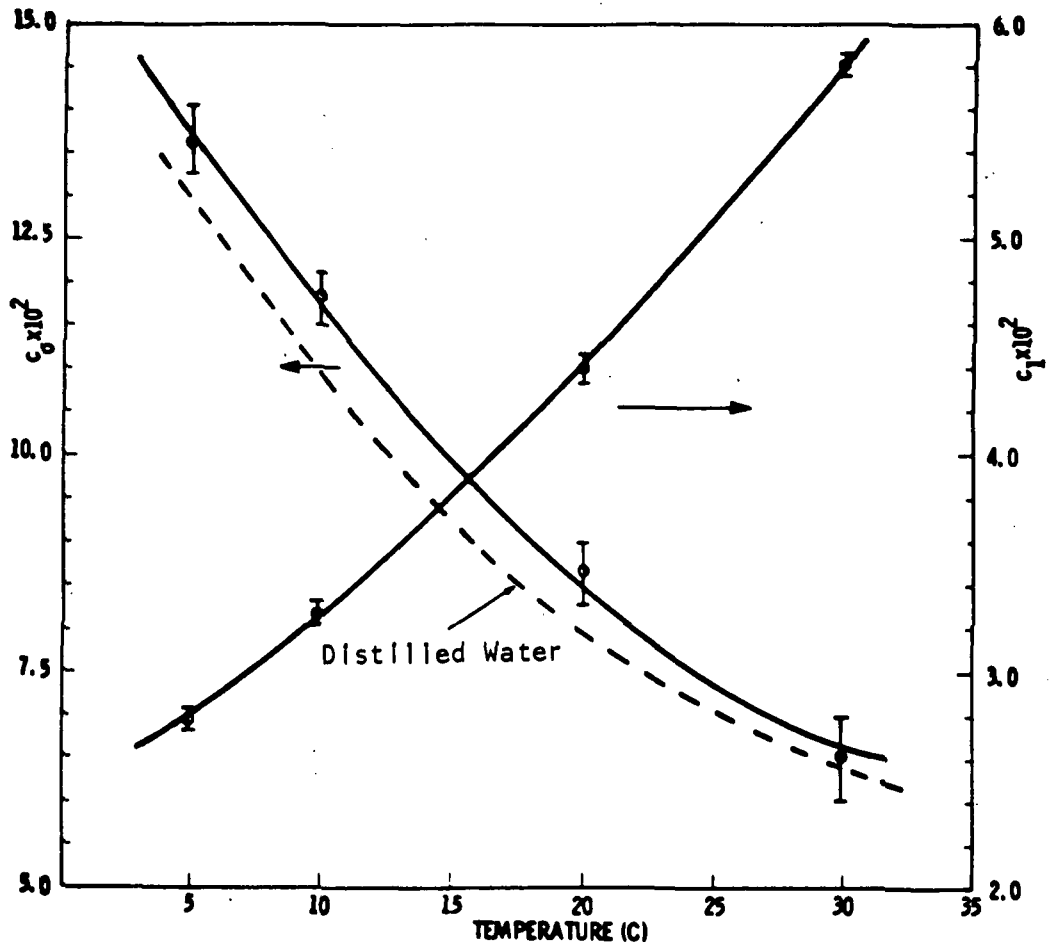


Figure 14. Coefficients  $c_0$  and  $c_1$  as Functions of Temperature

#### 4.0 EMISSIVITY AND BRIGHTNESS TEMPERATURE CALCULATIONS

The emissivity for radiation viewed normal to a smooth dielectric surface is given by

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

where  $\epsilon$  is the complex dielectric constant of the surface material.

The brightness temperature  $T_B$  is then given by

$$T_B = eT.$$

The emissivity and brightness temperature can be computed directly for sea water from the data given in Tables 2, 3, and 4, for conditions under which the present experiments were carried out. For this purpose, it is more convenient to rewrite the sea water expressions for  $\epsilon'$  and  $\epsilon''$  in the form,

$$\epsilon'(x,T) = (\epsilon'_w + a_0 + a_1 x - 1) / (a_0 + a_1 x)$$

$$\epsilon''(x,T) = (c_0 + c_1 x)(\epsilon'_w - 1) / (a_0 + a_1 x)$$

where  $\epsilon'_w$  is the real part of the dielectric constant for distilled water at temperature  $T$ ,  $x$  is the chlorinity in o/oo, and all other parameters are as previously defined.

It is noted in these expressions that all quantities are functions only of temperature, whose values can be obtained, within the range of validity of the experimental data, by fitting the values given in Tables 3 and 4 to expressions involving the temperature alone. These fits are strictly empirical but the results obtained are consistent with the expected accuracy of the measurements and hence may be used in subsequent calculations without introducing any additional error.

The expressions obtained for these parameters and coefficients are;

$$\epsilon'_w = 85.98 - 0.271T - 3.70 \times 10^{-3}T^2 + 6.0 \times 10^{-5}T^3$$

$$\epsilon''_w = 13.03 - 0.5062T + 9.91 \times 10^{-3}T^2 - 7.3 \times 10^{-5}T^3$$

$$a_0 = 1.0022$$

$$a_1 = 0.005786 - 1.96 \times 10^{-5}T$$

$$c_0 = 0.1564 - 4.12 \times 10^{-3}T + 2.07 \times 10^{-5}T^2 + 5.13 \times 10^{-7}T^3$$

$$c_1 = 0.02231 + 1.105 \times 10^{-3}T - 9.63 \times 10^{-6}T^2 + 4.18 \times 10^{-7}T^3$$

where the temperature is in degrees centigrade (i.e. Celsius).

The above expressions have been used to calculate the emissivity as a function of salinity at each of the four experimental temperatures, 5, 10, 20 and 30 C, and at two interpolated temperatures, 15 and 25 C. The results are given in Table 5 which also includes columns for chlorinity and for brightness temperature. Both emissivity and brightness temperature values have been rounded off to the third significant figure.

The same information given in Table 5 is presented in graphical form in Figures 15, 16 and 17. Inspection of the latter two families of curves shows that brightness temperature is only weakly dependent on physical temperature for salinities in the range of 20 to 40 o/oo.

Table 5 Relationship of Brightness Temperature and Emissivity to Salinity at 1.43 GHz

Salinity °/∞	Chlorinity °/∞	Brightness Temperature and Emissivity					
		T = 5 C		T = 10 C		T = 15 C	
		T <sub>B</sub> in K	Emissivity	T <sub>B</sub> in K	Emissivity	T <sub>B</sub> in K	Emissivity
36	19.927	91.7	0.330	91.8	0.324	92.0	0.319
34	18.820	92.3	0.332	92.6	0.327	92.8	0.322
32	17.713	92.8	0.334	93.3	0.329	93.7	0.325
30	16.606	93.4	0.336	94.0	0.332	94.6	0.328
28	15.499	93.9	0.337	94.7	0.334	95.5	0.333
26	14.392	94.4	0.339	95.4	0.337	96.4	0.335
24	13.285	94.8	0.341	96.1	0.339	97.2	0.337
22	12.178	95.3	0.343	96.7	0.342	98.1	0.340
20	11.071	95.7	0.344	97.3	0.344	98.9	0.343
18	9.964	96.1	0.346	97.9	0.346	99.6	0.346
16	8.857	96.5	0.347	98.4	0.348	100.3	0.348
14	7.750	96.8	0.348	98.9	0.349	101.0	0.350
12	6.642	97.1	0.349	99.3	0.351	101.6	0.352
10	5.535	97.4	0.350	99.7	0.352	102.1	0.354
8	4.428	97.6	0.351	100.0	0.353	102.5	0.356
6	3.321	97.8	0.351	100.3	0.354	102.9	0.357
4	2.214	97.9	0.352	100.5	0.355	103.1	0.358
2	1.107	97.9	0.352	100.6	0.355	103.3	0.358
0	0.0	98.0	0.352	100.6	0.355	103.4	0.359

Table 5 Relationship of Brightness Temperature  
and Emissivity to Salinity at 1.43 GHz - Continued

Salinity ‰	Chlorinity ‰	Brightness Temperature and Emissivity					
		T = 20 C		T = 25 C		T = 30 C	
		T <sub>B</sub> in K	Emissivity	T <sub>B</sub> in K	Emissivity	T <sub>B</sub> in K	Emissivity
36	19.927	91.6	0.312	90.3	0.303	89.2	0.294
34	18.820	92.7	0.316	91.6	0.307	90.7	0.299
32	17.713	93.8	0.320	92.9	0.311	92.2	0.304
30	16.606	94.9	0.324	94.2	0.316	93.7	0.309
28	15.499	96.0	0.327	95.6	0.320	95.2	0.314
26	14.392	97.0	0.331	96.9	0.325	96.8	0.319
24	13.285	98.1	0.335	98.3	0.329	98.4	0.325
22	12.178	99.2	0.338	99.6	0.334	100.0	0.330
20	11.071	100.2	0.342	100.9	0.338	101.6	0.335
18	9.964	101.2	0.345	102.2	0.343	103.2	0.340
16	8.857	102.1	0.348	103.4	0.347	104.7	0.345
14	7.750	103.0	0.351	104.6	0.351	106.1	0.350
12	6.642	103.7	0.354	105.6	0.354	107.5	0.354
10	5.535	104.4	0.356	106.6	0.357	108.7	0.358
8	4.428	105.0	0.358	107.4	0.360	109.7	0.362
6	3.321	105.5	0.360	108.0	0.362	110.6	0.365
4	2.214	105.8	0.361	108.5	0.364	111.2	0.367
2	1.107	106.1	0.362	108.8	0.365	111.6	0.368
0	0.0	106.2	0.362	109.0	0.365	111.8	0.369

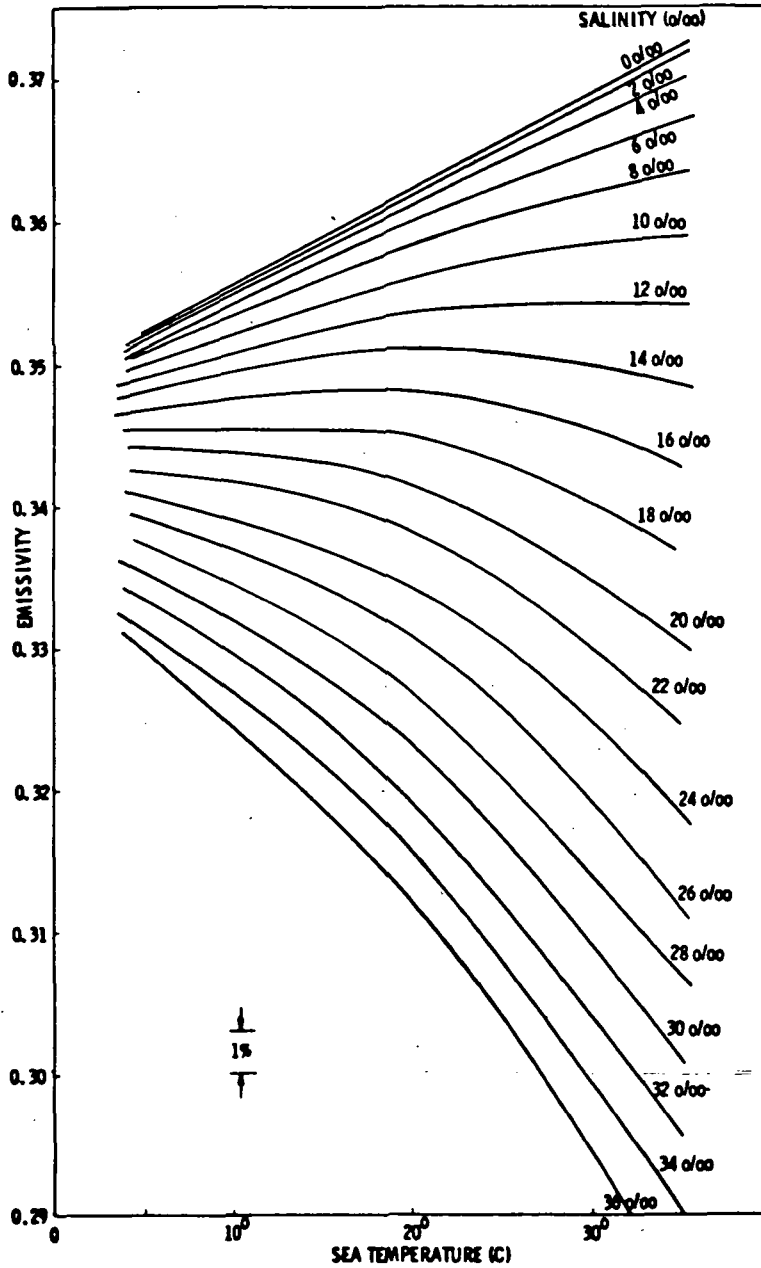


Figure 15 Emissivity Versus Sea Temperature with Salinity as a Parameter

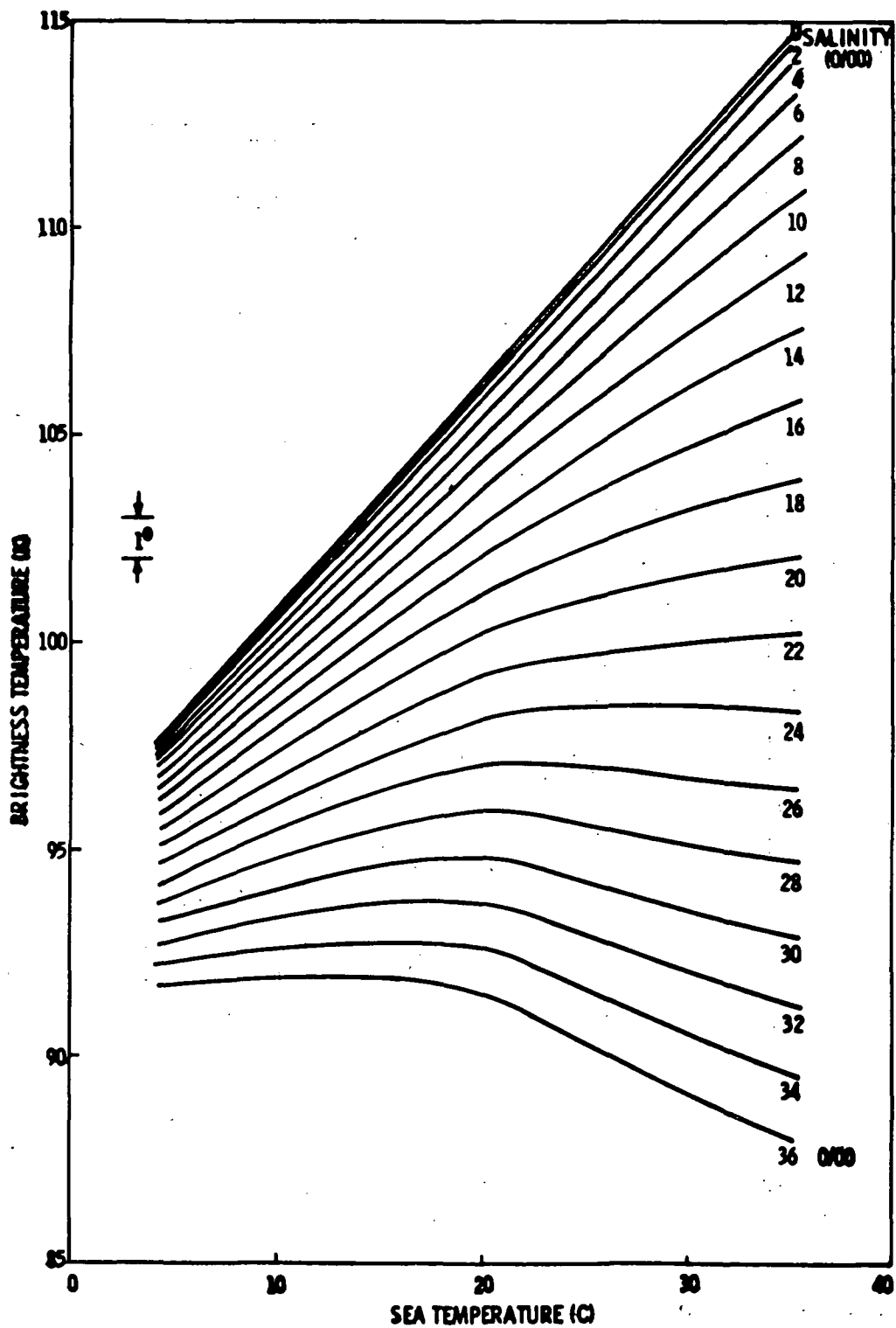


Figure 16 Brightness Temperature Versus Sea Temperature with Salinity as a Parameter

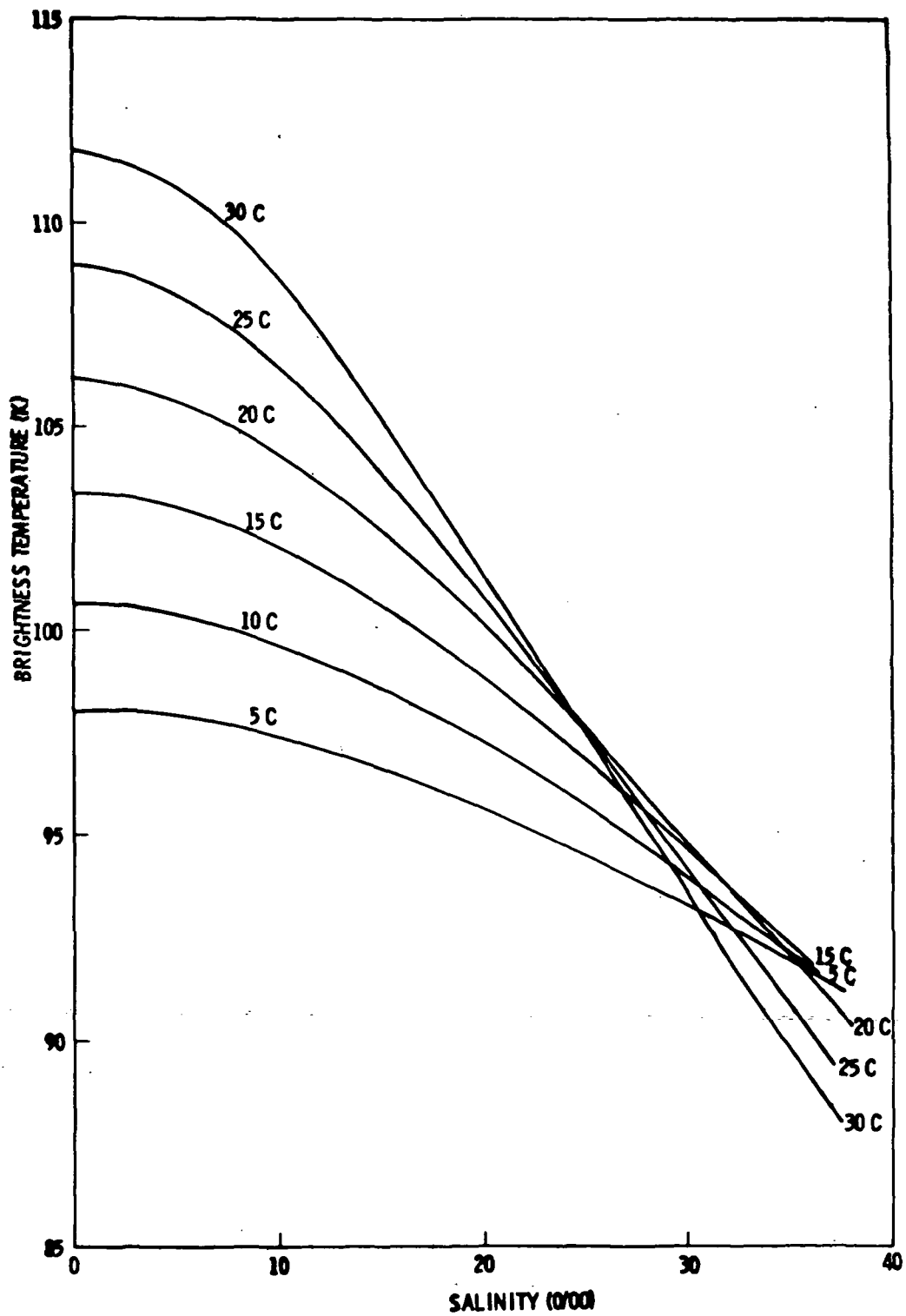


Figure 17 Brightness Temperature Versus Salinity with Sea Temperature as a Parameter



**Page intentionally left blank**

## 5.0 REFERENCES

- [1] W. W. Ho and W. F. Hall, "Measurements of the Dielectric Properties of Sea Water and NaCl Solutions at 2.65 GHz," J. Geophys. Res. 78, 603, Sept. 1973.
- [2] G. M. Hidy, W. F. Hall, W. N. Hardy, W. W. Ho, A. C. Jones, A. W. Love, M. J. Van Melle, H. H. Wang and A. E. Wheeler, "Development of a Satellite Microwave Radiometer to Sense the Surface Temperature of the World Oceans," NASA Contractor Report No. CR 1960, Feb. 1972.
- [3] J. B. Hasted, "Liquid Water: Dielectric Properties," Chapter 7 of "Water, a Comprehensive Treatise, Volume I, The Physics and Physical Chemistry of Water," edited by Felix Franks, Plenum Press, New York, 1972.
- [4] E. H. Grant, T. J. Buchanan and H. F. Cook, "Dielectric Behavior of Water at Microwave Frequencies," J. Chem Phys., 26, 156, 1957.



POSTMASTER: If Undeliverable (Section 158  
Postal Manual) Do Not Return

*"The aeronautical and space activities of the United States shall be conducted so as to contribute . . . to the expansion of human knowledge of phenomena in the atmosphere and space. The Administration shall provide for the widest practicable and appropriate dissemination of information concerning its activities and the results thereof."*

—NATIONAL AERONAUTICS AND SPACE ACT OF 1958

## NASA SCIENTIFIC AND TECHNICAL PUBLICATIONS

**TECHNICAL REPORTS:** Scientific and technical information considered important, complete, and a lasting contribution to existing knowledge.

**TECHNICAL NOTES:** Information less broad in scope but nevertheless of importance as a contribution to existing knowledge.

**TECHNICAL MEMORANDUMS:** Information receiving limited distribution because of preliminary data, security classification, or other reasons. Also includes conference proceedings with either limited or unlimited distribution.

**CONTRACTOR REPORTS:** Scientific and technical information generated under a NASA contract or grant and considered an important contribution to existing knowledge.

**TECHNICAL TRANSLATIONS:** Information published in a foreign language considered to merit NASA distribution in English.

**SPECIAL PUBLICATIONS:** Information derived from or of value to NASA activities. Publications include final reports of major projects, monographs, data compilations, handbooks, sourcebooks, and special bibliographies.

**TECHNOLOGY UTILIZATION PUBLICATIONS:** Information on technology used by NASA that may be of particular interest in commercial and other non-aerospace applications. Publications include Tech Briefs, Technology Utilization Reports and Technology Surveys.

Details on the availability of these publications may be obtained from:

**SCIENTIFIC AND TECHNICAL INFORMATION OFFICE**

**NATIONAL AERONAUTICS AND SPACE ADMINISTRATION**

Washington, D.C. 20546