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Retrieval of Chlorophyll Absorption Spectra from Remote Sensing Reflectance of Turbid Coastal Waters

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***Abstract* - The phytoplankton absorption coefficients of turbid coastal sea water with high sediment and chlorophyll content is retrieved by modeling of the remote sensing reflectance measured at the water surface. Sea-truth water sampling campaigns were carried out from Dec 1996 to Dec 1999 in coastal waters around Singapore. In-situ reflectance spectra and laboratory measurements of the total suspended solid (TSS) and chlorophyll-a (Chl-a) were made from the water samples. The phytoplankton absorption at 440 nm is retrieved by fitting the reflectance spectra to a theoretical model.**

I. INTRODUCTION

In optical remote sensing of sea water, the spectral reflectance is often used in characterizing the optical properties of water. The remote sensing reflectance is defined as the ratio of the upwelling radiance to downwelling irradiance just above the water surface. The optical properties of the sea waters are usually modeled by the three component model [1, 2] where the absorption and scattering coefficients of sea waters are determined by the concentrations of the coloured dissolved organic matter (CDOM), phytoplanktons and non-chlorophyllous particles. Of these constituents, the phytoplankton concentration and its spatial distribution is of particular interst to the marine scientists and those involved in th fishery industry.

In this work, spectral reflectance data acquired from Dec 1996 to Dec 1999 were analysed with an aim to retrieve phytoplankton absorption coefficients and to correlate the absorption coefficients with the in-situ measurements of chlorophyll-a concentration (Chl-a). Reflectance spectra were acquired using a portable GER 1500 spectroradiometer. Besides Chl-a, the concentration of the total suspended solids (TSS) was also measured. The TSS values measured included both the organic and nonorganic components. The Chl-a concentration ranges from 1 to 90 mg/m^3, with an average value of about 10 mg/m^3. The three component model for the sea water constituents is used to model the remote sensing reflectance of the water. The model includes the effects of chlorophyll fluorescence and surface reflectance due to skylight and sun glitter. The measured reflectance spectrum is fitted to the model by finding a set of the fitting parameters that best fits the reflectance curve to the model using the Marquardt-Levenberg algorithm. The retrieved phytoplankton absorption at 440 nm correlates well with the lab measurement of chlorophyll concentration.

II. SPECTRAL REFLECTANCE MODEL OF SEA WATER

The spectral reflectance $R(\lambda)$ is modeled by the following equation:

$$R(\lambda) = K \frac{b_b(\lambda)}{a(\lambda) + b_b(\lambda)} + R_F(\lambda) + R_S(\lambda) . \tag{1}$$

The first term in the sum is due to bulk water reflectance [3], where $a(\lambda)$ and $b_b(\lambda)$ are respectively the absorption and backscattering coefficients of sea water, and K is a factor dependent on the illumination and viewing conditions (assumed to be wavelength-independent). The contribution due to chlorophyll fluorescence is modeled by the term $R_F(\lambda)$, and $R_S(\lambda)$ is due to the sky light and sun glitter input.

The absorption coefficient is modeled by the sum of absorption coefficients due to water (w), phytoplankton (ϕ) and CDOM (g),

$$a(\lambda) = a_w(\lambda) + a_\phi(\lambda) + a_g(\lambda) \tag{2}$$

While the backscattering coefficient is the sum of backscattering contributed by water and particulate matters (p),

$$b_b(\lambda) = b_{bw}(\lambda) + b_{bp}(\lambda) . \tag{3}$$

The absorption and backscattering coefficients of water are taken from tabulated values in [4] and [5] respectively. The absorption coefficient of CDOM is modeled by an exponential relation,

$$a_g(\lambda) = G \exp(-S(\lambda - 440)) , \tag{4}$$

where G is the CDOM absorption at 440 nm, and the wavelength λ is measured in nm. The model for the phytoplankton absorption coefficient is adapted from [6],

$$a_\phi(\lambda) = P_0 a_0(\lambda) + P_1 a_1(\lambda) . \tag{5}$$

The basis functions for chlorophyll absorption $a_0(\lambda)$ and $a_1(\lambda)$ are taken from the tabulated values in [6]. The backscattering due to particulate matters is modeled by the inverse power law relation,

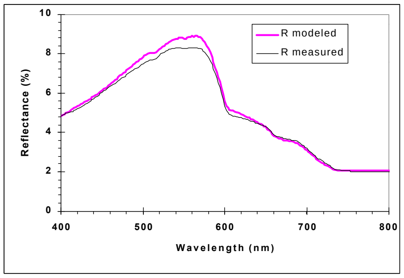

Fig. 1 An example of fitting a reflectance spectrum to the model, for the case of low Chl-a (2.0 mg/m^3) and low TSS (7.0 g/m^3). The best-fit parameters are A=0.017, B=0.79, C=0.998, P_0 =0.0466, P_1=-0.104, F=0.0755, X=0.0851, G=0.437, K=26.6, y=2.11, S=0.0151, β=0.00.

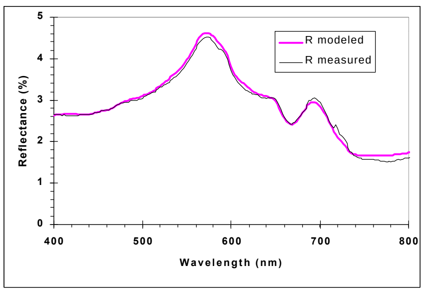

Fig. 2 An example of fitting a reflectance spectrum to the model, for the case of high Chl-a (38.3 mg/m^3) and high TSS (57.2 g/m^3). The best-fit parameters are A=0.351, B=0.399, C=0.881, P_0 =0.926, P_1=-0.671, F=0.450, X=0.0556, G=0.327, K=23.2, y=0.50, S=0.0290, β=0.00.

$$b_{bp}(\lambda) = X\left(\frac{440}{\lambda}\right)^{y} \tag{6}$$

Chlorophyll fluorescence is manifested as an elevation in the reflectance near to the fluorescence peak around 685 nm. This component is modeled by a gaussian function [7]

$$R_F(\lambda) = F \exp\left[-4\ln(2)\left(\frac{\lambda-\lambda_p}{w}\right)^2\right] \tag{7}$$

with a peak at λ_p=685nm and a width at half-maximum of w=25nm. The sky-light and sun-glitter contributions are modeled by [8],

$$R_S(\lambda) = A\left(\frac{440}{\lambda}\right)^{4.1} + B\left(\frac{440}{\lambda}\right)^{\beta} + C \tag{8}$$

There are altogether twelve parameters in the model, i.e. K, P_0, P_1, G, S, X, y, F, A, B, C and β. Of these parameters, P_0, and G are the absorption coefficients at 440 nm of phytoplanktons and CDOM respectively, X is the backscattering coefficients of particulates at 440 nm.

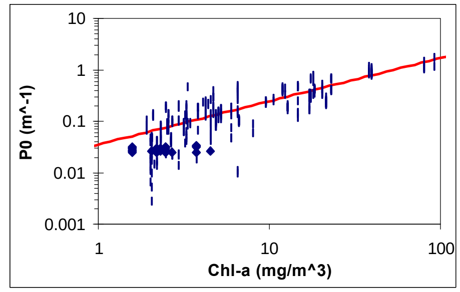

Fig. 3: Scatter plot of P_0, the retrieved phytoplankton absorption coefficient at 440 nm versus the measured Chl-a concentration. The linear relation in the log-log plot shows that P_0 is related to Chl-a by a power law relation.

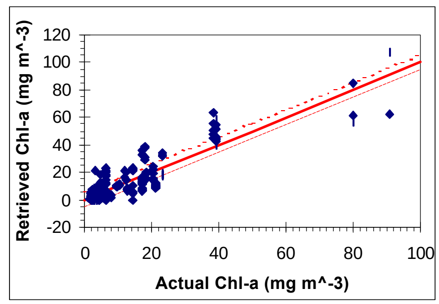

Fig. 4: Scatter plot of Chl-a values retrieved from reflectance spectra versus the measured values. The solid line is the line of identity and dashed lines are the error lines (one standard error).

III. Results

Each measured reflectance spectrum is fitted to the model reflectance by finding the set of twelve parameters that results in the least rms deviation within the wavelength range from 400 to 800 nm. Optimization is done using the Marquardt-Levenberg algorithm. Typical results of fitting to the reflectance model are shown in Fig. 1 (low Chl-a, low TSS) and Fig. 2 (high Chl-a, high TSS).

The phytoplankton absorption coefficient at 440 nm (P_0) retrieved for each measured reflectance spectrum is plotted against the measured Chl-a in the sea water sample, The log-log plot (Fig. 3) shows that P_0 (in m^{-1}) is related to Chl-a (in mg/m^3) by a power law relation of the form,

$$P_0 = 0.0353[\mathrm{Chl\text{-}a}]^{0.84}\,. \tag{9}$$

with a correlation coefficient of 0.81.

The equation (9) can be inverted to retrieve Chl-a from the phytoplankton absorption at 400nm obtained by fitting a measured reflectance spectrum to the model. The results are shown in Fig. 4, for the coastal waters around Singapore.

The absorption spectra due to phytoplanktons can be retrieved using equation (5) and the values of P_0 and P_1 obtained by fitting the reflectance spectra to the model. Examples of some retrieved absorption spectra are shown in Fig. 5.

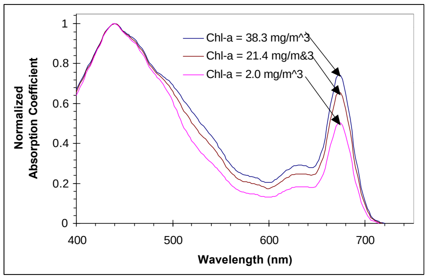

Fig. 5: Retrieved absorption spectra of phytoplanktons at three different Chl-a concentrations: 38.3, 21.4 and 2.0 mg/m^3. The spectra have been normalized by the absorption coefficient at 440nm (i.e. P_0 = 0.93, 0.23 and 0.05 m^{-1} for the three spectra shown).

The absorption coefficient of CDOM at 440 nm retrieved from the reflectance spectra for the coastal waters around Singapore during the three-year periods appears to be relatively stable, with a value

$$G = a_g(440nm) = (0.607 \pm 0.009)\ \mathrm{m}^{-1} \tag{10}$$

The parameter S in equation (4) for the wavelength-dependence of the absorption coefficient of CDOM is found to be

$$S = (0.0186 \pm 0.0003)\ \mathrm{nm}^{-1} \tag{11}$$

This value of S is consistent with the values reported in the literature [9].

The backscattering coefficient at 440nm (i.e. the parameter X in equation 6) due to suspended particulates in the water does not have good correlation with TSS or Chl-a. However, the exponent in (6) can be fitted to a linear equation of the form,

$$y = C_0 + C_1[\mathrm{TSS}] + C_2[\mathrm{Chl\text{-}a}] \tag{12}$$

and the coefficients in this relation are,

$$\begin{aligned} C_0 &= (1.94 \pm 0.05) \\ C_1 &= (-0.011 \pm 0.002)\ \mathrm{m^3 g^{-1}} \\ C_2 &= (-0.023 \pm 0.002)\ \mathrm{m^3 mg^{-1}} \end{aligned} \tag{13}$$

At low TSS and Chl-a, the value of the exponent is approximately 2, and it decreases with increasing values of TSS and Chl-a. The value of the exponent is an indication of the size of the suspended particles, and generally ranges from 0 (for large particles) to 2 (for fine particles). Thus, the decrease in the exponent value with increasing TSS and Chl-a suggests that the size of the scattering particles increases with increasing TSS and Chl-a.

IV. Conclusions

A model for spectral reflectance of coastal waters in terms of the inherent optical properties of water (equation 1) has been shown to be applicable to the coastal waters around Singapore. The model is inverted to obtain the absorption and backscattering coefficients at 440 nm of the water constituents, viz. phytoplankton, CDOM and suspended particulates. The phytoplankton absorption spectra can also be retrieved from the model parameters. The retrieved phytoplankton absorption coefficient at 440 nm correlates well with the field-measured chlorophyll-a concentration. Hence, it can be used in the retrieval of Chl-a from the measured reflectance spectra above the water surface.

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