REFLECTIVITY OF ELECTROMAGNETIC WAVES AT AN AIR-WATER INTERFACE FOR PURE AND SEA WATER

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ABSTRACT

Compilation of the optical properties of electromagnetic waves incident on pure (chemically pure) or sea water shows an abrupt divergence of behavior for the two water types at about the 3-centimeter wavelength. From this point on to all longer (radio) wavelengths, sea water behaves optically like a metal, whereas pure water behaves like a semiconductor. At shorter wavelengths (below 3 centimeters), both fresh and pure water behave as dielectrics with similar optical properties. Only at visible wavelengths are the optics of natural waters of all salinities well known. The reflectivity contrast (difference in reflectivity divided by average reflectivity) between pure and sea water to visible light is approximately 3%. The reflectivity contrast between sea and pure water at radio frequencies is approximately 44%.

CONTENTS

LIST OF FIGURES

INTRODUCTION

Present techniques for aerial detection of coastal springs or estuarine outflows involve remote measurement of temperature or color. At this time no aerial remote sensor is available for measurement of salinity anomalies *per se*.

The purpose of this report is to provide some background for a study to determine the feasibility of using surface reflectivity as a measure of salinity. Graphs of reflectivity of an air-water interface for both pure and sea water are plotted as a function of electromagnetic wavelengths ranging from ultraviolet to radio waves. The graphed values were taken from published tables (Dorsey, 1940) or computed from other parameters (Corson and Lorrain, 1962; Liebermann, 1962).

For the purposes of this report, a distinction between pure and fresh water must be made. Chemically "pure water" does not exist in nature but must be approximated by distillation, ion exchange, etc. "Fresh water" refers to natural potable water such as rain water. Pure and fresh water, as defined above, have different electromagnetic properties at radio frequencies and can therefore be expected to show different reflectances.

"Sea water" refers to ocean water containing 32 parts per thousand dissolved solids and can be approximated for electromagnetic measurements by 0.5 molar NaCl.

THEORY

The reflectivity of plane electromagnetic waves from a smooth water surface at normal incidence is related to the refractive index, n, and the adsorption index, k, both of which depend on wavelength. For a given wavelength in air, λ_o, the reflectivity is:

$$R = \frac{(n-1)^2 + (nk)^2}{(n+1)^2 + (nk)^2}$$

The refractive index, n, is defined as the ratio of wavelength in air, λo, to wavelength in water, λ, at a given λo: $n = \lambda o/\lambda = c/v$, where c is the velocity in air and v is the velocity in water. The refractive index, n, of water is a function of the angle of incidence for some frequencies, but only normal incidence will be considered here.

The absorption index, k, is a measure of the rate of attenuation of the radiation in the water in terms of wavelengths in air. It is defined as:

$$k = \frac{K\lambda o}{4\pi}$$

where K, the more familiar absorption coefficient, is the length of penetration through water required for the intensity of the radiation to be attenuated to 1/e (≃ 63%) of its initial value.

The spectra of the indices of refraction, n, absorption, k, and reflectivity, R, of pure (p) and sea (s) water are shown in Figure 1 as traces labeled n_p, $k_o p$, n_s, $k_o s$, R_p, R_s, respectively.

A special relationship exists between n and k for both pure and sea water at and near wavelengths of 3.0, 6.1, and 15.1 microns in the infrared. At these wavelengths where n increases with increasing wavelength, there are peaks in k (maxima in attenuation). At these "anomalous dispersion" wavelengths, the polar (asymmetric) water molecules resonate with the electromagnetic radiation. At wavelengths less than but approaching those corresponding to anomalous dispersion, the molecular oscillation increasingly lags behind the electromagnetic excitation. At wavelengths greater than but approaching those corresponding to anomalous dispersion, the molecular oscillation increasingly leads the electromagnetic excitation. Associated with the anomalous dispersion wavelengths there are changes of π radians in the phase difference between the excitation and the induced oscillation.

At the resonant frequencies, the induced alteration of phase causes destructive interference shown by high absorption index.

Figure 2 is a plot of refractive index, n, *vs* absorption index, k. The reflectivity, R, coordinates are represented by circular arcs on that same figure. The equation,

$$R = \frac{(n-1)^2 + (nk)^2}{(n+1)^2 + (nk)^2}$$

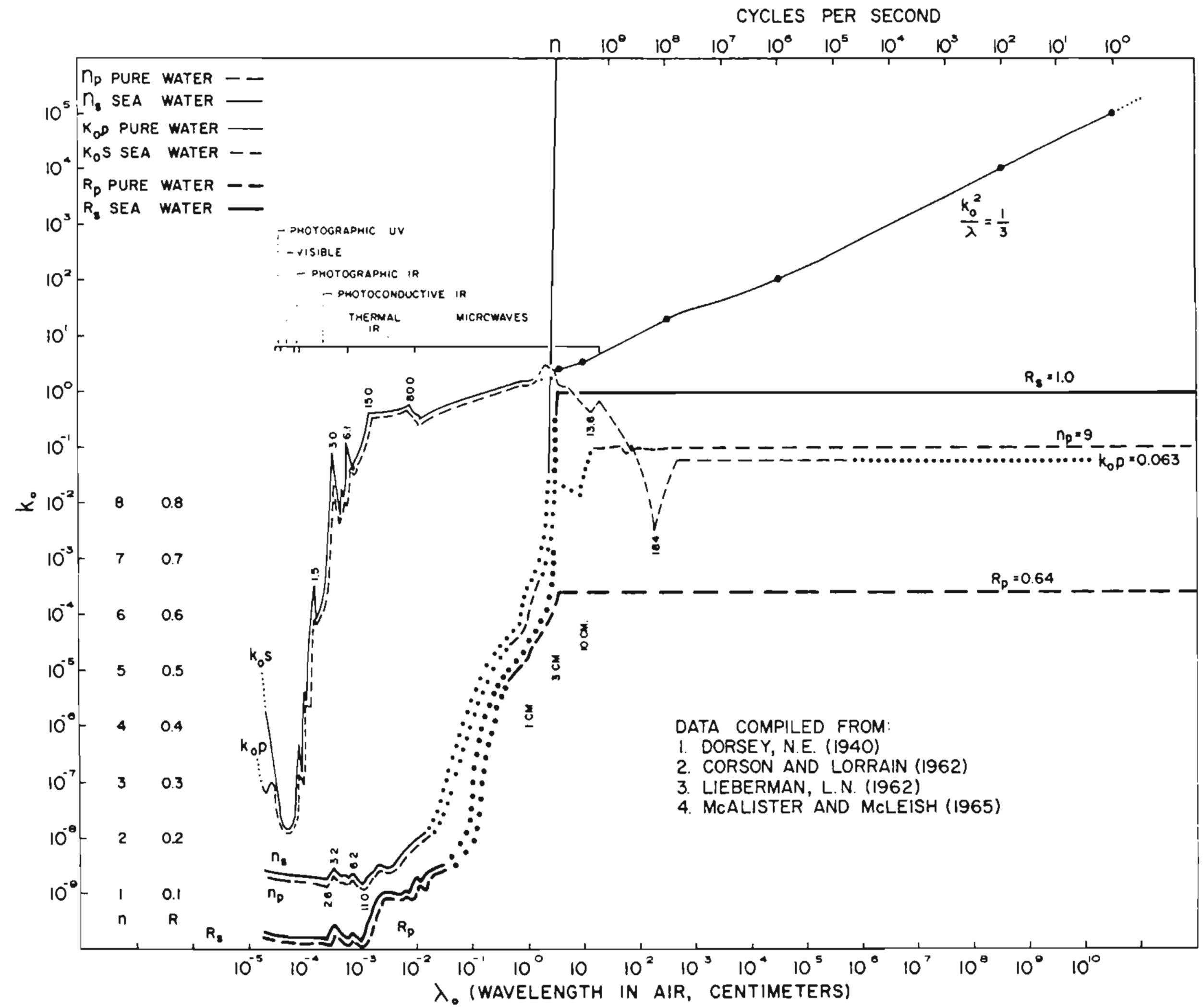

FIGURE 1: SPECTRA OF REFRACTIVE INDEX, n, ABSORPTION COEFFICIENT, k_0, AND REFLECTIVITY, R, OF PURE AND SEA WATER AS A FUNCTION OF ELECTROMAGNETIC WAVELENGTH IN AIR.

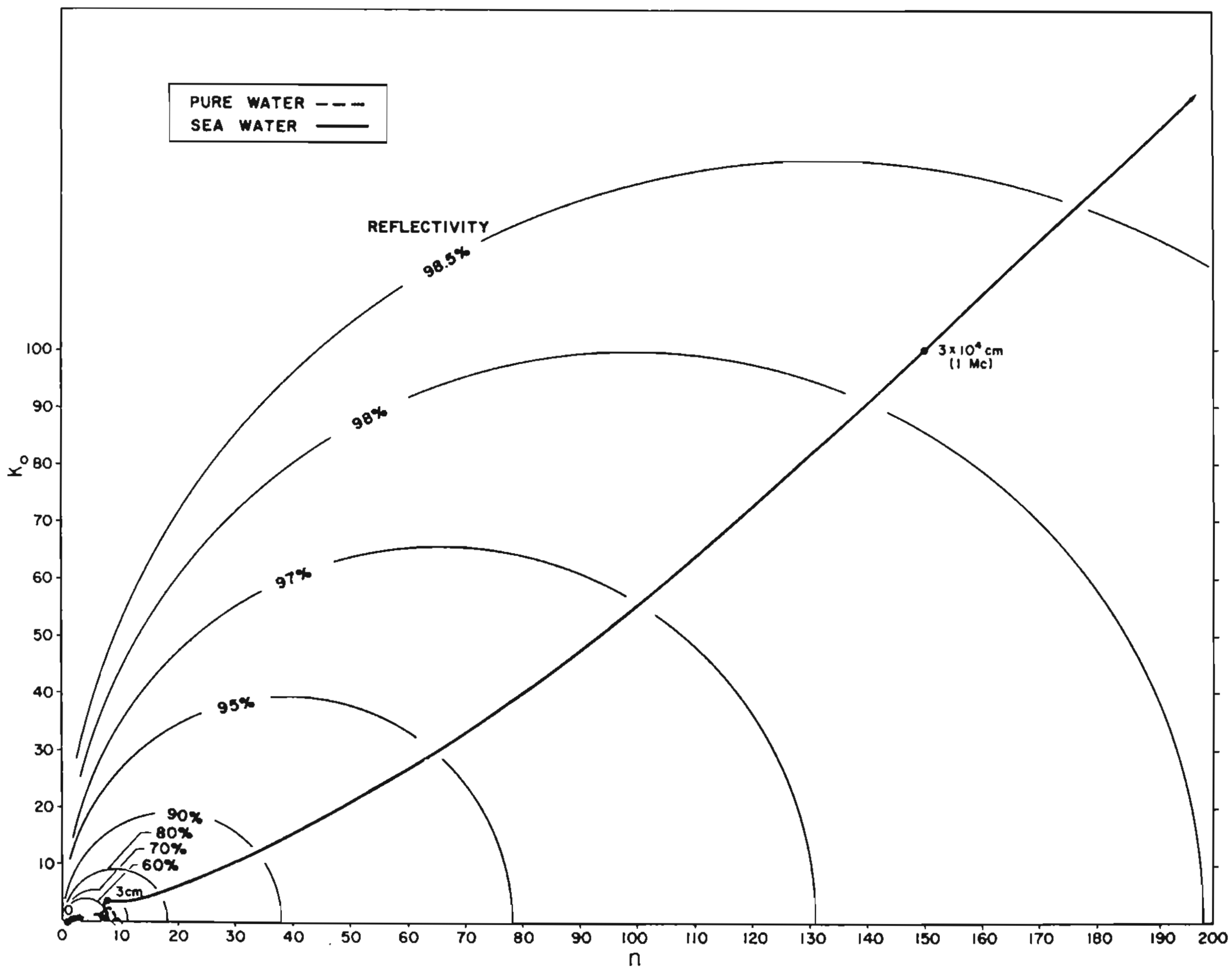

FIGURE 2: RELATION BETWEEN R, k_0, AND n FOR PURE AND SEA WATER TRACED THROUGH THEIR SPECTRA; 3 cm. TO 300 m.

may be written as,

$$k^2 + [(n-1 + R)(1-R)]^2 = 4R/(1-R)^2$$

which represents a family of circles with $2\sqrt{R}/(1-R)$ radii and centers at $(n-1 + R)/(1-R)$. The same relationship is replotted at increasingly larger scales in Figures 3 and 4 to show the trace in detail at various wavelengths. As the trace progresses through increasing wavelength, from 2.3 to 15.0 microns, each major band of molecular resonance absorption is represented by a clockwise loop in Figure 3.

Whereas in Figure 4, the optical properties of pure and sea water do not differ enough to be shown as separate traces, in Figures 2 and 3 a very significant divergence is shown. The long wave reflectivities are better shown in Figure 1 where the reflectivity values of both pure and sea water are shown increasing sharply with wavelength. There is a major divergence beginning at about 3 centimeters: sea water becomes nearly 100% reflective and pure water 64% reflective.

T. S. Moss (1961) has shown a relationship between refraction and absorption that can be used to fill in the data gaps for natural fresh and brackish water. In terms of the absorption coefficient, K,

$$n_a - 1 = \frac{1}{(2\pi)^2} \int_0^\infty \frac{K}{1-(\lambda_o/\lambda_a)^2}\, d\lambda_o .$$

The computations are beyond the scope of this paper, but since $K_o = 4\pi k/\lambda_o$, an examination of the k trace of Figure 1 indicates that the refractive index, and thus the reflectivity of sea water, can be expected to be higher than that of fresh water at most wavelengths.

L. N. Liebermann (1962) states that, although sea water is perfectly reflecting at radio frequencies at *normal* incidence, its reflectivity can be somewhat *less* at other angles; hence,

$$R = \frac{(S-1)}{(S+1)} ,$$

where

$$S = \frac{\sqrt{\omega\varepsilon}}{2\sigma} \frac{1+i}{\cos \Omega} ,$$

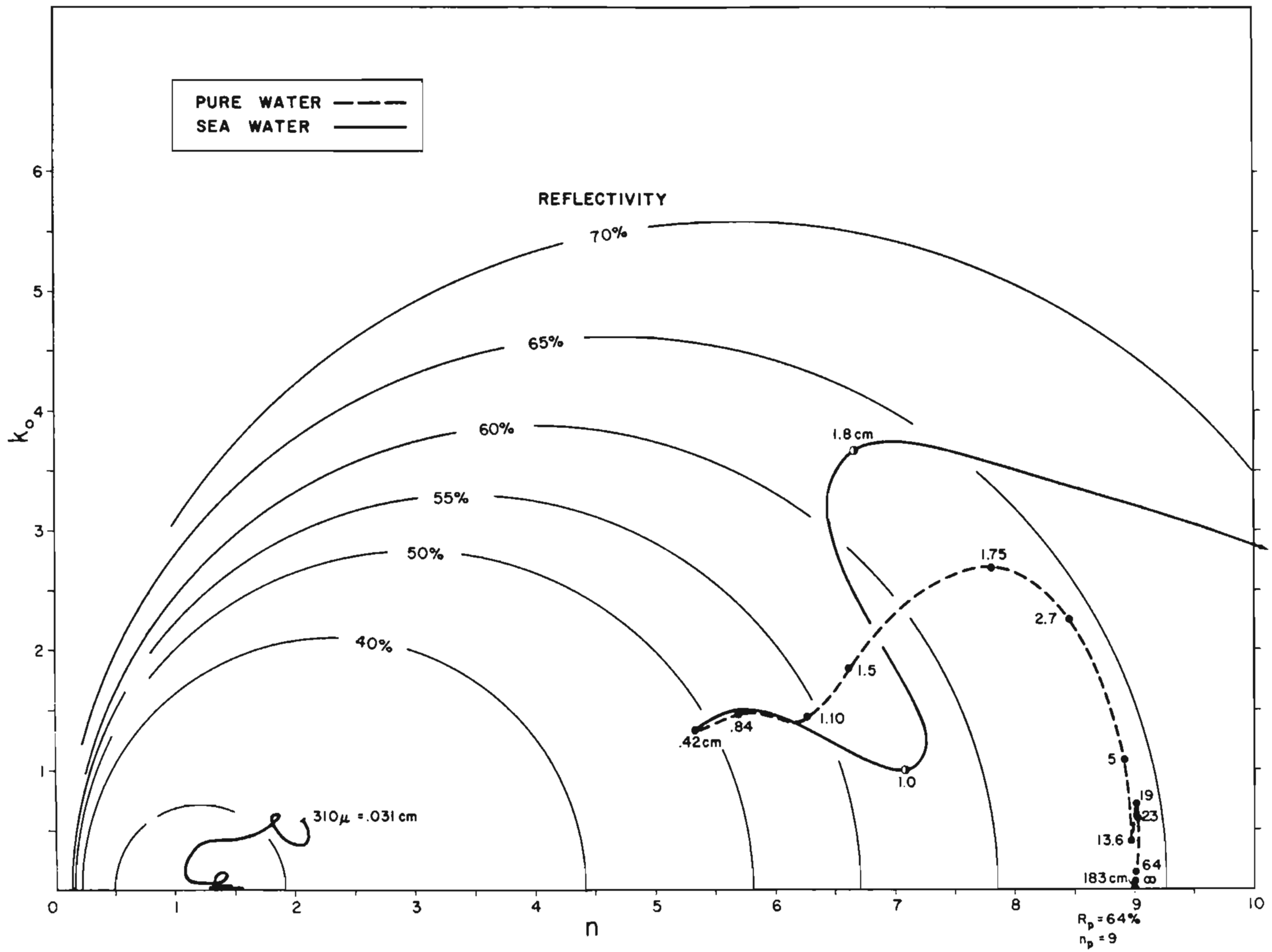

FIGURE 3: RELATION BETWEEN R, k_0, AND n FOR PURE AND SEA WATER TRACED THROUGH THEIR SPECTRA; 310 MICRONS TO 3 cm.

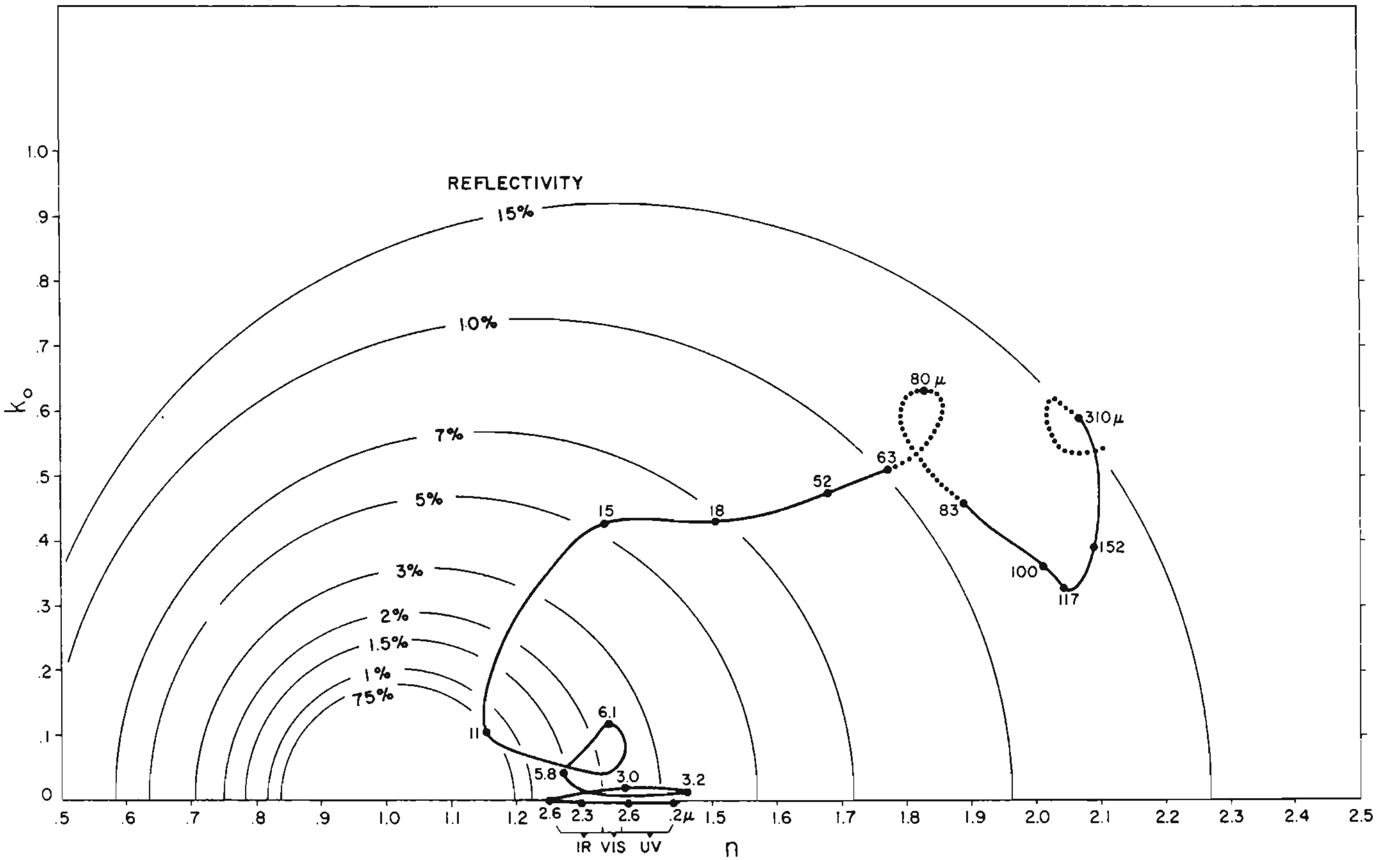

FIGURE 4: RELATION BETWEEN R, k_0, AND n FOR PURE AND SEA WATER TRACED THROUGH THEIR SPECTRA; .18 TO 310 MICRONS.

Ω is the angle of incidence measured from the vertical, σ is the conductivity, ε is the permittivity of free space ($\varepsilon = 8.85 \times 10^{-12}$ farad/meter), and ω is the angular phase velocity.

Since reflectivity is dependent upon conductivity, which in turn depends on temperature and salinity, in areas of great variations of salinity, such as areas of stream discharge, *e.g.*, estuaries and the vicinities of submarine springs, salinity may be the most significant factor. Reflectivity dependence upon salinity in visible light, where all natural waters are dielectrics, are an order of magnitude smaller than at radio frequencies, where sea water is a good conductor. At optical frequencies, reflectivity is closely related to salinity and density, rather than to temperature (Fig. 5). The probable range of coastal springs on Hawaii is shown on the plot by the shaded pseudo-ellipse.

Water can be classified into optical types as a function of its salinity and the electromagnetic wavelength. Figure 6 is a diagram of the type originated by McMahon (1950) and relating optical types to reflectivity, R, and absorption, K. The optical properties of water are traced through the spectrum in the diagram. At this scale, pure and sea water can be separated at ultraviolet frequencies by differences in transparency. With respect to ultraviolet light, sea water behaves as a more effective black body than does fresh water. As the trace progresses through the visible range, it takes a brief sharp excursion to the optically transparent region of the diagram (the visible window) and then returns abruptly to the black body region at infrared frequencies. As the wavelength progresses farther into the infrared toward microwaves, the trace remains at the opaque side of the diagram, but moves toward the metallic corner owing to an increase in reflectivity. When 64% reflectivity is reached at around 3 centimeters, the sea water and pure water traces separate abruptly. The sea-water trace goes to 100% reflectivity, whereas the pure water trace turns abruptly parallel to the 64% reflectivity contour and remains at 64% reflectivity as it progresses toward the radio window at 1 meter, above which it becomes a transparent body.

LABORATORY EXPERIMENTATION

Experiments of reflectance of water as a function of salinity to

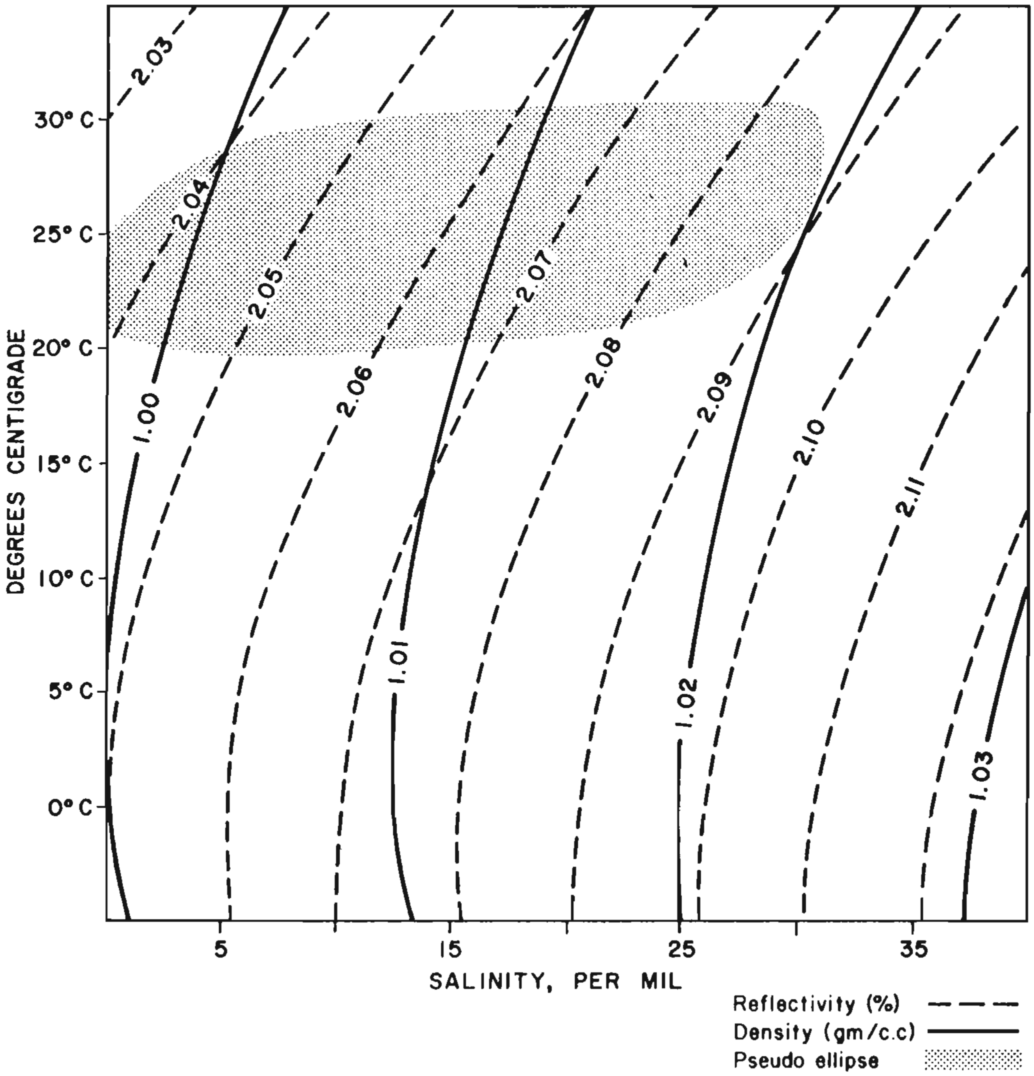

FIGURE 5: REFLECTIVITY TO VISIBLE LIGHT AND DENSITY *vs* SALINITY AND TEMPERATURE. SHADED PSEUDO-ELLIPSE SHOWS THE REGION IN WHICH THE NATURAL FRESH WATERS OCCUR.

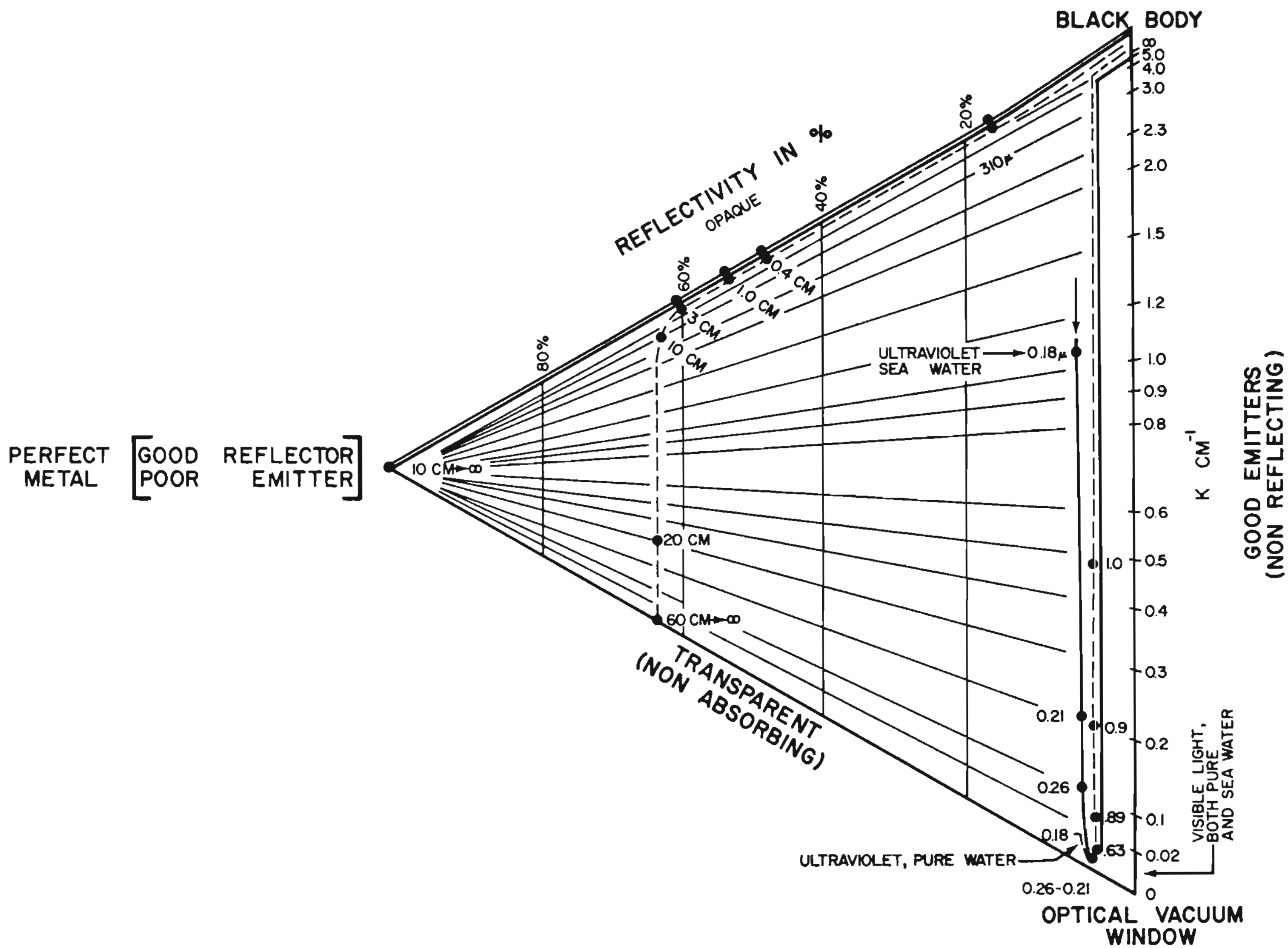

FIGURE 6: OPTICAL CLASSIFICATION OF WATER BY REFLECTIVITY AND ABSORPTION. (FORMAT AFTER McMAHON, 1950)

confirm the theoretical conclusions expressed in this report are not complete. The reflectance comparator now used utilizes visible light at 632.8 nanometers. One justification for continued optical experiments in the visible or near-visible range, in spite of the smaller optical contrasts with salinity, is the possible application of the results to the development of photographic techniques for airborne mapping of fresh or brackish water as it flows into the sea.

A helium-neon (Optics Technology, Inc.) laser was chosen as a light source because its narrow, collimated, monochromatic beam and ease of operation simplified the optics of the system. Silicon solar cells were used as sensors. Figure 7 shows the laser mounted on the right arm of the adjustable rack. The left arm contains two photovoltaic sensors, each in an aluminum tube. At the entrance of each tube is a pair of small diaphrams to pass the laser beam (less than 2 mm) and to block out the extraneous light. The beam-splitting prism and the front-surface mirror, which together split the laser beam into two equal parallel beams, can be seen at the exit of the laser head. These two beams are reflected, one each from the surfaces of the water placed in the two halves of the water tank. The problem of polarization of light by the beam-splitting optics (the O. T. laser does *not* polarize light) is avoided in one of two ways: the projector and sensors are rotated 45^{o} or they are at near normal incidence.

The sensors are in a Wheatstone bridge nulling system. Thus what is measured is only the difference in intensity of the twin beams reflected from the water samples. Asymmetries in the system can be detected by rotating the projector and sensor assemblies 180^{o} and by electrically reversing the sensor positions with a double pole-double throw switch. The output of the bridge is amplified and the signal read on a microammeter. The laser apparatus can also be used to measure the statistics of surface roughness due to ripples which affects the apparent or effective reflectance. It may also be modified by the "slicking" caused by a salinity gradient (fresh water on sea water).

SUMMARY AND CONCLUSIONS

Published values of electromagnetic properties of sea water with respect to wavelengths ranging from 200 nanometers in the ultraviolet

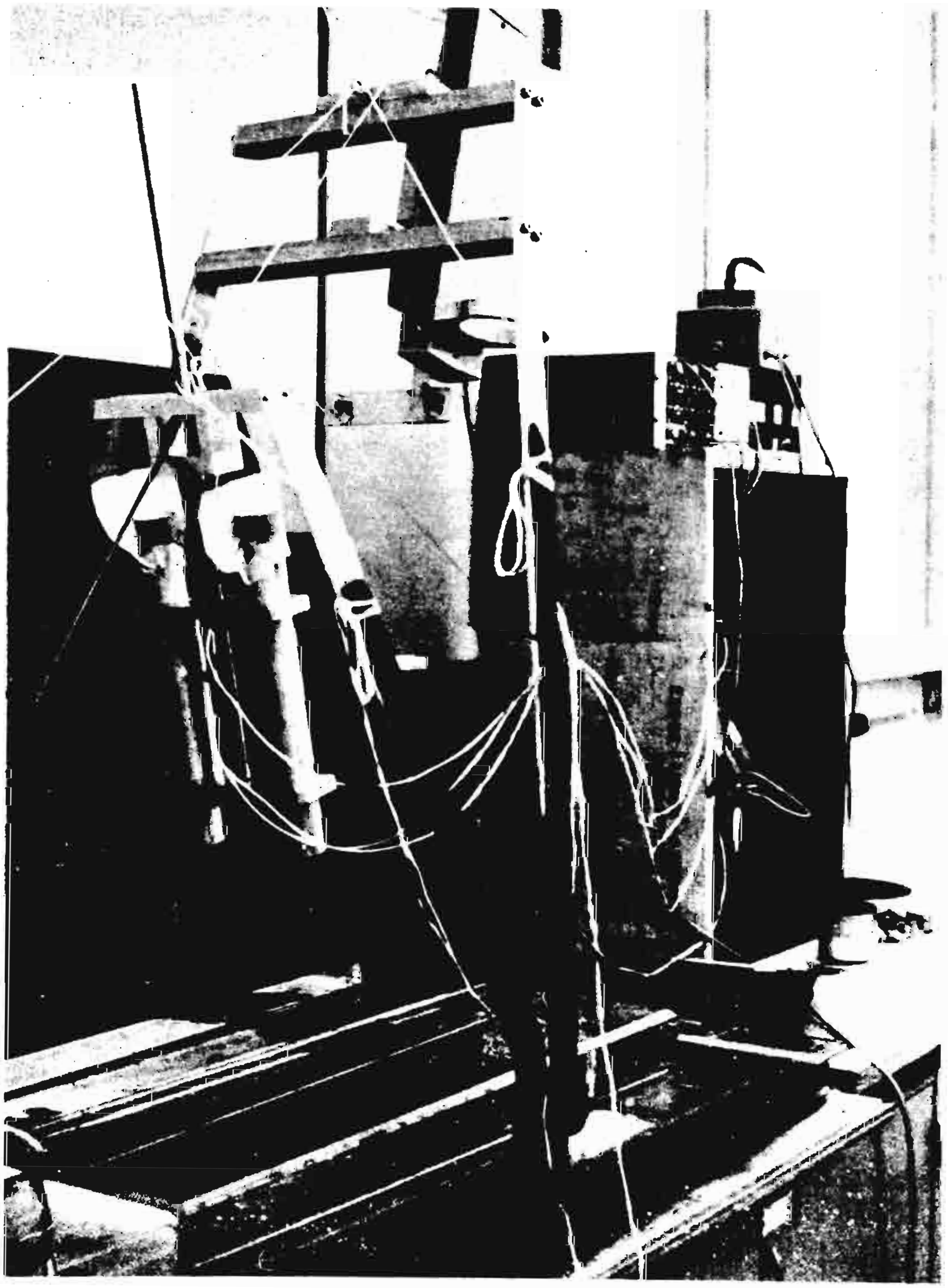

FIGURE 7: FRONT VIEW OF THE LASER REFLECTANCE COMPARATOR.

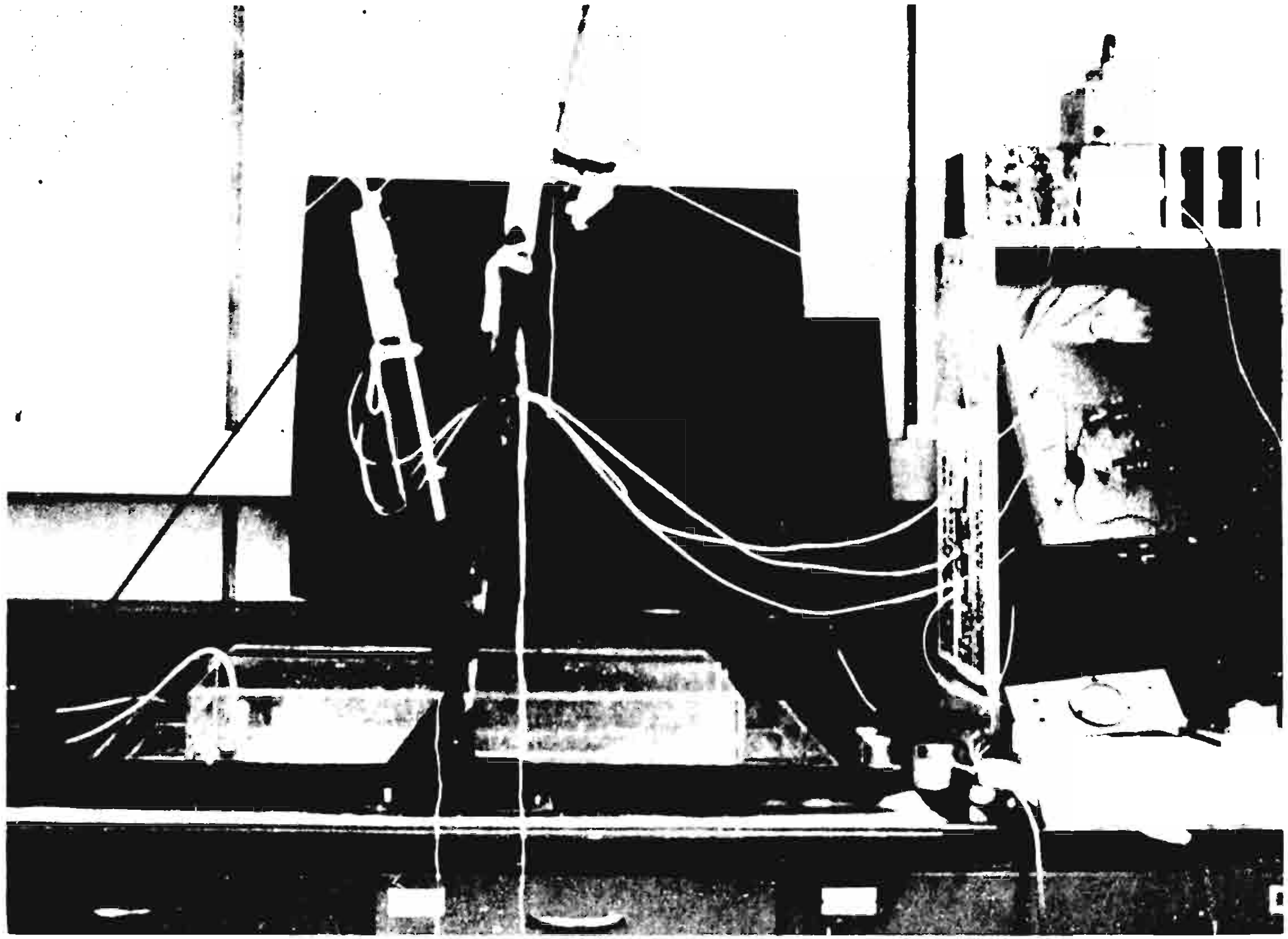

FIGURE 8: SIDE VIEW OF THE LASER REFLECTANCE COMPARATOR.

frequencies to 30,000 kilometers in the radio frequencies have been compiled and plotted on graphs. The resulting curves of measured and computed absorption index, k, refraction index, n, and reflectivity, R, *vs* wavelength, λ, show that the greatest optical contrasts between pure (p) and sea (s) water are at radio wavelengths longer than 3 centimeters. Whereas the computed average percentage reflectivity contrast for visible light (6×10^{-5} cm) is $100 \times (R_s - R_p)/\frac{1}{2}(R_s + R_p) = 3.7\%$, the computed reflectivity contrast at long radio wavelengths is 44.0%. (R_s is normal incidence reflectivity of sea water; R_p is normal incidence reflectivity of pure water.)

The reflectivity contrast increases at wavelengths greater than about 3 centimeters because k and n achieve constant values or decrease in pure water, whereas in sea water, k and n continue to increase as the wavelength increases. At any given wavelength,

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

The reflectivity contrast at optical wavelengths is almost linear with salinity contrast for waters intermediate between fresh and sea water.

To electromagnetic wavelengths over about 3 centimeters, the reflectivities of sea water and pure water are effectively 100% and 64%, respectively. Hence, the reflectivity contrast to radio waves is an order of magnitude greater than to light.

At optical frequencies, both fresh and sea water are dielectrics, but at radio frequencies, fresh water is a semiconductor whereas sea water has the reflective properties of a liquid metal.

This study indicates that the most effective part of the electromagnetic spectrum for use in the remote detection of large salinity anomalies from aircraft would be that of wavelengths of 3 centimeters or longer. Further study is needed to determine the optical contrasts of the waters intermediate in salinity between pure and sea water.

Studies might also be undertaken to determine the feasibility of exploiting the difference in transparency between fresh and sea water to ultraviolet light at 2,000 to 2,500 angstroms by ultraviolet photography.

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