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MEASUREMENT OF THE ABSORPTION COEFFICIENT OF HYDROSOLS

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FOREWORD

The work described in this report was supported in part by Contract NObsr-95251 between the Naval Ship Systems Command and the Visibility Laboratory, University of California, San Diego. This contract under Task I, Sub-paragraph c, directs the Laboratory to "Conduct a study . . . to provide the fundamental knowledge required to develop equipment and techniques in support of Naval requirements."

The general problem of the measurement of the optical absorption coefficient of ocean waters is of considerable importance to the understanding of light propagation in the ocean and the transmission of optical signals for Naval underwater image forming and signaling systems. In addition to increasing our understanding of the mechanism of light propagation and how it is affected by various amounts and kinds of absorbing and scattering materials, it is hoped that this study will result in the validation of a technique for the measurement of absorption in the open ocean. An instrument using this technique was invented by one of the authors and US Patent 3, 180, 210 issued 27 April 1965, entitled "Instrument for Measuring Volume Absorption Coefficients of Horizontally Stratified Water," resulted from work sponsored in the past by the U. S. Navy. Should this validation be successful, an additional valuable survey instrument could be made available to the oceanographic community.

The experimental study is being carried out in the Hydraulic Laboratory of the Scripps Institution of Oceanography which is ideally equipped to supply, filter, and discharge the large volumes of water needed.

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INTRODUCTION

Preisendorfer has shown that in any body of natural water, irradiated either by natural daylight, artificial light, or a mixture of both, the absorption coefficient (a) at a point, for monochromatic light, can be obtained from appropriate irradiance measurements taken as a function of position along three perpendicular axes of an arbitrary but fixed coordinate system based at that point. The equation setting forth this relationship is given in (1).

$$a = \frac{-1}{h}\left(\frac{d\bar{H}_x}{dx} + \frac{d\bar{H}_y}{dy} - \frac{d\bar{H}_z}{dz}\right) \qquad (1)$$

where $d\bar{H}_x/dx$, $d\bar{H}_y/dy$ and $d\bar{H}_z/dz$ are the rates of change of the net irradiance, e.g. $\bar{H}_x = H_x(+) - H_x(-)$, with respect to position along the three axes, evaluated at the origin and h is the scalar irradiance at the origin.

For the special case in which the natural water is optically horizontally stratified in the x, y plane; $d\bar{H}_x/dx$ and $d\bar{H}_y/dy$ will be zero, and the equation will reduce to:

$$a = \frac{1}{h}\left(\frac{d\bar{H}_z}{dz}\right) \qquad (2)$$

Although equation (1) is theoretically valid for any light field, its practical application to natural bodies of water has been prevented by our inability to confirm the numerical values obtained for a. One method for confirming the numerical values of a, obtained by employing equation (1) or (2), would be to accurately and simultaneously determine the total scattering coefficient (s) and the total attenuation coefficient (α), and solve for the absorption coefficient by means of the equation:

$$\alpha = a + s \tag{3}$$

However, practical application of equation (3) for that purpose has been held up by instrumentation problems associated with the measurement of the scattering coefficient, and by our inability, in this case also, to experimentally confirm the numerical values obtained for s.

In order to experimentally validate equations (1) and (2) and simultaneously reveal any severe instrumentation problems, an experiment is needed which will yield confirming evidence for the value of the absorption coefficient without introducing additional "unknowns". The experiment should also be conducted under conditions that provide maximum stability of the light field and maximum homogeneity of the hydrosol.

OUTLINE OF EXPERIMENT

In a laboratory based experiment it is proposed to prepare large volumes of scattering-absorbing media in a suitable tank and by means of artificial lighting to generate a light field within the tank which is symmetrical around the vertical axis. Nearly independent control of absorption and scattering can be achieved by employing a stable black dye and white scattering particles. Arrangements can also be made to change the apparent path length within the tank by inserting mirrors around the walls.

Determinations of the total attenuation coefficient (α), the absorption coefficient (a), and the relative scattering at a fixed angle $\sigma(\theta)$, will be made on hydrosols having controlled optical properties. A typical experiment will involve these measurements on a series of hydrosols containing a fixed amount of absorbing material to which equal successive additions of a scattering material are added.

The results obtained in such a series of experiments will be used in the following way. The coefficients, α, and, a, will both be plotted against the relative scattering $\sigma(\theta)$. It is expected that the resulting plot will have the form shown in Fig. 1. The vertical dashed line marks the relative scattering of the initial clean water with only absorbing material added. As scattering material is added the absorption coefficient will rise somewhat due to shortening of the mean free path within the hydrosol. The total attenuation coefficient will rise much faster since $\alpha = a + s$.

The two graphs should converge to a single point for $\sigma(\theta) = 0$ since for zero scattering $\alpha = a$. Failure of the curves to do this will indicate that the method of measurement is incorrect or that there are random errors associated with the measurement. Success of the curves to do this is strong evidence in support of the validity of the method of measurement as well as of the theoretical equations.

The relative scattering will also be plotted in linear coordinates against (α − a), as shown schematically in Figure 2. It has been demonstrated in laboratory experiments that the total scattering coefficient ($s = \alpha - a$) is directly proportional to the scattering function at a single angle $\sigma(\theta)$. The plot of $\sigma(\theta)$ vs (α − a) is therefore expected to yield a straight line through zero.

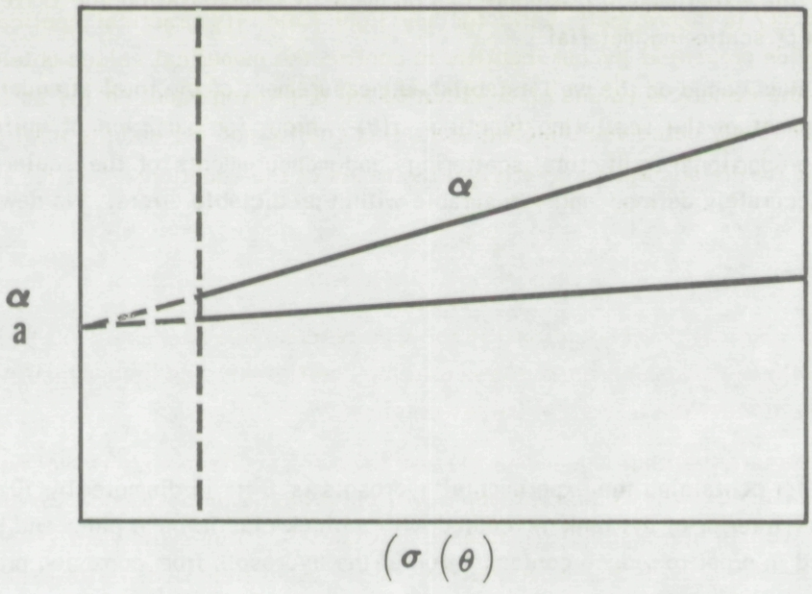

Fig. 1. Plot of α and a vs relative scattering ($\sigma(\theta)$ at 30°. α rises with $\sigma(\theta)$ because $\alpha = a + s$. a rises with $\sigma(\theta)$ because the mean free path for the photons become smaller with increasing $\sigma(\theta)$. The photons must therefore travel further, and suffer greater absorption, to traverse the same geometrical path length.

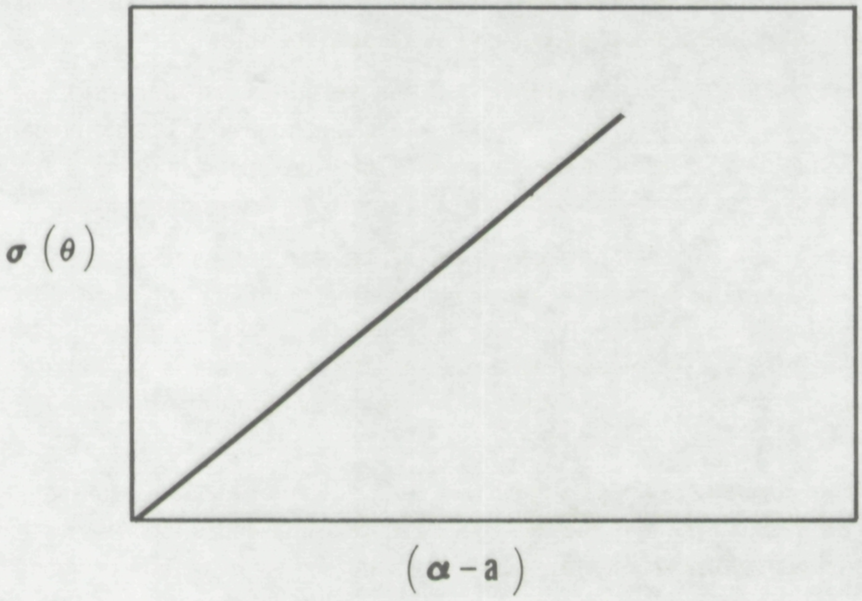

Fig. 2. Plot of $\sigma(\theta)$ vs ($\alpha - a$). Previous experimental work has demonstrated that $s = \text{constant} \times \sigma(\theta)$ for uniform scattering particles. By definition $s = \alpha - a$. If the value of a is correct, a plot of $\sigma(\theta)$ vs ($\alpha - a$) should yield a straight line through zero.

A further check on the experimental procedure can be made by demonstrating the correlation between $\sigma(\theta)$ and concentration of scattering material.

This experiment is thus based on the well established measurement of the total attenuation coefficient[*] (α), a relative measurement of the scattering function $\sigma(\theta)$ which, for particles of uniform size and shape, is known to be proportional to the total scattering, and measurements of the scalar and vector irradiances which are accurately defined and measurable within predictable errors. No new ''unknowns'' have been introduced.

MAJOR EQUIPMENT

TANK

The tank employed for containing the experimental hydrosols is 8 ft. in diameter by 10 ft. high and is shown in Figure 3. The interior of the tank is coated with a black plastic-base paint and heat treated for long-term durability and in order to reduce contamination of the hydrosols from corrosion products.

The water used is filtered through a large diatomaceous-earth filter and supplied to the tank through plastic pipe.

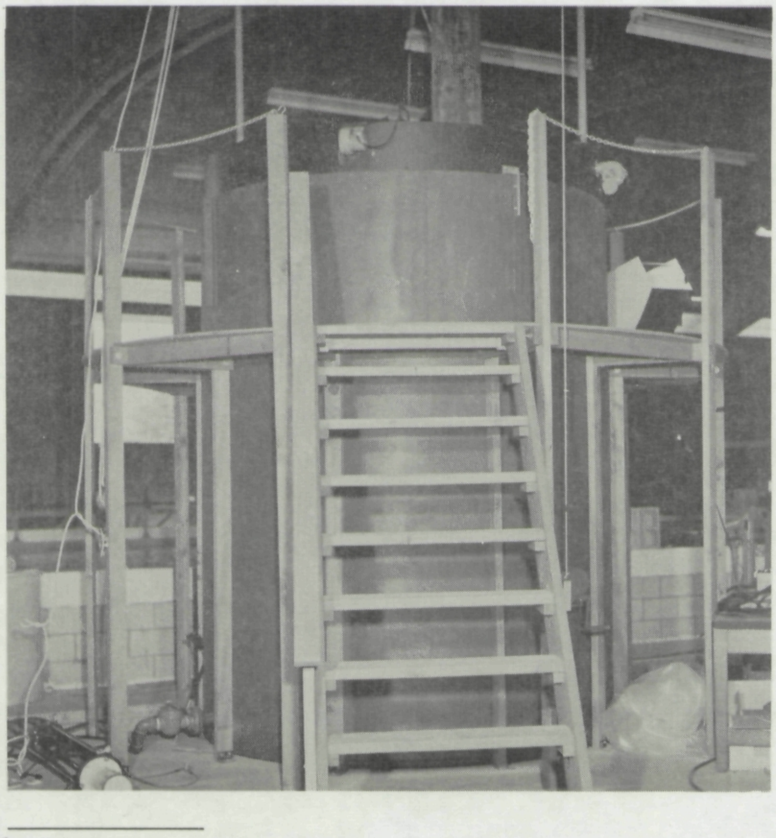

Fig. 3. General view of the experimental set-up.

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[*] Because of the nature of the measurements required for the experiment, the absorption coefficient, a is of much larger magnitude than the total scattering coefficient, s. Under these conditions the measurement of the total attenuation coefficient, alpha, by means of the beam transmissometer method, is relatively free of the errors which have been attributed to this type of measurement in some natural ocean water situations.

LIGHT SOURCE

The top of the tank is covered with a specially constructed light source shown closed in Figure 4 and with a section removed in Figure 5. Thirteen 86-watt tungsten-iodide lamps are arranged in a symmetrical pattern on the sheet metal backing as shown in Figure 4. The lamps themselves can be seen by reflection from the water surface in Figure 5.

The interior of the lamp housing is painted white and additional diffusion is provided by means of a white diffusing plastic sheet mounted near the lower rim of the lamp housing. The mounting rods which can be seen in Figure 5 are clear plastic.

Each lamp is mounted in an oversized hole to provide for air circulation and four blowers supply cooling air.

The diffusing plastic of the lamp housing is about 2 inches above the water surface during experimental measurements. The light source provides symmetrical irradiance around the vertical axis of the tank but the irradiance is not uniform.

Two sections of the light source can be independently removed in order to manipulate the measuring equipment.

During the experimental measurements the light source is operated from a voltage regulator to insure steady lighting conditions.

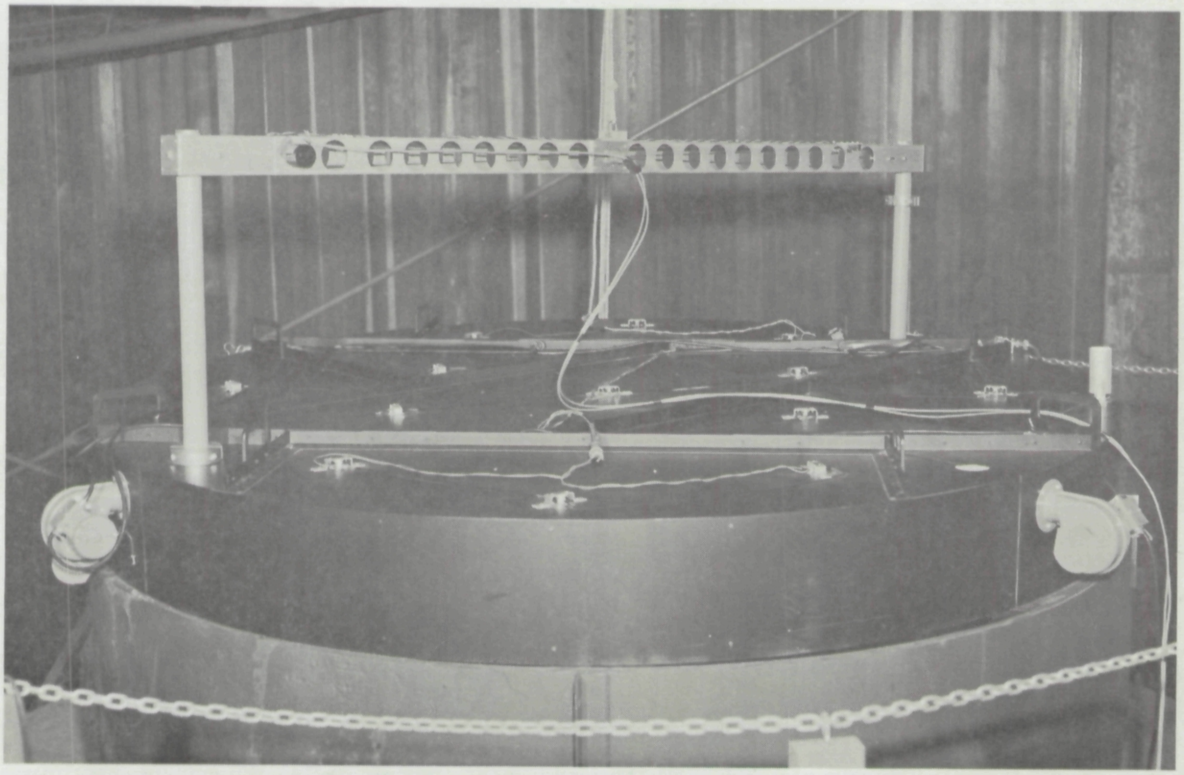

Fig. 4. Light source mounted on top of tank. Cooling is provided by four blowers which exhaust hot air through annular holes surrounding lamps. Photo also shows upper part of frame which holds phototube, protruding through light-source housing.

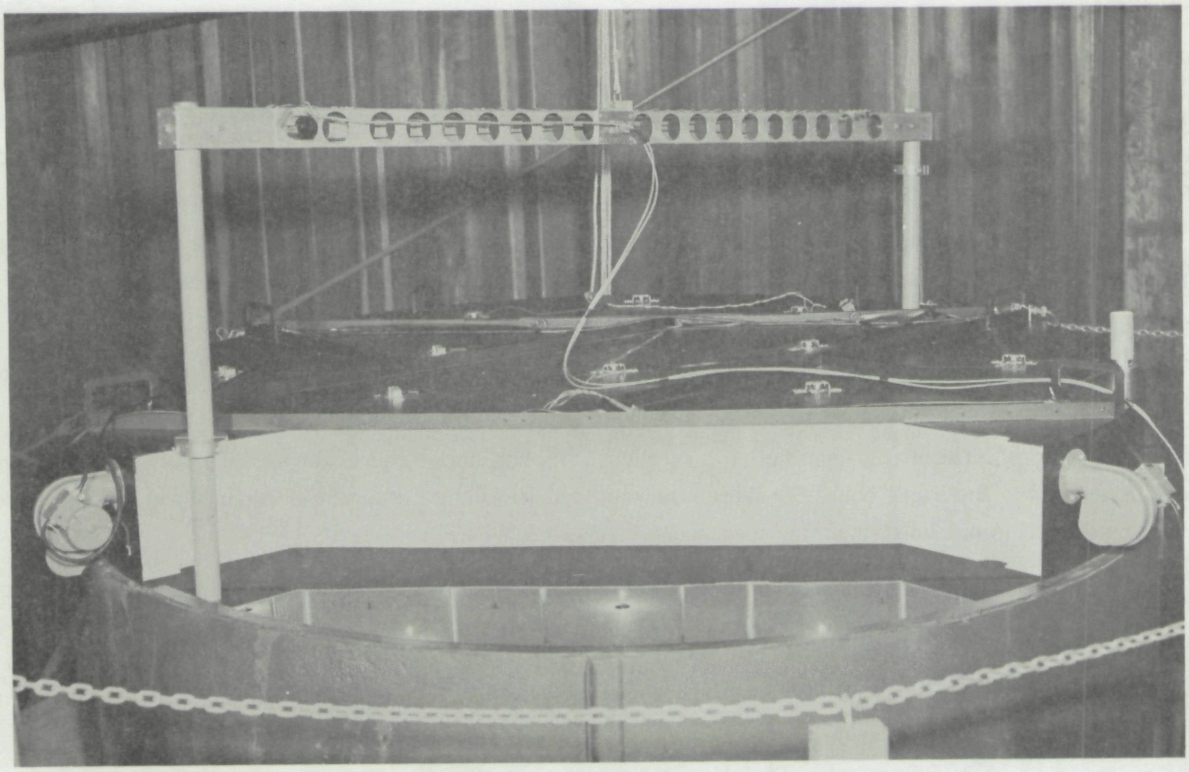

Fig. 5. Showing a section of light-source removed. Tungsten-iodine lamps can be seen by reflection from the water surface.

OPTICAL BENCH

Figures 4 and 5 also show the optical bench, or frame, which acts as a guide for the measuring equipment and as a means for manipulating and orienting it along the three orthogonal axes. By removing the two sections of the light source the optical frame can be rotated 90° and by means of an overhead block and tackle it can be raised or lowered in the tank.

Horizontal motion of the irradiance detectors along the x and y axes is by means of a cable and synchronous motor which drives a small cart along the horizontal lower limb of the optical frame.

The optical frame is constructed entirely of plastic (except for the top horizontal member), the lower limb and cart being of transparent plastic to reduce perturbation of the light field.

PHOTODETECTOR

A single RCA 7767 photomultiplier tube is used for all measurements except the measurement of α. A highly linear photometer provides an output voltage proportional to light flux on the photomultiplier tube over a flux range of 3 decades. This photometer is shown at the left in Figure 6. For measuring vector irradiance (H) the phototube is provided with an irradiance collector shown at the right in Figure 6. For scalar irradiance measurements the vector irradiance collector is replaced by the scalar irradiance collector shown in the center of Figure 6. Figures 7 and 8 show various aspects of the detector mounted on its carriage on the lower limb of the optical frame

The vector and scalar irradiance collectors have been carefully designed to perform the required integrations indicated by the defining equations

$$H = \int_{2\pi} N \cos\theta \, d\omega$$

and

$$h = \int_{4\pi} N \, d\omega .$$

In the case of scalar irradiance, the presence of the detector itself in the field of view of the scalar irradiance collector is known to introduce a small error. The magnitude of this error can be estimated from a knowledge of the light field and collector properties.

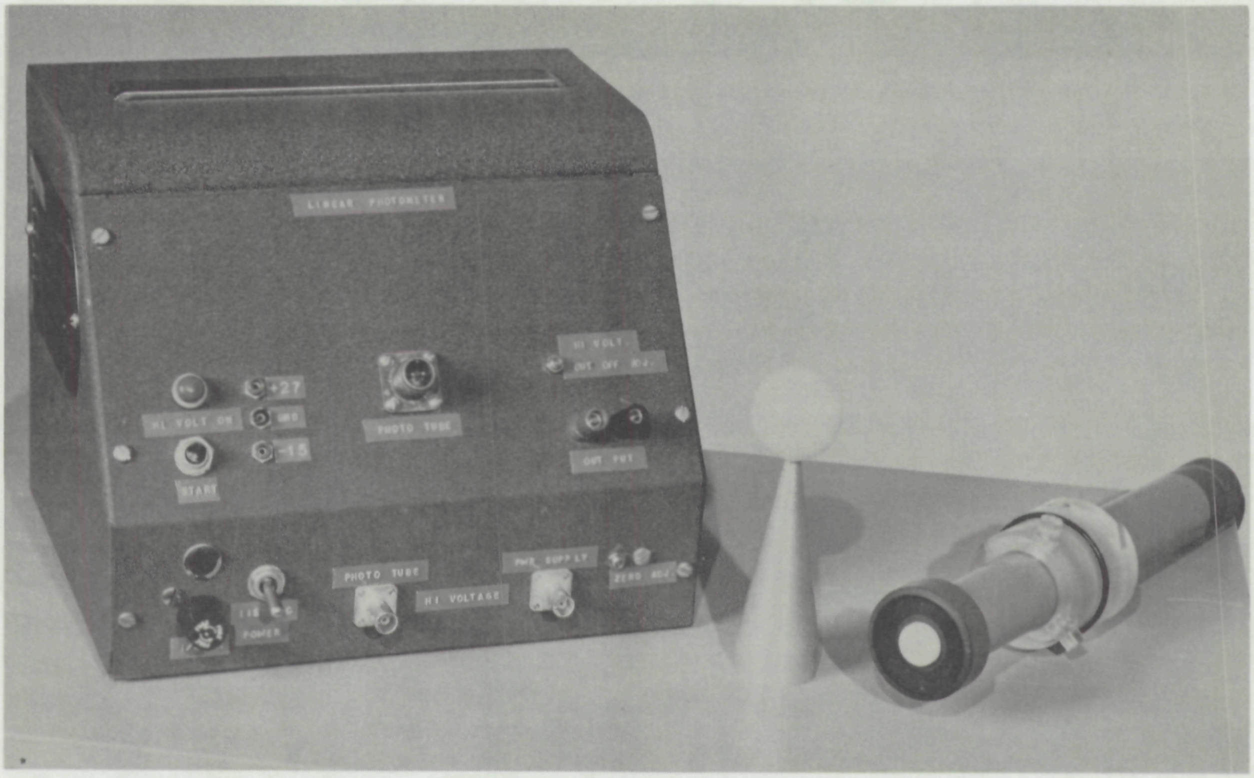

Fig. 6. The linear photometer is on the left, and the phototube with vector irradiance collector on the right. For measuring scalar irradiance the collector in the center is substituted for the vector irradiance collector.

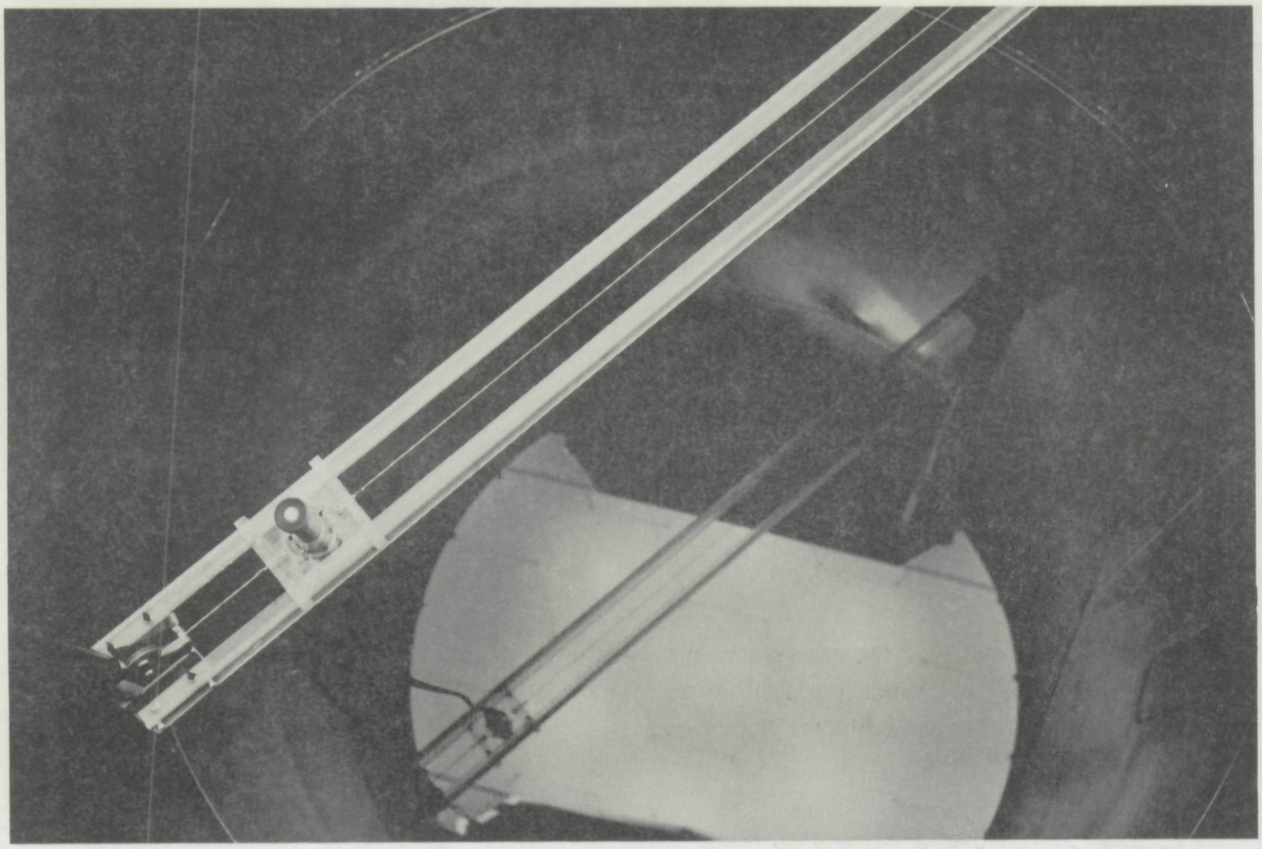

Fig. 7. Top view of vector irradiance collector mounted in carriage on lower horizontal limb of optical frame. Light-source can be seen in reflection from water surface below.

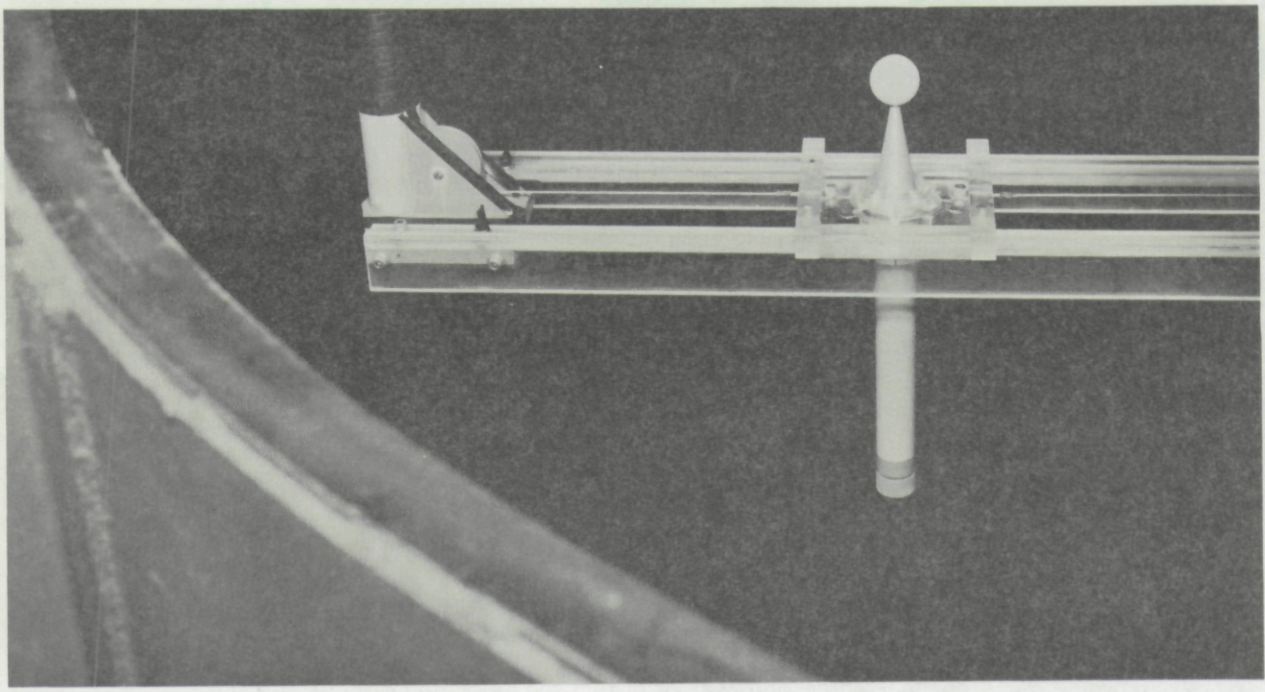

Fig. 8. Side view of scalar irradiance collector mounted in carriage on lower limb of optical frame.

MEASURING EQUIPMENT FOR α AND $\sigma(\theta)$

The equipment for measuring the total attenuation coefficient (α) and the relative scattering function $\sigma(\theta)$ at fixed angle (θ) is shown in Figure 9. This consists of a Marine Adviser's transmissometer with an attachment which provides a black trap and a means for holding the photodetector assembly used for making irradiance measurements in the tank.

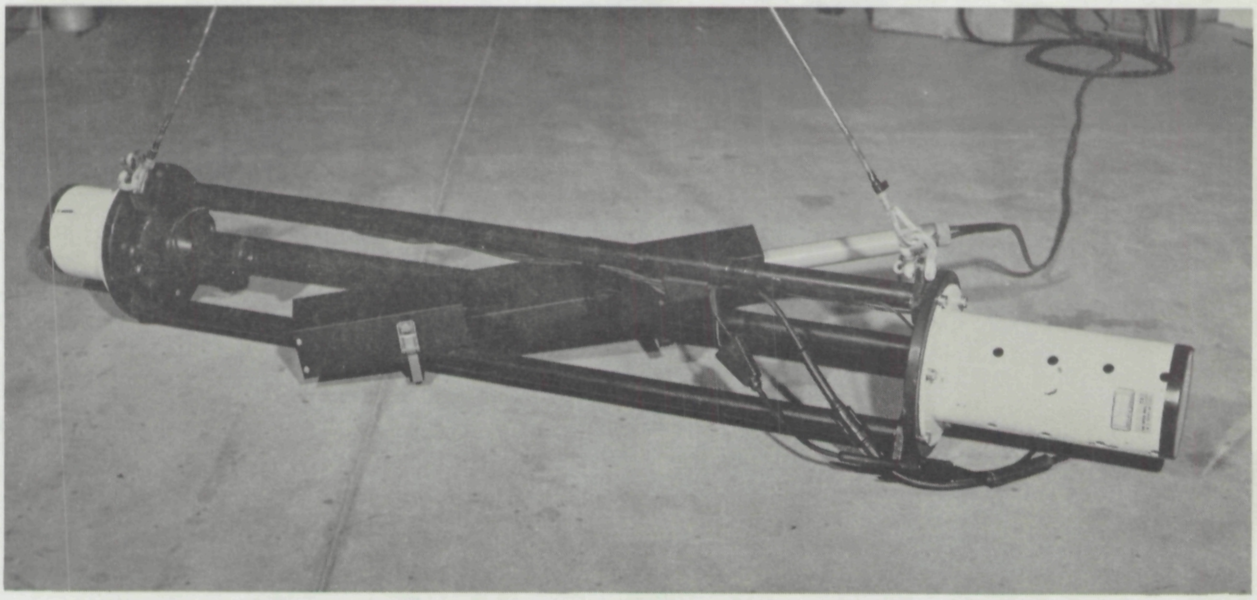

Fig. 9. Marine Advisers' transmissometer with attachment for measuring relative scattering at 30°.

ELECTRONIC CONTROL EQUIPMENT

The electronic control equipment is shown in Figure 10 and consists of (from left to right): a Moseley Model 1 (Autograf) x-y plotter with position recorded on the x-axis and phototube reading on the y-axis, a Trygon precision power supply which supplies power for the position potentiometer, an adjustable high voltage power supply for the phototube, the linear photometer control panel (on top of the H-V power supply). In front of the high voltage power supply is the control switch for controlling horizontal movement of the phototube carriage.

To the right again is the voltage regulator for the light source. The remaining units operate the α meter and consist of

Null-detector (located on top of the voltage regulator).

Power supply for the α-meter, and in front of that the balancing circuitry for the measurement of beam transmittance from which α is computed.

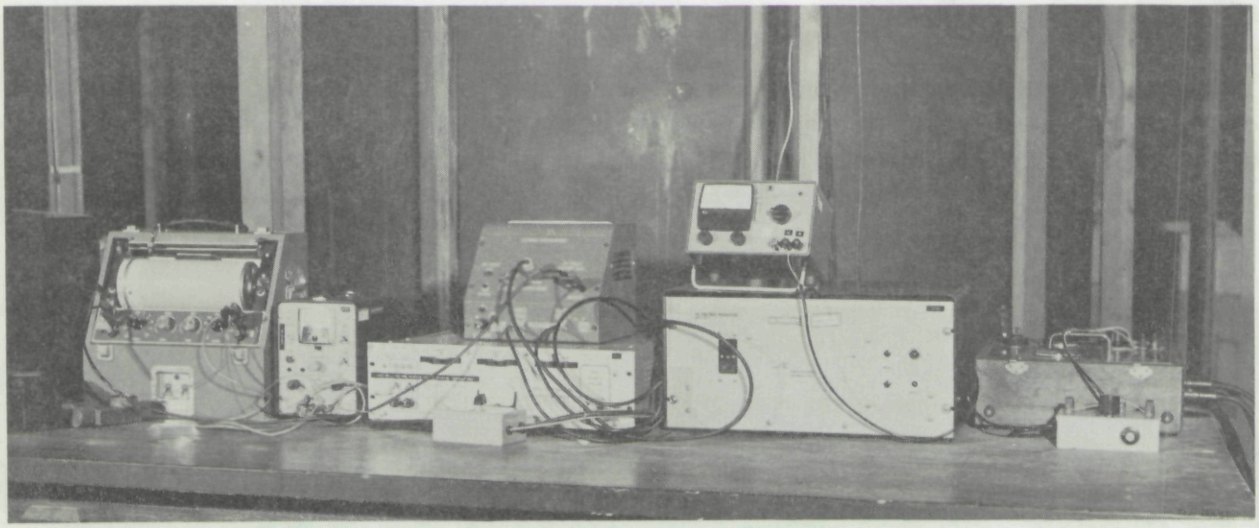

Fig. 10. Electronic recording and control equipment.

EXPERIMENTAL PROCEDURE

The experimental procedure is to first adjust the absorption of the clean water by adding a black dye. Scattering material is then added in several equal portions from a standard stock solution. For each addition of scattering material a complete set of measurements for determining the absorption coefficient is made.

Nigrosine dye was originally employed to control the absorption but this dye is sensitive to bleaching by chlorine and loses its strength depending on the concentration of chlorine in city water, which varies considerably from day to day. To avoid this difficulty we have substituted India ink which is stable in water containing chlorine but introduces a small amount of scattering due in part to the gum arabic constituent which precipitates out on dilution. The scattering introduced in this way does not seem to pose a serious problem.

A complete run including preparation of the hydrosol requires the major part of a day and yields one point on the final plot. To generate enough points for the plot shown in Figure 1 requires 3 to 5 days.

RESULTS

In a nearly symmetrical light field, the values for $H+$ and $H-$ along the x axis (and also along the y axis) are nearly the same. Consequently $d\bar{H}_x/dx$ and $d\bar{H}_y/dy$ are apt to be small numbers of low precision. Their sum combined with $d\bar{H}_z/dz$ is not likely to improve the precision of the latter number.

In the early measurements an attempt was made to work with levels of absorption similar to those found in ocean water but the loss of precision described above led to unacceptable random errors in the value of the absorption coefficient.

At higher absorption levels, values of, a, calculated for a series of depths in a stable hydrosol show far less random error, and if the calculations are based on a least-squares fit to the data, a nearly constant value for the absorption coefficient is obtained.

A check for accuracy of the calculated value of the absorption coefficient can be made by plotting α against $\sigma(\theta)$. At $\sigma(\theta) = 0$ (linear extrapolation) the value of α should be equal to a.

In the most recent experimental work the absorption coefficient has been calculated at 10 cm intervals of depth using experimental data rather than results obtained from a least-squares fit. The variation in the value obtained for the absorption coefficient was approximately ± 10% and the average value of a compared favorably with the value obtained by extrapolation of a linear plot of α vs $\sigma(\theta)$.

In the most recent experimental work, Figure 11, the absorption coefficient has been calculated at 10 cm intervals of depth using experimental data rather than results obtained from a least-squares fit. The variation in the value obtained for the absorption coefficient was approximately ± 10% and the average value of a compared favorably with the value obtained by extrapolation of a linear plot of α vs $\sigma(\theta)$. Also, a complete run including four independent experiments for determining α and a is shown in Figure 12, which may be compared with Figure 1.

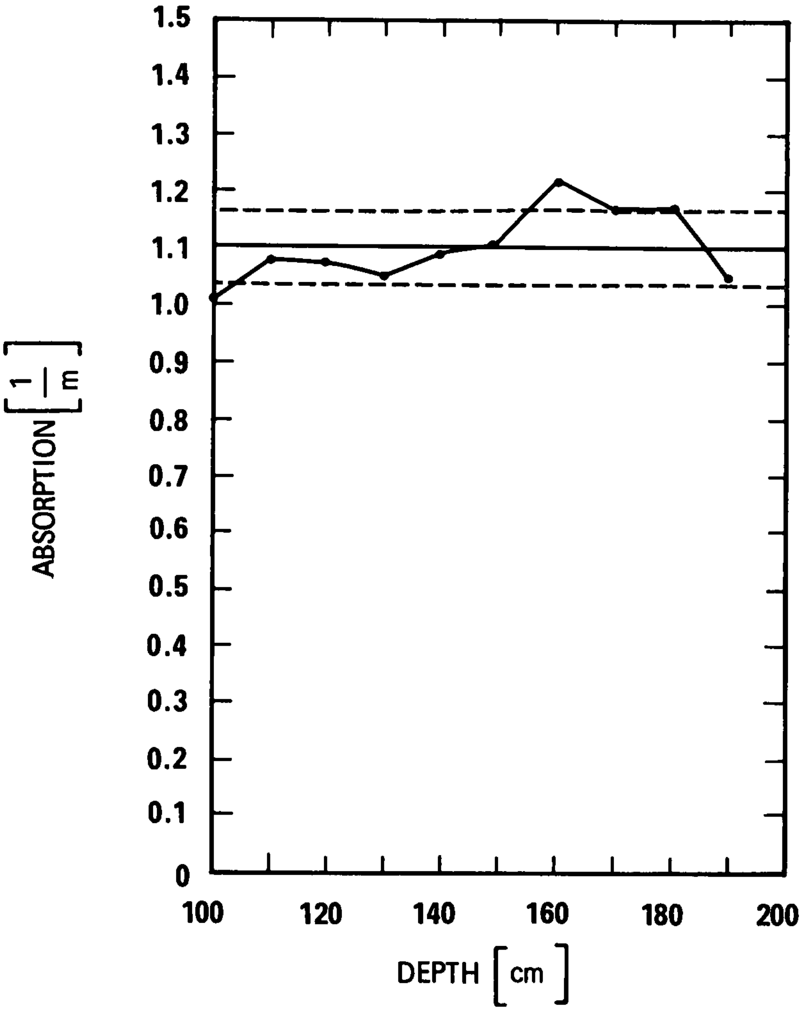

Fig. 11. Plot of absorption coefficient as a function of depth

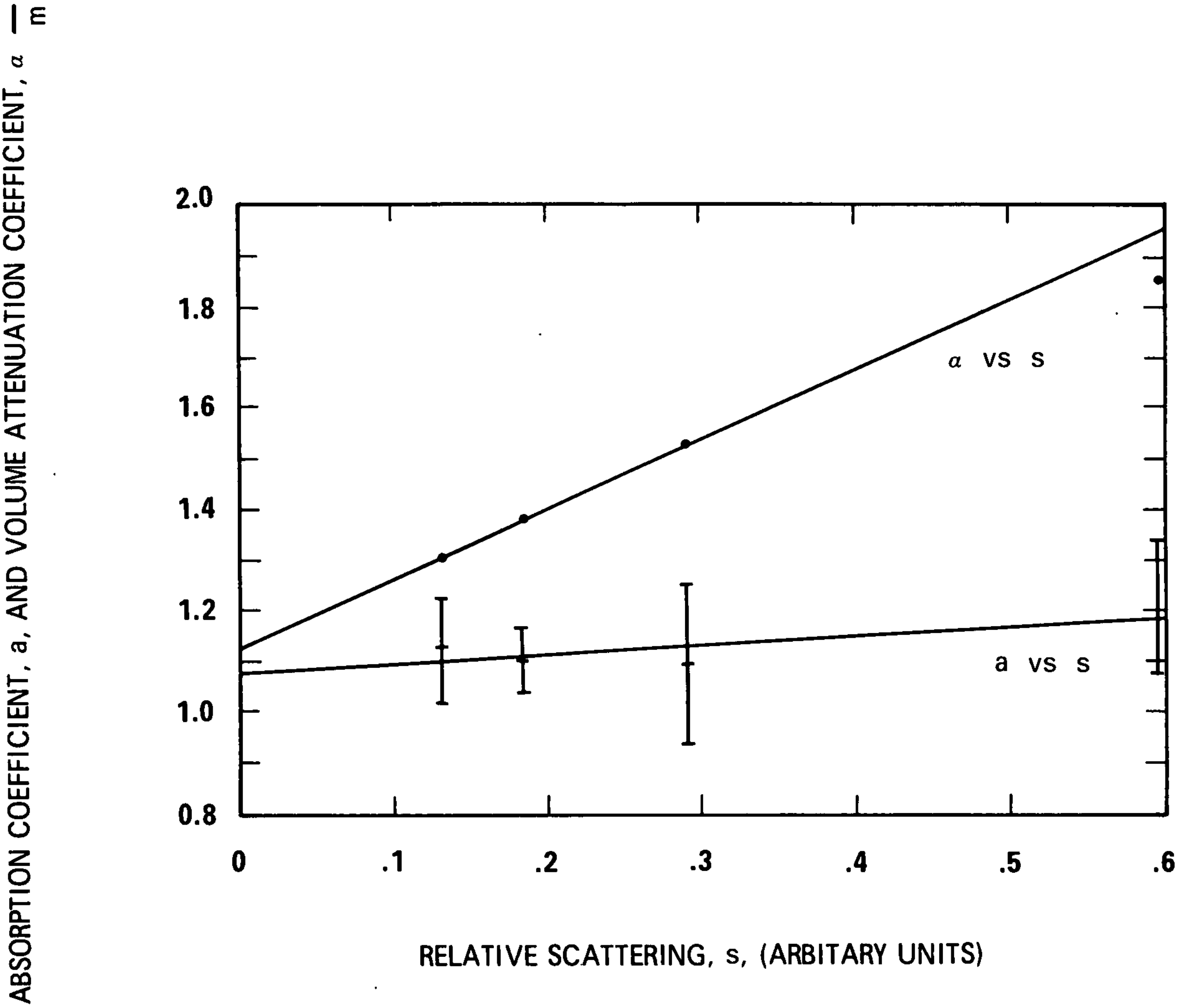

Fig. 12. Results of a complete run of four independent experiments. Compare with Fig. 1.

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13 ABSTRACT

A theoretical method is described for the measurement of the optical volume absorption coefficient of natural bodies of water using the divergence of the vector irradiance field. Laboratory equipment has been constructed for the evaluation of the feasibility of using the method. The laboratory equipment is described and preliminary data is show. If the laboratory evaluation indicates sufficient precision can be obtained with the method, instruments for the measurement of absorption in the open ocean using this direct method may be constructed.

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