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AN OCEANOGRAPHIC ILLUMINOMETER FOR LIGHT PENETRATION AND REFLECTION STUDIES

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Abstract

An improved illuminometer system is described which consists of a dual underwater illuminometer and a deck illuminometer both having improved light collecting properties and a new deck measurement unit The instrument can provide direct measurements of (1) the illumination on the ocean surface, (2) the ratio of the downwelling illumination in the ocean to that on the ocean surface, (3) the ratio of the upwelling to the downwelling illumination in the ocean, (4) diffuse attenuation coefficient, K, for the downwelling light field, and (5) the depth of the underwater sensor

Emphasis in the design of the equipment has been to provide a system with which the operator can quickly obtain direct, accurate settings and to minimize the opportunity for human error in reading the results

The design philosophy of the lambertian light collector and the photoelectric circuitry is given along with the resulting performance

Examples of the data obtained with this system and its applications are given

Introduction

This paper describes an oceanographic illuminometer system which has improved optical and electrical design features The system has been devised to serve the need for a self-contained, simple to operate, yet fast, sensitive and accurate equipment for optical oceanographic survey purposes With it, one can measure the depth dependence of (1) the natural light field in the ocean, (2) the attenuation coefficient for this light field, and (3) the water reflectance Equipments of this general class which have been available in the past have not been able to satisfy adequately the requirement for an instrument which will measure the variables properly, meet the listed needs, yet be a suitable instrument for use by the non-specialist in optical oceanography The significant design features will be described in some detail in order that an appreciation of the major effects which some of the apparently subtle factors may have on the operation of such instruments

Information regarding the magnitude of light levels and the depth dependence of the optical properties of the ocean is required for various reasons by workers in diverse fields of oceanography For example

1 For providing additional quantitative inputs to well formulated theories of radiative transfer in the ocean so that these theories may be further developed and may be applied by oceanographers, underwater photographers, and others working with light in the underwater world

2 For providing engineering information on light levels available for vision tasks, underwater photography, and underwater television

3 For providing attenuation and reflectance information about the particular region of the ocean in which vision tasks are to be performed or photo-optical systems are to be used

4 For documenting pollution studies of streams, lakes, harbors, etc

5 For assisting the biologist in his study of the important relationship of radiant energy to the life cycle of marine organisms

The physical nature of the light field which is to be measured and the optical characteristics which an instrument must have in order to measure this light field properly will be shown Finally the instrument itself will be described and some data obtained with it will be presented

The Underwater Light Field

Anyone who has critically examined the distribution of light underwater, either by direct observation or by means of wide angle photographs, is aware of the very large range of luminances encountered as one scans a vertical plane in the azimuth of the sun On a sunny day when there is no reflective bottom in view, this range may easily exceed 1000 to one at moderate depths, say 15 meters, becoming even greater as one approaches the surface and reducing asymptotically to 200 to 300 to one as the depth is increased On overcast days the change of luminance with angle is less rapid as there is no single bright source as in the sunny case, but still the luminance seen looking in the upward direction is as much as 200 times larger than that in the downward direction. For the overcast case, as one might suspect, this ratio of maximum to minimum does not change appreciably with depth. When there is a bottom within view, its reflective properties, of course, effect the light field

Figure 1 shows an actual luminance distribution measured on a sunny day in Lake Pend Oreille, Idaho at a depth of 10.4 meters.[1] Notice that there is a sharp lobe in the apparent direction of the sun. Notice also that the luminance which one sees when looking in the downward direction is so small compared to that looking toward the sun that it appears to be zero in the upper plot in Fig 1 In order to show how this luminance in the downward direction changes with angle, it has been replotted on a scale which has been enlarged 500 times.

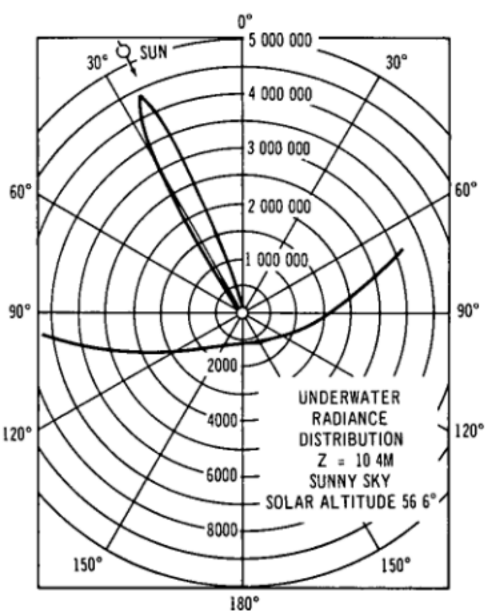


Fig. 1. Underwater radiance distribution as measured at a depth of 10 4 meters in Lake Pend Oreille by Tyler et al (note different scales used for plotting upward and downward portions of distribution).

[1] J.E. Tyler, "Radiance Distribution as a Function of Depth in an Underwater Environment." Bulletin of the Scripps Institution of Oceanography, University of California, Vol. 7, No. 5, pp 363-412 (1960).

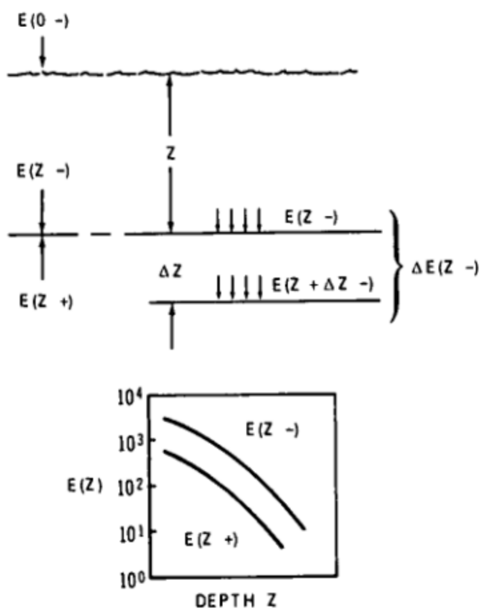
One would have complete information regarding the light field and the manner in which it propagates downward through the ocean if luminance distributions of this type could be obtained for each depth Such a procedure would be exceedingly difficult with regard to the equipment required, the time to obtain and reduce the data and the not inconsiderable difficulty of managing and utilizing the tremendous quantity of information which would be obtained

Fortunately the problems can be greatly simplified, albeit with a considerable loss of detailed information by measuring illuminances instead of luminances. As the illuminance is the sum total of all flux incident on a unit surface, it is possible to determine some very important and very useful information about the light field by measuring the illuminances incident on two sides of a horizontal surface as a function of depth. This, as opposed to measuring the luminance in all directions in the upper and lower hemispheres as a function of depth, represents a great economy of time and effort. The luminance (or radiance) distribution information is still sorely needed, however, in order that one may study ways of applying this abbreviated data in a more meaningful way.

Fig. 2 shows the rudiments of the illuminance measurement system. At the top is shown a plane at depth Z below the water surface. If one measures the downwelling illuminance, $E(Z,-)$, and the upwelling illuminance, $E(Z,+)$ as a function of depth, Z, one finds that both illuminances will decrease with depth somewhat as shown in the curves in the small graph Note that on the logarithmic scale of illuminance, the vertical separation of the upwelling and downwelling illuminance is shown as being approximately constant. This implies that the ratio of the two is a constant. This ratio, denoted $R_{U/D}$, is a kind of reflectance, representing the portion of the downwelling stream of flux that is returned upward. In the open ocean, this ratio is usually about 2% and is fairly constant in the absence of turbidity layers and in the absence of bottom reflectance. Either of these factors will usually cause this ratio to increase.

Consider next the downwelling illuminance and the manner in which it decreases with depth Equation (1) establishes the nomenclature and conventions which will be used. Its significance is obvious from an inspection of the diagram at the top of Fig. 2.

Note that in a source-free medium, one would expect $E(Z+\Delta Z,-)$ to be smaller than $E(Z,-)$ and $\Delta E(Z,-)$ as a consequence will be negative Equation (2) states in differential form that the increment in illuminance, $dE(Z,-)$ is proportional to (a) the magnitude of the illuminance at that depth, viz $E(Z,-)$, and (b) the size of the depth increment involved, dZ The constant of proportionality will be denoted by K It should be noted that it is not in general a constant but may well, and usually does, vary (a) with depth in a manner which depends upon the local optical properties of the water (b) with changes in angular luminance distribution with depth, and (c) with other subtleties of the measurement However treating K as locally constant over some arbitrarily small region is a perfectly proper procedure and for many practical problems it is possible to treat K as constant for relatively large regions or even for the entire ocean depth



$$\Delta E(Z\ -) = E(Z + \Delta Z\ -) - E(Z\ -) \quad (1$$

$$dE(Z\ -) = -K\,E(Z\ -)\,dZ \quad (2$$

$$K = -\frac{1}{E(Z\ -)}\frac{dE(Z\ -)}{dZ} = -\frac{d(\ln E(Z\ -))}{dZ} \quad (3$$

$$E(Z_2\ -) = E(Z_1\ -)\,e^{-K(Z_2 - Z_1)} \quad (4$$

$$E(Z\ -) = E(0\ -)\,e^{-KZ} \quad (5$$

$$R_{U/D} = \frac{E(Z\ +)}{E(Z\ -)} \quad (6$$

Fig 2 Illuminometer Measurement System Concepts

Equation (3) is a restatement of (2) in forms which are of use in the computation of K as will be seen later Equation (4) is the solution of the differential equation shown in (2) where K is constant between Z_1 and Z_2 Thus, by treating the ocean as comprised of successive layers of constant K, it is possible to compute the illuminance at any depth Z if the input illuminance at the surface E(0,−) is known Equation (5) is a special case of Eq (4) which may be used if the water from the surface to depth Z can be satisfactorily described as having a constant K Equations (4) and (5) are equations of transfer and the coefficient K in the exponent is the attenuation coefficient which determines the rate of decay of the natural illumination field in the medium It should be noted here that by taking the logarithm of both sides of Eq (5) and differentiating with respect Z one can obtain the second of the two relationships in Eq (3) Thus K can be obtained from the slope of semi logarithmic plots of E(Z) vs Z such as are shown in the small graph in Fig 2

The Instrument

General

The oceanographic illuminometer system has four photosensors and a depth sensor The four photosensors sense

1 The downwelling illuminance at the surface E(0,−),
2 The downwelling illuminance at depth Z, i e , E(Z,−),
3 The upwelling illuminance at depth Z, i e E(Z,+),
4 The downwelling illuminance at a depth (Z−2) i e , at 2 meters above the primary downwelling sensor

Because of variations in the general level of illumination due to changes in the solar elevation angle with time of day or due to clouds, it is desirable to measure ratios of illuminances directly rather than measure their individual magnitudes and subsequently attempt to compute the ratios In addition to removing most of the fluctuations from the data, the ratios can be obtained very simply and accurately by standard electrical circuits and the amount of computation required is, thereby, greatly reduced The surface illuminance is recorded directly, however, as an absolute magnitude in order that illumination levels at all locations at the time of measurement can be retrieved

The heirarchy of measurements is thus:

1 Depth, Z
2 Surface Illuminance, E(0,−)
3 The ratio of downwelling to surface illuminance at depth Z, i e , E(Z,−)/E(0,−)

4. The ratio of downwelling illuminance at depth Z to downwelling illuminance at depth (Z − 2), i.e., $E(Z_2,-) / E(Z_1,-)$

5. The ratio of upwelling to downwelling at depth Z, i.e.,

$$R = \frac{E(Z,+)}{E(Z,-)}$$

Spectral Sensitivity Consideration

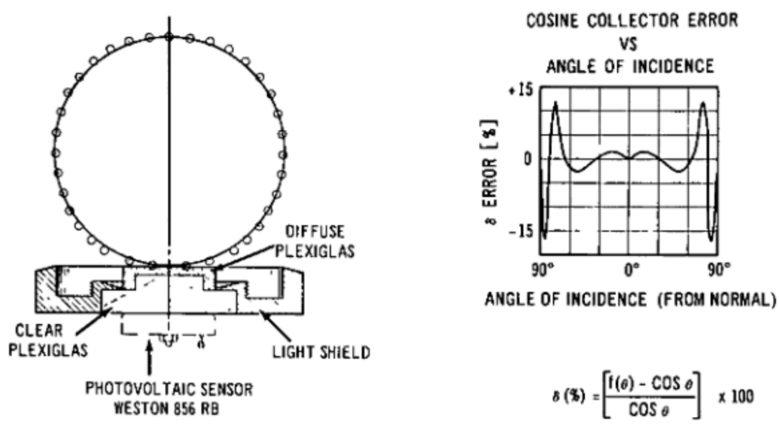
The spectral sensitivities of the photosensors used in the instrument were photopically corrected, i.e., they were adjusted to conform with the visibility function of the human eye. Consequently the instrument can be properly calibrated to measure illuminance and the values obtained through its use will describe variables which are significant to the solution of visibility problems involving direct human vision. If the measurement task is to determine variables for the solution of problems involving other photosensitive detectors as for example, photographic films, television camera tubes, or photosensitive marine life, then the photosensors used in the instrument should have their spectral sensitivities matched to those of the detectors in question and the instrument would be properly called an irradiometer. In this case, the calibration is not in illuminance (e.g. foot-candles or lux) but must be in irradiance (watts/cm^2) and the spectral sensitivity must be specified. For many applications involving moderately broad-band photodetectors, however, data obtained with the illuminometer will adequately satisfy the problem requirements as the spectral quality of the radiant flux available in the underwater natural light field becomes very strongly determined by spectral transmission properties of the water after penetrating relatively few meters of depth. Beyond this depth, the illuminometer and the irradiometer will measure approximately the same rates of decay of the light field if the irradiometer has a broad spectral sensitivity which brackets the visible spectrum. It should be emphasized, however, that although the illuminometer and some irradiometers may be used interchangeably in certain instances for the measurement of variables which depend upon the ratios of values, they may never be used interchangeably when absolute values are required. It is especially meaningless, for example, to attempt to measure the number of foot candles available for the performance of an underwater task with an instrument which is not photoptically corrected. Because of the gross changes in the spectral distribution of the flux with depth, such improper procedures are likely to result in much greater errors in underwater measurement than would occur in similar measurements performed in the atmosphere.

Illuminometer Collector Design

The single most important factor in the optical design of the instrument is the angular collection characteristic of the photosensors. The sensitivity of the photosensor to flux coming from angles other than perpendicular to the surface must vary in accordance with the cosine of the angle of incidence. To see that this condition must be met, one need only recall that the illuminance or irradiance incident on a plane surface is defined as the total flux incident on a unit area of that surface, and the projection of this unit area in the direction of incidence of the incoming flux varies as the cosine of the angle with the surface normal.

Figure 3 shows the collector design in the lower left with a cosine function plotted in polar form superposed on its collecting surface. Most illuminometers fail sadly

ILLUMINOMETER COLLECTOR CONFIGURATION AND PERFORMANCE CHARACTERISTICS



$$\delta(\%) = \left[\frac{I(\theta) - \cos\theta}{\cos\theta}\right] \times 100$$

Fig. 3. Illuminometer Collector Configuration and Performance Characteristics

when the incident flux approaches grazing incidence For many applications, this is of little consequence For example, for the downwelling sensor the radiance distribution in Fig 1 shows that for the particular sunny day depicted, almost all the flux came from a narrow range of angles around the apparent position of the sun Certainly under this situation, the angular sensitivity characteristics of the collector near grazing incidence are of little importance Consider however the radiance distribution situation which existed in the lower part of the diagram in Fig 1 The radiance in the horizontal direction was 3 to 10 times that coming from directly below For a sensor used in this location, improper collecting properties near grazing incidence can cause a significant error Similarly for the surface sensor mounted on the deck of the survey vessel, it is important that it be able to measure the illumination properly when the solar elevation is small

The design concept shown in Fig 3 was first used by Boyd at the University of Michigan[2] and has been successfully adapted to a number of illuminometer applications at the Visibility Laboratory

By having the side of the diffuser exposed, the sensitivity to flux arriving at large angles from the normal can be increased and by varying the amount of side exposure and the diameter of the light shield, it is possible to exert effective control over the collecting characteristic of the unit The circled points in the vicinity of the cosine polar plot represent actual underwater measurements of the collector shown here The error expressed as the difference between the measured value and the cosine divided by the cosine is plotted at the right The apparently large errors occurring near grazing incidence are of little actual significance in the overall measurement of illuminance under most luminance distributions, especially as compared with the effect of the errors introduced by most other designs

In order to evaluate the effect of this error on the apparent or measured illuminances the relative illuminances for actual underwater radiance distributions at 7 depths on a sunny day were calculated using a true cosine collector and using the actual collector characteristic The errors are shown in Fig 4 Notice that in no case was the error as great as 1% for the upwelling illuminance and was usually under 0 5% for the downwelling illuminance

[2]R A Boyd, "The Development of Prismatic Glass Block and the Daylighting Laboratory", Research Bulletin No 32, Engineering Research Institute, University of Michigan, Feb 1951, App C pp 64-68

DEPTH (M)	ERROR(%)	
	E(Z -)	E(Z +)
4 2	25 %	- 88 %
10 4	16	- 88
16 6	- 27	- 93
29 0	- 52	- 89
41 3	- 44	- 94
53 7	- 25	- 92
66 1	- 36	- 93

Fig 4 Percent error between measured and true illuminances as calculated for actual radiance distribution.

The Electrical Design

Figure 5 presents some elementary circuit review but it is important that the concepts shown are thoroughly appreciated in what is to follow Figure 5(a) represents the time-honored potentiometric measurement circuit Two sources e_1 and e_2 are compared by means of the potentiometer When the potentiometer is adjusted until the current through the null sensing device is zero then $e_1 = ke_2$ Thus the ratio of e_1 (the smaller) to e_2 (the larger) may be obtained directly from the physical position of the arm of the linear potentiometer The potentiometer may, for example, be an inexpensive multi-turn potentiometer with a turns counting dial such as one can obtain commercially off-the-shelf with linearities of 0 1% or better Or if the null detector is a servo amplifier and the motor connected to the potentiometer arm an automatic balancing system such as in a potentiometric recorder is obtained Note that at balance, no current flows in the null sensor or in the voltage source e_1, and the voltage which exists at e_1 is independent of the resistances of the potentiometer, the null sensor, or the source

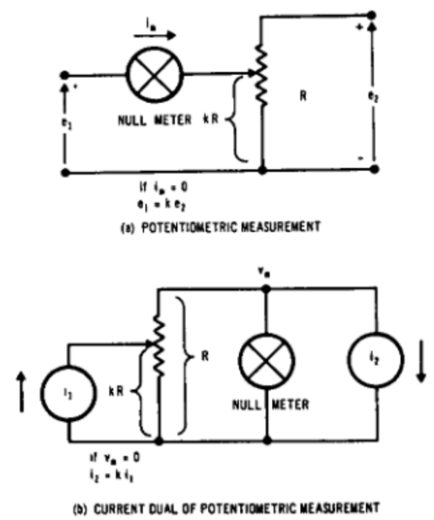


Fig. 5 Basic Potential and Current Measurement Circuits

Figure 5(b) is the dual of the circuit above If i_1 and i_2 are current sources whose internal resistance is large compared with R and if i_1 is greater than i_2 we can adjust the arm of the potentiometer until the voltage across the null sensor is zero and under that condition $i_2 = ki_1$ Thus we have a simple and accurate way to measure the ratio between two currents or if i_1 is known, to measure i_2 Note that at balance the voltage across the terminals of source i_2 is zero, the same situation that would exist if the terminals were shorted Thus we can effectively measure the short circuit output current of the generator, i_2 Also at balance the load resistance presented to source i_1 is the parallel combination of kR and (1 − k)R This parallel combination is k(1 − k)R When the arm is at the bottom k = 0 and the load resistance on the source is 0 When the arm is at the top 1 − k = 0 and the same condition is obtained When the arm is at the center k = 0 5, k(1 − k) = 0 25 and the load resistance on the source is R/4 Thus at null the source i_2 is effectively short circuited and the source i_1 has a load between 0 and R/4 These are important considerations in the design of the illuminometer

The photodetectors selected were selenium photovoltaic cells When they are properly used they have an output which is very nearly linearly proportional to input flux, are stable, and have a low temperature coefficient In particular, the Weston Model 856RB was chosen for its high sensitivity for the underwater cells and the Model 856YG which has lower sensitivity but superior linearity and stability at high illumination levels was selected for the deck or surface illuminometer

These cells have a relatively high source impedance and act as current sources whose current into a short circuit is linear with incident flux Furthermore, the short circuit current is only slightly affected by temperature over the normal range of temperatures which one finds in the ocean

There are two ways one can obtain the desired low impedance load for the photovoltaic cells The most elegant way is to use an operational amplifier so connected as to have its output voltage proportional to input current. When properly connected in this manner the input impedance to the amplifier can be reduced to extremely small values and the output signal brought up to levels which can be transmitted over long cables without concern for the minor leakage currents which are sometimes encountered in underwater cables and connectors The measurement of the voltage at the surface can then be accomplished in any of the conventional ways including the potentiometric method shown in Fig 5a The use of the amplifier increases the complexity and cost of the system, however, and in the interest of simplicity the output currents from the photovoltaic cells were compared with each other or with a reference current by means of the circuit in Fig 5b When the resistance of the comparison potentiometer is small compared with the source resistances and the sensitivity of the null detector is sufficient, excellent, rapid and precise balances may be obtained

Deck Illuminometer Circuit

The underwater photosensor outputs are not measured directly as illuminances but rather are ratioed against each other or against the surface or "deck" illuminometer output This technique has the benefit that it reduces to a major extent the fluctuations which are obtained in the data, thereby reducing the time required to obtain an instrumental balance and increasing the accuracy with which measurements may be made Also these ratios are used directly for the computation of water reflectances and diffuse attenuation coefficients, their direct measurement reduces the overall effort required to obtain the desired information and reduces the sources of error in a significant manner However, the absolute levels of underwater illuminance also may be of interest when one is concerned with the amount of light available for underwater television, photography, or visual tasks, or to determine if there is adequate flux available to the illuminometer's photosensors to permit accurate ratios to be obtained Consequently the downwelling illuminance on the ocean surface E(0, −) is separately measured directly in absolute units (foot-candles) thereby permitting the simple computation of the underwater downwelling and upwelling illuminances E(Z, −) and E(Z, +)

The photosensor of the deck illuminometer produces a short circuit output current which is a linear function of the illuminance incident upon it up to maximum daylight levels As the circuit of Fig 5b can only obtain the ratio of one current to another, the absolute measurement of the current output of the deck illuminometer requires the use of a calibrated internal reference current source Fig 6 shows the circuit which is used A 6 75 volt mercury battery in series with a resistance which is large compared to the 100 ohn ten turn precision measurement potentiometer, provides the required stable

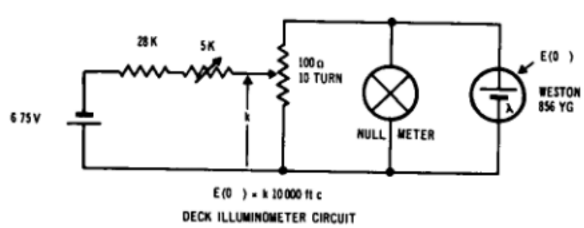


Fig. 6 Deck Illuminometer Circuit

reference current. The 5000 ohm series trimming resistor is adjusted during calibration to cause the turns-counting dial on the measurement potentiometer to read the illumination directly in foot candles. This calibration is performed by using standard photometric techniques and lamps whose calibrations as standards of luminous intensity are traceable to NBS.

Diffuse Transmission Circuit

The ratio of the underwater downwelling illuminance, E(Z, −) to the downwelling illuminance at the ocean surface, E(0, −), may be considered the effective transmittance of the ocean to a depth Z for the natural light field. The ratio is obtained by the circuit shown in Fig. 7 which is a simple extension of the circuit shown in Fig. 5b described earlier. For many purposes it is sufficient to study the manner in which this ratio varies with depth until the transmittance of the water column has decreased to about 0.01% or until the magnitude of E(Z, −) has been reduced to about 0.5 foot-candle. To obtain adequate sensitivity and a reasonable precision of measurement over this dynamic range of approximately 10^4 it is necessary to provide the underwater illuminometer with a photocell having a high sensitivity and to change the full scale ranges of the circuit as shown in Fig. 7. Because the photocell used in the surface or deck illuminometer has less sensitivity than its underwater counterpart (approximately 1/10), the measurement of illuminance ratios between 1.0 and 0.1 requires that the current from the more sensitive underwater photosensor be attenuated until its resultant effective sensitivity is the same as that of the less sensitive deck unit. The circuit shown at the top of Fig. 7 accomplishes the desired matching of sensitivities. The sensitivity ranging switch permits the rearrangement of the components to accommodate three other full scale ranges of ratios, viz., 0.1, 0.01, and 0.001, as shown in the circuit at the bottom of Fig. 7.

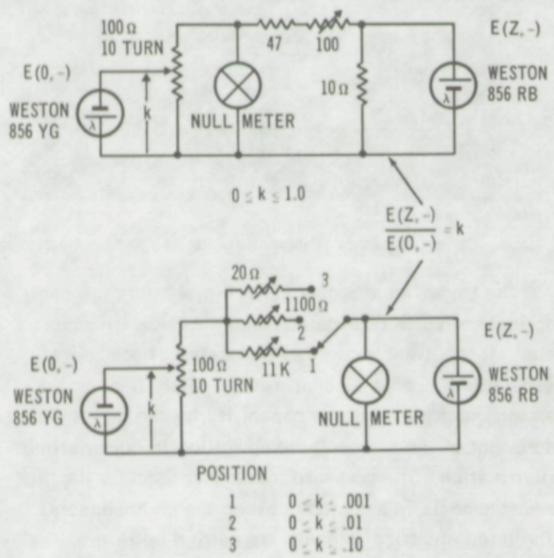


Fig. 7. Diffuse Transmission Circuit

Reflectance Measurement Circuit

As anyone knows who has flown over coral reefs or along the coast over shoal waters or river mouths, the reflectance of the ocean varies markedly with the nature and proximity of the bottom and with the type particulate matter suspended in the water. Deep blue oceanic waters have reflectances from about 1.5% to 2.5%. Reflectances as high as 15% have been measured in the vicinity of the mouth of a heavy silted river. Even higher reflectances could be expected over light sand or coral bottoms. In the design of the reflectance measuring portion of the instrument we allowed for the possibility of reflectances as high as 25% but realizing that most measurements would be made in darker water, a second range was provided with a full scale of 10%.

Figure 8 shows the circuit used for the reflectance measurement. By means of the range switch the current from the upwelling illuminance photosensor is ratioed against either 10% or 25% of the downwelling illuminance photosensor current. The photosensors are physically identical in design and sensitivity. Because the upwelling illuminance is usually only a few percent of the downwelling, the current available to the measurement circuit falls below that required for a satisfactory balance at a lesser depth than the other measurements.

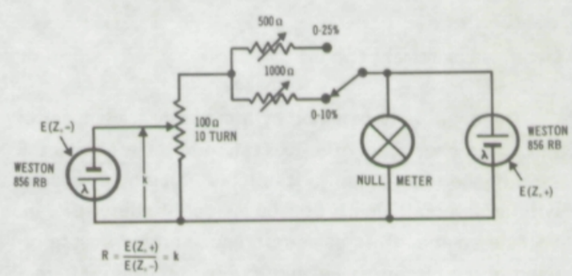


Fig. 8. Reflectance Measurement Circuit

K-Measurement Circuit

The diffuse attenuation coefficient, K, may be obtained from the slope of the plot of the logarithm of the diffuse transmission vs depth, viz,

$$K = -\frac{\ln E(Z_2, -) - \ln E(Z_1, -)}{Z_2 - Z_1} = -\frac{\ln [E(Z_1, -)/E(Z_2, -)]}{Z_2 - Z_1}$$

or more simply

$$K = -\frac{2.3 \log [E(Z_2, -)/E(Z_1, -)]}{Z_2 - Z_1} = -\frac{2.3 \log T(Z)}{Z_2 - Z_1}$$

(See for example, the data plotted in Fig. 14 below) Such a method provides sufficient information on the magnitude of K and its variations with depth for most purposes. However, for the detailed study of the coupling between K and other parameters it is sometimes helpful to obtain K from a measurement of the local diffuse transmittance as determined by the ratio of the output of two underwater photosensors vertically displaced by a known fixed distance. In this instrument the vertical displacement chosen was 2 meters. A measurement circuit is used which is similar to the reflectance circuit. Diffuse transmittance measurement ranges of 60% to 100% or 0% to 100% may be selected by a panel switch. For the 2 meter vertical sensor separation, these transmittance ranges correspond to K ranges of 0.25 to 0.0 and, ∞ to 0 (M^{-1}) respecively. As the accuracy of the determination of K by this method depends upon the accuracy with which one knows the vertical distance between the two photosensors, the presence of an appreciable wire angle precludes the use of this method. However, in cases where the wire angle is small, the method has been used to advantage to find local depth dependent variations in the diffuse attenuation coefficient and to permit comparison of these variations with those occuring in the reflectance, R, the volume attenuation coefficient, α, and in the water temperature.

Depth Measurement Circuit

The depth is determined by a pressure transducer of the strain gage type. The excitation voltage across the strain gage is adjusted to its proper value by comparison with an internal, lightly loaded mercury battery reference voltage source. This same reference voltage source is used in the circuit to measure the output of the strain gage by means of the potentiometric circuit shown in Fig. 5a. The circuit is so adjusted that the turns counting dial on the potentiometer reads directly in meters depth from 0 to 100 meters with a resolution of 0.1 to 0.2 meters and an overall depth accuracy of between 0.7 and 1.0 meter.

Physical Description

The Deck Control and Measurement Unit is shown in Fig. 9. It is self-contained in a small, rugged fiberglas case. An external null voltmeter is required to determine the balance position of the several measurement potentiometers previously described. Any null voltmeter having a sensitivity of ±2 microvolts or better will provide a satisfactory balance capability. The five turns-counting dials appearing across the face of the unit are coupled to ten-turn potentiometers used to balance the inputs from the various photosensors and the depth transducer. The combined dial-potentiometers have a linearity of 0.1% and have a readout precision of one part in 5000.

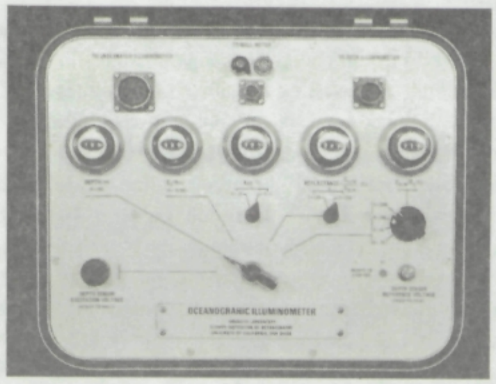


Fig. 9. Deck Control and Measurement Unit.

The Deck Illuminometer Photosensor Unit, Fig. 10, is fully gimbaled to permit the face of the illuminometer to remain approximately horizontal regardless of the pitch and roll of the vessel. In use, the illuminometer is mounted rigidly in a location that is not shadowed by objects such as masts, winches, etc.

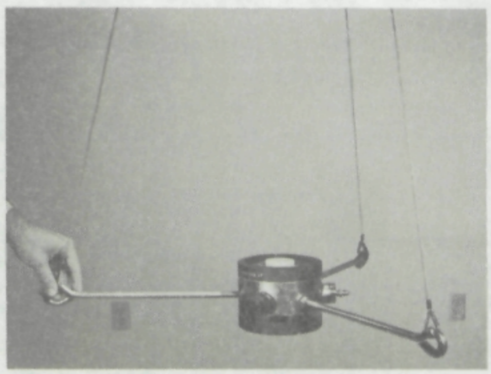


Fig. 10. Deck Illuminometer Photo Sensor Unit.

The Underwater Sensor Unit, Fig. 11, has the same optical collector configuration as the Deck Illuminometer. It has two photosensors mounted "back-to-back," separated by about 12 centimeters. The "back-to-back" arrangement provides the capability for the direct measurement of the ratio of the upwelling to downwelling illumination. The pressure transducer used for depth measurements is mounted between the photosensors. The three electrical signals are carried up to the deck unit through a watertight connector on the sensor unit and a neoprene, multiconductor, shielded, cable. The

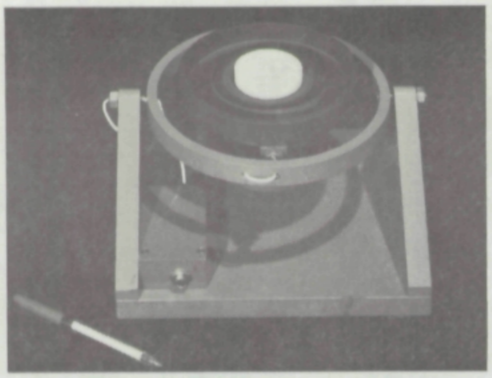


Fig. 11. Underwater Sensor Unit. Contains Downwelling and Upwelling Illuminometer Sensors and Pressure Transducer.

sling and bridle assembly that supports the unit was designed to maintain the unit horizontal and minimize any shadowing of the downwelling photosensor.

The Underwater Upper "K" Photosensor Unit, Fig. 12, has the same optical collector configuration as the other photosensors. It is suspended two meters above the downwelling illuminometer (see Fig. 13). The two meter separation provides sufficient flux differential on the two collectors to obtain good measurement precision. This separation also reduces substantially the solid angle of the light field which the upper K-unit would occlude from the lower sensor at, say, one meter or less.

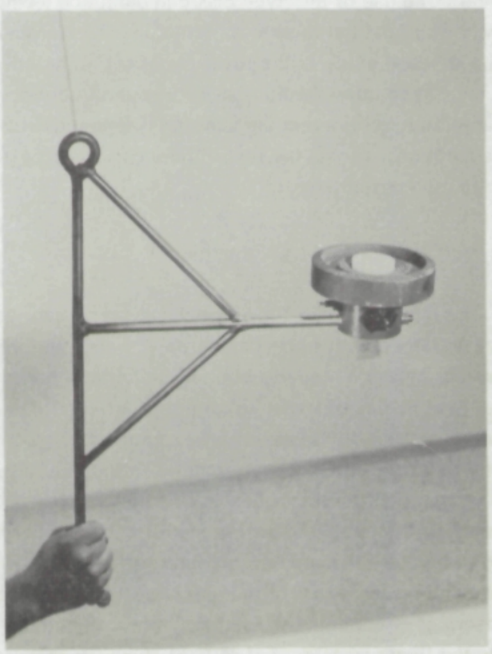


Fig. 12. Underwater Upper "K" Photosensor Unit.

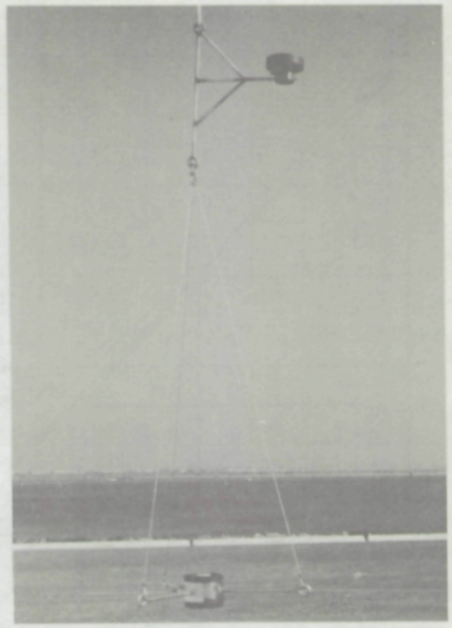


Fig. 13. Complete Underwater Sensor Assembly

Sample Data and Accuracy Considerations

A test of the Oceanographic Illuminometer along with a new transmissometer (α-meter) was conducted at sea in about 44 fathoms of water (80 meters) off San Diego, California. Data was taken at 5-meter depth increments for the first 40 meters and at 10-meter increments for the remainder of the lowering and retrieval. A plot of the diffuse transmittance, $E(Z,-)/E(0,-)$, as a function of depth, Z, is shown in Fig. 14. A period of approximately one hour elapsed between start and finish of the lowering. The diffuse attenuation coefficient, K, varied with depth as is evidenced by the slope of the plot. The average K of 0.094 (M^{-1}) was the same going down and coming up although the local variations were different due, presumably, to different water being measured resulting from the drift of the survey vessel.

Fig. 15 shows the reflectance data and the diffuse attenuation coefficients computed from the 2-meter diffuse transmittance data. The reflectances measured on lowering and retrieval were essentially identical. A steady increase in reflectance may be seen from 2% at 50 meters to about 6.5% near the bottom (80 meters). This change could be due simply to bottom reflectance or it may be due in part to the greater reflectance of the more turbid water that existed near the bottom as evidenced by the marked increase in alpha in this region. The K-values plotted for lowering and raising show more variation than the reflectance plot but considerably less variation than alpha. An outgoing tide carrying turbid water from San Diego Bay accounted in part for the vertical stratification observed. The difference in time between the K and alpha

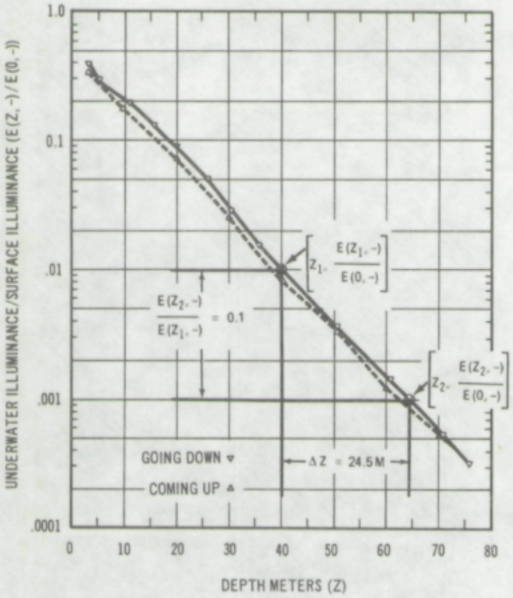


Fig. 14. Sample Data Showing Light Penetration in Coastal Water.

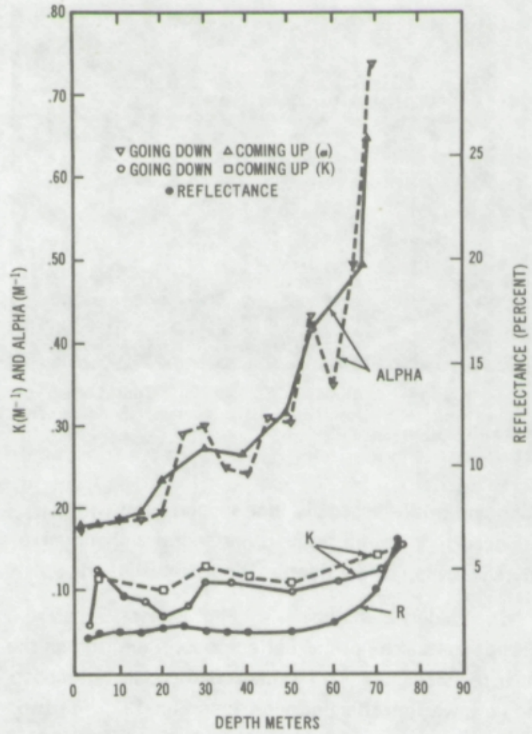


Fig. 15. Optical Constants of Coastal Water as measured by Oceanographic Illuminometer (Alpha Data attained from new Underwater Transmissometer).

measurements could account for the lack of exact correspondence between the features of the two vertical profiles.

The ability to obtain instrumental balances for depth, surface illuminance, diffuse transmittance, and reflectance were all excellent. The precision of the depth measurement was limited only by the surface wave action. Balances to better than 0.1 meter could easily be obtained in a calm sea. The accuracy of the depth measurement was limited by the pressure transducer to ± 0.7 meters. The precision of measurement of the surface illuminance was less than 0.1% of full scale although the absolute accuracy of the readings could not be stated to be better than ± 5% of the indicated value. The diffuse transmittance measurement precision was limited to a few tenths of one percent of the reading by motion of the deck illuminometer resulting from wave action. On the lowest range (0.1% full scale) the balance below about one tenth scale, i.e., diffuse transmittances below about 0.01%, started to suffer as a result of the extremely small currents generated by the underwater cell. Because it is the nature of the reflectance parameter to vary slowly with depth and only over a narrow range of values, the instrument could be designed and calibrated to make this measurement with an accuracy of about ± 1% of the reading. The precision of setting balance was about ± 0.1% of full scale, i.e., ± 0.025% R on the 25% reflectance range and ± 0.01% R on the 10% range.

The balance on the 2-meter diffuse transmittance data was not always precise near the surface but improved with depth. This may have been due to the spatial and temporal differences in the collimated light field near the surface. As the collimated light field became transformed into a more completely diffuse field with depth, the non-correlated fluctuations in the output of the two photosensors would decrease making the balance easier to obtain. The use of this type of K-determination method may well be limited to special research projects requiring a detailed study of the local variations in K with depth. Those interested in the more general survey type of applications may find the additional time required for this measurement and the restrictions on its successful application unwarranted.

Conclusion

The Oceanographic Illuminometer system described, successfully achieved its design objectives. The instrument can measure properly some of the optical parameters of natural bodies of water which are of interest to those working in such fields as visibility, biological processes, water polution, and radiative transfer in the sea. The lambertian light collector design provided excellent conformity with the desired cosine function thereby permitting the proper measurement of water reflectances. The method of measurement of the output current of the photosensors or of obtaining the ratio of two such outputs permits the linear measurement of light fluxes or their ratios with minimum temperature dependence and with the maximum simplicity. Data can be obtained accurately and quickly with a minimum of operator training.

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13. ABSTRACT

An improved illuminometer system is described which consists of a dual underwater illuminometer and a deck illuminometer both having improved light collecting properties and a new deck measurement unit. The instrument can provide direct measurements of (1) the illumination on the ocean surface, (2) the ratio of the downwelling illumination in the ocean to that on the ocean surface, (3) the ratio of the upwelling to the downwelling illumination in the ocean, (4) diffuse attenuation coefficient, K, for the downwelling light field, and (5) the depth of the underwater sensor.

Emphasis in the design of the equipment has been to provide a system with which the operator can quickly obtain direct, accurate settings and to minimize the opportunity for human error in reading the results.

The design philosophy of the lambertian light collector and the photoelectric circuitry is given along with the resulting performance.

Examples of the data obtained with this system and its applications are given.

14 KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Water reflection						
Water optical attenuation						

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