

# AN IMPROVED REGIONAL ALGORITHM TO RETRIEVE TOTAL SUSPENDED PARTICULATE MATTER USING IRS-P4 OCM DATA

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### ABSTRACT:

Data from six validation campaigns in the coastal waters of the Bay of Bengal (BOB) were used to develop a regional *SPM* (Suspended Particulate Matter) algorithm. The *in situ* data sets for this algorithm are composed of 60 stations with optical and 39 station with total *SPM* measurements, encompassing *SPM* concentrations between 13 and 189 mg L<sup>-1</sup>, with most of the observations in shallow (Case 2; average depth ~45 m) waters and a limited number of observations in Case 1 waters. A simple statistical analysis was carried out to evaluate the *SPM* concentration variation with diffuse attenuation coefficient,  $K(555)$  at 555 nm in the BOB coastal waters. The linear regression to the fit has coefficient of determination,  $r^2 = 0.95$  and a standard error of estimates  $S = 15$  mg L<sup>-1</sup>. The algorithm relating  $K(555)$  to  $Lwn(443)/Lwn(670)$  was also evaluated through regression analysis of radiometric profiles in the BOB. However, the new *SPM* algorithm failed to explain the estimates in Case 1 waters, where a spectral reflectance ratio algorithm [Tassan 1994] appears to produce better results. An integration of both the approaches performs better in generating the routine IRS-P4 OCM (Ocean Colour Monitor) *SPM* mapped product.

## 1. INTRODUCTION

Accurate physical, biological and chemical measurements of the upper-ocean are essential for understanding the structures and processes that affect the climate and environment. Ocean colour observation with remote sensors from air and space platforms has become popular during the last decades because of its continuous coverage of the earth surface, which allows for the identification of zones characterised by physical and biological processes occurring at the sea surface. Ever since the launching of CZCS (Coastal Zone Color Scanner), mapping and quantitative estimation of the surface bio-geophysical constituents such as chlorophyll-a, suspended particulate material (*SPM*), and gelbstoff (coloured dissolved organic matter or CDOM), through the remote sensing of ocean colour has gone through a quiet revolution. Extensive studies were carried out to relate explicitly radiance/reflectance with in-water constituents in the past three decades [Morel and Prieur 1977, Gordon *et al* 1988, Sathyendranath *et al* 1994, Lee *et al* 1998, *etc.*]. Previous studies confirm that for Case 1 waters (devoid of direct influence of land runoff and littoral drift), most of the observed variations in the colour and transparency can be related to varying concentration of marine phytoplankton and their metabolism decay (CDOM). But the presence of highly variable contributions of suspended sediment and minerals by river discharge and the presence of exceptionally higher pigment and CDOM concentration makes the coastal (Case 2) waters more optically complex. Also the global colour ratio algorithms break down in Case 2 regime because of the presence of multiple substances, which do not co-vary with chlorophyll concentration.

The Bay of Bengal is a region of large freshwater and sediment input [Emmel and Curray 1984], high sea-surface temperature,

and variable monsoonal forcing. The annual fresh water discharge into the bay exceeds  $1.5 \times 10^{12}$  m<sup>3</sup>, which reduces the mean salinity by about 7‰ in the northernmost bay [Laviolette 1967]. The bay receives about  $2 \times 10^9$  tons of sediments annually, mostly contributed through the Himalayan Rivers - the Ganga and the Brahmaputra (G-B) from the north (figure 1); the Indian Peninsular Rivers - the Mahanadi, the Godavari, the Krishna *etc.* from the west; and the Irrawady and the Salween from the east. It is, therefore, worth investigating the state of the surface particulate matters and their consequences over the bay, in the present context.

The Ocean Colour Monitor (OCM) aboard IRS-P4 makes available the opportunity to estimate the concentrations of chlorophyll-a, *SPM*, gelbstoff at the sea surface and atmospheric aerosol in the marine environment. Originally, the *SPM* retrieval algorithm using OCM data followed a similar approach outlined by Tassan (1994), tuned in Indian waters, which is valid for lower *SPM* concentrations within 30% [Anonymous 2000]. To validate/modify this approach in coastal (Case 2) waters, SAC (Space Applications Centre) and GSI (Geological Survey of India) have conducted six campaigns in the coastal waters of the Bay of Bengal during 2000-2002. From these observations we found that, it makes sense to calibrate the ocean colour algorithms in terms of the diffuse attenuation coefficient,  $K(I)$ , in the Bay of Bengal coastal waters. Based on the *in situ* measurements, we could generalise that *SPM* concentrations are highly correlated with  $K(555)$ , and propose a site-specific *SPM* algorithm with a standard error of estimates 15 mg L<sup>-1</sup>. Since most of the *in situ* observations were within the continental margin (average depth of ~45 m), we retain old (Tassan) approach valid for deeper waters (> 50 m depth) where we have very sparse measurements during the campaigns.

## 2. MEASUREMENTS AND MODEL DESCRIPTION

The coastal cruise database (CCDB) is composed of six OCM validation campaigns (joint ISRO-GSI) in the Bay of Bengal during 2000-2002, onboard R. V. Samudra Kaustubh (ST-131, ST-136, ST-140, ST-142, ST-149, and ST-151). Measurements of total SPM, chlorophyll-a and optical parameters from over the continental margin (8.8 - 775 m with an average depth of ~45 m), off the east coast of India (80.20-88.65°E and 14.6-21.34°N), were drawn on to examine the variation in optical properties with SPM and chlorophyll concentrations. Over this region the sediment loads are very high (13 - 189 mg L<sup>-1</sup>), particularly at the head of the bay and at the river mouths. Since the pigment concentrations are very low (0.011 - 1.84 mg L<sup>-1</sup>, from CDDDB), the changes in optical quantities are likely to be governed by inorganic sediments carried by major river systems in this region (figure 1), although the effects of pigment and CDOM are equally important in Case 2 waters.

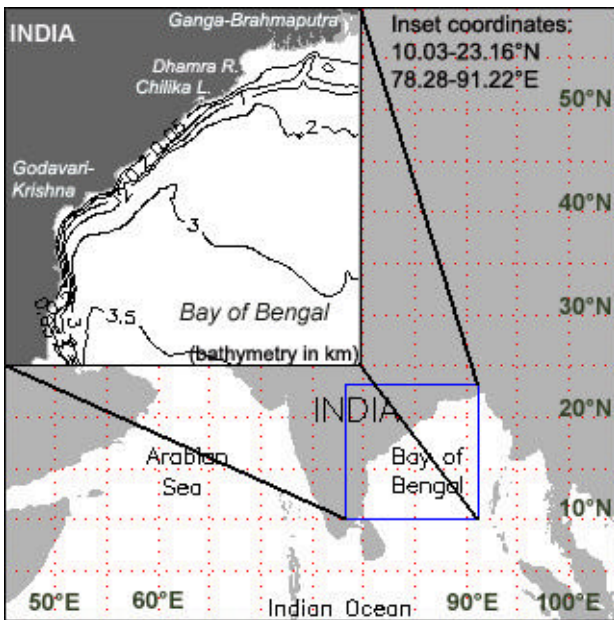


Figure 1: Object of investigation – the Bay of Bengal coastal waters with major river systems and bottom topography (inset)

### 2.1 Suspended Particulate Matter:

Suspended particulate materials (dry weight (mg L<sup>-1</sup>)) were determined gravimetrically as outlined in Strickland and Parsons (1972) and as specified in JGOFS protocols [UNESCO 1994]. Samples were filtered through 0.4 µm pre-weighed polycarbonate filters. The filters were washed with three 2.5 - 5 ml aliquots of distilled water and immediately dried in an oven at 75°C. The filters were then re-weighed in laboratory, using an electro-balance.

### 2.2 Radiometric measurements:

Measurements of the underwater light field were performed with (i) LiCOR portable underwater spectro-radiometer, (ii) SeaWiFS Profiler Multi-channel Radiometer (SPMR), and (iii) SeaWiFS Multi-channel Surface Reference (SMSR). These instruments are

basically designed to collect photons travelling in specific directions (upward/downward), which can be converted into physical values (viz. spectral irradiance, radiance). LiCOR measures the upwelling irradiance,  $E_u(z, \mathbf{I})$  and downwelling irradiance,  $E_d(z, \mathbf{I})$  within the wavelength domain 350 - 900 nm (continuous 1 nm interval). SPMR profiles both upwelling radiance,  $L_u(z, \mathbf{I})$  and downwelling irradiance,  $E_d(z, \mathbf{I})$  and SMSR measures the above surface incoming solar irradiance,  $E_s(0+, \mathbf{I})$ , using DSP techniques and 24 bit A/D converters in 7 spectral channels [Satlantic User's Manual 2000]. The optical sensor characteristics of Satlantic radiometer are akin of the Ocean Colour Monitor (OCM) [Anonymous 2000]. The apparent optical properties like, Water-leaving radiance,  $L_w(\mathbf{I})$ , Remote Sensing Reflectance,  $R_{rs}(\mathbf{I})$ , Normalised water-leaving radiance,  $L_{wn}(\mathbf{I})$ , and Diffuse attenuation coefficient,  $K(\mathbf{I})$  were computed (see appendix) as per standard protocols [Fargion and Mueller 2000].

The diffuse attenuation coefficient  $K(555)$  can be related to the ratio of normalised water-leaving radiance  $L_{wn}(443)/L_{wn}(670)$  as

$$\ln[K(555)-0.07] = \ln(A) + B \ln\left[\frac{L_{wn}(443)}{L_{wn}(670)}\right] \quad (1)$$

where, A and B are the regression coefficients; and the attenuation coefficient for pure water,  $K_w(555) = 0.07 \text{ m}^{-1}$ , is the minimum possible value for  $K(555)$  [Jerlov 1976].

The calibrated single component algorithm for SPM in terms of diffuse attenuation coefficient,  $K(555)$  in coastal waters may be expressed as

$$SPM_2 = mK(555) + n \quad (2)$$

where, m and n, respectively, the slope and intercept of the linear regression.

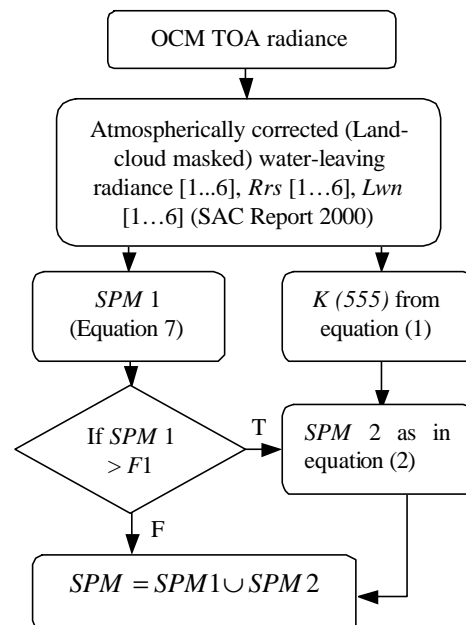


Figure 2: Schematic of the integrated model

The final product (SPM) is the integration of values below and above a case 1 flag, (F1 = 5.5 i.e. the boundary value at 50 m depth contour) from SPM1 [Tassan 1994] and SPM2 respectively. A schematic of the flow is shown in figure 2.

### 3. RESULTS AND DISCUSSION

In water diffuse attenuation coefficients can be calculated from in situ profiles of spectral irradiance and radiance field (see appendix). However, this is not possible from satellite measurements as it provides information at a single layer. Therefore, we propose an indirect method [similar as Austin and Petzold 1981] to estimate the in-water diffuse attenuation coefficients by establishing an empirical relationship with ratios of normalised water-leaving radiances, based on direct comparison with in situ radiometric profiles. Data from CDDB were combined to bring together a regression sample of size N = 59. The linear least-square fit to this data is

$$\ln \left[ K^*(555) - 0.07 \right] = -0.356251 - 0.871654 \ln \left[ \frac{Lwn(443)}{Lwn(670)} \right] \quad (3)$$

with coefficient of determination,  $r^2 = 0.87$ , and a residual standard deviation of 0.226 (in log space).

Now equation (3) can be transformed as

$$K^*(555) = 0.07 + 0.7003 \left[ \frac{Lwn(443)}{Lwn(670)} \right]^{-0.87} \quad (4)$$

with a standard error of estimate,  $s = 0.043 \text{ m}^{-1}$ , which is calculated as

$$s = \sqrt{\frac{\sum_{n=1}^N \left[ K^*(555) - K(555) \right]^2}{N - 2}} \quad (5)$$

where,  $K(555)$  is the model estimation and  $K^*(555)$  is from in situ profiles. Figure 3(b) illustrates the regression fit of the modelled  $K(555)$  and  $Lwn(443)/Lwn(670)$  (in log space).

An empirical relationship between  $K^*(555)$  from irradiance profiles (see appendix) and measured in situ SPM is formulated, using equation (2), as:

$$SPM2 = 93.2 K^*(555) + 13.24 \quad (6)$$

with a standard error of estimates  $15 \text{ mg L}^{-1}$ , for  $25 < SPM2 < 200 \text{ mg L}^{-1}$ . Scatter at different levels of SPM are shown in figure 3(a), where large discrepancies are observed at lower SPM concentrations.

The Case 1 SPM algorithm (SPM1) for OCM is a fine-tuning of Tassan's approach in Indian waters [Anonymous 2000]:

$$SPM1 = 25 \exp \left( a_0 + a_1 \left[ (Rrs(555) - Rrs(670)) \left( \frac{Rrs(555)}{Rrs(490)} \right) \right] \right) \quad (7)$$

where,  $0 < SPM1 < 25 \text{ mg/L}$ ;  $a_0 = 2.166$ ;  $a_1 = 0.991$

Figure 3(c) illustrates the scatter of in situ and modelled SPM. The maximum deviations from the regression fit occur at lower values of SPM. A comparison between SPM retrieved from OCM data with the new approach and using old algorithm (as in equation 7) is illustrated in figure 4. Plots of the resulting SPM distribution along two transects (figure 4 a) are shown in figure 5. There is a significant improvement in SPM concentrations as expected along the coastal waters and river mouths.

#### 3.1 Validation match-ups:

CCDB data for ST 151 and few points from ST 131 cruise, which were not included in the calibration procedure, are being used to evaluate the performance of the new approach. Comparisons between OCM derived and *in situ* SPM are shown in Table 1.

Table 1: Validation match-ups [OCM Vs *in situ*]

Date ddmmyyyy	In situ SPM mg L <sup>-1</sup> [hrs]	*OCM SPM mg L <sup>-1</sup>	Remarks
13012000	27 [14:00]	05.789	Water depth 775 m
15012000	20.2 [12:30]	27.391	Water depth 22.89 m
03032002	14 [11:30]	12.572	
03032002	15 [13:30]	13.973	
04032002	12 [12:00]	10.579	March 03 OCM
04032002	12 [14:20]	11.594	March 03 OCM
05032002	13 [11:45]	18.153	Part. Cloudy
05032002	11 [14:35]	09.012	Part. Cloudy
07032002	12 [11:40]	16.344	Part. Cloudy
07032002	10 [13:43]	15.853	Part. Cloudy

\* OCM pass for all dates - 12:00 noon local standard time.

### 4. OUTLOOK

The initial results are encouraging; however, need more in situ observations, in both coastal and oceanic waters to evaluate the presumption in Case 1 waters. Measurements on the inherent optical properties (absorption and scattering) and other constituents (Chlorophyll, and Gelbstoff) are also proposed to fully understand the inter-relationship among various components and develop an analytical model rather than an empirical one.

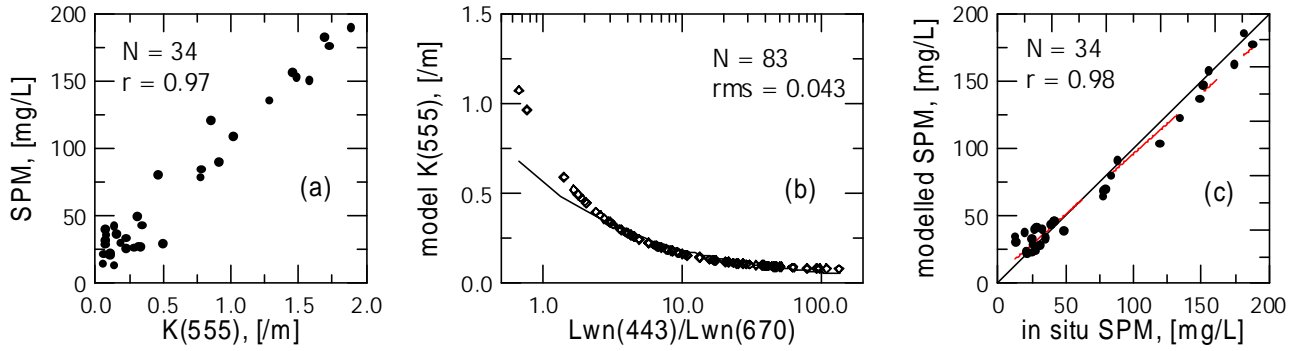


Figure 3: Scattergram of in situ K(555) and SPM (a), Linear K(555) (modelled) versus a logarithmic scaling Lwn ratio (b), and modelled SPM versus in situ SPM (c)

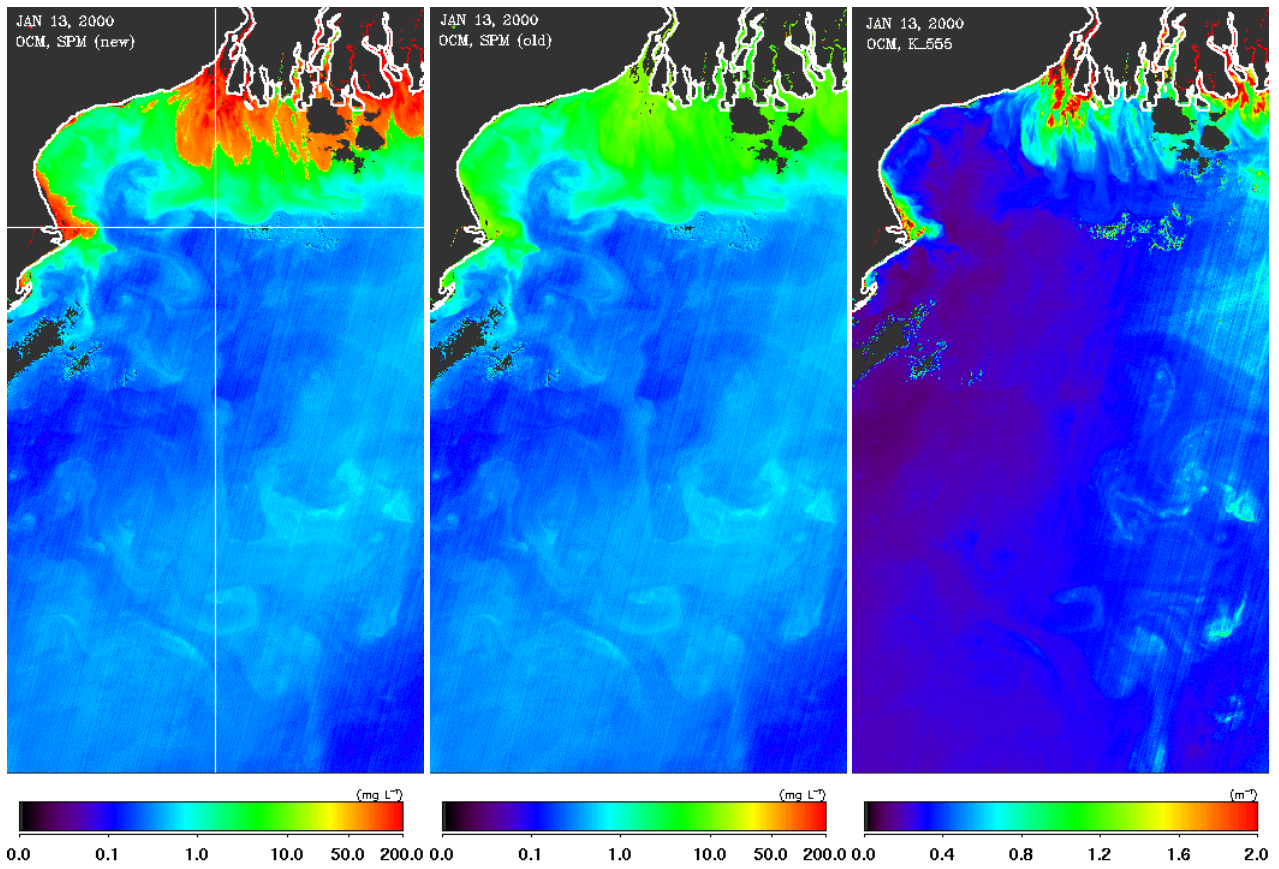


Figure 4: Model outputs using IRS-P4 OCM data (17.33-22.18°N to 86.65-89.29°E): (a) SPM with integrated approach, (b) SPM with old algorithm, (c) K(555) as in equation (4)

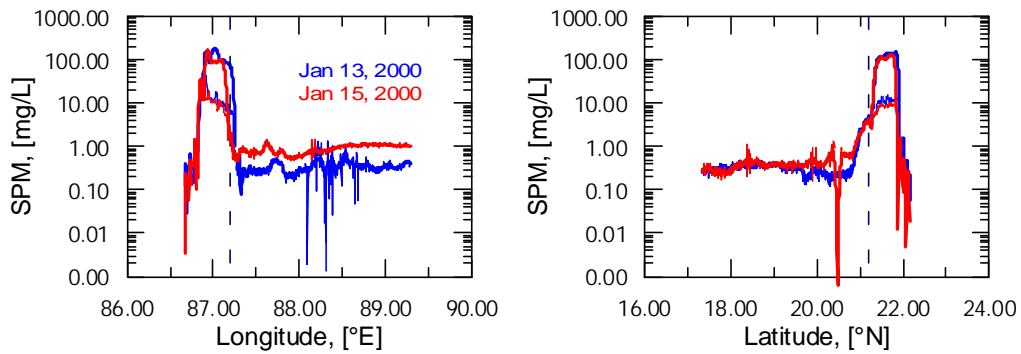


Figure 5: Zonal (over 20.79°N; left panel) and meridional (over 87.89°E; right panel) variation of SPM (also depicted in fig. 4a) with old algorithm (thin lines) and new approach (thick lines).

## References:

- Anonymous, 2000. Test & Evaluation Report on IRS-P4 OCM special product generation software, July 2000. *IRS-P4/SAC/RESA/MWRD/TR/12/2000*, 29 pp.
- Austin, R. W., and Petzold, T. J., 1981. The determination of the Diffuse Attenuation Coefficient of Sea Water Using the Coastal Zone Color Scanner. *Oceanography from Space* (J. F. R. Gower Ed.), Plenum Press, New York, pp. 239-256.
- Chauhan, P., 2002. Personal Communication.
- Emmel, F. J., and Curry, J. R., 1984. The Bengal submarine fan-Northeastern Indian Ocean. *Geo-Mar. Lett.* 3, pp. 199-124.
- Gordon, H. R., Brown, O. B., Evans, R. H., Brown, J. W., Smith, R. C., Baker, K. S., and Clark, D. K., 1988. A semi-analytic radiance model of ocean color. *J. Geophys. Res.*, 93, pp. 10909 - 10924.
- Jerlov, N. G., 1976. *Marine Optics*. Elsevier, Amsterdam, 231 pp.
- Lavolette, P. E., 1967. Temperature, salinity and density of the World's Seas: Bay of Bengal and Andaman Sea. Informal Rep. No. 67-57 (Naval Oceanographic Office, Washington DC).
- Lee, Z. P., Carder, K. L., Mobley, C. D., Steward, R. G., and Patch, J. S., 1998. Hyperspectral remote sensing for shallow waters. I. A semianalytical model. *Appl. Opt.*, 37, pp. 6329 - 6338.
- Morel, A., and Prieur, L., 1977. Analysis of variations in ocean color. *Limnol. Oceanogr.*, 22, pp. 709-722.
- Mueller, J. L., and Austin, R. W., 1995. Ocean Optics Protocols for SeaWiFS Validation, Revision 1. *NASA Tech. Memo. 104566*, Volume 25, S.B. Hooker, E.R. Firestone and J.G. Acker (eds.), NASA Goddard Space flight centre, Greenbelt, Maryland, 66 pp.
- Mueller, J. L., 2000. Ocean Optics Protocols for Satellite Ocean Color Sensor Validation, Revision 2. *NASA Tech. Memo. 209966*, Chapter 8 - 9, Giulietta S. Fargion and James L. Mueller (eds.), NASA Goddard Space flight centre, Greenbelt, Maryland, pp. 65-97.
- Neckel, H., and Labs, D., 1984. The solar radiation between 3,300 and 12,500 Å. *Solar Physics*, 90, pp. 205-258.
- Sathyendranath, S., Hoge, F. E., Platt, T., and Swift, R. N., 1994. Detection of phytoplankton pigments from ocean color: improved algorithms. *Appl. Opt.*, 33, pp. 1081-1089.
- Satlantic user's manual, 2000. *SeawiFS Profiling Multichannel Radiometer User's Manual SPMR/SMSR 041*, Issue/Rev. 1/1, 44 pp.
- Strickland, J. D. H., and Parsons, T. R., 1972. *A Practical Handbook of Seawater Analysis*. Fisheries Research Board of Canada, 310 pp.
- Tassan, S., 1994. Local algorithms using SeaWiFS data for the retrieval of phytoplankton, pigments, suspended sediment, and yellow substance in coastal waters, *Appl. Opt.*, 33, pp. 2369-2378.
- UNESCO, 1994. Protocols for Joint Global Ocean Carbon Flux Study (JGOFS) Core Measurements, Manuals and Guides. 29, 170 pp.

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## Appendix:

In-water apparent light fields can be computed from the *in situ* radiance/irradiance profiles. The different apparent optical properties (AOP) are calculated as follows:

1. Diffuse attenuation coefficient for downwelling irradiance:

$$K_{E_d}(z_0, \mathbf{I}) = -\frac{1}{dz} \frac{\ln E_d(z, \mathbf{I})}{\ln [E_d(z_0, \mathbf{I})]}$$

where,  $z$ : water depth,  $\mathbf{I}$ : wavelength

$E_d(z, \mathbf{I})$  may be substituted by  $E_u(z, \mathbf{I})$  and  $L_u(z, \mathbf{I})$  for the calculation of  $K_{E_u}(\mathbf{I})$  and  $K_{L_u}(\mathbf{I})$  respectively.

2. Water-leaving radiance:

$$L_w(\mathbf{I}) = \frac{1 - r(\mathbf{I}, \mathbf{J})}{h_w^2(\mathbf{I})} L_u(0^-, \mathbf{I})$$

where,  $r$  is Fresnel reflectance ( $\sim 0.021$ ) at nadir angle  $\mathbf{J}$

$h_w$  is the refractive index of seawater ( $\sim 1.345$ )

$L_u(0^-, \mathbf{I})$  is the upwelling radiance at null depth extrapolated from the profile

3. Q-factor:

$$Q_n(0^-, \mathbf{I}) = \frac{E_u(0^-, \mathbf{I})}{L_u(0^-, \mathbf{I})}$$

4. Remote sensing reflectance:

$$R_{rs}(\mathbf{I}) = \frac{L_w(\mathbf{I})}{E_s(\mathbf{I}, 0^+)}$$

5. Downwelling surface irradiance [equivalent  $E_s(0^+, \mathbf{I})$ ]:

$$E_d(0^+, \mathbf{I}) = (1 + \mathbf{a}) E_d(0^-, \mathbf{I})$$

where,  $\mathbf{a}$  is Fresnel reflection albedo from air+sky ( $\sim 0.043$ )

$E_d(0^-, \mathbf{I})$  is extrapolated from  $E_d(z, \mathbf{I})$  profile

6. Normalised water-leaving radiance:

$$L_{wn}(\mathbf{I}) = F_0(\mathbf{I}) R_{rs}(\mathbf{I})$$

$F_0(\mathbf{I})$ : extra-terrestrial solar irradiance [Neckel and Labs 1984]