Remote-sensing reflectance of turbid sediment-dominated waters. Reduction of sediment type variations and changing illumination conditions effects by use of reflectance ratios

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Variations of sediment type (grain size and refractive index) and changing illumination conditions affect the reflectance signal of coastal waters and limit the accuracy of sediment-concentration estimations from remote-sensing measurements. These effects are analyzed from numerous *in situ* remote-sensing measurements carried out in the Gironde and Loire Estuaries and then reduced and partly eliminated when reflectance ratios between the near infrared and the visible are considered. These ratios showed high correlation with the sediment concentration. On the basis of the obtained relationships, performing correspondence functions were established that allow an accurate estimation of suspended sediments in the estuaries from Système Probatoire d'Observation de la Terre, Landsat, and Sea-Viewing Wide Field-of-View Sensor data, independently of the date of acquisition. © 2003 Optical Society of America

OCIS codes: 010.0010, 280.0280.

1. Introduction

The presence of turbidity maximum in macrotidal estuaries strongly affects biological processes. The main influence of turbidity is the limitation of light penetration in the water column, which is a factor that controls primary production. The understanding of fine-sediment transport, notably in the high-turbidity zone, is also necessary to predict the fate of eventual pollutants and to design dredging strategies. Spatial remote sensing is the most efficient tool in that it allows retrieval of instantaneous horizontal distributions of turbidity and observation of seasonal movements of turbidity in estuaries. This information is essential for providing calibration data for numerical hydrosedimentary models,[1,2] in order to quantify sedimentary fluxes and estimate the fluvial solid discharges to the ocean. In clear oceanic waters, algorithms are used to interpret satellite data in term of chlorophyll concentration[3] and hence deduce primary production.[4,5] The signal becomes more complicated in coastal and estuarine turbid waters in which terrestrial substances, such as colored dissolved organic matter and suspended sediments, are present in addition to phytoplankton. Refined algorithms are needed especially to estimate accurately the suspended particulate matter (SPM) concentrations from ocean color remotely sensed data.[6–9]

The aim of this study is to develop such an efficient and invariant inversion algorithm in estuarine sediment-dominated waters, which could permit the accurate estimation of the SPM distributions from satellite remotely sensed data, without carrying out field measurements for validation at the moment of the image acquisition. Previous studies in the Gironde Estuary have shown that calibration relationships between reflectance ratios and SPM concentrations can be established during low river-flow periods,[10,11] when the main origin of suspended sediments is resuspension by tidal currents. It is now necessary to test the validity of these relationships for a long-term period including flood events, when new materials are supplied by rivers in the estuary. In this way, the complete set of data that has been collected in the Gironde Estuary between 1996 and 2001 is analyzed. It is also important to

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Received 22 July 2002, revised manuscript received 27 December 2002.
0003-6935/03/152623-12$15.00/0

test the validity of the results obtained in the Gironde in another similar study area: the Loire Estuary. As it is difficult to carry out calibration measurements for satellite data when illumination conditions are optimal (clear blue sky and Sun close to the zenith), it is finally interesting to determine the influence of the cloud cover on the calibration relationships that can be established. In this way, field reflectance measurements carried out under different illumination conditions are analyzed. The objectives are to display invariant relationships between reflectance measurements and SPM concentrations and to develop improved algorithms for satellite sensors.

The method adopted for the validation of remote-sensing data and the long-term field measurements carried out in the Gironde and Loire Estuaries are first presented. Spectral signatures of these highly turbid waters are determined and discussed. Then empirical relationships are established between reflectance measurements and SPM concentrations. These relationships are finally used to develop algorithms or correspondence functions adapted to satellite sensors of the Système Probatoire d'Observation de la Terre (SPOT), Landsat, and Sea-Viewing Wide Field-of-View Sensor (SeaWiFS).

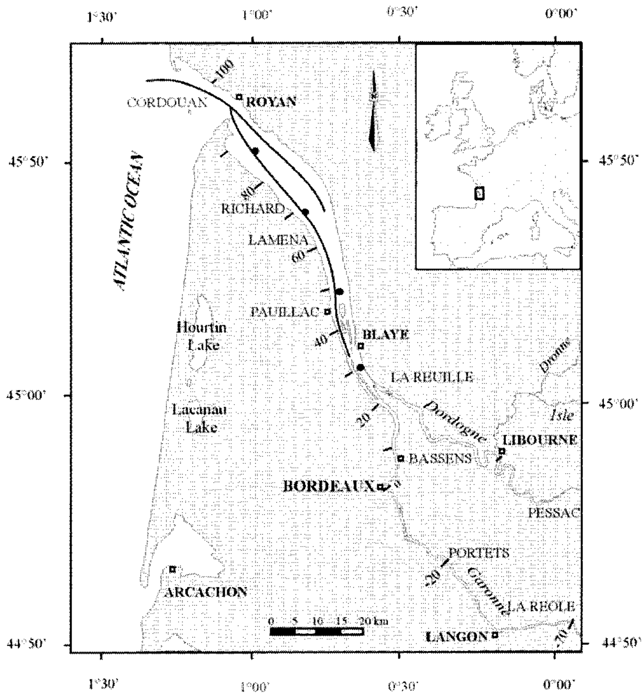

Fig. 1. Gironde Estuary, located in southwest France. Lines, main navigation channels; black circles, the four stations that took regular field measurements.

2. Study Areas

The first area of interest in this study is the Gironde Estuary, in southwest France, whose characteristics (hydrodynamics and sedimentology) are well known and where optical measurements have been carried out since 1996 to validate remote-sensing data. The second area of interest is the Loire Estuary, in west France, where optical data have been collected in 2002 to validate satellite data recorded during flood conditions. These two macrotidal estuaries are both characterized by highly turbid waters dominated by suspended sediments.

A. Gironde Estuary

The Gironde Estuary (see Fig. 1), resulting from the confluence of the Dordogne and Garonne Rivers, which supply freshwater at a mean annual rate of 1000 $m^3 s^{-1}$, is one of the largest estuaries of the European Atlantic coast. It presents a well-developed turbidity maximum, whose formation results from tidal asymmetry and density residual circulation.[12,13] The total sediment mass in the turbidity maximum–fluid mud system is approximately 5×10^6 tons.[14] Mean SPM concentrations vary from 150 to approximately 3000 mg l^{-1} in surface waters of the estuary.[15,16]

The mineral fraction of suspended matter is composed of micas (63%) and quartz (25%). The clay phases contain four argillous minerals: montmorillonite (30%), illite (40%), kaolinite (15%), and chlorite (15%).[12] The sizes of fine, median, mean, and coarse particles in surface waters of the estuary, determined from measurements on water samples collected from 1996 to 2001, are, respectively, 3.25 (i.e., 10% of particles are smaller than 3.25 μm), 8.80, 13.02, and 27.06 μm (i.e., 10% of particles are larger than 27.06 μm). *In situ* measurements of the flocculated particles' dimensions, 1 m below the water surface, showed a mean diameter around 120 μm practically independent of the sediment concentration.[17] The nature and grain size of the particles vary little with the seasons.[12,18] The particulate organic carbon has a value of 1.5% without seasonal variations.[19] Chlorophyll-*a* and dissolved organic matter concentrations are low, chlorophyll-*a* ranging from 1 to 3 μg l^{-1} (Ref. 20) and dissolved organic carbon ranging from 1 to 7 mg C l^{-1} (Ref. 21). Optical depths, which are limited in turbid waters of the Gironde Estuary, have been measured and related to SPM concentrations by Irigoien and Castel.[20]

B. Loire Estuary

The morphology of the Loire Estuary (see Fig. 2) changed significantly during the last century, as a

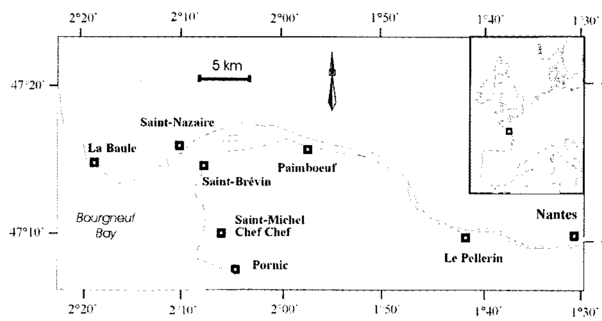

Fig. 2. Loire Estuary, located in west France.

Table 1. Mean Particle Grain-Size Distributions Measured in Surface Waters of the Loire Estuary in 2002 and of the Gironde Estuary (from 1996 to 2001)[a]

Estuary	Particle Size (μm)			
	Fine	Median	Mean	Coarse
Gironde	3.25	8.79	13.02	27.02
Loire	2.52	8.46	13.77	28.61

[a]See the text for the particle class definitions.

consequence of industrial activities and dredging strategies on the main navigation channel. This navigation channel is actually located along the right shore. Tides propagate to as much as 35 km upstream to Nantes during low river-flow periods, and salinity intrusion can be observed up to Le Pellerin. The Loire River drains a mean annual flow of 825 m^3 s^{-1}. In winter, peak floods can reach more than 4000 m^3 s^{-1}. In summer the mean freshwater flow is lower than 100 m^3 s^{-1}. The influence of the tidal asymmetry is predominant in the turbidity maximum's formation and mechanisms, comparable with salinity-induced effects.[22] Concerning the transport of cohesive sediments in the estuary and the associated seasonal movements of turbidity, studies with numerical models showed that the turbidity maximum is large during spring tides, whereas thick fluid mud layers appear on neap tides.[23] SPM concentrations in surface waters vary between 10 and more than 2000 mg l^{-1} in the high-turbidity zone. The clay phases contain the same four minerals as the Gironde Estuary, with different associated percentages: montmorillonite (10% to 30%), illite (30% to 50%), kaolinite (20% to 35%), and chlorite (5% to 15%).[24] The grain-size distribution of particles in surface waters is quite similar to that of the Gironde (see Table 1). The mean particulate organic carbon value is (3 ± 0.3)% of the SPM concentration, which is approximately twice as great as the values measured in the Gironde (our measurements).

3. Theory and Method

A. Theory

The physical parameter usually considered in ocean color analyses is the irradiance reflectance, $R(0-)$ (unitless), defined as the ratio of the upwelling to downwelling irradiances just beneath the surface, denoted, respectively, $E_u(0-)$ and $E_d(0-)$ (in watts per inverse square meters per inverse nanometers):

$$R(0-) = \frac{E_u(0-)}{E_d(0-)}. \tag{1}$$

$R(0-)$ can be written as a function of the inherent optical properties (IOPs) of the water body, namely, the absorption and backscattering coefficients a and b_b (in inverse meters), according to[25]

$$R(0-) = f\,\frac{b_b}{a + b_b}, \tag{2}$$

where the value of f is 0.324 for the Sun close to the zenith.[26]

For remote-sensing applications in oceanography, a specific water reflectance signal, called remote-sensing reflectance (R_{rs}, in inverse steradians) has been defined as[27]

$$R_{rs} = \frac{L_w}{E_d(0+)}, \tag{3}$$

where L_w (in watts per inverse square meters per inverse steradians per inverse nanometers) is the water-leaving radiance and Ed(0+) (in watts per inverse square meters per inverse nanometers) is the downwelling irradiance incident on the water surface.

The R_{rs} signal can be retrieved from airborne radiometric measurements or from satellite measurements corrected for atmospheric effects. R_{rs} can be related to the IOPs a and b_b[25,28] if the geometrical parameters that take into account the air–water interface transfer and bidirectional aspects are considered.[26,29] In the case of highly turbid waters dominated by suspended sediments, the obtained relationship can be approximately written as[10]

$$R_{rs} = 0.529\,\frac{f}{Q}\,\frac{b_b}{a + (1 - rf')b_b} \approx 0.529\,\frac{f}{Q}\,\frac{b_b}{a + b_b}, \tag{4}$$

where Q (in steradians) is a geometrical parameter defined as the ratio of the upwelling irradiance to upwelling radiance just beneath the surface (L_u). Q would be π if the L_u distribution were isotropic but may vary between approximately 3.1 and 5.6, and r, the water–air reflection, is of the order of 0.48.[26]

Expression (4) indicates that the R_{rs} signal depends both on geometrical parameters through the f/Q ratio and on the IOPs through the $b_b/(a + b_b)$ ratio. Comparing results obtained with a reflectance model to *in situ* measured reflectance spectra, Doxaran *et al.*[10] showed that, in the case of the highly turbid waters of the Gironde Estuary, spectral variations of R_{rs} are due to the $b_b/(a + b_b)$ ratio, whereas the f/Q ratio mainly influences the amplitude of the R_{rs} signal.

B. Method

The following satellite sensors were selected in this study: SPOT-High Resolution Visible (ground resolution of 20 m), Landsat Enhanced Thematic Mapper Plus ET (ground resolution of 30 m), and SeaWiFS (ground resolution of 1000 m). The details concerning their visible and near-infrared spectral bands are presented in Section 5. The adopted method for satellite data calibration has already been applied.[8,10,11,30,31] It is necessary to consider reflectance measurements carried out above the water surface or reflectance measurements recorded on board satellites and previously corrected for atmospheric effects. The obtained R_{rs} signals are then converted into SPM concentrations, according to an empirical relationship adapted to the study area. This empirical relationship is established from numerous *in situ* spectroradiometric measurements (400–1100 nm) carried out simultaneously with SPM concentration measurements within the surface waters (0–1-m depth). Spectroradiometric data are weighted by sensitivity to obtain the equivalent R_{rsi} signal in spectral band i of satellite sensors (e.g., SPOT, Landsat, and SeaWiFS). Finally, empirical relationships are established between the R_{rsi} signal and SPM, and the best ones are selected to quantify the SPM concentrations. Numerous *in situ* measurements are needed to improve the validity of the obtained relationship and to determine its limits.

The results obtained with a reflectance model showed that the optical properties (a and b_b) of sediments are predominant in highly turbid waters, such as the Gironde Estuary, in the visible domain.[10] In the near infrared, it was observed that the reflectance signal depends only on absorption by water and sediments' optical properties. Optical properties of sediments (absorption and backscattering coefficients) are approximately proportional to the sediment concentration. Consequently, results demonstrated that empirical relationships between R_{rs} in the near infrared and SPM concentration can be established. However, variations of particles' grain size and refractive index modify their optical properties, and, consequently, the established empirical relationships. The variations of the particles' grain size occur in estuaries during the tidal cycle.[17,18] The variations of the refractive index of suspended solids, which depend on their mineral composition,[32] can also occur when new materials are supplied by rivers during peak floods. As a consequence, Doxaran *et al.*[10,11] observed significant variations of the R_{rs} signal in the visible and near-infrared domains independently of the SPM concentration from *in situ* measurements carried out in 1996 and 1997 and then in 2000 and 2001. These observations highlight the difficulties one encounters when trying to establish invariant empirical relationships between R_{rs} and SPM concentration in dynamic areas such as estuaries. However, results obtained with a reflectance model also showed that appropriate reflectance ratios are slightly influenced by variations of sediment types and that invariant and accurate relationships may be established between R_{rs} ratios (ratios between near-infrared and visible wavelengths) and the SPM concentration.[10] This result was also observed from experimental measurements[9] and confirmed by *in situ* measurements.[10,11] In this study, relationships between R_{rs} and SPM and then between R_{rs} ratios and SPM are examined, considering the complete set of radiometric data collected in the Gironde Estuary since 1996. Equivalent relationships are established from radiometric measurements carried out in the Loire Estuary in 2002 and compared with those obtained in the Gironde, in order to validate the processing method and develop algorithms for quantifying SPM in the two estuaries.

4. Data and Analyses

Data samples were collected in the Gironde Estuary in 1996 (June and July), in 1997 (June and July), in 1999 (June), in 2000 (July, September, and November), and in 2001 (January, July, August, and September) at four fixed stations located along the sides of main navigation channel at the following distances from Bordeaux: 30, 52, 67, and 85 km (see Fig. 1). The measurements were carried out when there was a clear blue sky and a quasi-plane water surface, for different tidal conditions (neap–spring tides) independently of the tidal cycle (ebb–flood tides and low–high-water periods) and for different river-flow conditions. Data samples were collected in the Loire Estuary in 2002 during two field campaigns (from 25 February to 1 March and then from 2–5 April). Measurements were carried out in the downstream part of the estuary, between Paimboeuf and La Baule (see Fig. 2), during a high river-flow period (>1500 m^3 s^{-1}) corresponding to spring and mean tides. Environmental conditions were a clear blue sky and a plane sea surface, except for 1 March (11 field measurements) and 3 April (four measurements) when the sky was thickly overcast with no Sun visible.

Optical data were recorded with a Spectron SE-590 spectroradiometer with 256 photodiodes in the interval 400–1100 nm (bandwidth: 2.8 nm/sensor). The radiometer was directed vertically toward the water, 1 m above the surface, when the total upwelling radiance L_t was measured. This viewing direction was adopted after several field experiments performed to determine the direction less influenced by surface reflection effects (sun glint and sky glint). We observed that the upwelling radiance spectra were practically identical when pointing the sensor with a 0° or a 35° angle with the nadir, whatever the illumination conditions (blue or covered sky). Moreover, the measured L_t spectra were sometimes higher when the sensor was pointed with a 35° angle. According to our observations, and despite the recommendations recently done,[27,33] we have consequently adopted a viewing angle close to the nadir. Measurements of the upwelling radiance just beneath the surface (L_u) would be necessary for a conclusion. The radiometer was vertically directed toward a Spectralon target when the downwelling radiance L_d was measured and directed toward the zenith when the sky radiance L_s was measured. The target is near Lambertian for solar zenith angles between 0° and 40°, as its reflectance (R_p) varies by only 3%.[34] In these conditions the downwelling irradiance E_d was $\pi L_d/R_p$. Upwelling radiance measurements have been corrected for skylight reflection effects (sky glint) by subtraction of a percentage, denoted ρ, of the measured sky radiance,[35] to estimate the water-leaving radiance.[27] The measured R_{rs} was finally given by

$$R_{rs} = R_p \frac{L_t - \rho L_s}{\pi L_d}. \tag{5}$$

Table 2. Percentage of the Total Measured Upwelling Radiance (L_t) That Is to Skylight Reflection, Expressed as the $\rho L_s/L_t$ Ratio[a]

Sky and Date	Skylight Effects $\rho Ls/Lt$ Percentage at Various Wavelengths (nm)				
	450	550	650	750	850
Clear blue sky (28 February 2002)	18.8	8.0	5.8	8.0	10.1
Thick overcast sky (01 March 2002)	47.8	29.7	26.3	38.3	47.7

[a]Measurements were carried out in the Loire Estuary under a clear blue sky (28 February 2002) and a thick overcast sky (1 March 2002).

Five successive L_t, L_s, and L_d spectra were recorded at each station. For each optical measurement, we measured the SPM concentration near the surface (50-cm depth) by filtering a water sample on Whatman GF/F glass-fiber filters (diameter: 47 mm; pore size: 0.44 μm). In the Gironde Estuary, a total of 132 coincident R_{rs} and SPM data samples (18 recorded in 1996, 27 in 1997, 32 in 1999, 39 in 2000, and 16 in 2001) were available. In the Loire Estuary, a total of 68 equivalent data samples (39 recorded in February, 11 in March, and 18 in April) were available. The statistics concerning the SPM measured within surface waters of the Gironde Estuary are the following: minimum, mean, and maximum concentrations of 13, 286, and 2388 mg l^{-1}, with a standard deviation of 379 mg l^{-1}. Twelve measurements carried out along the limits of the Gironde turbid plume (four in 1996 and eight in 1999) and corresponding to lower SPM concentrations in the range (1–9 mg l^{-1}) were also considered in order to determine the limits of the empirical relationships that may be established in the estuary. SPM statistics in the Loire Estuary are the following: minimum, mean, and maximum concentrations of 7, 280, and 1623 mg l^{-1}, with a standard deviation of 275 mg l^{-1}. Before determining the R_{rs} signal [see Eq. (5)], the measured radiance spectra were analyzed to make sure that the five L_d spectra were superimposed (i.e., the incident solar light did not vary) and the corresponding five L_t spectra were also superimposed (i.e., the turbidity of surface water or surface reflection effects or both did not vary). Then the R_{rs} signal was determined from the average L_t and L_d measurements.

Values of the ρ coefficient were selected from results obtained by Mobley,[27] i.e., $\rho = 0.0337$ for a clear blue sky and $\rho = 0.0248$ for a thick overcast sky with no Sun visible. The $\rho L_s/L_t$ ratio was calculated to estimate the influence of skylight effects under these illumination conditions. As the total measured upwelling radiance (L_t) can be written as the sum of the water-leaving radiance (L_w) and the radiance directly reflected by the air–water interface (ρL_s),[27] this ratio represents the percentage of the measured L_t signal that is due to skylight reflection effects. It was calculated for measurements carried out in the Loire Estuary during two successive days: 28 February

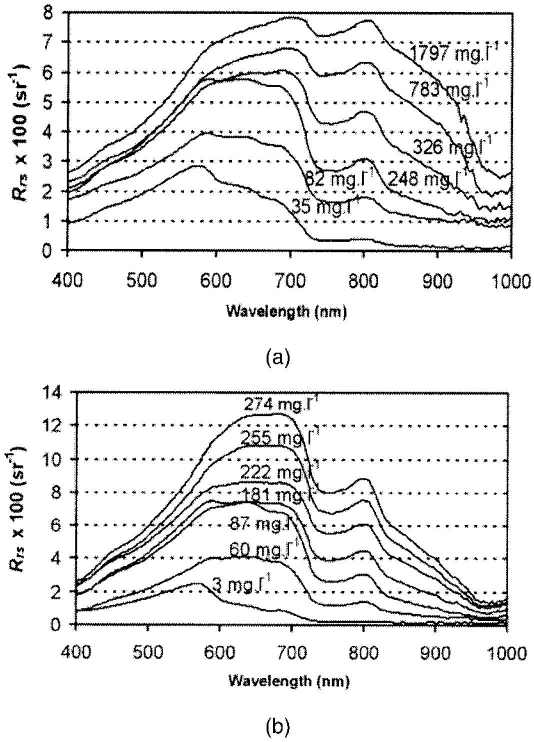

Fig. 3. Examples of typical *in situ* measured R_{rs} spectra carried out for different SPM concentrations in the Gironde Estuary in (a) 1996 and 1997 and then in (b) 1999.

2002 (blue sky, 14 data samples, and mean SPM concentration of 253 mg l^{-1}) and 1 March 2002 (thick overcast sky, 11 data samples, and mean SPM concentration of 244 mg l^{-1}). The results (see Table 2) indicate that under a clear blue sky, skylight effects were low (<11% from 500 to 900 nm). Under an overcast sky, skylight effects were higher, as they represent approximately 30% of the total measured signal from 500 to 700 nm and more than 40% in the near infrared. These observations highlight the importance of an accurate correction of these reflection effects when *in situ* measurements are carried out under diffuse illumination conditions.

5. Results

A. Spectral Signatures of Estuarine Waters

First, the spectral signature of the highly turbid waters of the Gironde and Loire Estuaries were examined and compared for various SPM concentrations. The corresponding measured chlorophyll concentrations were always lower than 10 μg l^{-1} and typically lower than 5 μg l^{-1}.

The measured R_{rs} spectra in the Gironde Estuary typically increased with SPM in the range of 400–1000 nm, especially between 550 and 900 nm (see Fig. 3). Concerning the lower SPM (<100 mg l^{-1}), the signal measured in the near infrared was weak, and the R_{rs} maximum was observed around 580 nm. Over 100 mg l^{-1}, the R_{rs} maximum was located around 700 nm, and a second maximum appeared at

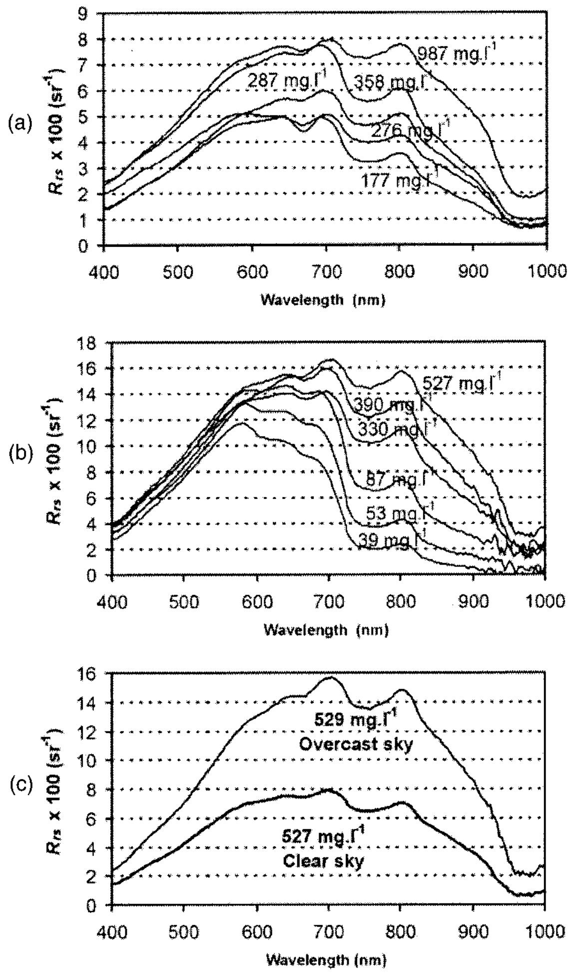

Fig. 4. Example of typical *in situ* measured $R_{\rm rs}$ spectra recorded in the Loire Estuary for different SPM concentrations: (a) on 28 February 2002 under a clear blue sky and (b) on 1 March 2002 under a thick overcast sky. (c) Comparison between $R_{\rm rs}$ spectra recorded at equivalent SPM concentrations under a clear sky (thick curve) and under an overcast sky (thin curve).

800 nm. For the highest SPM concentrations (>300 mg l^{-1}), the measured $R_{\rm rs}$ signal was far from zero in the near-infrared wavelengths (700–1000 nm). The same spectral variations were observed from measurements carried out in 1996, 1997, and 1999 and in 2000 and 2001. However, significant variations of the $R_{\rm rs}$ signal amplitude were also observed from one year to another. In fact, at equivalent SPM concentrations, $R_{\rm rs}$ spectra recorded in 1999 just after flood conditions [see Fig. 3(b)] were practically twice as great as the values recorded in 1996 and 1997 [see Fig. 3(a)]. As environmental (clear blue sky and plane sea surface) and geometrical conditions (Sun elevation and viewing directions) of measurements were practically the same in 1996, 1997, and 1999, these observations probably resulted from changes of the IOPs, induced by supplies of new materials in the estuary during the floods.

Typical measured $R_{\rm rs}$ spectra in the Loire Estuary (see Fig. 4) were quite similar to those measured in the Gironde, notably with two maxima located around 680 and 800 nm. The main difference was a weak decrease of the $R_{\rm rs}$ signal at 660 nm with respect to the Loire measurements. It is interesting to note that $R_{\rm rs}$ measurements carried out during two successive days, in the same area, showed similar spectral variations with increasing SPM but significant amplitude difference [see Figs. 4(a) and 4(b)]; the $R_{\rm rs}$ values measured on 1 March 2002 (thick overcast sky) were quite greater than those measured on 28 February 2002 (clear blue sky). At equivalent SPM, (528 ± 1) mg l^{-1}, the $R_{\rm rs}$ signal recorded under an overcast sky was at least twice that of the $R_{\rm rs}$ signal measured under a clear sky [see Fig. 4(c)], independently of the wavelength. In fact, the L_d signal measured on the Spectralon target decreased by a factor of 10 from 28 February 2002 to 1 March 2002, whereas the L_t signal decreased only by a factor of 5. For an explanation of these observations, refer to the approximate theoretical expression of $R_{\rm rs}$ (expression 4). During the two successive days of measurements, no significant variations of particle grain size were observed. The mineral composition, and so the refractive index, of suspended sediments varied slightly. As a result, the IOPs were probably quite similar during the two days, and variations of the $b_b/(a + b_b)$ ratio, independently of SPM concentration, could not explain the observations. Consequently, significant variations of the f/Q ratio certainly occurred with changing illumination conditions (a clear blue sky, then a thick overcast sky). It may be concluded from the above observations that both the sediment type variations and the changing illumination conditions significantly affect $R_{\rm rs}$ measurements from turbid sediment-dominated waters.

B. Reflectance as a Function of Suspended Particulate Matter Concentration

Spectral $R_{\rm rs}$ measurements have been weighted by sensitivity to obtain the equivalent $R_{{\rm rs}i}$ signal in spectral band i of the satellite sensors of the SPOT, Landsat, and SeaWiFS. The selected spectral bands were XS1 (500–590 nm) and XS3 (790–890 nm) for SPOT-High Resolution Visible; L1 (450–515 nm), L2 (525–605 nm), and L4 (750–900 nm) for Landsat-Enhanced Thematic Mapper Plus; and 555 and 865 nm for SeaWiFS. The variations of the obtained $R_{{\rm rs}i}$ signals were examined as a function of the SPM concentration.

In the Gironde Estuary (see Fig. 5) the $R_{{\rm rs}i}$ signal in visible spectral bands of SPOT and Landsat sensors first increased with SPM up to 500 mg l^{-1}, following a approximate logarithmic increase with a slope depending on the wavelength. The signal showed high irregularities between 100 and 1000 mg l^{-1}, then tended to saturate. In the near infrared, the $R_{{\rm rs}i}$ signal increased with SPM up to 500 mg l^{-1}, following a linear increase associated with high irregularities, then it tended to saturate when concentrations were higher than 1000 mg l^{-1}. These linear relationships appeared from measurements carried out during each field campaign, but the corresponding slopes changed from one field campaign to an-

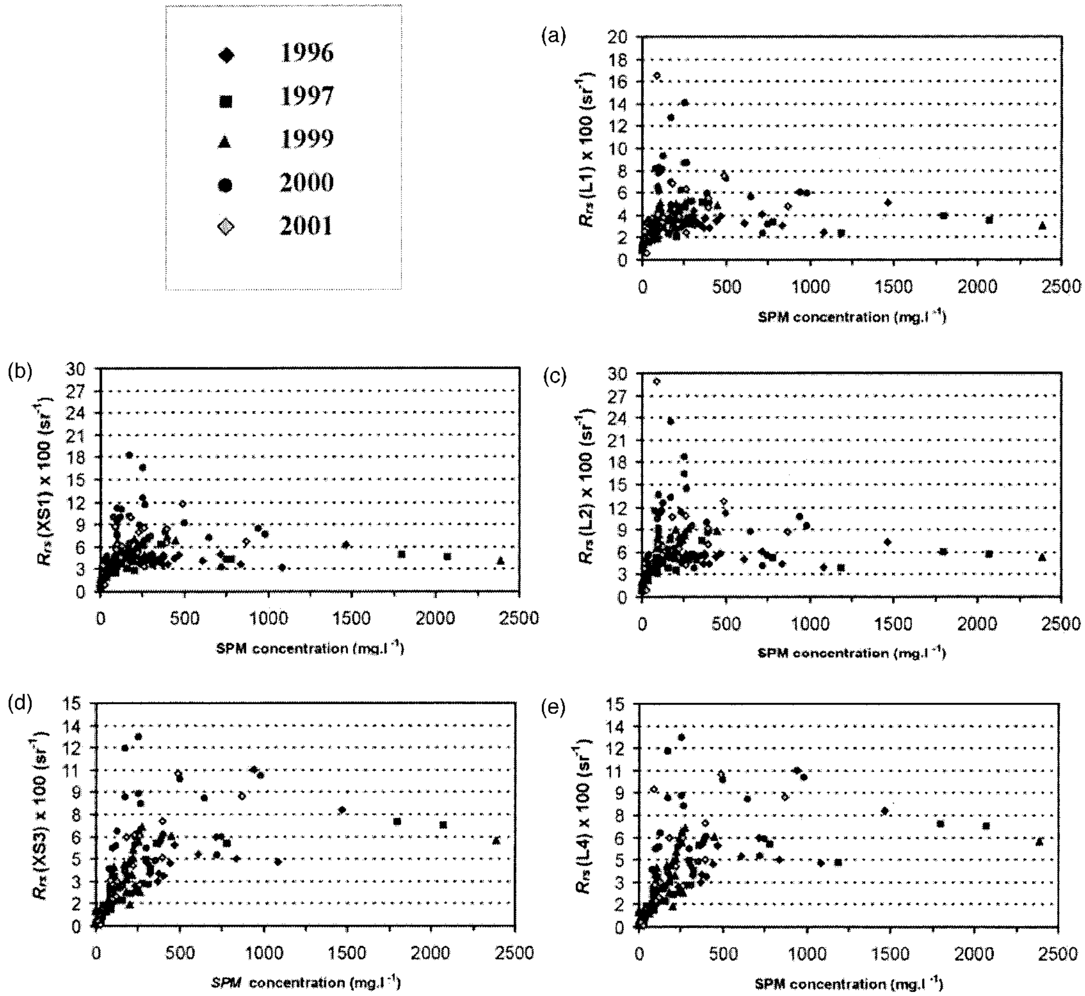

Fig. 5. Empirical relationships between R_{rsi} in (b) and (d) SPOT bands and in (a), (c), and (e) Landsat bands and SPM concentration established from all measurements carried out in the Gironde Estuary in 1996, 1997, 1999, 2000, and 2001.

other. It must be concluded that punctual empirical relationships between R_{rs} in the near infrared and SPM concentration can be established in the estuary, but their applicability is limited in time.

Concerning the Loire Estuary (see Fig. 6), no relationships were obtained between R_{rs} in SPOT and SeaWiFS visible bands and SPM concentration. In fact, variations of the measured R_{rsi} signals appeared insensitive to SPM up to 500 mg l^{-1}. Above this concentration, R_{rsi} tended to saturate. In the near infrared, a linear increase of R_{rsi} with increasing SPM up to 500 mg l^{-1} and then a saturation of the signal above this concentration were observed, which is consistent with results obtained in the Gironde. These variations may be observed from measurements carried out during the two field campaigns in the Loire.

To estimate the influence of illumination conditions on relationships established between R_{rsi} and SPM concentration, we distinguished measurements carried out under a clear blue sky and under a thick overcast sky. The R_{rsi} signal amplitude in visible and near-infrared bands was systematically higher when it was measured under an overcast sky (see Fig. 6). If the applied correction for skylight reflection effects was sufficient, it signifies that variations of the f/Q ratio with changing illumination conditions strongly influenced the measured R_{rsi} signal amplitude.

These observations tend to confirm that field measurements recorded for establishing empirical relationships used to validate satellite data should be carried out exclusively when environmental conditions allow satellite data acquisition, i.e., under a clear blue sky.

C. Reflectance Band Ratios as a Function of Suspended Particulate Matter Concentration

Results obtained with a reflectance model adapted to highly turbid waters demonstrated that appropriate reflectance band ratios are slightly influenced by variations of sediment type and are highly correlated to SPM.[10] These analytical results were confirmed by field measurements carried out in the Gironde Estuary in 1996 and 1997[10] and again in 2000 and 2001.[11] The ratios of the near-infrared (800–900 nm) and visible (500–600 nm) reflectance were robust to quantify the SPM. These results may now be

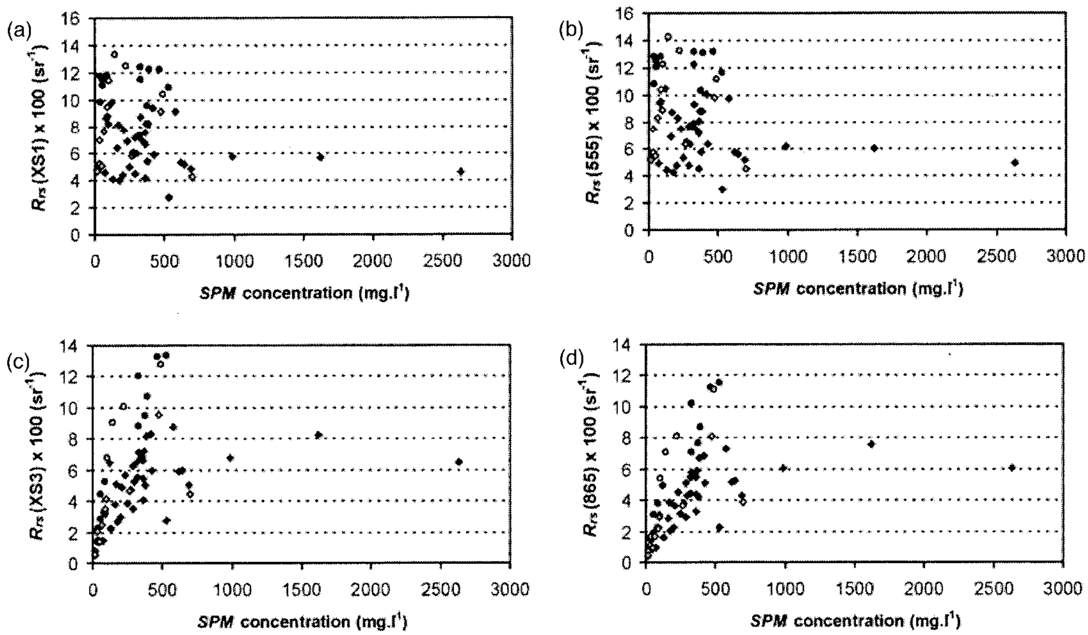

Fig. 6. Empirical relationships between R_{rsi} in (a) and (c) SPOT bands and in (b) and (d) SeaWiFS bands and SPM concentration established from measurements carried out in the Loire Estuary in February and March 2002 (black points) and in April 2002 (gray points), under a clear blue sky (diamonds) and under a thick overcast sky (circles).

tested with consideration of the complete set of sample data collected in the Gironde and measurements collected in the Loire.

First, we present the relationships between the ratios of the near-infrared and visible bands of the SPOT and of the Landsat sensors and SPM, established from all the measurements carried out in the Gironde from 1996 to 2001. The selected ratios, denoted $\Re$, are $R_{rs}(XS3)/R_{rs}(XS1)$ for SPOT bands and $R_{rs}(L4)/R_{rs}(L1)$ and $R_{rs}(L4)/R_{rs}(L2)$ for Landsat bands. In each case, high correlations were observed. The obtained relationships (see Fig. 7) were logarithmic, which means that the $\Re$ ratios first increased with increasing SPM up to 1100 mg l^{-1}. Then they tended to saturate at extreme concentrations (SPM > 1100 mg l^{-1}). These results confirm

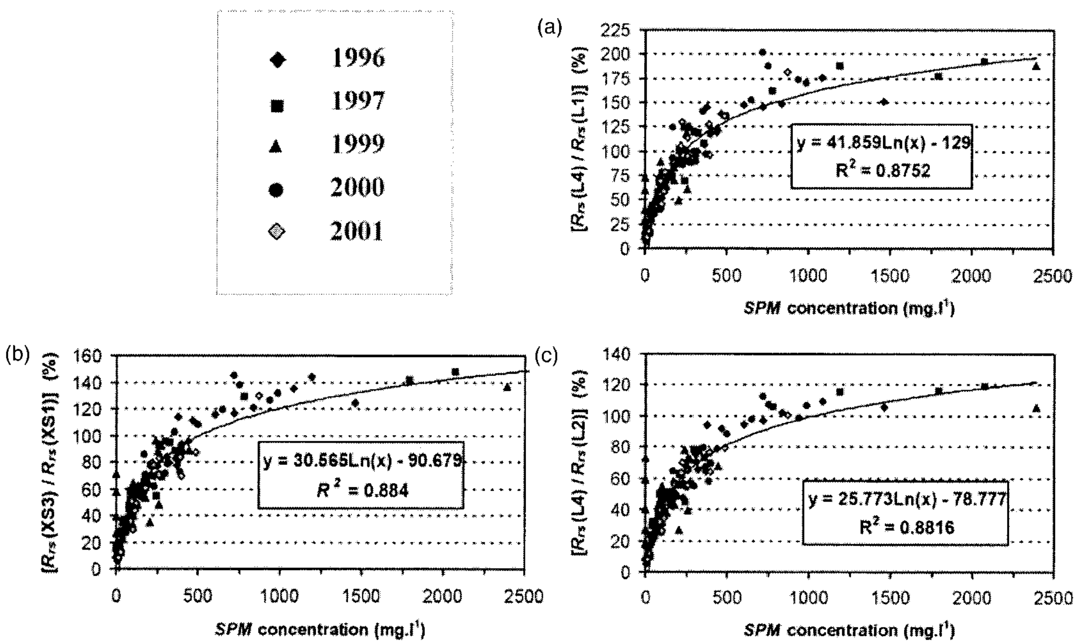

Fig. 7. Empirical relationships between reflectance ratios in (b) SPOT bands and in (a) and (c) Landsat bands and SPM, established from all field measurements carried out in the Gironde Estuary from 1996 to 2001. Plot of the logarithmic regression between 10 and 2500 mg l^{-1}.

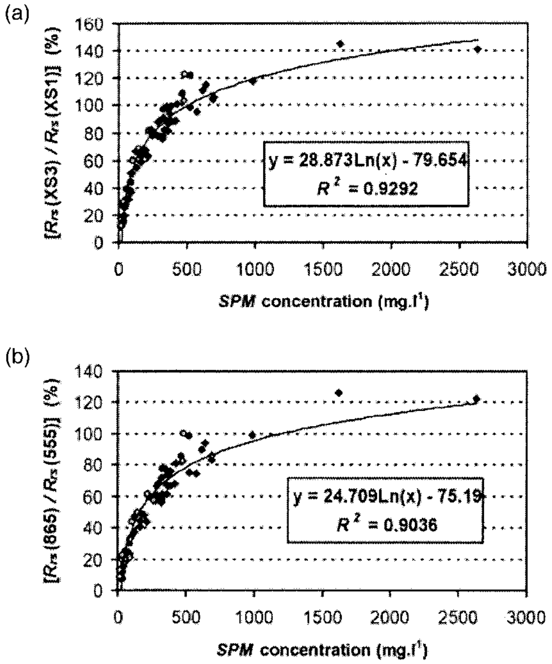

Fig. 8. Empirical relationships between reflectance ratios in (a) SPOT bands and in (b) SeaWiFS bands and SPM concentration, established from field measurements carried out in 2002 in the Loire Estuary in February and March 2002 (black points) and in April 2002 (gray points), under a clear blue sky (diamonds) and under a thick overcast sky (circles).

previous observations made from measurements carried out in 1996 and 1997 and then in 2000 and 2001 in the Gironde: That the reflectance ratios between near-infrared and visible bands are slightly influenced by sediment type variations that occur in estuaries, as was demonstrated with a reflectance model. In fact, sediment type variations induce significant variations of the sediment backscattering coefficient, denoted b_{bs}. As spectral variations of b_{bs} are weak between 500 and 900 nm,[36] the influence on the selected reflectance ratios is limited. Concerning absorption properties of sediments in the Gironde Estuary, knowledge is limited. It is thus actually difficult to assess their influence on the established relationships.

The established relationships include all the data collected in the Gironde from 1996 to 2001. Their validity is consequently demonstrated for this 6-yr period. They will allow the development of invariant and performing algorithms used to quantify the SPM in the estuary.

Measurements in the Loire Estuary were useful to test the validity of relationships established in the Gironde and to extend the method developed for remote-sensing data validation in another study area. Here are presented the resulting relationships established in the Loire when reflectance ratios were selected between the near-infrared and visible SPOT and SeaWiFS bands. Once again, high correlations were observed with SPM (see Fig. 8). The relationships were logarithmic and included all measurements carried out in 2002. The $\Re$ ratios first increased with increasing SPM up to 1500 mg l^{-1}, then tended to saturate at higher concentrations. It confirms that the method developed for the Gironde Estuary is valid for other estuarine waters dominated by suspended sediments. It is interesting to note that the established relationships between R_{rs}(XS3)/R_{rs}(XS1) (SPOT bands) and SPM are almost identical in the Gironde and the Loire. Doxaran *et al.*[10] demonstrated that these relationships essentially depend on the optical properties of sediments, i.e., on sediment type (grain size and refractive index). As particle grain-size distributions and mineral composition of sediments are similar in both estuaries, this result is logical. A second important result is obtained: The relationships (see Fig. 8) established from all the measurements carried out in the Loire in 2002 also include measurements carried out under a thick overcast sky. It was previously observed that R_{rs} signals measured in the visible and the near infrared under an overcast sky were systematically higher than those measured under a clear blue sky (see Fig. 6), probably because of an increase of the f/Q ratio for diffuse illumination conditions. These variations observed on the R_{rs} signals disappeared when reflectance ratios were considered. Consequently, it can be deduced that even if variations of the f/Q ratio with changing illumination conditions are significant, the associated spectral variation between 500 and 900 nm remain weak.

As pointed out by Gordon,[37] Morel and Gentili,[38] and then Loisel and Morel,[39] the similar trends of f and Q with solar elevation result in a approximate stability of their ratio. However, recent numerical computations concerning case 1 oceanic waters highlighted significant variations of this ratio with solar elevation and water optical properties.[26,29] By analogy, with case 1 waters with high chlorophyll-a concentrations, it was anticipated that the amplitude of the f/Q variations could be large in turbid, sediment-dominated, case 2 waters.[26,39] The results obtained in this study not only tend to confirm this assumption but also suggest that spectral variations of f/Q between 500 and 900 nm remain weak. Consequently, considering a reflectance ratio permits a limitation and even a part elimination of the f/Q variations. This result is important because it means that the relationships established in the Gironde and the Loire Estuaries are valid independently of the illumination conditions (clear or overcast sky). As a consequence, they can be applied regardless of, notably, the cloud cover conditions.

D. Correspondence Functions for Sensors of SPOT, Landsat, and SeaWiFS: Applicability and Limits

The invariant relationships obtained between R_{rs} ratios and SPM were used to develop simple algorithms, which will permit the quantification of SPM in the Gironde and Loire Estuaries from SPOT, Landsat, and SeaWiFS satellite data previously corrected for atmospheric effects. These algorithms are based on correspondence functions, which are the inversed

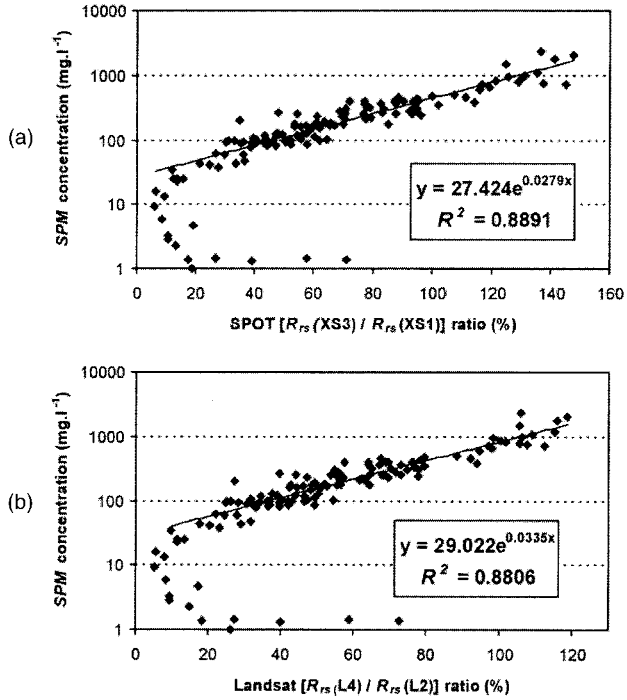

Fig. 9. Correspondence functions used to estimate SPM concentrations in the Gironde Estuary from reflectance ratios measurements in (a) SPOT bands [R_{rs}(XS3)/R_{rs}(XS1)] and (b) Landsat bands [R_{rs}(L4)/R_{rs}(L2)]. The best correlated function obtained for SPM concentration in the range (15–2500 mg l^{-1}) is plotted on the graphs.

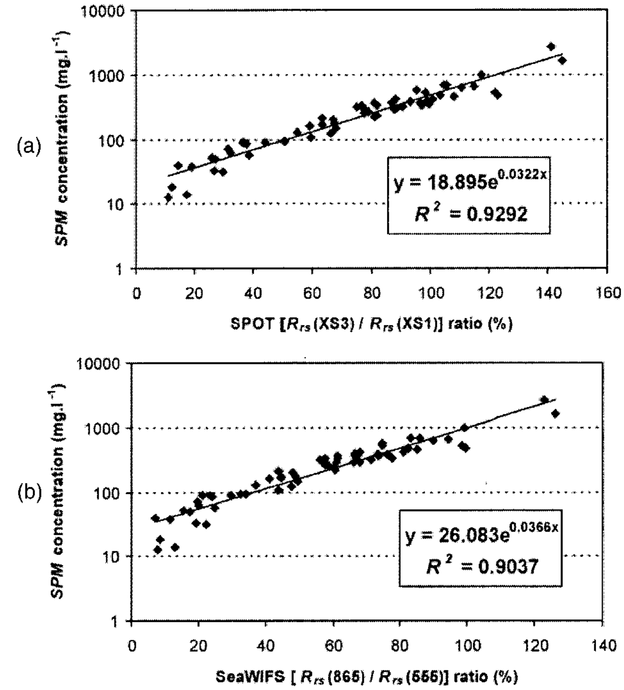

Fig. 10. Correspondence functions used to estimate SPM concentrations in the Loire Estuary from reflectance ratios measurements in (a) SPOT bands [R_{rs}(XS3)/R_{rs}(XS1)] and (b) SeaWiFS bands [R_{rs}(855)/R_{rs}(555)]. The best correlated function obtained for SPM concentration in the range [10–2600 mg l^{-1}] is plotted on the graphs.

established empirical relationships. In the Gironde the presented correspondence functions are based on the R_{rs}(XS3)/R_{rs}(XS1) (SPOT bands) and the R_{rs}(L4)/R_{rs}(L2) (Landsat bands) ratios [see Figs. 9(a) and 9(b), respectively]. The SPOT and Landsat sensors were selected because their high spatial resolutions (20 and 30 m, respectively) are well adapted to the confined area of the estuary. In both cases, these ratios allow an accurate estimation of SPM concentrations in the range of 15–2500 mg l^{-1}, which are concentrations usually found in surface waters of the estuary, according to an exponential relationship obtained with a high coefficient of determination (R^2 = 0.89 for SPOT; R^2 = 0.88 for Landsat). As the obtained relationships include all measurements carried out in the estuary from 1996 to 2001, they can be used to quantify the SPM from SPOT and Landsat satellite data independently of their date of acquisition, at least during this 6-yr period.

However, it must be noted that these relationships are not yet valid when SPM concentrations are lower than 10 mg l^{-1}, as the R_{rs} signal in the near infrared is close to zero. Consequently, points with a SPM concentration of less than 10 mg l^{-1}, which is not usually the case in the estuary, have not been used to determine the correspondence functions.

In the Loire the presented correspondence functions are based on the R_{rs}(XS3)/R_{rs}(XS1) (SPOT bands) and the R_{rs}(865)/R_{rs}(555) (SeaWiFS bands) ratios [see Figs. 10(a) and 10(b), respectively]. SPOT and SeaWiFS spatial resolutions (20 and 1 km) are adapted to the confined inner part and the large mouth of the estuary, respectively. As in the Gironde, the obtained correspondence functions are exponential with a high coefficient of determination (R^2 = 0.92 for SPOT; R^2 = 0.91 for SeaWiFS), which may allow an accurate estimation of SPM from remote-sensing data recorded from February to March 2002.

6. Conclusions

Numerous reflectance (R_{rs}) measurements have been carried out in the highly turbid waters of the Gironde and Loire Estuaries. Spectral signatures of these estuarine waters dominated by suspended sediments have been determined and analyzed. It was observed that the R_{rs} signal was influenced by variations of the IOPs and by changing illumination conditions (clear or overcast sky). As a consequence, it was difficult to establish invariant empirical relationships between R_{rs} and SPM, which would be robust to estimate concentrations from remote-sensing data. However, relationships with high correlations were obtained between reflectance ratios of near-infrared and visible bands and SPM. In fact, these reflectance ratios were almost insensitive to variations of sediment type that occur in estuaries and to changing illumination conditions. As a result, invariant relationships were established between reflectance ratios and SPM, including all measurements carried out in the Gironde Estuary during a 6-yr period. Correspondence functions were established from these invariant empirical relationships. They allow an accurate estimation of SPM concentrations in the Gironde Estuary from spatial remote sensing (SPOT and Landsat) data independently of their date of acquisition, which was the objective of the study. Similar results were obtained in the Loire Estuary, in which equivalent correspondence functions for the SPOT sensor and SeaWiFS were established, allowing an accurate quantification of suspended sediments within surface waters from remote-sensing data recorded from February to April 2002. Moreover, it was observed from measurements carried out in the Loire that the established functions were still valid when the sky was overcast. This result is important because it means that *in situ* measurements for satellite data calibration can be carried out regardless of the illumination conditions.

From our measurements, it was observed that the amplitude of the R_{rs} signal significantly varied with the illumination conditions (clear blue sky or overcast sky). These results highlight the difficulties encountered with the above-water reflectance measurements, notably concerning the correction of surface reflection effects. Simultaneous measurements of upwelling radiance just beneath the surface and above the surface in turbid sediment-dominated waters are needed for a conclusion. Moreover, improved modeling and field measurements are needed to determine the bidirectional aspects of reflectance (variations of the f and Q factors) in such turbid waters. In this study, these difficulties have been partly eliminated by consideration of reflectance ratios. Accurate and robust calibration relationships for satellite data have been established in two similar estuarine environments: the Gironde and the Loire. The validity of these relationships may now be tested in turbid coastal waters presenting different sediment characteristics (grain size and mineralogy).

In forthcoming studies the established correspondence functions will be applied to satellite images from the Gironde and Loire Estuaries to retrieve instantaneous horizontal distributions of suspended sediments and observe the seasonal movements of the turbidity maximum. This kind of information will be helpful for calibration and validation of numerical transport models.

This paper was supported by the Unité Mixte de Recherche 13 (Institut Français de Recherche pour la Mer, Université Bordeaux 1) and by Programme National d' Environnement Côtier–Atlantique, an oceanographic coastal French program. We express particular thanks to M. Staebler and V. Deshoux from the Cellule de Mesures et Bilans (CMB) de la Loire estuarienne (CMB, Nantes) and to L. Vilaine for their contributions to field measurements in the Loire estuary.

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