ESTIMATION OF IOP FROM INVERSION OF REMOTE SENSING REFLECTANCE MODEL USING IN-SITU OCEAN OPTICAL DATA IN THE SEAWATER AROUND THE KOREA PENINSULA

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ABSTRACT For estimation of three inherent optical properties (IOPs), the absorption coefficients for phytoplankton (a_{ph}) and suspended solid particle (a_{ss}) and dissolved organic matter (a_{dom}), from ocean reflectance, we used inversion of remote sensing reflectance model (Ahn *et al.*, 2001) at this study. The IOP inversion model assumes that (1) the relationship between remote sensing reflectance (R_{rs}) and absorption (a) and backscattering (b_b) is well known, (2) the optical coefficients for pure water (a_w, b_{bw}) are known, (3) the spectral shapes of the specific absorption coefficients for phytoplankton (a^*_{ph}) and suspended solid particle (a^*_{ss}) and the specific backscattering coefficients for phytoplankton ($b_b{}^*_{ph}$) and suspended solid particle ($b_b{}^*_{ss}$) are known. The input data of IOP inversion model is used in-situ ocean optical data at the seawater around the Korea Peninsula for 5 years (2001-2005). We compared the output data of the IOP inversion model and the in-situ observation for seawater around the Korea Peninsula.

KEY WORDS: IOP, Inverse model, absorption, backscattering, remote sensing reflectance, ocean color

1. INTRODUCTION

The color of the sea will be related to those photons which are backscattered from within the water column and are not absorbed before entering the atmosphere. Hence changes in the total absorption coefficient, $a(\lambda)$, and the backscattering coefficient, $b_b(\lambda)$, regulate the variations in ocean color spectra or remotely sensed reflectance [$R_{rs}(\lambda)$], where $R_{rs}(\lambda)$ is defined as the ratio of upwelled radiance to downwelled irradiance. Values of $a(\lambda)$ an be effectively partitioned into absorption due to water, phytoplankton, and nonalgal materials (e.g., Kishino *et al.*, 1984; Carder *et al.*, 1989; Garver *et al.*, 1994; Ahn 1999). The value of $b_b(\lambda)$ is typically much smaller than $a(\lambda)$ for CASE-I water (Gordon et al., 1988). In addition, there are no a priori reasons why absorption and scattering properties should be well correlated (Kitchen and Zaneveld, 1990).

According to the optical classification by Morel and Prieur(1977), oceanic waters may be characterized as CASE-I water, in which the optical properties are dominated by chlorophyll and associated and covarying detrial pigments, or as CASE-II water, in which other substances, which do not covary with chlorophyll, also affect the optical properties. Such substances include gelbstoff, suspended sediments, coccolithophores, detritus, and bacteria. Theoretically, all water constituents, including CASE-II water, can be estimated from the surface reflectance using an analytical method if all optical properties of seawater constituents, solar illumination conditions and precise reflectance values are known. To analyze ocean reflectance, Gordon and Morel (1983) explicated three different approaches to extract concentrations of the various constituents in the water: (1) an empirical method, (2) a semi-empirical method (semi-analytical method), and (3) an analytical method.

Theoretical studies have shown that remote sensing reflectance can be related to the IOPs (inherent optical properties) of the water column, which in turn are composed of the individual absorbers and scatterers, including water, particulates, and dissolved materials. Hence IOPs can be used to study upper ocean biological processes, including phytoplankton distributions, primary production rates, and biogenic gas fluxes. The most important of the IOPs is the absorption coefficient, as it dominates the downwelling attenuation coefficient and plays an essential role in energy transfer (e.g., primary production or heat).

In this study, we researched to estimate three IOPs, the absorption coefficients of phytoplankton (a_{ph}), suspended solid particle (a_{ss}), and dissolved organic matter (a_{dom}), from $R_{rs}(\lambda)$ using inversion approach method of remote sensing reflectance model. The validation comparisons are made with values derived from in-situ measurements in the seawater around the Korea Peninsula.

2. METERIAL AND METHODS

2.1 Field Measurements

Remote sensing reflectance, $R_{rs}(\lambda)$, was measured from 400nm to 750nm at 1nm intervals with a field dual spectroradiometer (ASD Inc.). Total suspended solid particulates (SS), chlorophyll concentration (<chl>), and

IOPs (a_{ph}, a_{ss}, a_{dom}) were measured *in-situ*. IOPs were measured at the same wavelengths as those of the $R_{rs}(\lambda)$. The measurements were obtained in CASE-II turbid water and in CASE-I clear water, around the Korea Peninsula from 2001 to 2005 (Figure 1). The *in-situ* values were used to validate the modeled IOPs (a_{ph}, a_{ss}, a_{dom}).

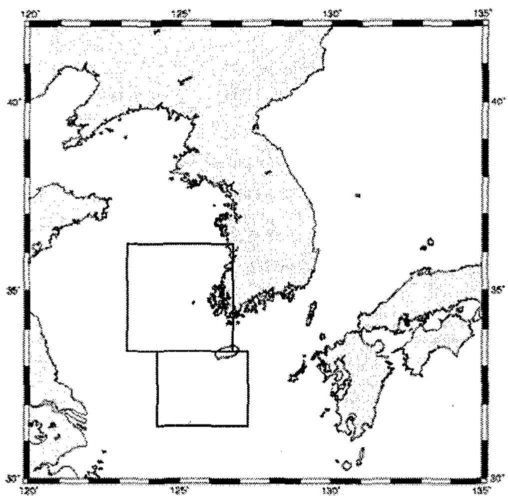

Figure 1. Map of *in-situ* area (red box area).

2.2 Inverse Model

To simplify the R_{rs} model, we assume clear skies, the sun position always at noon, a satellite sensor viewing angle within 20 degree from nadir, and no sun glint in the sensor direction. Irradiance reflectance (R) computed in previous research by Prieur and Morel (1975) was found to be related to IOPs of water such as total beam absorption (Σa) and total backscattering coefficient (Σb_b).

$$R(0^-) = f \frac{\sum b_{bi}}{\sum a_i + \sum b_{bi}} \tag{1}$$

where f varies weakly as a function of the volume scattering function of particles in seawater and of the radiance distribution within the submarine light field. 0- means just beneath of surface. Converting Eq. (1) for R_{rs}, we obtain (Ahn *et al.*, 2001),

$$R_{rs} = 0.044 \frac{\sum b_{bi}}{\sum a + \sum b_{bi}} \tag{2}$$

Considering optically active matter in seawater, the above terms for absorption and backscattering are separated into four elements (plus water),

$$a = a_w + a_{ph} + a_{ss} + a_{he} + a_{dom} \tag{3}$$

$$b_b = b_{bw} + b_{bph} + b_{bss} + b_{bhe} \tag{4}$$

where the subscript w, ph, ss, he, dom refers to water, phytoplankton (chlorophyll), suspended solid particle, heterotrophic organisms and dissolved organic matter (DOM), respectively. The biological detritus is assumed to be the component of suspended solid particle and heterotrophic organisms. From Eq.(2), (3), and (4), the following equation is obtained:

$$R_{rs}(\lambda) = 0.044 \frac{b_{bw} + b_{bph} + b_{bss} + b_{bhe}}{a_w + a_{ph} + a_{ss} + a_{he} + a_{dom} + b_{bw} + b_{bph} + b_{bss} + b_{bhe}} \tag{5}$$

The absorption and backscattering coefficients are converted to specific absorption and backscattering coefficients.

$$R_{rs}(\lambda) = 0.044 \frac{X_{he}B_{he}(\lambda) + X_{ph}B_{ph}(\lambda) + X_{ss}B_{ss}(\lambda) + B_w(\lambda)}{X_{he}A_{he}(\lambda) + X_{ph}A_{ph}(\lambda) + X_{ss}A_{ss}(\lambda) + X_{dom}A_{dom}(\lambda) + A_w(\lambda) + X_{he}B_{he}(\lambda) + X_{ph}B_{ph}(\lambda) + X_{ss}B_{ss}(\lambda) + B_w(\lambda)} \tag{6}$$

The absorption (A_w) and backscattering (B_w) of seawater are also considered to be constants (Morel, 1974). The terms X_{he}, X_{ph}, X_{ss} represent heterotrophic organisms, chlorophyll concentrations for phytoplankton, and total suspended solid particle concentrations, respectively. X_{dom} is the absorption coefficient at 400nm for DOM. A_{he}, A_{ph}, A_{ss} represent specific absorption coefficient of total heterotrophic organisms, phytoplankton, and total suspended solid particles, respectively. A_{dom} is the relative specific absorption coefficient of DOM. For the DOM, we know only the shape of the absorption spectrum with wavelength. A non-dimensional term, $A_{dom}(\lambda)$, is normalized to 0.01 at 400nm. B_{he}, B_{ph}, B_{ss} represent specific backscattering coefficient of total heterotrophic organisms, phytoplankton, total suspended solid particles, respectively.

$R_{rs}(\lambda)$ was measured in the wavelengths ranging from 400nm to 700nm at 1nm interval, and 301 bands for a single reflectance spectrum. Transformed equations for Eq.(6) to 301 linear equations are:

$$\begin{aligned}
&\alpha_{ph1}X_{ph} + X_{ss1}X_{ss} + \alpha_{dom1}X_{dom} = \beta_1(1 = 400nm) \\
&\alpha_{ph2}X_{ph} + X_{ss2}X_{ss} + \alpha_{dom2}X_{dom} = \beta_2(2 = 400nm) \\
&\alpha_{ph3}X_{ph} + X_{ss3}X_{ss} + \alpha_{dom3}X_{dom} = \beta_3(3 = 400nm) \\
&\cdots\cdots\cdots\cdots \\
&\cdots\cdots\cdots\cdots \\
&\alpha_{ph301}X_{ph} + X_{ss301}X_{ss} + \alpha_{dom301}X_{dom} = \beta_{301}(301 = 400nm)
\end{aligned} \tag{7}$$

where $\alpha_{ji} = R_i A_{ji} - 0.044B_{ji}$, and j is he, ph, ss, and DOM, respectively. i is band number.

$$\beta_i = 0.044(B_{wi} + X_{he}B_{he}) - R_i(A_{wi} + X_{he}A_{he}) \tag{8}$$

where R_i is the $R_{rs}(\lambda)$ ratio at a given band number (i), A_{ji} is the specific absorption coefficient for the 4 components (j=1-4) at a given band number (i=i-301). B_{wi} and A_{wi} are the backscattering and absorption coefficients of seawater at a band number i.

For the heterotrophic cell density value, a number "zero (0)" was entered as an initial value in the above equation β_i. Eq.(7) is then converted to matrix form:

$$\begin{bmatrix} \alpha_{ph1} & \alpha_{ss1} & \alpha_{dom1} \\ \alpha_{ph2} & \alpha_{ss2} & \alpha_{dom2} \\ \alpha_{ph3} & \alpha_{ss3} & \alpha_{dom3} \\ \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot \\ \alpha_{ph301} & \alpha_{ss301} & \alpha_{dom301} \end{bmatrix} \begin{bmatrix} X_{ph} \\ X_{ss} \\ X_{dom} \end{bmatrix} = \begin{bmatrix} \beta_1 \\ \beta_2 \\ \beta_3 \\ \cdot \\ \cdot \\ \cdot \\ \beta_{301} \end{bmatrix} \quad (9)$$

Solutions for the matrix are the same as the least square solution for linear equations. Therefore, the inverse matrix of [α] is needed for the final solution. However, [α] is not a square matrix and the inverse of [α] does not exist. Hence, [α] matrix is changed to a square matrix by multiplying by the transpose of [α]. The general solution is obtained by

$$[X] = [\alpha^T \alpha]^{-1} [\alpha^T \beta] \quad (10)$$

2.3 Estimation of IOPs from inversion of R_{rs} model

For estimation of three IOPs (a_{ph}, a_{ss}, a_{dom}) from inversion of R_{rs} model, we used,

$$\begin{aligned} a_{ph}(\lambda) &= a^*_{ph}(\lambda) \times < chl > \\ a_{ss}(\lambda) &= a^*_{ss}(\lambda) \times SS \\ a_{dom}(\lambda) &= a_{dom}(400) \times e^{-S(\lambda-400)} \end{aligned} \quad (11)$$

where <chl> and SS are chlorophyll and total suspended solid particle concentrations from inversion of R_{rs} model. $a_{dom}(400)$ is absorption coefficient of DOM at 400nm from inversion of R_{rs} model and S is inclination for spectrum shape of $a_{dom}(\lambda)$. $a^*_{ph}(\lambda)$ and $a^*_{ss}(\lambda)$ are specific absorption coefficients of phytoplankton and total suspended solid particle from average of in-situ data in the seawater around the Korea Peninsula.

3. RESULT

Figure 2, 3, and 4 are compared spectrum shapes of $a_{ph}(\lambda)$, $a_{ss}(\lambda)$, and $a_{dom}(\lambda)$ with *in-situ* data, respectively. Figure 5, 6, and 7 are compared values of $a_{ph}(\lambda)$, $a_{ss}(\lambda)$, and $a_{dom}(\lambda)$ at the given wavelengths with *in-situ* data, respectively.

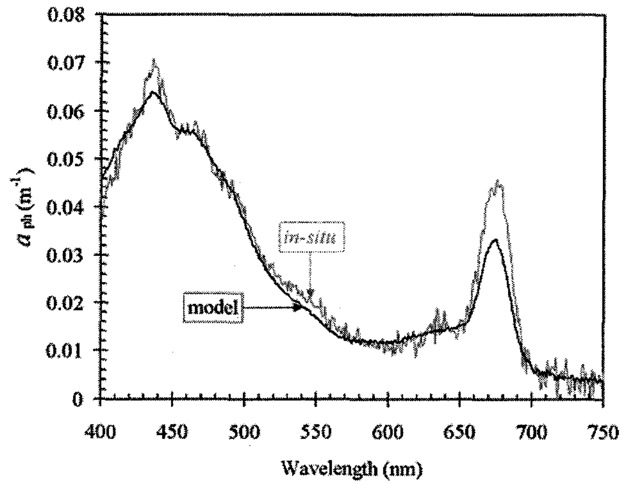

Figure 2. Comparison *in-situ* with model of $a_{ph}(\lambda)$ shape.

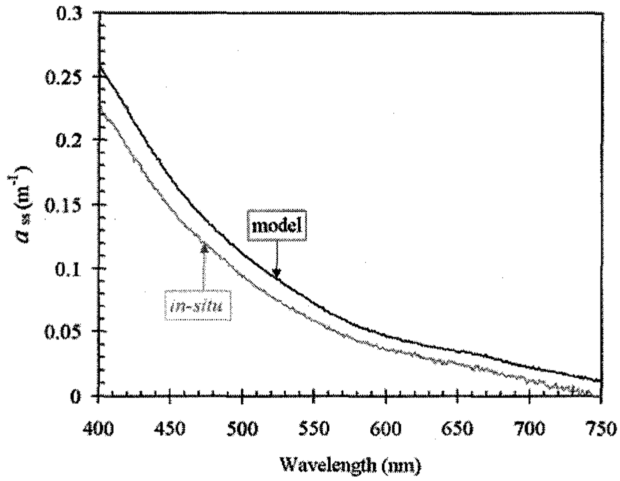

Figure 3. Comparison *in-situ* with model of $a_{ss}(\lambda)$ shape.

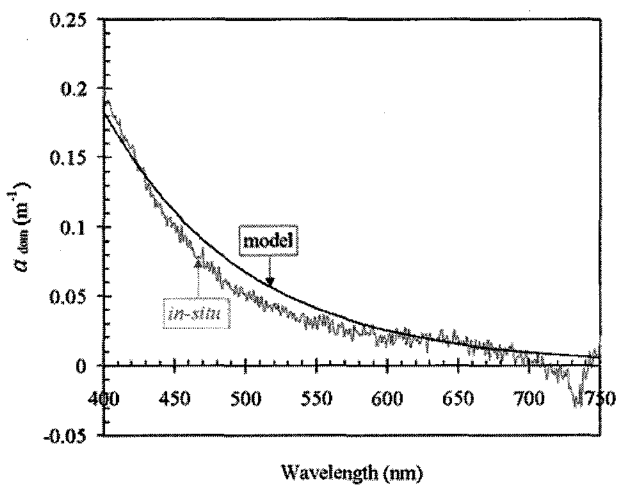

Figure 4. Comparison *in-situ* with model of $a_{dom}(\lambda)$ shape.

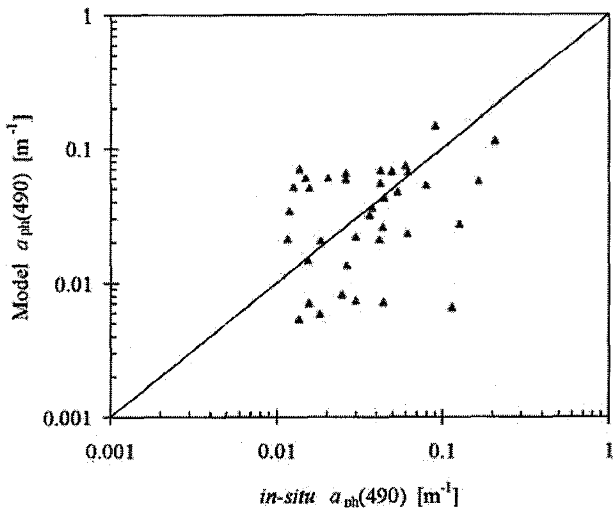

Figure 5. Comparison *in-situ* with model of $a_{ph}(490)$.

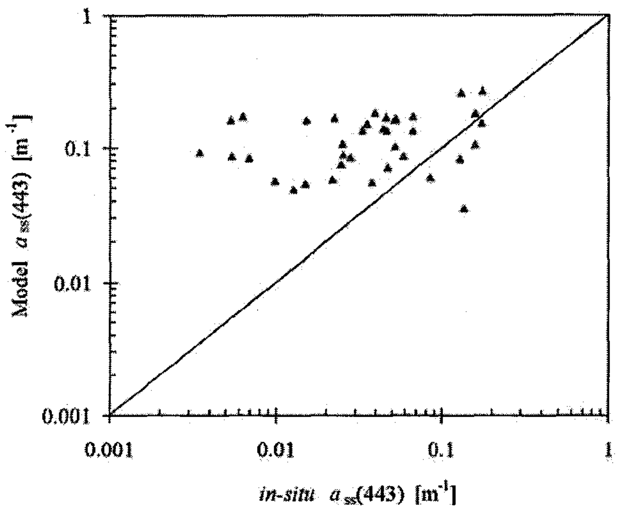

Figure 6. Comparison *in-situ* with model of $a_{ss}(443)$.

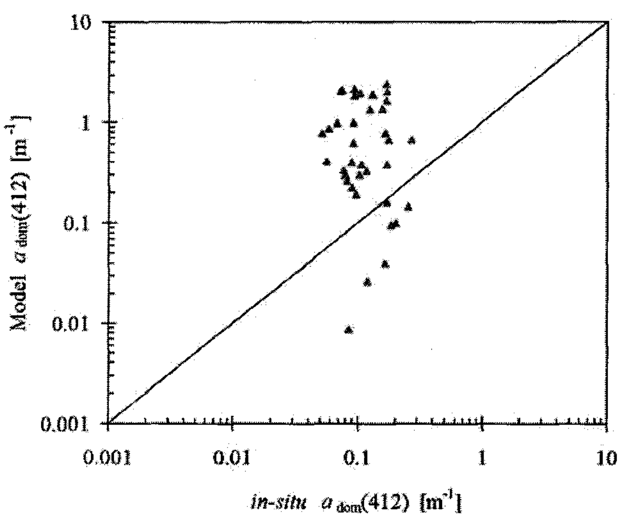

Figure 7. Comparison *in-situ* with model of $a_{dom}(412)$.

4. CONCLUSIONS

For estimation of three inherent optical properties (IOPs), the absorption coefficients for phytoplankton (a_{ph}) and suspended solid particle (a_{ss}) and dissolved organic matter (a_{dom}), from ocean reflectance, we used inversion of $R_{rs}(\lambda)$ model in this study. We compared spectrum shapes and values of $a_{ph}(\lambda)$, $a_{ss}(\lambda)$, and $a_{dom}(\lambda)$ with *in-situ* data, respectively. The spectrum shapes were very similar and the absorption coefficients at the given wavelengths were different.

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