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OPTICAL REMOTE SENSING OF WATERS AND TIDAL FLATS IN WESTERN WADDEN SEA*

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*Study about the applicability of optical remote sensing in coastal waters, executed in the western Wadden Sea, partly in cooperation with Rijkswaterstaat and Rijksinstituut voor Natuurbeheer.

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1. Summary

In order to investigate the optical remote sensing applications over the turbid waters and the tidal flats of the Wadden Sea, color measurements were performed during periods of three months in summer 1981 and of one week in 1982, combined from a mounted-tower and from an airplane.

Relationships between the optical properties and the seatruth were developed. A simple type of algorithm appears to be useful: reflectance ratio at two wavelengths in relation to the component concentration.

It appears possible to retrieve the different components of the waters like total and mineral suspended matter, pigment and chlorophyll a, as long as they are correlated to each other (which is the case in 1981), by using a ratio of red/green reflectances, from the tower, and a ratio of red/blue reflectances, from the airplane. Also the fluorescent effect of chlorophyll is detectable from airplane, which provides another method to determine the pigment concentration of the waters.

The pigment concentration of the microphytobenthos, which gives a browngreen color and which is an important parameter for global production in the Wadden Sea, can be retrieved from the ratio of airborne reflectances green/blue.

These relationships are the first results of remote sensing experiments above the Wadden area. Further measurements are needed, especially using airborne instruments to cover larger inhomogeneous areas and to provide a better statistical sample which is needed to validate these first results. More adapted methods for sampling the sea-truth (continuous for example) are also necessary to get a better precision on the estimation of the different components. In a first conclusion, the remote sensing of the different components of the waters appears positive, despite the great particulate matter concentration of the waters which mask the effect of the others substances on the optical properties.

2. Résumé

Dans le but d'étudier les applications de la télédétection aux eaux très turbides de la Mer de Wadden, deux séries de mesures de la couleur des eaux et de la vaste étendue vaseuse du Balgzand ont été effectuées en 1981 et en 1982 à différentes altitudes: d'une tour et d'un avion.

Les relations entre les propriétes optiques et les "vérite-mer" ont été développées. Un type simple d'algorithme paraît satisfaisant: le rapport de réflectances à deux longueurs d'onde en relation lineaire (log-log) avec la concentration de chaque composant.

Il paraît possible de retrouver les différents composants de l'eau, soit la matière totale ou minérale en suspension, pigments et chlorophylle a, tant qu'ils sont covariant entre eux (ce qui est le cas en 1981), en utilisant un rapport de réflectances "rouge/vert"pour l'expérience "tour" et un rapport "rouge/bleu" pour l'expérience "avion". La méthode de la fluorescence mesurée par avion s'avère être un succès dans ces eaux très riches en chlorophylle.

La concentration en pigment du microphytobenthos, qui donne une coloration brun-vert à la vase, et qui est un paramètre important pour la production globale en Mer de Wadden peut être détectée par avion grâce à un rapport de réflectance rouge/bleu.

Ces corrélations représentent les premiers résultats d'une expérience inédite en Mer de Wadden. Un plus grand nombre de mesures par avion serait utile de manière à couvrir une étendue plus large et à fournir un meilleur échantillon statistique de façon à valider les premiers resultats .

D'autre part, une meilleure méthode d'échantillonnage sur le terrain se révèle nécessaire pour obtenir des estimations plus précises des différents constituants.

D'ors et dejà, on peut conclure que malgré l'extrême charge particulaire de ces eaux qui a un effet masquant sur les propriétes optiques, on peut envisager la télédétection des eaux et de la vase,

ce qui est essentiel pour connaître les variations rapides de la biomasse et cartographier la distribution très inhomogène de la turbidité.

3. Introduction.

3.1. General

The use of remote sensing (RS) in the visible part of the spectrum allows to determine temporal and spatial variations of water color over large areas.

The reflectance (or color) of the sea water is depending on the quality and quantity of its diverse components (suspended and dissolved matter).

The application of optical RS i.e. the measurements of the spectral variations of reflectances combined with the knowledge of the relationships with the various particulate and dissolved components concentrations, would help understanding of biological and physical oceanographic processes.

Extensive studies of the relationships between spectral properties of the water and its diverse components have been performed in the open ocean and coastal areas (Gower, ed., 1980).

These investigations concern generally "case 1" waters, one of the two classes defined by Morel, (1980), for which the suspended algal material is covarying with the total suspended matter.

Much less is known about the "case 2" waters (2nd class),where (re)suspended matter not related to the chlorophyll content, and dissolved organic products of terrestrial origin dominate the optical effects.

Economically and ecologically important areas of the oceans belong to this type like most of the turbid coastal areas, shallow tidal regions as for example the Wadden Sea.

This region is characterized by extremely variable biological processes influenced by tides, seasonal variations, river discharge, mixing processes with the North Sea water, and a high productivity at all ecological levels. Study of the coastal dynamics by the mean of remote sensing is desirable.

3.2. Experiments

In order to investigate the spectral properties of these turbid waters and to study the problems linked to the remote sensing (RS) of these areas, measurements have been performed, from different altitudes, over the Western part of the Wadden Sea (Spitzer ed., 1981).In the same time, sea-truth measurements were taken. The results could provide data useful for interpretation of the color measurements from satellite sensors (LANDSAT, CZCS, SPOT and future).

3.2.1. Optical measurements

Spectral remote measurements with respect to the spatial and temporal variability of the tidal flats and water properties have been performed over the tidal flat and above waters, from a tower, several times during the day and over 3 periods: 30th april, 12 to 15th may, from the 13 to the 24th june 1981, and from the airplane on the 13th may 1981 and the 22th april 1982.

The location of the experiments is shown in Fig. 1:

The temporal variations of the upwelling radiance Lu, and of the downwelling irradiance Ed were observed from 400 to 700 nm, by a tower-mounted 11 channels spectro-radiometer (Spitzer and Wernand, 1981), approximately 7m above the sea level.

The spatial variations were measured from a low flying aircraft (150-800m) employing an Optical Multichannel Analyser (OMA) system (500 channels) CORSAIR (Coastal Optical Remote

Sensing Airborne Radiometer) (Spitzer et al., 1982b). Contamination of the signal by unwanted reflection of the direct sun radiation on the sea surface (sun glitter) has been avoided by measuring always at azimuths away from the sun at 15 degrees (from the aircraft), and 53 degrees (from the tower) from the nadir

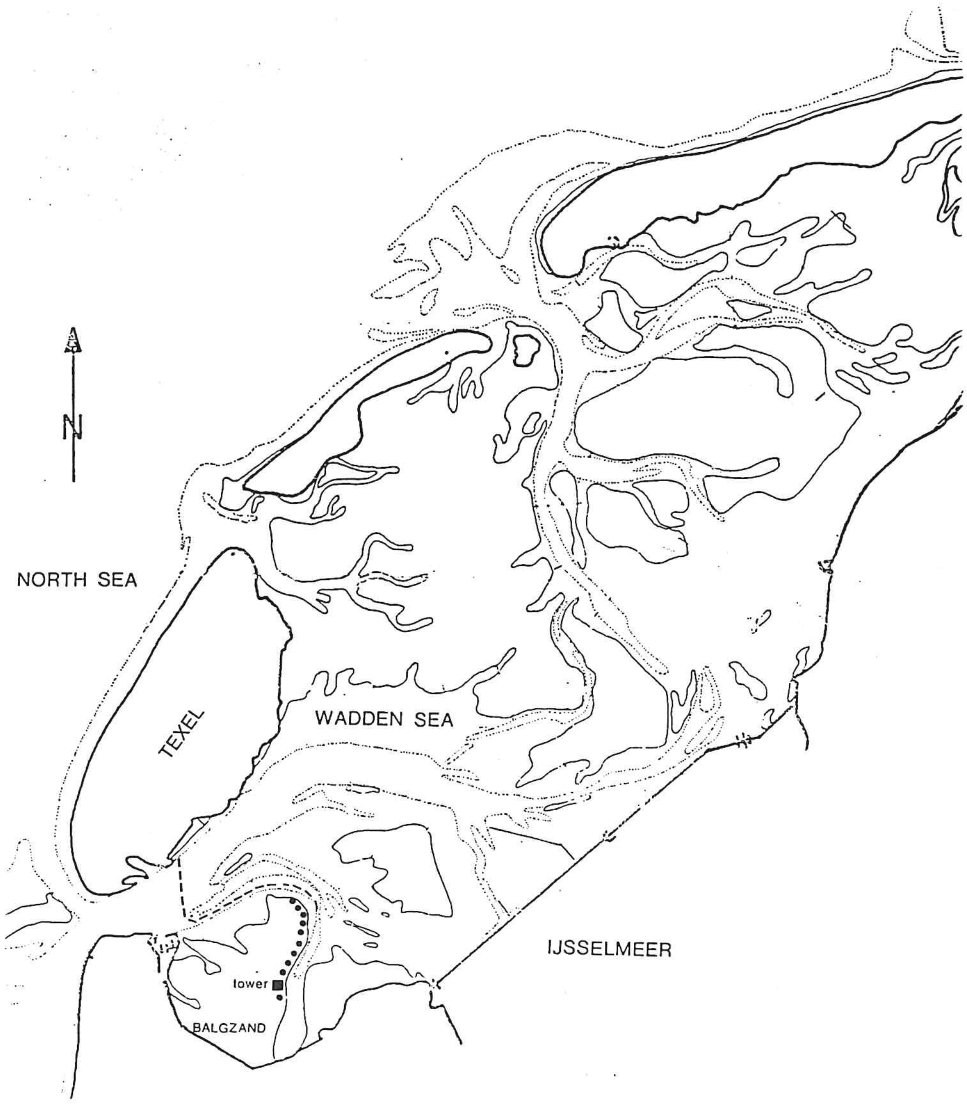


Fig.1. Location of the Wadden Sea Remote Sensing experiment (1981-1982). Sampling stations (ooo), corresponding to the airplane flight. Route of the boat (---).

(Spitzer et al. 1981a). The tower instrument was equiped with a polarizer to remove also a substantial part of the surface reflection of the indirect sky radiation (sky glitter).

Preprocessing of the optical data, included " cleaning " (removal of spikes) and smoothing (averaging over 7 nm bandwidth).

3.2.2. Sea truth measurements

Together with the optical measurements, secchi disk depths, samples of sea water or mud flat were taken and analysed (Spitzer ed., 1981). Concentrations of chlorophyll a and pheopigments were analysed by spectrophotometrical method, total suspended matter (TSM) and mineral particulate charge measured by the dry weight and burned filters weight method, according to Strickland and Parsons, (1972). The yellow substance (colored and fluorescent part of the dissolved organic matter) concentration was measured by the absorption (at 375 nm) and by fluorescence methods (Spitzer ed., 1981). The sea truth measurements are discussed in appendix I.

3.3. Objectives

The purpose of the investigation is to describe the relationships between remote and ground observations in the Wadden Sea areas, in order to develop appropriate algorithms.

Correlations have been previously found between reflectances ratios measured from the tower and concentrations of particulate matter for 1981 experiment (Spitzer et al. 1981a, 1981b and 1982). The fluorescence effect of the phytoplankton present in the waters has also been observed in the spectra recorded from the airplane .

Systematical statistical analysis has been employed. Various algorithms have been developed in order to retrieve the pigments and suspended particulate matter concentrations. Widely used algorithm type R(1) / R(2) have been applied to our measurements as well as reflectance differences and "special" ratios (R(1)- R(2))/ (R(1)+R(2)) of reflectances.

3.4. Aknowledgements

The present study was funded by the Dutch Ministry of Education and Science (exchange program). C. Rappoldt is aknowledged for the measurements and preprocessing of the tower data ; L. Nykjaer for the preprocessing of the aircraft measurements ; D. Arief for the final processing, programming and computing help. We wish to thank all persons from the NIOZ, RWS and RIN who helped with the field experiments and the sea truth analyses, and for stimulating discussions. The 1982 flight was financially supported by Shell Nederland B.V.

4. Biological and optical characteristics of the Western Wadden Sea waters and tidal flat

4.1. Range of variations of the components

All data presented in graph and/or Table form were previously published in the Internal Report (Spitzer ed., 1981). The ranges of variations of the components present in the Wadden Sea waters and bottom, as measured during the 1981 and 1982 experiments are summarized in the following Table I and II.

The water quality during the 1981 experiments differs from the 1982 one. During the 1982 experiment, all the values are generally lower and the range of variations is narrow, demonstrating absence of algal bloom during this period. In

TABLE I

Range of variations of components in waters, maximal values out of the ranges in parentheses.

Component (units)	1981 minim.	1981 maxim.	1982 minim.	1982 maxim.
chlorophyll a (mg m^{-3})	3	50	3	4.5
pheopigment (mg l^{-3})	1	50	0	4.5
chl.a + pheop. (mg m^{-3})	4	100	3	9
total suspended matter (g m^{-3})	7	250(548)	19	32
mineral suspended matter (g m^{-3})	1	170(340)	-	-
yellow substance abs. coef. (m^{-1}) at 375 nm	0.5	4.7	1	1.5
yellow substance fluorescence (mFl)	10	60	12	14

1981, late april and may, the pigment concentrations are very high, due to phytoplankton blooms, diatoms from march to early may and by flagellates (Phaeocystis sp.) in may and june (Cadee, 1982)

The seasonal variation observed during the 3 months tower experiment is high, though the tidal variation observed during one cycle is also substantial. The tidal and seasonal variations are shown in the Fig. 2, where total suspended matter is plotted versus total pigment (chl.a + pheop.) concentration, for 1981 tower, 1981 and

TABLE II

Range of variations of components of the tidal flat surface

Component (units)	minimum	maximum
chlorophyll a (mg m^{-3})	5	130
pheopigment (mg m^{-3})	2	150
chl.a + pheop. (mg m^{-3})	7	280
yellow substance abs. coef. (m^{-1}) at 375 nm in interstitial waters	3.9	16
yellow substance fluorescence (mFl) in interstitial waters	65	266

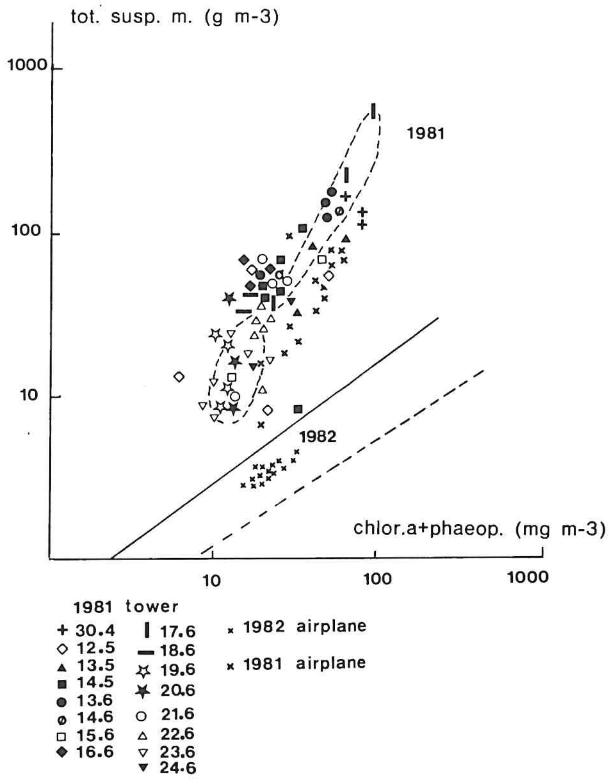


Fig. 2. Total suspended matter versus pigment concentration in 1981 (tower and airplane), and 1982 airplane of Wadden Sea waters . Different signs for days and months allow the distinction between tidal (---) and seasonal variations of the data. For comparison, relationships from Clark,(1980),(——), and Morel, (1981) (----) are shown.

1982 airborne experiments (in log coordinates). The cluster of the 1982 experiment is separate from the 1981 ones (tower and airborne), as it is mentioned above.

For comparison, the general case "1" relationships between the pigment and the TSM concentration (Morel, 1981, Clark et al., 1980) are shown on the same figure.

The maximal concentration for pigment and total suspended matter occurs generally with increasing tidal current velocity over the Balgzand area, as shown at some characteristic stations by Cadee, (1982).

TABLE III

Coefficients obtained for correlations between the different parameters measured in the Wadden Sea in waters and on tidal flat. The upper numbers correspond to correlations with 86 data (1981+1982 tower and airplane), the lower ones to correlations with 56 data (1981 tower).

Water component	mineral suspended matter $g\ m^{-3}$	total pigment $mg\ m^{-3}$	chl-a $mg\ m^{-3}$	pheop. $mg\ m^{-3}$	Yel. Substance absorpt. m^{-1}	Yel. Substance fluoresc. mFl
tot. susp. mat matter $g\ m^{-3}$	0.917 n=56	0.630 n=86 0.818 n=56	0.500 n=86 0.640 n=56	0.645 n=86 0.870 n=56	0.170 n=56	-0.077 n=56
mineral susp. matter $g\ m^{-3}$		0.779 n=56	0.599 n=56	0.853 n=56	0.122 n=56	-0.023 n=56
total pigment $mg\ m^{-3}$			0.945 n=86 0.911 n=56	0.891 n=86 0.946 n=56	0.268 n=56	0.141 n=56
chl-a $mg\ m^{-3}$				0.719 n=86 0.938 n=56	0.205 0.205 n=56	0.155 n=56
pheop. $mg\ m^{-3}$					0.280 n=56	0.133 n=56
Yel. subst. absorption m^{-1}						0.879 n=86 0.399 n=56

The values of yellow substance concentrations are much larger than those previously reported (Jerlov, 1976, Bricaud et al., 1981).

All the components (Table I) must be taken into account for the interpretation of the water colour. The same holds for the tidal flat, where all components show very high concentrations of chlorophyll a and yellow substances (Table II), due to high productivity in interstitial waters and on tidal flat itself.

4.2. Relations between the components

Concentrations (ranges in Tables I and II) show some interesting covariances. The correlation coefficients are all presented in Table 3. The significance of the results, measured by the Student variable statistical test (Draper and Smith, 1966) with a risk of 5 % is indicated.

The total number of data (86) consists of the tower 1981 experiment data (56) combined with those collected during the two aircraft flights in 1981 (15) and in 1982 (15).

In particular, the total suspended matter (TSM) of the 1981 tower series is well correlated with the:

--total pigment concentration (chl.a + pheop.), (r=0.82, n=56)

--pheopigment concentration, (r=0.87, n=56)

--mineral suspended matter (MSM), (r=0.92, n=56).

The covariations are shown in the Fig. 3, 4 and 5.

When all the experiments in 1981 and 1982, tower and aircraft, are considered together, the correlations are lower, indicating that the types of waters were different during the experiments (see Fig. 3' and 4'). The correlations with the TSM are then:

--total pigment concentration : r=0.63, n=86

--pheopigment concentration : r=0.64, n=86

-- MSM (no measurements in 1982)

These correlations prove that the suspended matter of turbid waters in the Wadden Sea contains, beside the mineral matter (sand or aggregates), also a large amount of (re)suspended planktonic particles.

The pigment concentration in water is related to planktonic blooms but also strongly to the diatoms resuspended from the flats (microphytobenthos), by the tidal flushing (increasing concentrations after the maximal current velocity).

The fact that the total suspended matter (TSM) is better related to the pheopigment concentration (r=0.87), than to the chlorophyll a concen-

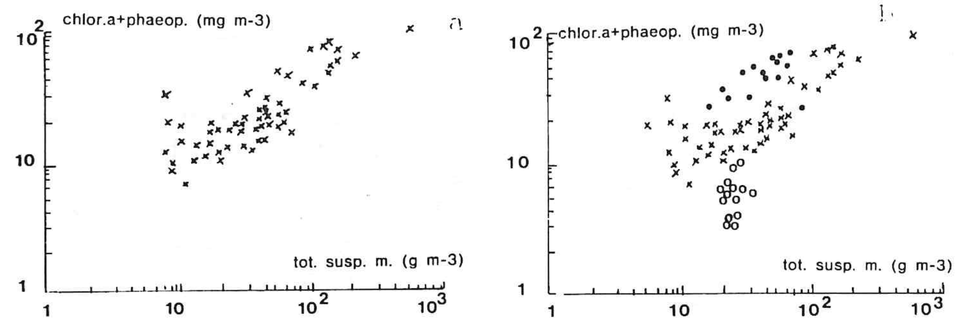


Fig. 3.a. Pigment concentration versus total suspended matter concentration for 1981 tower experiment (r=0.82, n=56). b. Pigment concentration versus total suspended matter concentration for all experiments: 1981 tower (x) and airplane(●), 1982 airplane(o), (r=0.64, n=86).

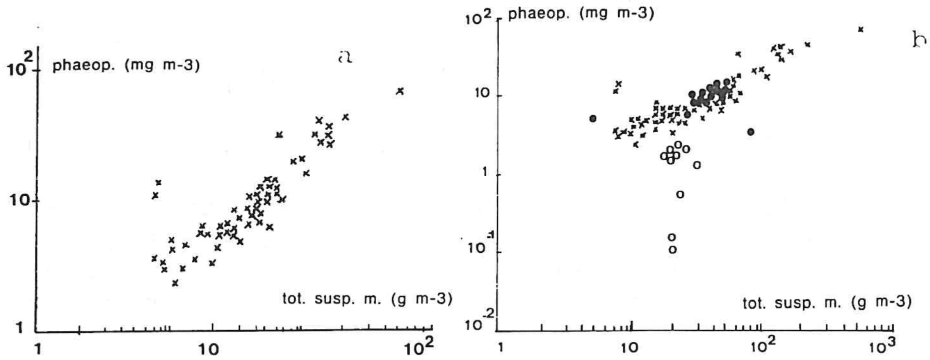


Fig. 4.a. Pheopigment concentration versus TSM concentration for 1981 tower experiment (r=0.87, n=56). b. Pheopigment concentration versus total suspended matter concentration for all experiments: 1981 tower (x) and airplane(●), 1982 airplane (o), (r=0.645, n=86).

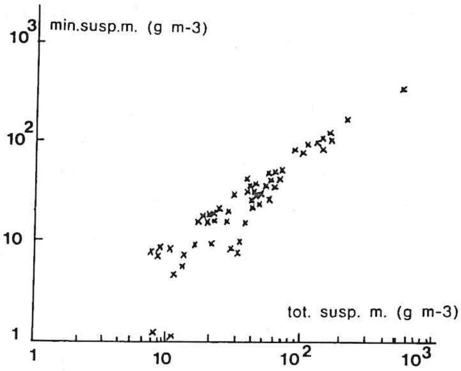
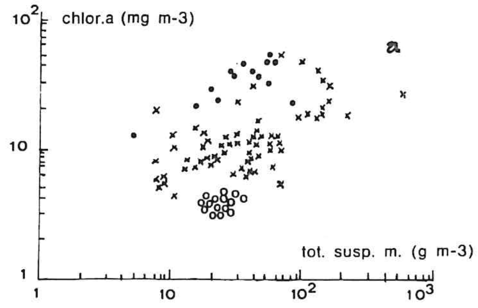


Fig. 5. Suspended mineral matter concentration versus TSM concentration for 1981 tower experiment (r= 0.92, n=56).



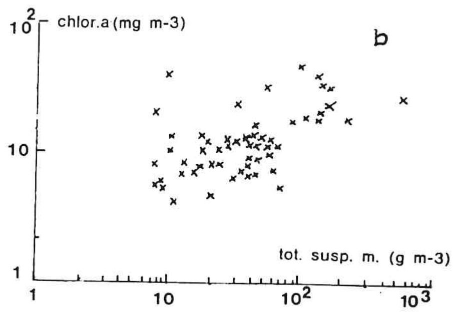


Fig. 6a. Chlorophyll a concentration versus total suspended matter concentration for 1981 experiment (r=0.64, n=56).
b. Chlorophyll a concentration versus total suspended matter concentration for all the experiments: 1981 tower (x) and airplane (●), 1982 airplane (o), (r=0.50, n= 86).

tration (r=0.5 and 0.64 see Fig. 6) could indicate that the dead phytoplanktonic cells are dominant in the turbid waters.

The TSM is also well related to the Secchi disk depth (Fig. 7).

These general relationships between the components suggest that the algorithms used for the retrieval of the total suspended matter concentration might also be useful for pigment and mineral matter prediction.

The Table III shows that the yellow substance (YS) concentrations, (absorption coefficient at

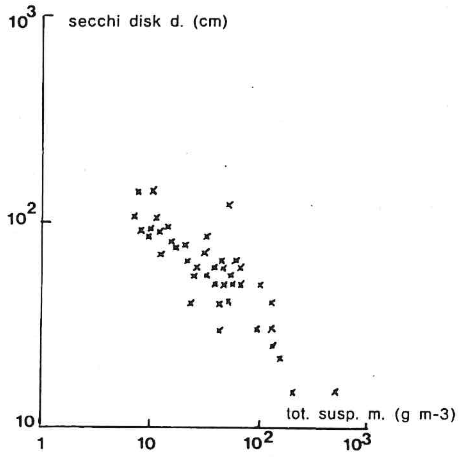


Fig. 7. Secchi disc depth versus total suspended matter concentration for 1981 tower experiment .

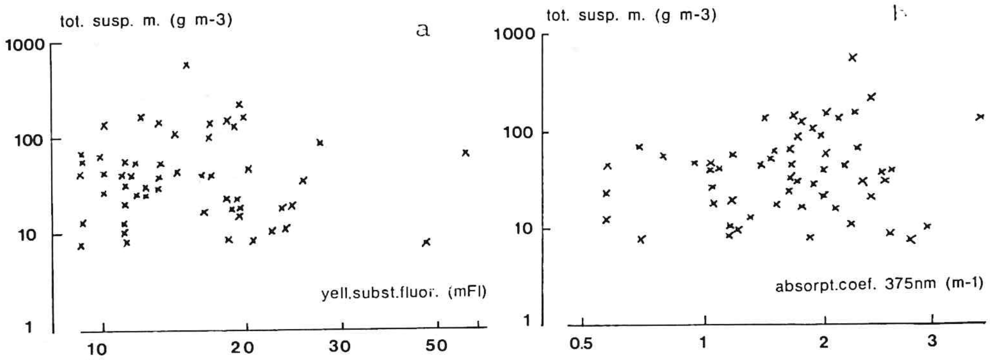


Fig. 8a. Total suspended matter versus yellow substance fluorescence for 1981 tower experiment (r=-0.08, n=56). b. Total suspended matter concentration versus absorption coefficient at 375 nm for 1981 experiment (r=0.17, n=56).

375 nm and millifluorescence), are not correlated to the other components (see also Fig. 8).The independance of the yellow substances has been previously found by Cadée (1982),in the Wadden Sea, where the dissolved organic carbon (related to the YS concentration) seasonal maximum follows the particulate organic carbon peak a month later. The input of the dissolved organic carbon by the Ijsselmeer waters is also important as indicated by maps of the fluorescence distribution of the waters at various seasons (Postma et al., 1976, Manuels ed., 1978). These two processes may explain the non-covariance of the yellow substances with the other components .

4.3. Optical measurements

The (preprocessed) graphs of spectra recorded from the tower and from the airplane in 1981 are presented in the internal report 1981-7 (Spitzer ed., 1981).

Tower measurements:

Most of the spectra measured over the Wadden Sea waters show a maximum at 560 nm, and the reflectances are decreasing after this wavelength. These spectra correspond to waters containing relatively low concentrations of suspended matter, with secchi disk depths larger than 60 cm. An example is given in Fig. 9 a , b.

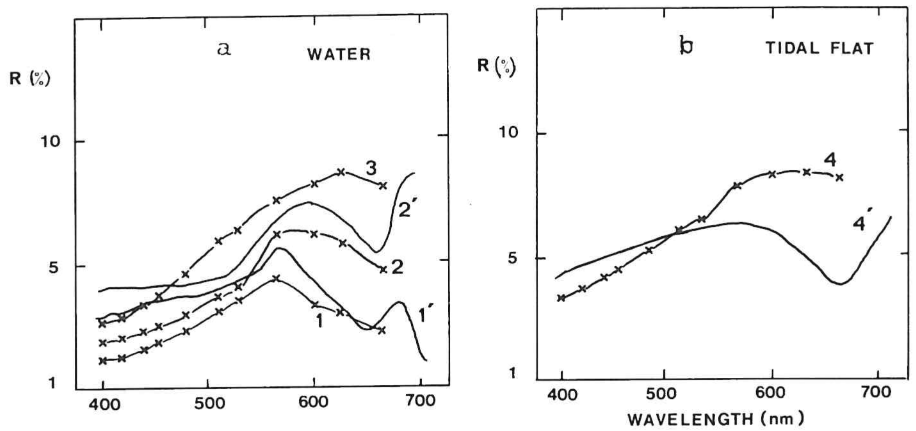


Fig. 9. Reflectance spectra during 1981 tower (xxx) and airplane (---) experiments. for water (up) and for tidal flat (down). Above waters, different TSM concentrations are considered (1 : 8 mg m^{-3}), (2 : 30 mg m^{-3}), (3 : 500 mg m^{-3}).

The spectra recorded above the tidal flat area are characterized by a maximum at 600 nm and contrary to the water spectra, by reflectances increasing from 560 nm to 660 nm (Fig. 9 d). Their general shape is flatter.

Some of the water spectra exhibit a shape similar to those of the tidal flat because of exhibiting maximum reflectance between 603 and 630 nm. These spectra belong to secchi disk depths of 30 cm or less, where the content in suspended matter is high due to the resuspension by the tidal flushing. An example is shown in Fig. 9 c . Such spectra appear to be characteristic for very turbid waters (Topliss, 1982, Whitlock et al., 1981).

The range of reflectance values for waters and tidal flat is given in Table IV.

The relatively high values of reflectances can be explained by the generally high content of suspended matter.

Airborne measurements:

The above water spectra have their maximum at 560 nm for the low TSM concentrations (Fig 9 (1')), and around 600 nm for the high TSM values. They show a peak at 695 nm due to chlorophyll a fluorescence. On tidal flat, the maximum is

TABLE IV

Minimal and maximal reflectances values for water and tidal flat, with indication of secchi disc depths.

	Minimal reflectance	Maximal reflectance
Waters	0.045 (560 nm)	0.081 (560 nm)
	0.042 (603 nm)	0.085 (603 nm)
secchi disc depth (cm)	140	15
Tidal flat	0.078 (630 nm)	0.093 (630 nm)

shifted to the longer wavelengths and the fluorescence peak can be also observed.

In general, the airplane spectra show higher reflectances in the blue part of the spectrum, indicating the influence of the sky glitter and of the atmosphere.

5. Interpretation

5.1. Backgrounds

The reflectance of the seawater (or tidal flat) is influenced by the concentrations of its different components:

-particulate matter

--phytoplankton + covarying material

--non covarying material: suspended (in)organic matter

-dissolved organic matter ("yellow substances")

The optical properties of these components have been studied (Morel and Prieur, 1977, Bricaud, 1979, Sathyendranath, 1981).Various possible algorithms have been developed for the retrieval of the components concentrations using single reflectances or, more commonly, reflectances ratios (review by Sathyendranath, 1981). The relationships have been established for the case 1 waters , influenced mainly by the phytoplankton, and can not be useful for the Dutch turbid waters. Algorithms applicable to the case 2 waters, where suspended matter and dissolved organic substances dominate the optical properties, are less numerous (Bukata et al. 1981).

5.2. Application to the Wadden Sea

To find algorithms adapted to this region, we have used a systematical statistical approach, which included investigation of various combinations of reflectances, in relation to the components concentrations (ratios, differences and "special" ratios (ratio of the difference of two wavelengths reflectances against their sum)). The ratios of single wavelengths, as treated further, are the most widely used type, though difference proved to be successful in certain cases (Viollier, 1980). The "special" type of ratio appears to be a good index of the presence of pigments in waters (Clark et al., 1980).

Then, the best linear regressions between the log of the ratios and the logarithms of the components has been chosen(log R2/R1 vs log Cx). This has been done separately for the tower and for the airplane experiments, on water on tidal flat, for 1981 and 1982. Combinations of the results have been discussed.

Using this systematical approach and applying some statistical rules, the best found relationships have been considered as general algorithms for turbid waters of the Wadden Sea.

Significance and tests of the results.

Standard error: Sx.y is the error on the estimation of the variable X by the variable Y from the least square process.

The errors will be indicated in Tables (for correlations with a sufficient number of measurements).

-Correlation coefficient: the significance of the r- value (calculated for correlations with sufficient number of measurements) will be verified, using the Student test (Draper and Smith, 1966), with a chosen risk p of 5%.

Following some restrictions given by Whitlock, (1982), some correlations will be considered as general algorithms. In the case where N, number of measurements is small , which is the case for the 1982 airborne experiments, we will simply consider the presence or absence of trend in the cluster of points rather than true correlations. Standard errors and r- values will not be calculated in this case.

Preparation of the data;

The tower reflectances (11 channels) do not require particular treatment before using them in correlations. The measured reflectances from airplane (continuous spectrum 400-720 nm) need to be reduced to a smaller number. The 500 smoothed reflectances have been averaged over 3 channels and the whole wavelength regions was divided in 20 nm intervals (16 bands) or in 10 nm intervals (31 bands). This treatment permitted comparisons between tower and airplane reflectances .

6. Results

Relationships between the reflectance ratios and the single components are further treated (algorithms). No good correlations have been found when single reflectances are considered. The reflectance differences do not provide better results . The special ratios (of the form (R2-R1)/(R2+R1) proved to be useful, in some cases. The correlations are better when double logarithmic scale is used.

Results will be presented first for tower and airplane experiments separately, then the combination of the two remote sensing methods will be considered.

6.1. Above waters

6.1.1. Tower measurements

The tower spectra include neither sun glitter, nor sky glitter contributions (see

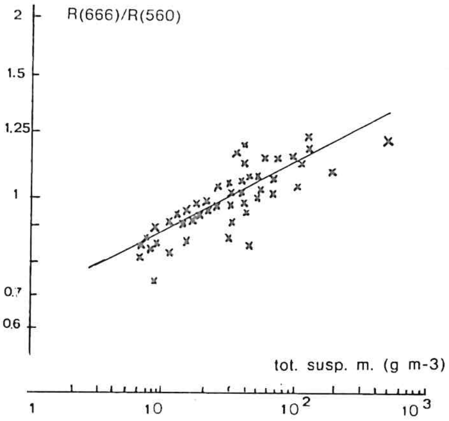


Fig. 10. Reflectance ratio versus total suspended matter concentration for 1981 tower experiment on waters (r= 0.87, n= 48 points).

chapter I). So, they contain only water reflectances information. The optimal developed correlations are presented in Table V.

Significant correlation between reflectance ratios at the wavelengths green/red and the total suspended matter (TSM) has been previously found (Spitzer et al., 1981a, 1981b), specially with the ratio R(666)/ R(520) as shown on Fig. 10:

R(666)/R(520), with r=0.87, n= 48 points .

Present investigation shows that all the reflectance ratios relating the wavelength region 513-603 nm against the region 603-666 nm, are well correlated with the TSM concentration (Table V).

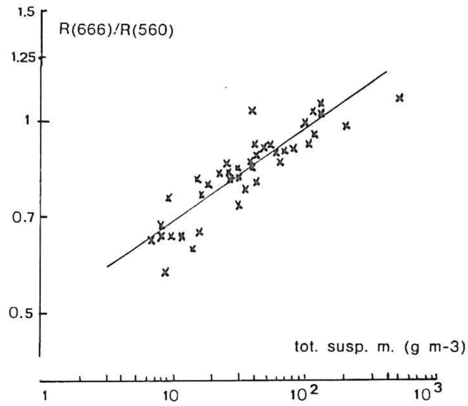


Fig. 11. Reflectance ratio "red/green" versus total suspended matter for 1981 tower experiment (r= 0.85, n= 40).

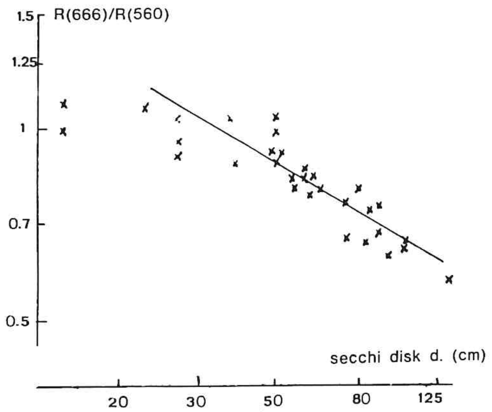


Fig. 12. Reflectance ratio "red/green" versus mineral suspended matter for 1981 tower experiment (r= 0.85, n= 40).

The best correlation is found for the ratio using the central wavelengths of these two spectral regions (see Fig.11):

R(666)/R(560), with r=0.87, n=40 points.

Similar correlations are found for the parameters which are covarying with the total suspended matter content, that are:

-the secchi disk depth (see Fig.12), with r=0.85, n=34

-the mineral suspended matter (see Fig.13), with r=0.86, n=38

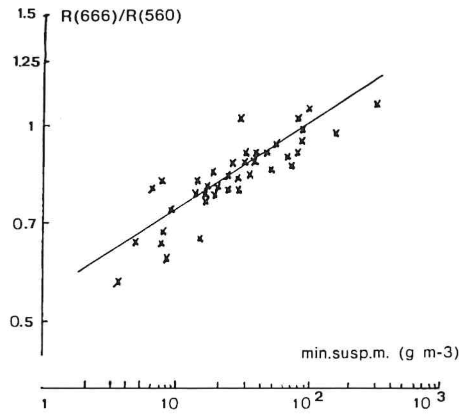


Fig. 13. Reflectance ratio "red/green" versus secchi disc depth for 1981 tower experiment on waters (r= 0.85, n= 40).

TABLE V

Summary of the least squares regression analysis between the concentrations of each component of the water and the optimal reflectance ratios measured from the tower. The relation is of the form (log R2/R1 = b logC + log a), where C stands for the concentration.

Water component	Ratios	regression $\log_{10} a$	coefficient b	correlation coefficient r	standard error $S_{y,x}$	number of measurements N
Total susp. mat. c. ($g\ m^{-3}$)	R 666 / R 560	− 0.291	0.135	0.87	0.42	40
Miner. susp. mat.c. ($g\ m^{-3}$)	R 666 / R 560	− 0.270	0.120	0.86	0.44	38
Secchi disk depth (m)	R 666 / R 560	0.375	− 0.259	0.85	–	31
Total pigment c. ($mg\ m^{-3}$)	R 630 / R 520	− 0.104	0.124	0.87	0.20	40
Chlorophyll a c. ($mg\ m^{-3}$)	R 630 / R 513	− 0.04	0.125	0.77	0.25	40
Pheopigment c. ($mg\ m^{-3}$)	R 666 / R 520	− 0.119	0.134	0.88	0.20	40

Good correlations can be expected for the pigment concentration if the algal material in the Wadden Sea waters is covarying with the TSM . From the covariances observed between components and shown in Chapter II, for 1981 values, a strong correlation can be found between the pigment concentration and the TSM content (see Table III, with r=0.81, n=56). This relation can explain the high correlation between the ratio of reflectances (at the same wavelengths as for the TSM), and the pigment concentration (see Fig.14 and Table V). The best correlation is found for the ratio:

R(630)/R(520), with r=0.875, n=40 points.

The variation of this ratio depends on the variations of R(520), which is influenced by

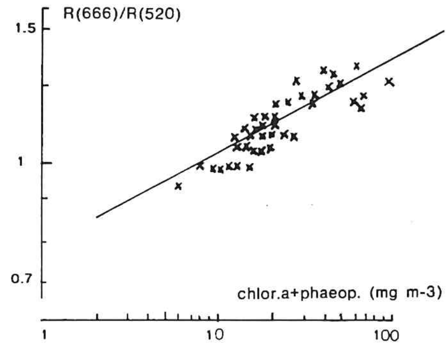


Fig. 14. Reflectance ratio versus total pigment concentration for 1981 tower experiment (r= 0.87, n= 40).

the pigment absorption. Main absorption effect is expected at 430 nm, wavelength of the chlorophyll absorption maximum, but the absorption effect at the short wavelengths could be substantially masked by the optical properties of the TSM.

It is also interesting to notice that ratios at the wavelengths around 630 and 520 nm, are much less correlated with the chlorophyll concentration (Fig. 15), than with the total pigment (Fig. 14), or even than with the pheopigment concentration (Fig. 16). The correlation coefficients are presented in the Table V. One example of this fact is given for the ratio R(630)/R(513), with r= 0.772, n=40 points. This may be due to the fact that chlorophyll is less covarying with the TSM than the total pigment or than the pheopigment concentration (report in Table III).

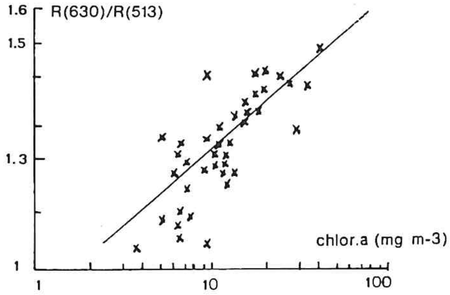


Fig. 15. Reflectance ratio versus chlorophyll a concentration for 1981 tower experiment (r=0.77, n= 40).

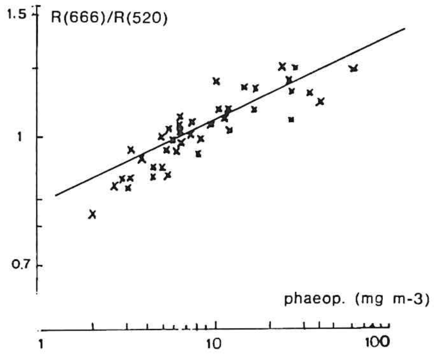


Fig. 16. Reflectance ratio versus pheopigment concentration for 1981 tower experiment (r= 0.88, n= 40).

Considering these correlations, summarized in Table V, as algorithms, the Student t-test has been applied and showed positive results (for p=5%, t/tp>2). The standard errors are also generally low (around 0.5 in log value for the suspended matter, and 0.2 for pigment).

No general relationships have been found between the concentrations of "yellow substances" and reflectance ratios, neither with the absorption coefficient in the U.V. nor with the fluorescence measurements.

Discussion;

Postma (1961) showed that a strong correlation exists between the TSM content and the secchi disk depth. Colijn (1982) has shown that the relationship between the total irradiance attenuation coefficient (Kd) and the amount of suspended matter (TSM) is not disturbed, in any way, by the presence of phytoplankton, even during spring blooms.

These previous studies prove that the optical properties depend mainly on TSM and explain why the best correlations are found for the retrieval of this parameter.

If we consider now the correlation coefficients between the seatruth and reflectance ratios red/green (see Table V), we find that they decrease as follows:

pheopigment	>	pigment and TSM	>	min. susp. matter	>	chlor.a
r=0.88		r=0.87		r=0.85		r=0.77

The chlorophyll a, which is the parameter least correlated to the reflectance ratio (see above) is also least correlated to the TSM content:

for example, the MSM and pheopigment have a r-value of 0.87, but the chlorophyll a shows an inferior value of 0.77

So, we can conclude that the reflectances of the turbid Dutch Wadden Sea waters are influenced firstly by the total suspended matter, and secondly by other components to a comparable extend as the TSM is influenced by them.

As mentioned above, no algorithms were found for the retrieval of the dissolved matter concentration (yellow substance). In the Wadden Sea waters, the high concentration of TSM may mask the optical influence of the yellow substances, despite of their large concentrations. The same effects have been observed in Canadian coastal waters by Topliss, (1982), where the suspended solid matter and the dissolved organic carbon concentrations are both high.

6.1.2. Airborne measurements.1981

The signal measured by the airborne radiometer is the sum of the atmospheric signal backscattered by the layer corresponding to the flight altitude (150 to 800 m), of the sky radiance reflected by the water surface and finally of the diffuse reflectance of the water body (or tidal flat).

Contrary to the tower spectra, the airborne apectra contain contamination by the atmospheric backscattering and by the sky glitter. These both effects affect chiefly the blue part of the spectra (increase in reflectance).

Contrary to tower measurements, the best correlations between the ratios R2/R1 and the seatruth have been found with the chlorophyll a concentration. The ratios composed of reflectances in the blue region against the

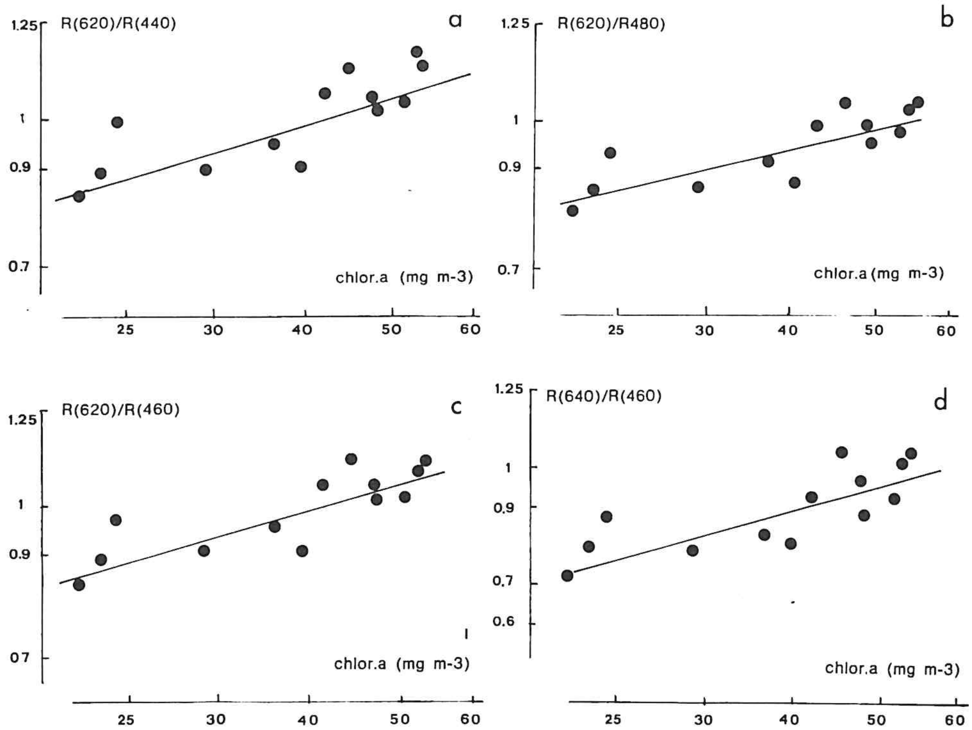


Fig. 17. Different reflectance ratio versus chlorophyll a concentration for the 1981 airplane experiment (o), (n= 12). a. R(620)/R(440); b. R(620)/R(480); c. R(620)/R(460); d. R(620)/R(480).

yellow/red region are correlated to the chl.a concentration (Fig.17,a,b,c,d).

The best correlation coefficient is found for the ratio:

R(620)/R(480), with r=0.83, n=13.

The other correlations in the same spectral region show r-values around 0.73.

The airborne spectra show the chlorophyll fluorescence peak around 690 nm (Fig.9). This maximum at 690 nm is shifted relatively to 685 nm as previously reported by Neville and Gower, (1977).The height of the peak is correlated to the chlorophyll a concentration e.g. (Fig. 18), from Spitzer et al., (1981).

It is surprising to find only low correlations between airborne reflectance ratios and total suspended matter concentration. This may be due to errors connected with a delayed

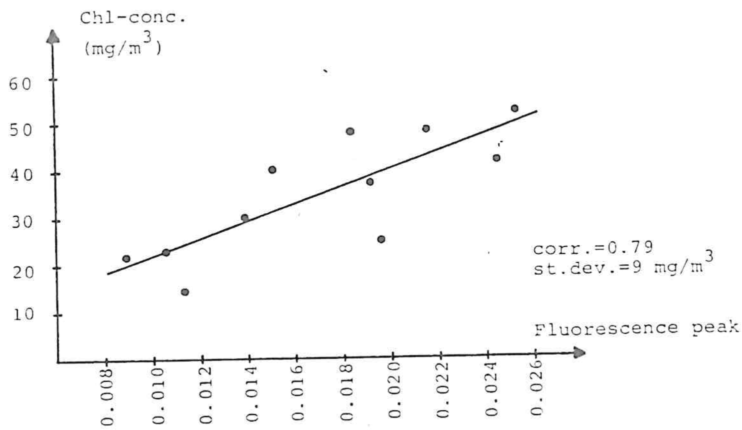


Fig. 18. Chlorophyll a concentration versus relative chlorophyll fluorescence peak height (from Spitzer et al. 1981, 1982).

analysis of the TSM samples and due to discontinuous sampling from the ship of the rather patchy area.

6.1.3. Airborne measurements.1982

Since the values of pigment concentrations are low and their range quite small in 1982, no good correlations have been found with the

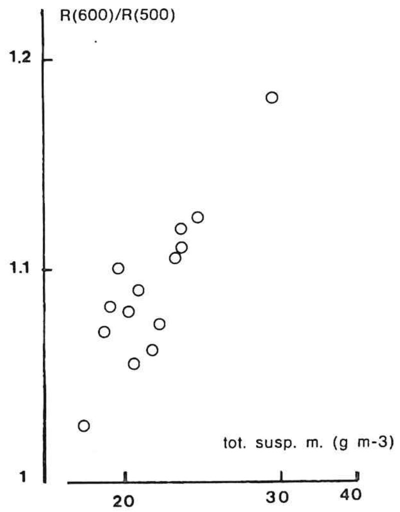


Fig. 19. Reflectance ratio versus total suspended matter for 1982 airplane experiment (o).

ratios R2/R1. Correlation has been found between a reflectance ratio and total suspended matter content (Fig. 19),though in the case of this component, the range of values is also low. The very patchy distribution of the TSM content and pigments in the waters during the experiment may explain these low correlations.

Discussion;

The above algorithms, developed for the retrieval of chlorophyll (1981) and TSM (1982) in waters from airplane reflectances, should be considered as first preliminary relationships, as they are based on a restricted number of measurements, and within restricted ranges of pigment and TSM values (1982).

Uncertainties due to spatial and temporal inhomogeneity of the components in the waters (patches) contribute to the scatter of the points in all figures. Continuous sampling would be more appropriate to this kind of experiment.

The correlation coefficients are low (though significant at 5% risk) and may not be considered as general algorithms. However, they indicate, at least for 1981 experiment, that chlorophyll may be estimated from reflectance ratios and from its fluorescence effect. For the total suspended matter, more accurate data are still required. In general, for airplane remote sensing, further experiments are needed.

6.1.4. Airborne measurements: combination of the 1981 and 1982 results

We have tried to combine the airborne data from the two years in order to find more general relationships for the Wadden Sea waters.

The two years are characterized by two separate clusters of points in the Fig. 20,a,b,c,d, relating blue/red reflectance ratios and the pigment or TSM concentrations.

In the Chapter II, where the relations between components are observed for the two years, (see Fig. 2), it has been seen that the

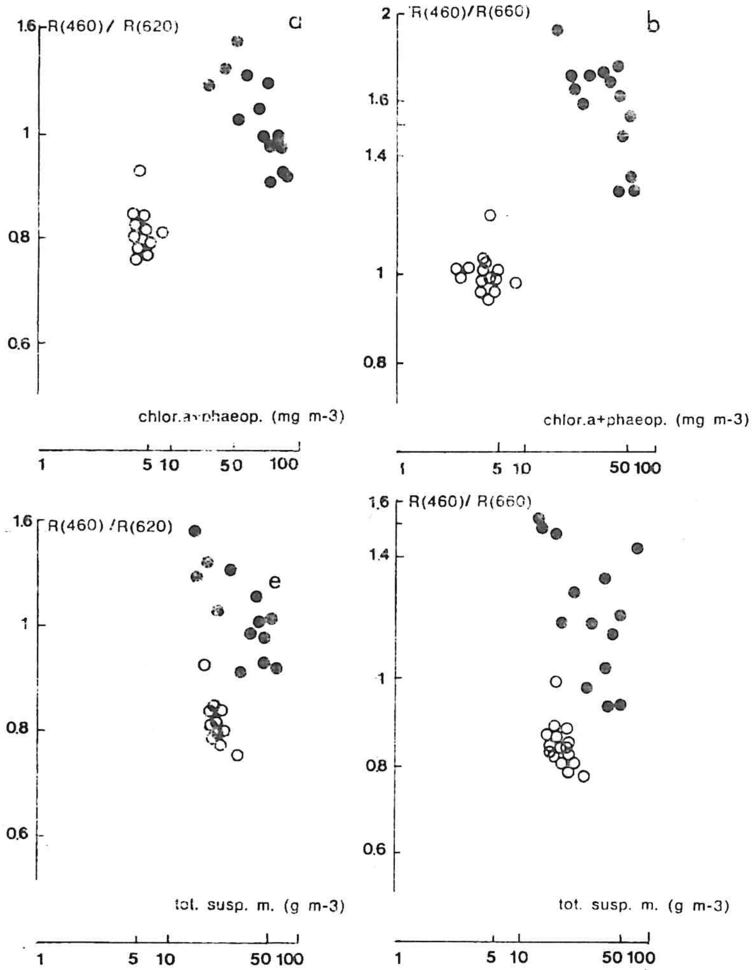


Fig. 20. Total suspended matter and total pigment concentration for the combined 1981 (●) and 1982 (o) airplane experiments for different reflectance ratio: a. R(460)/R(620); b. R(460)/R(660).

relationship pigment/TSM is also very different in 1981 and 1982, resulting from different ranges of values (see Table I).

The experiments in 1981 and 1982 are characterized by different types of waters:

in 1981 : high chlor.a
high TSM
high Yel. Subst.

in 1982 : low chlor.a
high TSM
low Yel. Subst.

Furthermore, in 1981, there is a covariance between pigment and TSM concentrations which does not exist in 1982.

We can thus assume that the different correlations between reflectance ratios and seatruth in 1981 and 1982 are due to the fact that waters belong to different types. This may bring restrictions for the remote sensing applications methods, which have been already pointed out by Bukata et al., (1981).

Further investigations on optical properties of the Wadden Sea waters are necessary.

6.2. Above tidal flat

6.2.1. Tower measurements

As shown on the Fig. 9(4), the spectra recorded above the tidal flat from the tower are characterized by increasing reflectances after 560 nm, and high values (see Table IV).

The variations of the chlorophyll a on the tidal flat is due to the microphytobenthos (essentially benthic diatoms) patchly distributed over the area. The maximum and minimum are 30 and 6 mg m-3.

It is possible to retrieve the chlor.a concentration using the reflectance ratio, in the spectral region where the absorption effect of chlorophyll may affect the reflectance, for example (see Fig. 21):

R(560)/R(520), with r=0.83, n=9 points. The significance of the correlation is given by the t-test (t/tp=2 at the 5% risk), but the number of observations does not permit to use this relation as an algorithm. As it is indicated in the final summary at Table VI, the correlation is lower when the total concentration of pigment is taken :

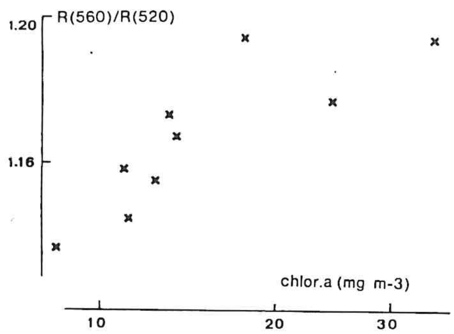


Fig. 21. Reflectance ratio versus chlorophyll a concentration for 1981 tower experiment on tidal flat (r= 0.84, n= 9).

for R(560)/R(520), the r-value is 0.74 for n=9 points.

6.2.2. Airborne measurements

The airborne spectra above the tidal flat allow also retrieval of the chlorophyll concentration.Ratios using two wavelengths, one in the blue and the other in the green region are correlated with chlorphyll a (see Fig.22 and Table VI). The best coefficient is found for:

R(560)/R(480), with r=0.63, n=16

but also for the ratio R(560)/R(520), like in the case of the tower measurements. .

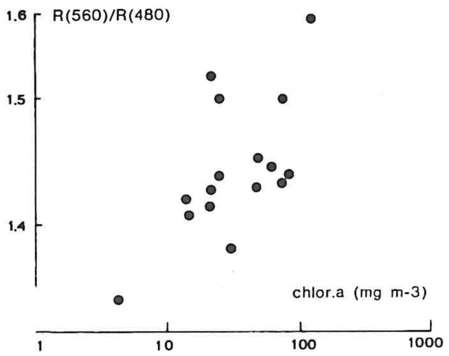


Fig. 22. Reflectance ratio versus chlorophyll a concentration for 1981 airplane experiment on tidal flat (r= 0.63, n= 16).

TABLE VI

Summary of the results of the different remote sensing experiments: tower and airplane, over waters and the tidal flat, in 1981 and 1982. For each component are indicated: the optimal reflectance ratio, the correlation coefficient, and the number of data. (- means no measurements; X means not significant).

Remote Sensing Method	chl a $mg\ m^{-3}$	pigment $mg\ m^{-3}$	total susp.mat. $g\ m^{-3}$	mineral susp.mat. $g\ m^{-3}$	Y.S. fluoresc. mFl	Y.S. absorpt. m^{-1}
TOWER 1981 waters	$\frac{R\ 513}{R\ 630}$ r= .77 n= 40	$\frac{R\ 520}{R\ 630}$ r= .87 n= 40	$\frac{R\ 560}{R\ 660}$ r= .87 n= 40	$\frac{R\ 560}{R\ 660}$ r= .86 n= 40	X	X
TOWER 1981 tidal flat	$\frac{R\ 520}{R\ 560}$ r= .83 n= 9	$\frac{R\ 520}{R\ 560}$ r= .74 n= 9	–	–	–	–
AIRBORNE 1981 waters	$\frac{R\ 480}{R\ 620}$ r= .83 n= 13	$\frac{R\ 480}{R\ 620}$ r= .83 n= 13	X	X	X	X
AIRBORNE 1981 tidal flat	$\frac{R\ 520}{R\ 560}$ n= 16	$\frac{R\ 520}{R\ 560}$ n= 16	–	–	–	–
AIRBORNE 1982 waters	X	X	$\frac{R\ 500}{R\ 600}$ n= 14	–	X	X

The t-test shows the significance of the correlation (t/tp=1.54, at 5% risk), but the variance of the data remains high.

For the "yellow substance" concentration in the interstitial water, no reflectance ratios allow their estimate on the tidal flat, though the concentrations measured are extremely high (260 mFl and 13 m-1 at 375 nm). Unfortunately, the decrease of reflectances that they cause in the 400-500 nm region of the spectra is masked by the very high reflectances of the mud flat.

6.3. Combination of the two remote sensing methods

6.3.1. Above waters

The graphs showing the reflectance ratios, obtained from the airplane and the tower, with the chlorophyll a and the TSM concentrations

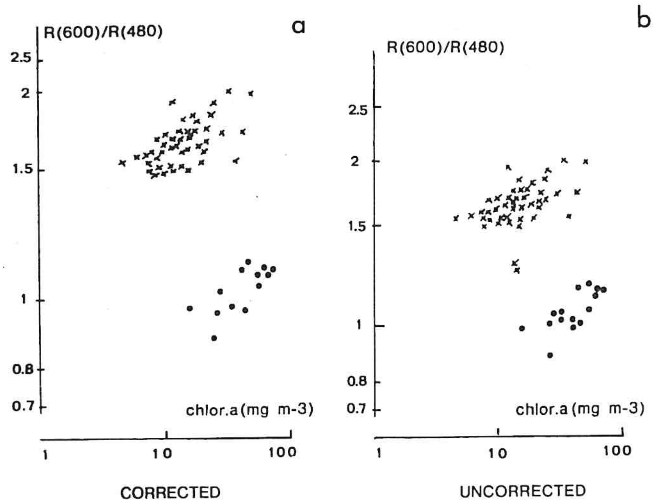


Fig. 23. Different reflectance ratios "red/ blue" versus chlorophyll a concentration for waters for 1981 airplane (o) and tower (x) experiments : a. with corrected; b. with uncorrected reflectances from the sky glitter.

(Fig. 23 a,b, and 24 a,b), allow comparison between the two remote sensing methods. Different wavelength ratios have been chosen in the red/green or red/blue region : they all show the same results: the reflectance ratios from the tower are systematically higher than the airborne ones. This fact may be explained if we examine the different contributions to the spectra, discussed in part I.2.

The reflectances from airplane are influenced by the sky glitter contribution, which increases reflectances particularly in the region 400-500 nm (Spitzer and Arief, 1983). This explains why the ratios R(600)/R(480) as function of chlorophyll e.g. Fig. 23, or R(666)/R(560) as function of TSM e.g. Fig. 24 are lower for the airplane measurements than for the tower measurements.

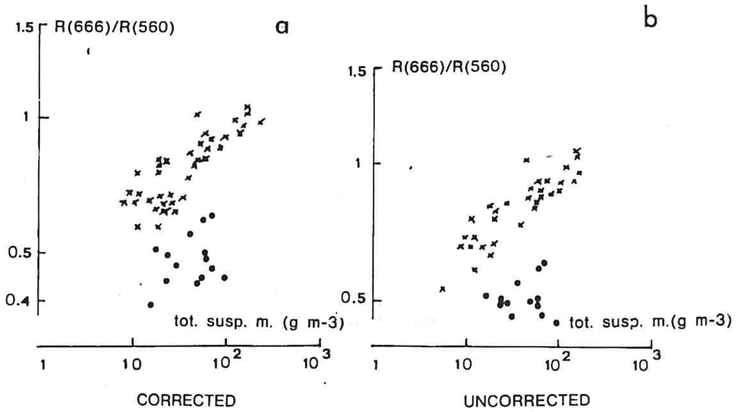


Fig. 24. Reflectance ratio versus total suspended matter concentration for waters for 1981 airplane (o) and tower (x) experiments: a. with corrected; b. uncorrected reflectances from the sky glitter .

Also, different viewing angles (53^{o} for the tower, 15^{o} for the airplane) may introduce differences. From Austin (1980), the factor Q= Eu/Lu (with Eu and Lu respectively upwelling radiance and irradiance) is a function of the zenith and azimuths angles, i.e. Q 53^{o} is different from Q 15^{o} while we have taken always Q=3.14 (isotropic distribution).

Finally, the atmospheric layer contributes to the signal received at the altitudes of the aircraft. This effect depends on the wavelength, and like the sky glitter effect, causes a shift of the maximal reflectance towards the short wavelength.

These three factors explain the different relationships "airplane" and "tower" found for the Wadden Sea waters.

6.3.2. Above tidal flat

The comparison of "tower" and "airplane" correlations has been done for tidal flat in the same way as for waters, but it was more successful (Fig.25). An algorithm is found for both methods for the retrieval of chlorophyll a concentrations, using the ratio R(560)/R(520).

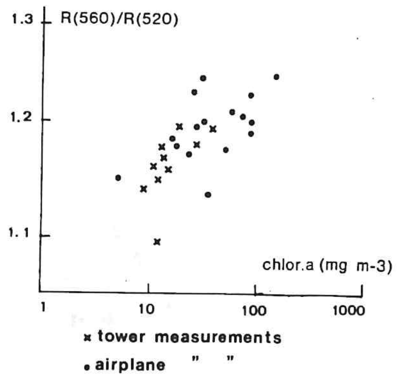


Fig. 25. Reflectance ratio versus chlorophyll a concentration for 1981 (o) airplane and tower (x) experiments over the tidal flat (n= 26).

The combination of the both types of measurements is possible for the tidal flat for the following reasons:

-the sky glitter effect is negligible (on the dry flat)

-the Q factor $Q \approx 3.14$ (i.e. isotropic Lu distribution for tidal flat), or Q $53^{o} \approx$ Q 15^{o} as can be expected for a sandy dry surface.

The atmospheric effect is generally lower at the wavelengths of these ratios (green/yellow) as the reflectances of the flat are much higher than those of the waters.

7. Discussion

A summary of the optimal correlations between the reflectance ratios and the different components of the Wadden Sea is presented in Table VI (waters and tidal flat). We will consider both remote sensing methods for the retrieval of the different components.

From the tower measurements, general algorithm has been found for the total suspended matter, including seasonal and tidal variability of the waters content. The ratio, of the red/green reflectances allows also the retrieval of all the components covarying with the TSM, which is the case in the Wadden Sea waters during the 1981 experiment.

This kind of algorithms appears to be characteristic of the very turbid regions, as it has been found by Topliss, (1982), and Bukata et al., (1982), the last authors using the ratio R(670)/R(520) for the estimation of the suspended solids in Lake Ontario.

The retrieval of the components of waters from airborne reflectances was less successful .For the TSM concentration, strong patchiness and discontinuous sampling caused low correlations. The distribution of chlorophyll was more homogeneous, and algorithms using green/yellow wavelengths have been found. Remote sensing of the chlorophyll distribution by fluorescence (695 nm) is also possible. To retrieve the seatruth data of waters from the aircraft, further studies are required, including better sampling methods (continuous), more numerous measurements and corrections from sky glitter and atmosphere.

The retrieval of chlor.a distribution over the tidal flat appears to be possible. A relationship is found combining the two RS methods (airplane and tower). The ratio of red/green reflectances can be used to measure variations in color of the flat, since the dominant pigments of benthic algae are rather brownish than green, contrary to the algae of clear waters.

The problem of the retrieval of the "yellow substances" concentration from the color of the ocean has been examined by many authors (Bricaud et al. 1981, Hojerslev, 1981) for clear waters, or Topliss (1982), and Bukata, (1981) for turbid waters. The possibilities of their estimation by remote sensing are still in question, (in waters as well as on the tidal flat).

The comparison of the algorithms or relationships developed and presented in this paper (see Table VI), with algorithms developed previously is difficult because they do not apply generally on

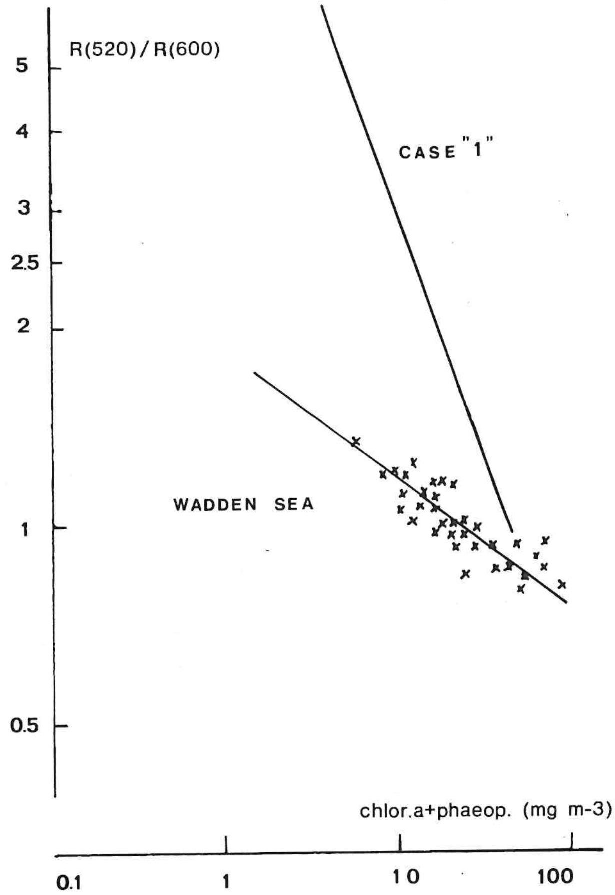


Fig. 26. Comparison of the Wadden Sea algorithm "red/green" with the general case "1" relationship from Gordon (1980) for the estimation of total pigment concentration in the waters.

turbid waters. Fig. 26 shows an example of general algorithm applying to "case 1" waters (Gordon et Clark, 1980), against the relationship "Wadden Sea" for the retrieval of pigment concentration.

This series of relationships, more or less significant constitutes a first approach which can be continued by the use of more thorough statistical analysis. Bricaud and Sathyendranath, 1981, recommend the use of 3 or 4 wavelengths in reflectance combinations for all the turbid waters. Also, the multiple regression and principal component analyses might be useful.

More measurements (optical and seatruth) are necessary during different tidal and seasonal situations in order to find algorithms representative for all the conditions (larger range of values and different types of covariances between components).

In the present study, possibilities of the low altitude remote sensing methods are investigated. The results could be helpful for the interpretation of the high altitude sensors (satellites) observations of the turbid waters. By introducing the algorithms developed here to the satellite data, we may be able to describe the spatial and temporal variations of the main components of waters and tidal flat.

8. References

AUSTIN, R.W. ,1980. Gulf of Mexico, ocean-color surface truth measurements. Boundary-layer Meteor. **18**, 269-285.

BRICAUD, A, 1979. Absorption, diffusion (et retrodiffusion) de la lumiere par les substances influant sur la couleur des eaux de mer. These de 3eme cycle, Univ. Pierre et Marie Curie, 134p.

BRICAUD, A., MOREL, A. & L. PRIEUR, 1981. Absorption by dissolved organic matter of the sea (yellow substance) in the UV and visible domain. Limnol. & Oceanogr. **26**, 43-53.

BRICAUD, A. & S. SATHYENDRANATH, 1981. Spectral signatures of substances responsible for the change in ocean color. Signatures spectrales d'objets en télédétection, Avignon, 8-11 septembre 1981.

BUKATA, R.P., JEROME, J.H., BRUTON, J.E., JAIN, S.C. & H.H. SWICK, 1981. Optical quality model of Lake Ontario. 2: Determination of chlorophyll a and suspended mineral concentrations of natural waters from submersible and low altitude sensors. Appl. Opt. **20**, 1704-1714.

CLARK, D.K., BAKER, E.T & A.E. STRONG, 1980. Upwelled spectral distribution in relation to particulate matter in sea water. Boundary-Layer Meteor. **18**, 287-298.

CADEE, G.C., 1982. Tidal and seasonal variation in particulate and dissolved organic carbon in the Western Dutch Wadden Sea and Marsdiep tidal inlet. Neth. J. Sea Res. **15**, 228-249.

COLIJN, F., 1982. Light absorption in the waters of the Ems-Dollard Estuary and its consequences for the growth of phytoplankton and microphytobenthos. Neth. J. Sea Res. **15**, 196-216.

DRAPER, N.R. and H. SMITH, 1966. Applied regression analysis. JOHN WILEY & SONS, New York.

HOJERSLEV,N., 1981. The colour of the sea and its relation to surface chlorophyll and depth of the euphotic zone. Eurasep Secretariat Newsletter, april 1981, 2, 6-11.

GORDON, H.R., CLARK, D.K., MUELLER, J.L. & W.A. HOVIS, 1980. Phytoplankton pigments from the Nimbus 7 CZCS. Comparisons with surface measurements. Science, **210**, 63-66.

GOWER, J.F.R., 1981. Oceanography from Space. COSPAR/SCOR/IUCRM Symp. Venice, may 1980, Italy, Plenum Press.

JERLOV, N.G., 1976. Optical Oceanography. ELSEVIER, New York, 194 p.

MANUELS, R. (ed.), 1978. Water-, stof- en warmtehuishouding van het Balgzand. Interne Verslagen 1978-2.

MOREL, A. & L. PRIEUR, 1977. Analysis of variations of ocean color. Limnol. and Oceanogr. **22**, 709-722.

MOREL, A., 1981. Relationship between remote assessment of optical properties for ocean waters primarily influenced by biogeneous material (case "1" waters). A collection of extended abstracts presented at the Symposium on the radiation transfer in the oceans and remote sensing of ocean properties. IAMAP, Third Scientific Assembly 17-28 august 81, Hamburg, p 25-26.

NEVILLE, R.A. & J.F.R. GOWER, 1977. Passive remote sensing of pytoplankton via chlorophyll a fluorescence. J. Geophys. Res. **82**, 3487-3493.

POSTMA, H., MANUELS, M.W. & W. ROMMETS, 1976. Breakdown and production of fluorescent substances in Dutch waters. Neth. J. Sea Res. **10**, 499-516.

POSTMA, H., 1961. Suspended matter and Secchi disc visibility in coastal waters. Neth. J. Sea Res. 3, 359-390.

PRIEUR, L. & S. SATHYENDRANATH, 1981. An optical classification of coastal and oceanic waters based on the specific spectral absorption of phytoplankton pigments, dissolved organic material and other particulate materials. Limnol. and Oceanogr. **26**, 671-689.

SATHYENDRANATH, S., 1981. Influence des substances en solution et en suspension dans les eaux de mer sur l'absorption et la reflectance. Modelisation et applications a la teledetection. These de 3eme cycle, Univ. Pierre et Marie Curie, 123p.

SPITZER, D. (ed.), 1981. Balgzand projekt 1981. Optische remote sensing van het water en het Waddopervlak methoden en resultaten. Interne Verslagen, NIOZ, Texel (7).

SPITZER, D. & M. WERNAND, 1981. In situ measurements of absorption spectra in the sea. Deep Sea Res. **28A**, 165-174.

SPITZER, D., RAPPOLDT, C. & L. NYKJAER, 1981. Experiments on the optical remote sensing of the particulate and dissolved material in the Dutch coastal waters. IAMAP R-1 Symposium, Hamburg 1981.

SPITZER, D., RAPPOLDT, C. & L. NYKJAER, 1982. Optical remote sensing of turbid coastal waters. First International Conference and air/sea interaction of the coastal zone. The Hague, May 10-14.

SPITZER, D., RAPPOLDT, C. & L. NYKJAER, 1982. Optical remote sensing of the dissolved and suspended materials in the turbid xoastal waters. Annalen der Meteorologie n^{o} **18**. Symposium uber Strahlungstransportprobleme und Satellitenmessun in der Meteorologie und der Ozeanographie.

STRICKLANDS & PARSONS, (ed.), 1972. A practical handbook of sea water analysis, Ottawa, Fish. Res. Bd Can., 310 pp.

TOPLISS, B.J., 1982. Water color in Eastern Canadian inshore areas. Special Session on Remote Sensing, September 1981, NAFO Sci. Coun. Studies, **4**, 63-67.

VIOLLIER, M., 1980. Télédétection des concentrations de seston et pigments chlorophylliens contenus dans l'ocean. These d'Etat n^{o}503, Univ. Lille I.

WHITLOCK, C.H., POOLE, L.R., USRY, J.W., HOUGHTON, W.M., WITTE, W.G., MORRIS, W.D. & E.A. GURGANUS, 1981. Comparison of reflectance with backscatter and absorption parameters for turbid waters. Appl. Opt. **20**, 517-522.

WHITLOCK, C., KUO, C.Y. & S.R. LECROY, 1982. Criteria for the use of regression analysis for remote sensing of sediment and pollutants. Remote Sensing of Envir. **12**, 151-168.

Appendix

Sea truth measurements

Important in any remote sensing experiment is to estimate the errors of the methods of the seatruth analyses and sampling. For this, we will examine relationships between different types of pigment: chlorophyll a and pheophytin; and also between the two methods of analyses of the "yellow substance" concentrations.

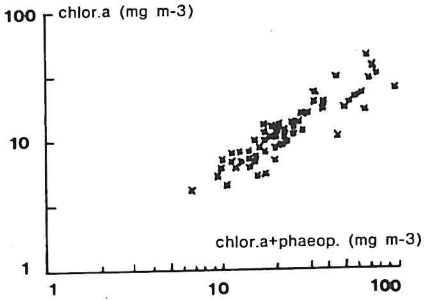


Fig. 1. Pigment concentration versus chlorophyll a concentration for 1981 tower experiment in waters (r= 0.91, n= 56).

Correlations between total pigment, chlorophyll a and pheophytine (see Fig. 1,2 and Table III) are strong if we consider only the 1981 tower series of data (n=56). The correlations are worse, when the airplane data from 1981 and 1982 are included (see

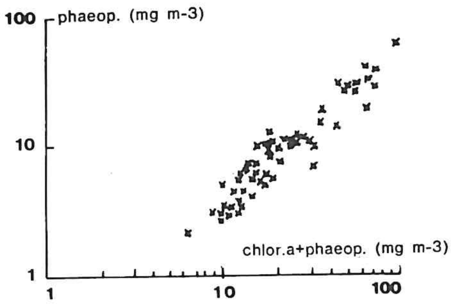


Fig. 2. Pigment concentration versus pheopigment concentration for 1981 tower experiment in waters (r= 0.95, n= 56).

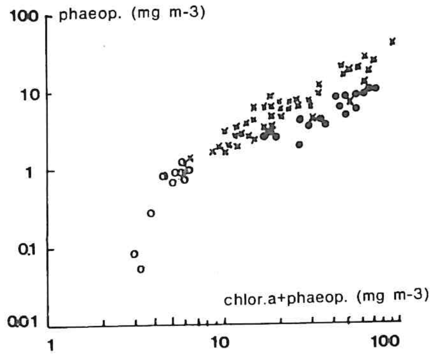


Fig. 3. Chlorophyll a concentration versus pigment concentration for 1981 tower (x) + 1981 airplane (●) + 1982 airplane (o) experiments (n= 86).

FIg. 3,4, n=86). Fig. 5 indicates that the 1982 pheopigment values are relatively much lower than the 1981 values. This may explain the low signifi-

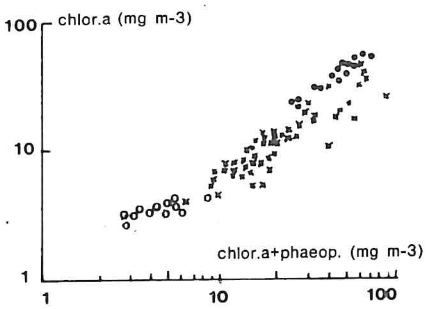


Fig. 4. Pheopigment concentration versus pigment concentration for 1981 tower (x) + 1981 airplane (●) + 1982 (o) airplane experiments (n= 86).

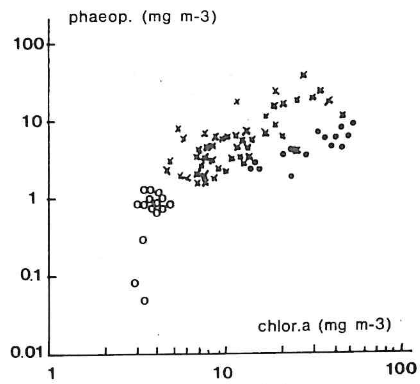


Fig. 5. Pheopigment concentration versus chlorophyll a concentration for 1981 tower (x) + 1981 airplane (●) + 1982 airplane (o) experiments (n= 86).

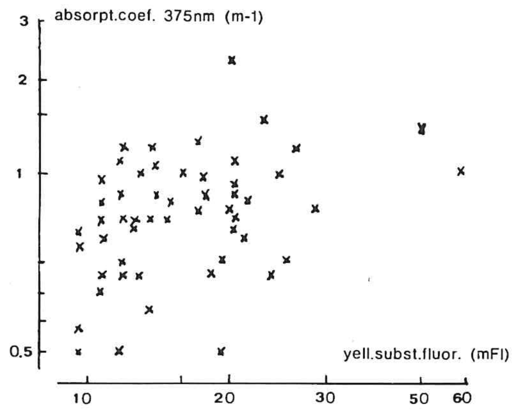


Fig. 6. Relationship between absorption and fluorescence of the yellow substances for 1981 tower experiment (r= 0.09, n= 56).

cance of the algorithm found for total pigment (including pheop.) concentration from airplane measurement in 1982.

Concerning the yellow substances analyses, it is interesting to compare Figs 6 and 7 (Fig.8 in linear coordinates), displaying the relation between the fluorescence and the absorption coefficient at 375 nm. In the first case (Fig.6), only 1981 data are considered, though in the second case (Fig.7), all measurements are included, 1981 and 1982 airplane experiment added, in water and on flats (in intersticial water).

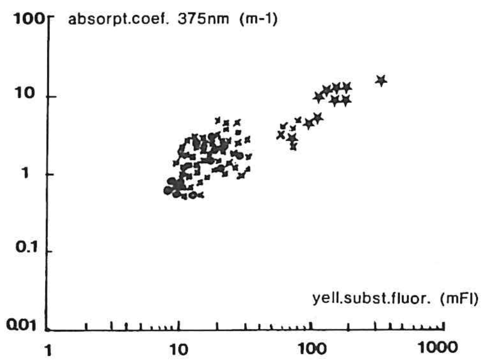


Fig. 7. Relation between absorption and fluorescence of the yellow substances for waters : 1981 tower (x), 1981 and 1982 airplane (•, o) , and for the tidal flat with interstitial waters (*), in log coor- dinates (r= 0.879, n= 104).

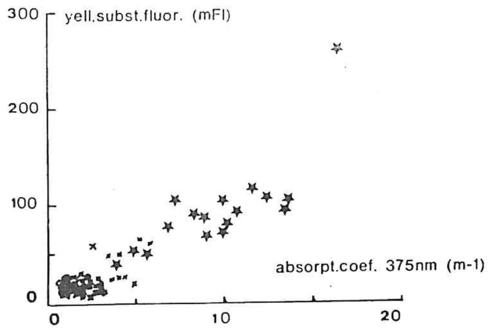


Fig. 8. Same legend as figure 7 but in normal coordinates (r=0.93, n=104).

Under a certain limit of YS concentration, no correlation was found between the two analysis methods. This limit value, is 50 mFl,and 4 m^{-1}. For the concentrations under this limit, the accuracy of one of the methods might be insufficient, (possibly the fluorescent method).