A three-component reflectance model that takes into account the contributions of dissolved organic matter, phytoplankton, and mineral particles is described. The principle of inversion of the model, in terms of chlorophyll a plus phaeopigments concentration, chl, sediment refractive index, \( m_r \), and absorption coefficient of yellow substance at 440 nm, \( a_y(440) \), is exposed. The inversion procedure is applied to experimental data collected in the Ebro river plume area. The obtained estimates of chl are accurate only in order of magnitude. However, we demonstrate that \( m_r \) and \( a_y(440) \) determinations are robust against chl variations within \(-50\%\), \(+100\%\) of experimental values. Investigation of possible variations with wavelength of \( m_r \), using measured concentrations and \( a_y(440) \) estimates, evidences a slight dependency as was previously observed. We support in conclusion that the inversion procedure could be exploited in a two-step process. First \( a_y(440) \) and the mean value of \( m_r \) are estimated from measured water quality parameters. Then \( m_r \) is calculated at each wavelength, considering \( a_y(440) \) value determined in the first step. ©Elsevier Science Inc., 2000

**INTRODUCTION**

Satellite remote sensing represents the most suitable technique for synoptic monitoring of coastal zones. However, quantitative use of remotely sensed data is a difficult task and is still a challenge. The radiometric signatures of coastal waters mainly depend on three optically active water components, namely, yellow substance, phytoplankton pigments, and sediment which are in highly variable proportions in space and time. Whereas chlorophyll is the main constituent responsible for spatial and temporal variations of reflectance spectra in oceanic waters, coastal and shelf waters often contain amounts of dissolved organic carbon and nonliving particulate matter that make interpretation of reflectance spectra more difficult.

The number of parameters that can be determined from visible satellite imagery is limited. Consequently, for a given site, some of these parameters or, alternatively, some inherent optical properties (IOP) must be known. When direct measurements are not feasible, hyperspectral data can be used for this purpose. The ratio of reflectances in two bands, e.g., “blue to green,” has been used for a long time to determine chlorophyll concentration in “case 1” waters (Morel and Prieur, 1977). Generally the use of this ratio for “case 2” waters yields unsatisfactory results, as quoted by various authors (Gower et al., 1984; Fischer et al., 1986; Sathyendranath et al., 1989), due to the strong masking effect of yellow substance. Nevertheless, the use of reflectance ratios is a way of minimizing overlapping spectral effects of different substances. For predicting purposes, statistical relationships have been established by searching correlations between reflectance and concentration at visible light wavelengths. Tassan (1988) showed that relationships based on dual reflectance ratios to retrieve sediment and chlorophyll concentrations considerably reduce the influence of yellow substance. Carder et al. (1991) successfully applied an algorithm using two reflectance ratios to quantify chlorophyll a. However, Arenz et al. (1996) suggested that ratios involving more than two wavelengths can be affected by cumulative variance and recommended to determine chlorophyll concentrations from single reflectance ratios. In addition, Hoge et al.
Lahet et al. (1995) showed that a two-band model inversion technique can be used to retrieve the absorption coefficient of chromophoric dissolved organic matter at 43 nm from CZCS normalized water-leaving radiances. The analysis was confined to non-bloom conditions. The drawback of the method is a poor accuracy in regions containing significant amounts of phytoplankton.

The inversion algorithms using reflectance ratios rely on the assumption that the effects of environmental variability are either small or can be considered as spectrally additive constants independent of wavelength. When these assumptions do not hold, an alternative algorithm is proposed by Chen et al. (1992) which correlates suspended sediment concentration with the first derivative of the reflectance spectra. Goodin et al. (1993) have shown that pure water effects can be removed using the first derivative spectrum and turbidity effects by the second derivative spectrum. Then reflectance second derivatives only consist of features associated with chlorophyll. Many applications of this method can be anticipated. For example, Peñuelas et al. (1993) used narrow bandwidth indices and reflectance indices calculated from first and second derivative spectra to assess plant physiological status.

Sugihara et al. (1985) proposed another approach to estimate water quality parameters, consisting in directly relating them to observed reflectances through the reflectance model of Morel and Prieur (1977). A system of \( n \) linear equations corresponding to \( n \) wavelengths is solved in order to produce an optimum fit in the least squares sense between computed and observed reflectance spectra by the Householder transformation. Hoge and Lyon (1996) showed that IOPs can be concurrently retrieved, with a low computation time, by inversion of radiance models without incurring singularities. Their study was successfully applied to a wide range of oceanic constituent absorption and backscatter combinations. The method developed in this article is based on a reflectance model similar to that of Sugihara et al. (1985), inverted in a linear way and involving more accurate models for the optical properties of sediment and phytoplankton. Our objective is to show the feasibility of using a simple semi-analytical model to retrieve water quality parameters with acceptable accuracy. Speed of computation is very important when inversions are applied to satellite images. Future work will be devoted to the possibility of the inversion method to multispectral satellite data. The use of our model represents a compromise between rapidity and precision requirements. The reflectance model depends on the absorption coefficient of yellow substance of 440 nm, \( a_y(440) \), the sediment refractive index \( m_r \), the chlorophyll plus phaeopigment concentration, \( 
\text{chl} \), the sediment concentration \( C \), and the minimum and maximum diameters of the particle size distribution, \( D_{\text{min}} \) and \( D_{\text{max}} \). Forget et al. (1999) discussed the inversion of \( a_y(440) \) and \( m_r \) from reflectance spectra of non-chlorophyllous turbid coastal waters. The study area was the Rhône River mouth area during a flood event. A simple two-component, namely, yellow substance and total suspended matter, reflectance model was developed. The optical effect of phytoplankton was taken into account in the present study of the Ebro River mouth area, making the reflectance model suitable in principle for a broader variety of coastal waters. In the first section of this article, we describe the field measurements. The reflectance model is then briefly presented in the third section. The inversion of this model in terms of three parameters (sediment refractive index, yellow substance absorption coefficient at 440 nm, and chlorophyll concentration) is addressed in the fourth section. Finally, possible spectral variations of the refractive index are examined.

### FIELD MEASUREMENTS

#### Reflectance Measurements

A PC1000 Ocean Optics spectroradiometer was used for reflectance spectra measurements. This device is a miniature photodiode array fiber optic spectroradiometer mounted directly on an analogue to digital (A/D) card, installed into a personal computer. The design uses a ruled plane grating to diffract the ancient light flux in the range 350–550 nm. An image of the spectrum is projected on a 1024-element photodiode array and is then transferred to the computer through the A/D card. The optical resolution, which depends on the groove density of the grating (600 lines/mm) and on the size of the entrance optics (200 \( \mu \)m), is 10 nm. The sample frequency of the A/D converter data is adjusted for each experiment to maximize the detector output voltage and the S/N ratio. The detector controller is run by a clock to effectively set this value for the photodiode array detector. The operating software permits one to set up the frequency (between 2 kHz and 500 kHz) and also the number of scans for signal averaging. The random noise is averaged in proportion to the square root of the number of scans averaged. More information on the spectroradiometer is available in Lahet et al. (1998a).

This optical instrument was used above the water surface, from the deck of the boat. The collector for irradiance measurements was a cosine collector of opaline glass diffusing material. This sensor was mounted on a perch, put at a few meters from the boat and placed in the azimuthal plane of the Sun to avoid ship-shadowing effects. \( E_d \) and \( E_u \) were measured by pointing the perch respectively upwards (directed towards the sky) and downwards (directed towards the sea), the sensor being orientated normally to the sea surface. Ideal environmental conditions are clear, uncloudy sky and smooth sea, without foam. The irradiance ratio is calculated by averaging 10 spectra of \( E_d \) and 10 spectra of \( E_u \) because of the great sensitivity of the sensor on its position and on
environmental conditions (clouds, sea surface variations). Then it is converted into sub-surface reflectance after removal of surface effects (Forget and Ouillon, 1998).

**Field Data**

The study area is the Ebro River plume area. The Ebro River, the main Spanish river flowing into the Mediterranean Sea, is 928 km long. Its mean annual flow is only 385 m$^3$ s$^{-1}$ as the result of the presence of many dams in the river basin. The Ebro delta is located at 40°40’N and 0°40’E. The tide amplitude along the coast is low, about 20 cm (Ibañez et al., 1997). Experimental data were collected in October and November 1996 during a 2-week field campaign in the frame of the FANS Program (Fluxes Across Narrow Shelves, MAST3, European Community). They consisted of chlorophyll concentrations, total suspended matter concentrations, and reflectance spectra measurements. Concentrations were measured near the surface (50 cm depth). A total of 29 coincident radiometric and water parameter measurements are available. Six stations, denoted from A to F in the following (Fig. 1), were selected to represent the variety of the reflectance spectra in shape and amplitude. The environmental conditions are given in Table 1. In every case, the river flow is low, about 100 m$^3$ s$^{-1}$.

**THE REFLECTANCE MODEL**

Spectral light absorption and backscattering coefficients are the two IOPs directly ruling the diffuse reflectance $R$ of the ocean. A classical model is given in Eq. (1) (Gordon et al., 1975; Morel and Prieur, 1977):

$$R(\lambda) = 0.33 \frac{b_{b}(\lambda)}{a(\lambda) + b_{b}(\lambda)},$$  \hspace{1cm} (1)

where $a$ and $b_{b}$ are respectively the absorption and backscattering coefficients of the water body. Coefficients $a$ and $b_{b}$ are expressed as the sum of contributions from optically active constituents in Eqs. (2) and (3):

$$a(\lambda) = a_{w}(\lambda) + a_{y}(\lambda) + a_{ph}(\lambda),$$  \hspace{1cm} (2)

$$b_{b}(\lambda) = b_{w}(\lambda) + b_{b}(\lambda) + b_{ph}(\lambda),$$  \hspace{1cm} (3)

where subscripts $w$, $y$, $ph$, and $s$, respectively, stand for water, yellow substance, phytoplankton, and sediment.

Little has been published on the absorption by inorganic sediment. Available measurements suggest that inorganic particles can present an absorption spectrum decreasing with wavelength. This coefficient is highly site specific (Bowers et al., 1996; 1998) and is generally small. Consequently, we chose to neglect the absorption coefficient of inorganic sediment. Values of $a_{w}(\lambda)$ are taken from Pope and Fry (1997).

Absorption by yellow substance has often been assumed to increase exponentially with decreasing wavelength from visible to ultraviolet (Bricaud et al., 1981; Carder et al., 1989; Roesler et al., 1989) and can be modeled by Eq. (4):

$$a_{y}(\lambda) = a_{y}(\lambda_{0}) \exp[-S(\lambda - \lambda_{0})]$$  \hspace{1cm} (4)

with wavelengths expressed in nanometers. $\lambda_{0}$ is a refer-
ence wavelength in the blue part of the spectrum, taken equal to 440 nm. The spectral slope $S$ has been estimated for various water types and has been found weakly variable (Bricaud et al., 1981; Carder et al., 1991; Boesler et al., 1989; Blough et al., 1993). A mean value of 0.014 nm$^{-1}$ can be considered representative of a great variety of coastal and oceanic waters.

Absorption by biogenic particulate matter originates from living pigmented algal cells and weakly pigmented or unpigmented particles mainly derived from phytoplankton. Iturriaga and Siegel (1989) indicated that detrital absorption is generally less than or equal to the phytoplankton chlorophyll particulate absorption. Duarte et al. (1998) examined the contribution of different components of plankton and suspended inorganic particles in a Mediterranean bay over a 2-year period. The shape of the average absorption spectrum is closer to that of chlorophyll $a$ in November and suggests a minor contribution of biogenic particles other than phytoplankton to light absorption. In this study we assume that absorption by detrital matter can be neglected. $a_{\mu}$ is calculated from Eq. (5):

$$a_{\mu}(\lambda) = a_{\mu}^{*}(\lambda)chl$$

(5)

The chlorophyll $a$ specific absorption coefficient of living phytoplankton, $a_{\mu}^{*}(\lambda)$, is dependent on phytoplankton concentration or phytoplankton community structure, which depend on the trophic status of the waters (Mitchell and Kiefer, 1988; Bricaud and Stramski, 1990; Cleveland, 1995). This suggests that it is necessary to use a parametrization taking into account biological and ecological variability (e.g., Cleveland, 1995; Bricaud et al., 1995). Bricaud et al. (1995) proposed a parametrization of $a_{\mu}$ as a function (chlorophyll $a +$ phaeopigments) concentration and merging typical variations in both package effect and pigment composition in various oceanic waters. They suggest that the power function [Eq. (6)]

$$a_{\mu}^{*}(\lambda) = A(\lambda)chl^{-B(\lambda)}$$

(6)

is the most appropriate for $a_{\mu}^{*}(\lambda)$. $A$ and $B$ are positive, wavelength-dependent parameters. $a_{\mu}^{*}(\lambda)$ is represented in Figure 2 for various values of chlorophyll $a$ concentration. The decrease of $a_{\mu}^{*}(\lambda)$ with increasing $chl$ seems counterintuitive. Bricaud et al. (1995) related this feature to two main causes: an increasing package effect from oligotrophic to eutrophic waters and a possible inverse covariation between the relative abundance of accessory pigments and $chl$ level.

Backscattering of light is due to water molecules and particles (sediment particles and phytoplankton). It can be assumed that the amount of light scattered by seawater in the forward and backward directions is the same (Morel, 1974). Then $b_{bb}(\lambda)$ is equal to one-half the total scattering coefficient of water, whose values are taken from Smith and Baker (1981).

We model light scattering by suspended particles in the sea using Mie theory (Van de Hulst, 1957) which allows to express $b_{bb}(\lambda)$ by (Forget et al., 1997):

$$b_{bb}(\lambda) = \frac{3C}{2\rho_{s}D_{min}^{2}}\int_{D_{min}}^{D_{max}}Q_{bb}(D,m_{r},\lambda)D^{-2}dD$$

(7)

where $\rho_{s}$ is the sediment density, $D$ the diameter of sediment particles, and $Q_{bb}$ the backscattering efficiency factor of sediment particles of refractive index $m_{r}$. A Junge particle size distribution of slope 4 (Bader, 1970; Nann and Robertson, 1993) has been assumed in Eq. (7).

The contribution of phytoplankton, $b_{ph}$, is calculated from a mean value of the chlorophyll a specific backscattering coefficient, $b_{ph}$, measured for nine species of phytoplankton (Ahn et al., 1992) [Eq. (8)]:

$$b_{ph}(\lambda) = b_{ph}^{*}(\lambda)chl$$

(8)

The spectral variations of $b_{ph}^{*}$ are plotted in Figure 3. Comparison of Figures 2 and 3 shows that $b_{ph}$ is much smaller than $a_{ph}$.

### INVERSION OF THE MODEL

Forget et al. (1999) studied the sensitivity of the model to various input parameters. They showed that several combinations of $m_{r}$ and $C$ values can result in nearly the same reflectance spectrum. Thus both parameters cannot be determined with precision. In this study, the inversion procedure is first applied to the determination of $chl$, $m_{r}$, and $a_{ph}(440)$ and then to the determination of $m_{r}$ and $a_{ph}(440)$ only for a range of values of $chl$. Here $C$ are fixed to the experimental values. In the next two subsections, a bulk value of $m_{r}$ is considered. The third subsection deals with possible variations of $m_{r}$ with wavelength.

### Determination of $m_{r}$, $a_{ph}(440)$ and $chl$

To estimate $m_{r}$, $a_{ph}(440)$ and $chl$ from experimental reflectance spectra, the other model parameters are fixed. Considering that most of backscattering is due to particles smaller than 1 $\mu$m and that the choice of the upper limit is not critical, we chose a realistic particle size range ($D_{min}$, $D_{max}$) = 0.1–100 $\mu$m (Stramski and Kiefer,
1991; Mobley, 1994). The procedure consists in minimizing the quadratic difference, $G$, between experimental reflectance values, $R_{\text{exp}}(\lambda)$ and modeled reflectance values, $R_{\text{mod}}(\lambda)$, calculated by varying the values of $m_r$, $a_y(440)$ and $chl$ [Eq. (9)]:

$$G(m_r, a_y(440), chl) = \sum \left[ R_{\text{mod}}(\lambda) - R_{\text{exp}}(\lambda) \right]^2$$ \hspace{1cm} (9)

Table 2 gives the results of inversion corresponding to our selected data set. The reflectance spectra, $R_{\text{mod}}(\lambda)$ (modeled) and $R_{\text{exp}}(\lambda)$ (experimental), are plotted in Figure 4. For stations A–E, $G$ is less than 1 and presents a unique minimum. When $G$ is greater than 1, as for station F, the minimization of the cost function can result in multiple values of $a_y(440)$ and $chl$, but the two inverted parameters are shown to vary within small intervals. Table 2 refers to mean values of these parameters. The sediment refractive index is found to vary from 1.10 to 1.16, which is close to the range 1.11–1.25 that can be found in literature for the common minerals (Aas, 1996). Furthermore, $a_y(440)$ is found to vary from 0.06 m$^{-1}$ to...
Table 2. Computed Values of Chlorophyll Concentration $chl_{mod}$, Sediment Refractive Index $m_r$, and Absorption Coefficient of Yellow Substance at 440 nm, $a_y(440)^a$

<table>
<thead>
<tr>
<th></th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>F</th>
</tr>
</thead>
<tbody>
<tr>
<td>$C_{exp}$ (mg$^{-1}$)</td>
<td>0.61</td>
<td>0.76</td>
<td>1.28</td>
<td>1.48</td>
<td>1.74</td>
<td>4.00</td>
</tr>
<tr>
<td>$chl_{mod}$ (mg m$^{-3}$)</td>
<td>0.0</td>
<td>0.2</td>
<td>0.5</td>
<td>2.5</td>
<td>1.4</td>
<td>1.5</td>
</tr>
<tr>
<td>$chl_{exp}$ (mg m$^{-3}$)</td>
<td>0.22</td>
<td>0.64</td>
<td>1.40</td>
<td>1.36</td>
<td>1.44</td>
<td>1.35</td>
</tr>
<tr>
<td>$m_r$</td>
<td>1.10</td>
<td>1.13</td>
<td>1.13</td>
<td>1.15</td>
<td>1.16</td>
<td>1.13</td>
</tr>
<tr>
<td>$a_y(440)$ (m$^{-1}$)</td>
<td>0.06</td>
<td>0.08</td>
<td>0.09</td>
<td>0.09</td>
<td>0.13</td>
<td>0.13</td>
</tr>
<tr>
<td>$G_{min}$</td>
<td>0.3</td>
<td>0.2</td>
<td>0.3</td>
<td>0.3</td>
<td>0.3</td>
<td>2.0</td>
</tr>
</tbody>
</table>

*a*Measured sediment concentrations $C_{exp}$ and chlorophyll concentrations $chl_{exp}$ and minimum of the cost function, $G_{min}$, for stations A–F.

0.13 m$^{-1}$. As inherent optical properties were not measured during the field campaign, absorption coefficient of yellow substance can only be compared with previously published data. Reported values in the Mediterranean Sea for this parameter range from 0 m$^{-1}$ to 0.03 m$^{-1}$ in oceanic waters (Kirk, 1994) and from 0.06 m$^{-1}$ to 0.65 m$^{-1}$ in coastal waters (Bricaud et al., 1981). Our inverted values are realistic as compared to these values. $chl_{mod}$ values, obtained from model inversion, are overestimated at stations D and F and underestimated at stations A, B, C, and E. The relative difference between experimental and inverted values is $-100\%$, $-69\%$, $-64\%$, $+84\%$, $-3\%$, $+11\%$ for stations A–F, respectively. The generally high values of these relative differences can be interpreted as follows. On the one hand, the time period of the field campaign (30 October–5 November), during nonbloom conditions, is such that absorption by phytoplankton pigments or related products is low. Absorption by yellow substance is dominant and induces a low sensitivity of the model to the phytoplanktonic component as shown in the next subsection. On the other hand, Hoge and Lyon (1996) showed that retrieval errors for all IOPs are strongly dependent on the phytoplankton model when using a linear inversion method. Modeling absorption by phytoplankton is a difficult task.

The natural spectral variability of this IOP, not only for individual species grown in culture but also for natural phytoplanktonic assemblages (e.g., Mitchell and Kieffer, 1988; Bricaud and Stramski, 1990), must be taken into account to parametrize $a_y$. This problem is enhanced when variability introduced by biological processes is important at local or regional scales (O’Reilly et al., 1998). We conclude that, although $chl$ estimates by model inversion are of the same order of magnitude as experimental values, they are unreliable for operational purposes.

We tried to relate the spatial variability of $C$, $chl$, $m_r$, and $a_y(440)$ to the location of the sampling stations. Stations C and D are submitted to the single influence of

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Figure 4. Reflectance spectra for stations A–F. Full lines: experimental data. Dashed lines: reconstructed spectra using values of $chl$, $m_r$, and $a_y(440)$ obtained by model inversion.
fresh water discharge. The other stations are also under the influence of northwesterly winds (stations A, F) or southwesterly winds (stations B, E). Durand et al. (1997) performed modeling tests showing that stations C, D, E, and F are clearly within the plume and that stations A and B are located close to the plume boundary. Our estimates of parameter \( a(440) \) are consistent with these observations. These estimates increase from stations A to E, which is in agreement with the spatial evolution of the water quality parameters concentrations, \( C_{\text{exp}} \), and \( \text{chl}_a \). Station E is closer to the mouth than station F, but it is characterized by lower values of \( C \) and \( \text{chl} \). Nevertheless, \( a(440) \) values are identical. As the two stations were not sampled at the same time, on 1 November (E) and on 30 October (F), environmental conditions were not identical. The plume thickness was more important on 1 November, inducing lower values of \( C \) near the water surface.

**Determination of \( m \) and \( a(440) \)**

Given the poor reliability of chlorophyll concentration estimates as compared with experimental data, we tested the robustness of the inversion procedure for the determination of \( m \) and \( a(440) \). This was done by varying \( \text{chl} \) values within \(-50\%\) and \(+100\%\) around the experimental values. Table 3 gives estimates of \( m \) and \( a(440) \) at stations A–F from model inversion using experimental chlorophyll concentrations. These estimates are only slightly different from the values of Table 2. \( m \) is identical for stations A–F. \( a(440) \) is the same for stations E and F, lower for stations A (\(-17\%\)), B (\(-12\%\)), and C (\(-22\%\)), and higher for station D (\(+22\%\)). The corresponding variations of \( a(440) \) do not exceed 0.02 m\(^{-1}\). Though \( \text{chl} \) estimates obtained by model inversion are in poor agreement with experimental values, we observe from \( G_{\text{rms}} \) values of Table 2 and Table 3 that a better agreement between experimental and modeled reflectance spectra is obtained by retrieving three parameters instead of two. \( G_{\text{rms}} \) values increase about twice for stations A–C, less markedly for station D and keep the same for stations E and F when estimating only \( m \) and \( a(440) \).

Table 4 reports the relative variations of \( \Delta(m-1) \), \( \Delta(a-1)/\Delta(m-1) \), and \( \Delta a/\Delta a(440) \), obtained when taking as input parameter of the reflectance model chlorophyll concentrations corresponding to \( \Delta a/\Delta a(440) = -50\% \) and \(+100\%\). The results show that high variations of \( \text{chl} \) slightly modify inverted \( m \) values. Relative variations of \( \Delta(m-1) \) do not exceed \( 8\% \). Determination of \( a(440) \) is more sensitive to \( \text{chl} \) variations, but relative variations of \( a(440) \) are smaller than \( 30\% \). Despite the poor accuracy of \( \text{chl} \) computation, the method of inversion appears robust for the retrieval of \( m \) and results in errors less than \( 30\% \) for the determination of \( a(440) \). We can also conclude that the reflectance model is characterized by a low sensitivity to the phytoplanktonic component at least when the chlorophyll concentration is smaller than 2 mg m\(^{-3}\) as here. This is explained by the particular feature of coastal waters where the optical effect of phytoplankton is often masked by those of sediment and yellow substance.

**Spectral Variations of the Refractive Index**

The spectral dependency of the refractive index is investigated here. For this, the cost function is minimized at each wavelength, from 400 nm to 700 nm, the values of \( a(440) \), \( C \), and \( \text{chl} \) being fixed to the values given in Table 3 \([a(440)]\) and Table 2 \([C_{\text{exp}} \text{ and } \text{chl}_a]\). The resulting values of \( m(\lambda) \) are presented in Fig. 5. In general, except for station A, \( m(\lambda) \) slightly deviates from the bulk values of Table 3 (A: 3.0%, B: 2.0%, C: 1.4%, D: 0.9%, E: 0.6%, and F: 1.3%), which would indicate that the refractive index is weakly wavelength-dependent. The variations of \( m \) around its mean value are much smaller than the variations observed by Bedidi and Cervelle (1993), who computed the complex refractive index of hematite and goethite from measured specular reflectance spectra using Koenigsberger formulæ. No characteristic wavelength dependency was found by the authors, which is in agreement with our results. Ahn (1990) studied the optical properties of four terrigenous particles and in particular the spectral variations of their com-

| Table 3. Computed Values of Sediment Refractive Index \( m \) and Absorption Coefficient of Yellow Substance at 440 nm, \( a(440) \) When Chlorophyll Concentration = \( \text{chl}_a \) |
|---|---|---|---|---|---|
| \( \text{chl}_a \) (mg m\(^{-3}\)) | A | B | C | D | E |
| 0.22 | 0.64 | 1.40 | 1.36 | 1.44 | 1.35 |
| 1.10 | 1.13 | 1.13 | 1.15 | 1.16 | 1.13 |
| 0.05 | 0.07 | 0.07 | 0.11 | 0.13 | 0.13 |
| 0.9 | 0.5 | 0.7 | 0.5 | 0.3 | 2.0 |

| Table 4. Relative Variations of \( \Delta(m-1) \), \( \Delta(a-1)/\Delta(m-1) \), and \( \Delta a/\Delta a(440) \), When Relative Variations of Chlorophyll Concentration Are \( \Delta \text{chl}/\text{chl} = -50\% \) and \(+100\%\) |
| \( \Delta \text{chl}/\text{chl} \) | A | B | C | D | E | F |
| \( \Delta(m-1)/(m-1) \) (%) | -50\% | 0 | 0 | 0 | 0 | 0 |
| +100\% | 0 | 0 | +8 | 0 | 0 | 0 |
| \( \Delta a(440)/a(440) \) (%) | +50\% | 0 | +14 | +28 | +18 | +15 |
| +100\% | -20 | -28 | 0 | -18 | -23 | -15 |
plex refractive index. The method used was, as here, an indirect method. Real and imaginary parts of the refractive index were computed by an iterative procedure from measured values of absorption coefficient, attenuation coefficient, and particle size distribution. Our results are, here too, consistent with Ahn’s results which evidence only a slight wavelength dependency consisting in a monotonous variation between 400 nm and 750 nm of, for example, 1.14–1.11 (brown soil), 1.11–1.09 (yellow clay), 1.16–1.13 (red clay), and 1.13–1.14 (chalky sand).

For stations A–F, $G_{\text{min}}$ is equal to 0.15, 0.20, 0.38, 0.44, 0.26, and 1.4, respectively. These values are very low which is explained by the fact that experimental and theoretical values are adjusted at each wavelength. Reconstructed reflectance spectra, $R_{\text{mod}}(\lambda)$, are closer to the experimental ones (Fig. 6). The quality of the inversion

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Figure 5. Spectral variations of $m$, determined from model inversion, $m_a(440)$, $C$, and $chl$ being fixed.

Figure 6. Reflectance spectra for stations A–F. Full lines: experimental data. Dashed lines: reconstructed spectra using values of the spectral refractive index of sediment, $m_i(\lambda)$, obtained by model inversion.
method is significantly improved, in particular as the water is more turbid.

CONCLUSION

A reflectance model adapted to coastal waters, including sediment, chlorophyll, and yellow substance, is presented to estimate three parameters, \( m_r \), \( a_b(440) \), and \( chl \) from experimental reflectance spectra and suspended sediment concentrations. We showed that \( chl \) values are not accurately retrieved using this model. They are only of the order of magnitude of the measured concentrations. Nevertheless, inverted values of \( m_r \) and \( a_b(440) \) appear little sensitive to \( chl \) variations. Taking into account the spectral variations of the refractive index should significantly improve the evaluation of water quality parameters. To this aim, the inversion procedure can be exploited in a two-step process. The first step consists in determining \( a_b(440) \) and a bulk value of \( m_r \), considering measured concentrations of chlorophyll and suspended matter. In the second step, the refractive index is calculated at each wavelength, considering the previous values of \( a_b(440) \).

The method of inversion presented here can also be applied to the retrieval of \( C \). For this, we can imagine a statistical approach to deal with \( m_r \), by constituting a data base of \( m_r \) values characterizing various water types (Lahey et al., 1998b). This strategy requires intensive in situ measurements over a given site and during a given period.

NOTATIONS

\[
\begin{align*}
 a &= \text{total absorption coefficient (m}^{-1}) \\
 a_y &= \text{absorption coefficient of colored dissolved organic matter (m}^{-1}) \\
 a_b &= \text{absorption coefficient of phytoplankton particles (m}^{-1}) \\
 a_b^s &= \text{specific absorption coefficient of phytoplankton particles (m}^{-1}) \\
 a_s &= \text{absorption coefficient of seawater (m}^{-1}) \\
 b_b &= \text{total backscattering coefficient (m}^{-1}) \\
 b_{bb} &= \text{backscattering coefficient of phytoplankton particles (m}^{-2}) \\
 b_{bb}^s &= \text{specific backscattering coefficient of phytoplankton particles (m}^{-2}) \\
 b_b &= \text{backscattering coefficient of inorganic particles (m}^{-1}) \\
 b_{bb} &= \text{backscattering coefficient of seawater (m}^{-1}) \\
 chl &= \text{chlorophyll a plus phaeopigments concentration (mg m}^{-3}) \\
 C &= \text{inorganic particles concentration (mg L}^{-1}) \\
 D &= \text{diameter of inorganic particles (m)} \\
 D_{\text{min}}, D_{\text{max}} &= \text{minimum and maximum diameters of the inorganic particle size distribution (m)}.
\end{align*}
\]

\[
G = \text{quadratic difference between modeled and experimental reflectance values.} \\
m_r = \text{index of refraction of inorganic particles.} \\
Q_{bb} = \text{backscattering efficiency factor of inorganic particles.} \\
R_{\text{exp}} = \text{experimental reflectance values (%).} \\
R_{\text{mod}} = \text{modeled reflectance values (%).} \\
\rho = \text{inorganic particles density (kg m}^{-3}).
\]

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