Algorithm Description Ver.0 (2011.09.30)
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Theoretical Description of the Inherent Optical Property Algorithm

1. Derivation of the inherent optical properties (IOPs)

1.1 Physics of the problem

The IOP algorithm assumes that the remote sensing reflectance (R_{rs}) *just above the sea surface* (denoted by z=0+, where z represents a depth), or the water-leaving reflectance (ρ), is obtained in prior to its implementation.

The R_{rs} for a wavelength λ is defined by

$$R_{rs}(\theta_v, \varphi_v, z=0+, \theta_s, \varphi_s, \lambda) = L_w(\theta_v, \varphi_v, z=0+, \theta_s, \varphi_s, \lambda) / E_d(z=0+, \theta_s, \varphi_s,\lambda) \quad (1)$$

where L_w and E_d are the radiance and the downward plane irradiance at the observation angle (zenith angle θ_v, azimuth angle, φ_v) and the solar angle (zenith angle θ_s, azimuth angle φ_s). The water-leaving reflectance ρ can be obtained by $\rho = \pi R_{rs}$. Morel and Gentili (1993, 1996) showed that the Eq. (1) can be related to the absorption coefficient a_t and the backscattering coefficient of the bulk water b_{bt} by

$$R_{rs} (\theta_v, \varphi_v, z=0+, \theta_s, \varphi_s, \lambda)= \mathcal{R}(W, \theta_s, \varphi_s, \lambda)\, F(\theta_v, \varphi_v, z=0-, \theta_s, \varphi_s, \lambda)\, [b_{bt} (z=0-, \lambda)/a_t(z=0-, \lambda)] \quad (2)$$

where W denotes the wind speed. For convenience, all dependencies of the variables in Eq. 2 are omitted hereafter, unless otherwise specified. In addition, $\mathcal{R}F$ will be denoted by F' so that Eq.2 is simplified by

$$R_{rs} = F' [b_{bt}/a_t]. \quad (3)$$

The absorption coefficient of the bulk seawater is decomposed into the absorption coefficients of the pure seawater (a_w) and any other materials (a_o),

$a_t=a_w+a_o.$ (4)

Similarly, the backscattering coefficient of the bulk seawater is decomposed into the backscattering coefficients of the pure seawater (b_{bw}) and any other particles (b_{bp})

$b_{bt}=b_{bw}+b_{bp}.$ (5)

In the following sections, retrievals of the absorption and backscattering coefficients and their components will be described.

2. IOP algorithm

2.1 Derivation of the IOPs of bulk seawater from the remote sensing reflectance

Substitutions of Eqs 4 and 5 into Eq. 3 give a set of equations for wavelengths λ_1 and λ_2:

$$R_{rs}(\lambda_1)\, a_0(\lambda_1) - F'(\lambda_1)\, b_{bp}(\lambda_1) = F'(\lambda_1)\, b_{bw}(\lambda_1) - R_{rs}(\lambda_1)\, a_w(\lambda_1)$$
$$R_{rs}(\lambda_2)\, a_0(\lambda_2) - F'(\lambda_2)\, b_{bp}(\lambda_2) = F'(\lambda_2)\, b_{bw}(\lambda_2) - R_{rs}(\lambda_2)\, a_w(\lambda_2), \quad (6)$$

where R_{rs} is obtained by satellite observation and a_w and b_{bw} are assumed known for each λ (i.e. they are approximated by those by Morel, 1974; Pope and Fry, 1997, although a_w and b_{bw} are not constant and varies with temperature and salinity). Therefore, Eq. 6 can be solved to derive a_0 (λ_1 and λ_2) and b_{bp} (λ_1 and λ_2), when (1) the wavelength dependencies of the inherent optical properties (b_{bp} and a_0) and (2) $F'(\lambda)$ are known.

2.2 The wavelength dependencies of the inherent optical properties

The wavelength dependency of b_{bp} (denoted by ε_{bb}) is defined by

$$\varepsilon_{bb} = b_{bp}(\lambda_1)/b_{bp}(\lambda_2) = (\lambda_1/\lambda_2)^{-m} \quad (7)$$

where m is related to the particle size distribution and set as a parameter in the present algorithm. The wavelength dependency of a_0 is given by

$$\varepsilon_a = a_0(\lambda_1)/a_0(\lambda_2) \quad (8)$$

and it is another algorithm parameter. According to in situ observation, $\varepsilon_a = a_0(\lambda=490\text{nm})/a_0(\lambda=510\text{nm})$ is least variable and therefore applicable for a wide range of seawaters (Fig. 1). Since

SGLI does not have 510nm, it is replaced by the SGLI 530nm. Substitutions of Eqs. 7 and 8 into Eq. 6, as well as a use of $R_{rs}(\lambda=490)$ and $R_{rs}(\lambda=530)$ observed by satellite, gives a_0 (490), a_0 (530), $b_{bp}(490)$ and $b_{bp}(530)$ for a known F' (Determination of F' will be described in the next subsection). Once $b_{bp}(490)$ (or $b_{bp}(530)$) are obtained, substituting them into Eq. 7 gives b_{bp} at any wavelength λ for an "m" assumed: (e.g.)

$$b_{bp}(\lambda)= b_{bp}(490)\ (\lambda/490)^m. \tag{9}$$

Eq. 9 allows us to derive a_0 at any SGLI short wavelength λ, using Eqs. 3-5:

$$a_0(\lambda)=F'(\lambda)\ [\ b_{bw}(\lambda) + b_{bp}(\lambda)\ ] - a_w(\lambda). \tag{10}$$

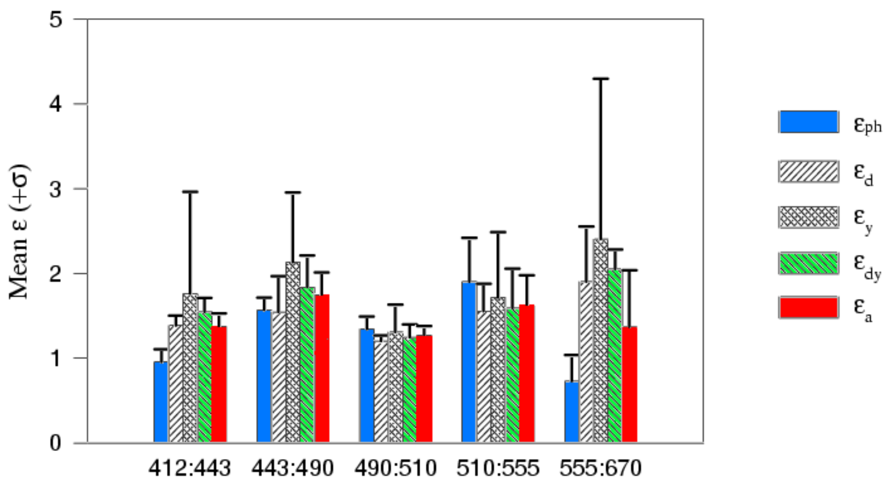

Fig. 1 Wavelength dependencies of the absorption coefficient of optical components determined from in situ observation (Smyth et al., 2006). $\varepsilon_{ph:}$ phytoplankton absorption, $\varepsilon_{d:}$ detritus absorption, $\varepsilon_{y:}$ CDOM, $\varepsilon_{dy:}$ detritus plus CDOM, $\varepsilon_{a:}$ total absorption without pure sea water component.

2.3 Derivation of F'

F' is initially assumed to be a certain value (e.g. a literature value). Firstly Eq. 6 is solved using the initially assumed value of F' (Fig. 2). The initial outputs a_t and b_{bt} are then used to search the new value of F' from a Look-Up Table (LUT) of F' which was pre-generated, by radiative transfer simulations in prior to the algorithm implementation, for the assumed conditions of the observation geometry (θ_v, φ_v), solar geometry (θ_s, φ_s) and inherent optical properties of seawater (a_t, b_t) at SGLI-wavelengths. Eq. 6 is again solved, and a_t (λ) and b_t (λ) are obtained from the second value of F' (λ), which are then used to search a third value, forth, … n^{th} value of F' (λ) from the LUT.

This procedure is repeated towards a convergence of $a_t(\lambda)$ and $b_t(\lambda)$ values (or equivalently, F' (λ)) obtained from Eq. 6. When either the IOP algorithm returns the outputs only within a tolerance range of $a_t(\lambda)$ and $b_t(\lambda)$ or a pre-fixed number of iteration is implemented, the iteration is terminated and a value of F' (λ) at the termination is given as a F' (λ) value wanted. At the same time, a_t and b_t at the termination are also given as the solutions for Eq. 6. In other words, F' (λ) and the set of $a_t(\lambda)$ and $b_t(\lambda)$ are simultaneously derived by the iteration.

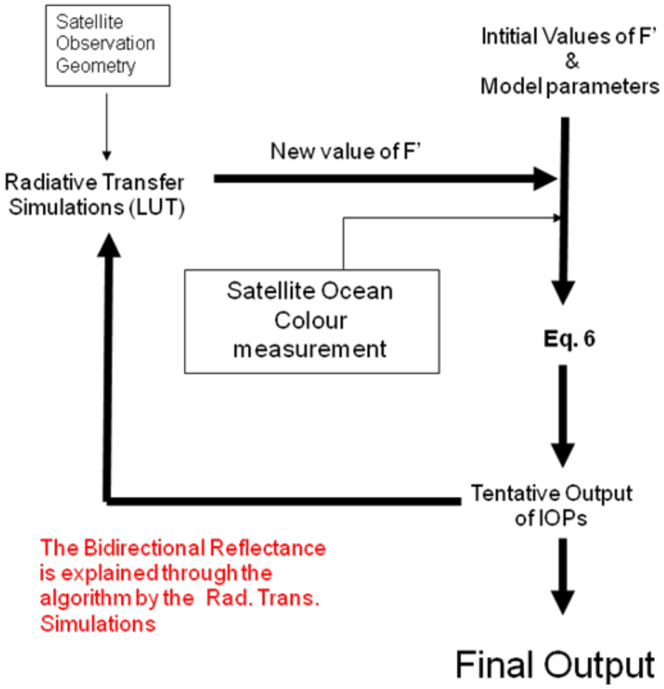

Fig. 2 Flow chart of the algorithm implementation

2.1 Decomposition of the IOPs of optical components from the IOPs of bulk seawater

The total absorption coefficient without pure seawater contribution a_o can further be decomposed by $a_o=a_{ph}+a_{dy}$ where the absorption coefficient of phytoplankton and of detritus plus chromophoric dissolved organic matters (CDOM) are denoted as a_{ph} and a_{dy}, respectively. The decomposition gives the simultaneous equations for two wavelengths λ_1 and λ_2.

$$a_o(\lambda_1)=a_{ph}(\lambda_1)+a_{dy}(\lambda_1)$$
$$a_o(\lambda_2)=a_{ph}(\lambda_2)+a_{dy}(\lambda_2). \tag{11}$$

In analogy to Eq. 8, Eq. 11 can be solved to obtain a_{ph} and a_{dy} at λ_1 and λ_2 when wavelength dependencies of a_{ph} and a_{dy} defined by $\varepsilon_{ph} = a_{ph}(\lambda_1) / a_{ph}(\lambda_2)$ and $\varepsilon_{ph} = a_{dy}(\lambda_1)$

$/a_{dy}(\lambda_2)$ are known. Fig. 1 shows that variations in ε_{ph} and ε_{dy} are least for the wavelength pair of λ_1=412nm and λ_2=443nm so that their values may be applied to a wide range of water types. Therefore, $\varepsilon_{ph}(412, 443)$ and $\varepsilon_{dy}(412, 443)$ are used in the present algorithm.

Since the wavelength dependency of a_{dy}, or equivalently ε_{dy}, can be expressed by (Smyth et al., 2006):

$$a_{dy}(\lambda)=a_{dy}(\lambda_1)\exp[-Y(\lambda-\lambda_1)], \qquad (12)$$

a_{dy} for any SGLI short wavelength λ can be obtained using $a_{dy}(413)$ and $a_{dy}(443)$ derived from Eq. 11. Given that $a_{dy}(\lambda)$ exponentially decreases with wavelength, $a_{dy}(\lambda)$ may be approximated to $a_y(\lambda)$(or $a_{CDOM}(\lambda)$) at relatively longer wavelengths within SGLI bands to the first approximation: i.e. $a_y(490) \sim a_{dy}(490)$. This however requires further investigations for a better estimation of $a_y(490)$.

Rearrangement of Eq. 11 gives

$$a_{ph}(\lambda)=a_0(\lambda) - a_{dy}(\lambda). \qquad (13)$$

Since $a_0(\lambda)$ and $a_{dy}(\lambda)$ can be obtained for any SGLI short wavelength, Eq. 13 completes the derivations of a_0 , a_{ph}, a_{dy} and b_{bp} at the SGLI wavelengths. Note that a_t and b_{bt} can also be derived from these IOPs using Eqs. 4 and 5. Fig. 3 summarizes the sequence of the IOPs retrieval.

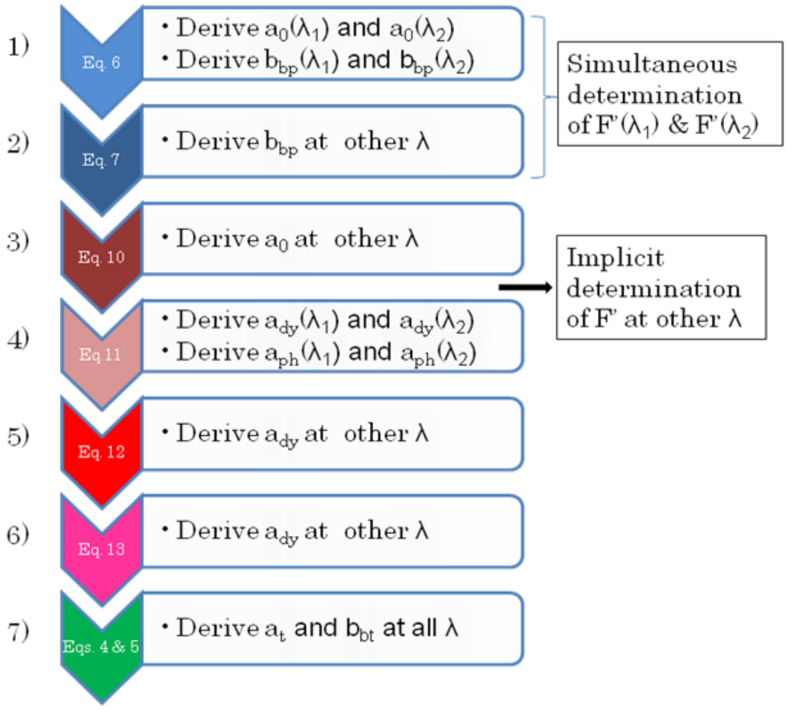

Fig. 3 The sequence of IOP retrieval.

3. Algorithm evaluation

Figs. 4-6 show examples of evaluation results of the IOP algorithm, using the NOMAD data set (Werdell and Bailey, 2005) from which simultaneous measurements of in situ R_{rs} and IOPs can be obtained. The in situ R_{rs} is given as an input to the present IOP algorithm, and the algorithm outputs were compared to the in situ IOPs in the data set. Also Table 1-3 below summarizes statistical results of the evaluation.

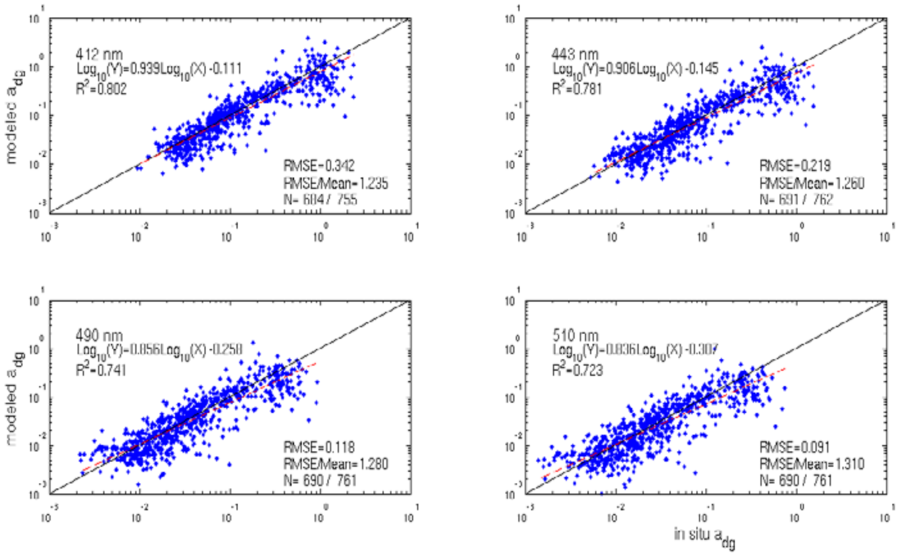

Fig. 4 Comparison between a_{dy} (a_{dg}) measured in situ and derived from the IOP algorithm.

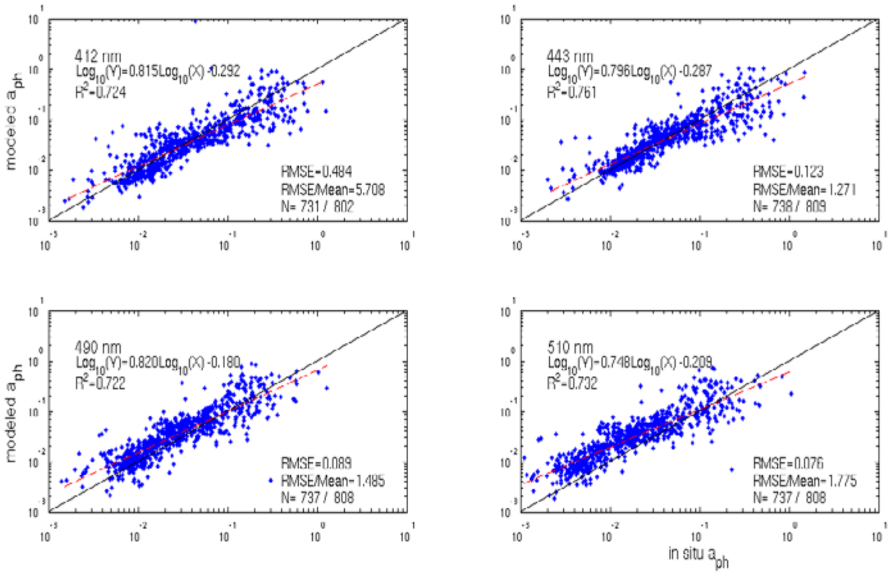

Fig. 5 Comparison between b_b measured in situ and derived from the IOP algorithm.

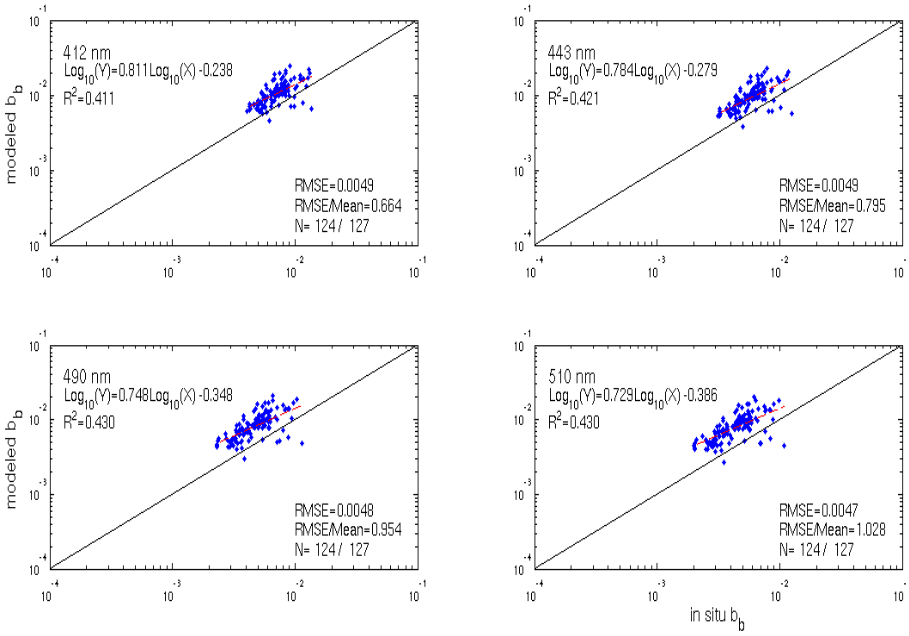

Fig. 6 Comparison between b_b measured in situ and derived from the IOP algorithm.

Table 1. Statistical results of algorithm evaluation for a_{dy} against in situ data

Wavelength#	slope#	intercept#	r^2#	RMSE*
412	0.939	-0.111	0.802	0.342
443	0.0.906	-0.145	0.781	0.219
490	0.856	-0.258	0.741	0.118
510	0.836	-0.307	0.723	0.091

#log scale, *Liner scale

Table 2. Statistical results of algorithm evaluation for a_{ph} against in situ data

Wavelength#	slope#	intercept#	r^2#	RMSE*
412	0.815	-0.292	0.724	0.484
443	0.796	-0.287	0.761	0.123
490	0.820	-0.180	0.722	0.089
510	0.748	-0.209	0.732	0.076

#log scale, *Liner scale

Table 3. Statistical results of algorithm evaluation for b_b against in situ data

Wavelength	slope#	intercept#	r^2#	RMSE*
412	0.811	-0.238	0.411	0.0049
443	0.784	-0.279	0.421	0.0049
490	0.748	-0.348	0.430	0.0048
510	0.729	-0.386	0.430	0.0047

#log scale, *Liner scale

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