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*An Underwater Spectral Irradiance Collector*¹

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ABSTRACT

The design, testing, and evaluation of the accuracy of a collector for measuring underwater spectral irradiance is the subject of this paper. A successful underwater irradiance collector is described. Emphasis is placed on the experimental techniques employed in testing its collecting properties and in measuring the immersion effect so that its accuracy can be estimated. It has been found that the immersion effect is a function of wavelength. The systematic errors introduced by the use of imperfect irradiance collectors have been quantitatively evaluated and the effects of these errors are discussed.

Introduction. Atkins and Poole (1933), in measuring submarine daylight, recognized the need to adopt a well-defined quantity that could be measured by all workers. Their optical collector was constructed so that its response was "very nearly proportional to the cosine of the angle of incidence of the beam," and a factor was applied to correct for the "immersion effect." Since this early work, many investigators engaged in making underwater measurements have not been quantitatively critical of their collector response and have frequently overlooked, or have merely estimated, the correction required for the immersion effect. Thus, to date it has rarely been possible to evaluate the accuracy of underwater irradiance measurements and to reliably compare such measurements by various workers.

Recent critical examination of the properties of the irradiance collector on the Scripps Spectroradiometer (Tyler and Smith 1966) has indicated that undesirable and unsuspected systematic errors may occur if underwater collectors are not properly designed. Even if high accuracy is not required in a particular measurement, it is valuable for the investigator to have a realistic estimate of the systematic errors in his measurements.

There are compelling reasons for measuring underwater irradiance. Irradiance is a well-defined and standardized physical quantity that can be critically

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compared. It is a principal quantity used in physical theories (Tyler and Preisendorfer 1962) concerned with the behavior of radiant energy in natural waters; thus irradiance allows direct comparison of experimental data with physical theories. Irradiance also serves as a useful measure of the radiant energy available for photosynthesis. Compared with other properties that might serve the above purposes (for example, radiance or scalar irradiance), irradiance is relatively easy to measure.

The upwelling and downwelling irradiances, $H(Z, \pm)$, are related to the radiance distribution, $N(Z, \theta, \varphi)$, at depth Z by the formulas

$$H(Z, \pm) = \int_{\Xi(\pm)} N(Z, \theta, \varphi) \cos \theta \, d\Omega(\theta, \varphi).$$

Here θ and φ are, respectively, the zenith and azimuth angles of the radiance vector, $d\Omega(\theta, \varphi)$ is the solid angle, $\Xi(+)$ indicates integration over the upper hemisphere, and $\Xi(-)$ indicates integration over the lower. So that an optical collector may perform the integration expressed in the above equation, it is necessary for its surface to receive flux in accordance with its projected area; i.e., as the cosine of the incident angle.

The Irradiance Collector. The materials available for the construction of a suitable collector are not accurate cosine collectors. Satisfactory collecting properties have been achieved in air by appropriate roughening of the surface of some materials. However, when such a collecting surface is submerged in water, the roughened surface ceases to be effective and the collecting properties change significantly. For use in water, it is particularly difficult to find a collecting surface that collects accurately at large angles from the vertical. Boyd (1951) seems to have been the first to publish the idea that a collector projecting outward, with some light passing through the edge, could improve the performance of the collector at large angles of incidence.

Guided by Boyd's work and by the work of Austin and Loudermilk (1968) in adapting Boyd's idea to the development of underwater cosine collectors at the Visibility Laboratory, the underwater spectral irradiance collector shown in Fig. 1 was constructed for the Scripps Spectroradiometer. The dimensions given in Fig. 1 can serve only as a first approximation in constructing a collector of different size. Experience has shown that the dimensions for a correct cosine collector do not necessarily scale linearly to different dimensions. Therefore I wish to emphasize that the technique of adjusting the collector's dimensions to achieve the desired collecting properties and the technique of testing the collector are more important in achieving accurate results than in following the particular dimensions given in Fig. 1.

The dimensions of the underwater cosine collector described here were experimentally determined by trial and error. This involved constructing and measuring the collecting properties of a series of trial collectors. The measured

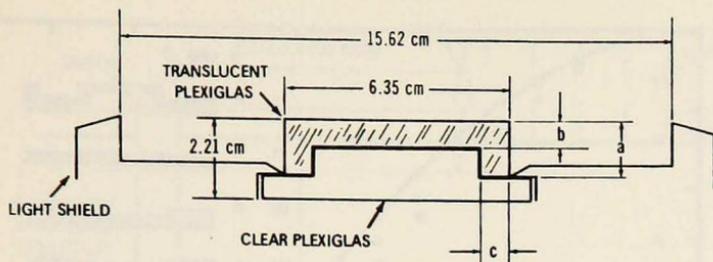


Figure 1. The underwater irradiance collector. The critical dimensions of this collector are: $a = 1.58$ cm, $b = 0.71$ cm, and $c = 0.76$ cm.

angular response of each trial collector was used to determine the dimensions of the succeeding trial collector until one was produced whose angular response in water was found to be acceptable. In general, the effectiveness of the collector at large angles of incidence can be increased with respect to the effectiveness at small angles of incidence by increasing the dimensions a and b and decreasing c (Fig. 1). The light shield—a concentric opaque ring—is employed to insure that the collector response goes to zero for an incident angle of 90° .

The collector is made of clear and translucent Rohm and Hass Plexiglas II—UVT (ultraviolet transmitting). The geometry of the diffusing plexiglas gives the desired cosine response. The clear plexiglas provides mechanical strength and a means of support for the diffuse collector. The two pieces of plexiglas were bonded together by slightly dissolving their common faces in ethylene dichloride and then pressing them together under pressure. The common faces were machined so that there was about 0.005 cm of extra material beyond the desired dimensions. This extra material, along with unwanted bubbles, was extruded when the two pieces were joined under pressure. The pressure must be maintained until the plexiglas sets (roughly 12 hours).

Plexiglas was chosen because it is resistant to seawater, is strong and resistant to impact, is easily fabricated, has dimensional stability, and is available in both clear and translucent forms. Also, while it is necessary to use translucent plastic to achieve cosine collection, it is desirable to keep absorbance within the collector to a minimum; because of this, ultraviolet transmitting plexiglas was used to extend the useful spectral range of the collector.

In order to determine the angular response of the Scripps collector, it was mounted underwater so that it could be rotated around an axis coincident with, and centered on, its surface. While irradiated by a stable and uniform beam of collimated light, the collector was rotated about the axis, and its response as a function of incident angle was recorded. The angular response of the accepted collector is shown in Fig. 2. The solid curve is a plot of $\cos \theta$ versus the angle of incidence, θ . The data points indicated by the solid black squares are of interest; these points indicate the measured angular response of the accepted

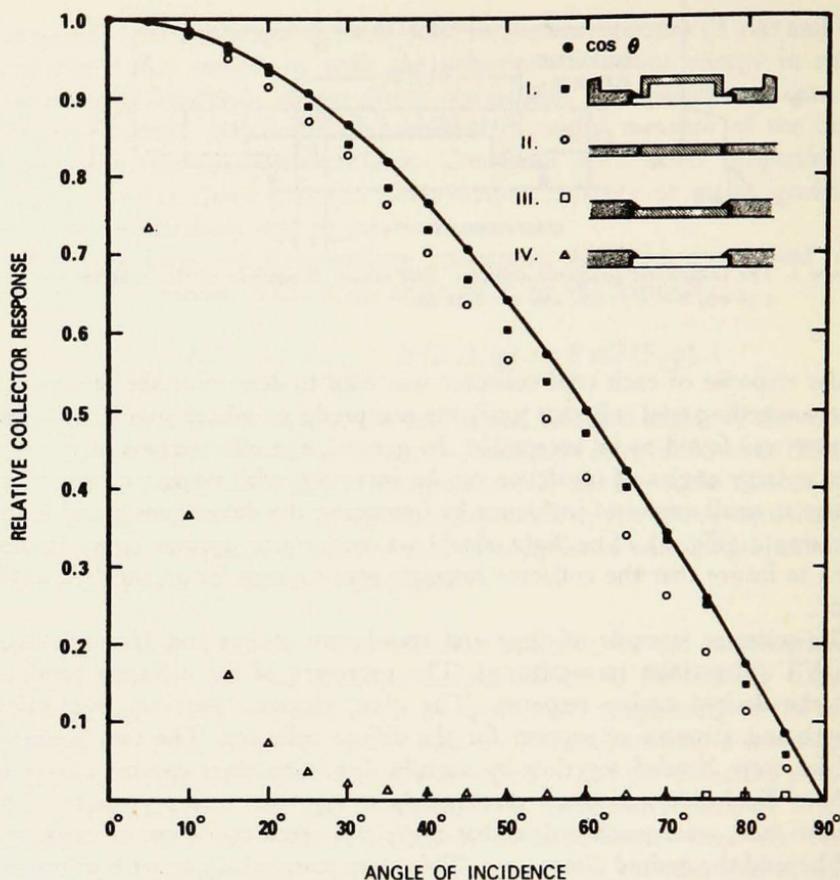


Figure 2. Relative collector response versus angle of incidence for various collectors described on p. 348. The solid curve is a plot of cosine θ versus θ ; i.e. the response of a perfect cosine collector. The data points are the relative measured responses of the collectors shown schematically in the figure and described in the text.

underwater irradiance collector normalized to 1.0 at 0° (perpendicular incidence). This angular response was measured by using a narrow band of wavelengths centered at $550 \text{ m}\mu$. Measured at other wavelengths, between $400 \text{ m}\mu$ and $700 \text{ m}\mu$, the angular response of the collector varied by only a few percent.

Immersion Effect. When a translucent diffusing material is submerged in water, thus changing the index of refraction at the boundary of the diffusing material, a larger percentage of the incident radiant flux is back-scattered into the water than into the air. This immersion effect results from changes in the interface reflections, both internal and external; in turn, these reflections change the optical pathlength within the diffusing material. By using some of

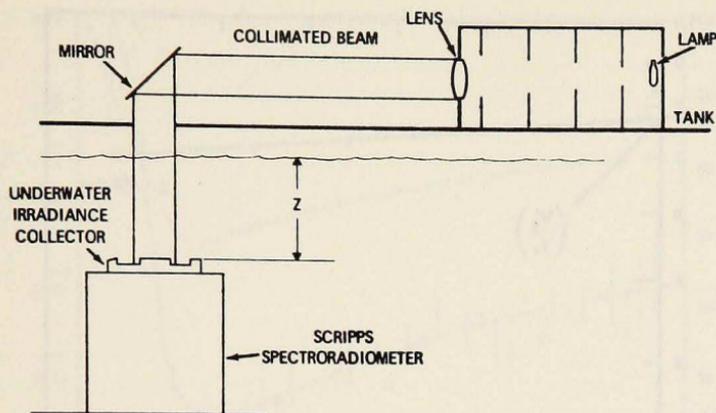


Figure 3. Experimental arrangement used to measure the spectral immersion effect correction.

Berger's (1961) results, Westlake (1965) has given a simplified illustration of the immersion effect. This effect must be considered whenever measurements above and below the water surface are compared.

Since the absolute spectral response of the irradiance collector on the Scripps Spectroradiometer was obtained in air, it was necessary to make a correction for the immersion effect in order to obtain absolute values of radiant energy underwater.

The immersion-effect correction for the underwater irradiance collector was experimentally measured in the following manner. A steady collimated beam of radiant energy was directed perpendicularly upon the collector through the flat calm air-water interface and through a depth (z) of water, as shown in Fig. 3. The degree of collimation was such that the presence in the optical path of two materials with varying thickness and different refractive index did not geometrically influence the amount of energy falling on the collector. The response of the spectroradiometer was recorded for numerous water depths and in the air. The response at each water depth, $v'_w(z)$, was divided by the response in air, V_A ; the results have been plotted in Fig. 4. Of course, some energy is attenuated in passing through the depth (z) of water; however, when the data are extrapolated to zero depth (i.e., as if the collector were immersed in water of zero attenuation) then the zero-depth response of the collector in water, V'_w , is less than the response of the collector in air, V_A .

Since we wish to transform the absolute calibration of the collector in air to an absolute calibration in the water, it is necessary to correct this water/air ratio (V'_w/V_A) for the energy loss at the air-water interface during these measurements. Reflection losses at the front surface of the collector do not enter into this correction. We are determining, first in air and then in water, the response of the instrument when 100 units of flux fall on the collector at perpendicular incidence. For the experimental arrangement shown in Fig. 3,

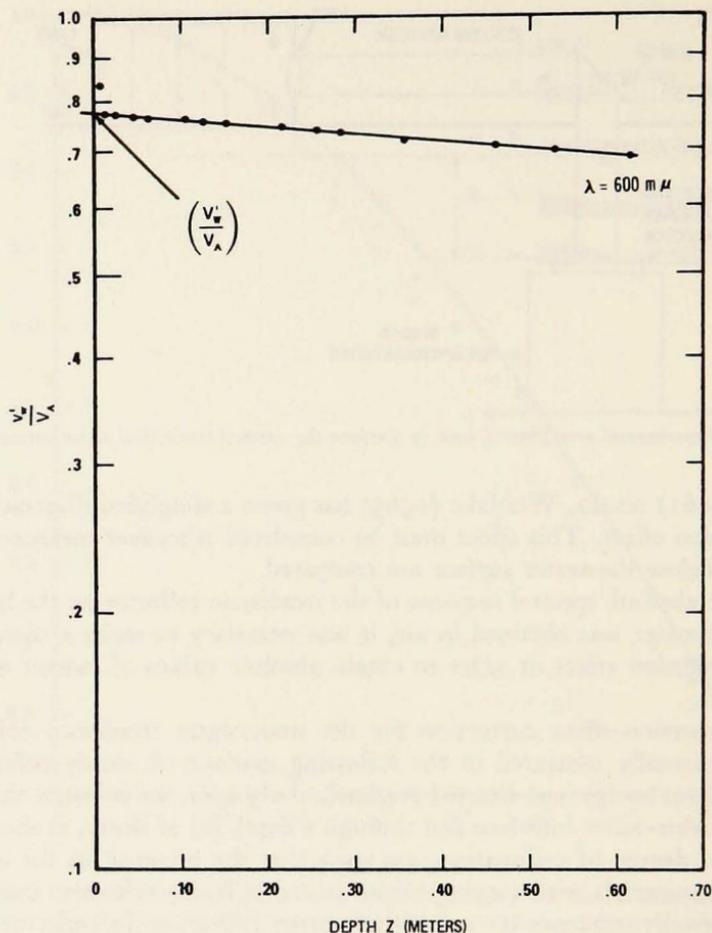


Figure 4. The response of the irradiance collector underwater divided by its response in air versus the depth of water above the collector's surface. The solid straight line is a least-square fit to the data (ignoring data taken at depths of less than a few collector diameters). V'_w/V_A is the zero depth intercept calculated from the least-squares fit.

this energy loss at the air-water interface is easily calculated by using the Fresnel equation. The correction of the underwater response for energy loss at the air-water interface is obtained by dividing the extrapolated zero-depth response in water, V'_w , by the calculated transmission, T , of the air-water interface. The ratio

$$\frac{V_w}{V_A} = \frac{V'_w}{T} \times \frac{1}{V_A}$$

gives the correct immersion-effect factor for the change in response of the collector under conditions of equal incident irradiance. Therefore, a response re-

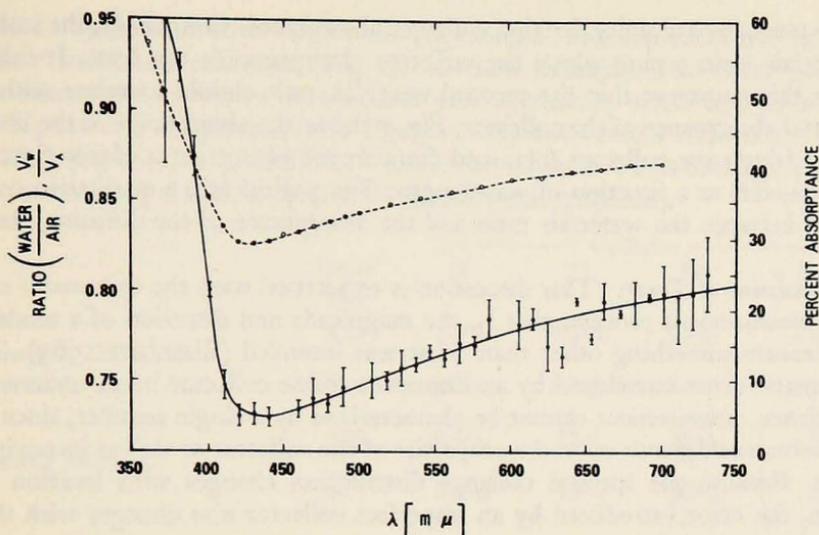


Figure 5. V'_w/V_A (solid curve) and collector absorbance (dashed curve) versus wavelength.

corded underwater can be multiplied by V_A/V_W to obtain an equivalent air response for which an absolute irradiance calibration exists.

The rapid rise in the water/air ratio, at depths small compared with the diameter of the collector, is due to energy that escaped from the collector, reflected from the air-water interface, and returned to the collector. Thus, the immersion-effect correction, V_W/V_A , is applicable only after the collector is submerged more than a few collector diameters.

Only one wavelength has been considered in the above discussion. It has been found experimentally that the water/air ratio is a function of wavelength (Fig. 5). The water/air ratio at each wavelength was determined by making a least-squares fit to the data, as shown in Fig. 4; the value of the intercept and the standard deviation of this intercept were then calculated. The data shown are the weighted averages of several intercept determinations at each wavelength.

A qualitative explanation of this wavelength dependence follows. The principal difference between the responses of the wet and dry collector is that the wet collector loses energy that in the dry collector is internally reflected back to the detector. In the case of a dry collector, more energy is reflected within the diffuser and more energy passes through the collector to the phototube, where it is detected. Thus the additional energy recorded with the dry collector is largely energy that has traversed a longer path through the collector—through internal reflection from the front surface and multiple scattering within the collector. Consequently, this additional energy is proportionally reduced as the absorbance of the collector is increased. Hence, the water/air

ratio tends toward unity for high collector absorptance. Conversely, the smallest water/air ratio occurs where the collector absorptance is the least. It follows from this argument that the spectral water/air ratio should correlate with the spectral absorptance of the collector. Fig. 5 shows the absorptance of the underwater irradiance collector (obtained from measurements in a Hardy Spectrophotometer) as a function of wavelength; Fig. 5 illustrates a qualitative correlation between the water/air ratio and the absorptance of the diffusing plastic.

Discussion of Error. This discussion is concerned with the systematic error of a measurement process; that is, the magnitude and direction of a tendency to measure something other than what was intended (Eisenhart 1963). The systematic error introduced by an imperfect cosine collector in an underwater irradiance measurement cannot be characterized by a single number, since the measurement depends upon the properties of the collector as well as its environment. Because the spectral radiance distribution changes with location and depth, the error introduced by an imperfect collector also changes with these variations.

The magnitude of the systematic error introduced by an imperfect cosine collector and the variability in this error are illustrated in Fig. 2, which shows the measured angular responses of four different collectors. I. The angular response of the irradiance collector shown in Fig. 1. II. The angular response of a flat piece of translucent plexiglas (of the same type as that used in Fig. 1) mounted so that its surface is not shadowed by any part of the instrument. III. The angular response of collector II, but with a 15° shadowing. IV. The angular response of a frosted quartz-glass window. II, III, and IV are typical of collectors described in the literature.

To realistically compare these collectors, I have calculated how accurately they would measure irradiance if they were placed in a natural radiance distribution. For this calculation, Tyler's (1960) data for radiance distributions on a clear sunny day were used. At 4.24 m the radiant energy was highly directional, with the incident angle of maximum radiance about 27° ; at 66.1 m the radiant energy was more diffuse, having approached an asymptotic distribution. For the lower hemisphere, the radiance distribution at both depths was diffuse in character, with maximum radiance values from the horizontal direction.

Using the measured angular responses of collectors I-IV in Fig. 2 and Tyler's radiance distribution data, the downwelling and upwelling irradiances were calculated. These "actual" values were compared with "perfect" irradiance values calculated from the same radiance data, assuming an exact cosine collector response. The results are presented in Table 1.

The errors for collectors I-III are shown as a percentage difference between the perfect and the actual irradiance values; in all three cases the actual values are less than the perfect values. For collector IV the numbers in Table I show

Table I. Systematic error due to the responses of four representative underwater irradiance collectors (Fig. 2). In these examples a collector having an exact cosine response would have zero systematic error. For collectors I, II, and III the percent error $[(\text{perfect response} - \text{actual response}) \times 100 / \text{perfect response}]$ is given. The "error" in collector IV is so large that it is presented as the ratio (perfect response/actual response).

	Depth (m)	Collector			
		I	II	III	IV
Downwelling irradiance	4.24	2.3%	5.3%	5.9%	$\times 16$
	66.1	2.8%	6.3%	7.4%	$\times 9$
Upwelling irradiance	4.24	6.4%	17%	32%	$\times 30$
	66.1	8.3%	19%	36%	$\times 35$

the perfect value divided by the actual value. Collectors I-III, intended to be cosine collectors, performed relatively well. Note that the error is larger for upwelling than for downwelling irradiance and that the error increases slightly with depth. In short, the systematic error increases as the radiance distribution becomes more diffuse. Collector IV, an extreme though not atypical example, obviously does not measure irradiance at all. Even for relative measurements, collector IV exhibits unacceptably large changes in the systematic error with depth and between the downwelling and upwelling measurements.

Values of irradiance measured as a function of depth are frequently used to calculate diffuse attenuation coefficients, reflection functions, or other optical properties of natural waters. Since the diffuse attenuation coefficient is a ratio of irradiance values, it is affected by only systematic errors that change with depth. On the other hand, the reflection function and other optical properties that are not obtained from ratios containing the same systematic error are affected in direct proportion to the size of the error in the irradiance measurement.

Total Irradiance Collector. The examples in Table I are concerned with only a narrow $5\text{-}\mu$ band of wavelengths. Energy in the interval between 350 and $700\ \mu$ has been taken (SCOR Working Group 15, 1965) as the total irradiance available for photosynthesis. Below depths of a few meters, this also is an acceptable interval over which to define total irradiance for most other purposes. Problems concerned with a collector's spectral response and the environmental spectral changes have already been discussed (Smith 1968). However, a relatively small, but previously unrecognized, spectral source of error deserves comment.

Fig. 5 shows that, if irradiance is to be measured accurately at various wavelengths, an immersion-effect correction must be made for each wavelength. Conversely, for an instrument designed to measure the total irradiance between 350 m μ and 700 m μ , the proper immersion-effect correction must depend upon the spectral properties of the water being measured. For example, if the collector in Fig. 1 were used as a total irradiance collector, the immersion-effect correction would be 24% near the surface of Jerlov's (1951) type I clear ocean water and 27% near the surface of his type 9 turbid coastal waters. The immersion-effect correction would remain about the same for deep coastal waters, but it would approach 33% for deep clear ocean waters. Thus we have the annoying fact that, for a total irradiance collector, the total immersion-effect correction can change with location and depth by an amount that is about half as large as the magnitude of the correction itself.

Discussion. The immersion-effect correction and the proper angular collecting response are of great importance for experiments concerned with measurements of energy loss at the air-water interface or with measurements of attenuation coefficients in the shallow layers of natural waters. For total irradiance instruments, the immersion effect and the rapid attenuation in water of all but a narrow band of wavelengths combine to give the appearance of an anomalously large attenuation in the first few meters. If not corrected, this should at least be recognized as an effect of the instrument and not as an inherent optical property of the water.

The immersion-effect correction will not affect diffuse attenuation coefficients measured in the deeper layers, and its neglect will have a diminishing affect with depth on relative measurements of irradiance. However, the immersion effect and cosine collecting response must be considered if absolute values of irradiance are to be measured at any depth (Tyler and Smith 1966).

The properties of a collector can be so poor that measurements become an indeterminable jumble of the collector's own properties interacting with a changing radiance distribution. Even relative measurements made with poor collectors will contain large variable and unknown systematic errors. Furthermore, if the response of the collector is unknown, or unpublished, it is impossible to reliably assign an estimate of systematic error to an underwater radiant energy measurement.

When underwater radiant energy measurements are reported, it is recommended that the angular collection and immersion-effect properties of the underwater collector be included so that the systematic error in the measurement can be reliably estimated.

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