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OLCI Level 2 Algorithm Theoretical Basis Document Transparency products

OLCI Level 2

Algorithm Theoretical Basis Document

Transparency products

- Kd(490)
- Secchi disk depth
- Heated layer depth

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1. INTRODUCTION

1.1 Purpose and scope

This Algorithm Theoretical Basis document (ATBD) is written for the Ocean and Land Colour Imager (OLCI) of the Earth Observation Mission SENTINEL 3 of the European Space Agency (ESA).

The purpose of this document is to lay out algorithms for the sea water transparency products. As much as possible, basic principles of the algorithm and the description of their various segments will refer to publications in the peer-reviewed scientific literature. When such literature exists, minimum information will be provided here for the sake of clarity, and the reader will be referred to the relevant literature for further information.

1.2 Algorithm identification

This algorithm is identified under reference "SD-03-C16" in the sentinel-3 OLCI documentation.

1.3 Acronyms

ATBD Algorithm Theoretical Basis Document

CWOC Clear Water Ocean Colour ESA European Space Agency

MERIS Medium Resolution Imaging Spectrometer

OLCI Ocean and Land Color Imager

PAR Photosynthetic Available Radiation

SENTINEL 3 Third series of "sentinel" (ESA satellites)



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1.4 Symbols

Symbol	definition	Dimension / units
Geometry, wavele	ngths	
λ	Wavelength	nm
hetas	Sun zenith angle $(\mu s = \cos(\theta s))$	degrees
$ heta_{\!\scriptscriptstyle m V}$	Satellite viewing angle $(\mu v = \cos(\theta v))$	degrees
$arDelta \phi$	Azimuth difference between the sun-pixel and pixel-sensor half vertical planes	degrees
Water properties		
Chl	Chlorophyll concentration	mg m ⁻³
$a(\lambda)$	Total absorption coefficient	m^{-1}
$b(\lambda)$	Total scattering coefficient	m ⁻¹
$bb(\lambda)$	Total backscattering coefficient	m^{-1}
$bbp(\lambda)$	Total backscattering coefficient due to particles	m ⁻¹
$b_{W}(\lambda)$	Total water scattering coefficient	m ⁻¹
$bbw(\lambda)$	Total backscattering coefficient due to pure water	m ⁻¹
$R(\lambda, 0^{-})$	Diffuse reflectance at null depth, or irradiance ratio (E _u / E _d) (upward and downward irradiances, respectively)	dimensionless
$Kd(\lambda)$	Diffuse attenuation coefficient for the downward plane irradiance	m ⁻¹
Kd(PAR)	Diffuse attenuation coefficient for the downward plane Irradiance for the whole visible spectrum	m ⁻¹
$K_{W}(\lambda)$	Diffuse attenuation coefficient for the downward plane irradiance, for seawater only	m ⁻¹
$Q(\lambda, \theta s, \theta v, \Delta \phi)$	Factor describing the bidirectional character of R(λ , 0^-) subscript 0 when $\theta_{\rm S} = \theta_{\rm V} = 0$	sr
$ ho_{\scriptscriptstyle{\mathrm{w}}}\!(\lambda)$	Normalised water-leaving reflectance (i.e., the reflectance if there were no atmosphere, and for $\theta_s = \theta_V = 0$)	dimensionless
Air-water interface		
$\Re(heta)$	Geometrical factor, accounting for all refraction and reflection	dimensionless
_	effects at the air-sea interface (Morel and Gentili, 1996)	
Transparency pro		
C_{SD}	Contrast between the Secchi disk and the surrounding water	ater compared to th
r	albedo of the Secchi disk	
$egin{array}{c} C_{ m obs} \ Z_{ m SD} \end{array}$	Detection threshold as can be detected by a human eye Secchi Disk Depth	m
$\sigma(Z_{ m SD})$	Standard deviation of the Secchi Disk Depth	m m
O(ZSD)	Standard deviation of the Second Disk Depth	1111



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2. ALGORITHM OVERVIEW

2.1 Objectives

The objective is to derive several ocean colour products characterising the transparency from the spectrum of the normalised water-leaving reflectances.

The following products are derived here:

- The diffuse attenuation coefficient at 490 nm, expressed in units of m⁻¹.
- The water transparency expressed under the form of a Secchi depth in units of m.
- The depth of light penetration into the sea water expressed as a heated layer depth in units of m.

Notes:

• The diffuse attenuation coefficient and the Secchi disk depth are derived from various combinations of the fully normalized water-leaving reflectances.



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3. The diffuse attenuation coefficient at 490 nm (Kd(490))

3.1 K_a (490) algorithm

The diffuse attenuation coefficient for the downward plane irradiance at wavelength λ and at a given depth z is defined as:

$$K_d(\lambda) = -\left[1/E_d(z, \lambda)\right] \left[dE_d(z, \lambda)/dz\right] \text{ or } K_d(\lambda) = -\left[d\left[lnE_d(z, \lambda)\right]/dz\right]$$
 (1)

Many realisations of this coefficient are possible, as a function of the depth range over which it is computed. It can be a local coefficient around a given small depth interval between any depths z1 and z2:

$$K_d(\lambda) = -\frac{\log[E_d(z_1, \lambda) / E_d(z_2, \lambda)]}{z_2 - z_1}$$
(2)

It can be computed for the upper layer defined from below the surface (0⁻) to a given depth z:

$$K_{d} = -\frac{\log[E_{d}(z) / E_{d}(0^{-})]}{z}$$
(3)

It can also be an Ed-weighted average value computed over a certain depth z, e.g., the 1% light level (Kirk, 2003)

$$K_{d,av}(\lambda) = \frac{\int_{0}^{z} K_{d}(z,\lambda)E_{d}(z,\lambda)dz}{\int_{0}^{z} E_{d}(z,\lambda)dz}$$
(4)

Practically speaking, the Kd's found in *in situ* data bases are essentially of the second category. The reason is simply that measuring properly Ed(Z) at sea requires that the irradiance sensor is placed at a depth where the irradiance fluctuations due to surface waves are small enough (or even absent). This depth can be as large as ~30 meters in clear waters. Then this Ed(z) measurement is combined with the downward irradiance measured above the surface after it is multiplied by the transmission across the air-sea interface, which provides $Ed(0^-)$, in order to get the Kd as per Eq (5) above.

We propose here to use the "OK2-560" algorithm proposed by Morel et al. (2007). It is based on the 490-560 reflectance ratio, and has the form:

$$K_{d}(490) = K_{w}(490) + 10^{\sum_{x=0}^{n} A_{x}(\log_{10} \rho_{490,560})^{x}}$$
(5)

Where Kw(490) is 0.0166 m-1, ρ 490,560 is the ratio of the normalized water-leaving reflectance at 490 and 560 nm, and the n+1=5 coefficients Ax have the values :

A0: -0,82789 A1: -1,64219 A2: 0,90261 A3:-1,62685 A4: 0,088504



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$3.2~K_d(490)$ validation

The expression of Kd(490) has been validated (Morel et al. 2007) against independent in situ measurements (the NOMAD database – Werdell and Bailey 2005) and indicates very good agreement (see figure below) with a determination coefficient of 0,921 and no bias.

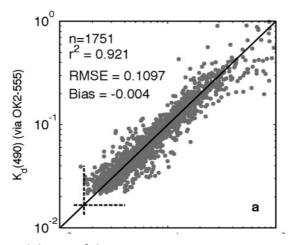


Figure 1- Validation of the OK2-555 algorithm against the NOMAD in situ data set (Werdell and Bailey, 2005)



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4. Secchi disk depth

4.1 Secchi disk depth algorithm

4.1.1 Background

The Secchi disk depth Z_{SD} is, by nature, a good characterisation of the vertical visibility underwater. It is linked to two optical parameters; the vertical diffuse attenuation coefficient K_d (m⁻¹) which gives the quantity of light available in the water column and the attenuation coefficient c (m⁻¹) that determines the propagation of light through the water mass.

Tyler (1968) has given a simplified expression of the Secchi disk depth:

$$C_{Obs} = C_{SD} e^{-(c+K_d)Z_{SD}} {1}$$

In which C_{SD} is the contrast between the Secchi disk and the surrounding water compared to the surrounding water and C_{Obs} is the detection threshold as can be detected by a human eye. Z_{SD} is the maximum depth to which Secchi disk can be observed.

The above expression is equivalent to:

$$Z_{SD} = -\frac{\log\left(\frac{C_{Obs}}{C_{SD}}\right)}{(c + K_d)} = -\frac{\gamma}{(c + K_d)}$$
(2)

The development that was done and published in (Doron et al. 2007) and which is the baseline for this ATBD is based on the determination of both part of this last equation (the numerator which is purely due to observation condition and the denominator which is linked to water optical properties) to estimate the Secchi disk depth.

4.1.2 Computation of (c+Kd)

The computation of the attenuation part of expression (2) is summarised here below.

(i) The reflectances used in the following are first expressed underwater starting from the fully normalised water leaving reflectances as follows:

$$R(0^{-}) = \frac{\rho_{w}}{\frac{\pi \Re}{O} + \rho_{w} \overline{r}}$$
(3)

in which, \Re =0,529 , Q=4 and \bar{r} =0,48

(ii) The particle backscattering coefficient b_{bp} (m⁻¹) is computed by using sub-surface reflectances at 560 nm and the ratio of reflectances at 490 nm and 560 nm.

$$b_{bp}(490) = function\left(\frac{R(560)}{R(490)}, R(560)\right)$$
 (3')



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The function transfer is based on a hyperbolic tangent.

(iii) The total backscattering coefficient b_b (m⁻¹) and absorption coefficient at 490 nm are computed as follows (where the pure sea water backscattering coefficient b_{bw} (m⁻¹) is known from its value at 550 nm

$$b_{bw}(\lambda) = 0.5 b_w(550) \left(\frac{\lambda}{550}\right)^{-4.32}$$
 (4)

$$b_b(490) = b_{bp}(490) + b_{bw}(490) \tag{5}$$

$$a(490) = \frac{0.422b_b(490)}{R(490)} \tag{6}$$

(iv) The diffuse vertical attenuation coefficient K_d (m⁻¹) and the attenuation coefficient c (in m⁻¹) are then computed as follows (where θ_s is the solar zenith angle) (Lee et al. 2005):

$$K_d(490) = (1 + 0.005\theta_s)a(490) + 4.18(1 - 0.52e^{-10.8a(490)})b_b(490)$$
(7)

and

$$c(490) = a(490) + b_{bp}(490) + b_{bw}(490)$$
(8)

After a first step of validation it appeared that, for clear water (i.e. high Secchi disk depths), as the uncertainties on c and K_d increase, the accumulation of adjustments (steps in the previous list) leads to a wrong estimates of Z_{SD} . In order to circumvent this problem and to cover all types of water with an equal quality a database of value of 1/(c+Kd) was created for both case 1 (Morel data) and case 2 waters (Coastlooc database). A fitting procedure has then been applied to adjust a ratio of reflectances to these data, leading to a final expression for the "optical term" under the form :

$$\frac{1}{c + K_d} \approx \alpha \frac{R(560)}{R(490)} \tag{9}$$

4.1.3 Computation of γ

$$\gamma(\lambda) = \log \left(\frac{R_{environment} \left(0^{+} \right)}{r - R_{environment} \left(0^{+} \right)} \left(C_{Obs} \right) \right)$$
(10)

 γ can be approximated by a simplified convolution with the photopic spectrum, using the values of γ at 490 and 560 nm.

$$\gamma = \frac{\gamma(560) + 0.4\gamma(490)}{1.4} \tag{11}$$



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4.2 Secchi disk depth validation

The validation of the Secchi's depth expression has been performed by collecting the maximum numbers of observations coincident with MERIS and/or MODIS acquisition. The table below indicates the data source (campaigns or observation networks), the number of available matchup and the range of Secchi depths.

Campaign	Geographical locations	Availability	Secchi depth min-max (number)
Biosope	Equatorial Pacific	October - December 2004	10.5-70
Calcofi	Santa-Barbara channel	Two weeks – each quaterly	3-50
Dyfamed	Western Mediterranean	One observation per month	8-27
Gauss	North Sea	Summer 2003 and 2004	3-18
IMR	Danish seas	April 2004	2-15
Modycot	Bay of Biscay	October 2002 and spring 2003	2-17
MREA-Elbe	Elba - Mediterranean	May 2003	18-21

Table 1– Available data set for evaluation and validation of Secchi disk depth

The correspondence with MERIS and/or MODIS is summarised in the following table; in total 461 matchups were found for MERIS and 706 for MODIS (by allowing a temporal window of [-2j, +2j] between the scene availability and the measurement.

	MERIS	MODIS
Biosope	10	15
Boussole	5	21
Calcofi	160	228
Dyfamed	24	57
Elbe	3	8
Gauss	102	187
IMR	42	25
Modycot	50	122
Optic	46	21
Seine	21	22
Total	463	706

Table 2– Results of matchup with MERIS and MODIS for validation of Secchi disk depth

The scatter plots of the matchups are presented on the two next figures – one for MERIS and one for MODIS. The determination coefficient is rather high and the slope is very close to 1, this makes the proposed algorithm an excellent candidate for the SENTINEL 3 mission applicable to all waters.

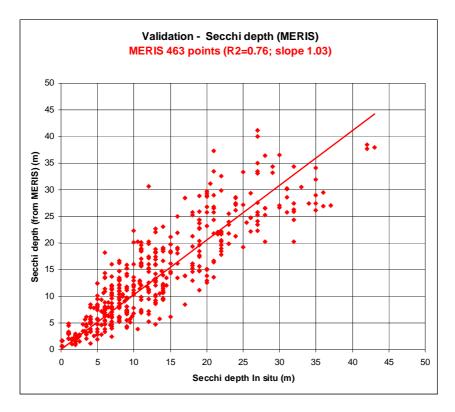


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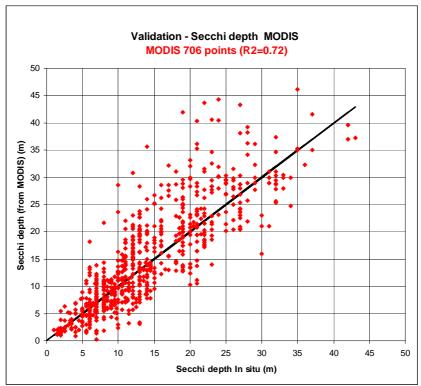


Figure 2- Validation of the Z_{SD} for various match-ups and for (up) MERIS and (down) MODIS



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4.3 Secchi disk depth error bars

The quality of the Secchi disk depth has been derived from the validation dataset, described in the previous section. The analysis has been performed for several classes of depth (by layer of 5 meters) in order to derive the level of accuracy that could be applied to SENTINEL 3 outputs. Since no real bias is observed, an analytical expression for the uncertainties (one sigma) is proposed as follows.

$$\sigma(Z_{SD}) = 1,686 \log(Z_{SD}) + 0,524 \tag{12}$$

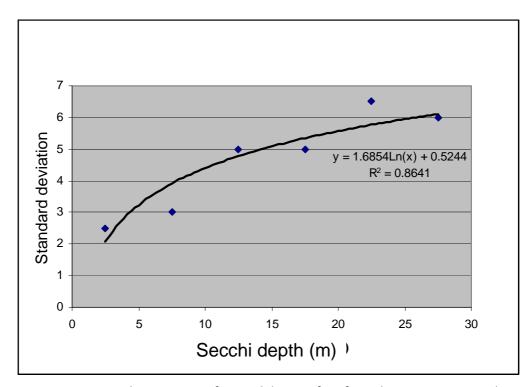


Figure 3- Error bar estimates from validation of Z_{SD} formulation vs in situ truth



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5. Heated layer depth

5.1 Heated layer depth algorithm

The heated layer depth is the sea surface layer that is impacted by the solar heat flux. It is a concept directly based on the light penetration for the whole solar spectrum and thus directly linked to the vertical attenuation of the light.

It is proposed to be computed through the knowledge of the vertical diffuse attenuation coefficient Kd at 490 nm (Morel et al. 2007)

$$K_d(\lambda) = K_w(\lambda) + \chi(\lambda) \cdot chl^{e(\lambda)}$$
(13)

with: $K_w(490) = 0.0166 \text{ m}^{-1}$

 $\chi(490) = 0.08349$

e(490) = 0.63303

From this knowledge, the heated layer depth (Z_{HL}) is directly computed using the following equation.

$$Z_{hl} = \frac{2}{K_d(PAR)} \tag{14}$$

with:

$$K_d(PAR) = 0.0665 + 0.874 \cdot K_d(490) - \frac{0.00121}{K_d(490)}$$
(15)

This algorithm is implemented and is used operationally in GlobColour. Here below is an example of a global map of heated layer depth (monthly average).



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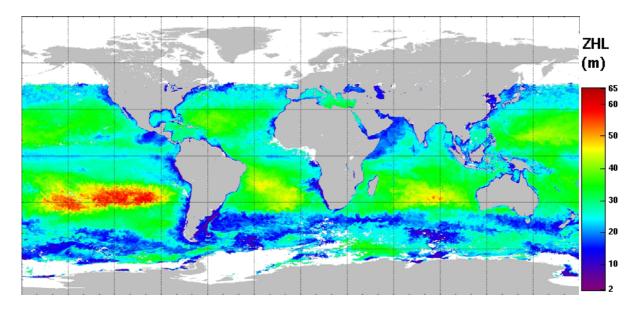


Figure 4- Z_{HL} monthly product – December 2003

5.2 Heated layer depth validation

By construction, the Z_{hl} directly depends on the $K_d(PAR)$ which is a measurable quantity. The validation of the former is thus based on the validity of the latter. Here below is a comparison (extracted from Morel et al. 2007) between the formulation (13) and an independent database; the SCAPA archive (Self-Consistent AOP Profiles Archive;S.B. Hooker) This database was created from an extensive set of field campaigns throughout the world ocean (McClain et al., 2004), primarily (albeit not exclusively) in Case-1 waters. The free-fall multichannel sensor profilers (measuring upward radiance and irradiance, and downward irradiance) were operated according to strategies (Hooker & Maritorena, 2000) which are in strict adherence to the Ocean Optics Protocols (Mueller, 2003); this includes a rigorous quality control of the data (acquisition and processing), and a set of quality assurance procedures during the sensor calibration. The radiometric calibration facilities are traceable to the National Institute of Standards and Technology (Hooker et al., 2002).

The figure below indicates a good agreement between the proposed algorithm and an independent dataset.



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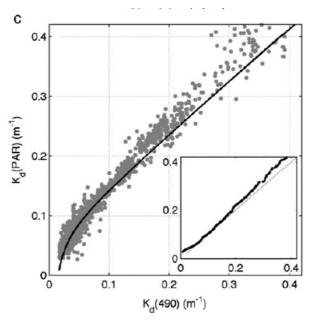


Figure 5- Proposed Algorithm for Kd(PAR) as a function of Kd(490) vs experimental observations



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6. ASSUMPTIONS AND LIMITATIONS

The algorithm proposed for the Secchi depth is valid for all types of waters. The reader is referred more specifically to Doron et al. (2006) for a detailed discussion about the Secchi depth algorithm.

The γ -factor is impacted by the sea-state, the sun irradiance and the cloud coverage. Some developments have been done with Hydrolight for the marine optical part. For effective sun irradiance over the scene, two models have been used, the first is RADTRAN (see Gregg and Carder, 1990). The second model computes the normalised distribution in all directions (Harrison and Coombes, 1988). The computations have been done for a range of wind speed values, solar zenith angles and cloud coverage. The impact would a few percent overestimate with increasing wind speed under clear sky conditions (which are the nominal conditions to apply the algorithm).

The algorithms proposed for Kd and Z_{HL} are valid above Case 1 waters, which means that they should be used with caution when applied over Case 2 waters. The same comment is valid for any other "non-nominal" conditions of applications, including but not being limited to, coccolithophorid blooms, residual, non-identified, sun glint, non-corrected adjacency effects, cloud shadows and unfiltered thin clouds. For the Kd and Z_{HL} algorithms, the reader is referred more specifically to Morel et al. (2007) for a detailed discussion.



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