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# Regional bio-optical relationships and algorithms for the Adriatic Sea, the Baltic Sea and the English Channel/North Sea suitable for ocean colour sensors

JEAN-FRANCOIS BERTHON, GIUSEPPE ZIBORDI, DIRK VAN DER LINDE, ELISABETTA CANUTI, ELIF EKER-DEVELI

Institute for Environment and Sustainability

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# Abstract

Regional bio-optical relationships and empirical algorithms were developed on the basis of measurements collected during the CoASTS 1995-2005 bio-optical time-series in the northern coastal Adriatic Sea as well as during ship campaigns performed in coastal regions of the Adriatic Sea, the Baltic Sea and the English Channel/North Sea between 2000 and 2005. The empirical algorithms aim at the retrieval from ocean colour data of the Chlorophyll *a* and Total Suspended Matter concentrations, of the absorption coefficient of the Coloured Dissolved Organic Matter, of the diffuse attenuation coefficient of downwelling irradiance and of the Secchi depth. Bio-optical relationships relating the marine optically significant components to their absorption or scattering properties are also presented for the investigated coastal areas.

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## Introduction

The Inland and Marine Waters Unit, within the institutional activities, is committed in the development of indicators for monitoring the status of the marine ecosystem. Among these, the phytoplankton biomass is one of the most relevant for the study of the marine ecosystems. It is typically approximated by quantifying the chlorophyll *a* concentration (Chla), the main phytoplankton photosynthetic pigment. Other relevant indicators are the Total Suspended Matter (TSM) and Colored Dissolved Organic Matter (CDOM). Methods ("algorithms") are thus necessary in order to retrieve an estimation of the marine constituents (Chla and others) at the synoptic scale from the remotely sensed optical signals in coastal waters.

Among those methods the simplest is represented by the empirical algorithms that statistically relate the marine constituents to the remotely sensed water leaving optical signal. Such relationships are intrinsically "local" or "regional" since they are based on "bio-optical" data sets collected in or simulated for a particular area and their application to other areas is obviously questionable. The "SeaBAM" OC algorithm series, a well known example of such relationship, was developed for the "SeaWiFS" sensor (NASA) and for the open ocean. Its failure when applied to coastal areas has often been demonstrated. Several degrees of complexity for such statistics are available, from the simple and traditional linear regression to the more recent "neural networks" and derived techniques.

A second class of algorithm is represented by the more universal "semi-analytical" approach adopting as intermediary step the retrieval of the water optical properties, the absorption and back-scattering coefficients, explaining the water leaving signal from the purely physical point of view. Further models are then needed to convert the optical property into a marine constituent (Chla, etc…).

## Objectives

The objectives of the sub-task 2.2 of the #2121-ECOMAR action are the development and the validation of regional algorithms for the Adriatic Sea and the Baltic Sea, in particular.

In the frame of the action 2003 work program, D'Alimonte *et al.* (2003a) developed a method to dynamically estimate the geographical domain of applicability of regional empirical algorithms dedicated to the retrieval of Chla. The conclusions showed that several regions within the European coastal waters were absolutely not represented by either the data set built for the SeaBAM algorithm or the one collected in the Adriatic Sea during the previous years (see Action work program 2003 and previous). Such waters are in particular the whole Baltic Sea and to some extent, the English Channel and North Sea.

Objectives of sub-task 2.2 thus included the collection of a bio-optical data set (ensuring the same methodology and data quality than the other data collected up to now) in the Baltic Sea, and potentially in the North Sea, for the development of regional algorithms.

## Summary of achievements

Development of the JRC reference bio-optical data set

A campaign was executed in April 2005 in the Baltic Sea in collaboration with the Institute of Oceanography (Polish academy of Sciences) in Sopot (Poland) and completed the Baltic Sea data set initiated in 2004. Seven measurement campaigns were performed onboard the "Acqua Alta" Oceanographic Tower (AAOT) off Venice in the northern Adriatic Sea and contributed to the JRC CoASTS bio-optical time-series started in July 1995.

A synthetic presentation of this data set is given in Section I.

Regional bio-optical models and empirical algorithms

Bio-optical models and empirical algorithms were developed on the basis of this reference bio-optical data set containing also data from the northern Adriatic Sea and English Channel and North Sea ship campaigns performed in 2000 and 2004, respectively. A synthesis of these developments is provided in Section I.

Specific campaigns of the CoASTS time-series were also dedicated to particular experiments in 2004 and 2005: the measurements of the Volume Scattering Function (VSF), an important optical variable in the frame of bio-optical and radiative transfer modelling. Such experiments were conducted in collaboration with Drs. Lee and Shybanov from the Marine Hydrophysical Institute in Sevastopol (Ukraina). The proceedings of a resulting joint presentation at the Optics of Natural Waters Conference 2005 in Saint-Petersburg (Russia) are provided in Section II.

*Acknowledgments are due to Rosanna Passarella (JRC-IES-IMW) for her contribution to the laboratory absorption measurements.*

# SECTION I

# BIO-OPTICAL RELATIONSHIPS AND EMPIRICAL ALGORITHMS FOR THE ADRIATIC SEA, THE BALTIC SEA AND THE ENGLISH CHANNEL/NORTH SEA.

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## The JRC reference bio-optical data set in 2005

### Adriatic Sea

During the year 2005 7 measurement campaigns have been performed onboard the “Acqua Alta” Oceanographic Tower (AAOT) off Venice in the northern Adriatic Sea and contributed to the JRC CoASTS bio-optical time-series started in July 1995 and now made of a total of 1863 stations (figure 1, see the position of AAOT in figure 2).

The northern Adriatic data set also includes 55 stations performed during the “Adria2000” campaign in July 2000 (figure 2) onboard the Italian vessel “FVG” in collaboration with the Laboratorio di Biologia Marina in Trieste (Italy).

### Baltic Sea

In addition to the two campaigns executed in May and September 2004, a third campaign was executed in April 2005 in the Baltic Sea in collaboration with the Institute of Oceanography (Polish Academy of Sciences) in Sopot (Poland). These campaigns covered the Baltic Sea area between 54N/14E and 56N/20E (see figure 3), for a total of 167 measurement stations.

### English Channel & North Sea

Using the same instrumentation a campaign was executed in June-July 2004 in collaboration with the Université du Littoral Côte d’Opale in Wimereux (France). It covered the french coast of the eastern English Channel and North Sea areas (figure 4), for a total of 55 stations.

In total and at the end of 2005, the JRC reference bio-optical data set is constituted by 2140 measurement stations within the European coastal area.

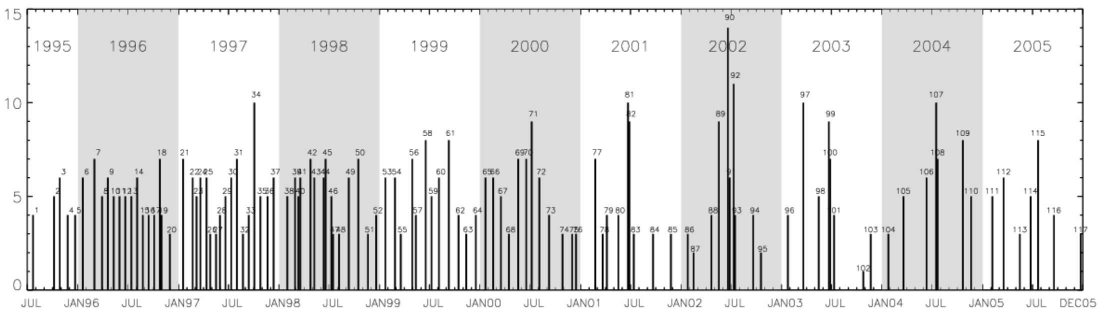


**Figure 1: CoASTS bio-optical time-series onboard the Acqua Alta Oceanographic Tower. The vertical bars indicate the number N of measurement stations per campaign.**

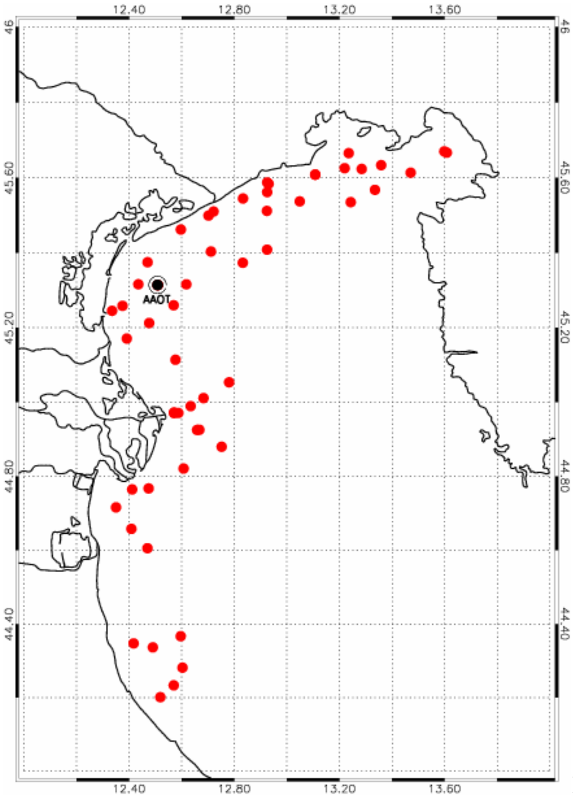


**Figure 2: Positions of stations during the July 2000 campaign (ADRIA2000) onboard the O. V. "FVG" (Laboratorio di Biologia Marina, Trieste, Italy). Black filled circle AAOT = position of the Acqua Alta oceanographic tower.**

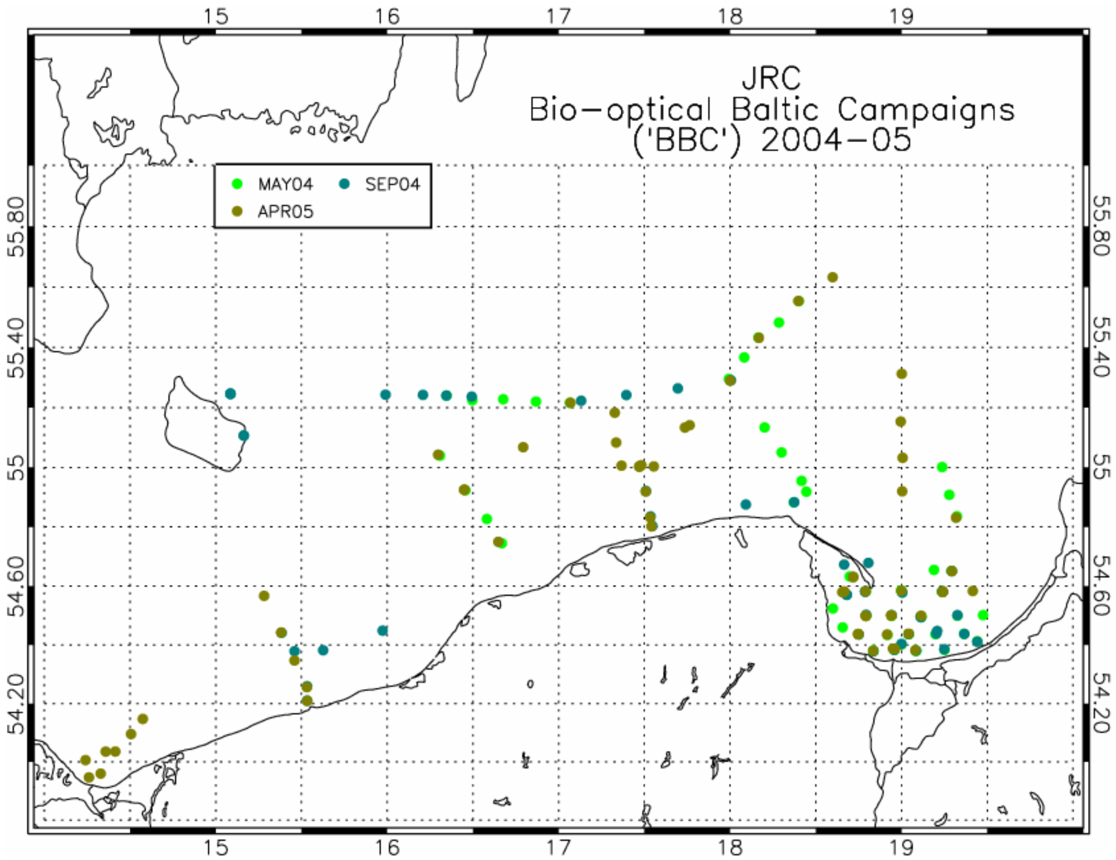


**Figure 3: Positions of stations during the May 2004, September 2004 and April 2005 campaigns onboard the O. V. "Oceania" (Polish Academy of Sciences, Sopot, Poland). Some stations were sampled during 2 or 3 campaigns.**

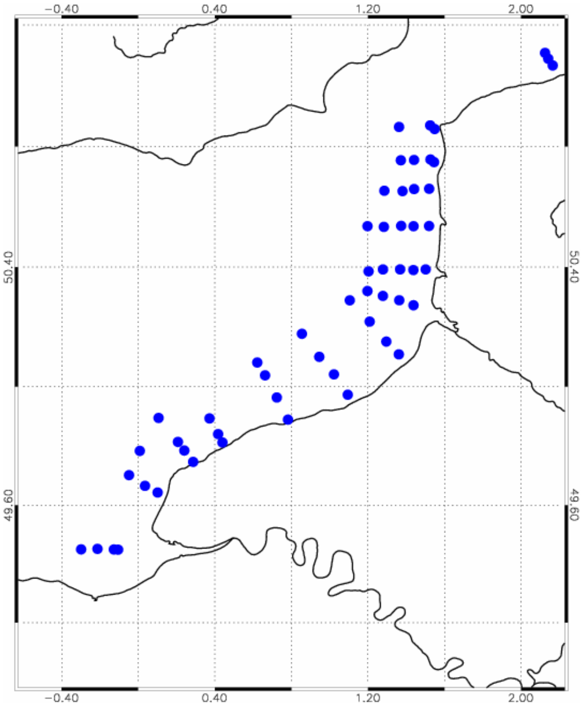

**Figure 4: Positions of stations during the June 2004 campaign onboard the O. V. "Côte de la Manche" (Université du Littoral Côte d'Opale, Wimereux, France).**

Each measurement station consituting the reference data set included:

*Underwater vertical profiles of:*

- up-welling radiance $L_u(\lambda)$, downward irradiance $E_d(\lambda)$ and upward irradiance $E_u(\lambda)$ at 7 wavelengths $\lambda$ in the 400-700 nm spectral range (required for the determination of subsurface radiometric values and apparent optical properties);
- absorption $a(\lambda)$ and beam attenuation $c(\lambda)$ coefficients at 9 wavelengths between 400 and 750 nm;
- backscattering coefficients $b_b(\lambda)$ at 6 wavelengths between 400 and 700 nm;
- temperature and salinity;

*Water samples for the determination of:*

- phytoplankton pigments concentration (HPLC);
- total suspended matter concentration;
- pigmented and non pigmented particles absorption coefficients, $a_{ph}(\lambda)$ and $a_{dp}(\lambda)$, between 400 and 750 nm with a 1 nm resolution;
- colored dissolved organic matter absorption coefficient, $a_{ys}(\lambda)$, between 350 and 750 nm with a 1 nm resolution;

*Sun-photometric measurements*

*Meteorological observations*

All the measurements were performed and processed using the same instrumentation and following the same protocols and post-processing methods.

## Bio-Optical characteristics of the different investigated European coastal areas.

In this part, a synthetic presentation of the bio-optical characteristics and relationships for the different investigated coastal areas is provided.

Surface spectral reflectance

The “just below” surface reflectance $R(0^-)$ is defined as the ratio of the upwelling to down-welling irradiances just beneath the water surface, $E_u(0^-)/E_d(0^-)$). It can be derived from the top of atmosphere radiances measured by an ocean colour satellite sensor.

Moreover, it can be related to the inherent properties of the water, namely, the back-scattering coefficient $b_b$ and the absorption coefficient a, according to (wavelength dependence is not made explicit):

$$R = f\ b_b/[a + b_b] \qquad (1)$$

The reflectance is thus the optical expression, detectable from the surface, of the water content and the quantity from which the marine indicators can be retrieved, after a proper inversion.

Figure 5 presents the spectral characteristics of surface reflectance measured in the different European coastal areas investigated. Both the spectra in absolute or normalized (with respect to the value at 555 nm) values are differing from a basin to another. Spectra measured at the AAOT site off Venice in the northern Adriatic Sea (in black) show large maximum laying between 490 and 555 nm and absolute values at 412 nm ranging between 0.02 and 0.12 (2 and 12 %). Spectra measured during the Adria2000 campaigns (in red) in different areas of the northern coastal Adriatic Sea show similar characteristics. These waters generally show a reasonably balanced contribution of the main optical components present in the water and defining the leaving surface reflectance: phytoplankton pigments, the non pigmented particulate matter and the coloured dissolved organic matter, as commonly considered.

Differently, spectra measured in the Baltic Sea show generally lower absolute values, in particular in the blue region (from 0.005 to 0.02), as well as maxima almost always located at 555 nm. This is explained by the very large contribution to the absorption in the blue by the coloured dissolved organic matter reaching important quantities in these waters. Up to now, such spectra were poorly represented in the JRC reference data used for the empirical algorithms development (see D'Alimonte *et al.*, 2003a).

The English Channel and North Sea waters show intermediate situations between the Adriatic and Baltic waters, with relative spectral shape similar to the Baltic (maxima at 555nm due to dissolved and particulate detrital matter absorption in the blue although the slope of decreasing reflectance is lower) but relatively higher absolute values (probably due to a higher contribution to scattering by suspended mineral particles).

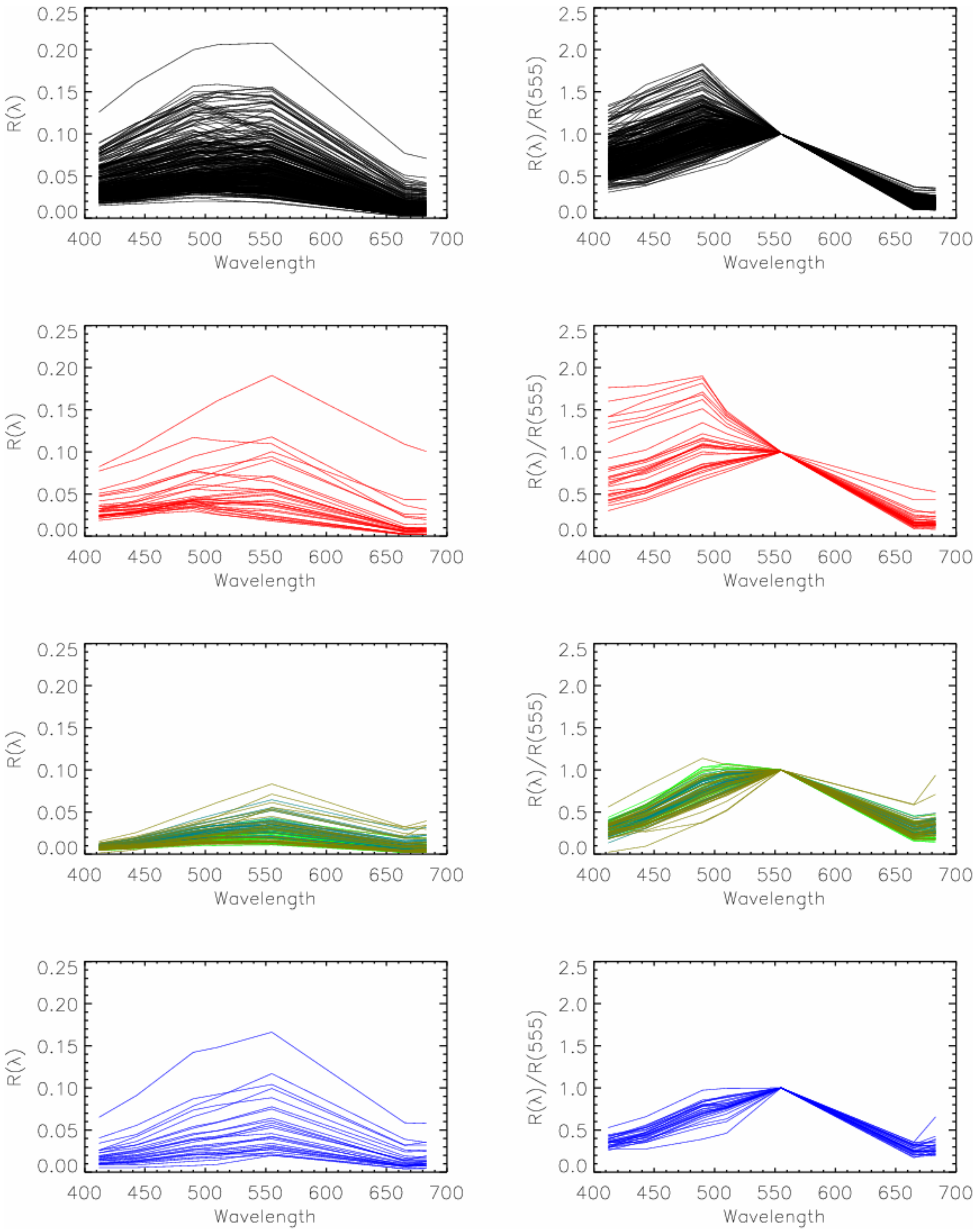


**Figure 5: Below surface (0-) reflectance spectra in absolute values, R(λ), and normalized with respect to the value at 555 nm, R(λ)/R(555) for all areas. The color meaning is as in figure 1, 2, 3, 4: black for AAOT 1995-2005, red for Adria2000, light green for Baltic May 2004, dark green for Baltic September 2004, brown for Baltic April 2005 and blue for English Channel/North Sea 2004.**

Inherent Optical  Properties (IOP): absorption and back-scattering

Figure 6 is synthesizing the different distributions of the main optical components by showing a ternary representation of their contribution to the absorption budget in the blue (412 and 443 nm). The key for reading the % value of each of the three components is the following:

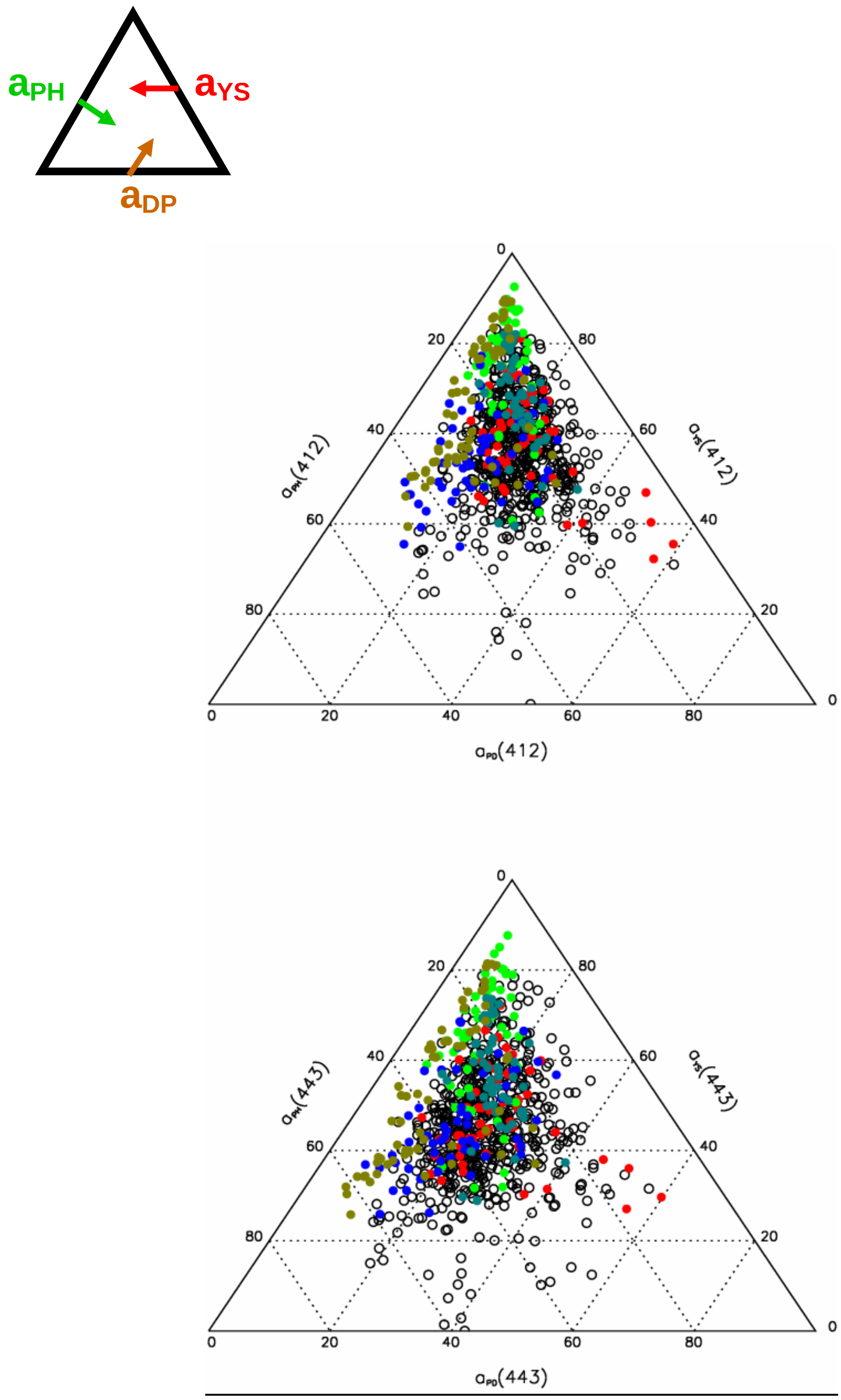


**Figure 6: Ternary plot (%) of the three main components of the absorption at 412 and 443 nm. PH=phytoplankton pigments, PD=non pigmented particulate matter ("detritus"), YS=coloured dissolved organic matter (Yellow Substances). The color meaning is: empty black circles for AAOT 1995-2005, red dots for Adria2000, light green dots for Baltic May 2004, dark green dots for Baltic September 2004, brown dots for Baltic April 2005 and blue dots for English Channel/North Sea 2004.**

.

For the Adriatic waters, the global distribution of the data show that the yellow substance (YS) absorption roughly represents 60 % percent of the total at 412 nm whereas each of the two other components represents 20%. In the Baltic waters the percentage of YS is globally 70-80%. At 443 nm and in the Adriatic Sea, the maximum of Chlorophyll *a* (and other phytoplankton pigments) absorption (PH) reaches the value of 30-40% whereas the YS represents 40-50% of the total. At the same wavelength the yellow substances in the Baltic Sea waters still represent 60 % of the total absorption, explaining the strong depression of the reflectance in the blue part of the spectrum (figure 5). English Channel and North Sea waters show, for the absorption, a behaviour that is rather similar to the Adriatic waters.

The inherent optical properties, physically determining the surface reflectance signal, can be related to the concentration of the different components contained in the waters. Figure 7 expresses this relationship for the absorption by phytoplankton pigments and the Chlorophyll *a* (Chla), the well known estimator of the phytoplankton biomass. Obviously, the variability observed in such a relationship is minimum at 443 and 665 nm ($r^2$ is equal to 0.82 and 0.84, respectively), the spectral position of the 2 absorption maxima of this pigment. At the other wavelengths, the PH absorption is mainly due to other pigments present in the cells, generally closely co-varying with the Chla.

The observed variability (the scattering of the points), even at 443 and 665, is the expression of the physiological differences due to the species composition (cell size and content of Chla per cell) and the environment variables, light and nutrients being the most important in this case. Table 1 presents the parameters of the fitted power function for each area investigated. The relationships established for the Baltic Sea show higher slopes than for the Adriatic but this is essentially due to the high concentrations found during one campaign. However, at first order, this relationship seems to remain quite stable from a basin to another and a single relationship could reasonably be used in order to retrieve the Chla from the $a_{PH}$ absorption, provided that this last be retrieved from satellite reflectance data (e.g. D´Alimonte and Zibordi, 2003b).

The retrieval of the total absorption from remote-sensing data is certainly an easier task than the above one (e.g. Loisel and Stramski, 2000). Thus, figure 8 presents the relationship between the total absorption (except pure water) and the Chlorophyll a (Chla) concentration. The goodness of these relationships is obviously reduced with respect to the previous ones involving $a_{PH}$ only (in particular for the Adriatic Sea, see $r^2$ in Table 2). Nevertheless, at 665 nm where the chlorophyll *a* shows an absorption maximum and where the influence of the particulate detritus and the yellow substance is reduced, the $r^2$ value amounts to 0.70. Table 2 presents the parameters of the fitted power function for each area investigated. Note the very good relationship still obtained for the Baltic Sea, in particular at 665 nm ($r^2 = 0.87$).

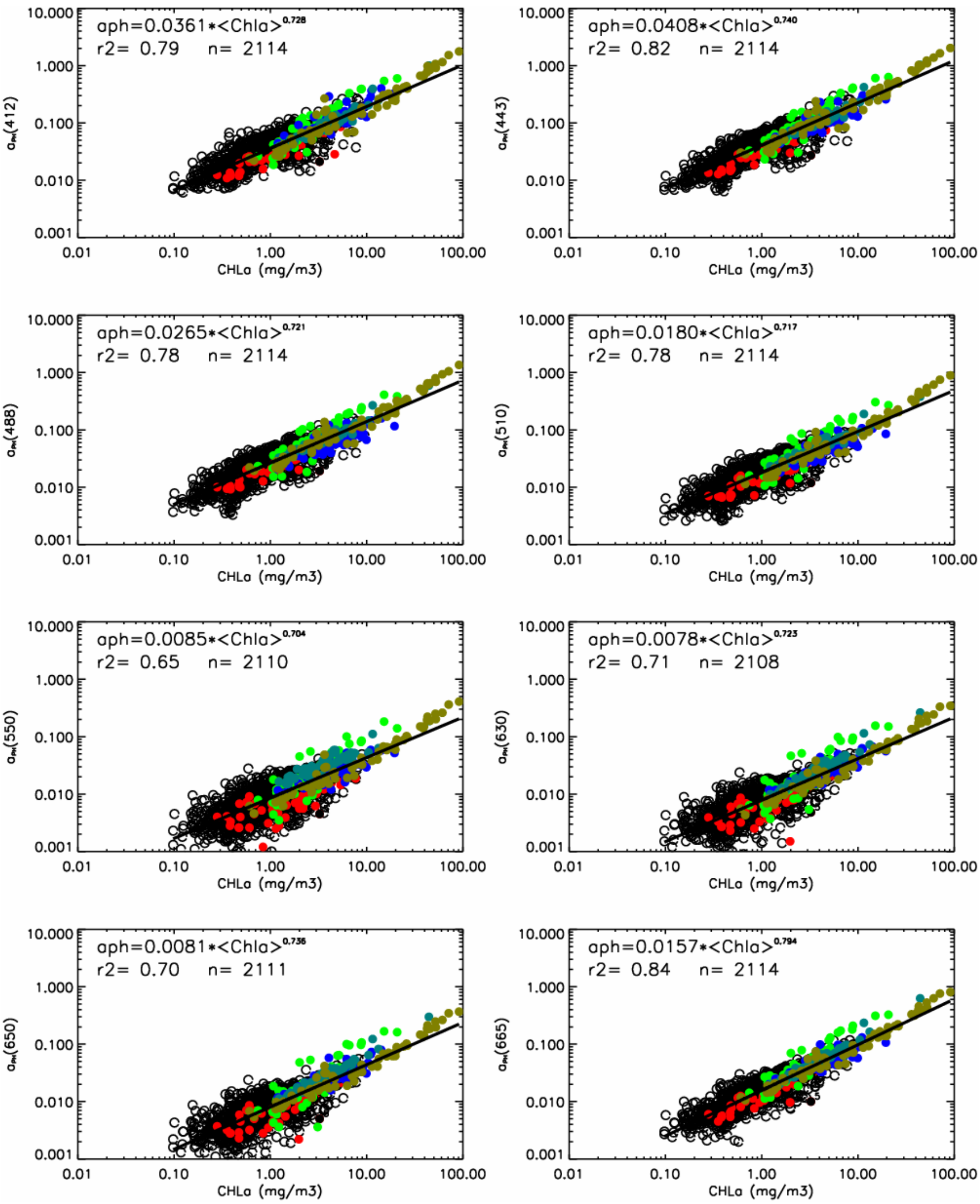


**Figure 7: Plot of the phytoplankton pigment absorption, $a_{ph}$, *versus* the Chlorophyll a absorption for 8 wavelengths. The black line represents the power function fitted on the data and indicated inside each panel, r2=determination coefficient, n=number of elements. Colors are as in Figure 6.**

**Table 1: Coefficients of the power function $a_{ph}(\lambda)=A0*Chla^{B0}$ fitted to the data collected in the different basins. N= number of elements, $r^2$=coefficient of determination.**

| | All Basins (N=2114) | | | Adriatic Sea (N=1896) | | | Baltic Sea (N=165) | | | Eng. Channel /North Sea (N=53) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Wav. | A0 | B0 | $r^2$ | A0 | B0 | $r^2$ | A0 | B0 | $r^2$ | A0 | B0 | $r^2$ |
| 412 | 0.0361 | 0.728 | 0.79 | 0.0358 | 0.689 | 0.69 | 0.0317 | 0.848 | 0.90 | 0.0383 | 0.707 | 0.69 |
| 443 | 0.0408 | 0.740 | 0.82 | 0.0407 | 0.720 | 0.73 | 0.0371 | 0.843 | 0.91 | 0.0366 | 0.699 | 0.75 |
| 488 | 0.0265 | 0.721 | 0.78 | 0.0265 | 0.704 | 0.69 | 0.0251 | 0.827 | 0.91 | 0.0198 | 0.691 | 0.76 |
| 510 | 0.0180 | 0.717 | 0.78 | 0.0180 | 0.691 | 0.68 | 0.0171 | 0.823 | 0.90 | 0.0152 | 0.672 | 0.76 |
| 550 | 0.0085 | 0.704 | 0.65 | 0.0084 | 0.636 | 0.49 | 0.0092 | 0.800 | 0.82 | 0.0087 | 0.632 | 0.69 |
| 630 | 0.0078 | 0.723 | 0.71 | 0.0077 | 0.664 | 0.57 | 0.0075 | 0.838 | 0.86 | 0.0095 | 0.622 | 0.74 |
| 650 | 0.0081 | 0.736 | 0.70 | 0.0079 | 0.668 | 0.55 | 0.0082 | 0.830 | 0.85 | 0.0102 | 0.636 | 0.72 |
| 665 | 0.0157 | 0.794 | 0.84 | 0.0155 | 0.758 | 0.76 | 0.0159 | 0.860 | 0.92 | 0.0185 | 0.652 | 0.75 |

Figure 9 and Table 3 present the relationship between another standard optical component of the coastal waters, the concentration of total suspended matter (TSM), and the back-scattering coefficient of particles, $b_{bp}$ (see equation 1). The back-scattering coefficient for natural populations of particles is generally spectrally neutral and no wavelength in particular is more indicated than another for such relationship (differently from the previous relationships). At the different wavelengths the slope of the linear relationship fitted on the data is almost identical except for the Adriatic Sea (Table 3) where the decrease of the slope from the blue to the red indicates a spectral dependence of $b_{bp}$. This last point could suggest that the average size of particles is lower in the northern Adriatic Sea than in the Baltic and English Channel/North Sea. Also, the slope of the relationship tends to decrease from the Adriatic Sea (0.011-0.014) to the Baltic Sea (0.007-0.008) and the English Channel/North Sea (0.006-0.007). In effect, the total suspended matter composition (also including the phytoplankton component) can be very variable regarding the particles size distribution and chemical nature (see above comment) from a coastal area to another and it may be more indicated to consider specific regional relationships once $b_{bp}$ has been retrieved from satellite data (for example using Loisel and Stramski, 2002).

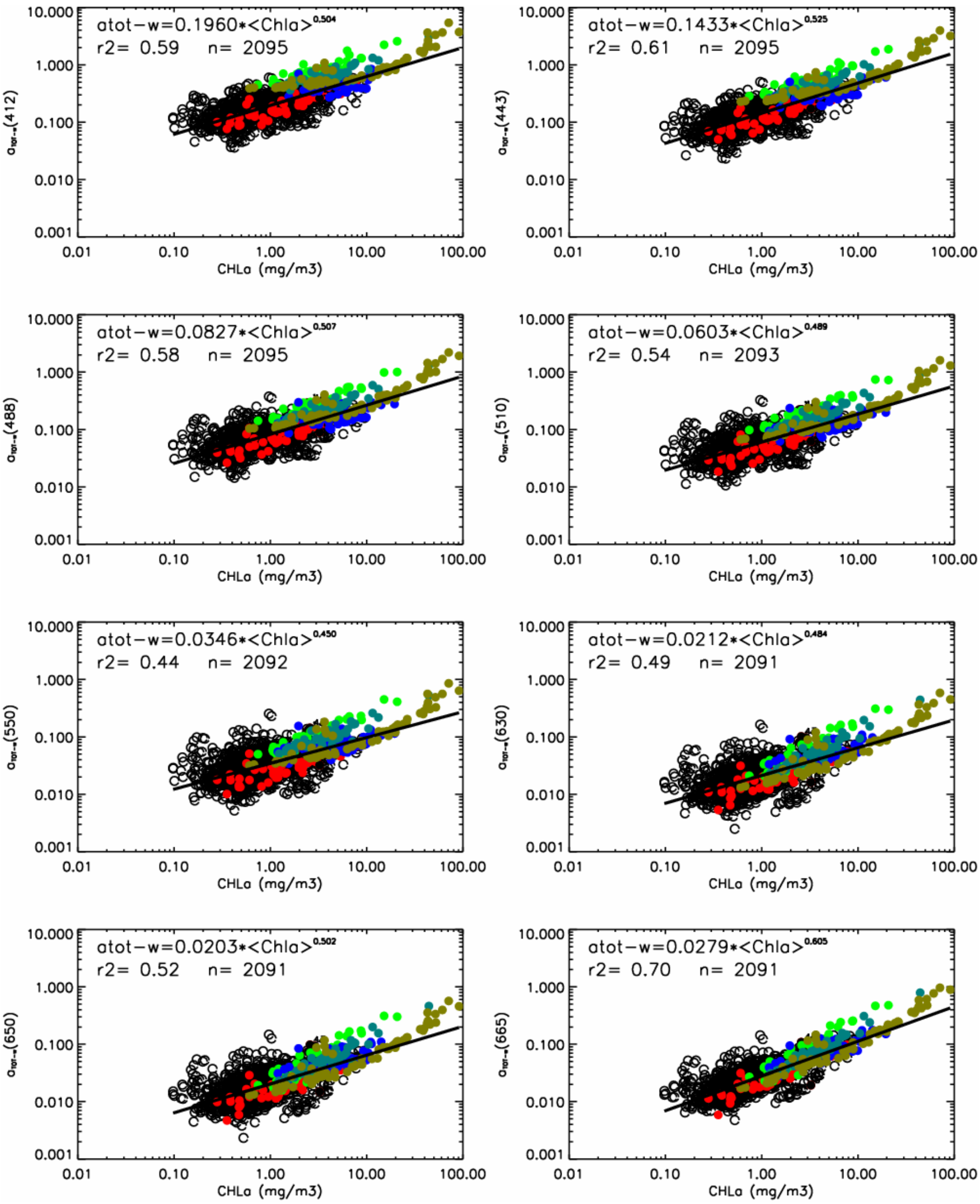


**Figure 8: Plot of the total (minus pure water) absorption, $a_{tot\text{-}w}$ for 8 wavelengths *versus* the Chlorophyll *a* concentration. The black line represents the power function fitted on the data and indicated inside each panel, r2=determination coefficient, n is the number of elements. Colors are as in figure 6.**

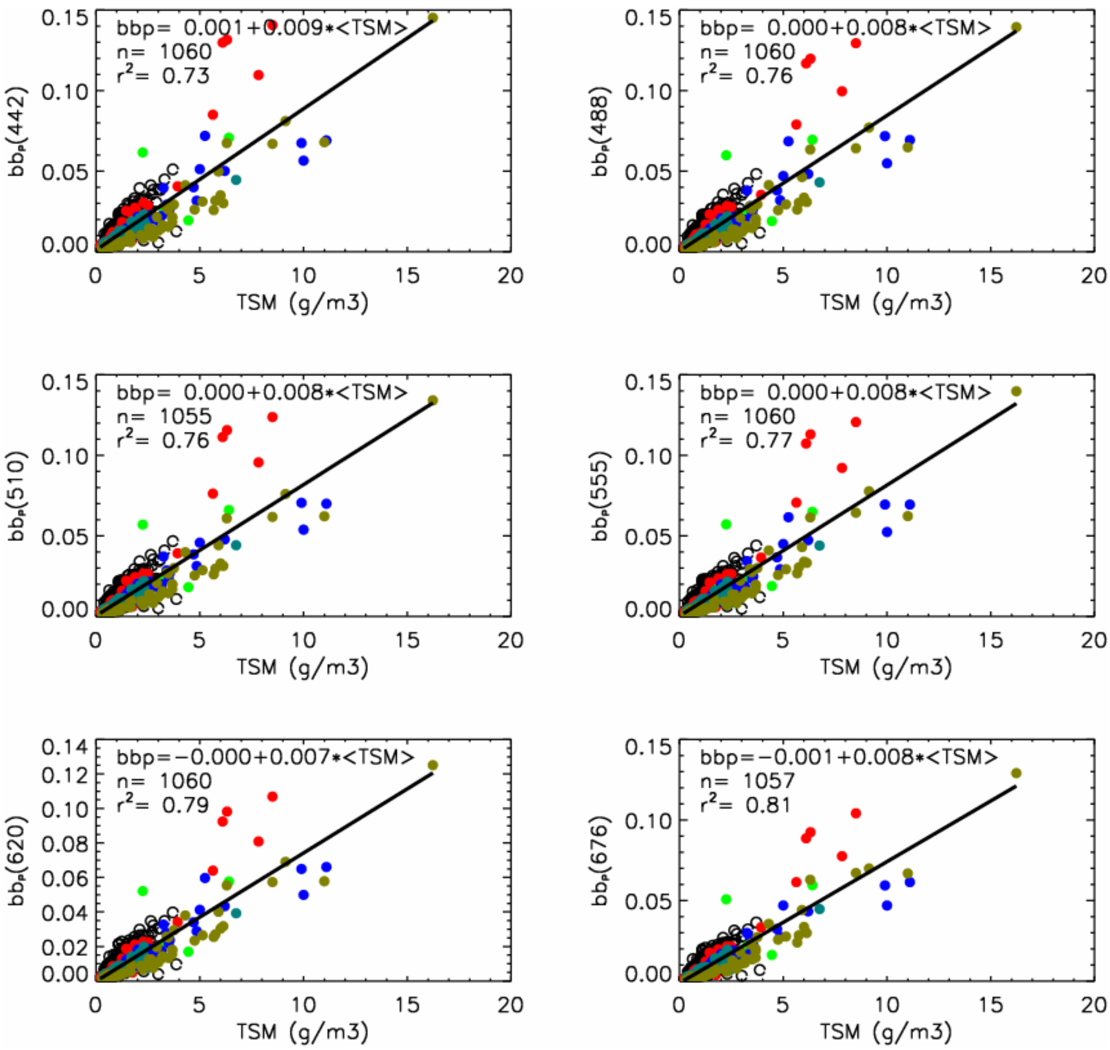


**Figure 9: Plot of the particulate back-scattering coefficient of particles, $b_{bp}$, at 6 wavelengths versus the concentration of Total Suspended Matter (TSM). The black line represents the linear function fitted on the data and indicated inside each panel. $r^2$=coefficient of determination, n=number of elements. Colors are as in Figure 6**.

**Table 2:Coefficients of the power function $a_{tot-w}(\lambda)$=A0*Chla$^{B0}$ fitted to the data collected in the different basins. N= number of elements, $r^2$=coefficient of determination.**

| | All Basins (N=2095) | | | Adriatic Sea (N=1877) | | | Baltic Sea (N=165) | | | Eng. Channel /North Sea (N=53) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Wav. | A0 | B0 | $r^2$ | A0 | B0 | $r^2$ | A0 | B0 | $r^2$ | A0 | B0 | $r^2$ |
| 412 | 0.1960 | 0.504 | 0.59 | 0.1850 | 0.371 | 0.40 | 0.3902 | 0.418 | 0.72 | 0.3256 | 0.202 | 0.18 |
| 443 | 0.1433 | 0.525 | 0.61 | 0.1366 | 0.410 | 0.43 | 0.2420 | 0.489 | 0.79 | 0.2163 | 0.249 | 0.27 |
| 488 | 0.0827 | 0.507 | 0.58 | 0.0794 | 0.403 | 0.38 | 0.1194 | 0.532 | 0.81 | 0.1163 | 0.242 | 0.25 |
| 510 | 0.0603 | 0.489 | 0.54 | 0.0580 | 0.383 | 0.33 | 0.0828 | 0.533 | 0.78 | 0.0872 | 0.236 | 0.23 |
| 550 | 0.0346 | 0.450 | 0.44 | 0.0332 | 0.334 | 0.23 | 0.0448 | 0.523 | 0.71 | 0.0516 | 0.225 | 0.18 |
| 630 | 0.0212 | 0.484 | 0.49 | 0.0206 | 0.381 | 0.57 | 0.0207 | 0.651 | 0.77 | 0.0300 | 0.344 | 0.37 |
| 650 | 0.0203 | 0.502 | 0.52 | 0.0197 | 0.396 | 0.31 | 0.0197 | 0.670 | 0.79 | 0.0281 | 0.39 | 0.42 |
| 665 | 0.0279 | 0.605 | 0.70 | 0.0273 | 0.524 | 0.53 | 0.0265 | 0.760 | 0.87 | 0.0353 | 0.483 | 0.59 |

**Table 3: Coefficients of the linear function $b_{bp}(\lambda)$=A0+B0*TSM fitted to the data collected in the different basins. N= number of elements, $r^2$=coefficient of determination.**

| | All Basins (N=1060) | | | Adriatic Sea (N=841) | | | Baltic Sea (N=164) | | | Eng. Channel /North Sea (N=55) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Wav. | A0 | B0 | $r^2$ | A0 | B0 | $r^2$ | A0 | B0 | $r^2$ | A0 | B0 | $r^2$ |
| 442 | 0.001 | 0.009 | 0.73 | -0.003 | 0.014 | 0.83 | -0.001 | 0.008 | 0.86 | 0.002 | 0.007 | 0.84 |
| 488 | 0.000 | 0.008 | 0.76 | -0.003 | 0.013 | 0.82 | -0.001 | 0.007 | 0.87 | 0.001 | 0.007 | 0.87 |
| 510 | 0.000 | 0.008 | 0.76 | -0.003 | 0.013 | 0.82 | -0.001 | 0.007 | 0.87 | 0.001 | 0.007 | 0.92 |
| 555 | 0.000 | 0.008 | 0.77 | -0.003 | 0.012 | 0.82 | -0.001 | 0.007 | 0.88 | 0.000 | 0.007 | 0.89 |
| 620 | 0.000 | 0.007 | 0.79 | -0.003 | 0.011 | 0.81 | -0.001 | 0.007 | 0.88 | 0.000 | 0.006 | 0.89 |
| 676 | 0.001 | 0.008 | 0.81 | -0.004 | 0.011 | 0.81 | -0.003 | 0.007 | 0.89 | 0.001 | 0.006 | 0.81 |

## Regional empirical algorithms for Chlorophyll *a* retrieval from Ocean Colour data

As previously said, empirical algorithm linking the satellite measured reflectance to the water content, e.g. the Chla or the TSM concentrations, are the simplest. Their uncertainty include all the terms of variability previously seen: the respective contributions of the optically significant components (PH, DP, YS, …), the varying relationships between the inherent optical properties (a and $b_b$) and the corresponding concentrations of components (Chla, TSM, …). However, their simplicity may advocate for their use in an operational processing of satellite data at regional scale. Moreover, methods can be developed to identify their (spatial) domain of applicability and combine them to avoid spatial discontinuity (e.g. D'Alimonte *et al.*, 2003a).

Figure 10 presents, for the investigated areas, the classical relationship between the ratio of remote-sensing reflectance at 490 and 555 nm and the Chla concentration. Such relationship is the basis of the ocean color interpretation in open ocean waters (e.g. the well known OC2v4 developed at NASA for the interpretation of the ocean colour sensor SeaWiFS data), where the Chla concentration co-vary between the other components (TSM, CDOM, …). Such an algorithm has already being developed on the basis of the first three years of data collected at the AAOT site (Berthon and Zibordi, 2004) for the Adriatic waters (the dashed line in figure 10) and the resulting global uncertainty (43%) on the Chla retrieval is significantly lower than the one associated to the use of OC2v4 (dotted line) (see Mélin *et al.*, 2003, 2005).

In a similar way, a global algorithm (solid line in figure 10) has been derived using the data collected in the different investigated areas (including the Baltic Sea and the English Channel/North Sea):

$$Log10(Chla) = a0 + a1*R35 + a2*R35^2 + a3*R35^3 \quad (2)$$

with R35=Log10(R490/R555) and a0= 0.131, a1=-2.552, a2=1.770, a3=-4.577 Although some continuity is observable from the lowest concentrations of the Adriatic Sea (0.1 mg $m^{-3}$) to the highest ones found in the Baltic (85 mg $m^{-3}$), the global uncertainty is 60 % and it can be seen that the highest Chla concentrations will be severely underestimated, whereas the lowest will be overestimated. The distribution of the English Channel/North Sea data seems to be in the right continuity of the Adriatic one.

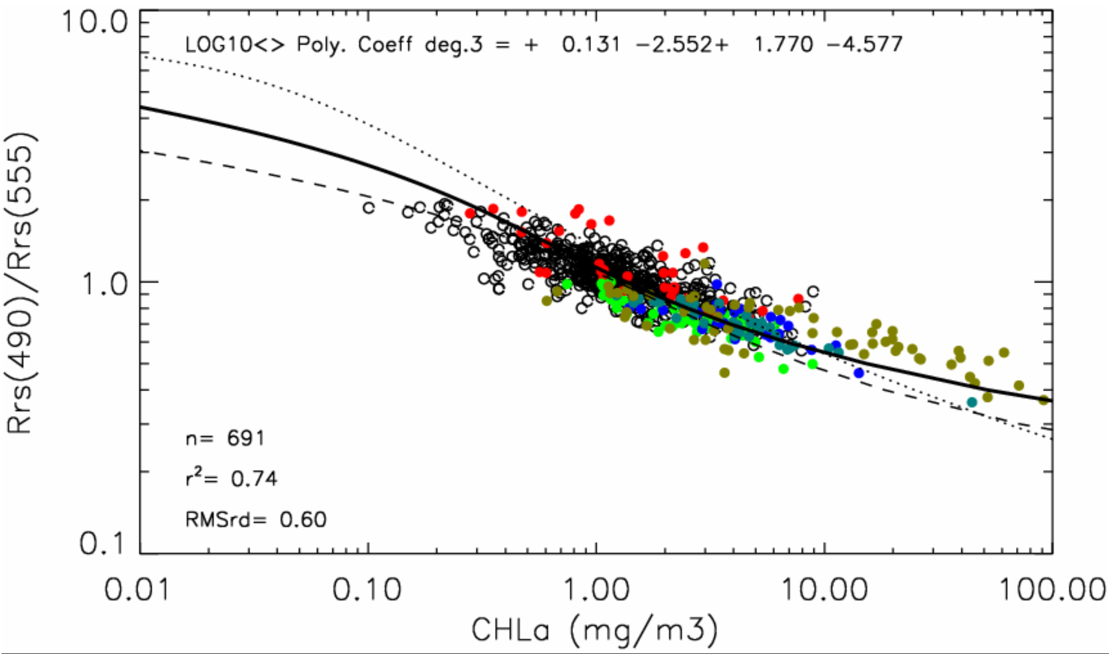


**Figure 10: Plot of the ratio of remote-sensing reflectances at 490 and 555 nm versus the concentration of Chlorophyll a. The black line represents the third grade polynomial function fitted on the whole data set and which coefficients are indicated inside the panel. $r^2$=coefficient of determination, RMSrd=Root Mean Square of relative difference, n=number of elements. The dashed line represents the AD2 algorithm for the northern Adriatic Sea (Berthon and Zibordi, 2004). The dotted line represents the SeaWiFS algorithm OC2v4. Colors are as in Figure 6.**

**Table 4: Coefficients of the polynomial or linear functions Chla=f R1/R2 used for the regional Chla algorithm development (see text and Eq. 2). $r^2$=coefficient of determination, RMSrd=Root Mean Square of relative differences, N=number of elements.**

| Basins | a0 | a1 | a2 | a3 | $r^2$ | RMSrd | N |
|---|---|---|---|---|---|---|---|
| All 490/555 | 0.133 | -2.343 | 0.793 | -5.892 | 0.74 | 0.60 | 691 |
| Adriatic Sea 490/555 | 0.133 | -2.343 | 0.793 | -5.892 | 0.60 | 0.53 | 526 |
| Baltic Sea 490/555 | -0.016 | -4.106 | - | - | 0.65 | 0.82 | 140 |
| Baltic Sea 555/665 | 2.234 | -2.878 | - | - | 0.79 | 0.56 | 140 |
| Eng. Channel/North Sea 490/555 | 0.247 | -2.546 | - | - | 0.52 | 0.44 | 25 |

Figure 11 and Table 4 show and provide the coefficients of the regional algorithms developed for the Adriatic, the Baltic and the English Channel/North Sea waters using the same reflectance ratio (490/555). For the Baltic and the English Channel/North Sea a linear function actually gave better results than a third grade polynomial function as the range of Chla concentrations does not include the low concentrations of the Adriatic data set (where a curvature of the relationship is observable).

It has already been observed that a lot of information is contained in the red part of the spectrum, in particular at 665 nm (secondary peak of absorption by Chla). In effect, the reflectance ratio involving 555 and 665 nm gives much better results that the previous one for the Baltic Sea but not for the other basins. The relationship is presented in figure 12 and its parameters are given in Table 4. In this area of the visible spectrum the influence of the high concentrations of blue absorbing coloured dissolved organic matter (yellow substances) is considerably reduced. This is not the case for the English Channel/North Sea (as well as Adriatic Sea) waters probably because of the strong contribution to back-scattering in the whole spectrum by the non pigmented suspended matter.

Provided that the signal in the red can be retrieved with a reasonable uncertainty from satellite data such a relationship should preferably be used for the Baltic Sea.

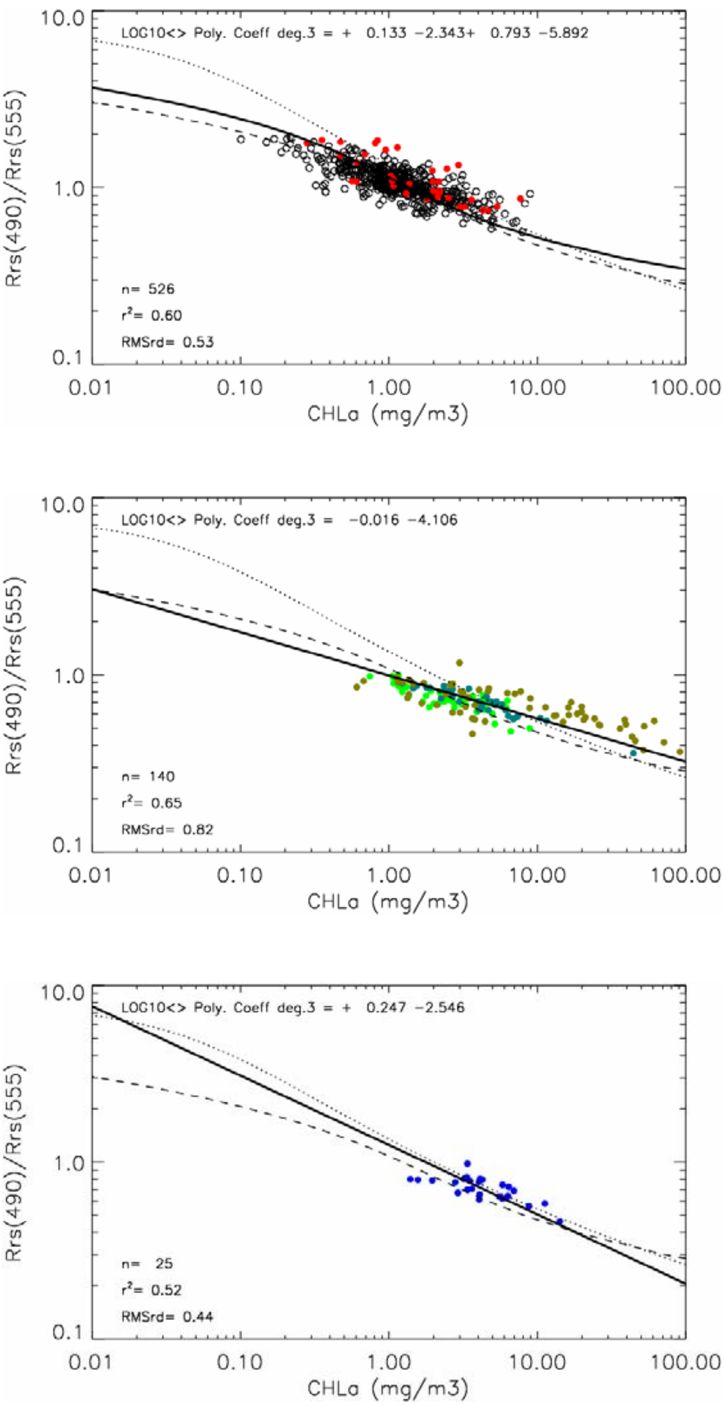


**Figure 11: As in figure 10 but for each of the three areas: Adriatic Sea, Baltic Sea, English Channel/North Sea. For the last two a linear function was chosen instead of a third grade polynomial function (solid lines).**

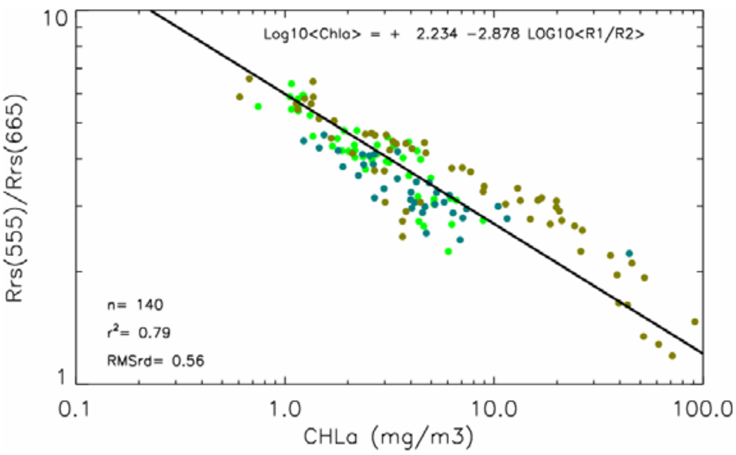


**Figure 12: As in figure 11 for the Baltic Sea and for the reflectance ratio 555/665.**

## Regional empirical algorithms for Total Suspended Matter (TSM) retrieval from Ocean Colour data

The Total Suspended Matter concentration in marine waters is also an indicator of interest and can be related to water turbidity. Obviously, Chlorophyll *a* and other pigments (phytoplankton) are included in this component but their corresponding concentrations only contribute for a very small amount to the TSM concentration.

Figure 13 presents, for the investigated areas, the relationship between the remote-sensing reflectance ratio at 510 and 665 nm and the TSM concentration. Such ratio was already observed to provide the best estimation of TSM for the northern Adriatic waters (Berthon *et al.*, 2002). It is evident that Baltic waters are not well represented by a global algorithm as they show significantly lower ratio of reflectance for the same TSM. Such low ratios are induced by the reinforced absorption by CDOM in the blue but also in the green part of the spectrum (510 nm).

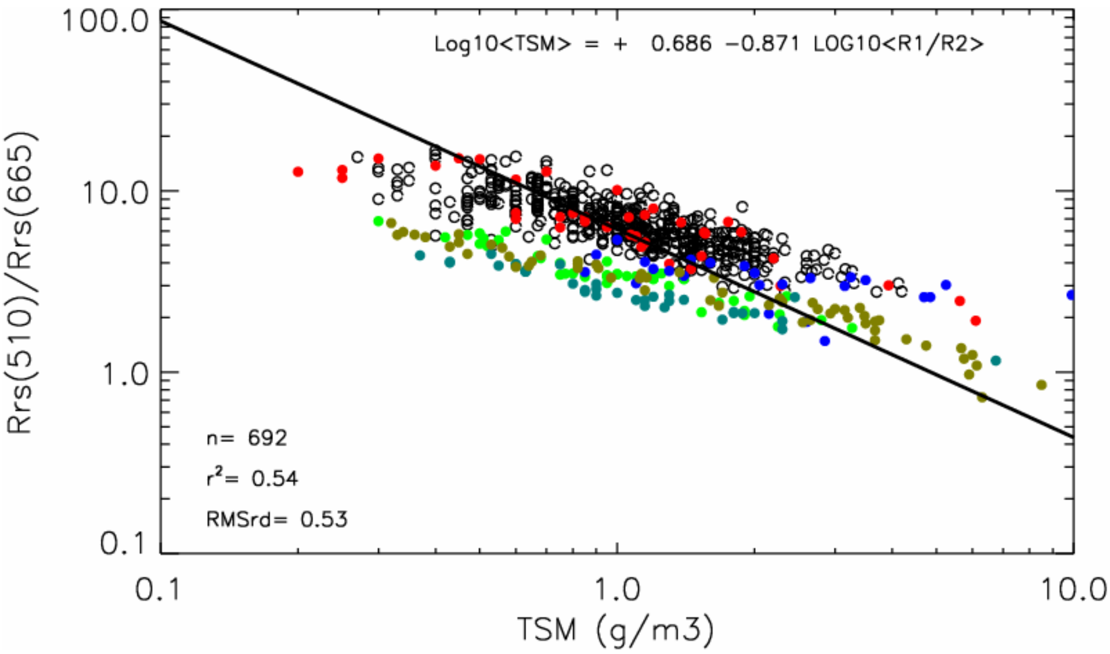


**Figure 13: Plot of the ratio of remote-sensing reflectance at 510 and 665 nm versus the concentration of Total Suspended Matter. The black line represents the linear function fitted on the whole data set and which coefficients are indicated inside the panel. $r^2$=coefficient of determination, RMSrd=Root Mean Square of relative difference; n=number of elements. Colors are as in Figure 6.**

Table 5 presents the coefficients of the regional algorithms. Note the reduction in uncertainty ($r^2$ and RMSrd) for each specific algorithm with respect to the global one. For the particular case of the English Channel/North Sea - small - data set the use of the 412/665 reflectance ratio results in much better performances.

**Table 5: Coefficients of the linear functions Log10(TSM)=a0+a1*Log10(R1/R2) used for the regional TSM algorithm development (see text). $r^2$=coefficient of determination, RMSrd= Root Mean Square of relative differences, N = number of elements.**

| Basins | a0 | a1 | $r^2$ | RMSrd | N |
|---|---|---|---|---|---|
| All 510/665 | 0.686 | -0.871 | 0.54 | 0.53 | 692 |
| Adriatic Sea 510/665 | 0.963 | -1.157 | 0.67 | 0.34 | 527 |
| Baltic Sea 510/665 | 0.869 | -1.665 | 0.90 | 0.27 | 140 |
| Eng. Channel/North Sea 510/665 | 0.948 | -1.238 | 0.30 | 0.51 | 25 |
| Eng. Channel/North Sea 412/665 | 0.557 | -1.531 | 0.64 | 0.40 | 25 |

## Regional empirical algorithms for Coloured Dissolved Organic Matter (CDOM) retrieval from Ocean Colour data

Figure 14 presents the relationship between the remote-sensing reflectance ratio at 412 and 665 nm and the CDOM absorption coefficient at 400 nm (a classical optical estimator of the concentration of colored dissolved organic material). On this figure one can easily distinct the three classes of CDOM absorption intensity: 0.05-0.4 $m^{-1}$ for the northern Adriatic Sea, 0.2-0.5 $m^{-1}$ for the English Channel/North Sea and 0.5-2 $m^{-1}$ for the "CDOM rich" Baltic Sea waters.

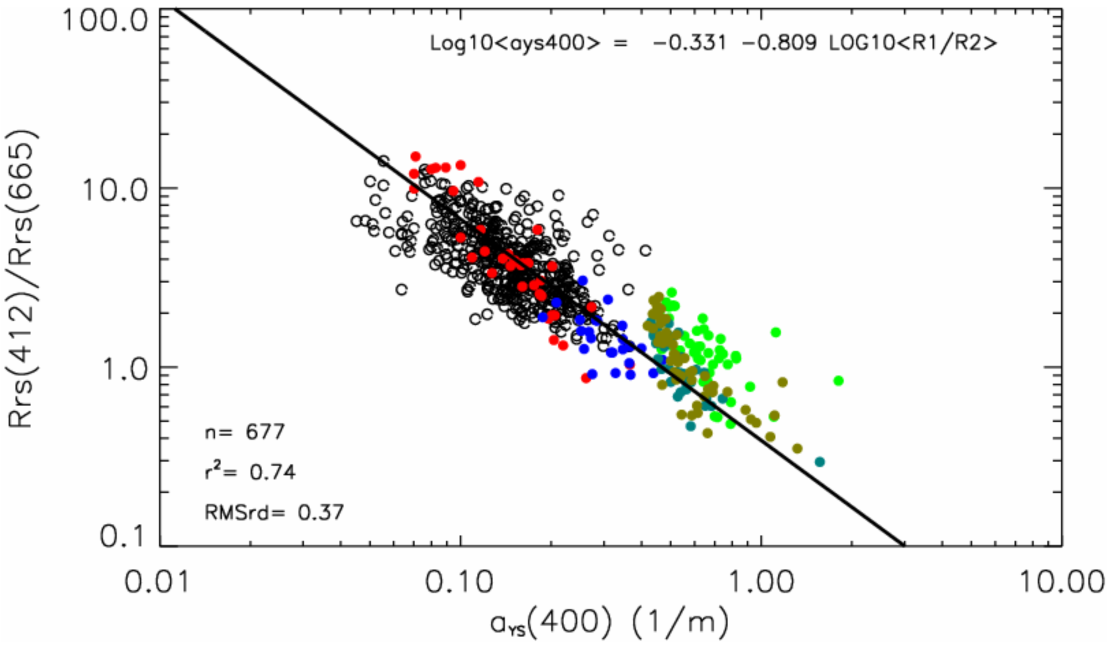


**Figure 14: Plot of the ratio of remote-sensing reflectance at 412 and 665 nm versus the absorption of CDOM ($a_{YS}$) at 400 nm. The black line represents the linear function fitted on the whole data set and which coefficients are indicated inside the panel. $r^2$=coefficient of determination, RMSrd=Root Mean Square of relative difference; n=number of elements. Colors are as in Figure 6.**

The global relationship shows a better $r^2$ than the individual regional relationships proposed in Table 6 due to the increased total range of absorption values. The use of the reflectance ratio 412/555 nm provided very similar performances for the northern Adriatic Sea waters but degraded performances for the Baltic and English Channel/North Sea waters. In these last the residual absorption by CDOM in the green part of the spectrum is probably still strong.

**Table 6: Coefficients of the linear function Log10($a_{YS}$(400))=a0+a1*Log10(R1/R2) used for the regional CDOM algorithm development (see text). $r^2$ = coefficient of determination, RMSrd= Root Mean Square of relative differences, N = number of elements.**

| Basins | a0 | a1 | $r^2$ | RMSrd | N |
|---|---|---|---|---|---|
| All 412/665 | -0.331 | -0.809 | 0.74 | 0.37 | 677 |
| Adriatic Sea 412/665 | -0.531 | -0.522 | 0.45 | 0.31 | 517 |
| Baltic Sea 412/665 | -0.215 | -0.375 | 0.41 | 0.19 | 135 |
| Eng. Channel/North Sea 412/665 | -0.441 | -0.441 | 0.38 | 0.18 | 25 |

## Regional empirical algorithms for the diffuse attenuation coefficient ($K_{Ed}$) retrieval from Ocean Colour data

Figure 15 presents, for the investigated areas, the relationship between the ratio of normalized water-leaving radiances $L_{WN}(490)/L_{WN}(555)$ and the diffuse attenuation coefficient for downwelling irradiance $K_{Ed}(490)$ computed for the optically homogeneous surface layer. $L_{WN}$, as the reflectance, is an apparent optical property and can be retrieved (even more directly than reflectance) from the top of atmosphere radiance data. The corresponding global algorithm, suggested from the SeaWiFS algorithm (Mueller 2000) for open ocean applications, is the following:

$$K_{Ed}(490) = 0.016 + 0.193\,[nL_w(490)/nL_w(555)]^{-1.856} \qquad (3)$$

where 0.016 $m^{-1}$ is the constant value of $K_{Ed}(490)$ for "pure" water (adopted by Mueller 2000). As previously seen for other bio-optical relationships, the Baltic Sea waters show a distinct behaviour and strongly contribute to the increase of the exponent from -1.785 for the Adriatic waters (close to the -1.754 found by Berthon and Zibordi, 2004 for the same waters) to -1.856 (see Table 7). The exponent for the Baltic Sea waters alone is equal to -2.548 and again can be explained by a persistent significant contribution of the colored dissolved organic mater at 490 and 555 nm. It must also be said that the uncertainty in the retrieval of $L_{WN}$ and $K_{Ed}$ can be reinforced in situations of strong subsurface stratification often encountered in the Baltic coastal waters.

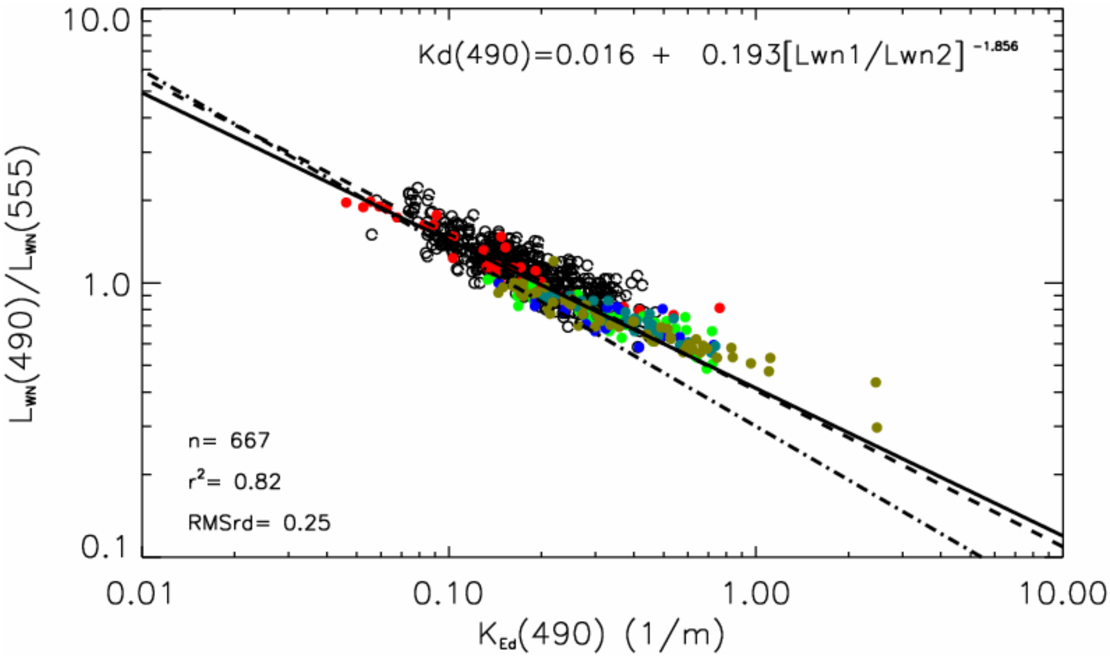


**Figure 15: Plot of the ratio of normalized water leaving radiances $L_{WN}$ at 490 and 555 nm *versus* the diffuse attenuation coefficient ($K_{Ed}$) at 490 nm. The black line represents the power function fitted on the whole data set ($r^2$ = coefficient of determination, RMSrd= Root Mean Square of relative differences, N = number of elements) whereas the dashed and dotted-dashed lines represents the relationships developed for the Adriatic by Berthon and Zibordi(2004) and for the open ocean by Mueller(2000).**

**Table 7: Coefficients of the power function $K_{Ed}$=a0*(Lwn1/Lwn2)$^{a1}$ used for the regional $K_{Ed}$ algorithm development (see text). $r^2$ = coefficient of determination, RMSrd= Root Mean Square of relative differences, N = number of elements.**

| Basins | a0 | a1 | $r^2$ | RMSrd | N |
|---|---|---|---|---|---|
| All 490/555 | 0.193 | -1.856 | 0.82 | 0.25 | 667 |
| Adriatic Sea 490/555 | 0.194 | -1.792 | 0.73 | 0.25 | 509 |
| Baltic Sea 490/555 | 0.152 | -2.548 | 0.86 | 0.20 | 134 |
| Eng. Channel/North Sea 490/555 | 0.152 | -2.378 | 0.62 | 0.23 | 24 |

# Regional empirical algorithms for the Secchi depth (SD) retrieval from Ocean Colour data

The Secchi Depth measurement is the traditional and oldest optical measurement bringing a rough, but easy to get, information on the attenuation of light in the water column and possibly on water content. The Secchi depth is often related to the diffuse attenuation coefficient for downwelling irradiance $K_{Ed}$ for the whole visible part of the spectrum (the so-called “PAR”, or photosynthetically available radiation). Figure 16 presents the relationship between the inverse value of the Secchi Depth ($m^{-1}$) and $K_{Ed}$ ($m^{-1}$) at 490 nm measured for the optically homogeneous surface layer as in previous section (a good relationship between $K_{Ed}(490)$ and $K_{Ed}(PAR)$ can reasonably be assumed). It is clearly visible that the Adriatic and Baltic waters do behave differently (see the parameters of the specific relationships in Table 8) inducing a considerable scattering of the data around the global relationship.

According to theory, the Secchi Depth (SD) is actually proportional to the sum of $K_{Ed}$ and of the beam attenuation coefficient c, rather than to $K_{Ed}$ alone (see in Kirk, 1994), particularly in coastal waters where other components than phytoplankton independently contribute to the light attenuation. Similarly to figure 16, figure 17 presents the relationship for the sum $K_{Ed}(490)+c(490)$ measured for the same surface layer. In this case the behaviour of the two areas is rather similar (see Table 8) and the global relationship is approximately linear. This is due to the fact that as a consequence of an increased level of particles, light scattering increases much more than absorption and c increases much more than $K_{Ed}$, the Secchi Depth thus depending more on $K_{Ed}$+c than on $K_{Ed}$ alone. For remote sensing applications the last (global) relationship could be used in conjunction with an algorithm allowing the retrieval of the surface inherent optical properties (e.g. Loisel and Stramski, 2000) as an alternative to the regional relationships.

**Table 8: Coefficients of the linear functions $1/SD=a0+a1*(K_{Ed})$ or $1/SD=a0+a1*(K_{Ed}+c)$ with SD= Secchi Depth (m) (see text). $r^2$=coefficient of determination, RMSrd=Root Mean Square of relative differences, N=number of elements.**

| Basins | a0 | a1 | $r^2$ | RMSrd | N |
|---|---|---|---|---|---|
| **$1/SD=f(K_{Ed}(490))$** | | | | | |
| **Adriatic+Baltic** | 0.096 | 0.289 | 0.64 | 0.27 | 430 |
| **Adriatic Sea** | 0.038 | 0.622 | 0.76 | 0.16 | 381 |
| **Baltic Sea** | 0.064 | 0.269 | 0.85 | 0.22 | 49 |
| | | | | | |
| **$1/SD=f(K_{Ed}+c(490))$** | | | | | |
| **Adriatic+Baltic** | 0.058 | 0.073 | 0.80 | 0.17 | 430 |
| **Adriatic Sea** | 0.061 | 0.070 | 0.71 | 0.18 | 381 |
| **Baltic Sea** | 0.063 | 0.075 | 0.91 | 0.16 | 49 |

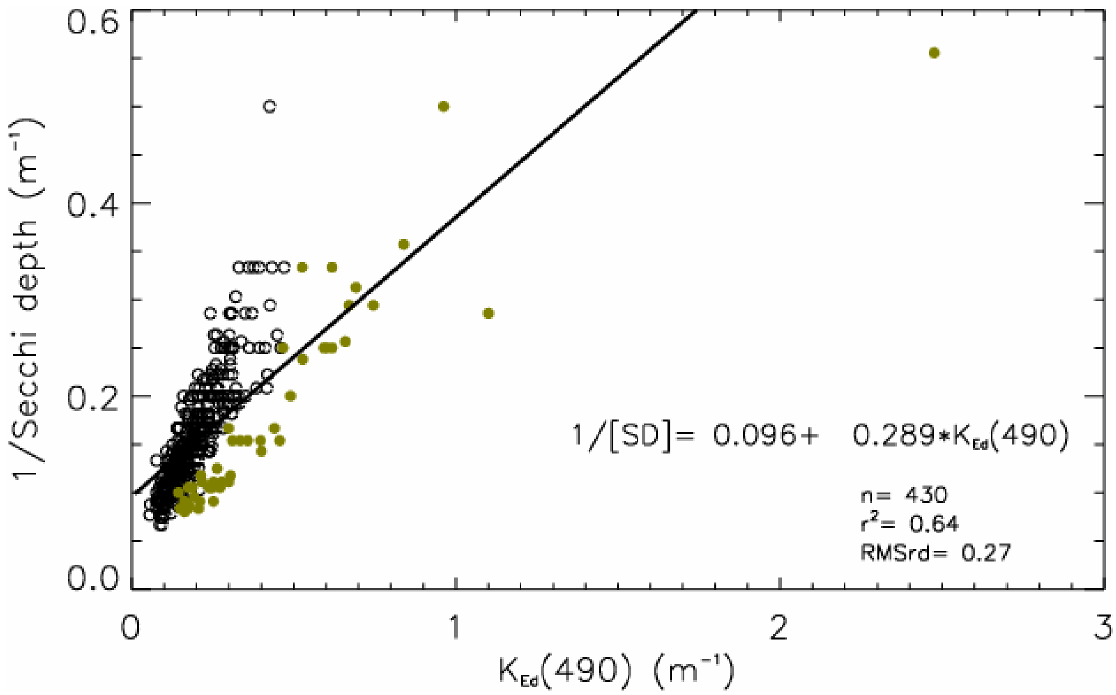


**Figure 16: Plot of the inverse of the Secchi Depth ($m^{-1}$) versus the diffuse attenuation coefficient ($K_{Ed}$) ($m^{-1}$) at 490 nm. The black line represents the linear function fitted on the whole data set which parameters are provided inside the panel. $r^2$=coefficient of determination, RMSrd=Root Mean Square of relative differences, n=number of elements.**

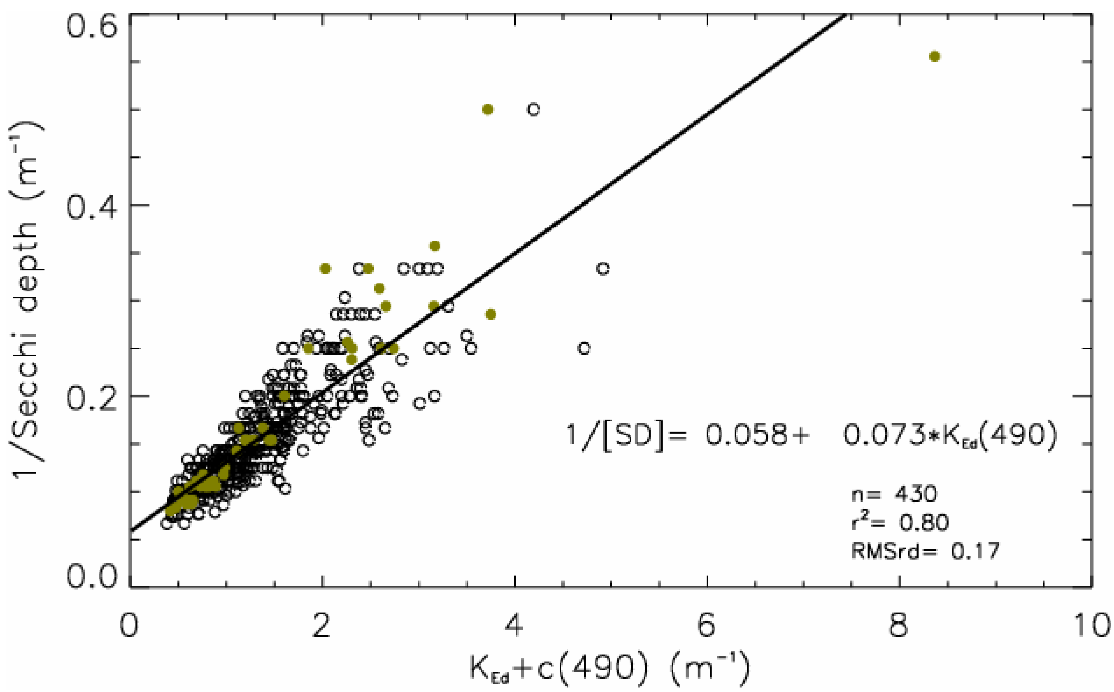


**Figure 17: As in figure 16 but for the sum of the diffuse attenuation coefficient ($K_{Ed}$ in $m^{-1}$) and of the beam attenuation coefficient (c in $m^{-1}$) at 490 nm.**

## Conclusions

The use of regional empirical algorithms is a simple approach which can give reasonable results within an operational scheme provided that methods are available in order to identify their domain of applicability and to allow their combination. Part of the relationships reported here (relationships between absorption, back-scattering and the optical components like Chla or TSM) will be used in order to develop a reflectance model (infer the surface reflectance properties from the water inherent optical properties) for the different investigated basins. New "semi-analytical" algorithms can then be developed and based on the inversion of such reflectance models.

The validity and resulting uncertainty of the reported empirical algorithms (and bio-optical relationships) obviously depend on the size of the data set used for their development as well as on the homogeneity of the methods and protocols adopted to collect the input data. The objective of developing a JRC reference bio-optical data set aims at filling these conditions. There is still a need for documenting the areas investigated in the present report (in particular the North Sea) as well as for other relevant European coastal areas like the Black Sea.

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# SECTION II

# MEASUREMENTS OF THE VOLUME SCATTERING FUNCTION IN THE NORTHERN ADRIATIC SEA.

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# MEASUREMENTS OF THE VOLUME SCATTERING FUNCTION IN THE NORTHERN ADRIATIC SEA.

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Abstract

Measurements of the Volume Scattering Function between 0.6° and 177.3° with an angular resolution of 0.3° were performed in the northern Adriatic Sea onboard an oceanographic platform in October 2004 using a prototype instrument. These data are presented and the derived scattering and back-scattering coefficients are compared to measurements performed with an AC-9 and a Hydroscat-6, respectively.

## INTRODUCTION

The back-scattering coefficient $b_b$ is an essential marine "inherent optical property" (IOP) as it determines, together with the absorption coefficient $a$, the irradiance reflectance R as well as the "remote-sensing" reflectance $R_{rs}$. The classical relationships linking these quantities is $R(\lambda) = f\, b_b(\lambda)/a(\lambda)$ (e.g. Morel and Prieur, 1977) where λ is the wavelength.

The back-scattering coefficient $b_b$ (omitting the wavelength dependence) is the integral of the Volume Scattering Function (VSF) $\beta(\psi)$ for the angles ψ corresponding to the backward directions:

$$b_b = 2\pi \int_{\pi/2}^{\pi} \beta(\psi) \sin\psi d\psi \qquad (1)$$

The integral of $\beta(\psi)$ over all the scattering directions (from 0 to $\pi$) gives the scattering coefficient *b*. The shape and the intensity of $\beta(\psi)$ depend on the size distribution of particles as well as on their index of refraction. Consequently, $\beta(\psi)$ is expected to vary from the open ocean to the coastal areas (Petzold, 1972).

Measuring the back-scattering coefficient and moreover the Volume Scattering Function is complicated. Because of this, different instruments providing measurements of $\beta(\psi)$ at one angle $\psi$ allowed for the derivation of $b_b$ (Maffione and Dana, 1997) and made possible numerous *in situ* observations of $b_b$. These measurements are based on the finding that at some angle in the backward direction (roughly between 120° and 140°) the relationship between $\beta(\psi)$ and $b_b$ is remarkably stable (Oishi, 1990; Boss and Pegau, 2001).

For what concerns the entire VSF, published measurements are rare beside the well-known ones made by Petzold (1972) for open ocean, coastal and harbor waters. These last have been "universally" used in the last decades for radiative transfer modeling and ocean color remote sensing interpretations although evidence of their non adequacy for coastal waters have often been reported (e.g. Bulgarelli *et al.*, 2003).

New instruments are now commercially available allowing the measurement of VSF for limited angular range and resolution (see Moore *et al.*, 2000 and Vaillancourt *et al.*, 2004). Additionally, a unique instrument allowing for the determination of the VSF over a wide range of angles (0.6°–177.3°) with an angular resolution of 0.3°, has recently been developed at the Marine Hydrophysical Institute in Sevastopol, Ukraina (Lee and Lewis, 2003).

The present work aims at presenting measurements of $\beta(\psi,\lambda)$ performed with this last instrument on a site located off Venice (northern Adriatic Sea) in October 2004. A comparison of the derived $b(\lambda)$ and $b_b(\lambda)$ with estimations simultaneously obtained using the well-known AC-9 (WetLabs Inc.) and Hydroscat-6 (Hobi Labs Inc.) are also presented.

## DATA

Within the CoASTS project, since fall 1995, atmospheric and marine measurements have been collected in the northern Adriatic Sea from the Acqua Alta Oceanographic Tower (AAOT). This project aims at supporting calibration and validation activities of ocean color sensors. The measurement site is located 8 miles off the Venice Lagoon (Lon. 45.314N, Lat. 12.508E) in a frontal region that, according to marine circulation, can be characterized by Case 1 or Case 2 water.

The VSF $\beta(\psi, \lambda)$ (in $m^{-1}$ $sr^{-1}$) was measured on water samples with angles $\psi$ going from 0.6 to 177.3 degrees with a resolution of 0.3 degrees and for six wavelengths $\lambda$ = 443, 490, 510, 555, 590 and 620 nm. As part of the processing the contribution of sea water is subtracted from $\beta$ providing the VSF for particles only, $\beta_p$ and consequently, $b_p$ and $b_{bp}$. More details on the instrument and the methodology can be found in Lee and Lewis (2003). Concentrations of pigments (determined with the High Pressure Liquid Chromatography method) and total suspended matter (TSM) were determined on the same water samples.

Simultaneously with the sample collections, *in situ* vertical profiles of total (except water) spectral beam attenuation and absorption coefficients $c_{t\text{-}w}(\lambda)$ and $a_{t\text{-}w}(\lambda)$ at the nominal wavelengths 412, 440, 488, 510, 555, 630, 650, 676 and 715 nm were measured with an AC-9 (Wetlabs Inc.). *In situ* vertical profiles of the back-scattering coefficients $b_b(\lambda)$ at the nominal wavelengths 442, 488, 510, 555, 620, and 665 nm were measured with an HydroScat-6 (Hyd-6, Hobi Labs Inc.). Binned profiles with 1m resolution were computed from the full resolution profiles of $a$, $b$ and $b_b$. Additionally, the resulting spectra of $c_{t\text{-}w}(\lambda)$, $a_{t\text{-}w}(\lambda)$ and $b_b(\lambda)$ were linearly interpolated in order to match the VSF wavelengths. The complete description of the CoASTS methodologies and measurements is given in Zibordi *et al.* (2002) and in Berthon *et al.* (2002).

Within the period 18-22 of October 2004, 8 complete measurement stations were performed at the AAOT including the collection of water samples at 3 different depths (surface, 8 and 14 m + one unique sample at 5m for the last station) resulting in 35 water samples. Additionally, surface water samples were also collected at stations located approximately every 2 nautical miles along transects going from the sea side of the Venice lagoon to the platform (but for which no AC-9 and Hyd-6 measurements are available) leading to a total of 47 VSF measurements.

RESULTS AND DISCUSSION

Optical characteristics and particles load of the sampled area

At the AAOT site, the beam attenuation coefficient $c_{t\text{-}w}(660)$, interpolated between measurements at 650 and 665 nm, showed variations between about 0.2 and 0.8 $m^{-1}$ whereas the values of $b_{t\text{-}w}$ and $b_{bp}$ at 412 nm varied between 0.2 and 1.0 $m^{-1}$ for the first, and between 0.004 and 0.02 $m^{-1}$ for the latter. TSM concentrations ranged between 0.5 and 1.1 mg $m^{-3}$ at the AAOT site with a rather homogeneous vertical distribution whereas they varied from 0.8 to 2.4 mg $m^{-3}$ at the surface for the coastal transects with maxima located very near the coast.

Volume Scattering Functions and Phase Functions

With the aim of comparing the measured functions with the Petzold ones (measured for λ=514 nm) their presentation will be made for λ=510 nm.

Figure 1 illustrates the individual VSF measured at the AAOT site and along the transects for 510 nm together with the 3 Petzold's $\beta_p$ ($\beta_w$ of water was computed and subtracted from Petzold's $\beta$ functions by using equation 3.28 and Table 3.8 in Mobley, 1994). It can be noticed that almost all $\beta_p$ functions are intermediate between the typical "coastal" and the "harbor" functions measured by Petzold. A few, those actually measured near the Venice Lagoon, are closer to the "harbor" type.

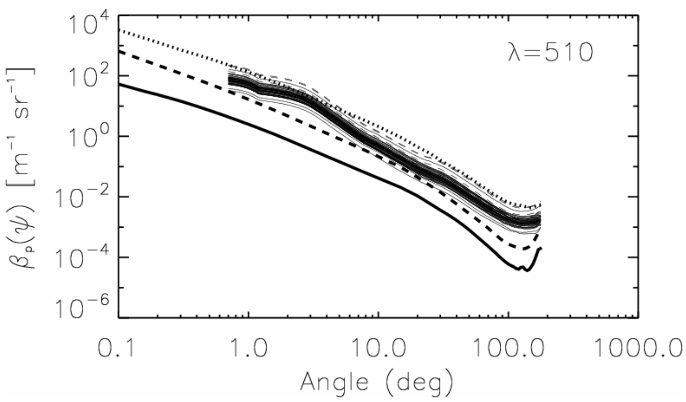


**Figure 2: VSF measured in Adriatic at 510 nm (thin black lines; dashed=stations near the Venice lagoon) and Petzold's VSF at 514 nm (thick black lines; solid=open ocean, dashed=coastal, dotted=harbor)**

Figure 2 presents the corresponding individual Phase Functions (PF) for particles $\widetilde{\beta}$ (ψ,λ) (i.e. $\beta_p$(ψ, λ)/$b_p$(λ) ). No difference can be observed between the PF measured at the AAOT site and those measured from samples collected in more turbid waters, thus demonstrating that the type and distribution of particles were very similar. It is highlighted that the PF are close to the "harbor" type of Petzold in particular for the backward directions (relative difference are between -10 and +25 %) where their shape is much more flat than for the "open ocean" and "coastal" types (relative differences with these last reach +150 and +250 %, respectively). In the forward direction, between 5 and 30 degrees they are more similar to the coastal type whereas for small forward angles (between 1 and 5 degrees) they bear no resemblance to any Petzold type (relative differences reach +190 %, respectively).

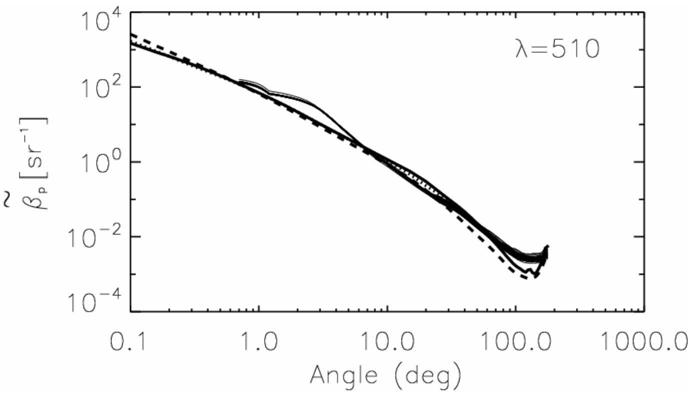


**Figure 3: Phase functions measured in Adriatic (510 nm) and Petzold's PH functions (514 nm) (lines are as in figure 1).**

<u>$b_p$(λ) and $b_{bp}$(λ) derived from the VSF and measured with the AC-9 and the Hyd-6.</u>

The scattering and back-scattering coefficients for particles were computed by integrating on ψ the measured $\beta_p$(ψ, λ) and were compared (as well as their ratio $b_{bp}/b_p$) with their estimation provided by the AC-9 and the Hyd-6 (after subtraction of the contribution by water). Figure 3 presents this comparison for λ=510 nm in terms of average relative differences, absolute (|PD| $=\frac{1}{n}\sum_{i=1}^{n}|y_i - x_i|/x_i$), quantifying the uncertainty) or signed (PD=$\frac{1}{n}\sum_{i=1}^{n}(y_i - x_i)/x_i$, quantifying the bias), where the VSF is taken as the reference value $x_i$.

Average values of |PD| at 510 nm are 14.4, 16.2 and 11.0 % for $b_p$, $b_{bp}$ and $b_{bp}/b_p$, respectively whereas values of PD (bias) are -3.2, -9.6 and -6.4 % expressing a slight average underestimation of the coefficients derived from the AC-9 or Hydroscat-6 measurements. The results are rather similar for the other wavelengths.

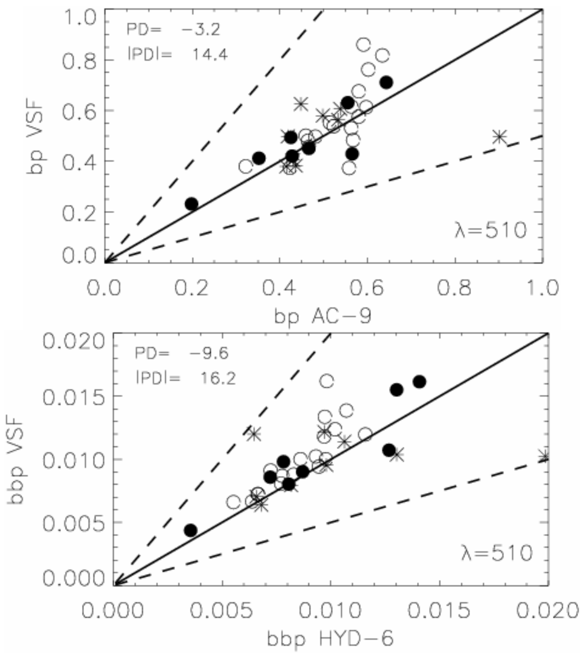


**Figure 4: $b_p$ (left panel) and $b_{bp}$ (right panel) at 510 nm derived from the measured VSF and measured with the AC-9 and the Hyd-6, respectively. Empty circle=surface, star=8m (+1 sample at 5m), filled circle =14m. Solid line=1 :1 ratio, dashed lines = 1:2 and 2:1 ratios**

Estimation of $b_b(\lambda)$ from the measurement of $\beta(\psi, \lambda)$ at one angle

The estimation of $b_b(\lambda)$ by the Hyd-6 instrument is made through the sole measurement of $\beta(140, \lambda)$ and the use of an empirical relationship linking the two quantities (Oishi, 1990; Maffione and Dana, 1997).

Using the measured VSF, linear relationships between total $b_b(\lambda)$ and $\beta(\psi, \lambda)$ for $\psi$ from 90 to 170 with an increment of 10 degrees were investigated here and are presented in Figure 4 for $\lambda$=510 and $\psi$=120 and 140 degrees. As already observed by Oishi (1990), relationships are very good as confirmed by the extremely high $r^2$ although the slopes of the linear regressions are slightly different from those he provided (note that for $\psi$=140 the local relationship is very close to that used in the Hyd-6 data processing). When considering all wavelengths, the $r^2$ are slightly higher for $\psi$=120 (from 0.998 to 0.999) than for $\psi$=140 (from 0.995 to 0.998).

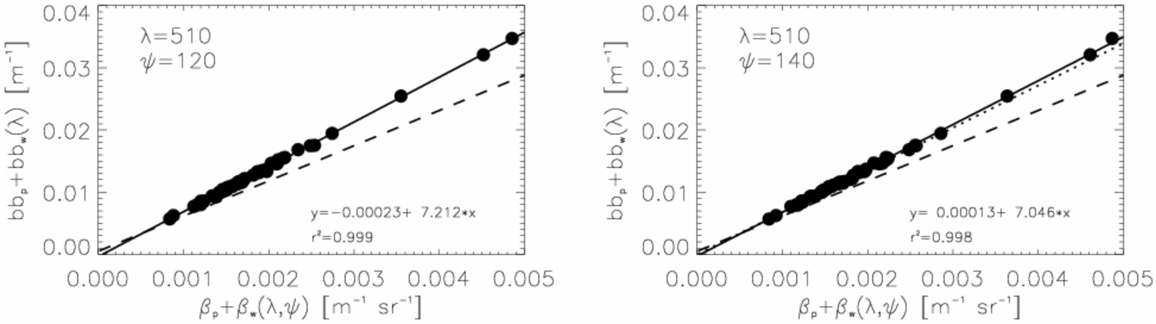


**Figure 5: $b_b$ versus $\beta(\psi)$ at 510 nm for ψ =120 (left panel) and ψ =140 degrees derived from the measured VSF. Filled circle=individual samples, solid line=linear regression, dashed line=Oishi (1990), dotted line=Hyd-6 processing.**

Boss and Pegau (2001) demonstrated that the best angle in order to predict $b_b$ from $\beta(\psi)$ is the one for which the following equality is respected:

$\chi_p(\psi) = \chi_w(\psi)$, where $\chi_i(\psi) = b_{bi} / 2 \pi \beta_i (\psi)$ with i= w (water) or p (particles)

Figure 5 presents for λ=510 the angular distribution of $\chi_w(\psi)$ and of the measured $\chi_p(\psi)$. Water and particles curves cross each other between 115 and 120 degrees. The average value (± standard deviation) of the angle for which the previous equality is respected is 116.6 (± 1.3), close to the value simulated by Boss and Pegau (near 118), and an average $\chi$ of 1.09 (± 0.01). Considering all wavelengths the average angles vary from 116.5 (555 nm) to 117.2 (620 nm).

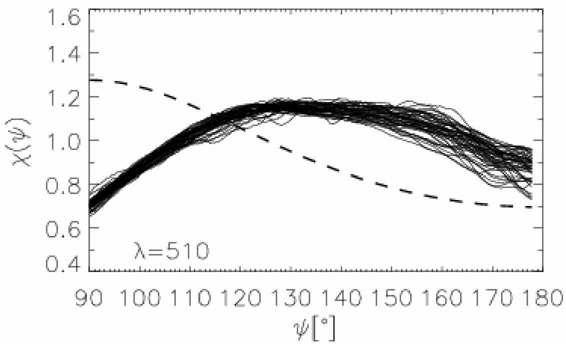


**Figure 6: Angular distribution of measured $\chi_p$ in the Adriatic (solid lines) and $\chi_w$ (dashed line) at 510 nm.**

CONCLUSIONS

The Volume Scattering Function $\beta(\psi,\lambda)$ was measured in the northern coastal Adriatic Sea from 0.6 to 177.3 degrees with a high angular resolution. Observed differences with the commonly used Petzold's functions are significant, in particular for the "open ocean" and "coastal" types in the backward directions (between 110 and 160 degrees).

The comparison of the derived scattering, b(λ) and back-scattering, $b_b(\lambda)$ coefficients with their measurements performed with the classical AC-9 and Hydroscat-6 showed good results. In particular, the use of an empirical relationship for the derivation of $b_b(\lambda)$ from a unique measurement of $\beta(\psi,\lambda)$ at ψ=140 for the Hydroscat-6 was validated for this coastal site at that season.

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