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A NEPHELOMETER FOR THE MEASUREMENT OF VOLUME SCATTERING FUNCTION

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INTRODUCTION

Scattering in natural waters is the result of multiple reflections from organisms, gas bubbles, and detritus as well as scattering by the molecules composing the hydrosol itself. It is commonly observed that the degree of scattering varies discontinuously with depth. This is true in waters having a high degree of biological activity and also in coastal waters where a major portion of the scattering agent may be detritus stirred up by wave action. The measurement of the scattering properties of natural waters presents some special problems that are not ordinarily encountered in the measurement of laboratory samples. Ocean and lake waters are balanced aquaria and are highly sensitive to environmental factors. Great changes can take place if these waters are bottled. Gas bubbles collect on the walls of the container, some species of plankton may die while others may undergo accelerated propagation, detritus settles out or rises to the surface. In a matter of minutes the sample in the bottle may no longer represent the part of the ocean from which it was taken, and one would be hard put to justify the effort required to collect it. Thus the usual laboratory procedure of putting the sample into the instrument must be reversed.

Depth is an important parameter in biological investigations and also in any program of physical measurements for which the homogeneity of the sample must be known. Instrumentation must consequently meet the mechanical and optical requirements imposed by this type of operation.

From the definition of scattering function,

$$\sigma(\theta) = \frac{dJ}{H dv} \quad *$$

*For Photometric Symbols see Committee of Colorimetry JOSA, Vol.34,245-66 (1944)

it is clear that in designing instrumentation for its measurement provision must be made to determine the sample volume (dV) and the irradiance input to this volume.

INSTRUMENT

In the instrument described here a well defined beam of light is used in conjunction with a Waldram stop to uniformly irradiate a sample volume which is defined by the intersection of a beam of detectivity with this light beam. The beam of detectivity can be rotated around the volume through an angle of about 180° . The details of the optical system are shown in Figure 1. The projection beam is obtained by means of a uniformly irradiated field stop which is imaged on the sample in such a way that its image is the same size as the exit pupil of the projection lens. The limiting rays are thus parallel to the axis of the system and can all be made perpendicular to the glass window of the water-tight enclosure. Under these conditions the limiting rays will not be deviated by changes in index of refraction at the window. The diagonal rays of the beam will, of course, be deviated inward if an increase in index of the medium occurs and a change in flux distribution within the beam will result, but the same total flux will be incident on the sample volume. (Changes in attenuation by scattering or absorption are not under consideration at this point.) This collimated light beam is ideally suited for use with a Waldram stop. Independent measurements at and near the image plane showed uniform flux distribution for a considerable distance on both sides of the image. Thus changes in the position of the image along the axis due to index of refraction changes will be unimportant to the operation of the Waldram stop as well as to the proper radiation of the volume.

The beam of detectivity is generated in the same manner as the light beam and is designed to intersect the light beam over the axis of rotation of the scanning system. The volume thus defined is about 3.2 cubic cm. and has a shape that depends on the angle of observation.

Uncertainties in the measured value of the scattering function will be present as a result of dimensional changes in the sample volume during the scanning process. Increasing the difference in path length between the near point and the far point of the volume leads to increasing uncertainty since the flux from these points does not average in the measurement. The use of a Waldram stop materially reduces changes in the dimensions of the volume and therefore reduces this uncertainty.

VOLUME CALIBRATION

The relative magnitude of the volume at each angle of observation is determined by means of a volume calibrating attachment (see Figure 2) which was suggested by the recent work of Mr. Pritchard*. This device consists of a lead screw mounted parallel to the beam of detectivity and driven at constant speed by a synchronous motor. The lead screw in turn drives a small carriage carrying a white Lambert reflector through the light beam and consequently through the sample volume. At any position of the Lambert reflector the phototube signal will be proportional to the reflectance (or transmittance) of the reflector (R), the radiant intensity of the light beam (J) and a sectional area (A) through the volume at this position, i.e.,

$$(1) \text{ Reading} = k R A J$$

*Vision Research Laboratory, University of Michigan, Private Communication.

By holding J constant the reading (at each fixed setting) becomes proportional only to the area.

Recording the phototube output on a synchronous drive chart gives a plot of (kA) vs χ , the longitudinal dimension of the volume, and the volume V will of course, be

$$(2) \quad V = \int_{\chi_1}^{\chi_2} kA dx$$

The experimental limits of χ are quite well defined and no difficulty has been experienced in their practical determination.

Figure 3 is a plot of the relative volume vs the angle of observation. The absolute magnitude of the volume can easily be found from geometrical considerations when the beams intersect at 90° .

The value of R (or T) called for by equation (1) can be determined by using the instrument as a goniophotometer. This involves removing the Waldram stop, positioning the Lambert plate at the center of rotation, and scanning through 180° . Since the flux incident on the plate is found by measuring the direct beam with the same optical system and the same phototube, instrumental factors cancel yielding true gonireflectance or goniotransmittance values directly.

CALIBRATION

The flux input to the volume when the instrument is immersed can be determined by measuring the flux input in air, again using the instruments own detection system, and correcting for the beam transmission of the water path between the source and the volume. No correction for the change in index of refraction is required.

CIRCUITRY

The phototube used in this instrument is an end-on multiplier phototube (Dumont #6291) selected for high sensitivity and low noise. Its characteristics are as follows:

Cathode sensitivity; 42 μ amps/lumen measured with 210 volts
between the cathode and all other electrodes.

Gain; 2.19×10^6 at 138 volts per stage plus 106 volts between
last dynode and anode.

Dark Current; not greater than .2 μ amps at 1600 volts.

Anode Sensitivity; 92 amp/lumen at 138 volts per stage and 106
volts between anode and last dynode.

The phototube signal goes to a logarithmic-type chassis, a development of the circuit described by Monroe Sweet*, and the output from the chassis goes to a strip chart recorder. The circuit and recorder are designed to accommodate a change of five log cycles in light level. A considerable effort goes into aligning the chassis to achieve a linear relationship between light input (in density units) and recorder scale reading. Aligning is done in 0.1 density steps on a 4-meter photometer bench using an aged light source.

THEORY

As previously stated, the value of the scattering function at any angle is;

$$(3) \quad \sigma(\theta) = \frac{J(\theta)}{H \, dV}$$

*An Improved Photomultiplier Tube Color Densitometer. Journal of the Soc. of Motion Picture and Television Eng., Vol. 54, January 1950.

where $J(\theta)$ is the intensity of the scattered light in the direction θ , H is the irradiance on the volume and dV the sample volume.

The value of $J(\theta)$ is the flux emitted by the sample volume per unit solid angle or; referring to Figure 4

$$(4) \quad J(\theta) = \frac{dp_1}{d\omega} = \frac{CR_\theta e^{-\alpha r_2}}{\frac{dA_1}{r_2^2}}$$

Here the instrument reading R_θ , at the angle θ is corrected for the attenuation suffered in traversing the water path r_2 , and is shown directly proportional to the flux collected by the phototube through the coupling factor C .

dA_1 is the area of the collector.

The irradiance on the volume is the flux input per unit area. This measurement is made in air with the same phototube and optics used to measure $J(\theta)$ and must be corrected for beam spread. Thus:

$$(5) \quad H = \frac{dp_0}{dA_0} = \frac{CR_0 e^{-\alpha r_1}}{dA_1} \times \frac{dA_2}{dA_0}$$

Where R_0 is the reading in air, coupled to the flux collected by the same coupling factor C , and corrected for the beam attenuation of the path r_1 . This flux is collected on an area dA_2 and is corrected by the factor dA_2/dA_0 to obtain the irradiance input to the sample volume.

At $\theta = 90^\circ$ the sample volume $dV = dA_1 x_0$ since the beam of detectivity is parallel sided. Thus at 90°

$$(6) \quad J(90^\circ) = \frac{R_{90}}{R_0} \times e^{\alpha(r_1+r_2)} \left[\frac{r_2^2 dA_0}{dA_1 dA_2 x_0} \right]$$

Values of $\sigma(\theta)$ at other angles are obtained by means of the equation

$$(7) \quad \frac{\sigma(90)}{R_{90}} \times R_{\theta} = \sigma(\theta)$$

The value of the scattering function at any angle is seen to be directly proportional to the measured reading at each angle θ and inversely proportional to the beam transmittance of the path ($\gamma_1 + \gamma_2$).

$$(8) \quad \sigma(\theta) = R_{\theta} e^{\alpha(\gamma_1 + \gamma_2)} \left[\frac{\gamma_2^2 dA_0}{dA_1 dA_2 \chi_0 R_0} \right]$$

MEASUREMENTS

A series of measurements was made in a 1300 gallon light-tight tank using San Diego tap water (i.e., Colorado River water) filtered through a 2 micron sintered bronze thimble*. In order to assure the same water basis for the whole series, the scattering agent was successively added to the tank of water. The scattering agent used in these tests was a single sample of skim milk.

Because of the circuitry employed, the measurements were made in a dark tank. Measurements were made of the filtered water and after contamination with 100, 200, 400, 600, and 800 cc of skim milk. At each concentration the beam transmittance of the hydrosol was also measured. Equation (8) was then employed to obtain the relative values of the scattering function shown in Figure 5.

*This device removes air from the water as well as particulate matters larger than 2 microns.

COMMENTS

This underwater nephelometer was designed for use in typical coastal or bay water. It can be seen from Figure 4 that the instrument has insufficient sensitivity to detect the back scattering from the filtered San Diego tap water. On the otherhand a degree of turbidity can be visualized which would also render the instrument useless, for as turbidity increases the collimated light beam becomes excessively diffuse before reaching the sample volume, the effective size of the sample volume will be increased, and the problems of determining irradiance input as well as sample volume will be greatly increased. This general problem and also the problem of mechanical interference between the light beam and the phototube housing seem to be inherent to this type of instrument:

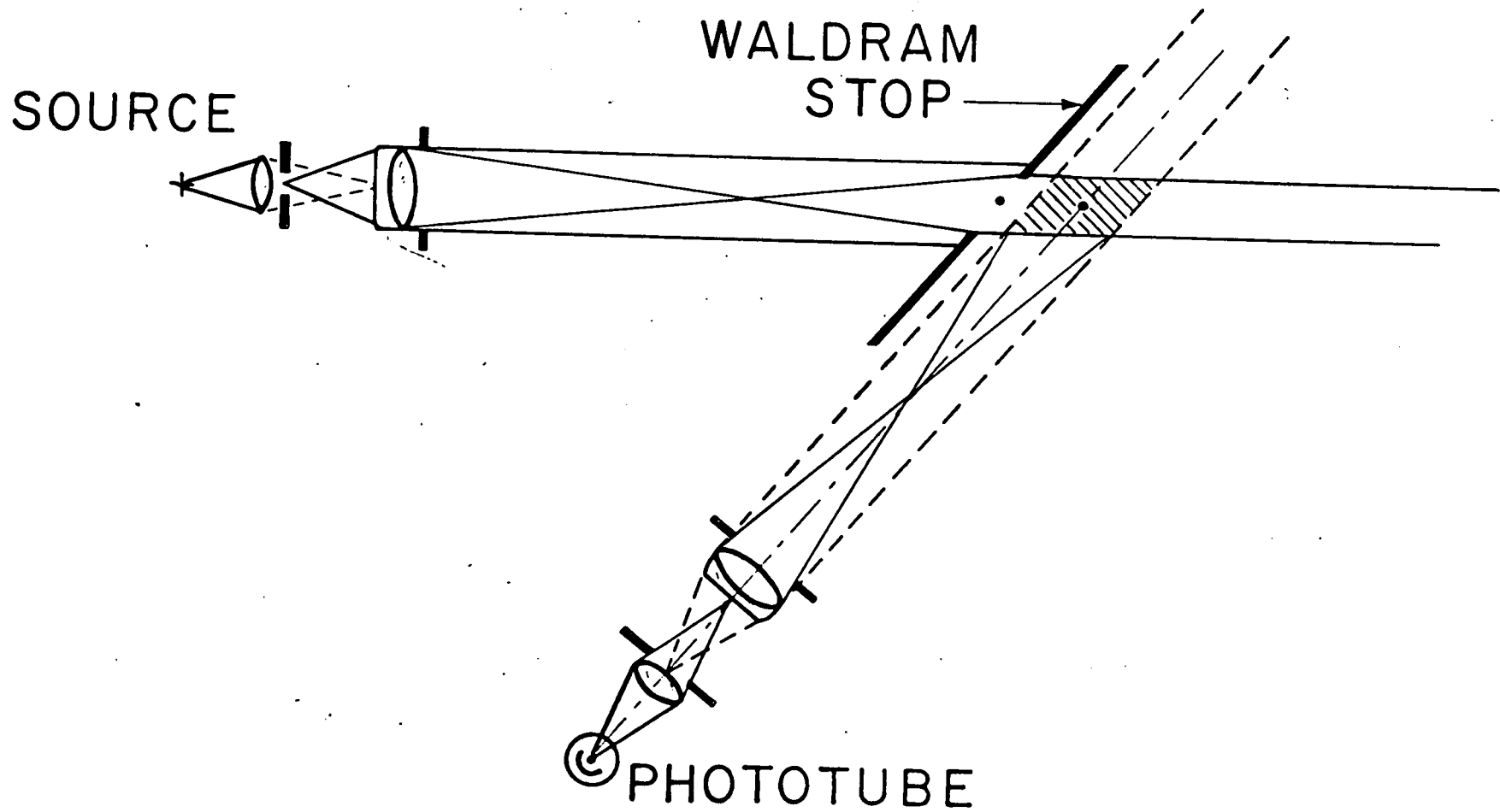
$$(9) \quad \mathcal{A} = 2\pi \int_0^{\pi} \sigma(\theta) \sin \theta d\theta \quad *$$

Accurate determination of the total scattering coefficient \mathcal{A} by means of Equation (9) is made difficult by the lack of information on the forward scattering between $\theta = 170^\circ$ and 180° . Since common methods of extrapolation have no physical basis they cannot be relied upon to fill in this portion of the data. However, it may be possible to obtain \mathcal{A} experimentally by another method^{***} and knowing \mathcal{A} as well as most of the values of $\sigma(\theta)$, determine a reasonable shape for the forward scattering lobe.

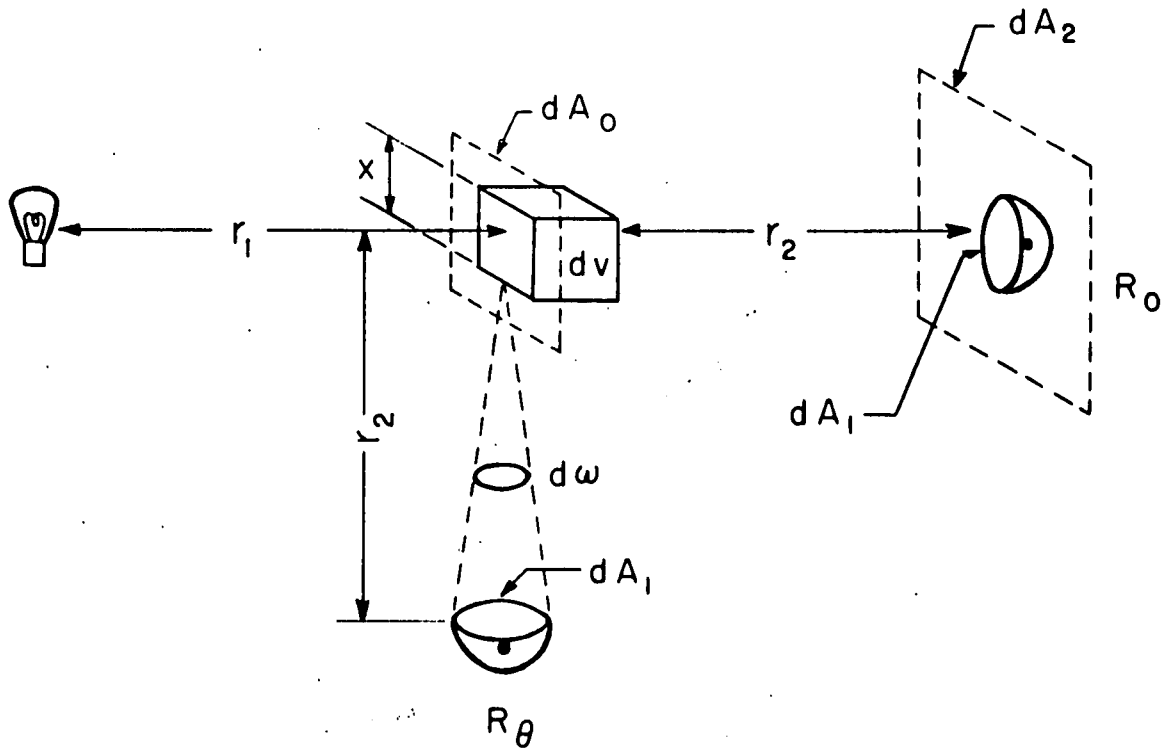
*JOSA, Vol. 35, #11, 1945, pp. 698-705.

**JOSA, Vol. 47, # 8, 1957, pp. 745-747.

OPTICAL SYSTEM OF SUBMARINE NEPHELOMETER



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