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AN UNDERWATER TRANSMISSOMETER FOR OCEAN SURVEY WORK

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Abstract

A transmissometer developed at the Visibility Laboratory, University of California at San Diego is described. This instrument is capable of being operated by nontechnical persons with little instruction. No compromise has been made in the precision of measurement to obtain the design objectives which include ease of operation, low maintenance and reliability. The optical system, which has a cylindrically limited beam rather than a collimated source of light, is discussed.

Introduction

The determination of the volume attenuation coefficient, alpha, for image forming light in natural waters has become of interest to many persons working in diverse fields. It is used, along with other knowledge of the water, to compute visibility range for divers or photographic work. It is of interest to biologists and oceanographers whenever they are concerned with the radiative transfer of light flux through the water environment.

One method of determining alpha is to measure the transmission of a beam of light as it passes through a known path length of water. From this transmission measurement the attenuation coefficient, alpha, may be computed and the attenuation for any other path length may be predicted. A transmission measurement is, at first glance, an easy measurement to make. To some extent this is true; but, there are some pitfalls to be avoided if the measurement is to be truly meaningful. The usual engineering problems of working underwater must be handled; such as, watertight enclosures, ease of handling and use at sea, optical and electrical stability, etc. These problems are familiar to engineers working with oceanographic instruments.

More unique to this type of instrument is the problem of the design of the optical system. An involved system is not required but some insight is called for. To properly measure α, it is necessary to determine how much useful image forming light remains after the light has traversed a water path. This is the residual light which has been neither absorbed nor scattered by the intervening media. Thus, the detector must be allowed to receive only light which arrives undeviated from its original direction of travel, if a true alpha is to be determined. The difficulty lies in separating the image forming light from the forward non-image-forming scattered light. In fact, it is difficult, if not impossible, to achieve complete separation of the image forming light from this forward scattered light in a practical field instrument. The transmission measurement will be contaminated by the acceptance at the detector of some of the unwanted scattered flux.

Various systems employing a light source or projector and a receiver or detector separated by a water path of known length, have been used to measure beam transmittance. All of these systems accept some forward scattered light, depending primarily upon the acceptance angle, i.e., field of view of the detector.

Although it is desirable to keep this error small, the designed and user of this type of instrument must obtain a compromise between the accuracy of the alpha measurement and such factors as reliability, cost, ease of operation, short time on station, etc. The important consideration is that accuracy be commensurate with the uses to which the instrument and the data it obtains are to be put.

Design Objectives

The instrument to be described is similar in its

The development of the instrument described herein was supported in part by the U.S. Naval Ship Systems Command under Contract NObsr-95251.

optical concept to previous transmissometers built at the Visibility Laboratory. The approach used in the instrument's design was to take known and proven techniques and develop a reliable instrument which can be readily used by inexperienced personnel to procure accurate data under field conditions. The instrument eliminates or reduces the undesirable features of previous transmissometers. Unnecessary complexity was avoided in the interest of reducing the cost of fabrication, increasing the reliability and ease of operation all without any sacrifice of accuracy of measurement. The salient features are

1. Fixed optical alignment.
2. Temperature stability.
3. Fatigue and drift stability.
4. Insensitivity to ambient light.
5. A means of checking calibration while instrument is submerged.
6. Operability by a technician with only a short period of instruction.

Optical Design

The optical system is somewhat different from a collimated system in that it produces a cylindrically limited beam rather than a diverging collimated beam. In the projection system (Fig. 1), a condensing lens forms an image of the light source in the field stop. The projector's objective lens then images the field stop, in air, at the receiver entrance aperture stop. The projector field stop is of such a diameter that its image is the same size as the projector's objective aperture stop. All rays in the illuminated sample path fall within the cylinder defined by the projector aperture and the image of the field stop.

TRANSMISSOMETER PROJECTOR OPTICS

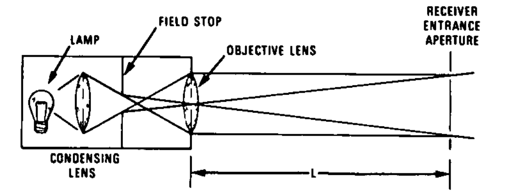


Fig 1

TRANSMISSOMETER RECEIVER OPTICS

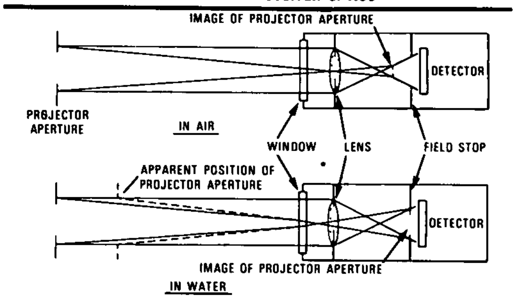
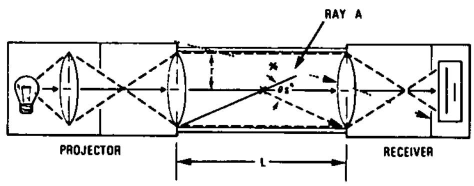


Fig 2

The receiver optics are similar (Fig. 2). Behind a window is an aperture, a lens, a field stop, and the detector. Again the lens forms an image of the receiver field stop at the aperture of the projector, but this time in water. This is important to insure that all of the projected flux will get through the system both in air and in water. If, for example, the receiver were designed so that the projector aperture was imaged in the plane of the receiver field stop in air, then when the instrument was submerged this image will fall beyond the field stop and be larger. Some of the rays would then be clipped by the receiver field stop and an erroneous transmission reading will result. The entrance aperture and field stop of the receiver are sized to give the receiver a field of view in water which is a cylinder just slightly larger and encompassing the cylindrical volume illuminated by the projector (Fig. 3).

TRANSMISSOMETER OPTICAL SCHEMATIC



$$\theta_s = \frac{2r}{\frac{1}{2}L} = 4\frac{r}{L} \text{ RADIANS}$$

$$\% \text{ ERROR} = \backslash = 100\,\frac{\alpha_{MEA} - \alpha_{TRUE}}{\alpha_{TRUE}} = -100 \times \frac{2\pi\sigma_0}{\alpha}\left(\frac{r}{L}\right)^2 \text{ PERCENT}$$

Fig. 3

Only those rays which appear to be coming from the projector aperture and enter the receiver aperture will arrive at the detector. Ray "A" which may be a ray of scattered light from the projector beam or ambient light, will enter the receiver lens as if it were coming from outside the projector aperture and will be stopped by the receiver field stop. All rays from the projector are not parallel to the optical axis. The sample volume is traversed by all rays which can be drawn between the area of the projector aperture and receiver aperture. The greatest angle a ray may be deviated and still be accepted by this type of system is indicated by θ_s in Fig. 3. This angle is specified by the ratio of the beam diameter to one half the beam length. This upper limit is a special limiting case. The preponderance of scattered light accepted will have a deviation angle much less than this. Preisendorfer (Ref. 1) has shown that for this type of system the percent error, Δ, will be:

$$\Delta = 100 \times \frac{\alpha' - \alpha}{\alpha} = -100 \times \frac{2\pi\,\sigma_0}{\alpha} \left(\frac{r}{L}\right)^2 \qquad (1)$$

Where:

- σ_0 is the forward scattering
- α' is the measured volume attenuation coefficient
- α is the true volume attenuation coefficient
- r is the radius of the beam
- L is the length of the beam

Fig. 4 is a curve of error due to forward scattering versus radius to length ratio, from Preisendorfer's paper (Ref. 1) and is based on characteristics of water which is intended to be "Representative of Moderately Clear-Near-Shore Ocean Water". Thus, this type of instrument designed with some care can give good measurements of α for moderately clear oceanic waters. For very turbid waters, the data would be suspect.*

ERROR DUE TO COLLECTION OF FORWARD SCATTERED LIGHT

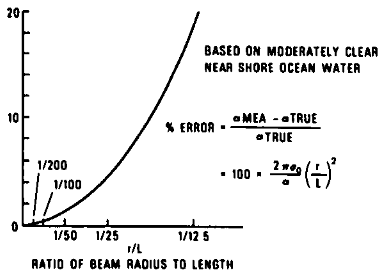


Fig. 4

Detector and Source Considerations

Measured alpha approaches true alpha as the ratio r/L approaches zero. The radiant flux in the beam is also a function of r/L and is given by the expression:

$$P = \pi \times T \cdot N \frac{r^4}{L^2} \qquad (2)$$

Where:

- P = Radiant flux arriving at the detector
- T = Transmission of optical system including filters
- N = Inherent radiance of the source
- r = Radius of beam
- L = Length of beam

The usable lower limit of the r/L ratio depends upon the inherent brightness of the source and the sensitivity of the detector. Using a very sensitive detector, such as a photomultiplier tube, allows the r/L ratio to be small, and the instrument will give a better α measurement in turbid waters.

For the instrument under discussion an r/L ratio of 1/100 was selected, i.e., 20mm beam diameter and one meter path length. This should provide adequate accuracy in the measurement of alpha in the ocean waters in which it is designed to be used. The chosen r/L ratio provides sufficient flux to allow the use of a solid state detector and avoid the problems of high voltage, temperature stability and fatigue, associated with photomultiplier tubes. Many types of solid state photovoltaic and photoconductive detectors were tested for sensitivity, temperature coefficient, stability, and fatigue characteristics. A silicon photovoltaic cell was chosen. A typical silicon detector has the spectral response shown in Fig. 5. It is responsive to flux in the region roughly from 350 to 1100 nanometers, with its peak response at 850 nanometers in the near infrared. This red sensitivity combined with the red-rich radiant energy from the tungsten source make it imperative that an infrared rejection filter be inserted in the optical system. Otherwise, one would be making an α measurement heavily weighted by the flux in the red and infrared region where the transmission is very low and of little interest. A Shott BG-18 glass filter was selected for this purpose. (Another excellent filter for this purpose

* A program is currently under way to study the magnitude of this error empirically for various optical designs in various types of water.

SPECTRAL RESPONSE OF SILICON PHOTOVOLTAIC CELL

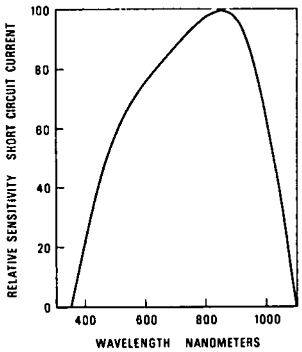


Fig. 5

is the Corning glass filter, color specification 4-76.) Further restriction of the spectral band width can be obtained through the use of Wratten gelatin filters. The IR rejection filter is still necessary since Wratten filters transmit freely in the near infrared. Using a Wratten 64 filter gives the instrument the overall sensitivity shown in Fig. 6, which falls in the region of maximum transmission for most natural waters.

The source is a 20W tungsten-iodide lamp selected for its stability and filament size and shape.

SPECTRAL SENSITIVITY OF TRANSMISSOMETER

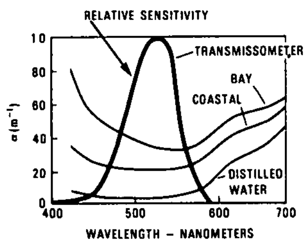


Fig. 6. Relative Sensitivity of Transmissometer with Tungsten Source, Silicon Detector and Shott BG-18 and Wratten 64 Color Filters.

Instrument Description

A schematic drawing of the instrument is presented in Fig. 7. A porro prism was used to fold the water path. This shortens the instrument making it more convenient to handle and puts the projector, receiver, and all electrical connections in one housing. More importantly, it places the projector and receiver in close proximity and it becomes a simple matter to have a light path directly from the lamp to the detector to obtain a "closed

TRANSMISSOMETER OPTICAL SCHEMATIC

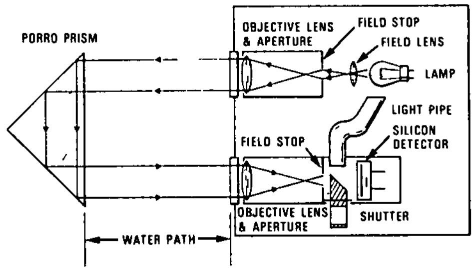


Fig. 7

loop" optical system. A light pipe runs from the lamp to the photocell and a shutter device enables the cell to receive light through the water path, through the internal reference path, or placed in the dark to check for dark current or leakage currents. With this arrangement the operator can check overall system sensitivity during the data taking process. With a sensitivity adjustment he can return the reference reading to its proper value and thus adjust out any changes in lamp output or cell sensitivity due to temperature or fatigue.

The shutter is driven through a geneva mechanism by a small D.C. motor running on a flashlight battery. The motor is held connected to the battery for one geneva cycle by a latching relay which draws its power from the voltage drop in the lamp leads in the cable and latches upon command from the operator. Fig. 8 is a schematic of the transmission measurement circuit. The lamp is operated from a highly regulated power supply operating in the current regulated mode. By regulating the current the changes in the voltage drop in the cable do not affect the output from the lamp.

The semiconductor photovoltaic cell must work into a low impedance in order to obtain linearity of output current with flux and have a low temperature coefficient. The output of the photocell is less than 20μa and is amplified by a small solid state

TRANSMISSOMETER CIRCUIT

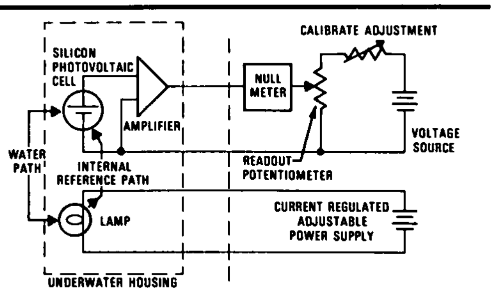


Fig. 8

operational amplifier connected to have an input impedance of ten ohms and to provide a full scale output of up to 10 volts. The signal from a strain gage type pressure transducer is amplified by a similar operational amplifier to obtain 40 mV/meter signal. Both signals go to the wipers of ten turn potentiometers by means of which they are compared to a reference voltage in the surface control unit. The potentiometer dials indicate beam transmission and depth directly. Alternatively the output from the two channels can be applied directly to an X-Y plotter to obtain a depth profile of transmission per meter directly.

The air reading for this instrument is set to be 85.5%. This accounts for the reflection loss on the four window interfaces being greater in air than water. The internal reference path is set to read some arbitrary value close to 100%.

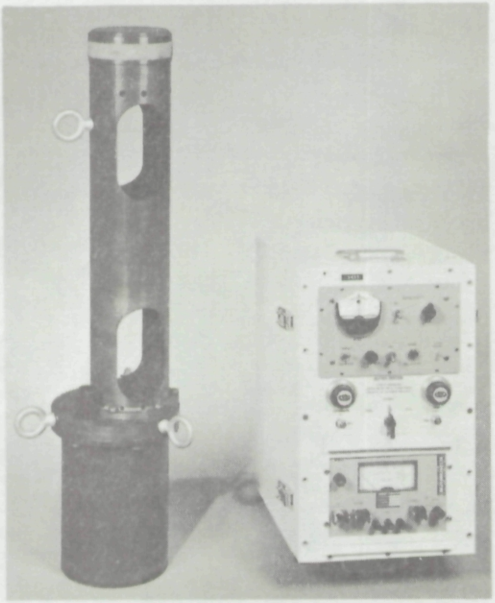


Fig. 9. Transmissometer with Control Unit.

A photograph of the instrument and its control unit is shown in Fig. 9, and the instrument with the watertight cover removed is shown in Fig. 10. The transmissometer alone is thirty-five inches long and weighs thirty-five pounds in air.

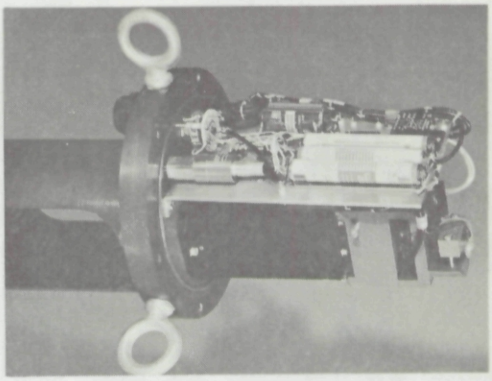


Fig. 10. Transmissometer with Cover Removed.

Summary

All transmissometers allow scattered light to reach the detector in varying degrees. The transmissometer which has been discussed confines the beam from the projector to a cylindrical volume and limits the field of view of the receiver to a cylinder closely matching the illuminated volume. This reduces the error, due to forward scattering. This error in a cylindrically limited beam transmissometer is a function of the forward scattering property of the water and the beam radius to length ratio. The lower limit of the radius to length ratio which may be used is determined by the radiance of the source and the sensitivity of the detector. The optics for this type of system must be designed carefully so that all of the flux passes through the system in both air and water to enable a reading in air to be used as a calibration check. The instrument described has an internal reference light path to allow a check of the stability of the calibration, and a sensitivity adjustment permits corrections to be made, if necessary, while the instrument is submerged. It is designed to be a readily usable, reliable instrument for ocean survey work and is sufficiently accurate for this purpose.

Acknowledgments

R. W. Loudermilk, Assoc. Engineer with the Visibility Laboratory, contributed much to this effort and supervised the design and fabrication.

References

1. A General Theory of Perturbed Light Fields, with applications to Forward Scattering Effects in Beam Transmittance Measurements by R.W. Preisendorfer, 1 May 1958, Index No. NS 714-100, SIO Ref. 58-37.

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13. ABSTRACT

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