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Chapter 3

SeaWiFS Algorithm for the Diffuse Attenuation Coefficient *K*(490) Using Water-Leaving Radiances at 490 and 555 nm

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Abstract

A new algorithm has been developed using the ratio of water-leaving radiances at 490 and 555 nm to estimate $K(490)$, the diffuse attenuation coefficient of seawater at 490 nm. The standard uncertainty of prediction for the new algorithm is statistically identical to that of the SeaWiFS prelaunch $K(490)$ algorithm, which uses the ratio of water-leaving radiances at 443 and 490 nm. The new algorithm should be used whenever the uncertainty of the SeaWiFS determination of water-leaving radiance at 443 is larger than that at 490 nm.

3.1 INTRODUCTION

The attenuation over depth z, in meters, of spectral downwelling irradiance $E_d(\lambda, z)$ in units of $\mathrm{mW\,cm^{-2}\,nm^{-1}}$, at wavelength λ, is governed by the Beer–Lambert Law

$$E_d(\lambda, z) \ = \ E_d(\lambda, 0^-)\, e^{-K(\lambda,z)z}, \qquad (1)$$

where $K(\lambda, z)$ is the diffuse attenuation coefficient in per unit meters, averaged over the depth range from just beneath the sea surface, 0^-, to depth z in meters. Gordon and McCluney (1975) showed that 90% of the remotely sensed ocean color radiance is reflected from the upper layer, of depth z_{90}, corresponding to the first irradiance attenuation length, thus satisfying the condition

$$\frac{E_d(\lambda, z_{90})}{E_d(\lambda, 0^-)} \ = \ e^{-1}. \qquad (2)$$

The depth z_{90} is found from an irradiance profile, by inspection, as the depth where condition (2) is satisfied. From (1), the remote sensing diffuse attenuation coefficient at wavelength λ can be found as $K(\lambda) = {z_{90}}^{-1}\,\mathrm{m}^{-1}$.

Austin and Petzold (1981) applied simple linear regression to a sample of spectral irradiance and radiance profiles to derive a $K(490)$ algorithm of the form

$$K(490) \ = K_w(490) \ + \ A\left[\frac{L_W(\lambda_1)}{L_W(\lambda_2)}\right]^B, \qquad (3)$$

where $K_w(490)$ is the diffuse attenuation coefficient for pure water, $L_W(\lambda_1)$ and $L_W(\lambda_2)$ are water-leaving radiances at wavelengths λ_1 and λ_2, and A and B are coefficients derived from linear regression analysis of the data expressed as $\ln[K(490) - K_w(490)]$ and $\ln[L_W(\lambda_1)/L_W(\lambda_2)]$. In Austin and Petzold (1981), $K_w(490) = 0.022\,\mathrm{m}^{-1}$ was taken from Smith and Baker (1981), and because the algorithm was derived for the Nimbus-7 Coastal Zone Color Scanner (CZCS), $\lambda_1 = 443$ nm and $\lambda_2 = 550$ nm.

The SeaWiFS ocean color instrument has channels at 443 and 555 nm. Mueller and Trees (1997) found a different set of coefficients for (3) using wavelengths $\lambda_1 = 443$ nm and $\lambda_2 = 555$ nm, and also used the ratio of normalized water-leaving radiances. The substitution of normalized water-leaving radiances in (3) had no significant effect, but the change in λ_2 yielded small, but statistically significant different coefficients A and B. Following Austin and Petzold (1981), Mueller and Trees (1997) also assumed $K_w(490) = 0.022\,\mathrm{m}^{-1}$ (Smith and Baker 1981). The Mueller and Trees (1997) result was adopted for the SeaWiFS prelaunch $K(490)$ algorithm.

SeaWiFS determinations of $L_W(443)$ are persistently lower than water leaving radiances determined from matched *in situ* validation measurements. The serious underestimates of SeaWiFS $L_W(443)$ yield correspondingly poor agreement between SeaWiFS and *in situ* $K(490)$ determinations. On the other hand, SeaWiFS determinations of $L_W(490)$ and $L_W(555)$ agree much more closely with validation measurements. This chapter reports an algorithm based on (3) using 490 and 555 nm, which should yield improved uncertainty in SeaWiFS $K(490)$ estimates. The algorithm also adopts a reduced value of $K_w(490)$ based on recently published values of pure water absorption (Pope and Fry 1997).

3.2 DATA AND METHODS

Two samples of $K(490)$ and normalized water-leaving radiances are used in the present analysis. Sample 1 is used for a regression analysis to derive coefficients A and B for (3) with $\lambda_1 = 490\,\mathrm{nm}$ and $\lambda_2 = 555\,\mathrm{nm}$. The data in Sample 2 are entirely independent from Sample 1 and are used to determine standard uncertainties of prediction in $K(490)$ calculated using the algorithm derived here from Sample 1, and using the prelaunch $K(490)$ algorithm (Mueller and Trees 1997).

The data comprising Sample 1 were drawn from spectral irradiance and radiance profiles locally archived at SDSU CHORS. Each Sample 1 profile was analyzed to determine $K(490)$ and water-leaving radiance using the integral method of Mueller (1995). Sample 1 includes the data analyzed by Mueller and Trees (1997), but excludes two cruises for which reliable $L_u(490, z)$ measurements were not available. Data from two additional cruises in the Gulf of California were added to Sample 1, bringing the total sample size to 319 data pairs.

Sample 2 was provided from the SeaBASS archives by the SIMBIOS Project Office at GSFC, and consists of 293 sets of $K(490)$, water-leaving radiances and incident surface irradiances (443, 490, and 555 nm) which are independent of Sample 1. Water-leaving radiances in Sample 1 were determined by the SIMBIOS Project using the standard methods employed at GSFC for SeaWiFS match-up validation analysis.

$K(490)$ and normalized water-leaving radiance ratio pairs were determined for each sample using the methods described in Mueller and Trees (1997). A linear regression analysis was performed on the Sample 1 data pairs to determine the values of coefficients A and B in (3), with $\lambda_1 = 490\,\mathrm{nm}$ and $\lambda_2 = 555\,\mathrm{nm}$. Based on Pope and Fry's (1997) recent determination of absorption for pure water $a_w(490) = 0.015\,\mathrm{m}^{-1}$, and the pure water scattering coefficient $b_w(490) = 0.008\,\mathrm{m}^{-1}$ reported by Smith and Baker (1981), the backscattering fraction is heuristically assumed to be less than 0.5 and performed three regressions assuming values of 0.018, 0.017, and $0.016\,\mathrm{m}^{-1}$ for $K_w(490)$. Finally, standard uncertainties of prediction were calculated, both for the present (490 and 555 nm) and the prelaunch (443 and 555 nm) algorithms, as the root-mean-square differences between the measured and predicted $K(490)$ in Sample 2.

3.3 RESULTS

Three regression analyses were performed on Sample 1 using successive values of 0.018, 0.017, and $0.016\,\mathrm{m}^{-1}$ for $K_w(490)$. The scatter between $\ln[K(490) - 0.016]$ and $\ln[L_W(490)/L_W(555)]$, in per unit meters is illustrated in Fig. 1a, together with the logarithmic regression line corresponding to the algorithm

$$K(490) \;=\; 0.016 \;+\; 0.15645\left[\frac{L_{WN}(490)}{L_{WN}(555)}\right]^{-1.5401} . \qquad (4)$$

In log space, the squared correlation coefficient R^2 increased monotonically from 0.931–0.937, and the standard error decreased from 0.186–0.167, as $K_w(490)$ decreased from 0.018–$0.016\,\mathrm{m}^{-1}$. On this basis, the appropriate algorithm selected for use with SeaWiFS was the $K_w(490) = 0.016\,\mathrm{m}^{-1}$ case.

In linear space, the standard uncertainty of the estimate, calculated as the root-mean-square discrepancy between predicted and measured $K(490)$ for Sample 1, is $0.012\,\mathrm{m}^{-1}$. The scatter between predicted and measured $K(490)$, relative to the one-to-one line, is illustrated in Fig. 1b.

Figures 2a and 2b illustrate the scatter about the one-to-one line when $K(490)$ predictions using (4) are compared to measurements from Sample 2. The standard uncertainty of prediction in $K(490)$ using (4) is estimated from these data to be $0.018\,\mathrm{m}^{-1}$ in the range of $K(490) < 0.25\,\mathrm{m}^{-1}$ (which is the range fit with Sample 1) and corresponds to 26% of the mean for this subsample of 249 pairs. When the algorithm of (4) is extrapolated into the range $K(490) > 0.25\,\mathrm{m}^{-1}$, the standard uncertainty of prediction increases to $0.193\,\mathrm{m}^{-1}$ (48% of the mean for this subsample of 31 pairs). The mean biases in predictions are $-0.002\,\mathrm{m}^{-1}$ for measured $K(490) < 0.25\,\mathrm{m}^{-1}$, and $-0.130\,\mathrm{m}^{-1}$ for measured $K(490) > 0.25\,\mathrm{m}^{-1}$.

The standard uncertainties and mean biases of prediction for $K(490)$ calculated with the SeaWiFS prelaunch algorithm (Mueller and Trees 1997) are 0.020 and $0.000\,\mathrm{m}^{-1}$, respectively, for the subsample of Sample 2 with measured $K(490) < 0.25^{-1}$, and 0.196 and $-0.085\,\mathrm{m}^{-1}$ for the subsample with measured $K(490) > 0.25\,\mathrm{m}^{-1}$.

3.4 DISCUSSION

There is little to choose between the *in situ* performances and uncertainties of the (4) $K(490)$ algorithm, using the ratio of water-leaving radiances at 490 and 555 nm, and the SeaWiFS prelaunch algorithm (Mueller and Trees 1997), using the ratio of water-leaving radiances at 443 and 555 nm. When used with SeaWiFS data, however, (4) may be expected to yield more accurate $K(490)$ estimates as long as the uncertainties in estimated $L_{WN}(490)$ are much lower than those for $L_{WN}(443)$. It is recommended, therefore, that (4) be substituted for the Mueller and Trees (1997) $K(490)$ algorithm for processing SeaWiFS data, at least until future improvements in atmospheric corrections may produce equivalent uncertainties in water-leaving radiances at 490 and 443 nm.

Neither algorithm performs well in water masses where $K(490) > 0.25\,\mathrm{m}^{-1}$. In part, this may be due to extrapolating a regression equation beyond the range of the data used to fit its coefficients. In the present circumstances, however, it is at least equally likely that the poor predictions result from extremely large uncertainties in both $K(490)$ and water-leaving radiances derived from radiometric measurements near the sea surface in extremely

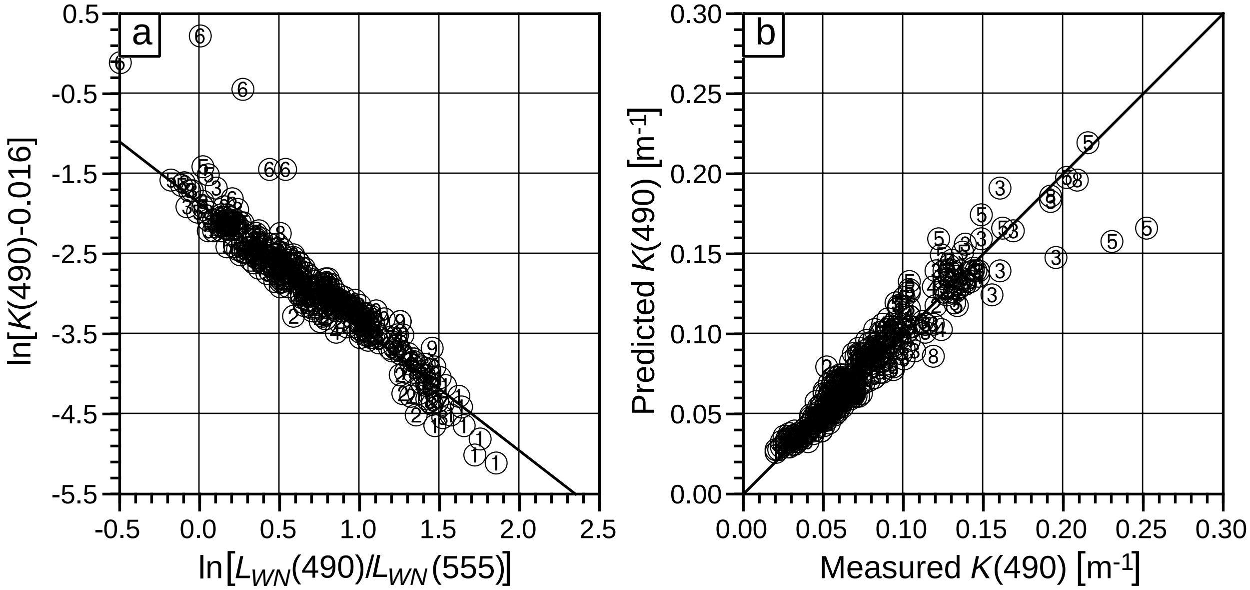

Fig. 1. Scatter comparisons of $K(490)$. **a)** Logarithmic scatter comparison of $K(490)$ versus the ratio of water-leaving radiances at 490 and 555 nm. The solid line is the least squares regression fit to the data (excluding the GoCal98A red tide data) given by (4). **b)** Linear scatter in measured $K(490)$ compared with predictions using (4) with the ratio of water-leaving radiances at 490 and 555 nm. The data are from Fig. 1a. The key for these panels are: 1. Siegel: Sargasso Sea 1994; 2. Mitchell: CalCOFI 1994; 3. GoCal 1995; 4. GoCal 1997; 5. GoCal 1998A (with Red Tide Station); 6. GoCal 1998A Red Tide Data; 7. Trees, Arabian Sea, JGOFS Proc. 2; 8. Trees, Arabian Sea, JGOFS Proc. 6; 9. Trees, Arabian Sea, JGOFS Proc. 7.

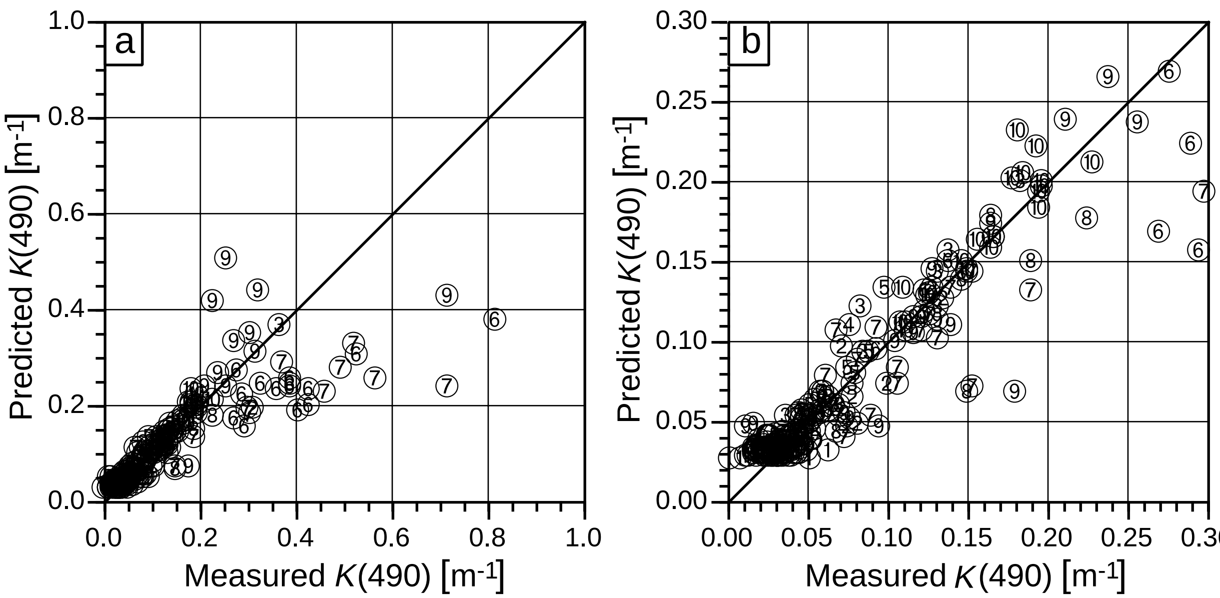

Fig. 2. Scatter comparisons of $K(490)$. **a)** Same as Fig. 1b, but for an independent sample of $K(490)$ and water-leaving radiances at 490 and 555 nm. The solid line corresponds to one-to-one agreement. **b)** A subset of panel **a)**, where the area of greatest concentration of data points is enlarged for better viewing. The key for these panels are: 1. BATS 1998; 2–5. CalCOFI-9802, -9804, -9807, and -9809, respectively; 6. April 1998 SMAB; 7. November 1998 SMAB; 8. Feb 1999 SMAB; 9. CARIACO 1998; 10. GoA97; and ◯ HOTS 1998.

turbid water masses. In such cases, instrument self shading, wave focusing, uncertainty in instrument depth determination, and uncertainty in extrapolating $L_u(\lambda, z)$ to the sea surface (especially when the linear slope estimation method of analysis is employed) contribute large and poorly understood uncertainties to measured $K(490)$ and water-leaving radiances alike. For the near term, the best policy is to regard SeaWiFS $K(490)$ data with values of $> 0.25\,\mathrm{m}^{-1}$ with caution and skepticism.

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