PERMITTIVITY OF WATER AT MILLIMETER WAVELENGTHS

Final Report for the Period

October, 1975 - August, 1976

NASA Grant No. NSG-5082

GT/EES Project Number A-1784

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FOREWORD

This is the final report for work performed on NASA Grant NSG-5082. The grant covered the period from October 1, 1975 to August 15, 1976. The amount of the grant was $31,971 in NASA funds and $1608 in Georgia Tech cost-sharing funds for a total of $33,579. During the course of this program, a semi-annual report covering the period October 1, 1976 to March 31, 1976 was prepared. In addition, six letter-type reports on progress have been written and sent to the NASA/GSFC technical monitor, J. Larry King, for the purpose of providing current information on the technical status of the program, and to provide a better opportunity to direct the program so as to maximize its value to the government. Copies of the six monthly letters covering the period 1 April 1976 to 30 June 1976 are attached to this report as an Appendix.

I. Introduction

This report covers work performed on the permittivity of seawater and ice at 100 GHz. Measurements on water covered the temperature range 0°C to 50°C. The measurements on ice were taken at temperatures near -10°C. In addition, a small number of measurements were made on reflectivity of absorber materials used in the program "Research in Millimeter Wave Techniques", NASA Grant No. NSG-5012.

II. Permittivity Measurement Techniques

Only within the last ten years has an extensive effort been made to measure physical properties of materials and to otherwise explore the spectral region lying between 50 GHz and 1000 GHz. The reasons depend largely on the lack of readily available hardware and on the experimental difficulties. In the microwave region, previous investigators have used cavity resonators or a length of waveguide as a means of defining configuration of the electromagnetic field with the precision needed for accurate determination of dielectric properties. In the millimeter wave region, such techniques become increasingly difficult to apply. The problems include the difficulty of accurate matching of specimens and cavities, air gaps between sample and cavity wall, and the problem of surface tension and accurate sample shape for liquid dielectrics.

On the other hand, the extension of optical techniques using lenses and prisms to the millimeter region encounters problems due to low source radiance, poor detector sensitivity, and a lack of available components.

The result has been the use of closed and open resonators at wavelengths greater than one millimeter, with free-space quasi-optical techniques employed at shorter wavelengths. Typically the quasi-optical and open resonator techniques give information about the index of refraction directly, while techniques employed in the microwave region usually give dielectric constant information.

An open resonator technique was briefly studied for this program. The details were described in the report covering the period 1 October - 31 December 1975. This report is attached in the Appendix. It was found that the dissipative component of the dielectric constant of water was too high to permit the open resonator technique to be used. The method involves measurement of the resonance frequency and cavity Q with the empty cavity and with a thin layer of specimen inserted.

A reflectivity method was selected for these measurements for several reasons. From previous measurements of the dielectric properties of water, the dielectric properties may be extrapolated through the millimeter/submillimeter region yielding approximate values. A method of improving the accuracy of these values is desired.

The use of reflectivity data provides such a method for the technique, as used in this program, yields reproducible data with a minimum of measured quantities and corrections. It can be quickly implemented and is adaptable to a wide range of wavelengths.

Briefly, normal incidence reflectivity is measured. The result is used to obtain the index of refraction $\underline{n} = n - ik$. Both reflectivity and phase information are required for an unambiguous determination. Phase information requires a more complex experimental arrangement with a concomitant reduction in accuracy. To avoid this problem, we make use of the frequency and temperature dependence of $\underline{n}$ as determined by extrapolation. Small corrections are sufficient to fit normal reflectivity. To check our assignment of n - ik values, we then measure reflectivity at oblique incidence. The quantities n and k contribute to reflectivity in varying amounts depending on the angle of incidence. If calculated reflectivity tracks experiment for oblique incidence, we have a set of refractive indices which agree with experiment. Normal incidence measurements have the highest accuracy, and are always used as the basis for adjusting n and k.

In Table I, we have collected several expressions relating the relative dielectric constant $\varepsilon = \varepsilon' - i\varepsilon''$ to the index of refraction, and expressions for power reflectivity for radiation polarized parallel or perpendicular to the plane of incidence.

TABLE I

RELATIONSHIPS BETWEEN POWER REFLECTIVITY AND REFRACTIVE INDEX

The refractive index $\underline{n} = n - ik$

and the dielectric constant $\underline{\varepsilon} = \varepsilon' - i\varepsilon''$

are related by $\underline{\varepsilon} = \underline{n}^2$

$$\varepsilon' = n^2 - k^2$$

$$\varepsilon'' = 2nk$$

$$n = (\varepsilon'/2)^{1/2} \left\{ \left[1 + (\varepsilon''/\varepsilon')^2 \right]^{1/2} + 1 \right\}^{1/2}$$

$$k = (\varepsilon'/2)^{1/2} \left\{ \left[1 + (\varepsilon''/\varepsilon')^2 \right]^{1/2} - 1 \right\}^{1/2}$$

for normal incidence, the reflectivity is given by

$$R = \left[(n - 1)^2 + k^2 \right] / \left[(n + 1)^2 + k^2 \right]$$

At an angle of incidence Θ, the reflectivity for radiation polarized parallel to the plane of incidence, $R_p(\Theta)$, and perpendicular to the plane of incidence, $R_s(\Theta)$, is given by

$$R_p(\Theta) = \left| \frac{(\underline{n}^2 - \sin^2\Theta)^{1/2} - \underline{n}^2 \cos\Theta}{(\underline{n}^2 - \sin^2\Theta)^{1/2} + \underline{n}^2 \cos\Theta} \right|^2$$

$$R_s(\Theta) = \left| \frac{(\underline{n}^2 - \sin^2\Theta)^{1/2} - \cos\Theta}{(\underline{n}^2 - \sin^2\Theta)^{1/2} + \cos\Theta} \right|^2$$

Both expressions reduce to the normal incidence case at $\theta = 0$. The above formulas refer to a dielectric-air interface.

Figure 1 shows the experimental arrangement for reflectivity measurements. The horns had dimensions of 2.85 cm x 3.40 cm at the output and were 8.5 cm in length. The absorbers and the transmission horn served to limit the radiation to a 12 cm diameter at the liquid surface. With the high attenuation of water, only the wave reflected from the surface is received. The use of absorber panels eliminates possible contributions from stray reflections. A similar arrangement was used for measurements made at oblique incidence.

Transmitter and receiver were separated and absorber panels served to define the geometry of the received energy.

For the case of normal incidence, reflectivity at a fixed temperature was reproducible to one percent for values near forty percent. For reflectivity measurements of ice, the lack of attenuation leads to reflection from the back surface of the sample. This complication was circumvented by using a wedge shaped sample and freezing the water in a container lined with absorber material.

III. Experimental Results

Measurements of reflectivity at normal incidence were made relative to liquid mercury whose reflectivity was taken to be unity. A typical experiment consists of exchanging dishes of water and mercury, each filled to the same height, while measuring the reflected energy for each surface. Surface height is adjusted to match a reference level and a further small adjustment is made to maximize reflected power if possible. For water at 20°C, we find

$$R = 0.392 \pm 0.014$$

where the stated error is the standard deviation. The frequency of the klystron was determined to be 103.8 GHz.

For measurements at temperatures away from room temperature, the experimental procedure was changed.

As the depth of mercury in the sample dish is only a few millimeters, a matching sample of water has low heat capacity with large surface area and will drift in temperature at an excessive rate. To avoid this problem, reflectivity at other temperatures was referenced to water at room temperature, and samples containing larger volumes of liquid were used.

The data were corrected for a small amount of horn-horn coupling. Other experiment problems were instrument drift and drift in klystron power. As

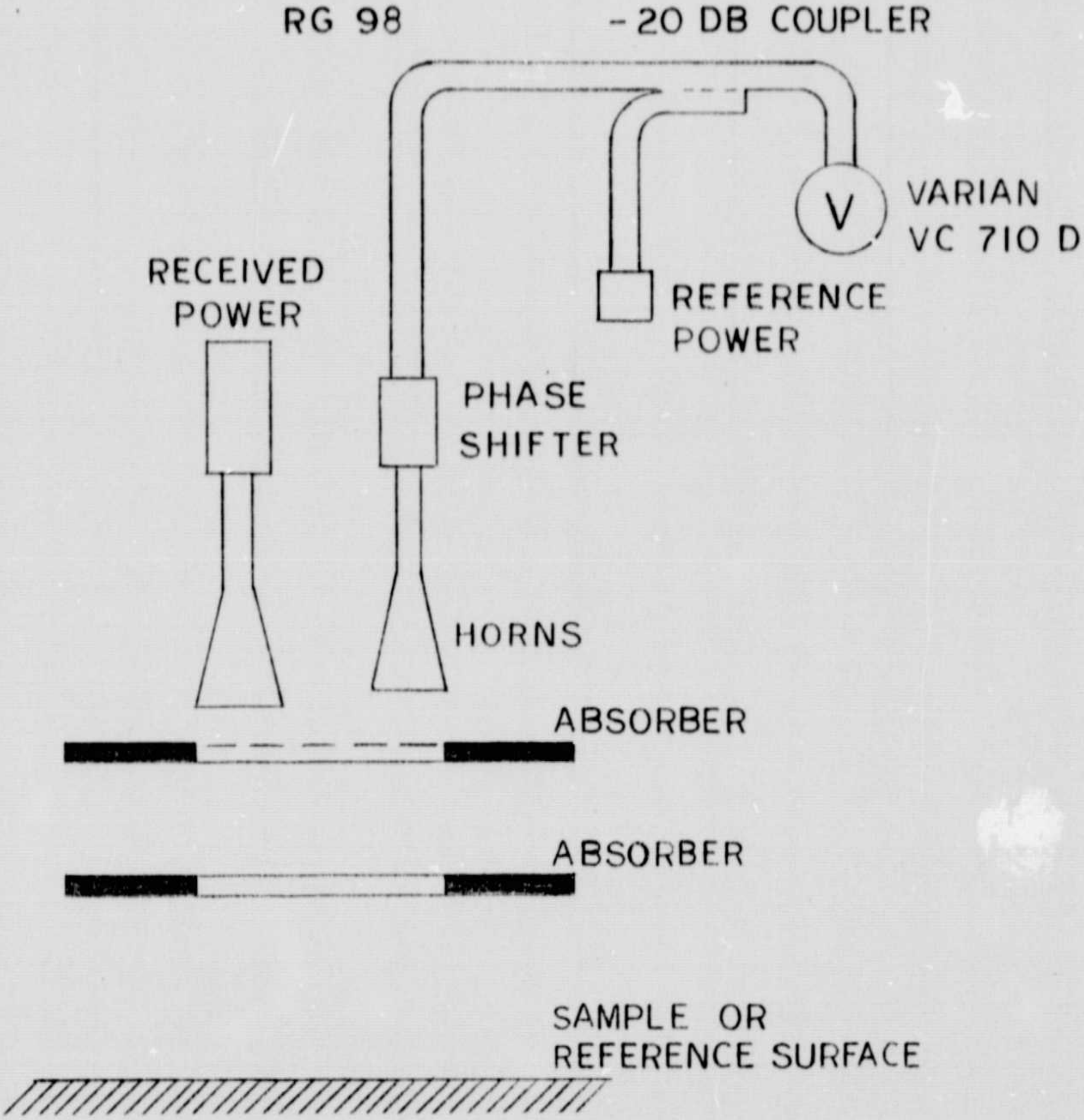

Figure 1. Experimental Arrangement for Normal Incidence Reflectivity Measurements at 100 GHz.

reflectivity is determined by the properties of the first few hundred μm of water surface, any temperature gradient near the surface caused, for example, by evaporation will result in an error no larger than the variation of reflectivity between wet and dry bulb temperatures. Because the variation between different runs was small and less than the standard deviation, we believe errors from all sources are no greater than the standard deviation.

The results for normal reflectivity are shown in Figure 2 over the temperature range 0°C to 50°C. The dashed line lying above the experimental curve at temperatures greater than room temperature is the extrapolation given by Peter S. Ray [1]. This extrapolation is within our experimental error up to 30°C, thus covering the temperature range of interest to most earth observation measurements. The diamond at 20°C represents reflectivity calculated from data supplied by NASA/GSFC [2]. These data, at 20°C, lead to a reflectivity approximately seven per cent low.

The experimental value for reflectivity at 103.8 GHz, 0.392 ± 0.014, represents the average of 122 measurements. The slope at 20°C is taken to be R = 0.0036/°C. A consistant index of refraction at 20°C is

$$n - ik = 3.24 - i\ 1.825.$$

Appropriate dielectric constants for water at 103.8 GHz and 20°C are

$$\varepsilon' - i\ \varepsilon'' = 7.16 - i\ 11.825.$$

As this program progressed, the klystron became less stable, and its output shifted to higher frequencies. Originally oscillating at a frequency near 96 GHz, the frequency shifted during the course of the program to a value near 104 GHz. The shift was accompanied by less signal, increased noise, and reduced power stability. The main effect on data has been an increase in the standard deviation. We find that with increasing numbers of measurements at temperatures near 20°C, the average value of reflectivity is not altered and the standard deviation does not decrease. Difficulties with the lock-in amplifier, as described in the Appendix in the report covering the period June 1 to June 30, have been overcome by a modification of the experimental procedure.

As a result, we obtain a reproducible value for room temperature reflectivity which agrees with the extrapolation of Ray [1] in this frequency region.

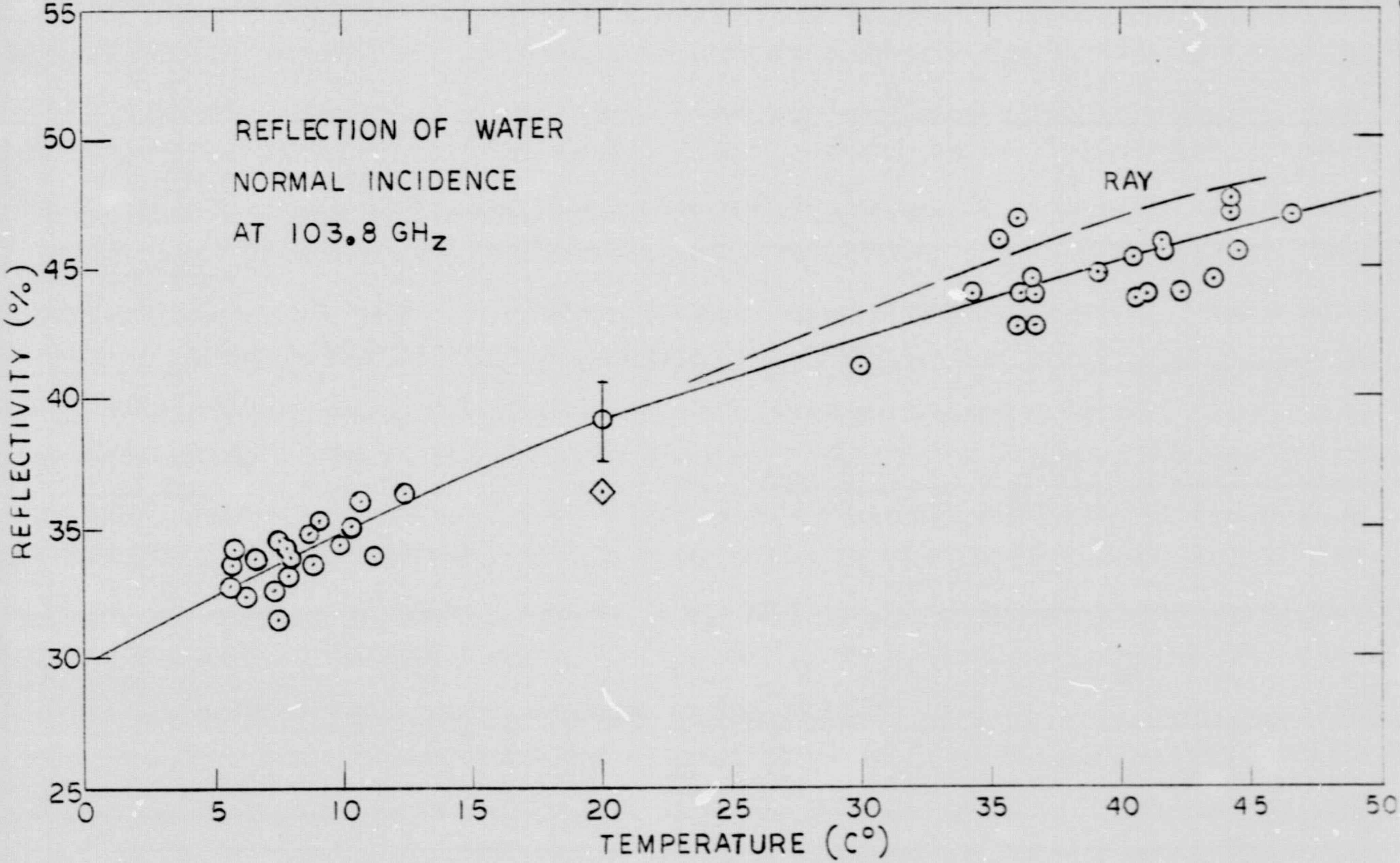

Figure 2. Reflectivity of Water at 103.8 GHz Between 0°C and 50°C. The Dashed Curve is the Result Predicted by Ray [1]. The Diamond at 20°C is the Result Predicted from NASA Data [2].

We have used Ray's extrapolation to calculate values of reflectivity for specified values of (1) temperature, (2) angle of incidence, and (3) polarization. The calculated values are compared with experimental measurements of reflectivity for two different angles of incidence in Table 2. Absolute values of reflectivity measured at room temperature used liquid mercury as a reference. For temperatures above and below room temperature, the ratio of the sample reflectivity to a water sample at room temperature was measured. Each of the experimental values listed in Table 2 represents an average of approximately 16 readings. These measurements had a larger standard deviation than measurements made at normal incidence. Coupling between transmitter and receiver horns was very small. The results provide a check on the reduction of normal reflectivity measurements into real and imaginary dielectric constants or indices of refraction.

The results discussed thus far have been obtained using tap water. Sea water contains salts and organic matter. In order to verify that these data are representative of sea water, two solutions were prepared. One contained NaCl to approximate the ionic content of sea water, and the other contained plankton to simulate the organic content.

A 0.7N solution of NaCl was used. This corresponds to 4.1% of salinity, equivalent to a very saline region of the ocean. The ratio of reflectivity at normal incidence of the salt solution to the reflectivity of fresh water was measured at room temperature. The result was R(salt water)/ R(fresh water) = 1.0056 ± 0.010. The deviation of the ratio from unity is less than the standard deviation. Therefore there is no measurable difference between the reflectivity of fresh water and a 0.7N solution of NaCl at 97.75 GHz.

Measurements were also made on sea water samples from the Gulf of Mexico near Panama City, Florida. The ratio of reflectivity at normal incidence of sea water to the reflectivity of tap water was R(sea water)/R(fresh water) = 1.004 ± 0.008. Again, in the 100 GHz frequency region, there is nothing in this sample of sea water to cause an anomaly in permittivity.

This result may be anticipated from the frequency dependence of the ionic conductivity of salt water. The imaginary part of the dielectric constant can be considered to comprise an effective conductivity arising from the orientation of the polar water molecules and a real conductivity arising from the mobile ions. The ionic conductivity has a frequency dependence given by

TABLE 2

REFLECTIVITY AT OBLIQUE INCIDENCE

A. Measurements Near 46° Incident Angle

Measurement	Angle	Temperature	Experimental Value	Calculated Value
R_s	46.2°	18.8°C	0.557	0.528
R_p	46.2°	19.7°C	0.271	0.268

B. Measurements Near 31° Incident Angle

Measurement	Angle	Temperature	Experimental Value	Calculated Value
R_s	31.0	19.0°C	0.478	0.454
R_p	31.0	17.6°C	0.452	0.449

C. Reflectivity Ratios for Different Temperatures

Measurement	Angle	T_1	T_2	Experimental Value	Calculated Value
$R_s(T_1)/R_s(T_2)$	47.2°	19.7°C	5.3°C	1.106	1.125
"	47.2°	19.2°C	4.5°C	1.098	1.153
"	47.2	39.6°C	20.1°C	1.093	1.1201
"	47.2	40.5°C	19.6°C	1.084	1.127
"	31.0°	17.7°C	3.9°C	1.133	1.176
"	31.4°	16.8°C	3.9°C	1.096	1.160
"	31.0°	39.9°C	17.7°C	1.159	1.239
"	31.4°	39.7°C	17.9°C	1.150	1.163

$$\sigma_I(\omega) = \sigma_o(1 + \omega^2\tau^2)^{-1/2} \qquad (1)$$

The imaginary part of the dielectric constant may then be written as

$$\varepsilon'' = \varepsilon''_o + 2\sigma_I(\omega)/f \qquad (2)$$

where f is the radiation frequency.

The conductivity of seawater is discussed by Halley [3]. Typical values of dc conductivity are in the range $35\text{-}45\times10^9$ sec^{-1} (ESU units) and relaxation times near 1.1×10^{-10} sec. At a frequency of 98 GHz, the conductivity will be $0.45 - 0.7 \times 10^9$ sec^{-1} using equation (1). At a frequency of 98 GHz, the ionic contribution to ε'' using equation (2) will be no larger than 0.014. The value of ε'' at this frequency is close to 11. The effect of the added conductivity, near one part per thousand, is less than the sensitivity of our measurements.

The organic component of seawater contains both dissolved matter and particulate matter. From estimates of the total amount of living cells [4], we can estimate the concentration of particulate matter for most ocean areas to be in the range of 150-300 g/m^3.

For these measurements, we prepared a solution containing 580 g/m^3. This concentration would correspond to a heavy concentration of organic matter representing fertile coastal waters during the spring and summer.

The reflectivity of this solution was compared to the reflectivity of fresh water. The result was R(plankton)/R(freshwater) = 0.999 ± 0.014. Again the deviation from unity was less than the standard deviation. We conclude that the presence of plankton in water does not alter its reflectivity at 97.75 GHz.

IV. Dielectric Properties of Ice

We have used our equipment to measure the normal reflectivity of ice at a frequency of 99 GHz. As mentioned previously, the sample holder was modified for this measurement. The bottom of the dish was lined with absorber material. Water was frozen in the dish in a wedge shape. Energy reflecting from the bottom of the dish will follow a different path than energy reflected from the surface.

Temperature was determined with a thermistor frozen 1/4 inch deep in the ice surface three inches from the center of the dish. The radiation was focused to a spot diameter of about eight centimeters. Liquid nitrogen was used to keep the water frozen. The ice surface tended to develop irregularities which were smoothed and polished with a damp cloth. The dish containing the ice was leveled with a spirit level to an accuracy of 1/8 degree. Care was taken to raise the surface of the reference mercury to the same position as the ice surface for the reference measurement.

The result for ice at 99 GHz is

$$R(\text{ice}) = 0.0783 \pm 0.0112$$

where no temperature dependence was observed in the temperature region -5°C to -20°C. Assuming negligible absorption, the index of refraction and dielectric constant for ice are

$$n = 1.78 \pm 0.08$$

$$\varepsilon = 3.17 \pm 0.27$$

The results of Cumming [5] at a wavelength of 3.2 cm give a value of 1.78 for the index of refraction of ice. The literature indicates no absorption bands and no dispersion in the millimeter-centimeter wavelength region. Thus the result quoted here near 3 mm is in excellent agreement with the measurement at 3.2 cm. Furthermore, the result should be independent of temperature in agreement with these observations.

As an independent check on the measurements reported here using the apparatus developed for water, we also determined the index of refraction of ice by sending radiation through an ice prism. The klystron energy, entering normal to the back face, was deflected 27° upon emerging from the front face of the prism with a prism angle of 28°. The index of refraction, by Snell's law, is given by

$$n = \sin(28° + 27°)/\sin(28°).$$

This gives a value of n = 1.745 for ice at 99 GHz. The result agrees well with the value, obtained from reflectivity, of 1.78. The results substantiate the expected result - a dielectric constant that is frequency and temperature independent in the millimeter-centimeter wavelength region.

V. Auxiliary Measurements

We have been preparing our 300 GHz carcinotron for use on this program. A diode detector and frequency measuring cavity were assembled and used with the unit. In our work to date, the tube has fluctuated in power output and we have not been able to obtain reproducible measurements.

An additional set of measurements similar to those reported here but at a higher frequency well removed from 100 GHz is desired to provide a check on a suitable expression for permittivity. The desired expression will be frequency and temperature dependent. In the event that the carcinotron cannot be stabilized sufficiently to permit useful measurements of reflectivity to be made, it would be desirable to proceed directly with measurements using frequency doubled klystrons at 140 GHz or 180 GHz. The objective is the development of a model for the complex index of refraction of sea water and ice over the millimeter wavelength region and over temperatures from -10°C to 50°C.

Additional measurements have been made on absorber materials to be used in the program "Research In Millimeter Wave Techniques," NASA Grant No. NSG-5012. Measured reflectivities have ranged from near 20% for Devcon plastic to 0.15% for a grooved Rexolite absorber panel. We anticipate using this facility for measurements on absorber and on window materials in the future.

VI. Summary

Our results indicate a power reflectivity for water at a frequency of 103.8 GHz and a temperature of 20°C of

$$R(\text{water}) = 0.392 \pm 0.014.$$

We find that the salt content and the organic content of sea water do not effect reflectivity at this frequency. No difference between the reflectivity of tap water, sea water, and solutions of NaCl and solutions containing plankton could be found.

Measurements on reflectivity of ice at 99 GHz gave a value of

$$R(\text{ice}) = 0.0785 \pm 0.0112.$$

Our measurements are consistent with the expectation that the reflectivity of ice should be frequency and temperature independent in this region.

From these experiments, we determine the index of refraction of water and ice to be

for water (103.6 GHz, 20°C)

$$\underline{n} = (3.24) - i\,(1.1825)$$

for ice (99 GHz, -10°C)

$$\underline{n} = 1.78$$

The result for ice agrees with the extrapolation of Peter S. Ray [1]. The result for water is in agreement with Ray's expression below 30°C. At higher temperatures, the experimental results fall below the value given by the extrapolation.

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PERMITTIVITY OF WATER AT MILLIMETER WAVELENGTHS

PROGRESS REPORT FOR THE PERIOD
1 October 1975 to 31 December 1975

NASA Grant No. NSG-5082
GT/EES Project Number A-1784

Project Director: M. D. Blue
Project Monitor: J. L. King

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PERMITTIVITY OF SEAWATER AT MILLIMETER WAVELENGTHS

Grant No. NSG-5082

Report for the Period 1 October - 31 December 1975

SUMMARY OF WORK

The dielectric properties of seawater have been measured to high accuracy from dc to the microwave region, and in the optical and infrared region of the spectrum. Measurements in the millimeter and submillimeter regions are lacking. The present program addresses this region.

Previous investigators have used a cavity resonator or a length of waveguide as a means of defining the configuration of the electromagnetic field with the high precision needed for accurate determination of dielectric properties. These methods have worked well, but they become increasingly difficult to apply as the wavelength decreases to the millimeter region and below. This difficulty arises from the difficulty of accurate machining of specimen and cavity, the problem of air gaps between specimen and cavity wall in the case of solid dielectrics, and the problem of surface tension and accurate sample shape for liquid dielectrics.

The extension of optical techniques using lenses and prisms encounters difficulties at longer wavelengths due to low source radiance, poor detector sensitivity, and a lack of available components.

As a result of these problems, techniques for dielectric measurements in the millimeter/submillimeter region have tended to employ closed and open resonators at wavelengths greater than one millimeter with free-space quasi-optical techniques employed at shorter wavelengths. Longer wavelength techniques usually give dielectric constant data directly, while the quasi-optical techniques yield the index of refraction.

Cullen and Yu [1] (Proc. Roy. Soc. 325 A, 493 (1971)) have described a method for the measurement of permittivity at microwave frequencies using an open resonator. This method was of interest to the program because it does not involve small cavities, and all quantities involved in the equations may be accurately determined. Moreover, a suitable resonator was available to the program.

Equations were derived for a semi-confocal cavity configuration based on the work of Cullen ar Yu. The real part of the index of refraction is obtained from the frequency shift in cavity resonance produced when a thin film of water is added to the plane mirror. The loss tangent (and therefore the imaginary component of the index of refraction) is determined from the drop in cavity Q factor after the water film is added.

During the month of October, the semiconfocal cavity was modified for use with liquid samples. A 95 GHz klystron was used as the radiation source. Diode detectors were used to monitor source power and signal power. A PAR lock-in amplifier was used to improve signal-to-noise ratio.

For the empty cavity, the resonance could be followed as source power was reduced 50 dB. The presence of a small amount of water attenuated the signal more than 50 dB, and no signal could be observed with a partial film of water in the cavity. We also checked the signal with a wet paper towel. No signal was observed. A slightly damp paper tower caused a drop of 40 dB to 50 dB in the signal.

The absorption coefficient of water can be estimated from permittivity data taken at longer wavelengths. The review by Hogg and Chu [2] (David C. Hogg and Ta-Shing Chu, Proc. IEEE 63, 1308 (1975)) indicates a value near 40 dB/mm for the absorption coefficient of water. Chamberlain [3] (John Chamberlain, "High Frequency Dielectric Measurement," IPC Science and Technology Press Ltd., Guildford, Surrey, England, p. 104 (1973)) indicates a value closer to 5 dB/mm. For values near 5 dB/mm, the cavity resonance scheme should be satisfactory. Values near 40 dB/mm will be too high. After spending several days attempting to follow the cavity resonance with small amounts of water added to the cavity, it was concluded that water was too lossy for the cavity method to be used with success, and the scheme was reluctantly abandoned. The measurements indicated that the attenuation coefficient of water was in the 40 dB/mm range, or at least above 24 dB/mm.

Several alternative methods for permittivity measurements were considered and discarded. The reflectivity method was selected on the basis of simplicity, and availability of necessary components. This method is currently being pursued. The relevant equations are the following:

The complex dielectric constant is given by

$$\varepsilon = \varepsilon' - i\varepsilon''$$

and the index of refraction by

$$\underline{n} = n - ik,$$

These quantities are related by

$$n = (\varepsilon'/z)^{1/2} \left\{ \left[1 + (\varepsilon''/\varepsilon')^2 \right]^{1/2} + 1 \right\}^{1/2}$$

$$k = (\varepsilon'/z)^{1/2} \left\{ \left[1 + (\varepsilon''/\;')^2 \right]^{1/2} - 1 \right\}^{1/2} .$$

The reflectivity for normal incidence is

$$R(0) = \frac{(n-1)^2 + k^2}{(n+1)^2 + k^2} .$$

For other than normal incidence, the radiation components with the E-vector parallel and perpendicular to the plane of incidence take different values. For the perpendicular case, the reflectivity for an angle of incidence θ will be

$$R_{\perp}(\theta) = \left| \frac{(\underline{n}^2 - \sin^2\theta)^{1/2} - \cos\theta}{(\underline{n}^2 - \sin^2\theta)^{1/2} + \cos\theta} \right|^2$$

Our plan is to measure reflectivity at three angles near 0°, 30°, and 45°. These measurements will be sufficient to determine n and k. The measurements will include pure water and seawater, and will cover an extended temperature range.

During the last half of November and the month of December, reflectivity measurements were made on water, aluminum plates, and an aluminum coated front surface mirror. Measurements were referenced to the mirror. Various horn and lens combinations were tried in order to focus the radiation to as small a spot as possible, and to minimize reflections. Measurements were reproducible to about 3% for the best horn lens arrangement.

A critical survey of the literature on the refractive index of water was performed by Peter S. Ray [4] (Peter S. Ray, Applied Optics 11, 1836 (1972)). The data were fit to equations by Cole and Cole [5] (Kenneth S. Cole and Robert H. Cole, J. Chem. Phys. 9, 341 (1941)) which were extensions of the Debye theory. The equations have parameters ε_s, ε_∞, λ_s, and α. In the equations, σ is the conductivity and λ is the wavelength of the radiation. The equations are,

$$\varepsilon' = \varepsilon_\infty + \frac{(\varepsilon_s - \varepsilon_\infty)\,[1 + (\lambda_s/\lambda)^{1-\alpha}\sin(\alpha\pi/2)]}{1 + 2(\lambda_s/\lambda)^{1-\alpha}\sin(\alpha\pi/2) + (\lambda_s/\lambda)^{2(1-\alpha)}}$$

$$\varepsilon'' = \frac{(\varepsilon_s - \varepsilon_\infty)(\lambda_s/\lambda)^{1-\alpha}\cos(\alpha\pi/2)}{1 + 2(\lambda_s/\lambda)^{1-\alpha}\sin(\alpha\pi/2) + (\lambda_s/\lambda)^{2(1-\alpha)}} + \frac{\sigma\lambda}{18.85 \times 10^{10}}$$

where for pure water $\sigma = 12.57 \times 10^8$.

The quantities ε_s, ε_∞, α, and λ_s are temperature dependent. The result implies an increase in reflectivity of 60% between 0°C and 50°C for pure water at 95 GHz. Our preliminary measurements tend to confirm this trend.

Also, our measurements indicate a value of reflectivity near 40% for water at 17°C at a frequency of 95 GHz. This is above the value obtained from Ray's equations but still reasonable. The attenuation coefficient, based on our preliminary work, appears to be near 31 dB/mm.

WORK PLANNED FOR NEXT MONTH

The first three months of the program have been used to verify that cavity resonance methods cannot be used because of the high attenuation coefficient of water, and that reflectivity measurements will be satisfactory. The next month will be used for measuring the radiation pattern of the horn and lens combination that has proven to be most useful. An absolute standard is also needed for our reflectivity measurements which are now referenced to the aluminum coated mirror. We plan to use mercury for this purpose.

When we have optimized the horn/lens arrangement for normal incidence, substitution of water for mercury, leaving the experimental arrangement otherwise unchanged, should provide the desired absolute reflectivity. A clean mercury surface will be considered to have 100% reflectivity at 95 GHz.

Measurements of reflectivity at temperatures between 0°C and 50°C and measurements at various salinity values will be completed for normal incidence. At that time, we will begin measurements at 30° and 45° incidence.

PERMITTIVITY OF WATER AT
MILLIMETER WAVELENGTHS

PROGRESS REPORT FOR THE PERIOD
1 January 1976 to 31 January 1976

NASA Grant No. NSG-5082

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PERMITTIVITY OF SEAWATER AT MILLIMETER WAVELENGTHS

Grant No. NSG-5082

Report for the Period
1 January - 31 January 1976

SUMMARY OF WORK

During the month, activity was directed toward establishing an accurate value for the reflectivity of water at room temperature for radiation at 95 GHz. Previous measurements using a mirror as a reference surface were consistent within a given day's data, but not sufficiently reproducible on later runs. The source of this deviation was believed to be the difficulty of matching surface height and maintaining the mirror surface level.

During the month, a fixture was constructed to hold a pyrex dish with provision for adjusting its height. Three pounds of mercury were purchased for use as a reference liquid. A typical experiment consists in exchanging dishes of water and mercury in the sample fixture and measuring reflected energy for each sample. Surface level is adjusted after each substitution to match a reference level, and a further slight adjustment is made if necessary to maximize reflected power.

The measurements have given us internal consistency. We find for water at 20°C,

$$R = 0.4343 \pm 0.0065$$

where the stated error is the standard deviation. The stated reflectivity is the result of 22 independent measurements corrected to 20°C. The slope of reflectivity at room temperature was taken to be 0.0038/°C. The reflectivity of a clean mercury surface at 95 GHz is taken to be 100%.

Following these measurements, the reflectivity was measured at temperatures between 0°C and 50°C. The experimental procedure was changed slightly from the previous set of measurements near room temperature. Because three pounds of mercury is already a bit heavy for easy handling, we do not wish to fill the sample dish to a higher level. The mercury depth is only a few millimeters. The matching water dish should also be filled to the same depth for ease in matching surface levels. However, with a volume of water sufficient to fill the dish to a few millimeters, temperature drift is a problem at temperatures away from room temperature. These difficulties were resolved by referencing high and low temperature measurements to a sample at room temperature using large volumes of water to reduce temperature drift. The room temperature data could then be referenced to the mercury surface.

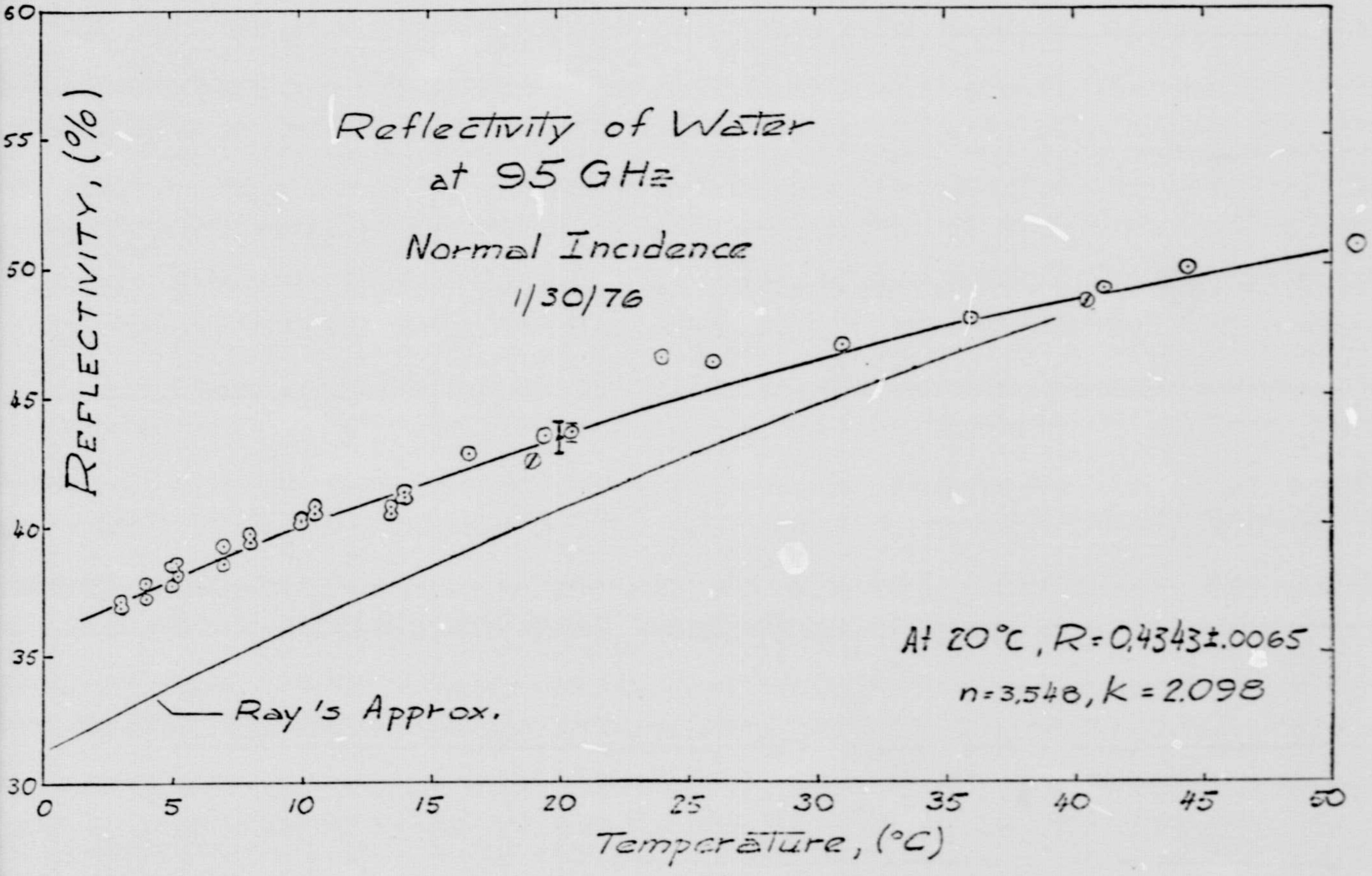
All data were corrected for a small amount of horn-horn coupling, drift in klystron power, and instrument drift. The results of reflectivity measurements between 0°C and 50°C are shown in the attached figure. The point at 20°C has error bars indicating standard deviation. Also shown is the approximation by Ray [Peter S. Ray, Applied Optics, <u>11</u>, 1836 (1972)] for this frequency. The value of reflectivity at 20°C is consistent with a refractive index of

$$n = 3.548;\ k = 2.098.$$

The standard deviation of 0.0065 is equivalent to an error in molecular temperature of 1.7°C. This error can be reduced as our experimental statistics improve.

<u>WORK PLANNED FOR NEXT MONTH</u>

The next month will be used to complete measurements at normal incidence. We will measure reflectivity of solutions of various salinity values, and mixtures containing plankton to simulate the organic component of seawater.


Reflectivity of Water
at 95 GHz
Normal Incidence
1/30/76
REFLECTIVITY, (%)
Temperature, (°C)
Ray's Approx.
At 20°C, R = 0.4343 ± .0065
n = 3.548, k = 2.098
60
55
50
45
40
35
30
0
5
10
15
20
25
30
35
40
45
50

PERMITTIVITY OF WATER AT MILLIMETER WAVELENGTHS

PROGRESS REPORT FOR THE PERIOD

1 February 1976 to 29 February 1976

NASA Grant No. NSG-5082

GT/EES Project Number A-1784

Project Director: M. D. Blue
Project Monitor: J. L. King

Engineering Experiment Station
Electromagnetics Laboratory
Georgia Institute of Technology
Atlanta, Georgia 30332

PERMITTIVITY OF SEAWATER AT MILLIMETER WAVELENGTHS

Grant No. NSG-5082

Report for the Period
1 February 1976 - 29 February 1976

SUMMARY OF WORK

During February, we have added additional data to our measurements of reflectivity of water at normal incidence. The best value at 20° C has changed slightly, and the best value for the refractive index has been adjusted accordingly. The room temperature reflectivity is reproducible to better than one percent. Additional data at higher temperatures have increased our confidence in reflectivity values in this region of the reflectivity-temperature curve. These results are shown in the attached figure. The value of reflectivity at 20° C shows the standard deviation.

Also shown in this figure is the normal reflectivity calculated from data supplied by J. L. King, GSFC and indicated by the diamond at 20° C. These data represent an extrapolation through the millimeter-centimeter wavelength region based on the limited amount of permittivity data on water for this wavelength region in the published literature. As might be expected, the extrapolation agrees well with that of P. S. Ray over the same region. However, both extrapolations lead to a reflectivity three percent low at 20° C, increasing to five percent low near 0° C in comparison to experiment.

We have calibrated the klystron used in this program using a Hitachi W2210 frequency meter. At the reflector voltage used in these measurements, the frequency was 97.75 GHz.

The polarization of the wave has also been checked in preparation for measurements of reflection at oblique angles of incidence where polarizations parallel and perpendicular to the plane of incidence have differing reflection coefficients. We find better than 25 dB difference between power received with the horns oriented for maximum power and the power received with the horns crossed. This result indicates a negligible amount of cross-polarized component in the wave.

As an approximation to sea water, we have measured the reflectivity at room temperature of a NaCl solution. The dielectric properties of sea water will be close to those of a 0.62 N solution of NaCl which corresponds to a salinity of 3.6%. The composition of sea water varies with season, location, depth and latitude, the southern hemisphere being somewhat more saline than the northern hemisphere.[1] An average figure is 3.5% salinity, or 0.6 N. Our measurements used a 0.7 N solution of NaCl which would be an approximation to a very saline ocean corresponding to 4.1% salinity. The <u>ratio</u> of the reflectivities of the salt solution to fresh water differed by less than 0.6%. The measured ratio was 1.0056 ± 0.010. The deviation from unity is less than the standard deviation for the ratio. Thus, we conclude that within the accuracy of our measurements, there is no difference between the reflectivity of fresh water and a 0.7 N NaCl solution at 97.75 GHz.

This result is consistant with out expectations. The contribution of the then added conductivity of the salt to the relative permittivity of water increases the imaginary (lossy) component. The relation is[2]

$$\varepsilon^{11} = \varepsilon_1 + \sigma(\omega)\lambda/18.85 \times 10^{10}$$

where ε_1 is the imaginary component of the dielectric constant in the absence of a conductivity contribution. λ is the wavelength in cm, and $\sigma(\omega)$ is the conductivity in Gaussian units at the angular frequency ω as given by

$$\sigma(\omega) = \sigma_o(1 + \omega^2\tau^2)^{-1/2}$$

where τ is the relaxation time for the conductivity. The conductivity of ocean water is discussed by Halley.[3] Values of dc conductivity are in the range

1 Dorsey, N. E. "Properties of Ordinary Water Substance," Reinhold Publishing Corp., New York (1940).

2 Peter S. Ray, Applied Optics <u>11</u>, 1836 (1972) "Broadband Complex Refractive Indices of Ice and Water."

3 P. Halley, "Introduction to the Electromagnetism of the Sea," Optics of the Sea (Interface and In-Water Transmission and Imaging), Advisory Group for Aerospace Research & Development, Neuilly sur Seine, France, AGARD LS-61, 1973, NASA-TTF-15658.

$30 - 45 \times 10^{9}\ sec^{-1}$ with a relaxation time of 1.08×10^{-10} sec. The conductivity at 97.75 GHz will then be $0.45 - 0.7 \times 10^{9}\ sec^{-1}$.

The contribution to the imaginary part of the dielectric constant is then approximately 0.001. Thus

$$\varepsilon^{11} = \varepsilon_1 + .001 \simeq 11.001.$$

The effect of the conductivity at 3 mm wavelength is an increase of one part in 10^4. This change is too small to be observed, in agreement with our measurements.

We have approximated the organic component of sea water by using a solution of freeze dried plankton[4] in fresh water. Organic matter in the sea includes particulate matter plus dissolved matter. From estimates of the total amount of living cells[5], we can estimate a value of 150-300 g/m^3 of particulate material for most ocean areas.

Our solution had a concentration of 580 g/m^3 which would correspond to a heavy concentration of organic matter such as might be found in fertile coasted waters during the spring and summer.

Reflectivity at normal incidence was compared to the reflectivity of fresh water. The measured ratio of reflectivities [R (plankton)/R (fresh water)] was 0.999 ± 0.014. The deviation from unity was less than the standard deviation. Thus we conclude that the addition of plankton to the water does not alter its normal reflectivity at 97.75 GHz.

WORK PLANNED FOR NEXT MONTH

During March we shall measure reflectivity at two different angles of incidence and at various temperatures. These data will serve to substantiate our semiempirical assignment of n and k from reflectance at normal incidence.

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4 Freeze dried plankton containing 69% protein was obtained from Breedmore Aquarium Products Ltd., Shohola, Pa. 18458.

5 J. P. Riley and R. L. Chester, "Introduction to Marine Chemistry," Academic Press, New York, p. 263 (1971).

We will also obtain a sample of sea water for measurement. Our salt soulution measurements tell us that the conductivity of the salt is not observable through the dielectric properties. However, sea water measurements will be necessary to provide assurance that unexpected effects do not arise.

We expect to complete work at 97.75 GHz with a graph of n and k over the measured temperature range. A set of equations giving n and k as functions of frequency and temperature can also be derived. However, additional data at other frequencies will be required as these measurements have already shown that data in this frequency region are not consistant.

Following completion of measurements at 97.75 GHz, we plan to move to 145 GHz using the second harmonic of a 70 GHz klystron as the source.

PERMITTIVITY OF WATER AT MILLIMETER WAVELENGTHS

PROGRESS REPORT FOR THE PERIOD

1 April 1976 to 30 April 1976

NASA Grant No. NSG-5082

GT/EES Project Number A-1784

Project Director: M. D. Blue

Project Monitor: J. L. King

Engineering Experiment Station
Electromagnetics Laboratory
Georgia Institute of Technology
Atlanta, Georgia 30332

PERMITTIVITY OF SEAWATER AT MILLIMETER WAVELENGTHS

Grant No. NSG-5082

Report for the Period 1 April - 30 April 1976

Summary of Work

During the month of April we obtained salt water samples from the Gulf of Mexico near Panama City, Florida. These samples were used for a reflectivity comparison with fresh water. No difference was detected. The standard deviation of a set of readings of reflected power is 0.4 percent to 0.8 percent with our present apparatus. The reflected power from salt water and fresh water agreed to within 0.04 percent, less than a standard deviation. The result indicates that there is nothing in this ocean water sample to cause an anomaly in permittivity in the 100 GHz frequency region.

Our measurement apparatus has been moved to a new location and the new arrangement is somewhat more versatile. Considerable effort was spent determining sources of coupling voltage between source and receiver. Some of the coupling signal was found to be pickup between cables. Additional coupling reduction was obtained by tilting all surfaces such as the lens and absorber panels with respect to horizontal; in effect spoiling resonances in the cavity-like arrangement. Finally, the coupling was reduced effectively to zero by removing the lens and separating the horns to give an angle of incidence of 3.6°. For this arrangement, the output signal from a mercury surface is 5.3 mV, while the coupling signal is less than 0.01 mV.

We have measured the normal reflectivity of ice at 99 GHz using different configurations of the apparatus. Temperature was determined with a thermister frozen 1/4 inch deep in the ice surface three inches from the center of the dish. The spot size has a radius of about 1.5 inches. Liquid nitrogen was used to keep the water frozen. The ice surface tended to have irregularities which were smoothed and polished with a damp cloth. The dish containing the ice was leveled with a spirit level to an accuracy of 1/8 degree. Care was taken to raise the surface of the reference mercury to the same position as the ice surface for the reference measurement.

Errors due to surface irregularities and tilted surfaces should cause a lower reflected power. We find values near 16 percent, which is larger than expected. The results of Cumming[1] at a wavelength of 3.2 cm give a value of 1.78 for the index of refraction of ice. As there should be no absorption bands and no dispersion in the millimeter-centimeter wavelength region, we would expect the index of refraction to be near 1.78 in the millimeter region. The expected reflectivity would be 7.9 percent.

We have tried various configurations in our apparatus and searched for possible means of reconciling the difference without success. For example, the bottom of the ice container is covered with absorber. Any reflection from this surface will increase the apparent reflectivity. We have determined that any contribution from this source is critically dependent on the orientation of the container. The maximum error is less than one percent, and in practice is probably much less.

Another possibility is the presence of a thin layer of liquid water on parts of the surface. The reflectivity of water is near 36 percent so it can greatly change the apparent reflectivity of ice. These measurements will continue.

We have also begun to set up the 300 GHz Carcinotron tube for measurements at this frequency. The tube has five power supplies including power for the electromagnet, and three water cooling systems.

1. W. A. Cumming, "The Dielectric Properties of Ice and Snow at 3.2 Centimeter," J. Applied Physics, 23, 768 (1952).

PERMITTIVITY OF WATER AT MILLIMETER WAVELENGTHS

PROGRESS REPORT FOR THE PERIOD
1 May 1976 to 31 May 1976

NASA Grant No. NSG-5082

GT/EES Project Number A-1784

Project Director: M. D. Blue

Project Monitor: J. L. King

Engineering Experiment Station
Electromagnetics Laboratory
Georgia Institute of Technology
Atlanta, Georgia 30332

PERMITTIVITY OF SEAWATER AT MILLIMETER WAVELENGTHS

Grant No. NSG-5082

Report for the Period 1 May - 31 May 1976

Summary of Work

During the month of April we were concerned with determining reflectivity of ice near 100 GHz. Our previous measurements gave a reflectivity larger than expected, and we were concerned with the reason for the larger value. This month we found two sources of error effecting these measurements. First, the expansion of the water upon freezing caused the surface of the ice to become slightly concave and thus gave rise to a focusing effect at the receiver horn. This effect was eliminated by repeated surface remelting and refreezing until the surface was level to 1/4 degree over the entire dish.

The second problem was the PAR model 124 lock-in amplifier. The amplifier was found to couple the two input channels. Thus, the reflectivity signal was mixed with the reference power measurement signal. In addition, the more sensitive gain positions had gradually become unstable and tended to oscillate.

The stability problem was solved by cleaning the contents of a rotary switch, but the coupling problem appears to be caused by a special dual transistor at the input. We circumvent this problem by shorting one input and connecting one signal at a time to the other input. Because the reflectivity of ice is small, the signal corresponding to the reflected energy is small. To minimize corrections to this signal we have eliminated the focusing lens and use separate transmitter and receiver horns. The horn-horn coupling signal is about 2% of the reflected energy signal.

As a result of these modifications, the most recent result for the reflectivity of ice is

$$R(\text{ice}) = 0.0785 \pm 0.0112$$

at a frequency of 99 GHz. The frequency of the klystron has been increasing, a result of its increasing age. Our previous measurements were at 97.75 GHz.

As an independent check on these measurements we determined the index of refraction of ice by sending the radiation through an ice prism. The klystron energy, entering normal to the back face, was deflected 27° upon emerging from the front face of the prism with a prism angle of 28°. The index of refraction, by Snell,s law, is given by $n = \sin(28° + 27°)/\sin(28°)$. This gives a value of $n = 1.745$ for ice at 99 GHz. This result is in excellent agreement with the value, obtained from reflectivity, of 1.78 ± 0.08. These results are also in excellent agreement with expected results from the literature as discussed last month.

It is worth mentioning that use of an ice prism must be accomplished quickly. As moisture accumulates on the surface, absorption rises rapidly. The experiment described here provides a convenient check on reflectivity data, but would require considerable effort to develop into a high accuracy technique. It is also unsuitable for water.

We are currently rechecking measurements on reflectivity of water. It is possible that the reflected signal was enhanced by coupling to the reference power signal as in the case of ice. The effect on the measured reflectivity should be less for water because the reflected power signal is stronger, but may still be significant. We shall continue to use the separated horn arrangement which gives a transmitter-receiver coupling signal of about 1% of the reflected energy. A disadvantage is that the received power is greatly reduced without the concentrating effect of the lens.

We have continued work with the 300 GHz carcinotron and have obtained oscillation. The power supply has been a source of problems and will require some further work to operate correctly. However, this does not appear to be a time consuming task.

Future Work

We shall recheck reflectivity versus temperature for water at 100 GHz, and duplicate these measurements at 300 GHz. The results will be compared with data and extrapolations in the millimeter wavelength region available in the published literature.

PERMITTIVITY OF WATER AT MILLIMETER WAVELENGTHS

PROGRESS REPORT FOR THE PERIOD

1 June - 30 June 1976

NASA Grant No. NSG-5082

GT/EES Project Number A-1784

Project Director: M. D. Blue

Project Monitor: J. L. King

Engineering Experiment Station
Electromagnetics Laboratory
Georgia Institute of Technology
Atlanta, Georgia 30332

PERMITTIVITY OF WATER AT MILLIMETER WAVELENGTHS

Grant No. NSG-5082

Report for the Period 1 June - 30 June 1976

Summary of Work

During June, an extension was granted moving the termination date for this Grant to August 15. The final technical report will be due on September 15. This is a no-cost extension. Program completion has been delayed because of our occasional use of the facilities and personnel from this program to supplement other ongoing programs for Goddard Space Flight Center on a temporary basis. We expect to complete this program on or before August 15.

During the month of June our major effort was spent working with the system components: klystron, detectors, lock-in amplifier. We have mentioned these problems in our previous monthly letter. The primary problem at this time appears to be the klystron.

As the klystron has shifted to higher frequencies, it has lost power and become less stable. As a result we have less signal, increased noise, and reduced power stability; all of which have made verification of our previous data difficult. Recently it appears that we can bring these problems under control and obtain reproducible data.

Our recent results at 103.6 GHz adjusted to a temperature of 20°C give a value of normal reflectivity of $R = 0.393 \pm 0.015$. This value is in excellent agreement with the value obtained from Ray's approximation as described in previous monthly reports.

We continue to use the PAR 124 lock-in amplifier using only one input channel at a time. The unused channel has its input shorted. The amplifier couples signals between the two channels to about 1%. The magnitude of the coupling depends on the resistance of the input, being highest for high resistance input networks. The coupling also causes a high frequency oscillation to appear at the inputs when the unused channel is not shorted.

Future Work

We shall complete a set of reflectivity versus temperature data at frequencies near 100 GHz for water. We will then obtain a similar set of data at 300 GHz using our carcinotron.