Spectral Diffuse Attenuation Coefficient

VERSION	**v1.0**
RELEASE DATE	**Apr 10th, 2024**
KEYWORDS	**OCEAN COLOR** Under: EARTH SCIENCE > OCEANS > OCEAN OPTICS **ATTENUATION/TRANSMISSION** Under: EARTH SCIENCE > OCEANS > OCEAN OPTICS **SPECTRAL IRRADIANCE** Under: EARTH SCIENCE > ATMOSPHERE > ATMOSPHERIC RADIATION
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DOI	**10.5067/E6JP5Z1CGRFT**

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Abstract

This algorithm returns the spectral diffuse attenuation coefficient of downwelling irradiance, $K_d(\lambda)$ [units: m^{-1}], a key parameter used to characterize the underwater light field. $K_d(\lambda)$ is an ecologically relevant variable used to assist our understanding of marine phytoplankton ecology and oceanic primary productivity. The algorithm described in this ATBD returns per-pixel spectral $K_d(\lambda)$ over the visible range (400 - 700 nm) using a physics-based model Lee et al., 2005a. The approach is contingent upon valid spectral inherent optical properties (IOPs; total absorption coefficient, total backscattering coefficient, and seawater backscatteirng coefficient) and the solar zenith angle.

Plain Language Summary

We use this algorithm to derive the spectral diffuse attenuation coefficient of downwelling irradiance, $K_d(\lambda)$, which describes how sunlight of different wavelengths (colors) is dissipated as it travels downward into the ocean. This data helps us understand the life of marine phytoplankton (microscopic algae) which require sunlight to grow. This data can also help use understand changes in water clarity in coastal and inland waters. The algorithm used is based on a scientific understanding of the physics of light in water. The approach relates the absorption and scattering properties of water, which are measured by ocean color satellites, to light attenuation.

1. Introduction

This algorithm returns the spectral diffuse attenuation coefficient for downwelling irradiance, $K_d(\lambda)$ [units: m^{-1}], calculated from inherent optical properties (IOPs) using a semianalytical model Lee et al., 2005a. The model requires the total spectral absorption coefficient, $a(\lambda)$ [units: m^{-1}], the total spectral backscattering coefficient, $b_b(\lambda)$ [units: m-1], seawater spectral backscattering coefficient, $b_{bw}(\lambda)$ [units: m^{-1}], and the solar zenith angle, θ_{solz} [units: degrees]. The model inputs $a(\lambda)$ and $b_b(\lambda)$ are derived using the default configuration NASA's Generalized Inherent Optical Properties algorithm framework (GIOP-DC) Werdell et al., 2013.

The implementation is contingent on valid remote sensing reflectances, $R_{rs}(\lambda)$ [units: sr^{-1}], in the visible (400 - 700 nm) spectral range such that the required IOPs can be derived using GIOP-DC. The algorithm is applicable to all current ocean color sensors supported by NASA. The $K_d(\lambda)$ product are distributed as part of the NASA standard Level-2 IOP product suite and the Level-3 IOP product suite.

2. Context / Background

2.1. Historical Perspective

Historically, the diffuse attenuation coefficient has been derived from ocean color satellite data using empirical models. Such approaches relate K_d, typically at a single wavelength, to the ratio of the remote sensing reflectances (or water-leaving radiances) at two wavelengths Austin & Petzold, 1981Mueller, 2000.

NASA Historical Approach

Since the SeaWiFS era, NASA has produced the diffuse attenuation coefficient product computed at a single wavelength at or near 490 nm, $K_d(490)$ [units: m^{-1}]. In past NASA ocean color reprocessings ($\leq$ R2022), the algorithm used for deriving $K_d(490)$ was an empirical band ratio algorithm. The algorithm modeled $K_d(490)$ using a fourth order polynominal relationship:

$$\log_{10}(K_{d,bio}(490)) = a_0 + \sum_{i=1}^{4} a_i \left(\log_{10}\left(\frac{R_{rs}(\lambda_{blue})}{R_{rs}(\lambda_{green})}\right)\right)^i \quad (1) \qquad (1)$$

and

$$K_d(490) = K_{d,bio}(490) + 0.0166. \quad (2) \tag{2}$$

The blue and green wavelengths (λ_{blue} and λ_{green}) are sensor-specific. The polynomial coefficients a_0, a_1, a_2, a_3, and a_4 were derived using the NASA bio-Optocal Maine Algorithm Dataset (NOMAD) version 2 (https://seabass.gsfc.nasa.gov/wiki/NOMAD) and are also sensor-specific.

Alternative approaches

Work by Lee et al. (2005b) compared three appraoches for deriving near-surface layer-averaged K_{d}: (i) an empirical two-band reflectance ratio model, (ii) an empirical model that relates K_d to chlorophyll-a pigment concentration, *Chla* [units: mg m^{-3}], and (iii) a seminalytical model that models K_d as a function of IOPs. The inter-comparison study showed that the IOP-based approach had better predictive skill than the emprical models Lee et al., 2005b. The IOP-based approach has other benefits including capturing variability in K_d due to changes in solar zenith angle and not requiring extensive field data training datasets. In addition, when the ratio of $R_{rs}(\lambda_{\text{blue}})$ to $R_{rs}(\lambda_{\text{green}})$ approaches an asymptotic value, typically at larger K_{d} values, the emprical models become much less senstive to changes in K_d Lee et al., 2005b. The IOP-based model also captures variability in K_d due to optical absorption and backscattering, whereas the empirical band ratio-type algorithms are typically senstive to just absorption Lee et al., 2005b.

2.2. Additional information

For the suite of standard PACE OCI data products and future OB.DAAC reprocessings of supported ocean color sensors, the IOP-based $K_{\text{d}}(\lambda)$ model of Lee et al. (2005a; 2013) will be used. Input IOPs are currently those derived using the default configuration of Generalized Inherent Optical Properties algorithm framework (GIOP-DC) Werdell et al., 2013.

The K_d model can utilize $a(\lambda)$ and $b_b(\lambda)$ derived using other (non-GIOP) IOP algorithms. We note that a number of other IOP algorithms are currently implemented within NASA's Ocean Color Software Suite (OCSSW) for those wishing to customize and experiment with ocean color data processing.

3. Algorithm Description

3.1. Scientific Theory

The spectral diffuse attenuation coefficient, $K_d(\lambda)$ [units: m-1], can be conceptialized by considering the propagation of light vertically downwards through a layer of water column. Downwelling irradiance just beneath the surface, $E_s(\lambda,0\text{-})$ [units: W m^{-2}], can be calculated at depth, z [units: m], using the Beer-Lambert law:

$$E_s(\lambda, z) = E_s(\lambda, 0^-)e^{-K_d(\lambda)z} \quad (3) \tag{3}$$

where, $E_s(\lambda,z)$ [units: W m^{-2}] is irradiance at depth z and $K_d(\lambda)$ is the average spectral diffuse attenuation coefficient of the layer from the surface to a depth z. From Eq. 3 we see that $K_d(\lambda)$ drives the extinction of light as it propagates vertically downwards through the layer. By rearranging Eq. 3, we can express layer-averaged $K_d(\lambda)$ as:

$$K_d(\lambda) = -\frac{1}{z} log\left(\frac{E_d(\lambda, z)}{E_d(\lambda, 0-)}\right). \quad (4) \tag{4}$$

Via radiative transfer simulations, analytical relationships have been developed that allow $K_d(\lambda)$ to be modelled as a function of IOPs, specifically, the total spectral absorption coefficient, $a(\lambda)$ [units: m^{-1}], and the total backscattering coefficient, $b_b(\lambda)$ [units: m^{-1}] Sathyendranath & Platt, 1989:

$$K_d(\lambda) = f(a(\lambda), b_b(\lambda)). \quad (5) \tag{5}$$

3.1.1. Assumptions

No content available.

3.2. Mathematical Theory

The IOP-based K_d model

The model used to derive per-pixel $K_d(\lambda)$ values was developed by Lee et al., 2005a Lee et al., 2013 and is expressed mathematically as:

$$K_d(\lambda) = m_0\, a(\lambda) + (1 - m_4 \eta_w) \times m_1 \left(1 - m_2\, e^{-m_3\, a(\lambda)}\right) b_b(\lambda) \qquad (6) \tag{6}$$

where,

$$m_0 = 1.0 + 0.005\theta_{solz} \;\; \text{and} \qquad (7) \tag{7}$$

$$\eta_w(\lambda) = \frac{b_{bw}(\lambda)}{b_b(\lambda)}. \qquad (8) \tag{8}$$

The coefficients m_1, m_2, m_3, and m_4 are 4.259, 0.520, -10.800, and 0.265, respectively. The coefficient $b_{bw}(\lambda)$ is the spectral backscattering coefficient for seawater which is computed usign a tempeature-salinity depenent model Zhang et al., 2009-03. Values of $a(\lambda)$ and $b_b(\lambda)$ are derived using the default configuration of the Generalized Inherent Optical Propeties algorihtm (GIOP-DC) Werdell et al., 2013.

Output quality control

After $K_d(\lambda)$ are generatd they are screened for validity and rejected if:

$$K_d(\lambda) < 0.016 \text{ m}^{-1} \qquad (9) \tag{9}$$

$$K_d(\lambda) > 6.4 \text{ m}^{-1} \qquad (10) \tag{10}$$

3.2.1. Assumptions

Note that in Eq. 6, we are computing the layer-averaged $K_d(\lambda)$ for a layer that extends from the surface to the depth depth at which $E_d(\lambda,z)$ is 10% of $E_d(\lambda,0\text{-})$. In Lee et al (2005a) this is expressed as $\bar{K}_d(E_{10\%})$. See section 5.4 in Lee et al (2005a) for further discussion.

3.3. Algorithm Input Variables

Name	Long Name	Unit
a_vvv	Total spectral absorption coefficient	m^{-1}
bb_vvv	Total spectral backscattering coefficient	m^{-1}
bbw_vvvv	Backscattering coefficient of seawater	m^{-1}
solz	Solar zenith angle	degrees

3.4. Algorithm Output Variables

Name	Long Name	Unit
Kd_vvv	Spectral diffuse attenuation coefficient	m^{-1}
Kd_unc_vvv	Spectral standard uncertainties for the diffuse attenuation coefficient	m^{-1}

4. Algorithm Availability

4.1. Location of Implemented Algorithm #1

URL	**https://oceancolor.gsfc.nasa.gov/docs/ocssw/get__Kd_8c.html**
DESCRIPTION	**This is the source code of NASA's Ocean Color Science Software (OCSSW) for Kd and Kd_unc which can be obtained from satellite remote sensing data via command line processing or using the graphical user interface to OCSSW known as SeaDAS (https://seadas.gsfc.nasa.gov). The following instructions provide guidance on processing data with SeaDAS: https://seadas.gsfc.nasa.gov/help-8.3.0/processors/ProcessL2gen.html#PRODUCTS_TAB.**

5. Algorithm Usage Constraints

The algortihm requires valid values of a(λ) and b_b(λ). End-users are advised to carefully consider the validity of IOP data products, and subsequently the derived K_d(λ), for extreme conditions such as highly turbid, optically shallow, and inland/freshwater systems.

6. Performance Assessment Validation

6.1. Performance Assessment Validation Methods

After production, K_d(λ) are validated using *in situ* data archived in the NASA SeaWiFS Bio-optical Archive and Storage System (SeaBASS; Werdell et al., 2003). The product validation analyses compare satellite and *in situ* measurements following the approach of Bailey & Werdell, 2006.

Using the time (T_{is}) and location (L_{is}) for an in-situ measurement in SeaBASS, a coincident level-2 (L2) swath resolution file is selected from OB.DAAC containing targeted K_d(λ) products and associated standard uncertainties. Note, an L2 file is not always available due to orbit gaps. A window centered closest to L_{is} (5×5 pixels) is designated, from which 25 pixels are extracted. To be considered for validation, T_{is} must be within +/- 3 hours of satellite measurement, the sensor zenith angle < 60°, and solar zenith angle <75°. Pixels within the 5 x 5 window are not considered valid if they are flagged during data processing (LAND, HIGLINT, HILT, STRAYLIGHT, CLDICE, ATMFAIL, LOWLW, FILTER, NAVFAIL, NAVWARN; https://oceancolor.gsfc.nasa.gov/resources/atbd/ocl2flags/). If more than 50% of pixels are invalid, the 5 x 5 window box is rejected as a potential validation point.

If more than 50% of pixels in the 5x5 window are valid, spatial homogeneity is evaluated. This is done by computing the median of the coefficient of variation (CV; standard deviation divided by the mean) for several ocean color products (R_{rs} between 405 and 570 nm, aerosol optical thickness at 869 nm). The median value of the CVs must be less than 15% for the 5 × 5 pixel window. We note that the center pixel of the 5 x 5 window closest to L_{is} does not have to be valid as long as there are sufficient valid pixels in the box that meet the homogeneity requirement.

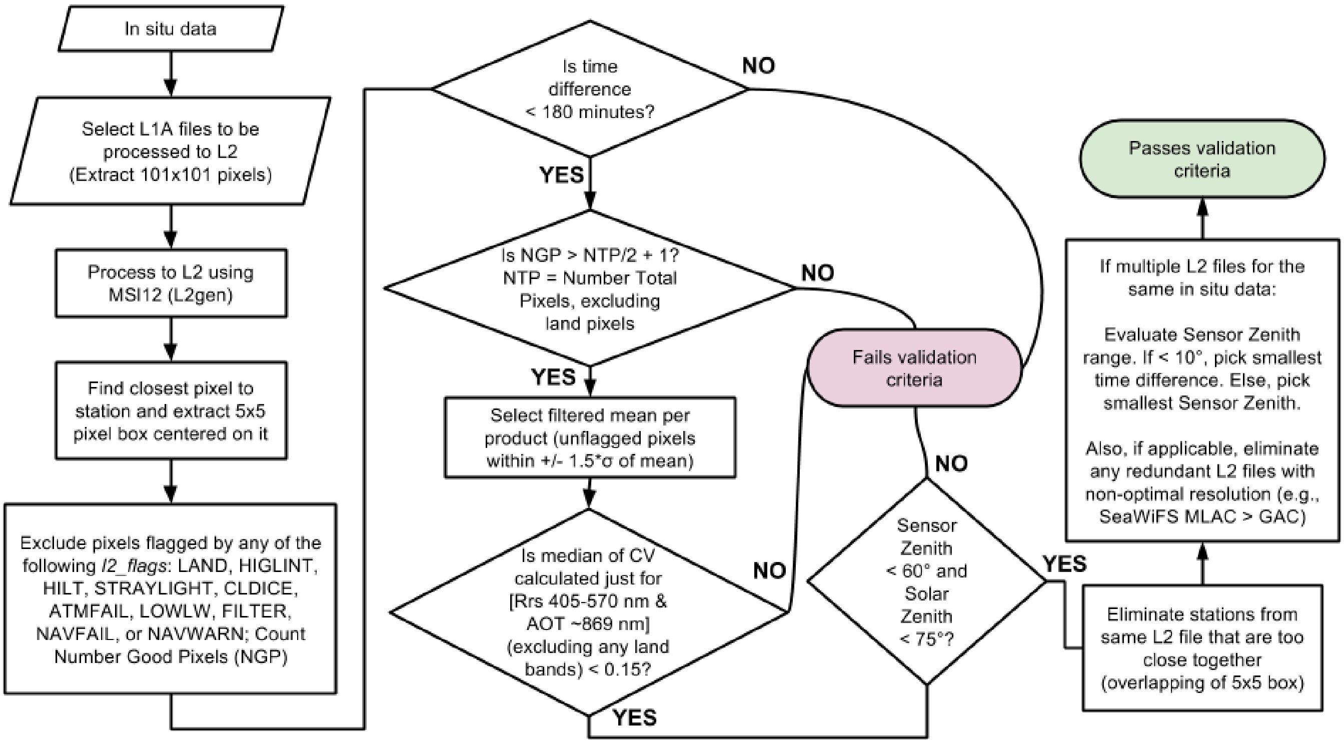

Figure 1: **Figure 1:** Flowchart of validation processing highlighting the applied exclusion criteria. Adapted and updated from Bailey and Werdell (2006).

This approach of validation is operationally applied by the OB.DAAC to most ocean color sensors. For complete details see: https://seabass.gsfc.nasa.gov/wiki/validation_description. There are a few key recommendations we make from our experience applying the described method to satellite data:

(1) Use a consistently processed in situ data set

(2) Eliminate suspect in situ data (e.g. from optically shallow waters) from the validation set

(3) Use a narrow time window for determining coincidence (i.e. no more than ± 3 h) between T_{is} and satellite data records

(4) Use native resolution satellite products (i.e., avoid sub-sampled data)

(5) Use the mean of a 5 × 5 pixel box centered on the in situ location

(6) Appropriately mask satellite pixels per the L2 quality flags

(7) Use a homogeneity test (e.g. CV) to minimize the impact of geophysical variability in the 5 × 5 pixel box on the satellite measurement meanFollowing these recommendations

will aid in the analysis of the resulting validation results by minimizing the systemic uncertainties.

6.2. Performance Assessment Validation Uncertainties

Uncertainties in $K_d(\lambda)$ are sourced from standard uncertainty in the spectral absorption coefficient, $u(a(\lambda))$, and the spectral backscattering coefficient, $u(b_b(\lambda))$, internal model uncertainties, u(mod), due to assumptions and approximations, and within pixel variability due to horizontal inhomogeneity. Standard uncertainties (1-σ) are estimated for all $K_d(\lambda)$ via analytical uncertainty propagation following the framework outlined by McKinna et al. (2019). More details can be found in IOCCG report 18 IOCCG, 2019 and McKinna et al., 2019.

6.3. Performance Assessment Validation Errors

Based on McClain, 2009, the satellite data product accuracy goals generally accepted by the international community are ± 5% for water-leaving radiances. The PACE mission adopted more rigorous uncertainties for $R_{rs}(\lambda)$ retrieved by its Ocean Color Instrument Ahmad et al., 2019. A number of evaluations have been published, such as the global analyses by Gregg & Casey, 2004 (SeaWiFS chlor_a) and Bailey & Werdell, 2006 (SeaWiFS water-leaving radiances, chlor_a, and $K_d(490)$) to name only a very few, and the regional analysis by Zibordi et al., 2006 that compared SeaWiFS, MODIS, and MERIS water-leaving radiances to SeaPRISM observations from the Acqua Alta tower. Overall, these results indicate quite good performance. However, regional differences can be large.

IOP-based $K_d(\lambda)$ is a new data product that has been evaluated in literature Lee et al., 2005bLee et al., 2013 and extends upon legacy $K_d(490)$ products derived using an empircal approah. At the release of this ATBD, we have yet to complete a full data reprocessing and validation of this new spectral product. However, validation of legacy band ratio $K_d(490)$ has been performed relative to all available match-ups from SeaBASS. Statistical analysis, scatter plots and frequency distribution comparisons of the satellite-derived legacy $K_d(490)$ to in situ match-ups are provided for each mission (SeaWiFS, MODIS Aqua/Terra, VIIRS SNPP/NOAA20, MERIS, OLCI S3A/S3B) on the following web pages:

https://oceancolor.gsfc.nasa.gov/data/reprocessing/r2022/seawifs/
https://oceancolor.gsfc.nasa.gov/data/reprocessing/r2022/aqua/
https://oceancolor.gsfc.nasa.gov/data/reprocessing/r2022/terra/
https://oceancolor.gsfc.nasa.gov/data/reprocessing/r2022/snpp

https://oceancolor.gsfc.nasa.gov/data/reprocessing/r2022/noaa20/
https://oceancolor.gsfc.nasa.gov/data/reprocessing/r2022/meris/
https://oceancolor.gsfc.nasa.gov/data/reprocessing/r2022/s3a/
https://oceancolor.gsfc.nasa.gov/data/reprocessing/r2022/s3b/

7. Data Access

7.1. Input Data Data Access

7.1.1. Entry #1

URL	**https://oceancolor.gsfc.nasa.gov/data/download_methods/**
DESCRIPTION	**a_vvv and bb_vvv level 2 products found in L2 IOP suite products can be used for valid Kd production. They can be downloaded from the ocean color website following the different methods described in the link.**

7.2. Output Data Data Access

7.2.1. Entry #1

URL	**https://oceancolor.gsfc.nasa.gov/data/download_methods/**
DESCRIPTION	**Kd as one of the NASA standard products can be downloaded from the ocean color website following the different methods described in the link.**

7.3. Important Related URLs

7.3.1. Entry #1

URL	https://seabass.gsfc.nasa.gov/search#val
DESCRIPTION	**SeaBASS validation search provides the satellite-derived Kd(490) (currently only legacy band ratio model) versus in situ data validation.**

8. Contacts

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