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AN UNDERWATER RADIANCE DISTRIBUTION CAMERA SYSTEM

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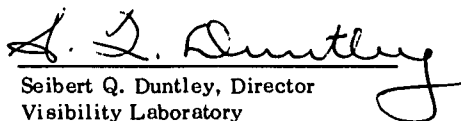
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Naval Ship Systems Command

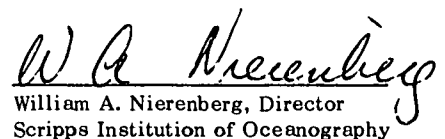
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FOREWORD

Under Contract NObsr-95251, Task I, subparagraph c, the Visibility Laboratory was required, in part, to "conduct a study to provide the fundamental knowledge required to develop equipment and techniques in support of naval requirements".

A knowledge of the manner in which natural light is angularly distributed underwater is important to the solution of many critical naval problems relating to the visual detectability of submerged objects and to the performance of underwater passive viewing systems. The underwater radiance distribution camera system described in this report has been designed to obtain the data needed for the solution of these important problems. Support received under NObsr-95251 provided for the development and construction of the camera system. This is the final report under Task I of the contract. The acquisition and reduction of data is being carried on under subsequent contracts.

AN UNDERWATER RADIANCE DISTRIBUTION CAMERA SYSTEM

Raymond C. Smith and Roswell W. Austin

1. INTRODUCTION

An oceanographic instrument has been designed, and constructed, to record the radiance distribution of natural radiant energy underwater. Essentially the instrument consists of two back-to-back cameras equipped with "fish-eye" (180° field of view) lenses packaged to be able to take photographs underwater upon command from the surface. From the films obtained, it is possible to determine the values of underwater radiance by means of photographic photometry.

Empirical radiance distributions obtained in natural waters are basic information needed for the study and solution of several problems in optical oceanography. First, the radiance distribution is an important input for the study of the interaction of electromagnetic radiation with the sea. From the distribution of radiance in the natural light fields in the ocean many of the important optical properties which relate to radiative transfer processes in the ocean can be calculated. Second, from these optical properties one can compute the magnitude of the deterioration of image contrast of submerged objects and thus furnish information for the study and solution of underwater visibility problems. Finally, since radiant energy is critical to the beginning of the marine food chain through photosynthetic plankton, radiance distribution measurements are of fundamental biological importance.

In Section 2, RADIANCE DISTRIBUTION AND ITS USEFULNESS, this report will describe more fully the measurement to be made and discuss the importance and use of these measurements. In Section 3, FISH-EYE LENS, the concept of making radiance distribution measurements with this lens will be outlined and tests of the lens and camera system will be described. Section 4, INSTRUMENT PACKAGE, will present the requirements and design solutions for making a complete instrument capable of measuring radiance distributions underwater. The final sections will discuss EXPERIMENTAL OBJECTIVES AND DATA ANALYSIS and the EXPECTED SIGNIFICANCE of the measurements.

2. RADIANCE DISTRIBUTION AND ITS USEFULNESS

2.1 Radiance

Radiance, N , is the flux (power) per unit (projected) area per unit solid angle in a specific direction. Figure 1 shows a schematic drawing of a radiance, or Gershun tube, an instrument for the measurement of radiance. The output of the instrument is proportional to the incident flux, P , the solid angle, Ω , and the area, A , of the photodetector. To measure the distribution of radiance about a fixed point one can imagine taking readings with the radiance tube over all directions about the point. The radiances measured in various directions from a point below the ocean surface can be visualized in three dimensions by picturing around this point, vector arrows whose lengths are proportional to the measured radiances. Such a display is called a radiance distribution solid. Thus radiance is the power per unit area per unit solid angle incident on a point from the direction (θ, ϕ) . The radiance distribution is the totality of radiance values for every (θ, ϕ) direction about the point.

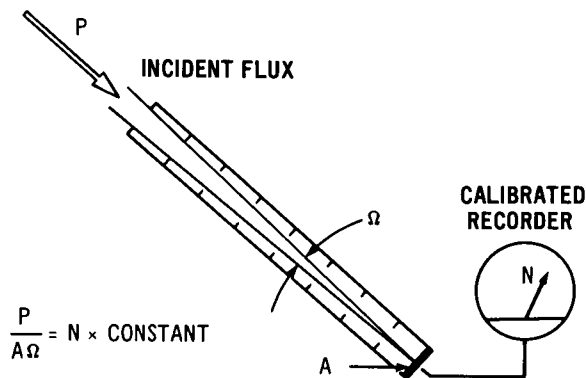


Fig. 1. Schematic drawing of a radiance, or Gershun, tube. The output of the photodetector area, A , is proportional to the incident flux, P , the solid angle, Ω , and the area, A , of the photodetector. The solid angle and area are fixed instrumental constants.

2.2. Similar Research

The general form of the distribution of radiance underwater was explored by Jerlov¹, Whitney^{2,3}, Takenouti⁴, and others. Incomplete data giving the relative magnitude of radiance in a few directions has been obtained by Jerlov and Fukuda⁵, and Sasaki et al^{6,7,8}.

Unfortunately, the fragmentary data reported by the above authors is of an exploratory nature only and is not satisfactory for the work proposed herein. The need for complete data was recognized by the Visibility Laboratory some time ago, but it was not until 1957, that the first sufficiently complete sets of data were obtained in lake water by Tyler⁹, one set representing the overcast case and the other representing the clear-sunny case. Computations from this data were described by Tyler et al¹⁰, and by Tyler and Shaules¹¹.

The instrumentation used by Tyler at Lake Pend Oreille to obtain the 1957 data was cumbersome, slow, and unsuited for the rapid accumulation of data from many sites. His work, however, confirmed the usefulness of radiance distribution data and stimulated further efforts to devise a simple method of measurement. The equipment described in this report is the outgrowth of those efforts.

2.3 Radiative Transfer Theory and Optical Properties of the Ocean

From radiance distribution data on the natural light fields many of the important optical properties which relate to radiative transfer processes in the ocean can be calculated. Although numerous measurements have been made of some single optical property, almost without exception the important related properties have not been determined. As a consequence, most existing data have been of limited usefulness. The radiance distribution cameras will surmount this problem to a large extent by making it possible to record the essential data rapidly and completely. The usefulness of radiance distribution data for the description and study of underwater light fields is outlined in Fig. 2¹².

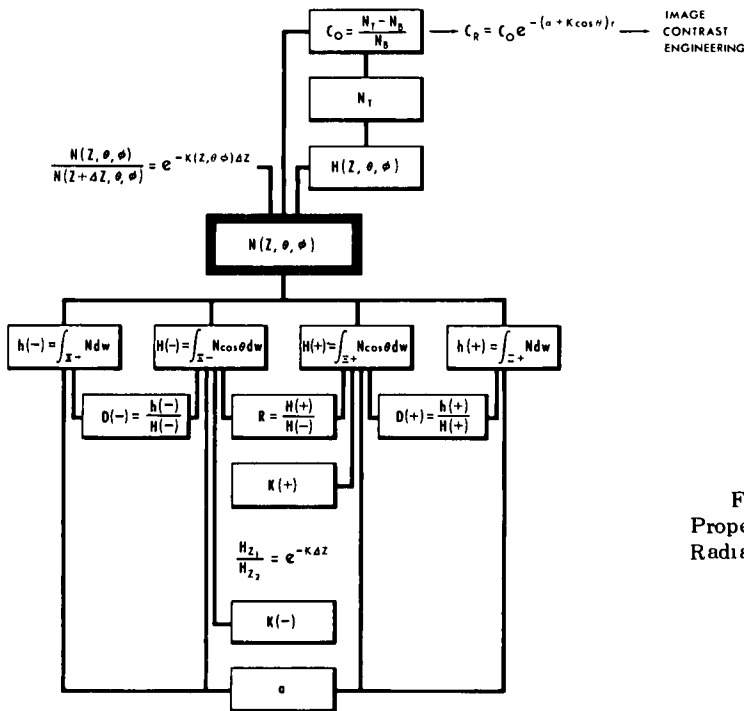


Fig. 2. Chart illustrating Optical Properties which can be derived from Radiance Focal Data.

$N(Z, \theta, \phi)$ is the radiance at a point at depth Z from the direction (θ, ϕ) . From the radiance distribution, measured as a function of depth, the following information can be determined.

Irradiances (H) and scalar irradiances (h) as a function of depth for the up- and downwelling streams of flux are of primary importance, and are closely related to the flux available for visual tasks, camera systems, and photosynthesis.

The irradiance, H , is the power per unit area arriving at a given point on a surface. Note that when speaking of irradiance, one must speak with respect to some fixed plane of reference – in the ocean it is usually convenient and practical to choose a horizontal plane. $H(-)$ is the downwelling irradiance; i. e., it is the power per unit area measured by a horizontally oriented collector facing upward (and is the quantity most classical underwater radiant energy measurements attempt to make). Similarly, $H(+)$ is the upwelling irradiance.

The Scripps Spectroradiometer¹³ was developed at this Laboratory to measure irradiance as a function of wavelength and measurements of spectral irradiance have been made for a number of lake¹⁴ and ocean¹⁵ waters. It is anticipated that the measurements of spectral irradiance made at the same time as radiance distribution measurements are made will complement and aid in interpreting the latter.

The scalar irradiance, h , gives a quantitative measure of the total radiant flux arriving at a point from all directions about the point. The physical significance of h is that, when divided by the velocity of light in the medium, one obtains the total amount of radiant energy per unit volume of space at the given point. To date, accurate measurements of scalar irradiance have not been made.

The distribution functions, D , are a simple means of characterizing the depth dependence of the shape of the radiance distributions. It is clear from the definitions in Fig. 2 that $D(Z, -)$ gives an index of the shape of the radiance distribution in the upper hemisphere (i. e., for downwelling flux) and $D(Z, +)$ provides similar information for the lower hemisphere (i. e., for upwelling flux). In addition to characterizing the depth dependence of the angular structure of the radiance distribution, $D(z, +)$ and $D(z, -)$ play indispensable roles in the equations of applied radiative transfer theory, particularly in those equations which link the inherent and apparent optical properties for the medium.

The reflection function, R , with respect to downwelling flux, is defined by $R = H(+)/H(-)$. The physical significance of R is that it may be thought of as the reflectance of a hypothetical horizontal plane surface at depth Z in the medium. It should be noted that $R(Z, -)$ depends upon and exhibits information about the scattering properties of the entire medium above and below the level Z .

The K functions are defined as the logarithmic depth derivatives of the irradiance functions. Thus,

$$K = \frac{1}{H} \frac{dH}{dZ} \quad (1)$$

or, by solving for H one obtains the relationship

$$\frac{H(Z_2)}{H(Z_1)} = e^{-K(Z_2 - Z_1)} \quad (2)$$

where K has units of reciprocal length, and Z is the depth at which H is measured. Physically the K functions are the quantities which characterize the individual depth dependence of the various irradiance functions. The K functions are experimentally motivated by the fact that in general radiant energy decreases exponentially with depth. These functions have been used in the study of both theoretical and experimental applications of radiant energy in natural waters.

Finally, Preisendorfer has shown, by a method which makes use of the divergence relation of the radiant energy field, that the volume absorption function, a , can be computed without the requirement of previous knowledge of the volume attenuation function or the volume scattering function. This may be done by dividing the rate of change of the net upwelling irradiance by the scalar irradiance. That is,

$$a(Z) = \frac{1}{h(Z)} \frac{d\bar{H}(Z, +)}{dZ} \quad (3)$$

where

$$\bar{H}(Z, +) = H(Z, +) - H(Z, -) \quad (4)$$

is the net upwelling irradiance and

$$h(Z) = h(Z, -) + h(Z, +) \quad (5)$$

is the total scalar irradiance.

2.4. Image Contrast Engineering

The upper part of Fig. 2 summarizes the application of radiance measurements to the problems of image contrast engineering. For an object to be visually detectable, it must differ photometrically from its background in the sensor's direction of view. Whatever difference does occur constitutes an optical signal. This optical signal at the target can be described by its inherent contrast¹⁶ defined as,

$$C_o = \frac{N_T - N_B}{N_B} \quad (6)$$

where N_T is the inherent radiance of the target and N_B is the inherent radiance of the background against which the target is seen. Thus the first major step in any detection problem is the assessment of the magnitude of the inherent contrast. In computing the inherent contrast of a submerged object, the background radiance, N_B can be obtained directly from the radiance distribution. The inherent radiance of the target, N_T , depends on the distribution of the flux incident upon the object and its angular reflectance properties. Thus knowledge of the gonireflecting properties of the object and the radiance distribution of the light field in which the object is immersed leads directly to the determination of inherent contrast for any path of sight.

Once the inherent contrast has been determined, one can then apply the equations of contrast reduction to problems of the visibility of submerged objects. The apparent contrast, C_R , seen by a sensor at a distance r along a path, is diminished by the concurrent action of two optical processes: (1) light from the object is attenuated by scattering and absorption, (2) daylight is scattered toward the sensor throughout the entire length of the path of sight thus producing a veil of light which lowers the apparent contrast of the object. At sufficient distance, the contrast falls below the sensor's threshold of detection and only the veiling radiance is detected. The equation of contrast reduction is:

$$C_R = C_o e^{-(\alpha + K \cos\theta) r} \quad (7)$$

where α is the volume attenuation function (the quantity measured by an α -meter) and K is the diffuse attenuation function (for radiance) which can be calculated from the radiance distribution data by the equation defining $K(Z, \theta, \phi)$ in Fig. 2. θ , as used in Fig. 2 and Eq. (7), is the angle between the vertical and the line of sight. Using Eq. (7) the apparent contrast can be calculated along any path of sight once the

inherent contrast of the object has been calculated. Thus it can be seen that the key to the problem of determining the contrast and detectability of submerged objects is a knowledge of the natural radiance distribution of the water in question since it provides all the information necessary for the solution of the above equation except α and the reflecting properties of the object.

2.5. Biological Applications

Radiance distribution information, in addition to the above uses, will provide new data and information which should be of interest to biologists. It is clear that radiant energy supplies the input into natural waters and supports its ecology through photosynthesis. However, it is not so clear which radiant energy measurements are biologically the most meaningful.

It is likely that the scalar irradiance and the volume absorption function, which to date have avoided careful measurement because of experimental difficulties, are among the more meaningful. As mentioned above, the scalar irradiance is a measure of the total energy per unit volume of space at a given point. It thus gives a measure of total energy incident from all directions on an organism in the water at the depth of interest. The volume absorption function, a , refers to the conversion of radiant energy into other forms of energy (heat, chemical, another wavelength of radiant energy, etc.). That is, it gives the actual energy absorbed by the medium (water plus organism) and is independent of the attenuation of energy due to scattering (without change of wavelength). Thus, h is a measure of the total energy incident on an organism and a is a measure of the energy absorbed by an organism. Therefore, radiance distribution measurements, correlated with appropriate biological experimentation, can provide new information on the problem of primary productivity.

3. FISH-EYE LENS

3.1. Properties of the Fish-Eye Lens

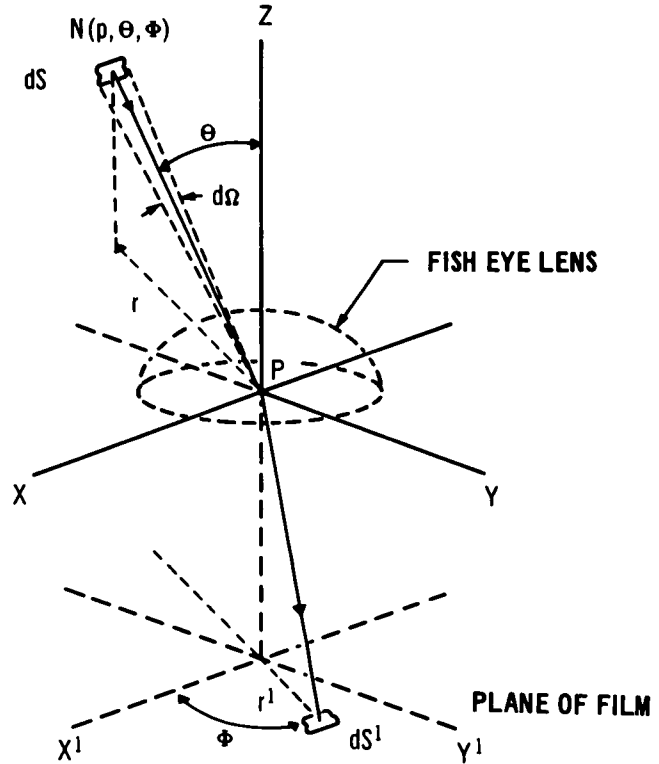
The 8 mm f/8 Fish-Eye Nikkor lens manufactured by Nippon Kogaku K. K. (Japan Optical Industry Company) will be used to measure the radiance distribution in the underwater environment. The properties of this lens which make it ideally suited for this application, as well as the limitations of the lens, have been investigated and are discussed below.

Note first that this lens is not an extension of a wide-angle lens¹⁷. The lens has an inherent distortion; however, this distortion should not be considered as an aberration but as a direct result of the projection of a hemisphere on a plane. Referring to Fig. 3, let the angle of an incident ray from an infinite object be θ (zenith angle) and the coordinates of the image of this ray on the plane of the film be (r', ϕ') . The projection of the Nikkor f/8 fish-eye lens conforms to an equidistant projection to within five per cent¹⁸; that is,

$$r' = f\theta, \quad (8)$$

where f is the lens focal length. Properties of the fish-eye lens which are of interest follow as a consequence of this projection.

Fig. 3 Schematic diagram showing projection geometry of fish-eye lens for photographing radiance distributions.



In Fig. 3, $d\Omega$ is an element of solid angle in object space and dS' is the corresponding area in the image plane, and for an equidistant projection the following relation holds:

$$d\Omega = \frac{1}{f^2} \frac{\sin\theta}{\theta} dS' \quad (9)$$

The field radiance, N , is the energy per unit time (power) per unit area per unit solid angle incident on a point P (projection origin of the lens) from the direction θ, ϕ . The exposure given to a film, as used in sensitometry, is proportional to the amount of radiant energy per unit area incident on the film. Miyamoto has shown, using the above expressions, that the film irradiance, H , has a one-to-one correspondence to the field radiance which is given as

$$H = N \left(\frac{n}{n'} \right)^2 \left(\frac{\pi}{4F^2} \right) \left(\frac{\sin\theta}{\theta} \right) \quad (10)$$

where n and n' are the indices of refraction of object and image space, respectively, and F is the f /number. Equation 10 shows that for a uniform radiance distribution, the irradiance on the film is relatively uniform, following a $\sin\theta/\theta$ relation, as compared to ordinary lenses which obey the $\cos^4\theta$ law. This relative uniformity, the known one-to-one correspondence between the image exposure on the film and the incident radiance distribution, and the hemispherical field of view, are the reasons why this particular lens is ideally suited for the purpose of measuring radiance distributions. Thus, by the methods

of photographic photometry the density of an area in a film negative can be related to the exposure (the energy/time-area) of that area and this can in turn be related to the desired value of field radiance.

One other comment is in order at this point. Mees¹⁹ has stated that "hardly any type of measurement contains so many pitfalls for the unwary as photographic photometry". These pitfalls, and the attendant lack of precision and inaccuracies, must be balanced against the chief advantage of photographic photometry; namely, that it can record a vast amount of information quickly on a single piece of film. Since the recording of a single radiance distribution with a 1° resolution represents over 50,000 pieces of information it can be seen that the chief advantage of photographic photometry may quickly override its disadvantages.

3.2. Tests of the Fish-Eye Lens

Our preliminary tests of the fish-eye lens indicate that it conforms to an equidistant projection to within two percent from 10° to 90° and that it varies by as much as five percent only in the 0° to 10° (zenith region). Similar tests have been published by Crowley²⁰. The $\sin\theta/\theta$ dependence has also been measured and found to be correct to within five percent.

As will be discussed fully in Section IV, the fish-eye lens is covered with an acrylic plastic dome for use underwater. This dome and the change from an air to a water environment will affect the projection properties of the lens. Thus, final testing of the lens and its protective underwater housing must be made underwater as an integral unit.

These tests are of a calibration nature; that is, once the projection properties of the lens plus protective dome have been measured in water, any departure from the theoretical projection are known and are a fixed property of the system. The measured, rather than the theoretical, projection properties can be used to analyze the data without loss of accuracy.

On the other hand, there are characteristics of the lens system which are not fixed but vary with the environmental radiance distribution. A major concern, in considering the fish-eye lens for radiance measurements, is the problem of flare light²¹. Flare is the illumination on the photographic material due to non-image-forming light which arises from various sources, such as inter-reflections between the glass-air surfaces of the lens system, reflection from the interior surfaces of the lens mount, shutter blades, and reflection from the interior surfaces of the camera body. For the purposes of the intended measurement it is important that the non-image-forming light due to flare, i. e., "flare spots" or "ghost images" be small compared to the image-forming light from the sought-for radiance distribution. If this is not the case, we must be able to detect and to correct for flare to the desired accuracy. For the discussion to follow, let H_o be the image-forming irradiance at the film coming directly from the object and H_f be the non-image-forming irradiance or flare light. We will speak of "error due to flare" as the ratio H_f/H_o , usually expressed as a percentage.

A Nikkor fish-eye lens was borrowed²² for the purpose of making quantitative estimates of the effects of flare. It should be emphasized that the amount of flare light incident on the focal plane in a camera equipped with some specific lens system is not determined entirely by the characteristics of the camera-lens system, but is dependent in a large measure upon the distribution of luminance within the scene being photographed. Further, it should be noted that the greater the range of radiances present in the scene

the greater the effects of flare will be. For our purpose it is thus both necessary and sufficient to consider flare light of the fish-eye lens for a typical underwater radiance distribution. Actually, an atypical situation was studied by choosing the most extreme underwater lighting conditions likely to be encountered in order to determine the upper limit of the error that may be expected due to flare light. The environmental scene chosen for these flare studies is the underwater radiance distribution of the upper hemisphere on a clear, sunny day at a shallow depth²³, because the range of radiances under these conditions is the greatest.

The Sky Simulator of the Visibility Laboratory proved to be a valuable facility for the flare light studied. This lighting simulator is an eight-foot radius hemisphere containing 196 individually controllable luminous panels which can accurately simulate different distributions of natural lighting. A number of techniques, which yielded similar results, were used to evaluate the error due to flare, the most straightforward being simply to photograph a simulated radiance distribution having symmetry about the vertical axis. One azimuthal sector of this distribution was unilluminated, i. e., left dark. Thus a photograph of this radiance distribution, with one section black, taken with the fish-eye lens would show the circular projected image of the hemispherical simulated radiance distribution with a pie-shaped wedge corresponding to the black sector. If there were no flare, this wedge would be completely unexposed. On the other hand, any density found in the negative in the "unexposed" area is a measure of the flare of this lens for the given lighting distribution.

Results of these tests indicate that the error due to flare, even under the most extreme underwater environmental conditions, will be less than a few percent between the zenith (0°) and 80° and that it may become greater than this only in the 80° to 90° zonal region. A camera pointed toward the nadir will record the radiance distribution from 90° to 180° and since the radiance distribution in the lower hemisphere has a range of radiances no greater than 2 orders of magnitude (current data indicate 1 order of magnitude), the accumulated flare light when photographing the lower hemisphere will always be considerable less than 0.1%. Thus, since the radiance distribution is essentially a smooth distribution, simultaneous photographs of the upper ($0^\circ - 90^\circ$) and lower ($90^\circ - 180^\circ$) hemispheres will disclose the presence of excessive flare in the 80° to 90° region, should it appear, and allow an interpolation over this region. The fact that we are dealing with a smooth distribution also allows one to interpolate over flare spots or ghost images, if they appear, with a minimum loss of accuracy.

From the results of these flare measurements we conclude: that even under the most unfavorable environmental conditions the error due to flare will be less than a few percent; that the flare light for an underwater scene is distributed in such a way that simultaneous photographs of the upper and lower hemisphere will detect the presence of flare, should it become greater than a few percent, and appropriate correction can be made; and that under more typical environmental conditions (greater depth and/or overcast sky) the error due to flare will become less than a few percent and thus will not degrade the accuracy of the measurement.

The Nikkor f/8 fish-eye lens has one other feature which is useful for our purposes, a built-in six-position bilter wheel. Neutral density filters have been mounted in this wheel to accommodate the high radiance levels encountered when the instrument is near the surface facing the sun.

3.3. Camera Tests

For the purpose of photographic photometry, the focal-plane shutter of the Nikon camera has the disadvantage that if the curtain speed is uneven it causes an uneven negative density. However, we must accept this disadvantage since the focal-plane shutter is the only one which can accommodate the fish-eye lens. That the curtain speed does not remain constant, a common condition in focal-plane shutters, is due to changes in spring tension and to friction during the exposure cycle.

Experiments to measure the camera shutter speeds and speed variation across the focal-plane have been made as a function of camera temperature from 5°C to 25°C. Results of a typical measurement are shown in Fig. 4 which shows the shutter speed, normalized to 1.0 at the center of the focal-plane, plotted against distance along the focal plane. It is seen that the greatest variations in shutter speed are at the edges of the focal-plane where the greatest accelerations of the shutter curtains occur. This is fortunate for our purposes since the fish-eye lens exposes only a 24 mm circle in the center of the focal-plane and does not make use of the edges. These experiments have shown that, except for the slowest (1 second) and fastest (1/1000 second) shutter speeds, the shutter speed variation, over the region of interest (center 24 mm), is less than plus or minus three percent.

These measurements also provide the actual shutter speed, as opposed to the rated speed, of the camera as a function of temperature. It was found that while the actual speed may be significantly different from the rated speed, the actual speed is reproducible to within plus or minus two percent over the range of expected temperature variations. This shutter speed measurement can be considered a calibration of the camera; however, this calibration will be checked before and after data is taken in the field for possible changes.

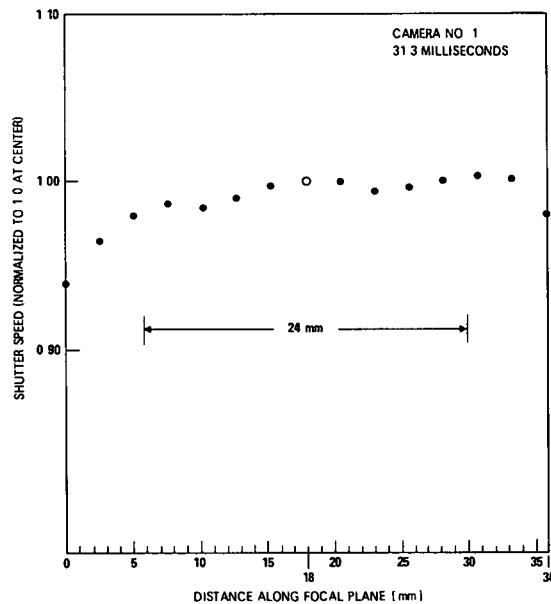


Fig. 4. Camera Shutter Speed vs Distance along the Focal Plane.

3.4. Summary

The above discussion has shown why the fish-eye lens is ideal for measuring underwater radiance distributions and discussed some of its limitations for such measurements. Some important characteristics peculiar to our particular lens-camera system which have been measured to date are presented. This, of course, does not exhaust the discussion of the difficulties and limitations inherent in this proposed technique of measuring underwater radiance or provide sufficient information for a full discussion of error. However, the additional difficulties come under the heading of photographic photometry and are fully described elsewhere^{19, 24, 25}.

Sources of error due to photographic photometry are known and their magnitudes can be estimated and to some extent controlled. Some errors peculiar to our lens-camera system have been measured and others, which must be measured in the final instrument configuration, have been estimated. With these considerations, it is estimated that a goal of 25% absolute accuracy and 10% relative precision for the radiance measurements is attainable with experience. It should be noted from Fig. 2 that most of the optical quantities which are calculated from radiance values are ratios and as such their values are not seriously affected by the anticipated magnitude of absolute errors.

4. INSTRUMENT PACKAGE

To obtain radiance distribution data as a function of depth successfully in natural underwater environments necessitates reliable seaworthy equipment capable of satisfying a number of requirements. The major requirements and the instrumentation to meet these requirements are discussed below.

The fish-eye lens is the central feature of the instrumentation. The instrument contains two motor operated Nikon F cameras each equipped with a fish-eye lens. The two cameras are mounted back-to-back, one oriented toward the zenith, the other toward the nadir. It is more economical, both in cost of construction and in time necessary to take data, to photograph the upper and lower hemisphere simultaneously rather than to build a device which would rotate the instrument package through 180° at each data-collecting depth. Also, as mentioned in Section 3.2, the simultaneous photographs provide a method of detecting and correcting for flare light, should it appear. Furthermore, simultaneous photographs insure that the upper and lower hemisphere data were obtained under identical lighting conditions which simplifies data interpretation. The lens-camera system is covered with polished acrylic plastic hemispheres which are centered with respect to the projection origin of the lens. This protects the lens from the environment and also provides an undistorted coupling of the lens to the water.

Each lens-camera system is housed separately in a pressure case consisting of the plastic hemisphere and a cylindrical aluminum case. The case is assembled using quick release bands to facilitate the process of changing film. This housing is capable of withstanding pressures to depths of 100 meters. One-hundred meters is also approximately the maximum depth from which data can be taken. This maximum depth is of course variable and is determined by the sensitivity of the film, the maximum exposure time permitted, and the clarity of the water.

The film exposure level, under consideration, varies from a low, determined by the film sensitivity and developing technique, to a high which will occur near the surface of the water under a clear, sunny sky. This exposure range is roughly six to eight orders of magnitude. Thus it is necessary to have some

means of determining the light level and of setting the correct camera exposure. It is also useful to have some method of normalizing the radiance values measured at the various depths to each other. This normalization can be used to correct for any reciprocity law failure of the film.

Photocells, constructed so as to measure upwelling and downwelling irradiance, are used to determine correct camera exposure settings. They also provide the information required to normalize the data taken at various depths. Provisions are made to read the magnitude of these irradiances, their ratio to each other, or their ratios to an illuminometer mounted on deck. The spectral sensitivity of these underwater irradiance collectors are matched as closely as possible to the spectral sensitivity of film and filter combination being used in the cameras. The choice of film-filter spectral sensitivity is made in turn after giving due consideration to the spectral selectivity of natural waters.²⁶

The orientation and position of the instrument package must be considered. The azimuthal orientation can be determined quite accurately, even at the greater depths, from the position of the sun spot on the film. In addition, the direction of the vertical may be determined from the film since the position of the nadir is unique by being the position of lowest radiance. (This is another reason why it is useful to take upper and lower hemisphere photographs simultaneously). However, it is conceivable that the location of the nadir on the film will not be sufficiently accurate to orientate the data. To ensure that the instrument package is level when an exposure is made, two gravity sensing electrolytic transducers orientated at right angles are used. Finally, the depth of the instrument must be known, and for this purpose an accurate depth transducer is included.

The upwelling and downwelling irradiance collectors, the two-axis gravity sensing device, the depth transducer and various electronics are housed in a third pressure case the same size as the camera cases. Fig. 5 shows the combined underwater unit consisting of the electronics unit in center foreground with its downwelling irradiance collector on top, the upper camera unit in the left background, and the pressure case

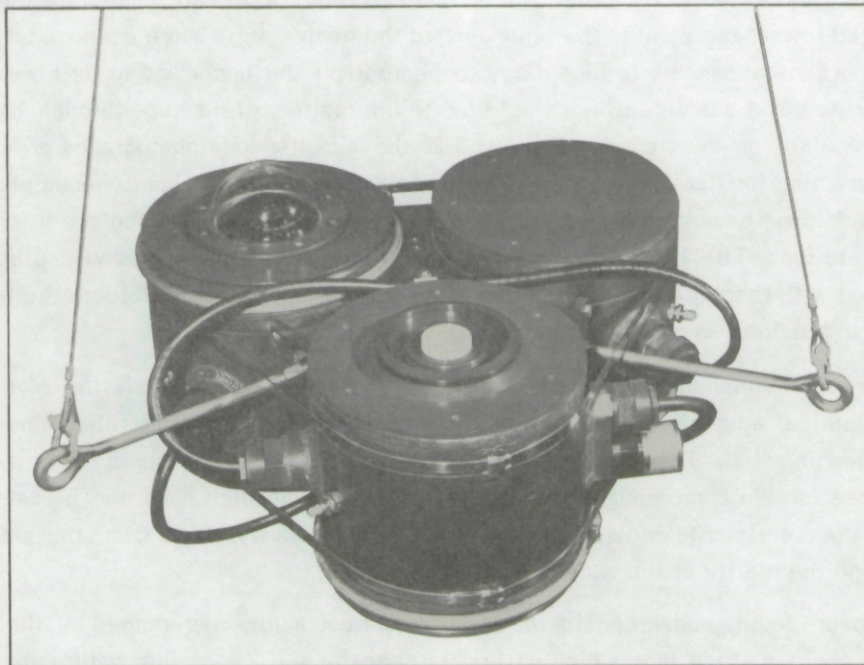


Fig. 5. Underwater Camera Assembly

for the lower camera in the right background. From the optical point of view the instrument package should be horizontally flat so that the up and down photographs are taken as close to the same depth as possible. For this situation the pressure cases are arranged as shown in Fig. 6. Here the projection origin of the two fish-eye lenses are at a depth separation of 29 cm.

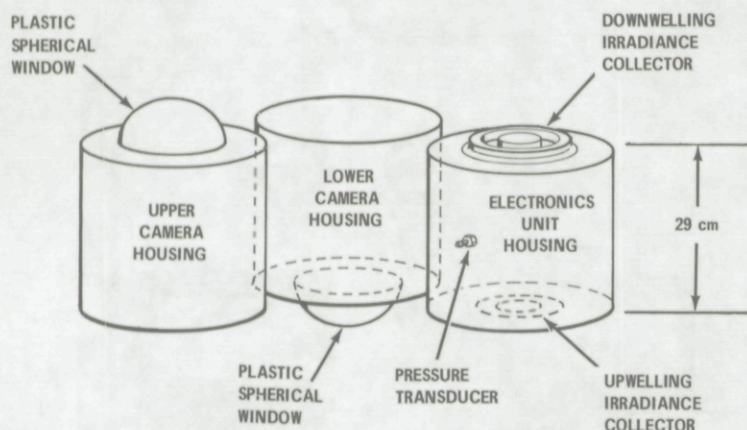


Fig. 6. Radiance Distribution Camera. Underwater Unit Mechanical Schematic showing physical location of components.

The first field work was in favorable environments where the problem of instrument orientation and stability was not of major concern. Subsequently, however, the instrument can be used in more demanding ocean environments. From the point of view of maximum stability in rough seas the instrument package should be long and thin in the vertical direction. The modular form of the instrument package allows the pressure cases to be arranged in this manner and to be gimballed so as to minimize tilt due to currents and cable drag should this prove necessary or desirable. This alternate configuration may necessitate a significant optical correction of the data to account for the separation of the two lenses.

The underwater instrument is remotely operated via a 14-conductor electrical cable from the deck control panel shown in Fig. 7. This unit provides the necessary information inputs and commands functions for the operation of the camera system. Fig. 8 is a block diagram of the complete camera system. It shows the flow of information and commands to and from the deck control unit, the underwater electronics unit, and the two underwater cameras.

The exposure control commands are encoded into frequencies at the control panel and transmitted to the underwater electronics unit where they are decoded by a system of frequency selective reeds. The decoded command information is then transmitted to the two cameras where motors operating geneva mechanism advance the shutter speed controls, the iris diaphragm controls or, in the case of the upper camera, a neutral density filter wheel. Potentiometers attached to the control shafts return analog voltage position information to the underwater electronics unit indicating the condition of each control shaft in the two cameras. The two analog voltages indicating shutter speed are compared and, if they are equal, one of these analog signals is sent to the surface confirming that the two shutters are set to the same speed and indicating what this speed is. Should there be a lack of correspondence between the two voltages the comparator will not pass a signal and the lack of signal will indicate a malfunction. The information on the iris diaphragm position is handled in a similar manner. The filter position analog voltage information from the upper camera is transmitted directly to the surface.

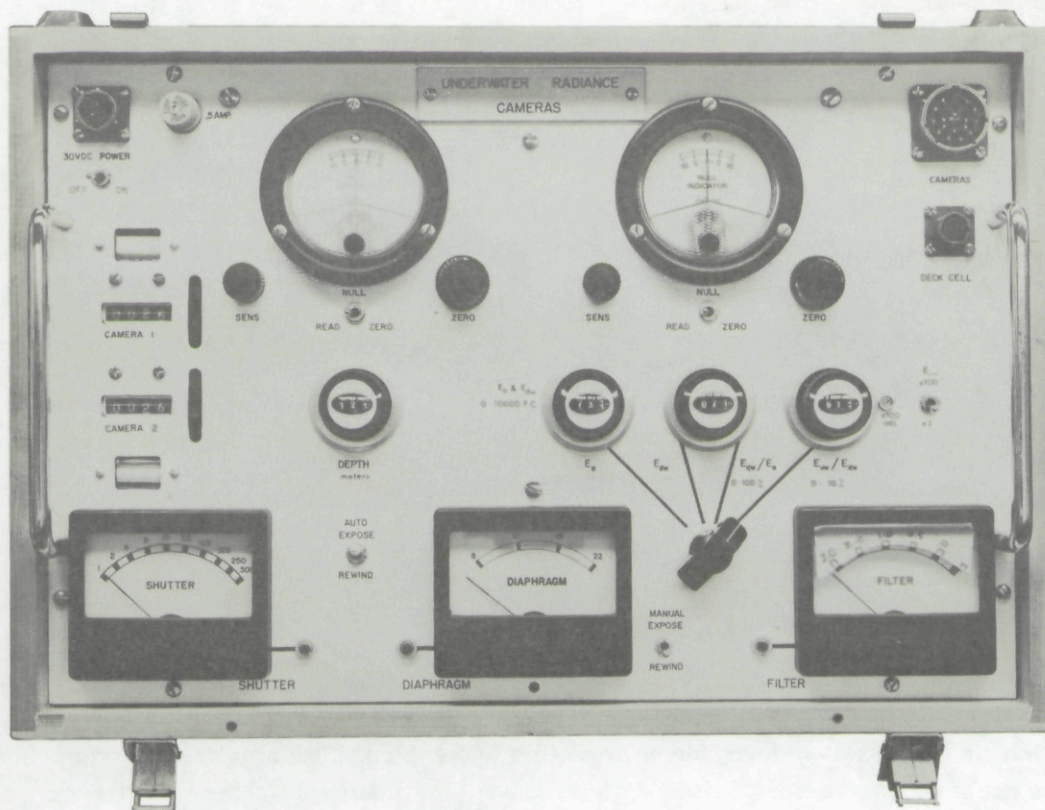


Fig. 7. Deck Control Panel

The exposure command can be given in an "Auto" mode in which case the camera shutters will be tripped when the underwater unit is within about one degree of vertical as sensed by the orthogonal pair of electrolytic level sensors. The requirement that the cameras be vertical can be overridden by giving the "Manual Expose" command. When the camera shutter is tripped, confirmation of the exposure is obtained from the closure of the flash synchronization contacts. This confirmation is transmitted to the surface where a counter is advanced showing the number of frames which have been exposed and a flag indicator shows the word "EXPOSED" in a window. After this confirmation of exposure is obtained, the exposure command switch is thrown into the "Rewind" position and the motorized film transport camera backs advance the film to the next frame. Upon completion of the advance the flag indicators change from "EXPOSED" to "READY" and the cameras are prepared for the next exposure.

As indicated in Figs. 7 and 8, the deck control unit also provides a continuous indication of camera depth by means of a manually balanced potentiometric measurement of the pressure transducer voltage. Similar measurement capability is provided for the various irradiances and irradiance ratios from which exposure, diffuse attenuation coefficient, and water reflectance can be determined.

Power for operation of the camera system can be obtained from batteries for remote field use or any convenient source of 30 volt DC. Internal regulators supply critically voltage sensitive components so that the regulation characteristics of the primary source are unimportant.

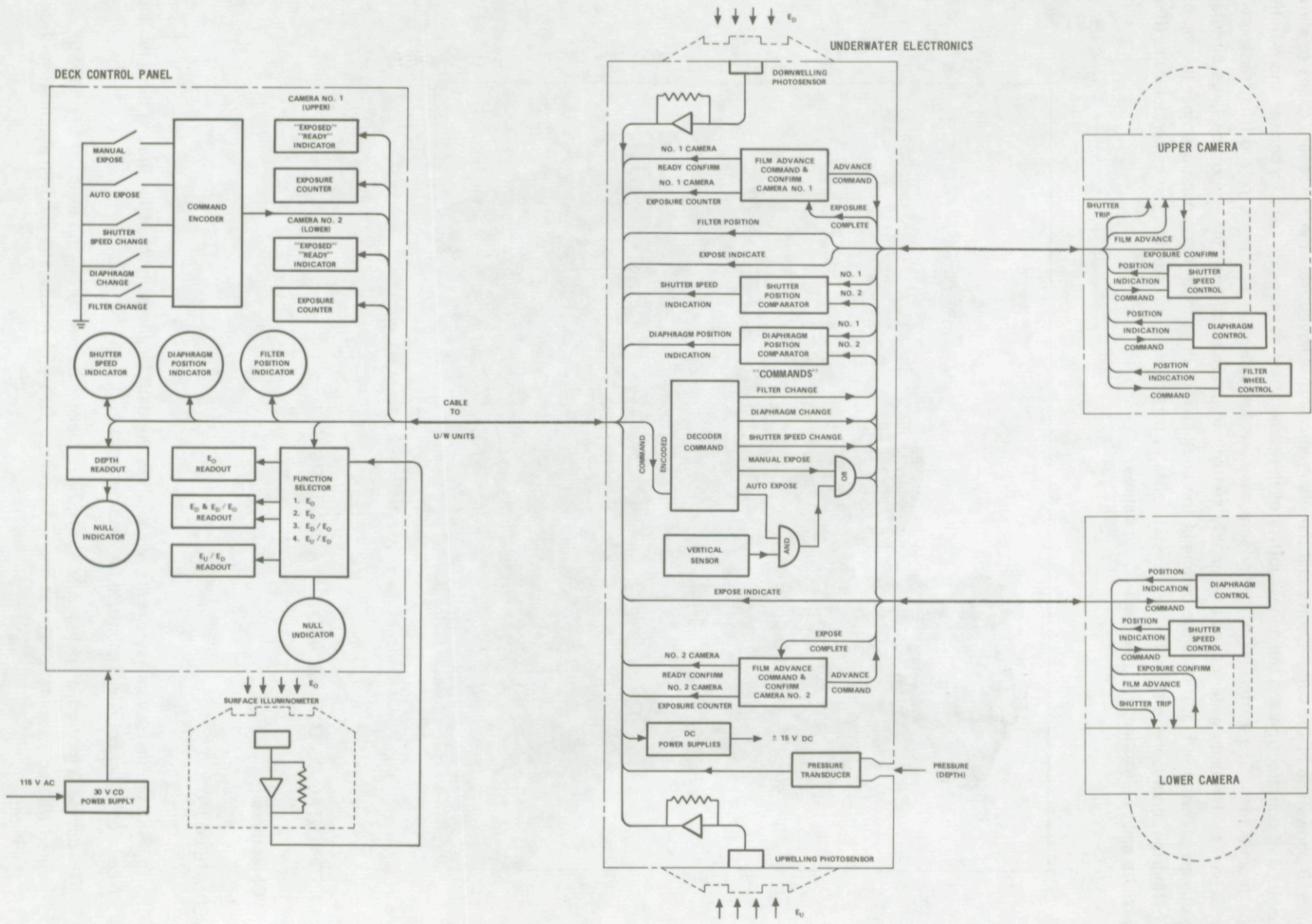


Fig. 8. Underwater Radiance Camera System Block Diagram

Fig. 9 shows one of the camera units and the electronic unit removed from their pressure cases to show the method of construction and the accessibility of the camera and components for film change and maintenance procedures. The batteries in the camera case are for operation of the motorized film transport camera backs. The underwater cases are quickly sealed and unsealed through the use of the large circular ring clamps showing in Fig. 5 near the bottom of the enclosure in the middle foreground and near the top of the cylindrical enclosure in the left rear. Easy access is particularly important in the cameras as the film magazines must be exchanged after each 36 exposures.

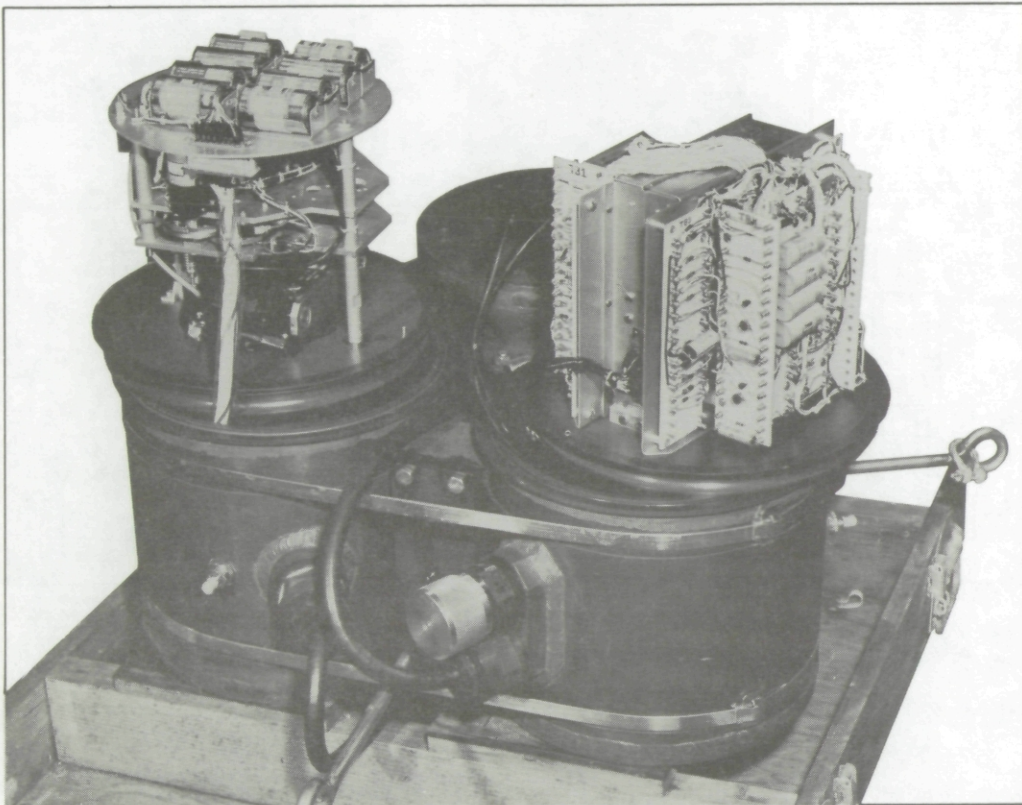


Fig. 9. Underwater Camera Assembly with camera and electronics removed.

5. EXPERIMENTAL OBJECTIVES AND DATA ANALYSIS

5.1. Objectives

IMMEDIATE OBJECTIVES:

1. To make preliminary measurements and analyze the data for the purpose of evaluating the data and developing an optimum technique for data analysis.
2. To devise a method of using a scanning densitometer for measuring the exposed film, and to develop related computer programs for reducing the data and making the desired calculations from the data.

3. To collect data on radiance distribution underwater at various sites, for various types of water, and for various optical bandwidths.
4. To compute from the radiance distribution data the various optical properties and tables of irradiance distribution for use in determining inherent contrast as discussed in the sub-sections 2.3 and 2.4.
5. To check theoretical relationships.
6. To correlate data with appropriate biological experiments.

LONGER TERM OBJECTIVES:

1. To categorize ocean masses in terms of their optical properties.
2. To extend and, where possible, simplify the theory of radiative transfer in the oceans.

5.2. Data Analysis

The chief advantage of photographic photometry, that it can record a vast amount of information quickly on a single piece of film, eventually poses the problem of how to handle the large quantity of information obtained. For preliminary or a limited amount of work, present Visibility Laboratory facilities, developed for image restoration work, are adequate to scan the developed film and reduce the data.

The density of the developed film will be measured with the use of a microdensitometer using standard techniques^{19, 24, 25}. Since the (r', ϕ') coordinates of the negative correspond to the (θ, ϕ) coordinates of the radiance distribution, the densitometer must have some provision for accurately scanning the negative and a facility for recording the film density as a function of position. In addition, since the aperture and magnification of the densitometer determine the area dS' of the scanned film, and since dS' is related to the object space solid angle $d\Omega$ by Eq. (9), it is the densitometer which determines the resolution, or apex angle of the cone of collection, of the radiance measurement. This resolution should be small enough so that detailed scanning of the sunspot can be made but not so small that the sensitivity of the densitometer measurement is sacrificed. It is also necessary to choose and vary the resolution so that the complete information on the film is obtained but the number of bits of information remains a minimum.

It is clear that if even a modest amount of data is to be taken and analyzed, that efficient procedures for scanning the film and reducing the data are necessary. As mentioned above this is one of our most immediate objectives.

6. EXPECTED SIGNIFICANCE

The collection of a comprehensive body of related data on the optical properties of natural waters will be significant in a number of ways. It will develop our knowledge and understanding of the role played by electromagnetic radiation in the ocean and perfect the optical instruments and techniques used in

studying the ocean. It will provide data from which many important related optical properties of hydrosols (listed in Section 2.3) can be determined. It will provide the means for determining the inherent contrast of submerged objects and thus furnish information for the study and solution of underwater visibility problems. It will furnish information which may be useful for categorizing natural waters into optical types. It will allow a more rigorous check of various aspects of the general theory of radiative transfer in hydrosols. Finally, a comprehensive related body of data should provide additional insight into many features of the radiative transfer process and the distribution of light in natural waters. Such insight is particularly important since light supplies most of the energy input into these waters and supports its ecology through photosynthesis.

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13 ABSTRACT An oceanographic instrument has been designed, and constructed, to record the radiance distribution of natural radiant energy underwater. Essentially the instrument consists of two back-to-back cameras equipped with "fish-eye" (180° field of view) lenses packaged to be able to take photographs underwater upon command from the surface. From the films obtained, it is possible to determine the values of underwater radiance by means of photographic photometry.			

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