

CHLOROPHYLL CONCENTRATION ESTIMATED FROM IRRADIANCE MEASUREMENTS AT FLUCTUATING DEPTHS

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ABSTRACT

Variations in the spectral shape of underwater irradiance at a fixed depth can be used to describe changes in water column constituents, such as chlorophyll concentration. However, random fluctuations of the depth of the monitoring sensor, caused by current variations, makes interpretation more challenging. Even in homogeneous water, the spectral underwater light field varies with depth because of spectral attenuation by the water column; the magnitude of this effect is demonstrated. By taking advantage of variations in depth, a method is then presented to estimate the chlorophyll concentration (C) and a yellow substance factor (Y) from irradiance measurements made at fluctuating depths. In model simulations, this simple, semi-empirical model is found to retrieve C and Y to within 1% using irradiances at 412, 443 and 555 nm. One application of this method is to interpret data from sensors attached to single-line, bottom-tethered moorings.

1. INTRODUCTION

Optical moorings are a relatively new addition to the oceanographic field.¹ In response to the recent and imminent launches of satellites bearing ocean color sensors, optical moorings have been developed and deployed with sensors that measure radiance and/or irradiance at wavebands similar to those of the satellite sensors. These moorings will play a major role in the vicarious calibration of the satellite sensors, as well as provide invaluable data of local water column dynamics during periods of cloud cover when satellite coverage of ocean color is not possible.

Several different optical moorings have been developed to address these needs. Examples of such moorings include: the Bio-Optical Moored System (BOMS)^{2,4}; the Marine Optical Buoy system (MOBY)⁵; the Yamato Bank Optical Moored Buoy System (YBOM)^{6,7}; the Moored Optical Radiometer System (MORS)⁸; and the Hale-ALOHA mooring currently in operation off the coast of Hawai'i (M. Abbott, Oregon State University). In most of these studies, the optical moorings have consisted of sensors attached to surface-to-bottom moorings,^{3,4,7,8} although multi-point, bottom-tethered moorings^{2,9} and buoys tethered to a slack-line mooring⁵ have also been used. These types of moorings provide relatively stable platforms for the attached optical instruments.

Disadvantages of such moorings include the cost involved in their deployment and, in some cases, shading of the optical sensors from surface and subsurface floats. A more cost-effective type of mooring to deploy is a single-line, bottom-tethered mooring with a sensor head attached to the top of the mooring line. Optical sensors attached to this type of mooring can experience large variations in depth caused by current changes.

This study will present a method to retrieve accurate estimates of the chlorophyll concentration (C) and a yellow substance factor (Y) from such irradiance measurements by making use of the variations in depth of the sensor.

2. WATER COLUMN OPTICS

The variation of irradiance with depth can be approximated by

$$(1) E_d(\lambda, z_n) = E_d(\lambda, z_m) \exp[-K(\lambda, z_{mn})\delta z],$$

where $E_d(\lambda, z)$ is the downwelling irradiance at wavelength λ and depth z , $K(\lambda, z_{mn})$ is the average downwelling diffuse attenuation coefficient between depths z_m and z_n , and δz is the depth difference $z_n - z_m$ (Figure 1). This relationship assumes that $K(\lambda, z)$ does not vary substantially between the depths z_m and z_n .

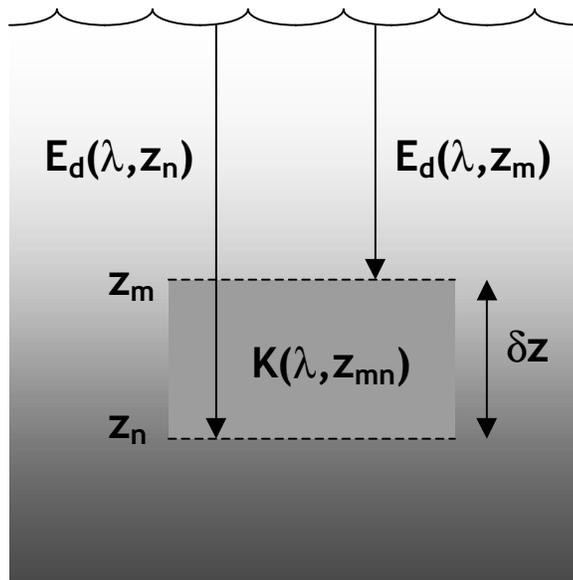


Figure 1: Schematic of the terms in (1).

At depths where the irradiance is at least 10% of its surface value, $K(\lambda, z)$ can be expressed in terms of the total absorption coefficient $a(\lambda, z)$ and the total backscattering coefficient $b_b(\lambda, z)$ ¹⁰:

$$(2) K(\lambda, z) = [a(\lambda, z) + b_b(\lambda, z)] / \mu,$$

where μ is the mean cosine for the downwelling light field. This form of the relationship assumes that the contribution to the downwelling light field from downward scattering of upwelling light is negligible.

In phytoplankton-dominated (case 1) waters near the sea surface, the total absorption and backscattering coefficients can be written in terms of C and Y^{11-13} as follows:

$$(3) a(\lambda, z) = a_w(\lambda) + 0.06a_{ph}^{*}(\lambda)C(z)^{0.65} + Y(z)a_{ph}(440)\exp(-0.014(\lambda - 440)),$$

$$(4) b_b(\lambda, z) = 0.5b_w(\lambda) + 0.3\tilde{b}_{bp}(C)(550/\lambda)C(z)^{0.62},$$

where $a_w(\lambda)$ and $b_w(\lambda)$ are the absorption and scattering coefficients for pure seawater respectively, $a_{ph}^{*}(\lambda)$ is the specific absorption coefficient for phytoplankton normalized at 440 nm, $a_{ph}(440)$ is the absorption coefficient for phytoplankton at 440 nm (equivalent to $0.06C(z)^{0.65}$), and $\tilde{b}_{bp}(C) = 0.0078 - 0.0042 \log_{10} C$. From this equation it can be seen that Y describes the relationship between the absorption by yellow substance (the last term in (3)) at 440 nm and the absorption by phytoplankton at 440 nm.

At the midpoint of the euphotic zone, where the irradiance is 10% of its surface value, $K(\lambda, z)$ can instead be expressed as a function of $a(\lambda, z)$ and the total scattering coefficient $b(\lambda, z)^{14}$:

$$(5) K(\lambda, z) = [a^2(\lambda, z) + (g_1\mu - g_2)a(\lambda, z)b(\lambda, z)]^{1/2} / \mu,$$

where g_1 and g_2 are constants for a given water type, and $b(\lambda, z)$ can be written as a function of C^{12} :

$$(6) b(\lambda, z) = b_w(\lambda) + 0.3(550/\lambda)C(z)^{0.62}.$$

Table 1 lists the values of the coefficients used in this study. Note that detritus has not been included in this analysis, although its incorporation would be a straightforward extension to this method.

Table 1: Values and sources for the parameters used to calculate the downwelling diffuse attenuation coefficient.

Parameter (units)	Value			Reference
	412 nm	443 nm	555 nm	
a_w (m^{-1})	0.0160	0.0145	0.0673	15
b_w (m^{-1})	0.0067	0.0048	0.0019	15
a_{ph}^{*}	0.887	0.982	0.219	16
g_1	0.473	0.473	0.473	14
g_2	0.218	0.218	0.218	14
μ	0.9 (surface) 0.7 (deep)	0.9 (surface) 0.7 (deep)	0.9 (surface) 0.7 (deep)	14

3. EFFECT OF DEPTH VARIATIONS ON IRRADIANCE RATIOS

Empirical relationships between C and irradiance ratios have been used previously to estimate C at constant depths.⁴ These relationships take the form:

$$(7) C(z) = \alpha_{ij}(z) r_{ij}(z)^{\beta_{ij}(z)},$$

where $\alpha_{ij}(z)$ and $\beta_{ij}(z)$ are empirical parameters that are functions of depth and the wavelengths chosen, and $r_{ij}(z) = E_d(\lambda_i, z)/E_d(\lambda_j, z)$. To apply this relationship to measurements made at fluctuating depths, it would be necessary to determine the depth-dependence of $\alpha_{ij}(z)$ and $\beta_{ij}(z)$. The depth-dependence of these parameters results from the depth variations of $r_{ij}(z)$ in homogeneous waters, which in turn result from spectral attenuation and scattering by the water column constituents. This can be shown by manipulating (1) into the form:

$$(8) r_{ij}(z_n) = r_{ij}(z_m) \exp([K(\lambda_j, z_{mn}) - K(\lambda_i, z_{mn})]\delta z).$$

This shows that the irradiance ratio at depth z_n differs from that at depth z_m by the factor $\exp([K(\lambda_j, z_{mn}) - K(\lambda_i, z_{mn})]\delta z)$. For example, for a depth variation (δz) of 5 m in homogeneous waters, the irradiance ratio $E_d(555)/E_d(443)$ at depth z_n can differ from that at depth $z_n - 5$ by factors of 0.8-20 in waters of low (0.01 mg m^{-3}) to high (40 mg m^{-3}) values of C , respectively (Figure 2).

Hence, fluctuations of an irradiance sensor with depth will affect the results from spectral relationships such as (7), if the parameters $\alpha_{ij}(z)$ and $\beta_{ij}(z)$ are not allowed to vary with depth. Since the depth-dependence of these parameters is difficult to retrieve, an alternative method is presented to retrieve C from irradiance measurements at fluctuating depths.

4. THE METHOD

Waters¹⁷ presented a method to derive C from ratios of downwelling irradiance measured simultaneously at two constant depths (his equation 20e) of the form:

$$(9) C(z_{mn}) = F \ln \left(\frac{r_{ij}(z_n)}{r_{ij}(z_m)} \right) / \delta z + G,$$

where F and G are unknowns. To implement this model, Waters assumed that F and G were constants, and derived them empirically. However, it is acknowledged in the same study that G is a function of C .

A similar method is derived here, with the following differences: (1) the model does not require the estimation of empirical constants, (2) it accounts for all dependencies on C , and (3) it is also a function of the yellow substance factor Y , and hence requires two relationships to solve for C and Y .

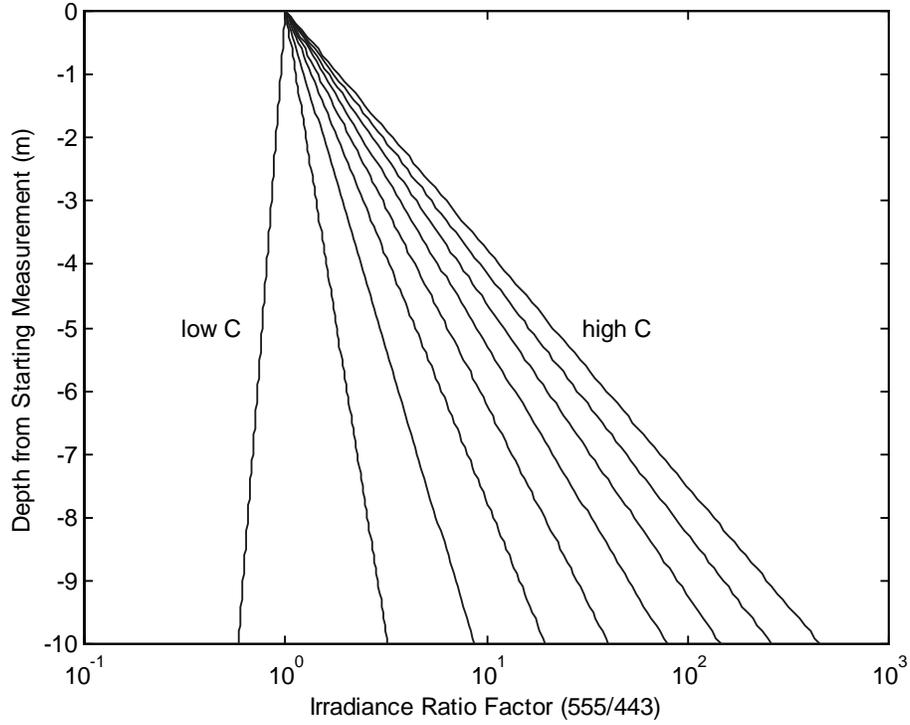


Figure 2: The relationship between the irradiance ratio factor for $E_d(555) / E_d(443)$ and the distance from the reference depth for a range of values of C . The irradiance ratio factor describes the relationship between the irradiance ratio at some depth and the irradiance ratio at a reference depth. The irradiance attenuation at each wavelength was calculated using (2)-(4) and the values in Table 1. The values used for C ranged from 0.01 to 40.01 mg m^{-3} in steps of 5 mg m^{-3} . The value used for Y was 0.2 . The value for C at which the irradiance ratio is independent of depth occurs at approximately 1 mg m^{-3} .

The derivation of the method is as follows. Equation (8) can be rearranged to yield:

$$(10) \quad \delta_{ji} K = \ln \left(\frac{r_{ij}(z_n)}{r_{ij}(z_m)} \right) / \delta z,$$

where $\delta_{ji} K = K(\lambda_j, z_{mn}) - K(\lambda_i, z_{mn})$.

Assuming that measurements are available from only one sensor head, measurements of r_{ij} may be available from different depths if the sensor fluctuates with depth. If the measurements are made frequently (<10 minutes apart) the assumption of simultaneity can be made. Over this time period it will be assumed that spectral variations caused by changes in solar elevation, sea state and cloud cover are minimal. Note that these effects must be accounted for if the measurements are made less frequently (hourly or daily). The remaining variability in spectral underwater irradiance is caused by variations in the water column constituents and the depth of the measuring

sensor. The quantities $r_{ij}(z_n)$, $r_{ij}(z_m)$ and δz can be calculated from the measurements, and hence $\delta_{ji}K$ can be estimated.

From (2)-(4), the quantity $\delta_{ji}K$ near the sea surface can be written as a function of the chlorophyll concentration, C , and the yellow substance factor Y :

$$(11) \quad \delta_{ji}K = A(\lambda_i, \lambda_j) + B(\lambda_i, \lambda_j)C(z)^{0.65} + D(\lambda_i, \lambda_j)Y(z)C(z)^{0.65} + E(\lambda_i, \lambda_j)\tilde{b}_{bp}(C)C(z)^{0.62},$$

where

$$A(\lambda_i, \lambda_j) = [a_w(\lambda_j) - a_w(\lambda_i) + 0.5[b_w(\lambda_j) - b_w(\lambda_i)]] / \mu,$$

$$B(\lambda_i, \lambda_j) = 0.06[a_{ph}^*(\lambda_j) - a_{ph}^*(\lambda_i)] / \mu,$$

$$D(\lambda_i, \lambda_j) = 0.06[\exp(-0.014(\lambda_j - 440)) - \exp(-0.014(\lambda_i - 440))] / \mu, \text{ and}$$

$$E(\lambda_i, \lambda_j) = 0.3[(550/\lambda_j) - (550/\lambda_i)] / \mu.$$

Similarly, $\delta_{ji}K$ at depth can be written as a function of C and Y using (3), (5) and (6). Both of these relationships can be solved for C and Y by either using a minimization technique (finding the best solution from all expected values for C and Y) or by solving two simultaneous equations. Note that to yield two different sets of ratios, measurements from at least three wavelengths are required.

An analysis of the commonly used wavelengths in ocean color measurements showed that the optimal wavelength pairs to solve these equations are (412, 443) and (443, 555). Using these wavelength pairs, the minimization technique yields a single solution for C and Y over realistic values for C and Y , except near $C = 0 \text{ mg m}^{-3}$ (Figure 3). This technique is implemented by matching measured values of $\delta_{443,412}K$ and $\delta_{555,443}K$ to the modeled values in this figure, and retrieving the values for C and Y where the $\delta_{ji}K$'s intersect. Note that the accuracy of this technique is limited by the chosen allowable error between the measured and modeled $\delta_{ji}K$'s.

By assuming that $\tilde{b}_{bp}(C)$ can be approximated by 0.01,¹³ and that $C^{0.62}$ can be approximated by $C^{0.65}$, (11) can also be solved as two simultaneous equations, yielding the following solutions near the sea surface with $\mu=0.5$:

$$(12) \quad C = [(\delta_{443,412}K - 0.686\delta_{555,443}K + 0.0753) / 0.0746]^{1.54} \text{ and}$$

$$(13) \quad Y = -(\delta_{443,412}K + 0.0049 - 0.0107C^{0.65}) / 0.0625C^{0.65}.$$

Note that there is no solution for Y when $C = 0 \text{ mg m}^{-3}$.

A test of these methods was performed using modeled values of $\delta_{ji}K$. In this test, C and Y were retrieved to within 1% with both methods when a 1% error was allowed for the minimization technique. Increasing the allowable error in the minimization technique between the measured values and the modeled values increases the error in the retrieval for C and Y .

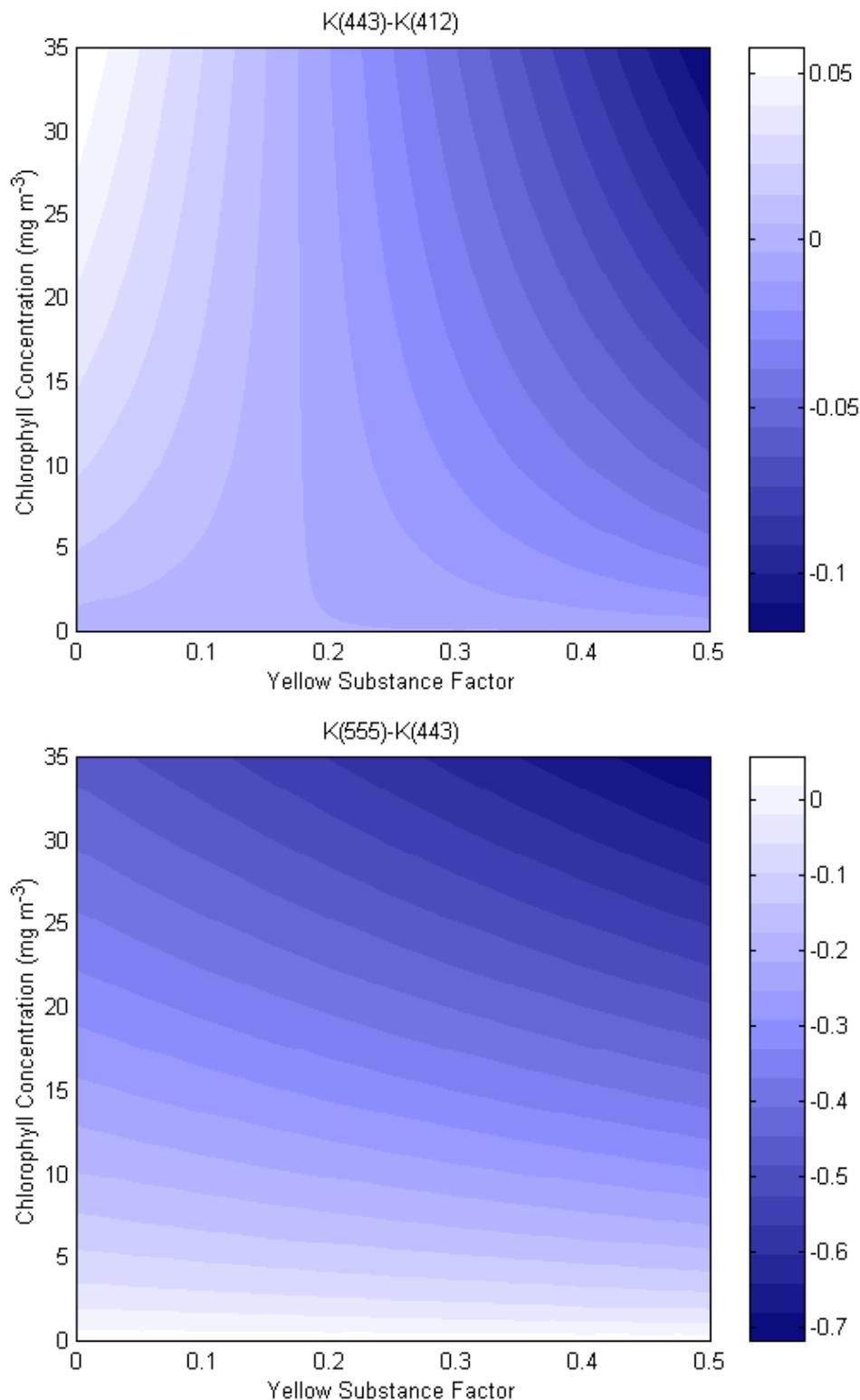


Figure 3: Relationship between $\delta_{ji}K$, C and Y, over ranges of typical values for C and Y, for (a) $\delta_{443,412}K$ and (b) $\delta_{555,443}K$. The $\delta_{ji}K$ values are in units of m^{-1} . These relationships were calculated using (11) with the coefficient values listed in Table 1.

5. CONCLUSIONS

A method has been presented to retrieve C and Y from downwelling irradiance measurements made at fluctuating depths. This method is easily implemented for data with high-frequency (e.g. 10 minute period) depth fluctuations. However, additional spectral effects would need to be accounted for (such as the effects of solar elevation and clouds) if this method is used to analyze measurements with low-frequency (one hour period or more) depth fluctuations. This method is useful for the study of biological dynamics in the water column using a single optical sensor attached to a single-line, bottom-tethered mooring. Since this type of mooring is more cost-effective to deploy than other types, the number of optical moorings that could be deployed is increased, thereby strengthening the statistical accuracy of vicarious calibration of satellite ocean color sensors. A practical test of this method is currently in progress.

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