

INTERPRETATION OF THE COLOUR SPECTRA OF COASTAL WATERS
IN FUNCTION OF THEIR PHYTOPLANKTON CONCENTRATION

by

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ABSTRACT

To quantify the pigment concentration in water masses from the remote measured spectral radiance requires the development of an atmospheric, interface and interpretation algorithms. The latter is used in a empirical or analytical methodology.

The empirical approach only appears to be suitable for CASE 1 waters (i.e. as optical properties are essentially defined by the phytoplankton and its derivative products). The analytical approach on the other hand seems to be more relevant as CASE 2 waters are considered (i.e. those waters rich in inorganic detritic particles and in various sediments and/or in dissolved organic matter).

With respect to this waters encountered in the Southern Bight of the North Sea are proved to belong to the CASE 2 water optical type with great reflectance values (noted R) above 600nm. Different algorithms including the R(435nm) value are shown to be sensitive to the pigment concentration, which can be namely explained by absorption spectra of acetone extracts peaked at this wavelength.

INTERPRETATION OF THE COLOUR SPECTRA OF COASTAL WATERS IN FUNCTION OF THEIR PHYTOPLANKTON CONCENTRATIONS

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ABSTRACT

The interpretation of the remote measured spectral reflectance of natural waters (which physically describes the intrinsic colour of the water) in function of their different optically active components, requires the development of three distinct algorithms. The last of those, the interpretation algorithm, must be first constructed from previous knowledge about the optical type of water encountered (optically defined essentially by the phytoplankton and its derivative products or by detrital inorganic particles and various sediments) and about the optical properties (spectral behaviour of absorption and (back-)scattering) of the studied in-water component (here the phytoplankton). With this in mind, a method (empirical or analytical) is used to infer quantitative information about this component from the observed spectral reflectance ($R(\lambda)$ curve), through the use of an appropriate interpretation algorithm. Results from three cruises in the Southern Bight of the North Sea seem to postulate the use of the $R(435\text{nm})$ value (included for instance in a difference) in the interpretation method. Moreover several considerations tend to promote the analytical interpretation approach in such turbid coastal and dynamical waters.

INTRODUCTION

The remote sensing of the phytoplankton concentration of water masses requires the analysis of the spectral composition of the backscattered radiant flux (in the visible part of the spectrum, *i.e.* between 400 and 700 nm) which originates from below the sea surface. The remote sensor (taken aboard an aircraft or a satellite) intercepts a spectral signal $L(\lambda)$ which integrates the contributions of the oceanographic and atmospheric systems (Fig. 1), and so these can be written:

$$L(\lambda) = [L_w(\lambda) + L_g(\lambda)] T(\lambda) + L_p^a(\lambda) + L_p^r(\lambda) \quad (1)$$

where the L-terms refer to the radiance and the T-term refers to the atmospheric transmittance. All the contributions expressed in the above equation are function of the wavelength:

- $L_w(\lambda)$ is the water-leaving radiance; it comprises the photons which have been transmitted at the air-sea interface and then back-scattered in the

atmosphere. These undergo interactions with the water column, so that

$L_w(\lambda)$ carries the useful information,

- $L_g(\lambda) = L_g^s(\lambda) + L_g^d(\lambda)$ where $L_g^s(\lambda)$ is the sun glitter radiance and $L_g^d(\lambda)$ is the diffused sky glitter radiance,
- $T(\lambda)$ (the atmospheric transmittance) applies to $L_w(\lambda)$ and $L_g(\lambda)$ because these are defined at the sea level,
- $L_p^a(\lambda)$ is the aerosol path radiance (due to the particular scattering),
- $L_p^r(\lambda)$ is the Rayleigh path radiance (due to the molecular scattering).

$$L(\lambda) = \{L_w(\lambda) + L_g(\lambda)\}T(\lambda) + L_p^a(\lambda) + L_p^r(\lambda)$$

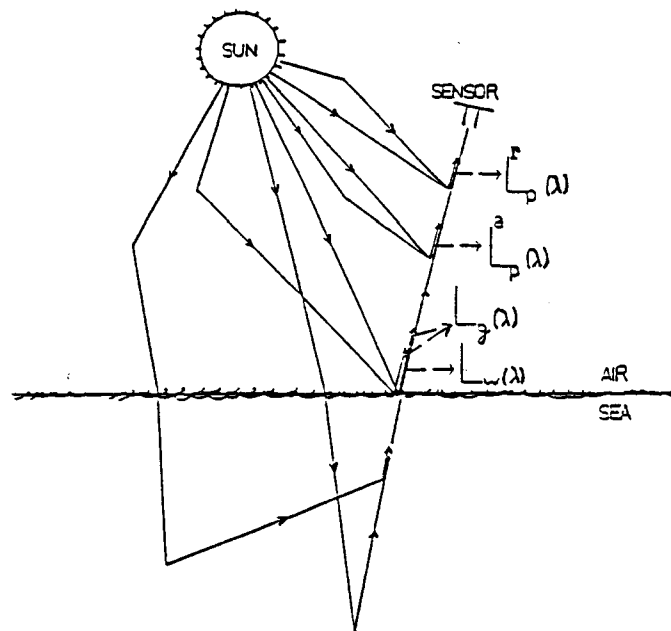


Fig. 1. Contributions of the ocean and the atmosphere in the remote sensing of water colour.

The equation (1) reveals that the qualitative and quantitative study of the different optically active components present in natural waters from the complete spectral signal $L(\lambda)$, requires the development of three distinct algorithms:

- an atmospheric algorithm which defines the $T(\lambda)$, $L_p^a(\lambda)$ and $L_p^r(\lambda)$ functions,

- an interface algorithm which aims at:
 - accounting for the effects of reflection and refraction at the sea-air interface, that is, the two processes which govern the radiance transfer at the sea surface,
 - deriving another function, the reflectance function $R(\lambda)$ just below the interface, from $L_{wp}(\lambda)$; the latter precisely depends on both the angular distribution of radiance and the intensity of irradiance incident on the sea surface. The $R(\lambda)$ function on the other hand shows a certain independence to the same conditions (*see below*),
- an interpretation algorithm: the $R(\lambda)$ values are often combined in a judicious mathematical form, *i.e.* the most sensitive to the variations of the phytoplankton concentration in the water mass. In most cases, the sum of the concentrations of chlorophyll *a* (the major photosynthetic pigment) and phaeophytin *a*, its degradation product, is taken into account (this sum is so-called the pigment concentration). These pigments show indeed absorption spectra that are about similar in shape and magnitude, and their respective effects on intrinsic ocean colour can therefore be considered the same, if the spectral resolution of the sensor is too weak to discriminate between them.

If the sensor is ideally located just below the sea surface, the atmospheric and interface algorithms need not be developed (except for the $L_{wp}(\lambda)$ to $R(\lambda)$ conversion). In this way, by using a submersible spectro-irradiance meter, the reflectance function can be derived and only the interpretation study must be developed. Such study actually poses a very intricate problem in turbid coastal waters for the simple reason that the effects of the non-biogenic products interfere all along the visible spectrum with those of the biological material on water colour.

The purposes of this study are:

- i) to express some arguments which object to the use of the empirical interpretation methodology (and more precisely, of the "blue/green" ratio method) in coastal and dynamical environments,
- ii) to develop $R(\lambda)$ experimental curves for distinct water bodies encountered in the Southern Bight of the North Sea during three cruises (May 16-20, July 25-28 and September 12-21). Such approach will allow us to define the interpretation method which is the most appropriate to *in situ* optical conditions, and to develop some efficient algorithms which are the most sensitive to pigment concentration variations.

2 THEORETICAL BACKGROUND

The reflectance function $R(z)$ (at depth z) is an apparent property of the optical medium, which means that it depends on both the in-water angular distribution of radiance $L(z, \theta, \phi)$ (where θ and ϕ are respectively the zenithal and the azimuthal angles defined in a spherical coordinate system) and on the inherent optical properties of the water body, *i.e.* independent of this same distribution. In the interpretation studies, $R(\lambda)$ curves are always defined at an ideal "zero depth" which actually means just below the sea surface (for $z < 1\text{m}$).

In most cases, reflectance function is the useful spectral information from which the interpretation is carried out; we may consider three reasons for this:

- the reflectance function (also called the diffuse reflectance, irradiance reflectance or even irradiance reflectivity) is defined as

$$R(\lambda) = E_u(\lambda) / E_d(\lambda) \quad (2)$$

where $E_u(\lambda)$ and $E_d(\lambda)$ are respectively the up- and downwelling spectral irradiances. This definition offers two advantages:

- the $R(\lambda)$ curves are independent of the intensity of the total irradiance (direct and diffuse solar fluxes) incident on the sea surface. Moreover, Gordon and Brown (1973) showed that for the angular radiance distributions defined by a sun at the zenith and by an uniform sky, the reflectance functions are nearly the same,
- provided a submersible spectro-irradiance meter equipped with a cosine collector is available, measurements of $R(\lambda)$ curves are easily carried out,
- using an appropriate algorithm which accounts for the interface effects and for the spectral composition of the total incident irradiance, spectral reflectance function can be derived from the water-leaving radiance as determined by the sensor,
- solving the equation of radiative transfer in water by using different approximations, several authors have defined the $R(\lambda)$ function in terms of inherent optical properties which in turn contain information elements about the different optically active components present in natural waters. Some of these relations are set in table I.

TABLE I

Theoretical relationships between reflectance function and inherent optical properties.

Type	Reference
$R(\lambda) = 1/2 \, b'(\lambda) / a(\lambda) [1 + b'(\lambda) / a(\lambda)]^{-1}$	Kozlyaninov and Pelevin (1965)
$R(\lambda) = \sum_{n=0}^N r_n [b'(\lambda) / a(\lambda) + b'(\lambda)]$	Gordon et al. (1975)
$R(\lambda) = 0.33 [b'(\lambda) / a(\lambda)]$	Morel and Prieur (1977)
$R(\lambda) = m [b_w(\lambda) / a(\lambda)] + n [b_p(\lambda) / a(\lambda)]$	Deschamps et al. (1977)
$R(\lambda) = 0.1076 [b'(\lambda) / a(\lambda)]$	Carder and Steward (1985)

As we can see the most general form of these equations is

$$R(\lambda) = f [b'(\lambda) / a(\lambda)]$$

where $b'(\lambda)$ and $a(\lambda)$ are respectively the total spectral back-scattering and absorption coefficients of the water. The f function depends on both the angular distribution of radiance and the volume scattering function $\beta(\theta)$ of the water. Such relations are of course interesting, because they can be used in remote sensing reflectance models to predict analytical $R(\lambda)$ curves from given components concentrations and adequate decomposition models of the total back-scattering and absorption effects (*see below*).

Such modelling and the empirical method are the two different approaches in the interpretation of $R(\lambda)$ curve in terms of in-water component concentration.

3 INTERPRETATION METHODS

3.1. The empirical approach

A statistic relation is studied between two sets of variables, the sensor-derived spectral reflectances (sometimes the radiances) and the concentrations of the studied water parameter, here the phytoplanktonic content, which are determined (*e.g.* from a ship) at the same locations. Such relation

implies covariation of all the in-water optically active components with the phytoplankton concentration (Morel, 1980) because developed empirical approaches take into account one single independent variable. This condition which exists in open sea where optical properties result mainly from biological activity (*i.e.* in case 1 waters as defined by Morel and Prieur, 1977), is less or even not satisfied in coastal waters influenced by resuspension of bottom sediments and/or terrigenous fluxes (which correspond to case 2 waters). However, efficient empirical algorithms have been already developed in turbid coastal waters to estimate the pigment concentration, but these algorithms are valid in limited space and time scales (*see below*). Besides the covariation condition which has to be satisfied in all situations to justify the applicability of empirical algorithms, the use of the classical "blue/green" ratio methodology (between 420-480nm and 500-560nm respectively) for the interpretation of ocean colour spectra may be questionable in case of turbid coastal waters. One has to recall indeed that the most common equation for empirical relationships is bi-logarithmic,

$$\log c = a + b \log [R(\text{blue})/R(\text{green})]$$

where the best fitting is theoretically found with c as the pigment concentration integrated to the $z(90\%)$ depth (Gordon and McCluney, 1975) and weighted by the attenuation function as defined by Gordon and Clark (1980). a and b are constants determined by regression.

(i) Use of the "blue/green" ratio empirical method for case 2 waters

Dissolved organic matter and inorganic particles are the two major inputs in the optical medium, which result from coastal proximity. Yellow substances induce only an absorption effect on the reflectance spectra. It indeed exhibits a typical exponential absorption curve which decreases from the UV domain towards the visible part of the spectrum.

This latter can be modelled as following

$$a(\lambda) = a(\lambda_0) \exp [-s(\lambda - \lambda_0)]$$

where λ_0 is chosen in the [UV visible] spectral domain. Covering a large range of water bodies different with respect to their particle and pigment content, s is shown to be about 0.014 with a standard deviation of 0.0032 (Bricaud *et al.*, 1981). This therefore emphasizes the weak variability of

the shapes of yellow substances absorption curves. For this reason, increasing amounts of dissolved organic matter may be thought as affecting ocean colour spectra through decreasing the "blue/green" ratio by increasing $a_y(\text{blue}) / a_y(\text{green})$ (where y refers to yellow substances), whenever other optically active components concentrations remain unchanged.

On the other hand, suspended inorganic particles which result from coastal situations modify reflectance spectra through the $b'_p(\lambda) / a_p(\lambda)$ ratio (where p refers to inorganic particles), and hence induce a more intricate effect on $R(\lambda)$ curves. Very little is known at the present time about the different spectral behaviours and magnitudes of the absorption and back-scattering coefficients for inorganic particles (which represent the major part of the particle coastal input). Their maximum absorption values seem to locate in the blue portion (see e.g. Bukata *et al.*, 1981a; Shook *et al.*, 1980) but the general shape of the observed absorption curves appears to depend on the type of particle. Moreover, considering their spectral absorption shape for non-chlorophyllous particles, Prieur and Sathyendranath (1981) suppose that its nearly exponential left side probably results from yellow substances in colloidal or adsorbed form. The spectral distribution of the back-scattering coefficient also presents great differences according to the type of particle (see e.g. Shook *et al.*, 1980; Bukata *et al.*, 1981a). Greater turbidity in fact induces greater but less spectrally selective back-scattering (Morel and Prieur, 1977). We may therefore conclude that:

- the effect of dissolved organic matter on reflectance spectra (limited to absorption) is predictable with sufficient accuracy,
- the effect of inorganic particles has on the other hand to be considered on a regional or even seasonal basis.

The influence of coastal inputs on water colour spectra (where $R(\lambda) = \frac{1}{2} [b'(\lambda) / a(\lambda)]$), more precisely on the "blue/green" ratio, is expressed through the inequality

$$b'_p(\text{bl}) [a_p(\text{bl}) + a_y(\text{bl})]^{-1} > \text{or} < b'_p(\text{gr}) [a_p(\text{gr}) + a_y(\text{gr})]^{-1} \quad (3)$$

where "bl" and "gr" refer respectively to blue and green wavelengths. The left-hand and right-hand terms in equation (3) represents effects on respectively blue and green portions of reflectance spectra. Covering a large range of water bodies, Morel (1980) shows that his case 2 waters points set systematically below the $[R(\text{blue}) / R(\text{green})] = f(c)$ regression

line defined by case 1 waters only. Considering the above reasoning, it seems that the case 2 waters observed by Morel obey to the second inequality of equation (3). Taking into account such inequality, the following graphical considerations may be expressed.

Figure 2 presents bi-logarithmic relationships between the "blue/green" reflectance ratio and the pigment concentration in three different cases:

- a) The solid line accounts for case 1 waters only. In such a situation, only pigment concentration is thought to affect the "blue/green" ratio. This implicit supposition may however not be strictly realist because yellow substances absorption can induce a significant effect on colour variations even in case 1 waters (Bricaud et al., 1981). In this case, the interpretation algorithm is no more an explicit physical relation between c and the "blue/green" ratio, due to the "masked" effect of dissolved organic matter. Taking into account however such supposition (which is always implicitly adopted), the empirical algorithm developed in this way may be extrapolated to the entire remote sensor scene.
- b) The dotted line accounts for case 1 and case 2 waters. This leads for a same pigment concentration to diminish the $R(\text{blue}) / R(\text{green})$ ratio through absorption by yellow substances (if second inequality in equation (3) is satisfied). In such a situation, a global algorithm can also be constructed but this may be questionable: it is characterised besides a decrease in the absolute value of the b exponent (*i.e.* the slope of the regression line), by a lower correlation coefficient and a greater standard error of estimate, as was observed by Morel (1980) and by Gordon *et al.* (1983). Such phenomena can be interpreted as a result of a smaller covariation of each of the non-chlorophyllous optically active components with pigment content, when case 2 waters are considered. The global algorithm will generally under- and overestimate pigment concentration for respectively case 1 and case 2 waters. Extrapolation of such interpretation algorithm on the entire scene (*i.e.* including open sea and coastal areas) may therefore be unreliable.
- c) If only case 2 waters are considered (dashed line on fig. 2), the empirical algorithm developed in this way will be still theoretically characterised by a lower correlation coefficient and a greater standard error of estimate. It will however not induce generally systematical overestimation of the pigment concentration, because case 1 waters are not included in the regression analysis.

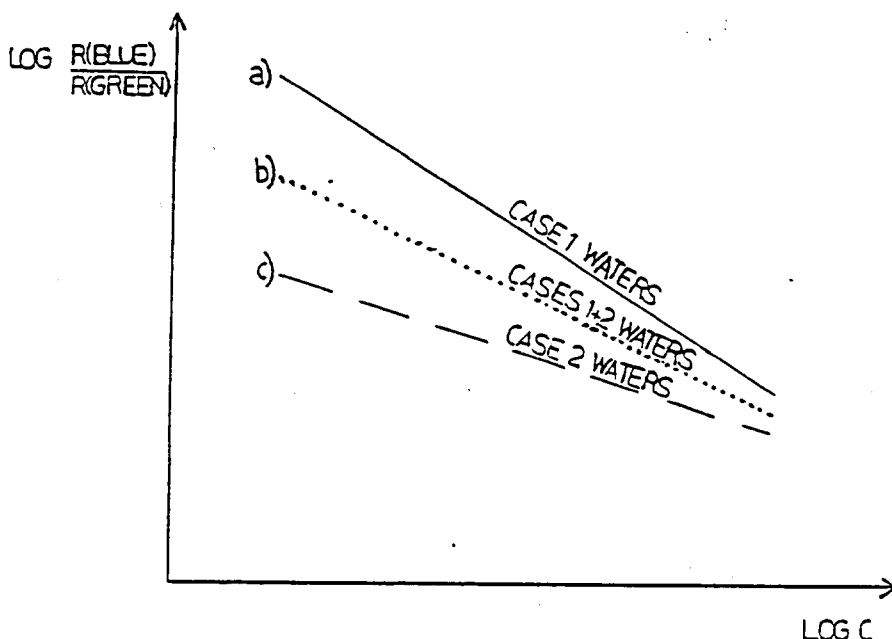


Fig. 2. Empirical regression lines between the "blue/green" ratio and the pigment concentration for (a) case 1 waters only, (b) cases 1 and 2 waters and (c) case 2 waters.

From our reasoning, we may anticipate that the above graphical observations, more precisely the under- and overestimation effects, would be inverted if the first inequality in equation (3) would be satisfied. The use of the "blue/green" ratio empirical method for case 1 and case 2 waters scenes appears therefore questionable. The greater standard errors of estimate for pigment concentration, when considering case 2 waters only in the $[R(\text{blue}) / R(\text{green})] = f(c)$ regression analysis, also make such a method questionable in single coastal environment.

ii) a and b parameters variations

Another consideration which deals with the a and b parameters variations similarly tends to support the above conclusion; to account for these variations, several authors gave some reasons, namely:

- "Environmental variability during the time required to obtain sufficient biological and optical data; variations in reflectance "blue/green" ratio due to non-chlorophyllic absorbing material, which can vary in space and time; biological variations which are treated as an ensemble average which smooth over variabilities such as carbon-to-chlorophyll and accessory-pigment-to-chlorophyll ratios due to change in community structure, hydrographic season, and location" (Smith and Baker, 1982).

- "Different phytoplanktonic types" (Viollier and Sturm, 1984).
- "Non-chlorophyllous ocean colour components for each region differing in the degree and form in which they covary with chlorophyll" (Carder *et al.*, 1986).

Some of these explanations are relatively similar. These above conditions are however met preferentially in coastal and dynamical environments. We may thus conclude that the a and b parameters variations -if defined- are valid on restricted space and time scales in such environments.

iii) Optical properties of phytoplankton

It is implicitly admitted that the biological material induces an effect on the $R(\lambda)$ curves only through $[a_{ph}(\lambda)]^{-1}$ (where ph relates to pigment concentration). The study of Bricaud *et al.* (1983) however shows that the shapes of the spectral scattering and back-scattering coefficients for different phytoplankton species are depressed near and inside the absorption bands (a theoretical explanation is provided). In this way, the influence of phytoplankton on ocean colour spectra (*i.e.* though $b'_{ph}(\lambda) / a_{ph}(\lambda)$) would be more severe than it is generally expected, as was argued by Bricaud *et al.* (1983). Moreover, several works (Morel and Bricaud, 1981; Bricaud *et al.* 1983; Bricaud and Morel, 1986) reveal that the specific coefficients for different phytoplankton species vary notably, while most interpretation methodologies (whatever they are, *i.e.* empirical or analytical) are based on the constancy of such functions. Effect of $b'_{ph}(\lambda)$ on water colour spectra and variability of the phytoplankton specific coefficients can be taken into account however in the analytical interpretation methodology.

3.2. The analytical approach

In the modelling methods, the calculated $R(\lambda)$ curve is compared with the measured curve to infer the pigment concentration. The general form of such a theoretical modelling and interpretation program is shown on figure 3. Modelling an analytical reflectance function requires mainly two different steps:

- The development of the most appropriate (*i.e.* to *in situ* optical conditions) decomposition models of the inherent optical properties of the water body into their different contributions. It means that the total spectral absorption and back-scattering (sometimes scattering) coefficients are split into the different contributing products, *i.e.* x_i the concentration of the i component times its specific coefficient, *i.e.* a_i^*

and b^*_i , that is, per unit concentration. Specific coefficients for each component must be known *a priori* in the modelling.

- The total spectral absorption and back-scattering coefficients are inserted in a theoretical relationship such as expressed in Table I to derive the analytical reflectance function, $R^t(\lambda)$.

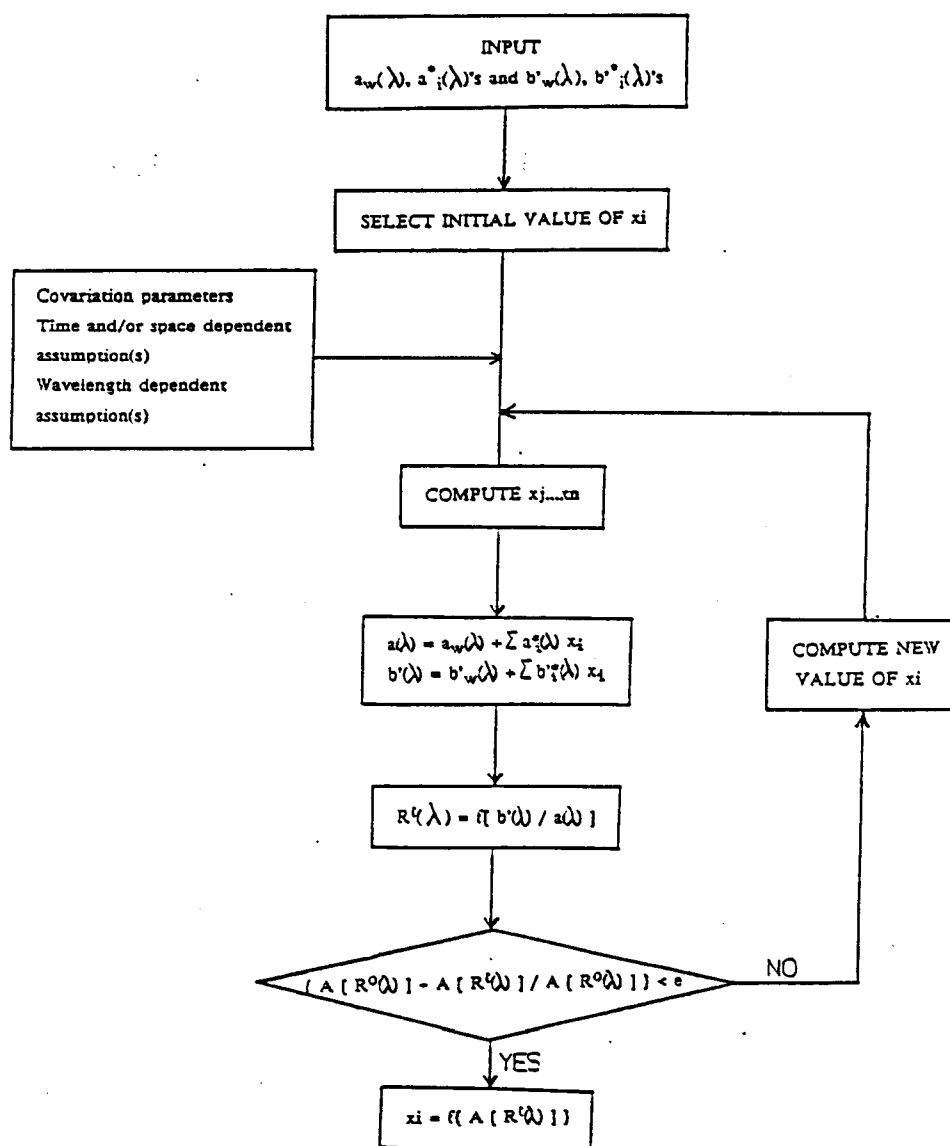


Fig. 3. The general form of the modelling and interpretation program of water colour spectrum.

In decomposition models, only inherent properties must be chosen because the additivity principle applies strictly to these, due to their independence to the in-water angular distribution of radiance.

The reflectance model is then tested:

- Observed in-water component concentrations are used for the adjustment of some parameters (e.g. covariation parameters). This is achieved when the comparison between the analytical and the experimental interpretation algorithms (i.e. $A \{ R^I(\lambda) \}$ and $A \{ R^O(\lambda) \}$ respectively, where A refers to the used mathematical form of reflectance) gives a quantity inferior to a predetermined value ϵ (see fig. 3),
- the concentration of the in-water studied component is then derived, using the same procedure.

Problem arises to determine other component concentrations (i.e. $x_j \dots x_n$). These can be computed from observed or assumed covariation parameters. Time and/or space and wavelength dependent assumption(s) are the two other degrees of freedom in the model. These can be used to neglect some component effects on ocean colour spectra. For instance, complete decomposition models of inherent optical properties in a turbid coastal medium can be written

$$a(\lambda) = a_w(\lambda) + a_{lo}^*(\lambda) x_{lo} + a_{nlo}^*(\lambda) x_{nlo} + a_{in}^*(\lambda) x_{in} + a_y^*(\lambda) x_y$$

$$b'(\lambda) = b'_w(\lambda) + b'_{lo}^*(\lambda) x_{lo} + b'_{nlo}^*(\lambda) x_{nlo} + b'_{in}^*(\lambda) x_{in}$$

where w , lo , nlo , in and y refer to pure seawater, living organic, non-living organic, inorganic and yellow substances respectively. We may assume for example that inorganic absorption is negligible in some wavelength and/or space and/or time condition(s). Predetermined interpretation algorithm must be promoted because it allows to account for spectral domain(s) where studied concentration variations induce the most significant effect(s). Moreover, it allows to introduce possibly wavelength dependent assumption(s) to neglect some component effect(s) at wavelength(s) considered in the interpretation algorithm.

In practice, the modelling approach therefore allows to account for the effects of all the different optically active components on water colour spectrum. This observation tallies with the above conclusions to argue that the analytical interpretation methodology has to be promoted in coastal and dynamical environments, due to its realism and flexibility (as was expressed by Smith, 1984) to specific *in situ* optical conditions.

The accuracy of the pigment concentration determination can be improved by using more complex models. For instance, using a mathematical model which predicts spectral reflectance curves for monospecific dinoflagellate bloom waters (red tide), Carder and Steward (1985) obtain an accuracy for pigment concentration which is always within 17.5 %, even in case 2 waters. One has to note finally that the use of covariation parameters of each of the non-chlorophyllous components with pigment concentration, and their modification in the reflectance modelling, allow "to respond to regional and seasonal differences in runoff, phytoplanktonic size and pigment colour groups", as was emphasized by Carder *et al.* (1986).

In vivo fluorescence of chlorophyll a

Another strategy which is used in interpretation studies of ocean colour spectra, is to take into account the peak of *in vivo* fluorescence of chlorophyll *a* as observed in reflectance spectra between 685-690nm (Morel and Prieur, 1977; Neville and Gower, 1977). Such strategy seems interesting for the interpretation of ocean colour in turbid coastal waters because "red" fluorescence is specific to chlorophyll *a* and can possibly help to discriminate the effects of phytoplankton and yellow substances on R(blue). It should be noted however that fluorescence peaks were only observed in case 1 waters by Morel and Prieur (1977).

4 MATERIALS AND METHODS

Three cruises (May 16-20, July 25-28, September 12-21) were performed in the Southern Bight of the North Sea with the Belgian oceanographic research vessel BELGICA. Due to the strong tidal currents, the shallowness of the sea and the frequent storms, no thermocline exists in the studied area and the water column is thus homogeneous. Hence, it was sufficient to collect surface samples.

A submersible spectroradiometer ("Spectral Irradiance meter" (SIR)) constructed at the "Netherlands Institute for Sea Research" (Texel), was used to measure the spectral down- and upwelling irradiances just below the sea surface. Reflectance functions were derived using equation (2). The SIR scans 11 spectral channels between 404 and 690nm (centered at the 404, 419, 436, 450, 480, 513, 570, 599, 627, 663 and 690nm wavelengths). The spectral bandwidth of each channel is within 10nm. The light is collected by two cosine diffusers at each side (up and down) of the instrument. The spectral response of the SIR is then calibrated to derive the irradiance value.

Besides the $R(\lambda)$ values, the following sea data were collected:

- the total suspended matter was measured by filtration on Millipore membrane filters (0,45µm porosity) and weighting,
- the chlorophyll *a* and phaeophytin *a* concentrations were measured using the Strickland and Parsons (1968) method. Acetonic extracts were scanned between 350 and 700nm at 5nm-interval. The phaeopigment *a* concentrations for the Septembre sampling points were determined using the linear relationship equation between the phaeopigment *a* and chlorophyll *a* contents, which was defined using the data of May and July cruises (see fig. 4),

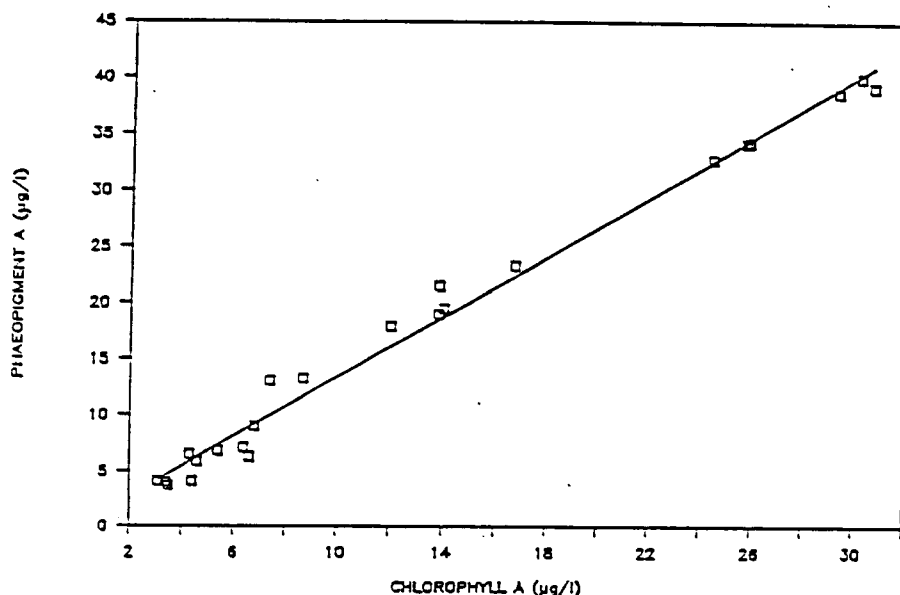


Fig. 4. Relationship between the phaeopigment *a* and chlorophyll *a* concentrations (Data from May and July cruises). The regression equation is

$$[\text{Phaeo.a}] = 0.162 + 1.331 [\text{Chl.a}]$$

($r^2 = 0.99$; standard error of est. = 1.46; $N = 23$).

- the sum(UV) quantity, which is a measure of the concentration of dissolved organic matter (Foster and Morris, 1971), was measured using the method of Monahan and Pybus (1978). Water samples were filtered through Whatman GF/C glass fiber filter papers and stored in bottles protected from light (at 4° covered by aluminium paper). Within one week, measurements of absorbance were made on the samples at 5nm-interval between 250 and 350nm. The 21 values were then summed to obtain sum(UV),

- the water colour was determined by matching its apparent hue with one of the numerous paint chips on the Ocean Colour Scale based on the Munsell system of colour notation.

5 RESULTS AND DISCUSSION

The reflectance functions of different water bodies (see fig. 5) with respect to their pigment concentration, total suspended matter concentration, dissolved organic matter content, salinity and colour are given in figure 6. All the $R(\lambda)$ curves show a relatively limited spectral dependence. However, a clear distinction appears in the yellow and red portions of the spectrum, between coastal and estuarine waters on one hand, and more oceanic waters on the other hand. Indeed, the waters of the stations 3, 4 and s09 show their greatest reflectance values in these portions of the spectrum, while the waters of the sampling points 7, 8 and 9 present these maxima rather in the blue and blue-green parts of the spectrum.

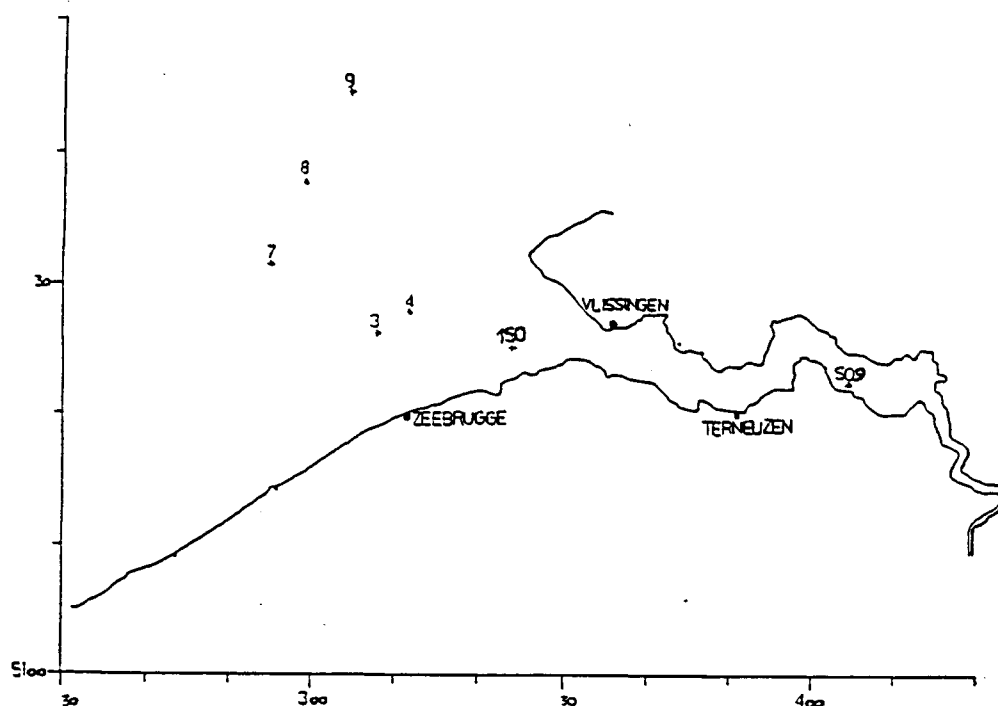


Fig. 5. Map of the September sampling points.

Such distinction can result from a difference in back-scattering magnitude and thus in turbidity level (see e.g. Morel and Prieur, 1977; Bukata *et al.*,

1980). No significant relationship seems however to exist between absolute or combined $R(\lambda)$ values and the total suspended matter concentration.

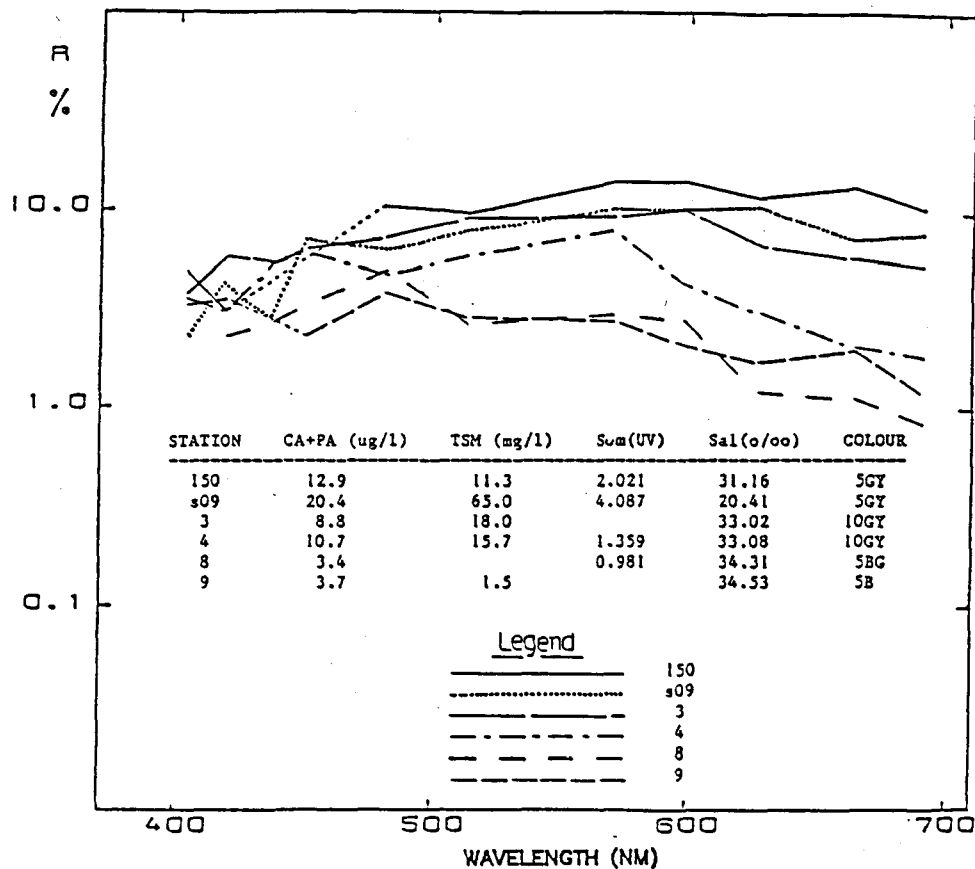


Fig. 6. Experimental reflectance curves for water bodies different with respect to their pigment concentration (CA+PA in ug/l), total suspended matter concentration (TSM in mg/l), dissolved organic matter (Sum(UV)), salinity (Sal. in o/oo) and Munsell colour (B, G and Y refer to blue, green and yellow hues respectively).

Experimental $R(\lambda)$ curves from this study are compared with those obtained by Morel and Prieur (1977), which were considered as representative of the case 2 water optical type (Fig. 7). A certain agreement is found between the two sets of curves except for wavelengths superior to $\pm 570\text{nm}$. This may be still interpreted as a result of a greater turbidity level of the water masses encountered in the Scheldt estuary and off the Belgian coast.

Figures 8a, 8b and 8c show absorption spectra normalized at 435nm, for acetic extracts of waters from points all over the studied area, sampled respectively in May, July and September. Each curve has a specific shape depending on the different phytoplanktonic pigments effects present in the

extract. All absorption curves are peaked at or near 435nm. The sensibility of the $R(570) - R(436)$, $R(599) - R(436)$, $R(570) / R(436)$ and $R(599) / R(436)$ quantities to pigment concentration variations is shown in figures 9a-9c. The good correlation between the $R(570) - R(436)$ difference and c ($r^2 = 0,86$) makes this difference apparently the most interesting to use in the interpretation methodology, whatever it is, *i.e.* empirical or analytical. Such sensibilities may be explained by maximum absorption values observed at or near 435nm, associated with assumed little spectrally selective absorption and back-scattering of the non-living particles.

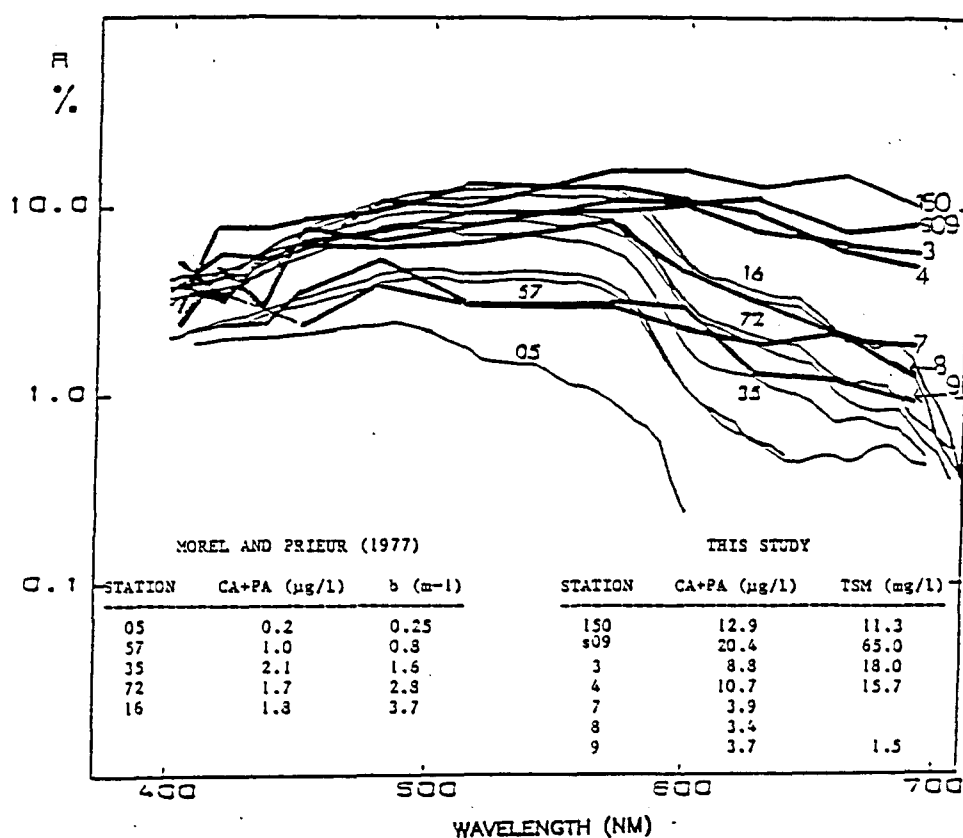


Fig. 7. Experimental reflectance curves observed in this study (thick lines), compared to those of Morel and Prieur (1977) (fine lines) illustrating case 2 waters.

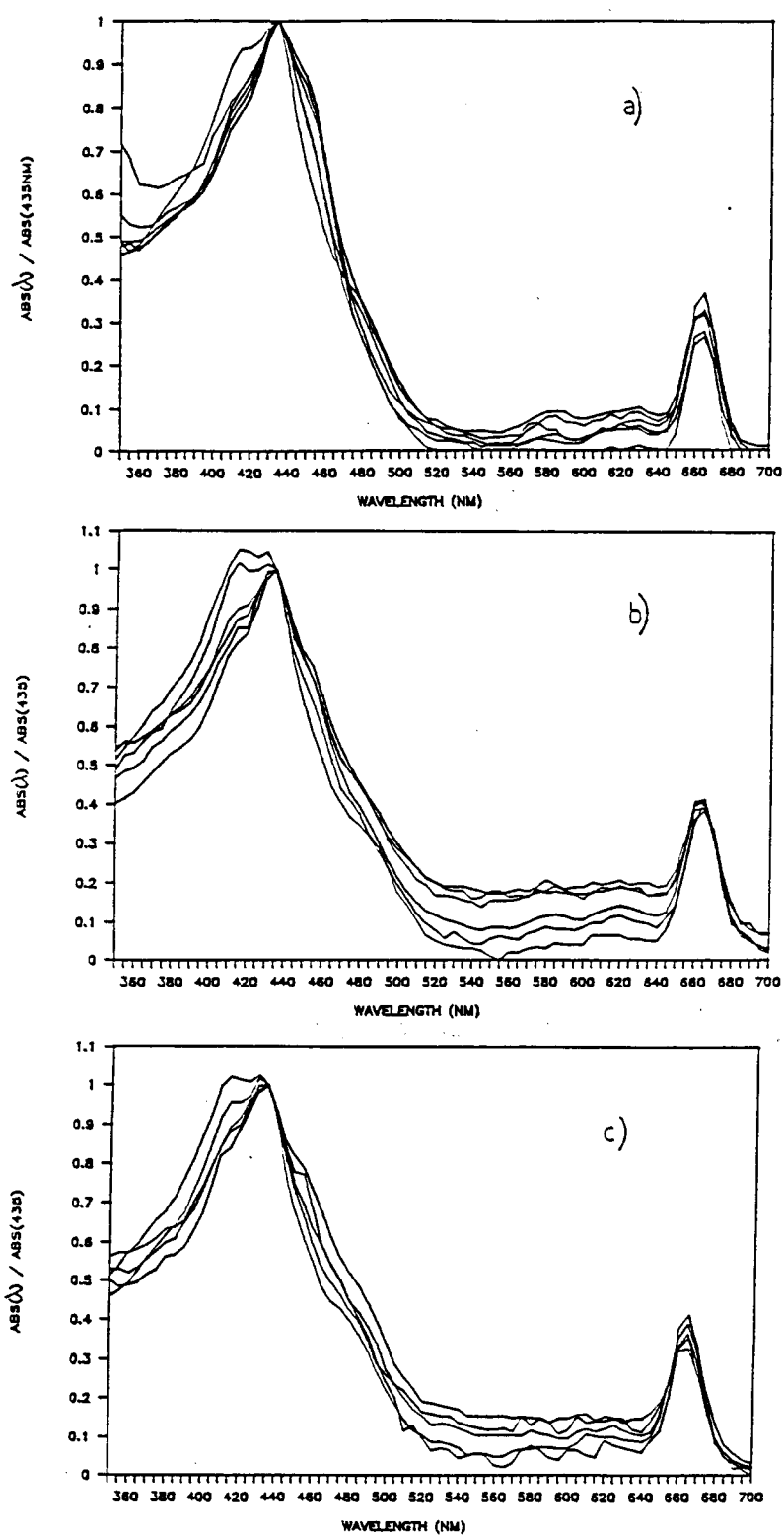


Fig. 8. Absorption spectral curves of acetonc extracts normalized at 435nm for (a) Mai, (b) July and (c) September stations. Within one cruise, curves refer to water bodies covering estuarine, coastal and more oceanic geographical situations.

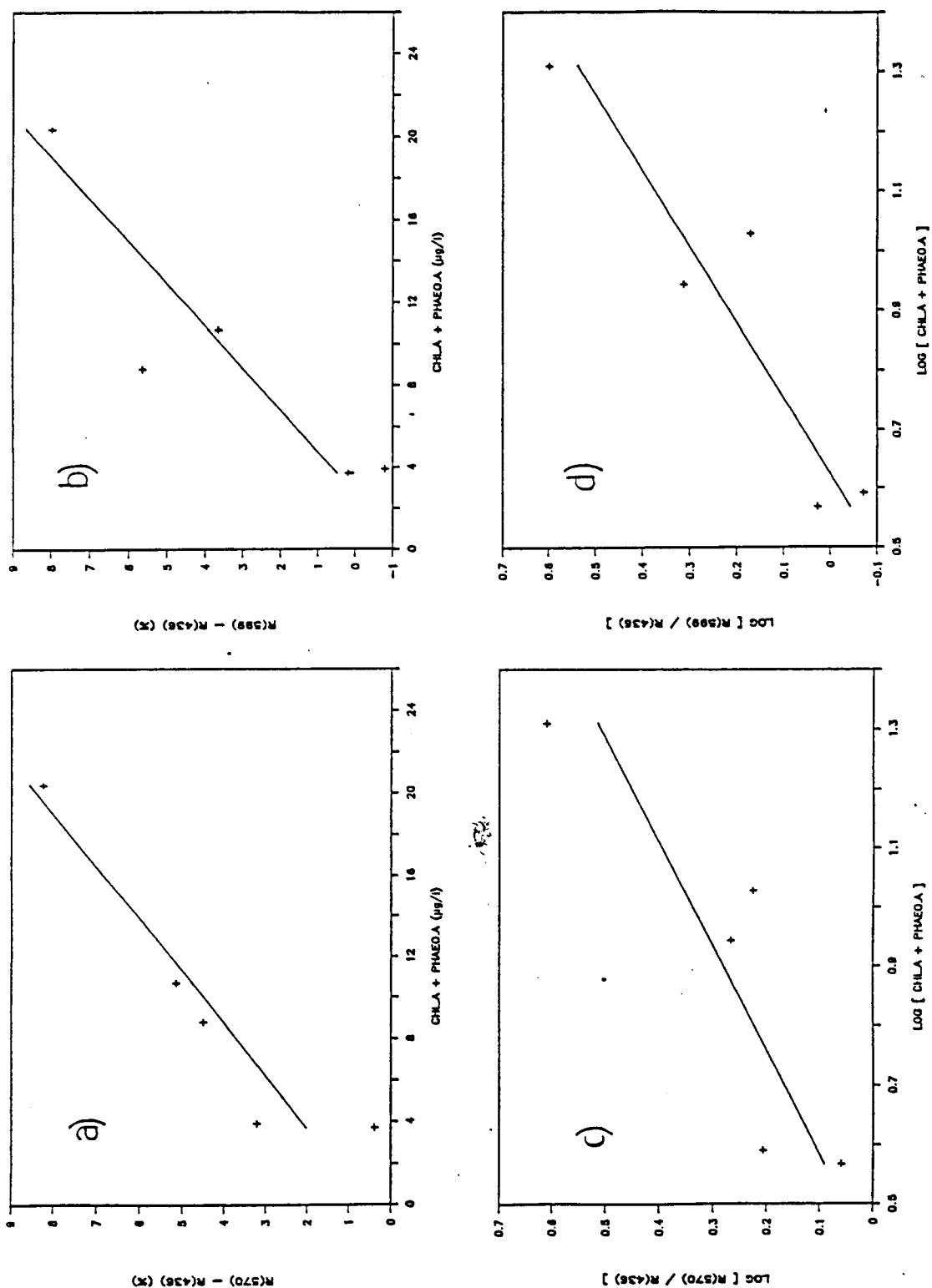


Fig. 9. Sensibility of (a) $R(570) - R(436)$, (b) $R(599) - R(436)$, (c) $R(570) / R(436)$ and (d) $R(599) / R(436)$ to pigment concentration variations. Correlation coefficients are respectively 0.86; 0.82; 0.77 and 0.87. All data are from the September cruise.

The interpretation algorithms developed using the Ocean Colour Scanner, during the EURASEP experiment in the Southern Bight of the North Sea in summer 1977 (Sorensen, 1979) are given in table II. While a single sediment algorithm was developed (with an accuracy of 30 percent for $\log s$, where s is the total suspended matter concentration in mg/l), two local chlorophyll algorithms were determined (accuracy of 6 percent for $\log c$, where c is the chlorophyll a content). It was argued (Sorensen, 1979) that "the limited amounts of good c determinations and the low variability of the data did not enable an unique algorithm to be developed". The lower correlation coefficients for these chlorophyll algorithms, compared to those obtained in this study, may be ascribed to the fact that only the chlorophyll a content was taken into account. Reflectance ratios were more sensitive to chlorophyll a than to suspended matter concentrations. This seems to be confirmed to some extent in the present study. The present data set however indicates that a reflectance value more sensitive to pigment concentration, i.e. at $\pm 435\text{nm}$ (rather than the $R(472)$ used in the O.C.S. data regression) should be used. Note finally that peaks at 690nm proportional to chlorophyll a content were not observed in the reflectance spectra.

TABLE II

Interpretation algorithms developed during the EURASEP experiment.

Type	r^2	N	Accuracy	s, c range
$\log s = 1.35 - 0.674 \log [R(472)/R(586)]$		41	30% $\log s$	$2 < s < 36$
$\log c = 1.244 - 3.09 \log [R(472)/R(586)]$	0.65	10	6% $\log c$	$2.3 < c < 4.4$
$\log c = 1.29 - 1.223 \log [R(472)/R(586)]$	0.68	19	6% $\log c$	$4 < c < 9.5$

6 CONCLUSIONS

Several considerations (Covariation condition, greater standard error of estimate and variations of the a and b parameters,...) are advanced which indicate that the modelling methodology is more adequate in the ocean colour interpretation in coastal and dynamical environments. Reflectance spectra of different water bodies studied in the Southern Bight of the North Sea show the best agreement with the case 2 water optical type. However, differences at great wavelengths (for $\lambda > \pm 570\text{ nm}$) are assumed to result from stronger magnitude of the back-scattering process and thus of the turbidity level in the waters encountered. Although no relationship has been however establi-

shed between the water colour spectrum and the total suspended matter concentration, several combinations of the observed $R(\lambda)$ values such as the $R(570) - R(436)$ difference present a good degree of correlation with the pigment concentration. This is supposed to result from absorption values of acetonic extracts observed at or near 435nm, associated with little spectrally selective absorption and back-scattering of the non-living particulate fraction. Reflectance peaks at 690nm, ascribed to *in vivo* chlorophyll *a* fluorescence, were not observed.

In spite of the small number of ocean colour spectra available at present, our observations together with several considerations seem to promote the use of the $R(435)$ value (included e.g. in a difference) in an analytical interpretation approach, intended to derive quantitative information about the biomass in the studied area. It appears essential however to confirm these "guidelines" by a more complete data set.

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