In G. Eglinton and M. T. J. Murphy [eds.], Organic geochemistry. Springer.
NISHIZAWA, S. 1971*a*. Concentration of organic and inorganic material in the surface skin at the equator, 155°W. Bull. Plankton Soc. Jap. **18**(2): 42–44.
———. 1971*b*. Concentration of particulate and dissolved organic material at the sea surface skin [abstr.], p. 267–269. *In* M. Uda [ed.], The ocean world. Jap. Soc. Promotion Sci.
PARKER, P. L., C. VAN BAALEN, AND L. MAURER. 1967. Fatty acids in eleven species of blue-green algae: Geochemical significance. Science **155**: 707–708.
PIOTROWICZ, S. R., B. J. RAY, G. L. HOFFMAN, AND R. A. DUCE. 1972. Trace metal enrichment in the sea surface microlayer. J. Geophys. Res. **77**: 5243–5254.
RAYBAUD, H. 1972. Les biocides organochlorés et les détergents anioniques dans le milieu marin. Analyse et accumulation en surface. Ph.D. thesis, Univ. Marseille.
ROY, V. M., J. L. DUPUY, W. G., MCINTYRE, AND W. HARRISON. 1970. Abundance of marine phytoplankton in surface films: A method of sampling, p. 371–380. *In* W. G. Weist, Jr., and P. E. G. Reeson [eds.], Hydrobiology —bioresources of shallow water environments. Am. Water Resour. Assoc.
SEBA, D. B., AND E. F. CORCORAN. 1969. Surface slicks as concentrators of pesticides in the marine environment. Pesticides Monit. J. **3**: 190–193.
SHORLAND, F. B. 1963. The distribution of fatty acids in plant lipids, p. 253–311. *In* T. Swain [ed.], Chemical plant taxonomy. Academic.
STRICKLAND, J. D. H., AND T. R. PARSONS. 1972. A practical handbook of seawater analysis. Bull. Fish. Res. Bd. Can. 167, 2nd ed.
TAGUCHI, S., AND K. NAKAJIMA. 1971. Plankton and seston in the sea surface of three inlets of Japan. Bull. Plankton Soc. Jap. **18**(2): 20–36.
TSYBAN, A. V. 1971. Marine bacterioneuston. J. Oceanogr. Soc. Jap. **27**(2): 56–66.
WHEELER, J. R. 1972. Some effects of solar levels of ultra-violet radiation on lipids in artificial sea water. J. Geophys. Res. **77**: 5302–5306.
WILLIAMS, P. M. 1967. Sea-surface chemistry: Organic carbon and inorganic nitrogen and phosphorus in surface films and subsurface waters. Deep-Sea Res. **14**: 791–800.

Submitted: 3 March 1975
Accepted: 18 August 1975

The design and evaluation of a measurement system for photosynthetically active quantum scalar irradiance[1]

Abstract—An instrument system has been developed to measure photosynthetically active quantum scalar irradiance, the number of photosynthetically active photons arriving at a point from all directions. One instrument in the system is designed to measure vertical profiles in the ocean, one to monitor solar radiation for reference purposes, and one to measure quantum scalar irradiance in laboratory incubators. A method of evaluating the performance of light measuring instruments and estimating the errors in actual field use is described and applied to these instruments and also to instruments in common use.

Accurate measurement of the total radiation available for photosynthesis by randomly oriented organisms in an uncontrolled environment (like the ocean) is difficult: one reason for this is that most light measuring instruments have directional collecting properties that do not match the collecting properties of the organisms. Light measuring instruments with a restricted field of view, such as flat plate "cosine" irradiance collectors and radiant flux meters, will perform adequately if the radiance distribution of the environment is known; the total radiant flux available to an organism can then be calculated. This is seldom the case as this measurement and calculation are difficult.

A second reason that photosynthetic light measurement is difficult is that the spectral sensitivities of commonly used light measuring instruments do not relate to the radiant flux utilized by photosynthetic organisms. Tyler (1973*a*) has shown how the measurement of light in the ocean with a lux or foot-candle meter could cause errors of 600–700%

[1] This work was supported by Atomic Energy Commission contract AT(11-1) GEN 10, P.A. 20 and National Science Foundation grants GX39139/Holm-Hansen and GV-41705/Holm-Hansen. The Visibility Laboratory at Scripps provided use of calibration equipment.

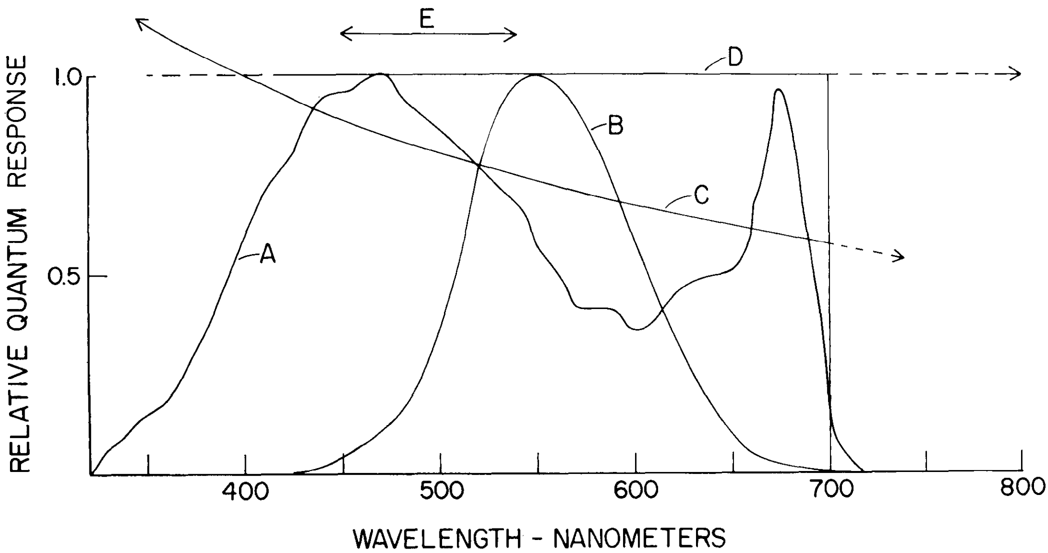

Fig. 1. Comparison of relative quantum responses: A—quantum levels necessary for constant O_2 production in a mixed phytoplankton culture (Haxo 1970); B—the photopic response of a foot-candle or lux meter; C—an equal energy response of an ideal radiometer (measuring watts); D—the ideal quantum response (quanta s^{-1}); E—the typical range of maximum quanta levels in the ocean at depths greater than 5 m.

in estimating the available quantum or energy levels. There is no widespread agreement on the exact spectral response that would most accurately measure photosynthetically useful light, but a measurement of either total energy (W cm^{-2}) or total quanta, between the wavelength limits of 350–400 and 700 nm, is generally accepted (Fig. 1).

The recent recommendation of SCOR Working Group 15 is that biologists should measure the total quanta available for photosynthesis within wavelength limits of 350–700 nm (Tyler 1974). The instruments described here are designed accordingly.

Pettersson (1938), Atkins and Poole (1940, 1958), and others have suggested that in measuring the total radiant flux available for photosynthesis, light from all directions should be measured. Scalar irradiance, the measurement of the total radiant flux arriving at a point from all directions, solves this problem. Tyler and Preisendorfer (1962) define it as follows:

$$h(p) = \int_{\theta=0}^{\pi} \int_{\phi=0}^{2\pi} N(p,\ \theta,\ \phi)\ \sin\theta\ d\theta\ d\phi, \quad (1)$$

where $h(p)$ is the scalar irradiance at point p and $N(p, \theta, \phi)$ is the field radiance at p from the direction indicated by (θ, ϕ) using spherical coordinates.

Several described instruments could measure scalar irradiance (e.g. Tyler 1955; Austin 1959; Maddux 1966; Rich and Wetzel 1969; Sasaki et al. 1966; Currie 1960). For various reasons the spectral responses of these devices are unsuitable for the measurement of light in photosynthetic research. Flat plate quantum irradiance collectors have also been built (Jerlov and Nygard 1969) but do not measure the total flux available for photosynthesis in the ocean. Smith and Wilson (1972) have proposed, but not yet built, a quantum scalar irradiance meter using fish-eye lenses.

The design and performance of a photosynthetically active quantum scalar irradiance measurement system for use in biological studies in both the laboratory and the ocean are described here. The instrument system is composed of three detecting devices capable of measuring quantum scalar irradiance: a handheld one designed

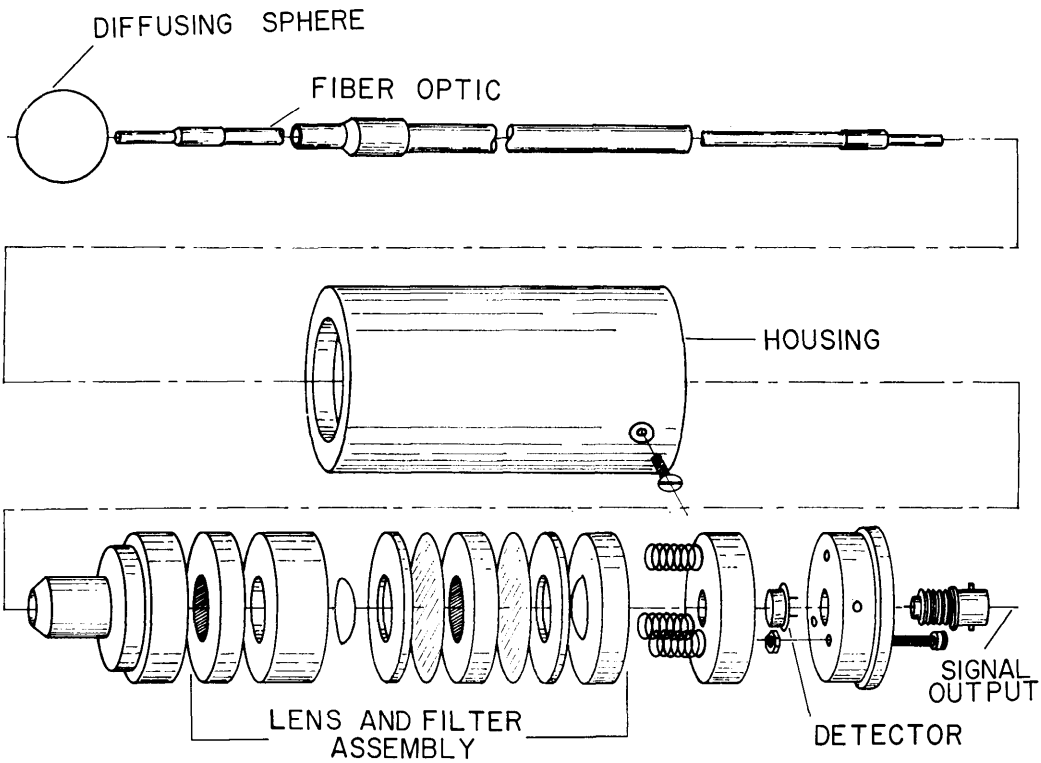

Fig. 2. The handheld, laboratory quantum scalar irradiance meter.

for measurements in laboratory incubators where photosynthetic experiments are carried out, one designed to measure the quantum scalar irradiance incident on the ocean surface or on incubators exposed to natural light, and one capable of measuring the quantum scalar irradiance at various depths in the ocean.

The laboratory quantum scalar irradiance meter (Fig. 2) is composed of a 2.5-cm-diameter solid sphere machined from Teflon, which serves as a spherical collector and diffuser, and a fiber optic bundle inserted toward the center of the sphere. The fiber optic bundle (ULGM-2-12, American Optical Co.) position is adjusted to give the best approximation of a true scalar response. This fiber optic collects light after multiple scattering inside the sphere and guides it to the detector and filter system where the light is roughly collimated by a positive lens of short focal length for passage through the filters. The filters include a Corning 1-62 blue filter, a heat absorbing glass filter, a thin film hot mirror, and Kodak color-compensating filters used as needed to correct the spectral responses; the exact combination is determined after measuring the spectral response of the combination of sphere, fiber optics, lenses, IR filters, and detector. The components mentioned have lot-to-lot variations, so no set combination can be given that would consistently approximate a quantum response (*see Fig. 6*).

The photodiode (UV-100, E.G. & G) generates a current (10^{-7} to 10^{-12} A) in proportion to the incident radiation. This current is amplified by a current to voltage converter mode FET type operational amplifier such as a Burr-Brown 3523. The resulting voltage is displayed on a meter in conjunction with appropriate scaling circuitry.

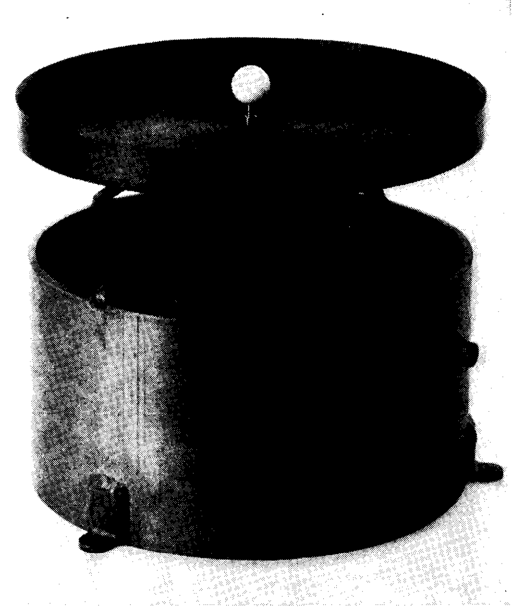

Fig. 3. The solar reference quantum scalar irradiance meter.

This design, with the receptor sphere separated from the filter and detector assembly by the fiber optic, minimizes perturbation of the light field being measured.

The second component of the system is a reference cell (Fig. 3) designed to measure the quantum flux arriving at the sea surface. It consists of a solid Teflon ball 1.9 cm in diameter mounted above a 25.4-cm-diameter flat nonreflective plate with a ring protruding from the edge of the plate. The position of the ball is adjusted so that the directional response function closely approximates a hemispherical response (Fig. 4). A solid quartz light-conducting rod receives the diffused light from the center of the Teflon ball and conducts it into the housing, containing a series of lenses and filters and a silicon photodiode similar to those in Fig. 2. A current-to-voltage amplifier in this housing allows transmission of a high level voltage signal to the main electronics housing. The entire assembly is mounted in gimbals to maintain the cutoff plate parallel to the horizon.

The voltage signal from the solar reference quantum meter is sent to the signal processing unit, where the signal is digitally displayed in quanta s^{-1} cm^{-2} and is also fed to an electronic integrator which integrates the voltage over time. This value may be digitally displayed as quanta cm^{-2} for the time the integration is performed (such as all day). The quantum flux can be recorded on a strip chart recorder. The inte-

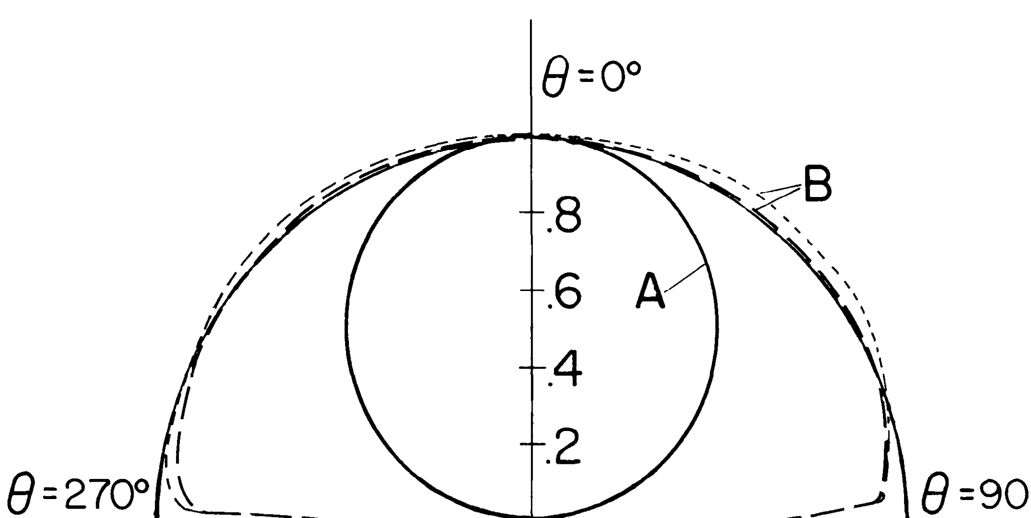

Fig. 4. Angular response of the reference (hemispherical) quantum scalar irradiance meter. A—Flat plate (cosine) collector; B—dashed lines show limits for all ϕ angles.

grated quantum values from the solar reference cell are useful in estimating the integrated quanta available underwater (by comparison with underwater profiles obtained at specific times with the underwater sensor) and in incubators exposed to the sun (by comparison with measurements with the hand-held sensor).

The third component of the system is the underwater quantum scalar irradiance meter (Fig. 5). This instrument uses two partially shaded solid 1.9-cm Teflon diffusing spheres, horizontally separated by 40 cm, with cylindrical shields placed around their midsection so that the two spheres in combination present a spherical surface of $4 \pi r^2$ to the surrounding light field.

There are several advantages to this arrangement of the two spheres. If a horizontally stratified light field is assumed (an acceptable assumption in this case), the separation of the diffusing spheres allows the instrument package to be as large as necessary without optical compromise. A further advantage is that displacement from the normal horizontal orientation of the housing due to rough water causes no error greater than that caused by the vertical displacement of the balls from their normal horizontal position. This possible error (vertical displacement <40 cm) would not generally be noticeable with this instrument in the ocean. Thus no complicated and awkward bridle or weights are needed in normal use.

A bifurcated fiber optic bundle is used to sum the light collected by the two spheres and transmit it to a single filter-detector assembly (similar to that of the handheld detector: Fig. 2). The silicon diode detector that receives the light is used in conjunction with a logarithmic amplifier which provides 4–5 decades of signal compression for transmission to the surface. Signals from pressure and temperature transducers in the underwater housing are also transmitted to the surface by a multiconductor cable to the electronic signal processing unit where they are converted for direct digital display in meters (depth)

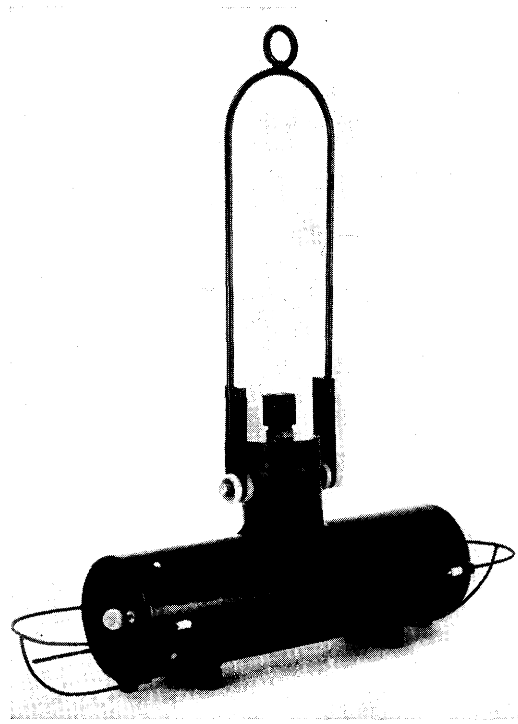

Fig. 5. The underwater quantum scalar irradiance meter showing the Teflon ball detectors and guards.

and degrees. These signals are also available for X-Y recorder display.

The logarithmic form of the signal from the underwater housing is retained in the output to facilitate display and recording without scale changes. This output O_s is defined as

$$O_s = \log h_{ss} - \log h_s, \qquad (2)$$

where h_{ss} is the maximum scalar irradiance within the linear range of the detector and h_s is the measured submarine scalar irradiance. A change of 1.0 in O_s represents a decade change in h_s. This output is also available for X-Y recorder display and digital display at the signal processing unit.

The output from the solar reference quantum meter is logarithmically amplified at the signal processing unit. This signal O_r is

$$O_r = \log h_{rs} - \log h_r, \qquad (3)$$

where h_{rs} is the maximum allowable scalar irradiance for the reference cell and h_r is the measured surface scalar irradiance. These signals are combined and a new output R is generated such that (from Eq. 2, 3)

$$R = O_s - O_r - c = \log\ (C_n \frac{h_r}{h_s}), \qquad (4)$$

where C_n is adjusted by a control on the signal processing unit so that $R = 0$ just below the surface. R thus becomes a direct readout of light penetration in the ocean, in optical density units, as the instrument is lowered. This signal too is available for X-Y recorder display and digital readout.

On clear or uniformly illuminated days, when the ambient lighting conditions are constant for the 3–5 min necessary for a typical 50-m vertical profile in the ocean, the value of O_s can be plotted on an X-Y recorder. The scalar irradiance h_s can then be calculated using the value of h_{ss} determined by calibration and Eq. 2. When weather conditions (such as cloudy or partially cloudy days) make it both impractical and undesirable to directly record O_s, it is best to use the signal processing described by Eq. 4, plot the log-ratio of the underwater and surface irradiances, and then compute the diffuse attenuation coefficient for that water mass under the prevailing lighting conditions. Approximate underwater irradiance levels can then be calculated by comparison with the light levels recorded by the reference detector and integrator. These results are subject to the variability in light penetration of the air–water interface and the diffuse attenuation coefficient due to varying spatial distributions of the above surface light field caused by changes in sun angle, clouds, etc.

The relative spectral responses of the instruments were determined with a Cary 14 spectrophotometer as a monochromatic light source and an optical chopper to direct the light to the instrument under test or to a thermopile. The output of each sensor was fed to a lockin amplifier and the ratio of the outputs of these amplifiers was recorded versus wavelength. Response was measured over the range of silicon diode sensitivity (350–1,200 nm), the thermopile and the device under test reversed in position, and the ratio of the responses was measured again. The average of these two ratios was then used to compute the quantum response.

The directional response of each instrument was measured by rotating the instrument in a collimated beam of white light and recording the response versus angle on a X-Y recorder. The underwater instrument was rotated, submerged in a tank, about an axis through the Teflon ball and perpendicular to the axis of the fiber optic probe. Each end was separately calibrated in this manner and the response of the complete instrument was calculated.

Linearity of the detectors and associated electronics was measured by exposing the detectors to a low level 100-Hz modulated light field, produced by a light-emitting diode driven by a sine wave, on which a light field generated by a tungsten lamp powered by a highly regulated constant voltage power supply was superimposed. The AC component of the resulting output from the detector was tracked with an AC voltmeter. The DC component of the signal from the tungsten lamp was varied by neutral density filters in front of the tungsten lamp but not in the path of the LED. The maximum range of DC signal from the detector that would not result in a change of the magnitude in the 100-Hz AC signal was then the range of linearity. Typically 3.5–4 decades could be covered with better than 2% linearity.

Absolute calibration of each unit was done on an optical bench using a standard of spectral and absolute irradiance. The quantum output from this 200-W tungsten-halogen lamp was calculated from the spectroradiometric data supplied with it (Optronic Labs). Each end of the underwater unit was separately calibrated by placing the instrument in a water tank with a glass window at one end. This tank was mounted

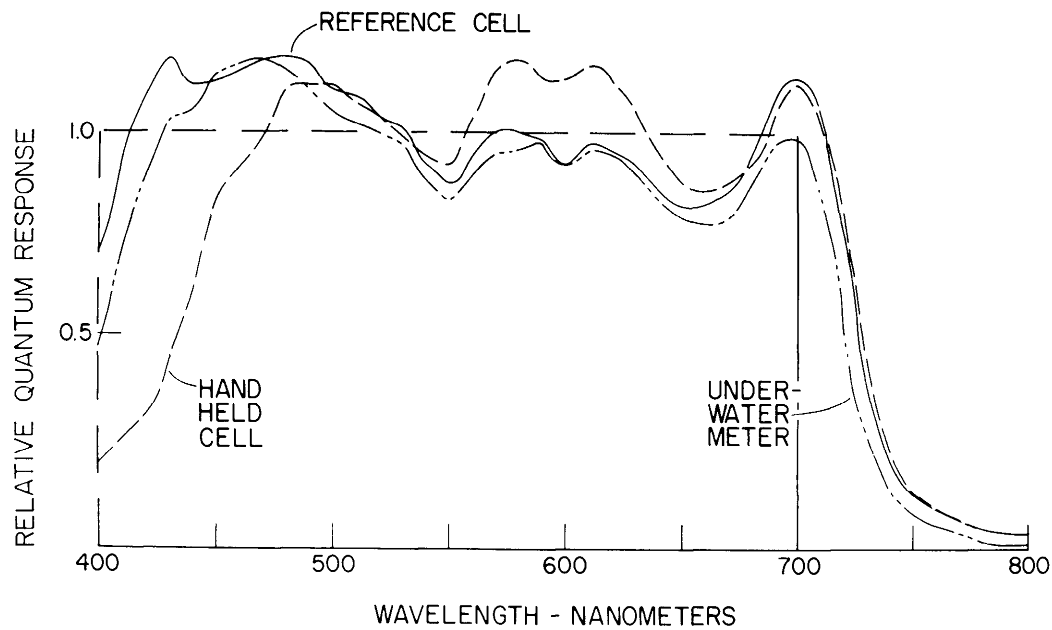

Fig. 6. Typical spectral response functions for the three quantum scalar irradiance meters.

on the optical bench at the prescribed distance. The spectral transmission of the glass window water path and the reflection at the glass–air interface were taken into consideration in computing the irradiance at the underwater sensor.

In the above discussion I have assumed that the instrument actually measured photosynthetically active quantum scalar irradiance, but the instrument only approximates this. Its spectral response is not perfect (Fig. 6), and the directional response is not perfectly scalar. To help judge the errors introduced by these imperfections, let us restate the defining equation for scalar irradiance (Eq. 1) in terms of photosynthetically active quantum scalar irradiance:

$$h_q(p) = \int_{\lambda=400}^{700} \int_{\equiv} N(p, \lambda, \xi)\ (\lambda/hc)\ d\lambda\ d\xi, \quad (5)$$

where N is the field radiance at point p, of wavelength λ, from the direction specified by the inward normal solid angle ξ. The integration is performed over the desired spectral range and over the entire sphere ($\equiv$).

Using Eq. 5 we can describe the output of a real, imperfect quantum scalar irradiance meter:

$$h_q(p)' = C \int_{\lambda=400}^{700} \int_{\equiv} N(p, \lambda, \xi)\ R(\lambda)\ R(\xi)\ d\lambda\ d\xi, \quad (6)$$

where $R(\xi)$ is the directional response function and $R(\lambda)$ is the spectral response function. C is a calibration constant. If $R(\xi) = 1.0$ for all ξ and $R(\lambda) = \lambda/hc$ for all λ, 400 to 700 nm and $R(\lambda) = 0$ for all other λ, then

$$h_q(p) = h_q(p)',$$

and the instrument would be a perfect quantum scalar irradiance meter. No quantum scalar irradiance meter available or likely to be available has these ideal qualities. It is therefore necessary to evaluate these response functions and then the total error that these imperfect functions would contribute in actual use.

First let us consider the spectral response

Table 1. Spectral response error analysis. Normalized values of R_s from Eq. 7 for ten sources and three detectors.

Detector	Source* 1	2	3	4	5	6	7	8	9	10
A. Underwater quantum meter	1.012	0.982	0.918	1.041	1.024	1.018	0.996	1.008	1.024	1.048
B. Lux or footcandle meter	0.996	1.19	2.19	0.57	0.63	0.83	1.12	1.07	1.00	1.01
C. Microwatt (energy) meter	1.14	1.104	0.965	1.18	1.183	1.165	1.133	0.984	1.00	0.932

* 1. Islas Tres Marias, "clear blue tropical water," (25.0 m), 20°21'N, 106°22'W (Tyler and Smith 1970).
2. Same (5.0 m).
3. San Vincente Reservoir (a eutrophic lake) (10.0 m) (Tyler and Smith 1970).
4. Caribbean (13°10'N, 78°58'W) (81.2 m) (Tyler 1973b).
5. Caribbean (13°10'N, 78°58'W) (54.9 m) (Tyler 1973b).
6. Caribbean (13°10'N, 78°58'W) (29.2 m) (Tyler 1973b).
7. Caribbean (13°10'N, 78°58'W) (9.9 m) (Tyler 1973b).
8. Sun and sky light, noon, sea level (Wyszecki and Stiles 1967).
9. Equal energy at all wavelengths.
10. 3,300°K Blackbody radiation (calculated, similar to standard lamp).

function $R(\lambda)$. The most useful evaluation of the spectral performance of the different filter combinations was made using a computer program that took the spectral distributions of light sources that might be encountered in the use of the various instruments and compared these to the spectral response data from the quantum scalar irradiance meters. The computer calculated a spectral response error value R_s:

$$R_s = C \frac{\sum_{\lambda=250}^{1,200} R(\lambda)\ N(\lambda)\ (hc/\lambda)}{\sum_{\lambda=400}^{700} N(\lambda)\ (hc/\lambda)}, \quad (7)$$

where C is a normalization constant for each instrument, and $N(\lambda)$ is the spectral irradiance from the source being considered. This ratio can be calculated for many different possible spectral distributions, and the probable errors in using the detector can be estimated by comparing R_s for the various sources. Table 1 presents some typical values calculated for the underwater quantum scalar irradiance meter.

The measured directional response function $R(\xi)$ of the instruments was then numerically evaluated for error in different radiance distributions similar to those likely to be encountered. The measured response data in the form $R(\theta, \phi)$ was weighted according to a construct that was a spherical solid over which a grid was laid, dividing the sphere into segments, corresponding to the θ, ϕ angles of the response function data, which were given weights according to their areas—"$\Delta\Omega$." These weights were calculated as follows:

$$\Delta\Omega = \frac{3}{8} \sin\left(\frac{\Delta\theta}{4}\right) \Delta\theta\ \Delta\phi,$$

for $\theta = 0, 180°$;

$$\Delta\Omega = \left[\sin\ \Delta\theta + \frac{\sin(\Delta\theta/4)}{8}\right] \Delta\theta\ \Delta\phi,$$

for $\theta = \Delta\theta,\ 180° - \Delta\theta$;

$$\Delta\Omega = \left[\cos\ \Delta\theta + \frac{\cos(\Delta\theta/4)}{8}\right] \Delta\theta\ \Delta\phi,$$

for $\theta = 90° \pm \Delta\theta$;

$$\Delta\Omega = \frac{3}{4} \cos\left(\frac{\Delta\theta}{4}\right)\ \Delta\theta\ \Delta\phi,$$

Table 2. Integrated directional response function R_t (Eq. 8). Calculations for different spatial radiance distributions measured at Lake Pend Oreille, Idaho. The detector was the underwater quantum scalar irradiance meter whose measured response function is shown in Fig. 7.

$N(\theta, \phi)$	R_t
Clear skies, 4.24, sun elevation 56.6°	1.014 ± 0.061*
Clear skies, 66.1, sun elevation 56.6°	1.0207 ± 0.0044
Overcast sky, 6.1, sun elevation 40.0°	1.0231 ± 0.0041
Overcast sky, 55.0, sun elevation 40.0°	1.0204 ± 0.0023
Totally diffuse light field	1.0000

* 95% confidence limits (normalized) calculated from mathematically rotating the instrument about the vertical axis to simulate the rotation about the instrument cable.

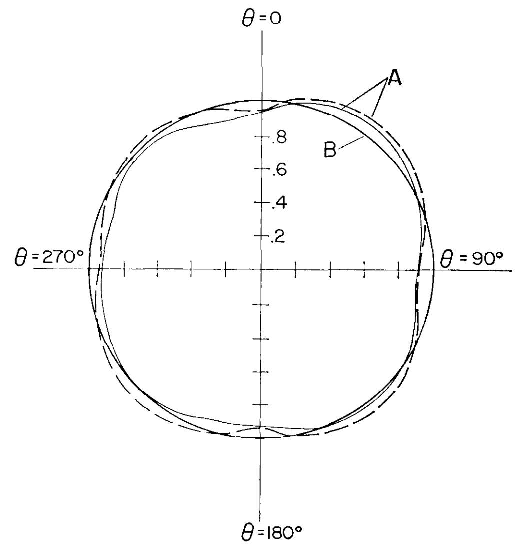

Fig. 7. The directional response function for the underwater quantum scalar irradiance meter showing representative variations (A) with incident angle (θ) compared to (B) the ideal response.

for $\theta = 90°$;

$$\Delta\Omega = \sin\theta\ \Delta\theta\ \Delta\phi,$$

for all other θ (developed from Tyler et al. 1959). θ and ϕ are the angular increments. All of the resulting segments are spherical rectangles except the first series ($\theta = 0°$, $180°$) which are segments of the spherical caps, extending from $\theta = \theta/2$ to $\theta = 0$ at the top and from $\theta = 180° - \Delta\theta$ to $\theta = 180°$ at the base and of width $\Delta\phi$.

To determine the response of the instrument to different radiance distributions we calculate the overall response term R_t as follows:

$$R_t = C_d \frac{\sum_{\theta=0}^{180} \sum_{\phi=0}^{360} N(\theta, \phi)\ \Delta\Omega\ (\theta, \phi)\ R(\theta, \phi)}{\sum_{\theta=0}^{180} \sum_{\phi=0}^{360} N(\theta, \phi)\ \Delta\Omega\ (\theta, \phi)}. \quad (8)$$

The constant C_d, the normalization factor for the response function $R(\xi)$, is selected so that $R_t = 1.0$ in the case of the totally diffuse light field where all $N(\theta, \phi)$ are equal.

The constant C_d is incorporated into factor C in Eq. 3, as the instrument is calibrated for response in a diffuse light field.

Table 2 shows values of R_t from the directional response of the underwater quantum scalar irradiance meter. The data are measurements by Tyler (1960) from Lake Pend Oreille, Idaho. The response function $R(\xi)$ for the scalar irradiance meter had to be incremented in values of ϕ to simulate random rotation of the instrument underwater because the angular response of the underwater instrument was not inherently symmetrical about the vertical axis (Fig. 7).

Evaluation of the spatial response function $R(\xi)$ and calculation of R_t (Eq. 8) for representative radiance distributions (Table 2) indicate that the imperfections in the directional response of the underwater instrument are not serious. The spectral response (Fig. 6) of the underwater quantum meter was evaluated (Table 1). Departures from the ideal response are larger than I would desire, but the calculated effects (R_s) do not greatly increase the uncertainty of the measurements. These deficiencies could be reduced further by improved filter design.

The effects of the variations in R_s for a given quantum meter due to the inherently imperfect spectral filtering can be reduced by using slightly different calibration factors (or "fudge factors") for the major types of light fields (incandescent, fluorescent, solar, underwater) where one might use the instrument.

Analysis of the responses of a "cosine" detector (*see Fig. 4*) to a point source at normal incidence would give a value of $R_t = 1.0$, but the response of such an instrument to a totally diffuse light field would be $R_t = 0.25$. Values for an ideal scalar detector would by definition be $R_t = 1.00$ in all cases. Submarine light fields would typically give R_t values from 0.65 to 0.85 for a cosine collector. Measurements taken with cosine collectors in laboratory incubators can vary over a much greater range.

If we accept the premise that typical marine photosynthetic organisms more closely resemble scalar collectors than flat plate collectors, we can readily see the dangers inherent in measuring light fields with cosine collectors and directly applying these measurements to photosynthetic studies. The errors associated with using spectrally and spatially misdefined instruments can approach or exceed an order of magnitude when the photosynthetic efficiencies of different light fields are compared. The value of a quantum scalar irradiance measurement system is obvious.

There has been some discussion of whether quantum or energy spectral response should be used in biological light measurement. I believe that the quantum response is generally best for measuring photosynthetically active radiation. However, the design of these instruments permits alteration of the spectral response by a change of filters so that energy response could be substituted for quantum response for particular applications.

I wish to thank J. E. Tyler and O. Holm-Hansen for their help and encouragement and C. R. Stearns for his help in the mechanical design.

Charles R. Booth

Institute of Marine Resources
Scripps Institution of Oceanography
La Jolla, California 92093

References

ATKINS, W. R. G., AND H. H. POOLE. 1940. A cubical photometer for studying the angular distribution of submarine daylight. J. Mar. Biol. Assoc. U.K. **24**: 271–280.

———, AND ———. 1958. Cube photometer measurements of the angular distribution of submarine daylight and the total submarine illumination. J. Cons., Cons. Int. Explor. Mer **23**: 327–330.

AUSTIN, R. W. 1959. Water clarity meter, operating and maintenance instructions. Scripps Inst. Oceanogr. Ref. 59-9.

CURRIE, R. I. 1960. Solar irradiance as a parameter in phytoplankton photosynthesis and a proposed method for its measurement, p. 107–112. *In* Radiant energy in the sea. Proc. Symp., Int. Assoc. Phys. Oceanogr., Helsinki.

HAXO, F. I. 1970. Photosynthetic action spectra of marine phytoplankton. Scripps Inst. Oceanogr. Ref. 70-12.

JERLOV, N. G., AND K. NYGARD. 1969. A quanta and energy meter for photosynthetic studies. Univ. Copenhagen Inst. Phys. Oceanogr. Rep. 10. 19 p.

MADDUX, W. S. 1966. A 4π light meter. Limnol. Oceanogr. **11**: 136–137.

PETTERSSON, H. 1938. Measurements of the angular distribution of submarine light. Rapp. P.-V. Reun. Cons. Int. Explor. Mer **108**: 9–12.

RICH, P. H., AND R. G. WETZEL. 1969. A simple, sensitive underwater photometer. Limnol. Oceanogr. **14**: 611–613.

SASAKI, T., G. OSHIBA, AND M. KISHINO. 1966. A 4π underwater photometer. J. Oceanogr. Soc. Jap. **22**: 1–6.

SMITH, R. C., AND W. H. WILSON. 1972. Photon scalar irradiance. Appl. Optics **11**: 934–938.

TYLER, J. E. 1955. Measurement of light in the sea. J. Opt. Soc. Am. **45**: 904(A).

———. 1960. Radiance distribution as a function of depth in an underwater environment. Bull. Scripps Inst. Oceanogr. **7**: 363–412.

———. 1973*a*. Lux vs. quanta. Limnol. Oceanogr. **18**: 810.

——— [Ed.]. 1973*b*. Measurements of photosynthesis, available radiant flux and supporting oceanographic data. SCOR Discoverer Expedition, May 1970. Scripps Inst. Oceanogr. Data Rep. Ref. 73-16.

———. 1974. SCOR Working Group 15 recommendations. Int. Counc. Sci. Unions, Proc. Sci. Comm. Oceanic Res. **10**: 37–42.
———, AND R. W. PREISENDORFER. 1962. Light in the sea, p. 397–451. *In* M. N. Hill [ed.], The sea, v. 1. Interscience.
———, W. H. RICHARDSON, AND R. W. HOLMES. 1959. Method for obtaining the optical properties of large bodies of water. J. Geophys. Res. **64**: 667–673.
———, AND R. C. SMITH. 1970. Measurements of spectral irradiance underwater. Gordon and Breach.
WYSZECKI, G., AND W. STILES. 1967. Color science, concepts and methods, quantitative data and formulae. Wiley.

Submitted: 8 April 1975
Accepted: 20 October 1975

A new, simple method for gently collecting planktonic protozoa[1]

Abstract—An easy and gentle method for collecting planktonic protozoa is described: a 1-liter polyethylene bag attached to a stainless steel, spring-hinged sampling device is operated from a standard heavy-duty fishing rod and reel. The sampler has been used successfully at depths from 1 to 300 m in ocean and in coastal waters. Acantharia and Foraminifera collected by this technique appear in excellent physical condition.

Zooplankton have been notoriously difficult to capture in good condition for culturing, using conventional methods (Tranter and Smith 1968; Fraser 1968; Gehringer and Aron 1968). The Sarcodina are no exception. For the past several years we have attempted to culture planktonic Acantharia, Radiolaria, and Foraminifera from samples collected in standard plankton nets at sea. We were able to maintain some Foraminifera, but the Acantharia and Radiolaria perished. It was not possible to determine if our failures were due to the collecting method or the culturing method, but because of the delicacy of the Acantharia we suspected the former and addressed ourselves to methods of collection.

It seemed logical that plankton would be captured in the best condition if they had minimal contact with the collecting gear or with other plankters. Underwater jar sampling (Hammer 1974) is a good alternative to netting. In this method the collector, by skin or SCUBA diving, locates individual specimens and gently urges them into collection jars. Foraminifera were successfully captured by this method and we hoped to be successful in collecting Acantharia. We tried many times in Rhode Island and Vineyard Sounds but the waters were so turbid with silt and phytoplankton during summer that it was impossible to distinguish our specimens from other plankters. We compared visual to blind or random sampling from the same area and found the numbers of Acantharia per sample were similar, indicating that we were not, in fact, visually identifying our organisms. Although diving yielded specimens in good condition, it was dependent on tide, wind, and weather and demanded a sizable collecting party; since no advantage over blind sampling was apparent, the added risk was unwarranted.

We next tried to take 1-liter samples from depths of 0.5 to 6 m using a 6-m pole sampler with a mechanism on the pole which opened and closed a plastic bag; this worked but had limited sampling depth and was cumbersome to use, store, and transport. We then incorporated the basic principle, that of opening and closing a 1-liter plastic bag at depth, into a more versatile sampler.

This sampler permits one to lower at the end of a fishing line, a folded, 1-liter polyethylene bag which can be opened at depth by a sharp upward jerk on the line. A small weight in the bag causes the bag to unroll while a spring hinge opens the mouth allowing the bag to fill with water. The bag mouth is closed initially as retrieval

[1] This work was supported by the Sarah Scaife Foundation and by U.S. Energy Research and Development Administration contract E(11-1)-3563. Contribution 3645 from the Woods Hole Oceanographic Institution.