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INVESTIGATION OF ERRORS IN THE MEASUREMENT OF RADIANT ENERGY FOR CORRELATION WITH PRIMARY PRODUCTIVITY

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INVESTIGATION OF ERRORS IN THE MEASUREMENT OF RADIANT ENERGY FOR CORRELATION WITH PRIMARY PRODUCTIVITY.

J. E. TYLER

INTRODUCTION

Biologists who are interested in the primary productivity of the ocean are often unable to make productivity determinations by the ''in situ'' technique because of the demands of other groups on the ship's time. Under these conditions it has been the practice to use a substitute technique called the ''deck incubator'' technique, in which the sample of plankton-bearing ocean water is transferred to a deck incubator and allowed to propagate for an appropriate length of time before determining the ^{14}C uptake.

From a radiometric point of view these two techniques differ to a considerable degree. In the ''in situ'' technique the plankton-bearing ocean water is returned to its original depth location where propagation takes place at normal radiant energy levels and with normal spectral and geometric distribution of the radiant energy. In the ''deck incubator'' technique the radiant energy level available is usually much too high and must be controlled, the spectral distribution and band width are abnormally different and the geometrical distribution of the radiant energy has no similarity whatsoever with the natural geometrical distribution underwater.

Experimental results for any individual case are still further confused by the fact that the measured radiant energy must be sensed by a detector, usually of the photovoltaic type, having spectral and directional sensitivity properties unrelated in any way to those of the phytoplankton which are being studied, and magnitude response which is often arbitrarily nonlinear.

These problems have been recognized to some extent by various workers engaged in primary productivity work and effective measures have generally been taken to control the magnitude of the radiant energy in deck incubator determinations. However, not enough has been done to control its spectral distribution, and very little, if anything, has been done to control the geometrical distribution of the radiant energy or to design a suitable photodetector or to design an appropriate deck incubator.

Perhaps the most curious effort, in connection with the control of the spectral sensitivity of the photocell-filter combination, has been the deliberate selection of photodetectors which measure ''lumens'', and the general adoption of ''lumens'' as a radiometric unit for productivity work. The ''Lumen'' is, of course, a unit which was specifically orginated for radiant energy measurements relating only to human vision at the levels of photopic response. Its use in connection with photosynthesis is meaningless and is so recognized by many biologists who nevertheless continue to measure and publish in ''lumen'' units.

From the point of view of international cooperation, the communication of results is exceedingly difficult. Not only do we have measurements of radiant energy which are meaningless for correlation with productivity, but every laboratory seems to have a somewhat different type of meaningless measurement.

WORKING GROUP 15

The problems outlined above have been recognized by International Oceanographic Organizations and in 1964 a working group was convened by UNESCO, SCOR, and IAPO, called Working Group 15 – *Photosynthetic Radiation in the Sea,* for the purpose of determining the correct radiometric measurement for correlation with primary productivity determinations.

Working Group 15 had its first meeting in 1964. At this meeting it was agreed that future radiant energy measurements should be in energy units, e.g. watts per unit area, (rather than in lumens-per unit area) and that the "total available energy" (or the "total available photons") within the wavelength limits 350 to 700 nm should be measured.

One of the tasks assigned by the working group to individual members was the task of searching for instrument components that could be used both in air and in water to measure total energy between 350 and 700 nm and of calculating the errors to be expected from various combinations of components.

This work, together with its application to a deck incubator has been carried out under ONR contract number N00014-66-C0107-A02 and is reported herein.

CALCULATIONS

Having adopted the more or less arbitrary position that "total available energy in the wavelength region 350 to 700" should be the measured quantity, W.G. 15 decided that an effort should be made to determine if a photodetector-filter combination existed for the purpose and what magnitude of errors could be expected from its use – that is, how much of the desired energy would the detector fail to measure and to what extent would the detector measure energy outside the desired wavelength region.

To obtain these results it is necessary to perform calculations of the type

$$\sum_{\lambda_1}^{\lambda_2} H(\lambda)\Delta\lambda = H_T \tag{1}$$

$$\sum_{\lambda_1}^{\lambda_2} S(\lambda)F(\lambda)H(\lambda)\Delta\lambda = R_T \tag{2}$$

$$S\sum_{\lambda_1}^{\lambda_2} F_O(\lambda)H(\lambda)\Delta\lambda = R_T \tag{3}$$

Equation (1) is used to calculate the total irradiance, H_T when the spectral distribution of the irradiance, $H(\lambda)$ is known.

Equation (2) is used to calculate the relative response of a photodetector having spectral sensitivity $S(\lambda)$, to irradiance ($H(\lambda)$) which has passed through a specific filter having spectral transmittance $F(\lambda)$.

Equation (3) is used to calculate the relative response of a photodetector whose spectral sensitivity S is invariant with wavelength to irradiance, $H(\lambda)$, which has passed through a filter having ideal spectral transmittance $F_0(\lambda)$. The wavelength limits (λ_1 and λ_2) for each computation are chosen with respect to the photosynthetically important radiation.

SOURCE OF DATA

The computations illustrated by equations 1, 2, and 3 require the following data:

- $S(\lambda)$ The relative (or absolute) spectral sensitivity of selected photodetectors.
- $F(\lambda)$ The spectral transmittance of selected optical filters.
- $H(\lambda)$ The spectral irradiance of the radiant energy impinging on the irradiance-collecting element of the photometer or thermopile.

In all cases the data needs to cover a wavelength range greater than the photosynthetically active band in order to estimate the errors due to the inclusion of spurious flux.

Data for the spectral sensitivity of photodetectors was obtained from manufacturers specifications. In general these are average values and are well suited for this kind of calculation. However, the spectral range covered is usually limited. Manufacturer's specifications have therefore been extrapolated to 10^{-5} and have been listed as ''zero'' at sensitivities below that level.

In the case of the thermopile, its relative sensitivity has been tabulated as 1 for all wavelengths.

Data for the spectral transmittance of optical filters has been obtained from manufacturer's specifications or has been measured experimentally. In spectral regions of strong absorption where accurate data were difficult to obtain the minimum measurable value has been assigned to the remaining wavelengths. Thus for the Schott BG 18 filter the transmission is assumed to be .0001 between $.22\mu$ and $.31\mu$.

Data for spectral irradiance incident on the surface of the water has been assumed to be equal to the spectral irradiance of sunlight above the earth's atmosphere as given by Johnson's* smoothed data.

No data for the spectral irradiance of the radiant energy under water was available, nor was there, at the outset, spectral data for the diffuse attenuation coefficient of natural water. Uncontaminated water was therefore represented by means of the equation

$$H_z = H_0 e^{-\alpha z} \tag{4}$$

* F. Johnson, Jour. of Meteorology Volume 11, p. 431 (1954).

in which Johnson's data were used for H_O and Hulburts* a values were used in the exponent. This procedure leads to values of H_Z which are low for the specified depth and probably somewhat distorted with respect to wavelength. However, there was no alternative and the unreality introduced should not distort the estimate of errors by a large factor.

Later in the program, experimental data on the spectral radiant energy available at a depth of 19 m in plankton-rich water was obtained from the Gulf of California and this was used directly for H_2 in the calculation.

In tabulating the underwater irradiance data some extrapolation was necessary and H values less than 10^{-5} times the peak H value were tabulated as zero.

The summation procedure in all cases was performed in the manner expressed by equation (5).

$$\sum_{a}^{d} xy\Delta\lambda = \left[\frac{(xy)a}{2} + (xy)b + (xy)c + \frac{(xy)d}{2} \right] \tag{5}$$

The computations were carried out independently for four regions of the spectrum using a different value for $\Delta\lambda$ for each region. In each region summations were made to determine the total radiant energy available, the radiant energy actually measured, and the energy desired to be measured, according to the W.G. 15 recommendation. Table I gives a summary of computations performed and indicates the symbol assigned to each summation.

Table I

Wavelength Limits	Energy Available	Energy Measured	Energy Measurement Desired	$\Delta\lambda$
.22 to .35μ	a	A	O	.005μ
.35 to .70μ	b	B	b	.01μ
.70 to 4.0μ	c	C	O	.1μ
4.0 to 7.0μ	d	D	O	1.0μ

Complete computations were made using the following variables:

For irradiance, H

H_O = irradiance at the water surface
H_1 = 50 m deep in water specified by Hulburt's distilled water
H_2 = Gulf of California water
H_{10} = 10 m deep in water specified by Hulburt's distilled water

For spectral Sensitivity of Photodetector, S

S_1 = Thermopile
S_{10}, S_{11}, and S_{17} = Photomultiplier tubes with the spectral sensitivities indicated by the subscript.

* E.O. Hulburt J.O.S.A. 35, 698 (1945).

For optical Filters, F

F_o = the ideal filter, transmitting 100% between .35 and .70μ; 0% elsewhere.

F_1 = Pittsburg Plate Glass Company 2043, heat absorbing glass

F_2 = Schott BG 18

The available radiant energy in each region of the spectrum is given by:

$$a = \sum_{.22}^{.35} H\Delta\lambda \qquad b = \sum_{.35}^{.70} H\Delta\lambda \qquad c = \sum_{.70}^{4.0} H\Delta\lambda \qquad d = \sum_{4.0}^{7.0} H\Delta\lambda \tag{6}$$

Where H represents any of the above listed spectral irradiance distributions.

The experimentally measured radiant energy within these bands is given by:

$$A = \sum_{.22}^{.35} SFH\Delta\lambda \qquad B = \sum_{.35}^{.70} SFH\Delta\lambda \qquad C = \sum_{.70}^{4.0} SFH\Delta\lambda \qquad D = \sum_{4.0}^{7.0} SFH\Delta\lambda \tag{7}$$

Where S and F represent combinations of these spectral functions (except F_o) as previously listed.

The desired measurement of radiant energy is given by:

$$b = \sum_{.35}^{.70} F_o H\Delta\lambda \tag{8}$$

In the other regions of the spectrum the desired measurement of radiant energy is zero, (by the arbitrary decision of W.G. 15).

In order to compensate for the different peak sensitivities of the various photodetectors as well as for the difference in filter factors for the optical filters used, the results have been normalized by setting the maximum value of SFH equal to H_o. There are fundamental differences between the action of a thermopile and that of a photoemissive detector which make it difficult to compare their relative outputs. A thermopile responds to total radiant energy, regardless of wavelength, whereas a photoemissive surface responds to quanta with an efficiency that is a function of wavelength. Furthermore, the output of photoemissive devices is generally given in amps/watt, whereas the output of thermopiles is generally given in volts/watt. Thus, direct comparison depends on circuitry. In these calculations, the spectral sensitivity of the thermopile (S_1) has been taken as 1 at all wavelengths, consequently, results for the thermopile cannot be compared directly with those for the multiplier phototubes. However, the photomultiplier tubes can be compared with each other for relative sensitivity.

Tables II and III summarize the results. Calculations involving a thermopile are given in Table II. Column 1 gives the percent of the instrument's reading which is due to radiant flux outside the wavelength limits .35 to .70μ. Column 2 gives the percent of the radiant flux within these limits which is measured.

Table III gives the same information for three photomultiplier tubes combined with two different filters, used in situ and above the surface.

The errors of omission and commission indicated in the tables are all manifestations of the mismatch between the realizable band width isolation and that specified as photosynthetically important. The large errors of commission exhibited by the thermopile when used out of water are due to insufficient filtering out of infrared and U. V. radiation. When a stronger filter is used, (the F_2 filter in this case) the error of commission is reduced (Column 1) but at the same time the error of omission is increased (Column 1 – Column 2).

The fact that photoemission is inherently restricted to the higher energy photons puts a natural band width restriction on the response of photomultiplier tubes which in large measure accounts for both the low error of commission and the high error of omission when these devices are used out of water.

The fact that water absorbs radiant flux in the red region of the spectrum and also in the blue beyond .35μ means that at great depths errors of commission and omission are both reduced (possibly to zero) as depth increases, because the band width of the flux passed by the water itself becomes the limiting band width and lies wholly within the band width of the detector.

APPLICATION TO INCUBATOR

In the deck incubator technique there are four situations to be considered:

The response of the phytoplankton in situ
The response of the phytoplankton on deck
The response of the photodetector in situ
The response of the photodetector on deck

Because photosynthesis is a nonlinear function of the available radiant energy it is the practice in the deck incubator technique to reduce the radiant energy in the deck incubator and simultaneously on the detector, by means of a screen or other non-wavelength selective filter (T) until,

$$\text{Photodetector response on deck} \times T = \text{Photodetector response in situ}$$

It is then desired or assumed that:

$$\frac{\text{Phytoplankton response in situ}}{G \times \text{Photodector response in situ}} = \frac{\text{Phytoplankton response on deck} \times T}{G \times \text{Photodetector response on deck} \times T}$$

where G is a controllable circuit gain factor adjusted to a fixed setting for the experiment.

Table II

	(1) $\frac{A+C+D}{A+B+C+D}$ $\frac{\text{\% of reading which}}{\text{is unwanted}}$	(2) $\frac{B}{b}$ $\frac{\text{\% of b which}}{\text{is measured}}$
$S_1F_1H_O$	21.8	97.3
$S_1F_2H_O$	15.4	58.1
$S_1F_1H_1$	<1	99.6
$S_1F_2H_1$	<1	94.4
$S_1F_2H_{10}$	<1	81.7
$S_1F_1H_2$	<1	100.0
$S_1F_2H_2$	<1	81.2

Table III

	(1) $\frac{A+C+D}{A+B+C+D}$	(2) $\frac{B}{b}$
$S_{11}F_1H_O$	2.56	56.7
$S_{11}F_2H_O$	<1	47.3
$S_{17}F_1H_O$	6.57	62.7
$S_{17}F_2H_O$	<1	49.7
$S_{10}F_1H_O$	3.52	65.6
$S_{10}F_2H_O$	<1	50.3
$S_{11}F_1H_1$	<1	84.2
$S_{11}F_2H_1$	<1	83.8
$S_{17}F_1H_1$	<1	95.5
$S_{17}F_2H_1$	<1	90.0
$S_{10}F_1H_1$	<1	89.6
$S_{10}F_2H_1$	<1	88.6
$S_{11}F_2H_{10}$	<1	69.8
$S_{17}F_2H_{10}$	<1	74.5
$S_{10}F_2H_{10}$	<1	73.7
$S_{11}F_1H_2$	<1	82.9
$S_{11}F_2H_2$	<1	73.6
$S_{17}F_1H_2$	<1	83.5
$S_{17}F_2H_2$	<1	75.0
$S_{10}F_1H_2$	<1	88.2
$S_{10}F_2H_2$	<1	78.5

Thus, the essential condition for exact correlation between rate of photosynthesis and radiant flux is

$$\frac{\int RH_z d\lambda}{G\int SFH_z d\lambda} = \frac{T\int RH_o d\lambda}{GT\int SFH_o d\lambda} \tag{9}$$

R = spectral response of phytoplankton
S = spectral response of photodetector
H_z = spectral irradiance in situ
H_o = spectral irradiance on deck
F = transmittance of optical filter

The factors G and T are invariant with wavelength and have been brought outside the integral sign where they cancel out of the equation leaving

$$\frac{\int RH_z d\lambda}{\int SFH_z d\lambda} = \frac{\int RH_o d\lambda}{\int SFH_o d\lambda} \tag{10}$$

The spectral response of the phytoplankton to radiant energy is unknown. For purposes of comparison in the tables it is assumed that the spectral response of the phytoplankton is unity between .350 and .700μ and zero at all other wavelengths. This assumption conforms with the basic assumption adopted by W.G. 15 that for a measure of the photosynthetically important radiant flux, all the available flux (or quanta) between .35 and .70μ should be measured.

Equation 10 can thus be written with integration limits as follows:

$$\frac{\int_{.35}^{.70} RH_z d\lambda}{\int_{.22}^{7.0} SFH_z d\lambda} = \frac{\int_{.35}^{.70} RH_o d\lambda}{\int_{.22}^{7.0} SFH_o d\lambda} \tag{11}$$

Tables IV and V compare these ratios for equality. Table IV is for an incubator with clear glass and neutral filters used to control the level of radiant energy. Table V is for an incubator with F_2 glass. Neutral filters are again used to control the energy level.

DISCUSSION OF TABLES IV AND V

In interpreting the results shown in Tables IV and V it is important to remember that the spectral response of the phytoplankton has been assumed to be 1 between $.35\mu$ and $.70\mu$, and zero at all other wavelengths. This assumption undoubtedly leads to incorrect ratios throughout the tables. Thus, the tables are more valuable to indicate trends than they are to indicate the absolute error.

Tables IV and V are, in essence, a tabulation of about 50 independent experiments in which the ratio of real productivity to photodetector response in situ, has been determined and then compared with this same ratio obtained in an incubator on deck.

In Table IV, section B last entry, ($S_{10}F_2H_1$), the in situ ratio was determined to be 84.8 and the incubator ratio (Section A last entry) was 146.5. Thus, the incubator ratio is 72.8% too high (+).

In Table V, section B last entry, ($S_{10}F_2H_1$) the same experiment has been performed, but incubation has taken place under an F_2 glass filter. The incubator ratio is now found to be only 6.45% high.

Other pairs of ratios can be compared similarly and it can be seen that the use of an F_2 filter over the incubator has had a profound effect, greatly improving the correlation. A more carefully selected filter could, of course, be expected to bring about an even greater improvement in correlation.

Table IV

		Section A		Section B			Section C			Section D		
		1	2	1	2	3	1	2	3	1	2	3
Summation Limits	$\sum(\ )\Delta\lambda$	H_0	Ratio	H_1	Ratio	Error	H_{10}	Ratio	Error	H_2	Ratio	Error
.35 → .70	H=RH	.0616		.0039		$\frac{\Delta}{\text{in situ}}$	.0258		$\frac{\Delta}{\text{in situ}}$	2.83		$\frac{\Delta}{\text{in situ}}$
.22 → 7.0	S_1H	.1396	.441	.0039	1.00	-55.9%	.0260	.992	-55.5%	2.83	1.0	-55.9%
.22 → 7.0	S_1F_1H	.0672	.917	.00342	1.14	-19.6				2.481	1.14	-19.6
.22 → 7.0	S_1F_2H	.0287	2.14	.00249	1.565	+36.7	.01438	1.79	+19.5	1.728	1.635	+30.9
.22 → 7.0	$S_{11}F_1H$	.00157	39.2	.000141	27.6	+42.0				.0869	32.5	+20.6
.22 → 7.0	$S_{11}F_2H$	.00092	66.2	.000102	38.2	+73.3	.000568	45.4	+45.8	.0627	41.2	+60.7
.22 → 7.0	$S_{17}F_1H$	.00300	20.5	.000268	14.55	+40.9				.1750	16.15	+26.9
.22 → 7.0	$S_{17}F_2H$	.00173	35.5	.000197	19.8	+79.3	.001079	23.9	+48.5	.1277	22.2	+60.0
.22 → 7.0	$S_{10}F_1H$	.000767	80.2	.000063	62.0	+29.2				.0411	69.0	+16.2
.22 → 7.0	$S_{10}F_2H$	.000420	146.5	.000046	84.8	+72.8	.000257	100.3	+46.0	.0293	96.5	+51.8
		← On Deck →		← In Situ →								

This table for incubator with clear glass and neutral filter. It is assumed that the plankton response is directly proportional to $\sum_{.35}^{.70} H\Delta\lambda$

Column 2 Section A is the right side of equation 11; Columns 2 in Sections B, C, and D are the left side of equation 11.

$$\text{Error} = \frac{(\text{deck}) - (\text{in situ})}{\text{in situ}} \times 100$$

Another trend that can be seen in Table IV, section B, column 2, is that the ratio of in situ productivity to photodetector response has varied by a factor of 84.5 as a function of only the spectral sensitivity of the photodetector-filter combination. The change with water type (detector-filter combination remaining the same) has been only a factor of 1.2. This result emphasizes the importance of properly designing the photodetector-filter combination.

Table V

		Section A		Section B			Section C			Section D		
		1	2	1	2	3	1	2	3	1	2	3
Summation Limits	$\sum ( )\Delta\lambda$	H_o	Ratio	H_1	Ratio	Error	H_{10}	Ratio	Error	H_2	Ratio	Error
.35 → .70	$HF_2=RHF_2$	.0242		.00249		$\frac{\Delta}{\text{in situ}}$	.01438		$\frac{\Delta}{\text{in situ}}$	1.728		$\frac{\Delta}{\text{in situ}}$
.22 → 7.0	S_1F_1H	.0672	.360	.00342	.728	-50.5%				2.481	.697	-48.3%
.22 → 7.0	S_1F_2H	.0287	.843	.00249	1.00	-15.7	.01438	1.00	-15.7%	1.728	1.00	-15.7
.22 → 7.0	$S_{11}F_1H$	.00157	15.4	.000141	17.65	-12.8				.0869	19.9	-22.6
.22 → 7.0	$S_{11}F_2H$	.00092	26.4	.000102	24.4	+ 7.57	.000568	25.4	+ 3.94	.0627	27.6	- 4.35
.22 → 7.0	$S_{17}F_1H$	.00300	8.6	.000268	9.30	- 7.53				.1750	9.87	-12.9
.22 → 7.0	$S_{17}F_2H$	.00173	14.0	.000197	12.65	+10.7	.001079	13.35	+ 4.87	.1277	13.55	+ 3.32
.22 → 7.0	$S_{10}F_1H$	.000767	31.6	.000063	39.6	-22.0				.0411	42.1	-24.9
.22 → 7.0	$S_{10}F_2H$	.000420	57.7	.000046	54.2	+ 6.45	.000257	56.0	+ 3.04	.0293	59.0	- 2.2
		← Deck →		← In Situ →								

This table is for incubator with F_2 glass + neutral filter.

Detector is not placed under F_2glass in incubator, but has its own filter as shown + the incubator neutral filter.

It is assumed that the plankton response is directly proportional to $\sum_{.35}^{.70} H\Delta\lambda$

Column 2 Section A is the right side of equation 11; Columns 2 in Sections B, C, and D are the left side of equation 11.

$$\text{Error} = \frac{(\text{deck}) - (\text{in situ})}{\text{in situ}} \times 100$$

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A calculation has been made to determine the accuracy of the correlation between measurements of Radiant Energy and the ^{14}C Determination of Primary Productivity in the ocean as determined by the "deck incubator" technique.

14 KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Primary Productivity Radiant Energy Biological Oceanography						

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There is no limitation on the length of the abstract However, the suggested length is from 150 to 225 words

14 KEY WORDS Key words are technically meaningful terms or short phrases that characterize a report and may be used as index entries for cataloging the report Key words must be selected so that no security classification is required Identifiers, such as equipment model designation, trade name, military project code name, geographic location, may be used as key words but will be followed by an indication of technical context The assignment of links, roles, and weights is optional