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VALIDATION OF MERIS WATER PRODUCTS FOR BELGIAN COASTAL WATERS: 2002-2005

Y. Park[(1)], B. Van Mol[(2)] and K. Ruddick[(3)]

Management Unit of the North Sea Mathematical Models (MUMM),Royal Belgian Institute for Natural Sciences (RBINS),100 Gulledelle, B-1200 Brussels, Belgium
Email: [(1)]Y.Park@mumm.ac.be, [(2)]B.VanMol@mumm.ac.be, [(3)]K.Ruddick@mumm.ac.be,

ABSTRACT

This paper describes the validation of MERIS water products for Belgian waters for the period July 2002 to August 2005. During this period, 23 match-ups were obtained for the parameters, water-leaving reflectance spectra, chlorophyll *a* concentration and total suspended matter concentration, of which 7 are in optimal conditions. The water-leaving reflectance comparison shows good agreement in green and red bands but worse in blue bands, which might indicate the need for further improvement in estimation of the spectral slope of aerosol reflectance. The chlorophyll concentration analysis is inconclusive due to the limited range of the case 2 chlorophyll in the match-ups while the total suspended matter error is about 59% for match-up data. Finally, comparison of two MERIS processors shows that improvements are necessary in atmospheric correction at highly turbid pixels and in chlorophyll image quality.

1. INTRODUCTION

Since launch on 1st March 2002, the Medium Resolution Imaging Spectrometer (MERIS) has successfully acquired images all around the Earth until the present (June 2006). During this period, a number of cruise measurements were made at the time of the MERIS overpasses for acquiring match-up data. The previous MERIS validation reports ([1] and [2]) describe the 2002 and 2003 match-up data, focusing on the validation of the water-leaving reflectance spectra ($\rho_w(\lambda)$) and the visual inspection of the images of algal pigment index 2 (Algal2 or Chl2) and total suspended matter (TSM).

Since then, the MERIS processor has been updated a few times with the latest official version corresponding to the "2nd reprocessing" (MEGS7.4)[3]. Also many match-ups in Belgian coastal and North Sea waters were added in 2004 and 2005. In this paper, the latest MERIS products are compared with the match-up measurements in order to estimate errors in the MERIS water products and to make recommendations for future improvements.

2. OVERVIEW OF MEASUREMENTS

Validation measurements have been made during a series of seaborne cruises in Belgian, Dutch, French and UK coastal waters and in open sea on the transect Cadiz (Spain) – Cork (Ireland) – Zeebrugge (Belgium), from the oceanographic Research Vessels Belgica (51m), Zeeleeuw (56m) and Tuimelaar (7m).
Tab. 1 summarizes 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 minimize uncertainties associated with temporal variability of marine and atmospheric properties. The "best" match-up stations after filtering with MERIS PCD flags will be described in section 4.1.

Table 1. Summary of MERIS Validation cruises undertaken in 2002-2005 and corresponding MERIS match-up possibilities.

Month	Days at sea	Potentially optimal match-up images	Sub-optimal match-ups images
Mar 2002	5	0	0
Apr 2002	8	0	0
Jun 2002	4	0	1
Jul 2002	5	3	1
Oct 2002	1	0	0
SUBTOTAL 2002	**23**	**3**	**2**
Mar 2003	2	0	0
Apr 2003	4	2	1
Jun 2003	7	1	0
Jul 2003	4	1	0
Aug 2003	2	1	0
Sep 2003	5	0	0
SUBTOTAL 2003	**24**	**5**	**1**
May 2004	8	0	0
Jun 2004	1	0	0
Jul 2004	6	1	0
SUBTOTAL 2004	**15**	**1**	**0**
Apr 2005	5	1	0
May 2005	2	1	1
Jun 2005	14	2	1-2
Jul 2005	3	0	0
Aug 2005	2	1	0
Sep 2005	4	0	1
SUBTOTAL 2005	**30**	**5**	**3-4**
TOTAL	**92**	**14**	**6-7**

3. MEASUREMENT METHODS

At each station measurements of seaborne water-leaving reflectance, Algal2 and total suspended matter are made, following measurements methods based on the MERIS validation protocols [4] and described hereunder.

3.1 Water-leaving reflectance

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

3.1.1. 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 [5] and detailed in Web Appendices 1 and 2 of [6]. The water-leaving reflectance, ρ_w , as defined in the MERIS product, is then calculated by,

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

where the air-sea interface reflection coefficient, ρ_{as} , is estimated for sunny conditions [6] as function of wind speed in m/s, W :

$$\rho_{as} = 0.0256 + 0.00039 * W + 0.000034 * W^2 \qquad (2)$$

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 and is fixed to the prow of the ship facing forwards to minimize ship shadow and reflection.

3.1.2 TriOS system data processing, quality control and measurement uncertainty

The data processing of the TriOS measurements is described in Web Appendix 1 of [6], see http://www.aslo.org/lo/toc/vol_51/issue_2/1167a1.pdf, which includes details of scans rejected because of high inclination, large temporal fluctuations (spikes) and possible instrument malfunctioning. For the present study the stations considered as optimal matchups all fulfill the clear, sunny skies conditions given in [6] as $L_{sky}/E_d^+(750nm) < 0.05$ and the sea state condition of wind speed < 10 m/s necessary for optimal above-water measurements. For some of these stations the standard deviation of the 5 scans used for reflectance measurement exceeded 10% of the mean reflectance for some wavelengths in the red and near infrared(NIR). These stations are not rejected in the present study, but the temporal variability over the 5 scans is presented.

The measurement uncertainty for the TriOS measurements is described and evaluated in detail in Web Appendix 2 of [6], see http://www.aslo.org/lo/toc/vol_51/issue_2/1167a2.pdf for near infrared wavelengths. The instrument calibration uncertainty (including laboratory calibration uncertainty, temporal drift and polarization sensitivity) is relatively limited, typically 3-4% and spectrally rather flat. However, the measurement uncertainty associated with correction for the air-sea interface reflection can be significant for low reflectance measurements. It is shown in [6] that the *absolute* reflectance error associated with the air-sea interface correction is proportional to $L_{sky}/E_d^+(\lambda)$, which is independent of water reflectance (as is intuitively obvious) and relatively constant in time and space (sun zenith angle) for the clear, sunny sky conditions considered here in a ocean colour validation context. The *relative* reflectance error is therefore inversely proportional to reflectance itself and hence most significant for clear waters and for the red and NIR. Supposing a typical uncertainty of $\Delta\rho_{as} = 0.003$ for low/moderate wind conditions and using typical $L_{sky}/E_d^+(\lambda)$ spectra from [6], the corresponding absolute reflectance uncertainty, $\Delta\rho_w$, is given spectrally in Tab. 2 (uncertainties for intermediate wavelengths can be deduced approximately by interpolation). For the spectra presented here these absolute uncertainties correspond to about 3-10% uncertainty at 412nm and less than 2% at 560nm. Percentage uncertainties can be more significant in the NIR, but the absolute uncertainties are generally too small to be visible in the spectral plots shown later.

Table 2. Reflectance measurement uncertainty associated with correction of the air-sea interface reflection for typical clear, sunny sky and low/moderate wind conditions.

λ(nm)	400	500	600	700	800	900
L_{sky}/E_d^+	0.0934	0.0483	0.0297	0.0204	0.0154	0.0121
$\Delta\rho_w$	0.00088	0.00046	0.00028	0.00019	0.00015	0.00011

In addition to these *a priori* estimates of measurement uncertainty, *a posteriori* estimates can be made for each reflectance spectrum based on the similarity spectrum for the NIR water-leaving reflectance as described in [7]. For the spectra presented here this method yielded estimates of water-leaving reflectance error in the NIR ranging from 0.0001 to 0.001.

3.1.3. 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 [5] and described in detail in [7]. The MERIS product is then calculated by,

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

where $L_{sky-corr}$ is a correction for residual skylight reflected at the air-sea interface and passing through the polarizing filter. Details of practical operation are given in the SIMBADA user's guide (http://www-loa.univlille1.fr/recherche/ocean_color/src/).

The SIMBADA system is only used in 2002-2004 and only for clear sun and low cloud (<2/8) conditions.

For stations where both TriOS and SIMBADA systems were used reflectance measurements are generally within about 5% for the range 412-620nm giving confidence in the methods which differ significantly in treatment of air-sea interface reflection.

3.2 Algal pigment index Chl2 (Algal2)

The algal pigment index Chl2 is validated as defined in the MERIS validation protocols [4] 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 [8]. The chlorophyll pigments are separated with reversed phase HPLC.

3.3 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 [9] based on [10]. Further water samples are taken at 3m depth and measurements were made on GF/C filters for comparison with the conventional water quality monitoring program of MUMM – the latter measurements which do not conform to the MERIS validation protocol are not presented here.

4. RESULTS

4.1. Match-up stations

During the period of 2002-2005, in total 23 "potentially optimal" match-ups (14 match-up images) were obtained as listed in Tab. 3, which have optimal sea-state condition, clear sky and less than ~1hr time difference to MERIS overpass. Fig. 1 shows the locations of these match-up stations.

Table 3. Match-up stations. The stations in red bold face are accepted for subsequent analysis while the stations in italic font were excluded by match-up selection criteria (see text).

date	Stations	Time diff.	Flags	Remark
20020716	*130*	55min		Geolocation error
	230	9min		
20020719	*130*	62min	H_Glint	
20020729	*130*	55min	PCD1_13	
	230	22min		
	MC5	65min	PCD1_13	
20030422	**230**	16min		
	MC5	68min		
20030423	**230**	4min		
20030616	**MC16**	9min		
20030710	*230*	54min	H_Glint	
	MC4B	8min	H_Glint	
20030805	*130*	17min	H_Glint	
	230	31min	H_Glint	
20040713	*MH3*	80min	H_Glint	
	MH4	25min	H_Glint	
20050427	**435**	10min		
20050531	**CC2**	1min		
20050603	*CC5*	9min		Heavy ship rolling
20050628	*MH1*	33min	H_Glint	
	MH2	67min	H_Glint	
20050822	*130*	10min	PCD1_13	
	230	58min	PCD1_13	

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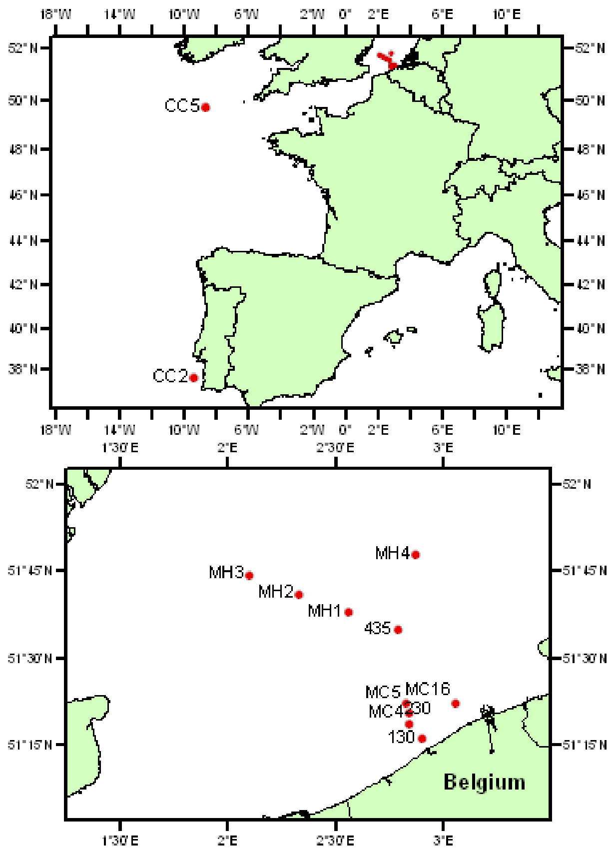

Figure 1 Locations of match-up stations: all stations (top) and southern North Sea stations (bottom).

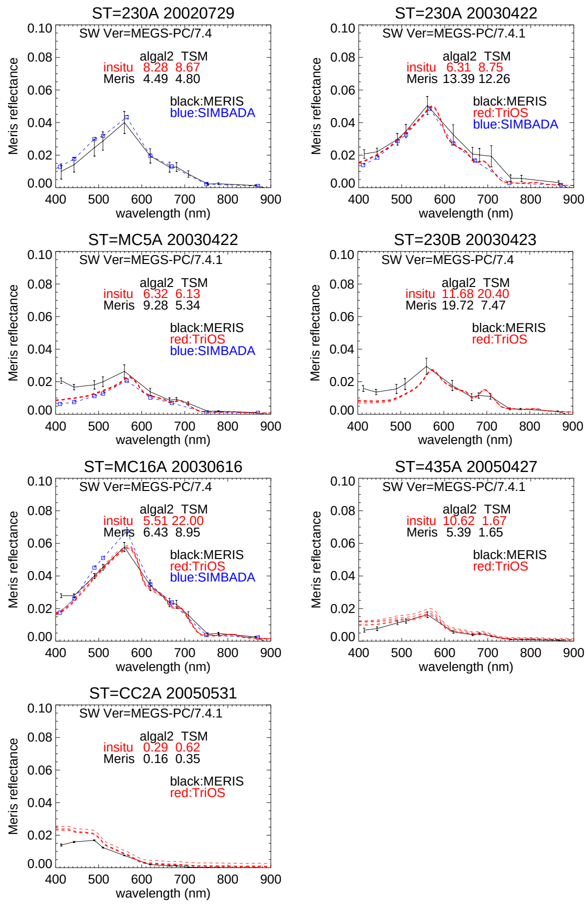

Figure 2. MERIS and seaborne measurements comparison for the seven best match-ups. For the MERIS spectra, mean (solid lines) and standard deviation for the surrounding 3x3 box are indicated. For the TriOS spectra (dotted red lines), the five replicate measurements are shown.

The majority of the match-ups are classified as turbid case 2 water, except stations CC2, CC5, MH1, MH2 and MH4.

Of these match-ups, nine stations (four images) were affected by high glint, indicated as H_Glint in the "Flags" column, and four stations have negative MERIS reflectance in the blue indicated as PCD1_13 in the Flags column. The 20020716 MERIS image has geolocation error and the 20050603 CC5 data was influenced significantly by heavy ship rolling. After exclusion of these 16 stations, indicated in italic font above, finally the seven "best" match-ups remain as indicated in red bold face.

Statistics such as coefficient of determination (R^2), error and regression slope and offset are presented in this section for quantitative comparison. As error indicator, the root-mean-square error (RMSE) is used for water-leaving reflectance and relative error for Chl and TSM.

4.2. Water-leaving reflectance spectra

Fig. 2 shows the satellite-seaborne comparison for these seven match-ups. In general, water-leaving reflectance spectra match well between MERIS (continuous black curves) and seaborne (dashed red or blue curves) measurements, indicating that the turbid atmospheric correction works reasonably. However, a larger difference at blue bands esp. at 412nm can be seen for several stations such as 20030422 MC5, 20030616 MC16 and 20050531 CC2.

4.3. Water-leaving reflectance scatter plots

For the seven best match-ups, scatter plots of MERIS versus seaborne reflectance are shown in Fig. 3 as blue squares for six bands. The 560, 620 and 665 bands show excellent agreement while blue, especially 412nm, and NIR, 753nm, bands show lower correlation. The statistics for each band is listed in Tab. 4. It is clear that the green to red bands (488-680) shows R^2 values higher than ~0.9 and slopes close to 1, indicating good agreement between MERIS and seaborne measurements. On the other hand, low correlation is seen at both edges

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of the wavelength range, blue and NIR. At the NIR bands (753, 778 and 865nm) the absolute error, RMSE is small, indicating that the low correlation at NIR bands could be due to relatively weak signal. On the contrary, low correlation at blue bands (412, 443 nm), where RMSE is large is considered due to the extrapolation error in the aerosol reflectance. Therefore, further improvement should be made for accurate estimation of aerosol spectral properties (e.g. Angstrom exponent). This improvement could be achieved by more accurate estimation of NIR reflectance or by improving aerosol model selection, although how to achieve this is beyond the scope of this report.

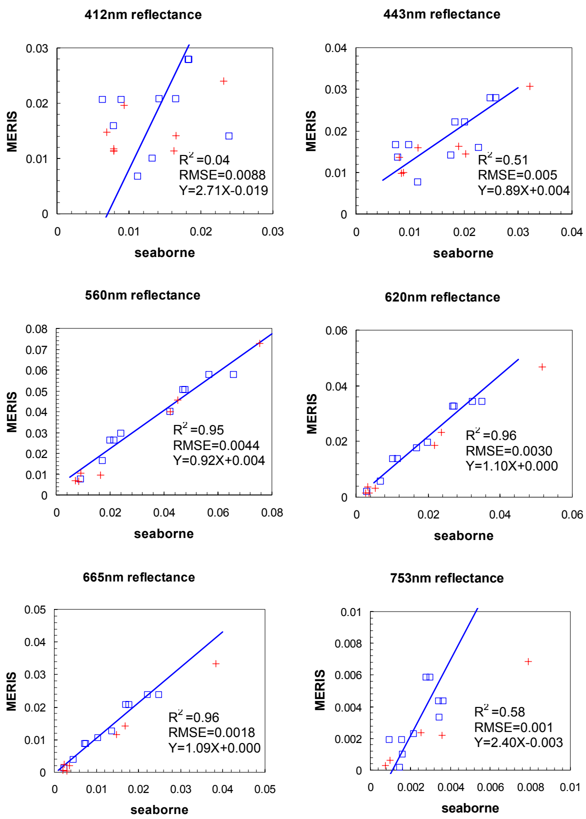

Figure 3. MERIS vesus seaborne water-leaving reflectance for selected six bands. High-glint pixels are indicated as red. Regression (blue solid lines) was done for best match-ups only.

High-glint match-ups are shown as red crosses in Fig. 3, although they are not included for statistical analysis. Interestingly, many of them are within the variability of the best match-ups. Glint reflectance is relatively weak in Belgian waters or higher latitudes. This implies that some of high-glint pixels could be used if , for example, a high-glint threshold is applied depending on the reflectance of the pixel.

Table 4 Statistics of water leaving reflectance comparison, MERIS vs in-situ. R2 and RMSE represent correlation coefficient and root-mean-square error. Slope and offset are derived from the reduced major axis fitting.

λ(nm)	R^2	RMSE	slope	offset
413	**0.04**	0.0088	***2.71***	*-0.019*
443	**0.51**	0.0052	*0.89*	*0.0034*
488	0.88	0.0043	0.81	0.0049
510	0.91	0.0043	0.86	0.0046
560	0.95	0.0044	0.92	0.0039
620	0.96	0.0030	1.10	-0.0003
665	0.96	0.0018	1.09	-0.0005
680	0.94	0.0026	1.20	-0.0007
709	0.74	0.0041	1.58	-0.0027
753	**0.58**	0.0015	***2.40***	*-0.0027*
778	**0.64**	0.0016	***2.52***	*-0.0025*
865	**0.58**	0.0008	***2.98***	*-0.0026*

4.4. CHL comparison

Fig. 4 shows comparison of CHL products combining algal1 and algal2 by choosing the appropriate product according to the Case2 flag. This comparison has R^2=0.81 and relative error=52%. Algal1 and algal2 vary over 0.2-2 mg/m3 and 5-12 mg/m^3 respectively in the match-up data. It is noted that, if very low algal1 is excluded, algal2 shows much less correlation. For a clearer analysis of the algal2 accuracy it would be necessary to have a wider range of algal2 match-up values.

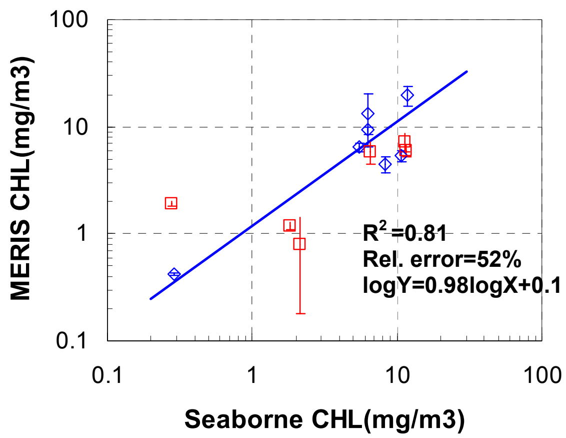

Figure 4. MERIS versus seaborne Chl: Best match-ups in blue and sun-glint affected match-ups in red. Error bar indicates standard deviation for 3x3 surrounding box.

4.5. TSM comparison

Fig. 5 shows TSM comparison, showing R^2=0.86 and rel. error=59%. The TSM ranges from below 1 to 22g/m^3. Considering the sub-pixel scale (<1km) variability of in-situ TSM distribution, which is often found in shallow coastal waters, MERIS TSM seems reasonable. This may indicate that MERIS estimates reflectance with an accuracy high enough for TSM estimation, although higher accuracy may be required for algal2 or yellow substance estimation.

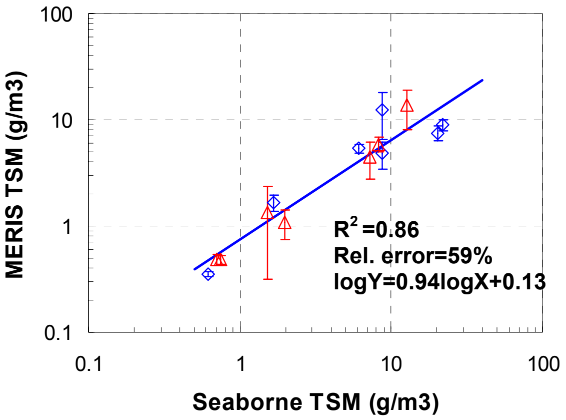

Figure 5. MERIS versus seaborne TSM: Best match-ups are in blue and sun-glint affected match-ups in red. Error bar indicates standard deviation for 3x3 surrounding box.

5. REMARKS ON MERIS PROCESSOR VERSIONS

The 20050822 match-up shows a significant difference between two MERIS processor versions, previous ("MERIS/4.1") and latest ("MEGS7.4"). This match-up was good in the "MERIS/4.1" version without PCD1_13 flag raised. However, in the "MEGS7.4" version, PCD1_13 was set for both stations shown in Tab. 3.

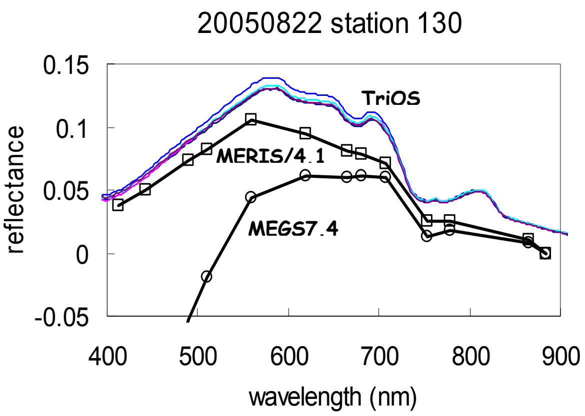

Figure 6. MERIS water-leaving spectra for different processor versions - station 130 of 22. 08. 2005. MERIS spectra are shown in thick lines: square for MERIS/4.1 and circle for MEGS7.4. Five insitu spectra measured using TriOS are shown as thin lines.

Fig. 6 shows the water leaving reflectance spectra from two processor versions. The "MEGS7.4" spectrum is clearly worse than the "MERIS/4.1" spectrum for this particular very turbid match-up. From Fig. 6, it is thought that this difference might be related to the aerosol model and possibly to the NIR water reflectance ratio. However, a full inspection of aerosol spectral reflectance (not available) is needed to clarify.

The Chl images from the two versions also look quite different for the 2005.08.22 image as shown in Fig. 7. Pixels where PCD flag was set were masked by grey. MEGS7.4 shows more pixels valid than MERIS/4.1, which is good. However, in the MEGS7.4 image (left), very low Chl (blue) patches are visible along the Belgian-Dutch coast. This is probably wrong because such a low Chl and high spatial irregularity is not expected. It's not clear whether it comes from atmospheric correction or the in-water NN algorithm. This irregularity should be fixed urgently since Chl images in coastal areas are widely used for applications.

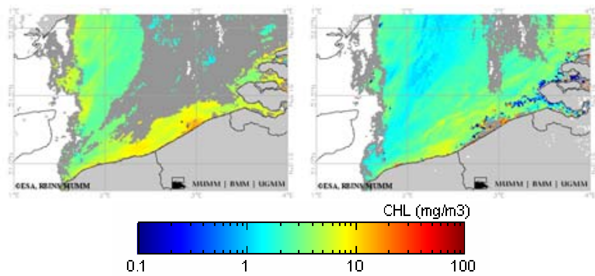

Figure 7. MERIS Chl images of 22.08.2005 for southern North Sea from processors MERIS/4.1(left) and MEGS7.4 (right). In the images, white is cloud, light grey is land, and dark grey is pixels where the PCD flag is set.

6. SUMMARY AND RECOMMENDATION

After filtering the original set of 23 match-ups with sea-state condition, sky/cloud condition, less than 1 hour time difference, and PCD flags, the seven best match-ups were obtained, and have been used to estimate the MERIS product errors.

The water-leaving reflectance comparison shows acceptable agreement in the green to red spectral region while blue and NIR bands are less accurate. This could indicate that the aerosol spectral properties are not retrieved accurately enough. It is recommended to investigate the spectral properties of the selected aerosol models to improve the blue reflectance comparison.

The Chl comparison shows that MERIS Chl could agree well with in situ measurements if low values in case 1 waters and high values in case 2 waters are put together. However, when considering algal2 alone, the match-ups shows much less correlation in the 5-12mg/m^3 range. Obviously, a wider range of Chl2 data is needed to draw a conclusion regarding the quality of the algal2 products. Therefore it is recommended to collect and analyse all the match-ups from all MAVT members.

The TSM comparison shows 60% error, which could be reasonable considering the small scale variability in shallow coastal waters can deteriorate the TSM comparison with water sample data.

From the 20050822 match-up, it is shown that the MEGS7.4 processor needs to be further improved in atmospheric correction for very turbid pixels and also that the spatial irregularity in Chl images should be fixed.

Many of the high-glint flagged pixels seem usable in Belgian waters or higher latitudes. It is recommended to investigate a new high-glint threshold depending on the water-reflectance in order to increase data usability.

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