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PRELIMINARY VALIDATION OF MERIS WATER PRODUCTS FOR BELGIAN COASTAL WATERS

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ABSTRACT

This paper describes the methods used to acquire sea-level data for validation of MERIS water products in Belgian coastal waters and comparison of such measurements with MERIS level 2 data as available in November 2002. Results are presented for two Reduced Resolution level 2 images for which sea-level match-up data exists. One image was acquired during partially cloudy skies – while not appropriate for quantitative validation of the water products themselves, this image is useful for validation of the various quality and confidence flags supplied with the MERIS products. The second image was acquired during clear sky conditions and is optimal for quantitative validation of water-leaving reflectance, algal pigment index (chlorophyll concentration) and total suspended matter concentration. Firstly, a qualitative assessment is made of the images based on knowledge of the region and of inconsistencies between the products themselves. This assessment suggests that many pixels which are partially or wholly cloudy are not identified as such, giving an unreliable impression of product quality to users. Furthermore, unrealistic spatial discontinuities are observed in products because of switching of the case 2S flag. It is recommended that more attention be paid to validation of the MERIS L2 flags and especially cloud pixel identification and the impact of spatial variability of the case 2S flag. Secondly a quantitative assessment is made of products using the sea-level match-up data. For the image with clear sky conditions water-leaving reflectance in the blue is severely overestimated by MERIS because of underestimation of aerosol optical thickness and epsilon factor. It is recommended that the performance of the turbid water atmospheric correction be investigated in more detail and with more imagery for this and other regions.

1. INTRODUCTION

The Medium Resolution Imaging Spectrometer (MERIS) was launched aboard the Envisat-1 satellite on 1.3.2002. After stabilisation of MERIS settings (gain controls, etc.) on 29.4.2002 MERIS has acquired reduced resolution imagery almost continuously for the Belgian coastal waters test site until the time of writing (November 2002). During this time a number of seaborne cruises have been undertaken in Belgian waters in order to provide sea-level validation data and a sunphotometer has been operated continuously at Oostende. The objective of these measurements was[1]:

1. to provide a quantitative assessment of the accuracy of MERIS water products,
2. to highlight any major discrepancies in the products and,
3. to provide recommendations to the European Space Agency in the area of data quality improvement, further algorithm development and reliability and usability of the geophysical products.

The primary MERIS products to be validated here are :

- Water-leaving reflectance
- Algae pigment index 2 (Chl2)
- Total suspended matter (TSM)

In addition to these products, various flags supplied with MERIS data and used to denote potential poor quality of MERIS products and/or special conditions (e.g. turbid water) have been analysed. Finally, sunphotometer measurements have been made to support sea-level validation of the abovementioned products by validation of the aerosol optical thickness atmospheric product.

As an essential element of quality control and to ensure compatibility of sea-level validation measurements throughout the MERIS Validation Team (MAVT) the methods and instruments used here have been compared with those of other teams participating in MERIS validation in a number of intercomparison exercises. These exercises coupled with internal procedures and theoretical considerations allow assessment of the reliability of the sea-level validation measurements themselves and, thus, quantification of the minimal uncertainty that could be attributed to MERIS water products using these methods.

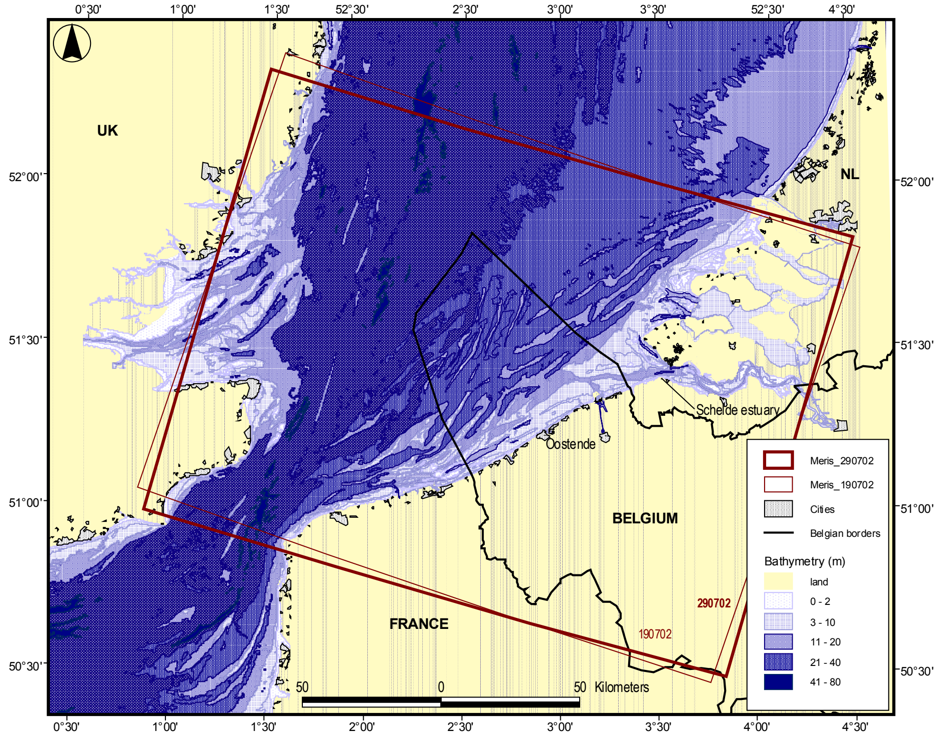
This paper describes the sea-level validation campaigns, the measurement methods, including brief details of intercomparison exercises and uncertainty estimates, and the results of analysis of a first set of « match-up » level 2 MERIS images.

2. DESCRIPTION OF TEST-SITE

The Belgian coastal waters (Fig. 1) have been monitored intensively for over 30 years in the framework of national water quality monitoring programmes and numerous research initiatives. Over the last 5 years the optical properties of these waters have been studied in detail as support for remote sensing activities [2-5], focussing especially on the SeaWiFS sensor. The highly turbid nature of this test site makes it particularly useful for validation of turbid water « case 2S » atmospheric correction algorithms[6].

Owing to the shallow water depths (0-40m), strong tidal currents (e.g. 1.2 m/s amplitude) and frequent strong wind events (e.g. 10 m/s at 10m above sea level), resuspension of bottom sediments yields high suspended matter concentrations. These range from ~1 g/m3 in clearer offshore waters to ~50 g/m3 closer to shore (e.g. 3 km offshore, 10m water depth). Concentrations as high as 500 g/m3 have been measured on occasions near Zeebrugge. Yellow substance absorption at 440nm, from both coloured dissolved organic matter (CDOM) and non-phytoplanktonic particulate matter (tripton) is also high in nearshore waters, e.g. 0.1-6.0 /m for CDOM, 0.05-1.25 /m for tripton[4], decreasing offshore. Chlorophyll-a concentrations are typically low (< 1 mg/m3) in winter, reaching a peak of 10-50 mg/m3 during the spring bloom[7, 8], with mainly intermediate concentrations (1-10 mg/m3) during summer and autumn though occasional higher concentrations (10-20 mg/m3) within a few km of the coast. Secchi depths range from only a few cm in the most turbid waters to a few metres in clearer, offshore waters. The water column is generally well-mixed vertically by the turbulence caused by strong tide- and wind-driven currents.

Atmospheric conditions are dominated by the passage of low pressure systems with associated clouds (mainly cumulus), interspersed by periods of more stable, clearer high pressure systems lasting typically a few days. During summer about 50% of satellite acquisitions are entirely cloudy, about 25% show scattered clouds or haze and about 25% correspond to clear skies which are optimal for validation of ocean colour sensors. Even for relatively clear sky conditions it is not uncommon to find thin cirrus clouds and/or contrails over some parts of the Southern North Sea.



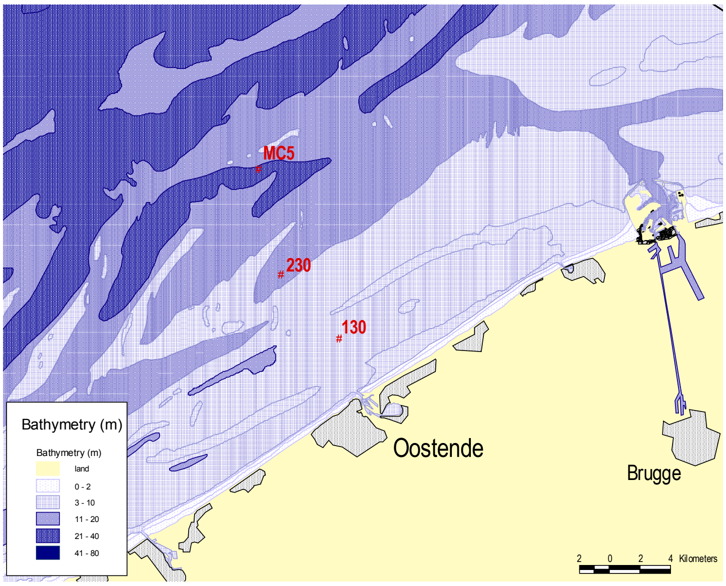


Figure 1. (top) Map of the Southern North Sea. Belgian waters are enclosed by a solid black line. The red rectangles show the location of the images presented in this study. (bottom) Close-up of the Oostende transect where in situ measurements were made at three stations : 130, 230 and MC5.

3. OVERVIEW OF MEASUREMENTS

Validation measurements have been made during a series of seaborne cruises in Belgian and UK coastal waters from the oceanographic Research Vessels Belgica (51m) and Zeeleeuw (56m). Table 1 summarising these cruises and the corresponding MERIS imagery. In this context only « match-up » MERIS imagery acquired within one hour, or preferably 30 minutes, of seaborne measurements has been considered in order to minimise uncertainties associated with temporal variability of marine and atmospheric properties. Atmospheric measurements were also made continuously from a CIMEL sunphotometer installed in Oostende. This data is not presented here, pending recalibration of the instrument and final quality control.

Table 1. Summary of MERIS Validation cruises undertaken in 2002 and corresponding MERIS match-up possibilities.

Month	Days at sea	Optimal match-ups	Sub-optimal match-ups	CIMEL match-ups
March	5	0	1 ?	0
April	8	2 ?	1 ?	3 ?
May	0	0	0	2
June	4	0	1 ?	2
July	5	2	2	4
August	0	0	0	3
September	0	0	0	?
October	1	0	0	?
TOTAL	23	2-4	2-5	11-14

4. MEASUREMENT METHODS

4.1 Water-leaving reflectance

Water-leaving reflectance is measured using two different methods as described below.

4.1.1. Instrumentation and method – TriOS system

A system of three TriOS-RAMSES hyperspectral spectroradiometers is used to make measurements above-water of :

- Upwelling radiance, L_u^+, at zenith angle of 40° and azimuth of 135° relative to the sun
- Sky radiance, L_{sky}, at the same zenith and azimuth angles, and
- Downwelling irradiance, E_d^+

as outlined in Method 1 of [9]. The water-leaving reflectance, ρ_w, as defined in the MERIS product, is then calculated by,

$$\rho_w = \pi \frac{L_u^+ - \rho_{as} L_{sky}}{E_d^+} \tag{1}$$

where the air-sea interface reflection coefficient, ρ_{as}, is estimated for sunny conditions from Figure 9 of [10] as function of wind speed in m/s, W :

$$\rho_{as} = 0.026 + 0.0001 * W + 0.00006 * W^2 \tag{2}$$

The sensors measure over the wavelength range 350-900nm with sampling approximately every 3.3nm with spectral width of about 10nm. The radiance sensors have a field of view of 7°. A two-axis tilt sensor is incorporated inside the downwelling irradiance sensors. The instruments are mounted on a steel frame, similar in concept to that used by [11]. This is fixed to the prow of the ship facing forwards to minimise ship shadow and reflection.

4.1.2. Instrumentation and method – SIMBADA system

The handheld SIMBADA radiometer/sunphotometer system is used to make measurements above-water of :

- Upwelling radiance, L_{pu}^+, viewing at zenith angle of 40° and azimuth of 135° relative to the sun and through a filter set to pass only the vertically polarised component of radiance
- Direct sun radiance, from which aerosol optical thickness and, using an atmospheric radiative transfer model, downwelling irradiance, E_d^+, are deduced.

as outlined as Method 3 in [9] and described in detail in [12]. The MERIS product is then calculated by,

$$\rho_w = \pi \frac{L_{pu}^{+} - L_{sky-corr}}{E_d^{+}} \tag{3}$$

where $L_{sky-corr}$ is a correction for residual skylight reflected at the air-sea interface and passing through the polarising filter. Details of practical operation are given in the SIMBADA user's guide (http://www-loa.univ-lille1.fr/recherche/ocean_color/src/).

4.1.3 Quality control, intercomparison and error estimates

The TriOS spectra are quality controlled by comparing the water-leaving reflectance estimated at 750nm from the reflectance measured at 705nm using a simple model of optical properties with the corresponding measurement at 750nm. This enables identification of spectra with poor air-sea interface correction. Simultaneous TriOS and SIMBADA measurements have been compared over a number of cruises in 2001-2002 and with other MERIS Validation team participants using both above- and under-water reflectance measurement methods in the Plymcal-1 exercise. These exercises, combined with theoretical indications suggest an uncertainty for the methods of about 10% for high reflectances rising to about 20% in the near infrared. For comparison with satellite pixels covering 1km square, sub-pixel scale variability of reflectance (and TSM) is estimated to give uncertainty of 20% in the satellite vs in situ comparison. The reflectance spectra are presented without any correction for bidirectional effects. Since MERIS reflectances in case 2 waters are also not normalised to nadir there is a different viewing geometry for the satellite and the in situ measurements (also the case for under-water nadir measurements). This is, however, not thought to be the main source of uncertainty here.

4.2 Algal pigment index Chl2

The algal pigment index Chl2 is validated as defined in the MERIS validation protocols [13] by HPLC measurements of the chlorophyll-a concentration (chl.2.hplc). Water samples taken in surface water (0.5m depth) are filtered on-board with GF/F filters, which are then frozen in liquid nitrogen and stored long-term at –80°C. Pigments are extracted in 90% acetone with the use of a cell-homogenizer, followed by centrifugation[14]. The chlorophyll pigments are separated with reversed phase HPLC. MUMM's measurements have been compared with those of the MERIS Validation team during the NIVAcal exercise (final results pending) and with Plymouth Marine Laboratory for 18 samples taken at sea during a cruise with the Research Vessel Belgica in June 2002 (results also pending).

4.3 Total suspended matter (TSM)

The Total suspended matter, TSM, is validated as defined in the MERIS validation protocols by the gravimetric method. Water samples taken in surface water (0.5m depth) are filtered on-board with pre-weighed pre-ashed GF/F filters and rinsed with milli-Q water (including the filter rim). After the cruise the filters are dried and weighed for determination of dry weight. Full details of the method are found in REVAMP protocols [15] based on [16]. Further measurements were made on GF/C filters for comparison with the conventional water quality monitoring programme of MUMM – the latter measurements which do not conform to the MERIS validation protocol are not presented here. MUMM's measurements have been compared with Plymouth Marine Laboratory for 18 samples taken at sea during a cruise with the Research Vessel Belgica in June 2002.

4.4 Aerosol optical thickness

Aerosol optical thickness (AOT) measurements were made at sea from direct sun measurements with the SIMBADA radiometer using the method described in [17].

4.5 Aerosol epsilon factor

The aerosol epsilon factor, ε, is derived from the SIMBADA AOT measurements by fitting a power function of wavelength to the AOT spectrum from 443nm to 670nm with Angström coefficient, α. Then, assuming the spectral fit extends to 870nm and that the 778nm:870nm ratio of single-scattering albedo and phase function can be neglected [18]

$$\varepsilon = \left(\frac{778nm}{865nm} \right)^{-\alpha} \tag{4}$$

5. RESULTS - MERIS IMAGERY

5.1 Overview of imagery

A summary of MERIS level 2 RR imagery requested and an overview of corresponding sea-level data and general conditions is given in Table 2.

Table 2. Summary of MERIS level 2 RR imagery and corresponding atmospheric conditions and sea-level measurements.

Date	Status	Conditions	Seaborne
10.4.2002	Not received	Good	Yes
11.4.2002	Not received	Good	Yes
17.4.2002	Not received	Sub-optimal	Yes
17.5.2002	Received		No
23.5.2002	Received		No
21.6.2002	Received	Sub-optimal	Yes
24.6.2002	Received		No
16.7.2002	Not received	Optimal	Yes
19.7.2002	Analysed	Sub-optimal	Yes
26.7.2002	Received	Sub-optimal	Yes
29.7.2002	Analysed	Optimal	Yes
14.8.2002	Received		No
17.8.2002	Not received		No
23.8.2002	Received		No

This imagery has been processed up to level 2 for the European Space Agency by ACRI/Brockmann Consulting using calibration information from orbit 1858 and after correction for smile as described at the Envisat-MERIS Commissioning workshop on 10.9.2002. Level 2 imagery was supplied to MUMM on 4.11.2002. This imagery has then been processed using the VISAT and IDL software. Georeferencing was checked and found accurate to within one pixel for reduced resolution data.

5.2. Presentation of imagery

Fig. 2 and 3 show for the 19.7.2002 and 29.7.2002 images a quasi-true colour RGB composite of the level 1B image using bands 7 (665nm), 5 (560nm) and 2 (443nm), as well as the following level 2 products : case 2S flag (red where true), aerosol epsilon factor (the ratio of aerosol reflectances 778nm:865nm), aerosol optical thickness at 865nm, total suspended matter, yellow substance (particulate and dissolved) absorption at 442nm, and the algal pigment indices Chl1 and Chl2. The stations where match-up in situ data exists, in a transect extending 20km offshore from Oostende, are shown on these images as crosses. These stations, named 130, 230 and MC5 are located at (51° 16.25'N, 2° 54.30'E), (51° 18.50'N, 2° 51.00'E) and (51° 20.38'N, 2° 50.38'E). Pixels flagged as clouds are shown in white.

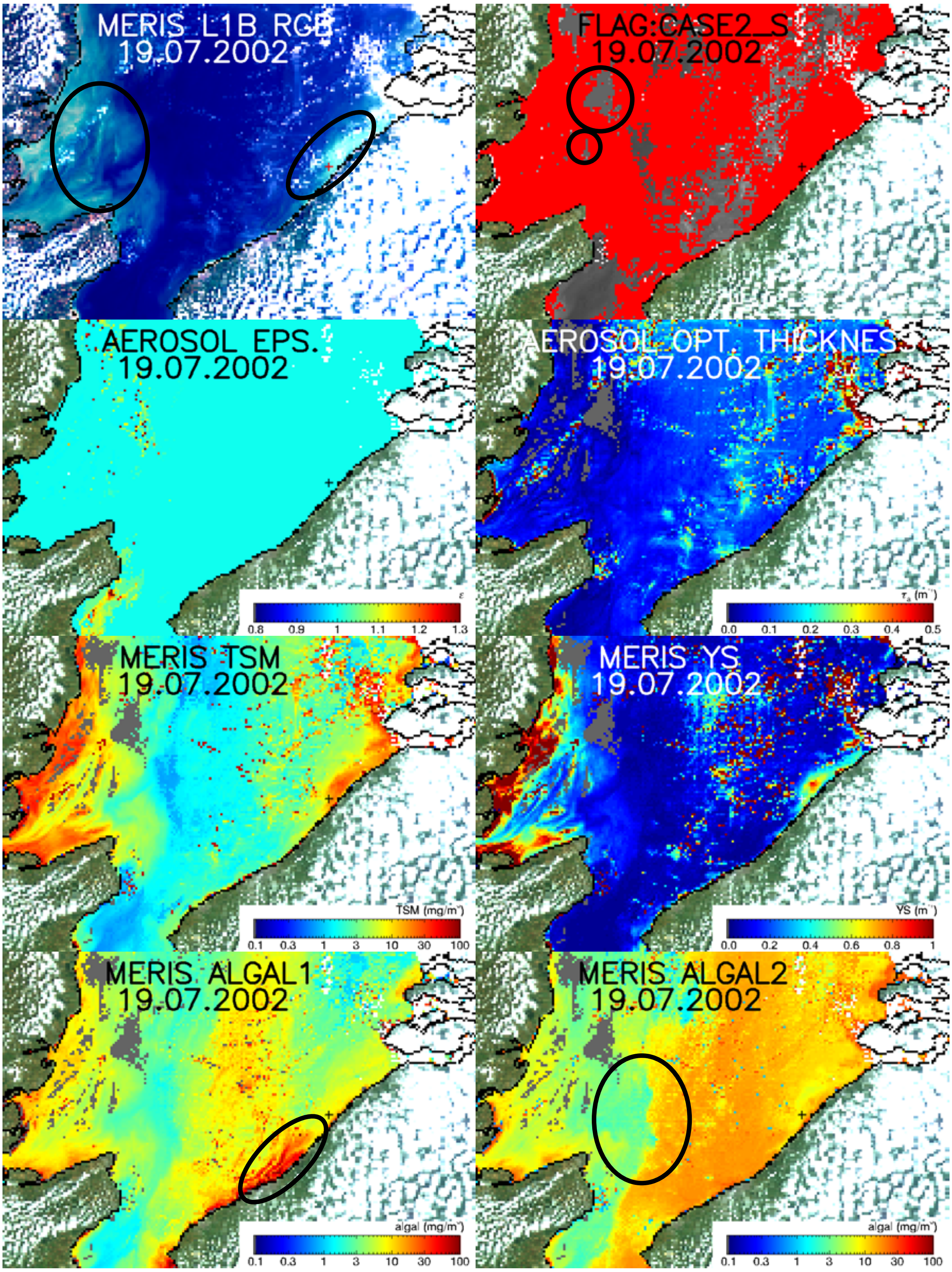


Figure 2. MERIS imagery for the Southern North Sea on 19.7.2002 (UTC 10:44) : Level 1B composite, case 2S flag, aerosol epsilon factor, aerosol optical thickness, total suspended matter, yellow substance absorption, Chl1, Chl2 (see text for further details).

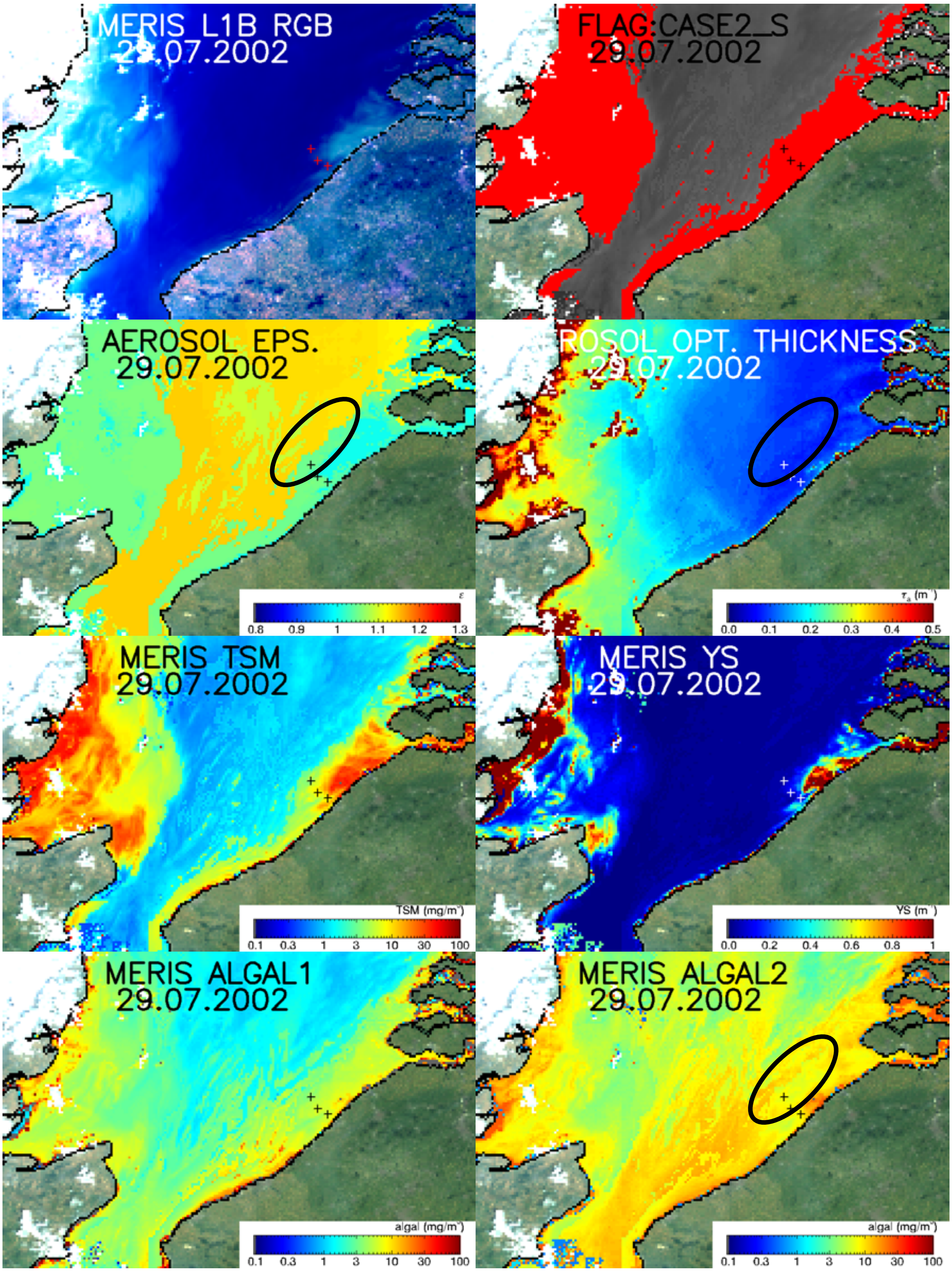


Figure 3. MERIS imagery for the Southern North Sea on 29.7.2002 (UTC 10:30) : Level 1B composite, case 2S flag, aerosol epsilon factor, aerosol optical thickness, total suspended matter, yellow substance absorption, Chl1, Chl2 (see text for further details).

6. DISCUSSION – QUALITATIVE ANALYSIS

In addition to the quantitative match-up analysis (sections 7 and 8) some aspects of the sensor/algorithm performance can be assessed by visual inspection of these images based on existing knowledge of the region.

6.1. Image of 19.7.2002

It is evident from the L1B RGB composite of the 19.7.2002 image that atmospheric conditions were partially cloudy over much of the test region, as confirmed by sky photos taken from the Zeeleeuw at the moment of the overpass. In addition to the full cloud pixels, there seem to be many thin cloud or cloud-edge pixels. Such conditions are clearly sub-optimal and, therefore, not appropriate for quantitative validation of the MERIS level 2 products as defined by the MERIS protocols. However, for maximising exploitation of MERIS it is useful to assess performance in such conditions. In particular, users will need to know what confidence can be attributed to the level 2 products. In such cases the level 2 flags are essential. For this image the fact that many cloudy pixels have not been identified as such is clearly a problem and could lead to misinterpretation of products.

The turbid water within 10km of the coast between Oostende and the Scheldt Estuary (circled in Fig. 2) and along the UK coast appear in the RGB composite as yellow-green while the darker waters further offshore in the RGB image appear dark blue (or light blue if overcast with thin clouds).

The case 2S flag image shows that much of the Southern North Sea has been identified as case 2S water. However, there are also many pixels (brown) not classified as case 2S giving strong spatial inhomogeneities, which can be expected to degrade products. Since the case 2S flag[19] is essentially a threshold test for suspended particulate matter (above about 2 mg/l) derived from a preliminary dark pixel atmospheric correction there are two reasons for certain pixels not to be flagged. Firstly, for clear sky conditions TSM for some of the offshore waters will be close to the threshold with small spatial variabilities in TSM giving discontinuous variability in the case 2S flag. Secondly, if skies are partially cloudy over turbid water the TSM will be severely underestimated giving erroneously false values for the case 2S flag. In the latter case processing should detect such an anomaly and reject the pixel as unsuitable for marine products.

Considering the atmospheric products for this image, the thin and scattered clouds give a very uniform epsilon factor for Belgian waters (since clouds have a similar colour to white aerosols with $\varepsilon = 1.0$) but considerable variability of the aerosol optical thickness. These results are physically reasonable. If identification of such thin clouds via flags is not successful, the aerosol optical thickness image gives probably the best indication of such a problem both via the spatial noise (a more uniform field is expected for cloud-free skies) and via the magnitude (>0.2 indicates strong haze or clouds).

The high (>1.1) and noisy epsilon factor found in UK coastal waters in this image cannot at present be explained since the RGB image does not suggest clouds in this region, but is mainly darker there. For this patch (large circle in Fig. 2, case 2S) atmospheric correction failure has occurred (seen as a black patch in the case 2S flag image and violet in the level 2 water products where data is given as 0.0). It is noted that the high glint flag is raised for these and many other surrounding pixels although this is somewhat surprising for the near-nadir viewing and low wind speed (<5 m/s). A detailed analysis of processing of these pixels as well as results from other regions may help clarify this anomaly.

Comparison of the Chl1 product with the aerosol optical thickness suggests that Chl1 is severely contaminated by the partially cloudy conditions. Zero values are found offshore of England corresponding to atmospheric correction failure as mentioned above but also to very shallow water. The latter pixels (small circle in Fig. 2, case 2S) are seen as elongated patches corresponding to known bathymetric features and may even be exposed, i.e. land, pixels at low water. In addition to the problems associated with atmospheric conditions the Chl1 product shows unrealistically high concentrations associated with submerged sandbanks along the French-Belgian coast (see circle in Fig. 2, Chl1). This product is not expected to work here because the case 1 assumptions are not valid.

The Chl2 product is similarly contaminated by partially cloudy conditions. In this case there is an apparent front running approximately North-South across the image (circled in Fig. 2). This is thought to be an artefact from the atmospheric conditions (see aerosol optical thickness) and is stronger here than for the Chl1 image presumably because the problem is more severe in bands used for Chl2 but not for Chl1.

Considering the atmospheric conditions further analysis of the level 2 water products seems inappropriate for this image.

6.2. Image of 29.7.2002

In contrast with the previous image, the image of 29.7.2002 was acquired during excellent conditions (clear sky, low wind) at least for Belgian waters. Thus, the L1B RGB image shows clear waters offshore with turbid water visible near the coast between Oostende and the Scheldt Estuary. This area of turbid water has been found previously in most SeaWiFS images of the region – see for example, Fig. 1 of [2]. TSM is high here because of resuspension of bottom sediments in shallow water (water depth of 2-10m, Secchi depth about 1m) by tide and wind-generated turbulence.

For this image the case 2S flag has been set only for the two bands of Belgian and UK coastal water. While it seems entirely plausible that this flag would show such a distribution here since TSM decreases from coast to open sea and will, thus, reach the threshold value at some offshore distance, the impact of this flag on subsequent processing of products is significant.

The aerosol epsilon factor image shows strong correlation with the case 2S flag. The sharp discontinuity of epsilon at the boundary between true and false values of the case 2S flag (circled region) is clearly unphysical since this parameter should in reality show strong spatial homogeneity except near atmospheric fronts where aerosol particle size/type may vary strongly. Moreover, in this image shapes are seen in the aerosol epsilon image both sides of the case 2S flag boundary which correspond to bathymetric features, indicating imperfect atmospheric correction on both sides of the discontinuity. This is discussed further in the quantitative assessment of section 8.

As a consequence of the aerosol epsilon factor discontinuity, the aerosol optical thickness image shows a slight unphysical discontinuity at the case 2S flag boundary on the UK side.

The Chl1 and Chl2 images show significant differences (e.g. factor 2) for both the deeper offshore water and the coastal water, flagged as case 2S. Moreover, both images show spatial structures related to bathymetric features. While phytoplankton may be correlated with bathymetry for a number of reasons (slightly warmer temperatures in shallower areas, increased/decreased depth-averaged primary production because of difference in euphotic and total water depth), the spatial differences seen in these images across submerged sandbanks (e.g. factor 10 over 10km length scale) seem excessive. This raises the suspicion that backscatter from non-phytoplanktonic suspended matter, which is very strongly related to bathymetry via resuspension, is contaminating retrieval of both Chl1 and Chl2 either via the atmospheric correction or via the bio-optical model inversion.

The yellow substance image, which shows high absorption in the turbid water North-East of Oostende and in the Scheldt Estuary, seems qualitatively reasonable in view of generally high tripton and CDOM absorption in these regions.

The TSM image reproduces spatial features well-known from processed AVHRR and SeaWiFs images (see Fig. 4) and seems qualitatively reasonable.

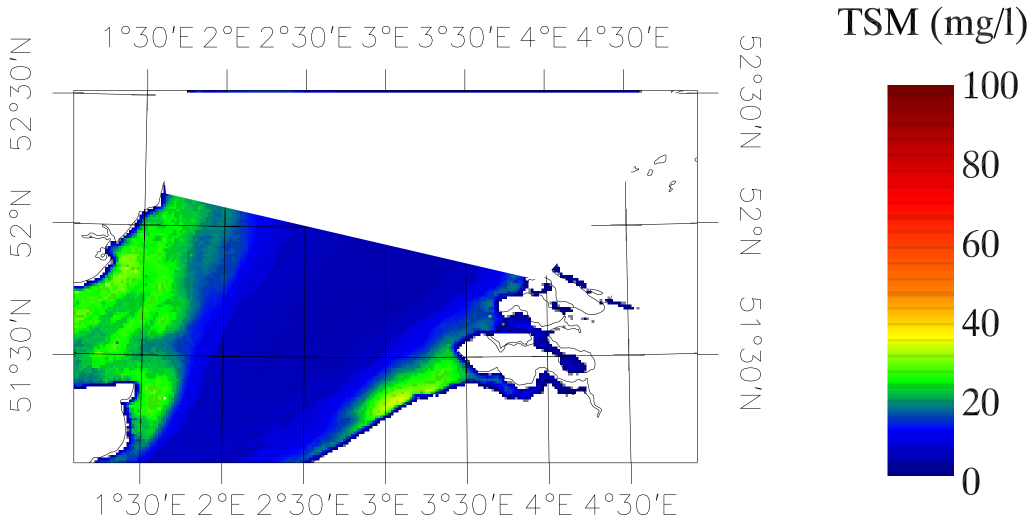


Figure 4. TSM for this region averaged over 62 SeaWiFS images (1997-2002).

7. RESULTS – QUANTITATIVE ANALYSIS

For the 19.7.2002 image one station of meaurements, just one hour from the overpass, is considered as useful for validation, the other two being cloud-covered at the moment of the MERIS acquisition. For the 29.7.2002 image both stations where measurements were made within 30 minutes and a third station within 60 minutes of the MERIS acquisition are acceptable . For each of the four match-up pixels numerical values are given in Table 3 for MERIS products and corresponding sea-level measurements and plots of spectral reflectance are shown in Fig. 5. For each image only one of the reflectance measurement systems was operational (TriOS for 19.7.2002 because cloud cover degrades the SIMBADA data and SIMBADA for 29.7.2002 because of damage to the TriOS system).

Table 3. Match-up comparisons – for image 19.7.2002 (top) and 29.7.2002 (three pixels).

Station 130, 19.7.2002	MERIS [standard deviation]	In situ
Time (UTC)	10:44	09:41
Reflectance 442nm	0.0309 [0.0037]	0.0331 (442.5nm)
Reflectance 559nm	0.0674 [0.0100]	0.0766 (560nm)
Reflectance 709nm	0.0229 [0.0081]	0.0256 (710nm)
Reflectance 753nm	0.00835 [0.0024]	0.0080 (752.5nm)
Algal pigment 2 (µg/l)	8.34 [1.21]	6.49
Total Suspended matter (mg/l)	10.9 [3.9]	12.60
Aerosol optical thickness 865nm	0.0630 [0.025]	-
Aerosol epsilon factor	1.00 [0.00]	-

Station 130, 29.7.2002	MERIS	In situ
Time (UTC)	10:30	09:35
Reflectance 442nm	0.0270 [0.0024]	0.0203 (443nm)
Reflectance 559nm	0.0467 [0.0038]	0.0497 (565nm)
Reflectance 709nm	0.0130 [0.0027]	
Reflectance 753nm	0.00571 [0.00082]	0.0030 (750nm)
Algal pigment 2	8.81 [0.66]	5.33
Total Suspended matter	8.49 [2.00]	15.07
Aerosol optical thickness 865nm	0.0882 [0.0045]	0.146 (870nm)
Aerosol epsilon factor	1.043 [0.014]	1.183

Station 230, 29.7.2002	MERIS	In situ
Time (UTC)	10:30	10:07
Reflectance 442nm	0.0270 [0.0034]	0.0179 (443nm)
Reflectance 559nm	0.0461 [0.0061]	0.0459 (565nm)
Reflectance 709nm	0.0140 [0.0014]	
Reflectance 753nm	0.00560 [0.00039]	0.0026 (750nm)
Algal pigment 2	9.82 [1.06]	8.29
Total Suspended matter	9.82 [1.33]	8.67
Aerosol optical thickness 865nm	0.0756 [0.0033]	0.137 (870nm)
Aerosol epsilon factor	1.035 [0.015]	1.179

Station MC5, 29.7.2002	MERIS	In situ
Time (UTC)	10:30	11:00
Reflectance 442nm	0.0207 [0.0019]	0.0096 (443nm)
Reflectance 559nm	0.0271 [0.0047]	0.0249 (565nm)
Reflectance 709nm	0.00649 [0.00110]	
Reflectance 750nm	0.00336 [0.00036]	0.0016 (750nm)
Algal pigment 2	7.09 [0.53]	2.82[1]
Total Suspended matter	3.69 [0.74]	5.67
Aerosol optical thickness 865nm	0.0882 [0.0033]	0.145 (870nm)
Aerosol epsilon factor	1.047 [0.005]	1.181

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[1] The value given here is for the HPLC Chl2 as measured on a GF/F filter at 0.5m depth. A second sample taken 6 minutes earlier at 3m and analysed for a GF/C filter (MUMM's standard monitoring protocol) gave Chl2=7.53 µg/l. The difference might be attributed to patchiness caused by a Noctiluca bloom.

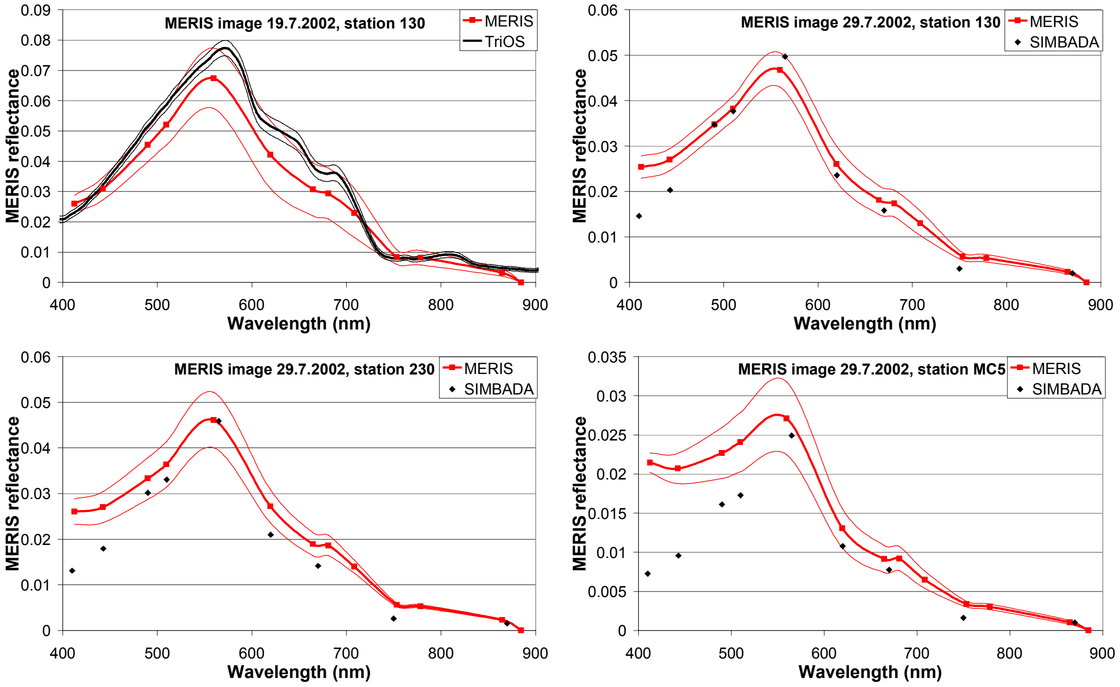

Figure 5. Comparison of MERIS water-leaving reflectance with seaborne reflectance measurements (TriOS system for 19.7.2002, SIMBADA for 29.7.2002). The MERIS match-up pixel is shown as a thick red curve (smoothed between bands) with surrounding thin red curves showing spatial variability via the standard deviation of the surrounding 3*3 pixel block. The SIMBADA measurements are shown as black diamonds and the TriOS hyperspectral measurements are shown as a thick black line with standard deviation over the replicates shown as surrounding thin black lines.

8. DISCUSSION – QUANTITATIVE ANALYSIS

Comparison of the MERIS and TriOS reflectance spectra for station 130 of the 19.7.2002 image shows agreement to within the standard deviation of spatial variability (10-30%) of the adjacent MERIS pixels. While this spatial variability (related to atmospheric conditions) is clearly significant, it is notable that excellent agreement is found between the MERIS and TriOS measurements in the near infrared (700-860nm), a region where direct validation of satellite measurements of water-leaving reflectance has not before been attempted. Good agreement also in the blue indicates that no serious problems have been encountered in correcting for turbid water effects in the atmospheric correction. It is noted that ε for this station is given by MERIS as exactly 1.00 for this and surrounding pixels. Such values are suspicious and may be related to a software or algorithm malfunction.

For the 29.7.2002 image a more detailed quantitative analysis can be performed. In Table 3 there are clear discrepancies between MERIS and the SIMBADA measurements for aerosol optical thickness and epsilon factor. Moreover the comparison of water-leaving reflectances shows an increasing difference going from red to blue. From inspection of the spectra alone, especially for station MC5 where the MERIS spectrum has unrealistically higher reflectance at 412nm than at 443nm, it is deduced that the MERIS spectrum is in error for the blue spectral range (400-500nm). The spectral shape of this error, increasing towards the blue, is clearly related to underestimation by MERIS of both the aerosol optical thickness and the epsilon factor as corroborated by the corresponding aerosol measurements presented in Table 3. The cause of this underestimation is likely to be an overestimation of near infrared water-leaving reflectances in the case 2 atmospheric correction algorithm. It is noted that for these waters the « absorbing aerosols – dust » flag was raised, whereas for the nearby water on the other (false) side of the case 2S flag front the « absorbing aerosols – continental » flag was raised.

On the basis of the small number of available match-up pixels and the similar range of concentrations found for Chl2 and TSM it is difficult to establish the accuracy of these MERIS products. However, it is encouraging that MERIS and in situ values are comparable for these products and that no obvious problems can be detected.

9. CONCLUSIONS AND RECOMMENDATIONS

A qualitative and a quantitive analysis have been made of two MERIS images for the Southern North Sea corresponding to match-up sea-level data in Belgian waters.

The image of 19.7.2002 contains scattered clouds and haze and is not optimal for validation of water products, but has been used primarily for validation of flags. A number of problems are noted :

- Many cloudy pixels have not been identified as such. The resulting water products are, thus, highly inaccurate, though this is not obvious from the level 2 flags. It is recommended that MERIS validation consider more carefully validation of flags, and especially the cloud pixel identification flag, in order to avoid unreliable data reaching users.
- Patches of atmospheric correction failure are also found, though no explanation could be given. It is recommended that this anomaly be investigated in the context of any similar problems found in other regions.

For a clear pixel in this image, comparison of MERIS water-leaving reflectance with seaborne measurements show agreement to within the spatial variability (10-30%) of surrounding MERIS pixels, for the entire spectrum 412-865nm. The agreement in the near infrared is particulary encouraging and indicates effective estimation of turbid water effects for the case 2 atmospheric correction. However, a suspicious ε value of exactly 1.00 for some pixels is noted.

The image of 29.7.2002 has clear skies over Belgian waters and is optimal for validation of water products. Comparison of MERIS and sea-level SIMBADA measurement of aerosol optical thickness and epsilon factor show significant differences and corresponding errors in the blue for water-leaving reflectance indicating severe overestimation of turbid water effects in the case 2 atmospheric correction. Moreover, the spatial discontinuities in the case 2S flag induce severe and unrealistic discontinuities in the aerosol epsilon factor and optical thickness and, hence, all water products. It is recommended that the performance of the case 2 atmospheric correction be further investigated and that the case 2S flag be modified (perhaps set true everywhere) to avoid unrealistic discontinuities.

On the basis of the limited data available and the restricted range of concentrations it is difficult to draw clear conclusions regarding the Chl2 and TSM products, though it is notable that no obvious problems have been detected.

It is clear, however, that the present study is made on the basis of only two images and the scope of conclusions is, thus, clearly limited. A more general assessment of MERIS performance could be made after analysis of more imagery and in particular the image of 16.7.2002, unavailable at the time of writing, and for which the best sea-level validation measurements exist (concurrent measurements of water-leaving reflectance by both TriOS and SIMBADA systems).

Notwithstanding the discrepancies noted above, the performance of both the sensor and the algorithms seems impressive for this stage of the system life-time. Optical remote sensing of turbid coastal waters with high yellow substance absorption is notoriously difficult because of the need to consider near infrared water-leaving reflectances in the atmospheric correction algorithm[6] and the difficulty to distinguish between chlorophyll absorption and yellow substance absorption in the inversion of water-leaving reflectances with a bio-optical model[20]. The MERIS sensor and algorithms are arguably the first to be designed to meet such a challenge.

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