Delivery report

PV-LAC: advances Land, Aerosol and Coastal products for Proba-V

PV-LAC: D-1-A3 Requirements Baseline Document Activity 3

Sindy Sterckx, Nitin Bhatia, Els Knaeps

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Author(s)	:	Sindy Sterckx, Nitin Bhatia, Els Knaeps
Reviewer(s)	:	Philippe Goryl, Fabrizio Niro
Approver(s)	:	Philippe Goryl, Fabrizio Niro
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CHANGE RECORD

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V1.1	23/05/2016	13	Sentence added/modified "To obtain an increased temporal coverage the dredging sector is interested in combining TSM/T products from different sensors. As one single sensor provides only limited information on the TSM dynamics in the areas of interest to the dredging industry."	Sindy Sterckx	Philippe Goryl, Fabrizio Niro, Else Swinnen
		14	Temporal frequency		
		14	Probability discussion remove in Table 1 as this is related to prediction/forecasting models and out of the scope of PVLAC. Out of scope clarified.		
		16	Pixel-by-pixel replaced with per pixel (P 18)		
		19	Reference Viollier et al., 1980 and Neuckermans et al., 2009 added.		
		19	Pixels probably affected by sun glint can be flagged based on sun and view geometry information. (sentence added)		
		19	a wind speed mask could be applied in processing based on ECMWF wind speed data if available (sentence added)		
		19	Distinction between Rayleigh (air molecules) scattering (ρ_r) and transmittance (T_r) clarified		
		19	Oxygen gaseous transmittance added		

		20	Typo corrected : Waters		
		25	BPAC (instead of BWAC)		
		35	While		
		22	Sentence changed (p22): A drawback of using a RED and a NIR band, instead of 2 NIR bands is that the assumption of a constant ratio of water reflectance is only valid for SPM concentration of ~ 27 g		
		31	Caption of Figure 2 changed.		

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LIST OF ACRONYMS

A/C	Atmospheric correction
AOT	Aerosol Optical Thickness
BEAM	Basic ERS & ENVISAT (A)ATSR and MERIS
BWAC	Bright Pixel Atmospheric Correction
CDOM	Colored Dissolved Organic Matter
CHL	Chlorophyll ; the concentration of chlorophyll-a (mg m^{-3})
C2R	Case-II Regional processor
DDV	Dense Dark Vegetation
EO	Earth Observation
IOP	Inherent Optical Properties
LUT	Look-Up-Tables
MODIS	Moderate Resolution Imaging Spectroradiometer
MOMO	Matrix Operator Model
NAP	Non-Algal Particles
NIR	Near Infrared Red
PROBA-V	Project for On-Board Autonomy - Végétation
SIOPS	Specific Inherent Optical Properties
SNR	Signal-to-Noise Ratio
SPM	Suspended Particulate Matter
SWIR	Short-Wave Infrared
T	Turbidity
TOA	Top Of Atmosphere
TSM	Total Suspended Matter
WQ	Water Quality
WFD	Water Framework Directive
WMS	Web Map Service

CHAPTER 1 INTRODUCTION

The aim of this document is to make a critical review of the algorithms for TSM retrieval and atmospheric correction in turbid coastal waters, to identify the most suitable method (TSM and A/C method) for PROBA-V, to define the validation approach (including identification of the validation data and test sites) and to assess the utility and benefits of 100m coastal products through interaction with the user community.

The structure of the document is as follows :

In CHAPTER 2 an understanding of user requirement for PROBA-V 100 m coastal products, as derived from projects with similar activities/products as PV-LAC and face-to-face discussions with the dredging section, is given.

In CHAPTER 3 a literature review of existing atmospheric correction algorithm for coastal waters is performed and their applicability to PROBA-V data is discussed.

Algorithms for TSM/Turbidity retrieval are reviewed in CHAPTER 4 and the choice of the proposed TSM algorithm for PROBA-V is discussed.

Finally, the validation approach, the needed validation data and test sites is discussed in CHAPTER 5

CHAPTER 2 REVIEW OF USER REQUIREMENTS

To assure that the coastal products developed within this proposal respond to the specific user needs and expectations and to evaluate the usefulness and benefits of a 100 m coastal product, a user requirement assessment at an early stage of the project is required.

The user requirement assessment has been done based on face-to-face discussions with users from the dredging sector and review of documentation on user requirements available from various projects with similar activities (e.g. CoBiOS, CoastCololour, Inform). At the time of writing, user requirements from the Highroc project were not available to the public. If they become available or can be made public, an update of the user requirements will be made.

2.1. THE DREDGING SECTOR

The dredging sector (including dredging companies, oil and gas companies, environmental consultants and port authorities) is one of the main user groups. Dredging activities are ongoing worldwide to construct new ports, to assure access to ports, to construct new islands and new canals. In most of the dredging projects there is a huge demand for environmental information where remote sensing can play an important role.

In the last 6 months we attended several conferences, workshops and visited several companies in the dredging sector to discuss their used needs. A short overview of the meetings is provided:

- 5-6 November 2015, Dredging Days, oral presentation

  Website: http://www.cedaconferences.org/dredgingdays2015

- 29 January 2016, meeting Boskalis (dredging company)

  Website: http://www.boskalis.com/

- 23-24 March 2016, World Water Works, booth

  Website: http://www.worldwaterworks.nl/

- 20 April 2016, meeting IMDC (environmental consultancy)

  Website: http://www.worldwaterworks.nl/

- 28 April 2016, meeting DEME (dredging company)

  Website: http://www.deme-group.com/

The meetings and workshops provided information on the way environmental information is collected now, how remote sensing can contribute and their current experience with remote sensing.

Environmental impacts of a dredging operation are mainly monitored with in situ turbidity sensors linked to sediment transport models. Remote sensing is finding its way in the dredging industry but the use is still limited to the ad-hoc monitoring of background concentrations (baseline data against which future information can be compared) and visual site inspection.

The dredging sector has a clear interest to use remote sensing to monitor the background concentrations (i.e. natural variability), to monitor the sediment plume generated during dredging, to specify and evaluate the location of in situ turbidity buoys and to calibrate and validate the sediment transport models.

Requirements:

- **Near real-time** (e.g. 12-24 hours after the image is available from the satellite ground station) **TSM** concentration maps of the study sites, during and after the dredging works. TSM is of prime interest because thresholds are expressed in mg L-1. **Turbidity** could be an alternative product in several cases were TSM-turbidity relationships are known. The products can be used, in combination with in situ data and modelling, to study the sediment plumes generated during dredging. By providing a complete 2D coverage of the site of interest, they can identify the direction and extent of the complete dredging plumes. Further, they allow to distinguish natural sediment (e.g. from a river) plumes from the dredging plumes and can prevent any incorrect interpretation of the available in situ stationary measurement data. For near real-time monitoring a spatial resolution of 100-200 m or 30 m is acceptable. A 100-200 m product is sufficient in areas with high currents where sediment plumes can extend up to several km. A 30 m product is preferred in areas with low current and plumes in the order of 100 meter.
- **Historical** (min. 1 year) time series of the TSM concentration. New projects are often carried out in remote locations with little or no historical baseline data**.** And even when limited information is available, spatial & seasonal dynamics of the region are not known. Hence**,** remote sensing can give historic information on the surface suspended sediment for the site of interest which may in some cases provide a first source of information**. A spatial resolution of 100-200 m i**s acceptable.
- The dredging sector has a clear need for **more frequent data** to not only monitor the background concentrations but also monitor the sediment plume generated during dredging. To obtain an increased temporal coverage the dredging sector is interested in combining TSM/T products from different sensors. As one single sensor provides only limited information on the TSM dynamics in the areas of interest to the dredging industry.
- TSM maps should be preferably presented in GEOTIFF format, downloadable preferably by FTP or WMS in the framework of a more operational service
- TSM maps should be accompanied with a RGB map for visual inspection
- Required accuracy of TSM maps. For historical background maps the order of magnitude is essential. For near real time maps an **absolute accuracy** in the order of 10-20% error seems appropriate (they will still rely on in situ turbidity meters for official reporting).
- The areas of interest to IMDC are different coastal regions across the world where dredging activities are ongoing (e.g. areas in Panama, Doha, Uruguay, Australia,..).

2.2. Sediment transport modelling Community

Through regular informal contacts with the sediment transport modelling community their remote sensing needs were collected and the added value of a Proba-V TSM products was evaluated. A list of contacts is provided:

→ **RBINS-MUMM**

The Management Unit of the North Sea Mathematical Models and the Scheldt estuary, MUMM, is a department of the Royal Belgian Institute of Natural Sciences (RBINS). MUMM studies the ecosystems of the North Sea using mathematical modelling techniques and collects marine information required to validate the models and make them operational. The Remote Sensing and Ecosystem Modelling team (REMSEM) is specialized in the development and use of remote sensing.

→ **KULEUVEN, Department of Civil Engineering, Hydraulics Section**

The research activities at the Hydraulics Section KU Leuven and the Coastal Engineering Unit focus on process understanding and numerical modelling of hydrodynamics (currents and waves) and sediment mechanics (sand, mud and sand-mud mixtures). Applications are mainly in the coastal zone including estuaries and in shelf seas.

-> Deltares

Deltares is a large independent research institute focusing on rivers and coastal areas. They are known worldwide for the development of sediment transport models.

-> IMDC

International Marine and Dredging Consultants, IMDC, is a private consultancy specialized in a large variety of water related projects. One of their key expertise is sediment transport modelling, where they assist dredging companies and government agencies.

All see a clear potential in PROBA-V 100 m data in the frame of a multi-mission concept for sediment modelling purposes. There is no direct interest in the daily PROBA-V 300 m data as similar resolution and frequency is provided by Ocean Color sensors. The 5-daily 100 m PROBA-V data, on the other hand, fills the gap between the daily lower resolution data provided by MODIS/S3 and the high resolution data (in the order of 20m-50m) provided by missions as Landsat-8 or Sentinel-2 at a lower temporal frequency.

In the case of RBINS-MUMM, they have in-house capacity to process remote sensing data up to TSM maps, and are mainly interested in PROBA-V 100 m (projected) at-sensor radiance data. However consistency analyses of both the atmospherically corrected PROBA-V data and the TSM maps generated with independent A/C and TSM algorithms, gives them a better insight in the accuracy of the generated products and allows to identify cases/situations where the applied A/C and/or TSM algorithm might fail.

2.3. Summary User Requirements Other Projects

2.3.1. The CoBiOS project

The objective of the CoBiOS project is to integrate satellite products and ecological models into a near real time and forecast operational and user-relevant information service on high biomass blooms in Europe's coastal waters. Key improvements expected from the CoBiOS project are improved EO products, especially focusing on Kd and suspended matter, and expansion of model-based product with probability estimates.

In Table 1 we summarize the key findings (and of relevance for the PVLAC project) of the user requirement survey performed within the CoBios project.

Table 1 Summary of CoBiOS user requirements survey (reproduced from [http://www.cobios.eu/media/downloads/Cobios_deliverable_2_6.pdf)](http://www.cobios.eu/media/downloads/Cobios_deliverable_2_6.pdf)

Organisation	Country	Key parameters	Preferred resolution	Accuracy
SYKE	Finland	Algal bloom descriptors Chl, ***TSM***, CDOM, Secchi/Kd, SST Physical/chemical parameters, stratification Species composition Basic and aggregated data	Coastal: **200-**300m Open sea: 2000m Near shore applications: **30m**	**Whatever possible**; Accuracy not necessary
NST	Denmark	***TSM***,Nutrients, chl, oxygen, salinity,… Basic and aggregate data	**100-**1000m in areas of local interest (coastal areas) 1000-5000m in open waters	**As good as possible**; no specific requirements
Rijkswaterstaat	The Netherlands	CHL, ***SPM***, CDOM, Kd	**100 m**	Chl/SPM/CDOM: accuracy **within 20-30%** of the laboratory analyses; EO **confidence** maps of WQ parameters
BSH (Bundesamt für Seeschifffahrt und Hydrographie)	Germany	Chl, ***TSM***, YS, Secchi, SST	300-1000m (preferred 250-500)	Important that **accuracy is stated** but **no limit to accepted accuracy**

RBINS	Belgium	SPM (incl. profiles), chl, O2	Basic and aggregated data 1000m (**25-50m for special areas** of interest, e.g. harbours)	Info on accuracy not required

2.3.2. THE COASTCOLOUR PROJECT

The ESA funded CoastColour project exploited the potential of the MERIS instrument for remote sensing of the coastal zone. CoastColour aimed at developing, demonstrating, validating and inter-comparing different Case 2 algorithms over a global range of coastal water types, identifying best -practices, and promoting discussion of the results in an open, public form.

Within the Coastcolour project a critical review the user requirements has been performed and document in a RBD (http://www.coastcolour.org/documents/Coastcolour-RB-V1.2.pdf).

Here, we summarize the requirements of relevance for Proba-V 100 m coastal products :

- **Clear user demand for higher spatial resolution**
    - Clear need to get data very close to the coast in order to gather information required for **Water Framework Directive** reporting. The Water Framework Directive covers the coastal water up to 1nm off the baseline Several users indicate that neither the products from **SeaWiFS and MODIS**, **not** the currently operational available **MERIS** products **fulfil this requirement**.

- **Scientific/Validation requirements:**

  Three areas on how the quality of the data can be assessed, monitored and documented for the user :

    - **associated quality algorithms** should provide uncertainty information in the form of **flags** and/or quantify the degree as numbers. The scope of the algorithm has to be defined and a procedure has to be developed to detect conditions which are out of scope (for instance assumption of A/C algorithm only valid for TSM concentrations below a certain threshold value).
    - The products can be verified without any in situ data by tests regarding the **noise level, artefacts such as striping or camera boundaries**. One important issue is the quality of the atmospheric correction, i.e. the separation of the water leaving radiance reflectance from the TOA reflectance. This can be tested by **analyzing** the water leaving radiance reflectance **along transects** with cross strong gradients such as for example present in river plumes.
    - The data products have to be **compared with in situ observations**

2.3.3. THE INFORM PROJECT

The 4-years EU FP7-SPACE INFORM project started on 1 January 2014 aims to develop novel and improved user-driven products for inland water quality (WQ) monitoring by using innovative remote sensing methods integrated into biogeochemical models which fully exploits the improved spectral, spatial and temporal capabilities of upcoming Earth Observation (EO) missions (Sentinel-2, Sentinel-3, EnMAP and PRISMA). Validated INFORM EO-model products will form a basis for future Copernicus products to assess e.g. the implementation of the Water Framework Directive (WFD). INFORM developments will lead to recommendations for future E0 missions taking into account requirements for inland water quality monitoring.

A user survey on requirements for information was conducted within the INFORM end-users advisory board which covered experts on aquatic management, monitoring and research within governmental administration, academic sector and other public and private parties involved. The emphasis was on requirements and potential for practical use of information, which is derivable with satellite remote sensing.

The user survey results can be consulted on-line at http://www.copernicus-inform.eu/sites/default/files/documents/INFORM_D3.2_v1.0.pdf. A brief summary with respect to desired water quality products, preferred spatial and temporal resolution for Turbidity and TSM is given in Table 2.

Table 2 Summary of the INFORM end-users answers about desired water quality products, preferred spatial and temporal resolution (only Turbidity and TSM info extracted)

EO products	Not useful	Little use	Medium use	Very useful	Most useful	Useful for (e.g. WFD, …)
Turbidity (NTU)			17%	50%	33%	
Total suspended matter (TSM)/Suspended Solid concentration (g/m^3)				50%	50%	*

EO products	Daily	Weekly	Monthly	Other (specify)
Turbidity (NTU)	50%	17%	33%	
Total suspended matter (TSM)/Suspended Solid concentration (g/m^3)	67%		33%	

EO products	5 m	30 m	100 m	300 m	1 km	Other (specify)
Turbidity (NTU)	25%	25%	25%	25%		
Total suspended matter (TSM)/Suspended Solid concentration (g/m^3)	25%	25%	25%	25%		

2.4. Conclusion user requirements

Accuracy: The accuracy of the TSM/T products should be as a good as possible with a 'goal' absolute accuracy better than 20-30%. This should not be interpreted as the minimum required accuracy as some users can still use data with lower accuracy, however in that case it is important that the actual accuracy is stated.

Quality control: Quality flags should be provided indicating the probability that the retrieved TSM/T value is within the expected uncertainty or not. There is also some interest in knowing the actual per pixel uncertainty value.

Algorithm : Robust and flexible A/C and TSM/T algorithms which can be adapted to extreme water conditions (e.g. extremely turbid waters).

Parameters: Both TSM and Turbidity are considered by the user community as (very) useful parameters to be retrieved by PROBA-V

Product format : GEOTIFF (downloadable preferably by FTP and/or WMS)

Temporal/spatial resolution: There is a high interest in a daily coverage at resolution of 100m or better. A high spatial resolution (< 100m) is needed for fulfilling monitoring requirements within the Water Framework Directive and for nearshore mapping. A high temporal frequency helps the identification of extreme events (e.g. due to dredging or storm event). As this high temporal coverage combined with a high spatial resolution can't be provided by a single sensor, a multi-sensor approach, with data coming from different satellites (including PROBA-V 100 m products), is therefore being considered by both dredging and modelling community .

Consistency: In the frame of the multi-sensor approach users require consistency between TSM/T products derived from different sensors (including PROBA-V)

Spatial coverage: Turbid coastal and estuarine regions across the world are envisaged. The specific area of interest is highly user depended.

CHAPTER 3 REVIEW OF ATMOSPHERIC CORRECTION APPROACHES FOR COASTAL WATERS

3.1. INTRODUCTION

In the PROBA-V processing facility the TOA radiances recorded by PROBA-V (L_{TOA}) are converted to TOA reflectances (ρ_{TOA}) :

$$\rho_{\mathrm{TOA}} = \frac{\pi \cdot L_{\mathrm{TOA}}}{E_0 \cdot \cos(\theta_s) \cdot \left[\frac{d_0}{d}\right]^2}$$

with

E_0 the mean extra-terrestrial solar irradiance integrated over the spectral response of the different PROBA-V spectral bands,

θ_s the solar zenith angle,

$\frac{d_0}{d}$ the ratio of Sun-Earth distance at the acquisition date to the mean Sun-Earth distance.

Over water the TOA reflectance ρ_{TOA} can be decomposed as (Viollier et al., 1980; Neuckermans et al., 2009),

$$\rho_{\mathrm{TOA}} = \rho_r + \rho_a + T \cdot \rho_w,$$

ρ_w the water leaving radiance reflectance,

T the two-way (sun-to-surface and surface-to-sensor) atmospheric transmittance for aerosols (T_a), molecules (T_r) (i.e. Rayleigh transmittance), and atmospheric gases (T_g) (ozone, water vapor, oxygen, methane carbon dioxide) ($T = T_a . T_r . T_g$),

ρ_r the path reflectance due to multiple scattering of air molecules (i.e. Rayleigh scattering) ,

ρ_a the path reflectance due to multiple scattering by aerosols and by combined successive scattering by molecules and aerosols (Aerosol reflectance).

We ignore here the surface foam and white caps reflectance, which is negligible for surface wind speeds under 10 $\mathrm{m \cdot s^{-1}}$ (a wind speed mask could be applied in processing based on ECMWF wind speed data if available). The specular reflection of direct sun light or the sun glint reflectance is also ignored as Sun glint reaches the PROBA-V sensor only for specific sun-view geometries. Pixels probably affected by sun glint can be flagged based on sun and view geometry information.

The Rayleigh/molecular scattering component, the two-way gaseous transmittance (T_g) and the total two-way molecular transmittance (T_r) can be calculated with radiative transfer codes based on ancillary data (surface pressure, amount of ozone and total perceptible water, wind speed, sun, and view and illumination geometry).

In order to obtain the water-leaving radiance reflectance (ρ_w), the aerosol reflectance (ρ_a) and the two-way aerosol transmittance (T_a) remain to be calculated. ρ_a and T_a depend on the aerosol optical thickness (AOT) and the aerosol model.

Open ocean atmospheric correction schemes typically assume that the water–leaving radiance reflectance in NIR bands is zero. Therefore, at NIR bands the total radiance reaching the sensor is of atmospheric origin. This assumption, referred to as NIR black pixel assumption, holds for Case-I waters with low chlorophyll concentration and where phytoplankton is the only optically significant water column contributor. The signal in the NIR bands can thus be assumed to be entirely atmospheric and NIR bands can then be employed for the aerosol determination (Gordon and Wang, 1994).

Coastal water are however usually termed Case-II because the major influence on the water color are suspended particulate matter (SPM) and yellow substances. For Case-II waters the water leaving reflectance in the NIR has distinctive values as illustrated in Figure 1 . For Case-II waters the black pixel assumption is no longer valid thus other types of atmospheric correction schemes need to be applied. Even under relatively low concentrations of SPM (>2 $\mathrm{g.m^{-3}}$) (Lavender et. al., 2005), the significant backscatter results in a water reflectance at NIR wavelengths, negating the "NIR black pixel" atmospheric correction approaches (Figure 1).

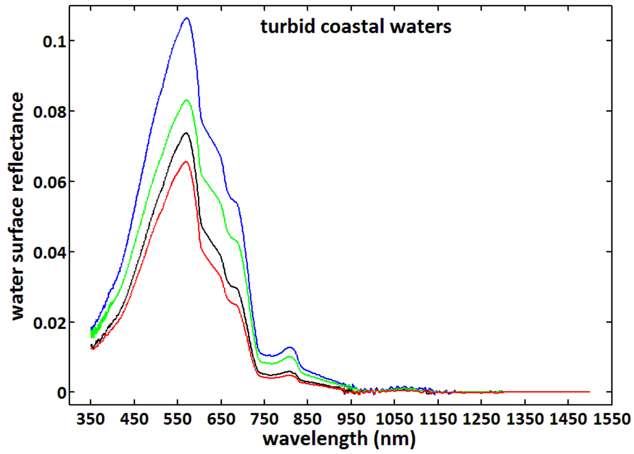


Figure 1. Water-leaving reflectance spectra from turbid coastal waters showing non-zero values at NIR wavelengths.

If the marine contribution of turbid waters is not properly taken into account, the aerosol reflectance is overestimated, leading to underestimated and even negative marine reflectances in the visible bands (Ruddick, Ovidio, & Rijkeboer, 2000). These errors in the atmospheric correction scheme directly translate to errors in the final products. Thus, methods based on the NIR black-pixel assumption are not valid for turbid waters.

3.2. EXISTING ALGORITHMS

Different types of correction schemes have been proposed in the literature to deal with the non-negligible water-leaving reflectances in the NIR. An overview of the different approaches is given in the paragraphs below. It should be noted that many of these approaches have been developed for typical ocean color satellites which have a larger number of spectral bands than PROBA-V with signal-to-noise (SNR) characteristics optimized for ocean color monitoring. Therefore, some of the algorithms might not be applicable to PROBA-V or significant adaptations are needed as discussed in the next paragraphs. Finally in 3.3 a summary table is given.

3.2.1. ALGORITHMS DERIVING AEROSOL INFORMATION FROM CLEAR WATER PIXELS IN THE SCENE ASSUMING SPATIAL HOMOGENEITY

A first type of approaches derives the aerosol type from clear water pixels in the scene assuming spatial homogeneity of the aerosols . This is for instance the basis of the algorithm of Ruddick et al. (2000). The algorithm is often referred to as the “MUMM" algorithm after the name of the authors institute.

The Ruddick et al. (2000) algorithm is based on two major assumptions.

The first assumption is that the aerosol type does not vary over the scene and therefore the ratio of the aerosol reflectance at two NIR bands, denoted with ε , is constant:

$$\varepsilon(\lambda_{\mathrm{NIR}_1},\lambda_{\mathrm{NIR}_2}) = \frac{\rho_a(\lambda_{\mathrm{NIR}_1})}{\rho_a(\lambda_{\mathrm{NIR}_2})}$$

The aerosol reflectance ratio is extracted from clear water pixels in the scene for which the water reflectance is assumed to be zero. In clear waters the aerosol reflectance can be approximated by the Rayleigh corrected reflectance. In the original work of Ruddick et al (2000) clear water pixels were identified by visually inspecting the correlation, using scatterplot, of Rayleigh corrected reflectance in the two NIR bands. A cluster of points in the lower left corner with low Rayleigh-corrected reflectance defined the aerosol reflectance ratio $\varepsilon(\lambda_{\mathrm{NIR}_1},\lambda_{\mathrm{NIR}_2})$. Jiang and Wang (2014), however, noted that such visual inspection based approach is not realistic in an operational processing environment. Automatic approaches to select the clear water pixels are, thus, proposed in Vanhellemont and Ruddick (2015) and Goyens et al (2013). For these automatically detected clear water pixels the $\varepsilon(\lambda_{NIR1,}\lambda_{NIR2})$ value can then easily be derived from the slope of the regression line or from the median ratio of the Rayleigh corrected reflectance in two NIR bands.

The second assumption in the Ruddick et al. (2000) algorithm is that for all water pixels in the scene the ratio of the water reflectance in two NIR bands, denoted with α , is constant:

$$\alpha(\lambda_{\mathrm{NIR}_1},\lambda_{\mathrm{NIR}_2}) = \frac{\rho_w(\lambda_{\mathrm{NIR}_1})}{\rho_w(\lambda_{\mathrm{NIR}_2})}$$

The theoretical approximations behind the latter assumption is that in the NIR the absorption is determined entirely by the pure water absorption and that the backscattering has only weak spectral variations. Therefore, the shape of water reflectance in the NIR is considered as invariant. This invariant shape of water leaving reflectances has been later referred as the NIR similarity spectrum for turbid waters (Ruddick et al , 2006). In Ruddick et al (2006) the similarity spectrum in the NIR defined by normalization at 780nm, is tabulated at 2.5 nm intervals allowing to calculate $\alpha(\lambda_{\mathrm{NIR}_1},\lambda_{\mathrm{NIR}_2})$ for any NIR band pair.

The accuracy of the MUMM method is highly depended on the validity of the two assumptions for the scene of interest. The first assumption, an uniform aerosol reflectance ratio over the entire scene, might introduce errors when the clear waters area is situated far from the area of interest.

The validity of the second assumption is violated in highly turbid waters as spectral relationship between the marine reflectance at two NIR bands is no longer linear (Doron et al., 2011; Goyens et al., 2013).

→ **Applicability to PROBA-V:**

The original approach of Ruddick et al. (2000) requires the availability of two NIR bands, where PROBA-V has only one NIR band. Therefore the approach cannot be used as such and some modifications are needed. In Neuckermans et al. (2009), the Ruddick et al. (2000) principle was used to atmospherically correct images acquired by the SEVIRI geostationary sensor over Case-II waters. As SEVIRI has only one broad NIR band centered at 810 nm, a broad visible band ($560 - 710$ nm) instead of a second NIR band was used in the two assumptions. A similar approach was followed in Vanhellemont and Ruddick (2014) for the correction of Landsat-8 scenes over coastal waters where the second NIR band was replaced by the Landsat-8 RED band ($630 - 680$ nm). A drawback of using a RED and a NIR band, instead of 2 NIR bands is that the assumption of a constant ratio of water reflectance is only valid for SPM concentration of ~ 27 g·m-3 (Vanhellemont and Ruddick (2015)), making the approach not applicable to relative turbid near-coastal waters and estuaries.

3.2.2. Algorithms based on extending the 'black' pixel approach to SWIR

A second type of algorithms is conceptually rather similar as the standard Gordon and Wang (1994) approach. However, instead of using two or more NIR bands for quantifying the aerosol contribution, switching to longer short-wave infrared (SWIR) bands were proposed in the second type of algorithms. These approaches assume that the contribution of in-water constituents is zero due to the high absorption of pure water in this spectral region and therefore, often termed as SWIR black pixel methods.

The SWIR black pixel methods have the advantage that no assumptions have to be made on the water optical properties. SWIR based atmospheric correction schemes have been developed for ocean color sensors with SWIR bands like MODIS and VIIRS and recently also for the higher resolution sensors, such as Landsat-8 (Vanhellemont and Ruddick, 2015) and Sentinel-2.

The common procedure of the SWIR black pixel approaches is as follows: First, the spectral ratio of Rayleigh-corrected reflectances at two SWIR bands is used to deduce the aerosol model or aerosol spectral shape as represented by the epsilon factor as:

$$\varepsilon(\lambda_s, \lambda_l) = \frac{\rho_a(\lambda_s)}{\rho_a(\lambda_l)}$$

where λ_s and λ_l represent the shorter and longer SWIR bands and ρ_a is the aerosol reflectance which can be approximated by the Rayleigh corrected reflectance under the SWIR black pixel assumption.

The retrieved epsilon values are compared against tabulated values for a suite of aerosol models to select the appropriate aerosol model. As both wavelength bands, λ_s and λ_l, are assumed to have zero marine contributions no selection of clear water pixels have to be performed. This allows to calculate a pixel-by-pixel aerosol type.

Once the aerosol model is determined, the aerosol optical thickness (AOT) can be derived, from the aerosol reflectance in a single SWIR band using aerosol reflectance look-up-tables (LUT) as a function of AOT. Finally, the atmospheric correction parameters for the visible and NIR bands can be derived from a LUT based on the retrieved AOT and aerosol model or through simple exponential extrapolation of the spectral epsilon (Vanhellemont and Ruddick,2015).

SWIR black pixel approaches have, among others, been integrated in the SEADAS development environment for the correction of MODIS images and in the ACOLITE processor (Vanhellemont and Ruddick, 2015) which has been designed for the atmospheric correction of high resolution sensors like Landsat-8 and Sentinel-2

→ **Applicability to PROBA-V :**

This approach can be applied to the atmospheric correction of PROBA-V images over coastal areas, however, as there is only one SWIR band some adaptations are needed. Using the SWIR band the AOT can be theoretically derived on a pixel-by-pixel basis once the aerosol type is known or fixed. For deriving the aerosol type, however, a fully SWIR based approach cannot be applied as 2 SWIR bands are needed for this. An alternative NIR-SWIR approach, like proposed by Vanhellemont and Ruddick (2015) for Landsat-8, could be applicable for PROBA-V. This approach combines the SWIR-based approach with an aerosol type spatial homogeneity assumption. It requires the presence of clear water pixels which have to be selected first. For these clear water pixels the ratio of the aerosol reflectance at the NIR and SWIR is assumed to be constant and used to derive a scene constant aerosol type. Although aerosol type over the offshore clear waters might be different from the coastal waters, the impact on the atmospheric correction of a wrong aerosol type selection is relatively small for turbid waters as the marine reflectance is very strong compared to the aerosol reflectance (Vanhellemont and Ruddick, 2015). An issue might be the high noise levels of PROBA-V in the SWIR over very low radiance scenes. The complexity in processing due to the presence of noise further aggravate as the noise level varies for each pixel due to pixel- dependent dark current anomalies in the PROBA-V data. To reduce the impact of the inherent noise in SWIR bands on the retrieved marine reflectance and final products, Wang and Shi (2012) proposed a spatial smoothing on the TOA SWIR radiances of MODIS through application of a simple box-averaging approach.

3.2.3. ALGORITHMS BASED ON SPATIAL EXTENSION OF AEROSOL INFORMATION RETRIEVED FROM NEARBY LAND

By spatial extension of the aerosol information derived from nearby land pixels assuming local spatial invariability of the aerosol, a-priori assumptions on the water composition or on the spectral dependency of the water reflectance are avoided. For the retrieval of aerosol over land the dense dark vegetation (DDV) method, originally developed by Kaufman and Sendra (1988), is often used. They either rely on the assumption that surface reflectance of dark vegetation is a known constant or that the ratio between short and long wavelengths is fixed. A DDV based approach has been used by Vidot and Santer (2005), for the correction of Seawifs data over lake Balaton and lake Constance. Campbell et al. (2011) used such an approach for the atmospheric correction of MERIS imagery from freshwater impoundments. A major issue of the DDV method is that pixels fulfilling the requirement of dark pixels are sparse. For instance over Western Europe less than 1 % of the land pixels can be considered as pure DDV pixels (Borde et al., 2003).

A different land-based aerosol retrieval approach was proposed by Guanter et al. (2010) for the correction of MERIS data over inland and coastal waters which does not rely on the presence of DDV pixels. The approach estimates the AOT per macro-pixel, typically 30 km by 30km, through a multi-parameter inversion of the TOA radiances in five reference pixels. These five reference pixels are land pixels which are characterized by a large spectral contrast (Guanter et al., 2007). It is assumed that these reference pixels can be represented by the linear combination of two endmember spectra, a vegetation and a soil spectrum. In the inversion step the endmember abundances and the aerosol optical thickness are retrieved concurrently. The approach is implemented in SCAPE-M (Self-Contained Atmospheric Parameters Estimation for MERIS data) (Guanter et al., 2010) and in the scene and sensor generic atmospheric correction scheme OPERA (Sterckx et al., 2015b). Guanter et al. (2010) obtained a good correspondence between the SCAPE-M derived MERIS water reflectances and the in-situ data over turbid waters. Jaelani et al (2013) showed that although overestimating the reflectance values with SCAPE-M over clear waters the spectral shape of water-leaving reflectance is well-maintained. In Sterckx et al. (2015) the OPERA approach applied to inland and coastal waters scenes acquired with MERIS and Landsat-8 showed good correspondence with the in-situ measured reflectances. Furthermore, it should be noted that extensive inter-comparisons between OPERA , ACOLITE, and SEADAS for processing of Landsat-8 coastal water scenes, performed in the framework of the HIGHROC FP-7 project, showed a good correspondence between the three processors.

Many literature references (e.g. Ramon and Santer, 2005; Grey et al., 2006) report on difficulties about the retrieval of a reliable estimate of aerosol model over land. Therefore, the aerosol type is often not derived from an image itself. The appropriate aerosol type can be selected based on climatology and/or local site information; however, often just a fixed continental/rural type of aerosol model is used (Béal et al., 2007; Guanter et al., 2010). However, as illustrated in by Vanhellemont and Ruddick (2015) the atmospheric correction over turbid waters is relatively insensitive to differences in aerosol type.

In general the main advantages of the application of land-based aerosol retrieval methods for the atmospheric correction of turbid waters is that it is applicable to high turbid waters as well as very complex water bodies where most of the water-based aerosol approaches fail. The difficulties in retrieving information on the aerosol type and uncertainties in the assumption of spatial homogeneity of the aerosol over large water bodies are the main disadvantages of this type of approaches.

→ **Applicability to PROBA-V :**

Spatial extension of land-based AOT retrieval is in principle suitable for the atmospheric correction of PROBA-V over coastal waters, but the drawbacks (i.e. spatial homogeneity of both aerosols and AOT; aerosol type a priori fixed) should be carefully considered.

3.2.4. SIMULTANEOUS RETRIEVAL OF ATMOSPHERIC AND WATER COMPONENTS

Several approaches have been developed which simultaneously retrieve the water reflectance and bio-optical components by taking into account the entire TOA spectrum. Because of the non-linear interactions in the radiative transfer, a non-linear inversion method is required for correcting for the atmospheric effect and retrieving the water leaving signal. For the non-linear inversion these methods either employ spectral optimization or neural network techniques.

Some artificial neural network approaches, such as the Case-II Regional processor (C2R) (Doerffer and Schiller, 2007) and the FUB processor (Schroeder et al., 2007), have for instance been designed for application to MERIS data and are included in the BEAM (Basic ERS & ENVISAT (A)ATSR and

MERIS) toolbox. The HYDROLIGHT radiative transfer code is used in the C2R forward neural network. The C2R processor is trained with IOPs and water constituents concentration data from optically complex coastal waters. The FUB processor consists of four neural networks. One network performs the atmospheric correction, while the other three networks retrieve the concentrations of the water constituents directly from the TOA measured radiances (Schroeder et al., 2007). The neural networks are trained with radiative transfer calculations performed with the MOMO (Matrix Operator Method) code for a range of atmospheric and water constituent concentrations. An overview of the training ranges of the different MERIS neural network based processors is given in Palmer et al. (2015). The main limitation of these neural network approaches is that the performance of these algorithms depend on how much the water optical properties differ from those used in the training of the network as the neural network cannot accurately extrapolate beyond the input range of their training set. Application of the algorithms outside the range of training (for example to very turbid waters) or to coastal areas with different optical properties might therefore result in erroneous retrieval of the TSM.

The POLYMER algorithm developed by Steimnetz et al.(2011) employs a spectral optimization technique to retrieve the atmospheric and water parameters simultaneously from all available spectral bands. It combines a water reflectance model which depends on two parameters i.e. the chlorophyll concentration and particle backscattering, and an atmospheric polynomial model with three spectral components which models the reflectance of the atmosphere including aerosols and contamination by sun glint. The spectral optimization technique consists in optimizing the different parameters (five in total) of atmospheric and water reflectance model in order to obtain the best spectral fit between measured and modelled TOA reflectances. POLYMER has been proven successful for the retrieval of MERIS Ocean color data even under high sun glint conditions and has therefore been selected as the baseline MERIS processor for the Ocean Color Climate Change Initiative. A non-linear spectral optimization approach has also been proposed by Kuchinke et al. (2009) to simultaneously determine the parameters of the aerosol and bio-optical model over Case-II waters. The algorithm assumes that some parameters, used to constrain the bio-optical model, are known a priori from e.g. in-situ observations. This assumption makes the algorithm site specific. Furthermore, it should be noted that because aerosol and bio-optical model parameters are retrieved simultaneously an error in the bio-optical model coefficients will impact the retrieval of all parameters including the aerosol parameters. In the spectral optimization the parameters to be retrieved are constrained by pre-defined lower and upper bounds. Therefore the algorithm will probably fail under conditions with unusual high concentrations.

→ **Applicability to PROBA-V :**

This type of approaches is **not applicable** to PROBA-V. With only 4 spectral bands it will be an ill-posed inversion problem: different combinations of atmospheric and water constituent parameters may result in the same TOA spectrum in these 4 spectral bands. Spectral optimization techniques need at least as many spectral bands as the number of parameters to be retrieved. For instance, POLYMER requires at least 7 spectral bands while PROBA-V has only four spectral bands. Therefore optimization methods are only applicable to typical ocean color satellites with many spectral bands or hyperspectral sensors.

3.2.5. CORRECTION/MODELLING OF NON-ZERO REFLECTANCE IN THE NIR

These type of approaches consists in first estimating the non-negligible water-leaving reflectance radiance in the NIR, subtracting this signal from the TOA reflectance and then performing a standard Gordon and Wang (1994) atmospheric correction approach.

The Bright Pixel Atmospheric Correction (BPAC) developed by Moore et al. (1999) is the MERIS operational atmospheric correction scheme for Case-II waters. It uses a coupled atmosphere-hydrological optical model in an iterative approach to remove the water contribution caused by suspended sediments from the TOA signal. The hydrological model assumes that the water reflectance can be determined by the absorption of water together with the absorption and scattering of particles. The atmosphere is modelled using a simple single scattering model, which assumes that the atmospheric path radiance and absorption can be separated into the Rayleigh and aerosol components. The aerosol component is modelled by a simple angstrom exponent. The algorithm then relies on three NIR bands to retrieve in an iterative way and on a pixel-by-pixel basis the three unknowns: the TSM concentration, the angstrom coefficient, and the aerosol reflectance at the reference NIR band.

Also the official standard NASA A/C procedure for the processing of SeaWiFS and MODIS includes a NIR-modeling iterative scheme with a bio-optical model to account for water contribution in the NIR (Bailey et al., 2010; Stumpf et al., 2003).

The use of empirical optical models limits the applicability of this type of algorithms to waters that are similar to those over which these empirical models were developed. In addition, the practical implementation of the iteration scheme can result in conditions of non-convergence. Several literature references have, however, shown that the BPAC approach does not allow to predict sufficient high concentrations of SPM which leads to an over-correction of the blue water-reflectance, with causing negative reflectance values in the blue spectral region.

→ **Applicability to PROBA-V :**

As several NIR bands are required the approach cannot be applied as such.

3.3. Discussion

3.3.1. Summary table

Table 3 Atmospheric correction for coastal waters: summary table

	Algorithmic approach	Applicability to PROBA-V	Main limitations	Some references
1	Spatial extension of aerosol information from nearby clear water pixels	Yes, with adaptations: use of RED and NIR band instead of 2 NIR bands	Assumptions made in the approach only valid uptill SPM concentation of ~ 27 mg m-3; presence of clear water pixels required; uncertainty in aerosol type spatial homogeneity	Ruddick et al. (2000)
2	SWIR black pixel approach	Yes, with adaptations: use of NIR and SWIR band instead of 2 SWIR bands	High noise level in PROBA-V SWIR bands might increase uncertainty ; presence of clear water pixels required ; uncertainty in aerosol type spatial homogeneity	Wang et al. (2011), Vanhellemont and Ruddick (2015)
3	Spatial extension of aerosol information from nearby land	Yes	Uncertainty in aerosol type and AOT spatial homogeneity; requires presence of nearby land pixels with dark dense vegetation or with sufficient spectral contrast	Vidot and Santer (2005), Guanter et al. (2010), Sterckx et al. (2015b)
4	Simultaneous retrieval of atmospheric and water components	No	N/A for PROBA-V	Doerffer and Schiller (2007), Schroeder et al. (2007), Steimnetz et al.(2011), Kuchinke et al. (2009)
5	Correction/modelling of non-zero reflectance in the NIR	No	N/A for PROBA-V	Moore et al. (1999) , Bailey et al. (2010), Stumpf et al. (2003)

3.3.2. PROPOSED A/C METHOD FOR PROBA-V

In this section we summarize the A/C approaches considered for PROBA-V. As discussed in section 3.2 the main challenging components of A/C are the retrieval of the AOT and aerosol type at the time of imaging. Aerosol information can be derived from on-ground sun photometer measured, however image based techniques, i.e. extracting the aerosol information from the retrieved at-sensor radiance, are often preferred in operational satellite data processing.

Taking into account the specifications of PROBA-V, we are considering A/C methods evolving from two broad techniques:

1) based on extending the “black pixel” approach to the SWIR as discussed in Section 3.2.2;

2) based on spatial extension of aerosol information retrieved from nearby land as discussed in Section 3.2.3.

From the first approach i.e. black pixel based, we will use the alternative NIR-SWIR approach, like proposed by Vanhellemont and Ruddick (2015) for Landsat-8, as it is applicable for PROBA-V with one SWIR band. The basic assumption of this approach is the spatial homogeneity of an aerosol type. Besides, it also requires the presence of clear water pixels which have to be selected first. Although aerosol type over the offshore clear waters might be different from the coastal waters, the impact on the atmospheric correction of a wrong aerosol type selection is relatively small for turbid waters as the marine reflectance is very strong compare to the aerosol reflectance (Vanhellemont and Ruddick, 2015). An issue might be the high noise levels of PROBA-V in the SWIR over very low radiance scenes. To reduce the impact of the inherent noise in SWIR bands on the retrieved marine reflectance and final products, we can utilize a spatial smoothing approach on the TOA SWIR radiances as proposed by Wang and Shi (2012) for MODIS through application of a simple box-averaging approach.

For the approach based on the land-based aerosol retrieval methods, the main advantages is its applicability to high turbid waters as well as very complex water bodies where most of the water-based aerosol approaches fail. The difficulties in retrieving information on the aerosol type and uncertainties in the assumption of spatial homogeneity of the aerosol over large water bodies are the main disadvantages of this type of approaches. However, the impact on the atmospheric correction of a wrong aerosol type selection is relatively small for turbid waters as the marine reflectance is very strong compare to the aerosol reflectance (Vanhellemont and Ruddick, 2015).

Both approaches will be prototyped and their performance will be evaluated. Based on this performance assessment the most appropriate A/C approach will be selected. It is important to note that this final A/C approach might be a “merging” of both methods e.g. where for nearshore pixels a land-based approach is used, while for offshore pixels the NIR-SWIR approach is preferred.

CHAPTER 4 REVIEW OF TOTAL SUSPENDED MATTER (TSM) RETRIEVAL ALGORITHMS FOR COASTAL WATERS

4.1. INTRODUCTION

Total Suspended Matter (TSM) is one of the three main optically active constituents in natural waters. The other optically active constituents are Chlorophyll (CHL) and Colored Dissolved Organic Matter (CDOM). Since these constituents affect the color of the water, it is possible to detect their presence in water using remote sensing and to quantify their respective concentrations. Estuarine and coastal waters are, however, complex in their composition and optical properties. Therefore, relatively simple global algorithms developed for open oceans are not applicable to these waters. Several authors pointed out the strong regional variations in optical properties for these coastal and estuarine areas. TSM algorithms developed for coastal waters range from purely site-specific empirical relationships between measured remote sensing reflectance and TSM to complex analytical methods.

4.2. EXISTING ALGORITHMS

4.2.1. EMPIRICAL TSM ALGORITHMS

The empirical approach is based on a statistical calibration and utilizes the relationship between spectral data and TSM measured (e.g. in-situ TSM measurements). A large variety of empirical based TSM retrieval algorithms have been published. These empirical relationships have been set-up based on in-situ reflectance data (e.g. Forget and Ouillon, 1998; Doxaran et al., 2002), satellite-derived reflectances (Miller and McKee, 2004; Wang et al., 2009), and atmospherically uncorrected at-sensor radiances (Onderka and Pekarova, 2008). Empirical relationships are established through linear (Forget and Ouillon, 1998; Binding et al., 2004), logarithmic (Siswanto et al., 2011), and exponential (Doxaran et al. , 2003) regression analysis on the data. Both single band (Forget and Ouillon, 1998; Miller and McKee, 2004) and multi-band based empirical algorithms (Doxaran et al., 2002, Siswanto et al., 2011) have been developed.

The optimal wavelength used to retrieve TSM depends strongly on the turbidity of the water. In general NIR bands are appropriate for higher TSM concentrations, whereas visible bands are appropriate for lower TSM concentrations. In the NIR band the turbidity of the water should be sufficiently high so that particle scattering overcomes the strong water absorption in this region. For instance, Binding et al. (2005) found a relationship between TSM (concentration in the range of 0–25 $\mathrm{mg \cdot l^{-1}}$) and in-situ measured reflectance in the red region for the Irish Sea. Also, Miller and McKee (2004) found a linear relationship between the MODIS Terra Red band and in-situ measurements of TSM (concentration range: 0–60 $\mathrm{mg \cdot l^{-1}}$) for the coastal waters of the Northern Gulf of Mexico. Whereas, Sterckx et al. (2007) used NIR bands for mapping TSM concentrations in the turbid Scheldt estuary with TSM concentrations up to 400 $\mathrm{mg \cdot l^{-1}}$. The usefulness of single RED and NIR bands to quantify similar concentration ranges has been confirmed by various authors (Onderka and Pekarova, 2008; Harrington et al. ,1992; Han and Rundquist,1994).

Both linear and non-linear relationships have been proposed. In general, relationships tend to be linear for relatively low concentrations, a logarithmic relationship is observed when TSM concentration is increasing and finally saturation is reached. This saturation occurs at higher TSM values for longer wavelengths because of the higher pure water absorption at the longer wavelengths. This was also shown in the tank experiment by Shen et al. (2010). This experiment showed first a rapid increase of the NIR reflectance with increasing TSM concentration (up to 150 $\mathrm{mg \cdot l^{-1}}$) and then a logarithmic increase (TSM from 150 $\mathrm{mg \cdot l^{-1}}$up to 2500 $\mathrm{mg \cdot l^{-1}}$). Although NIR bands could be very useful for high to very high concentrations of TSM concentration due to the higher sensitivity of the water reflectance to TSM compared to shorter wavelengths; however, these wavelengths might not be suited for low TSM concentrations because of the low signal. The increase in the pure water absorption (Figure 2) will require increasing TSM to ensure a sufficient reflectance signal (Ruddick et al., 2006) while less absorbing portions of the spectrum are more suitable for low TSM concentrations. The choice of the optimal band depends therefore strongly on the TSM concentration ranges within the area of interest. In order to cope with large range of TSM concentrations (from 2 $\mathrm{mg \cdot l^{-1}}$ up to 1762 $\mathrm{mg \cdot l^{-1}}$) as found in the Yangtze estuary, Feng et al. (2014) developed a piecewise linear regression between the TSM and surface reflectance in the MODIS red band at 645 nm and the NIR band at 869 nm. Shen et al. (2010) proposed switching between 560, 650, 709, and 779 nm MERIS bands for TSM thresholds of 20, 80, and 250 $\mathrm{mg \cdot l^{-1}}$ respectively.

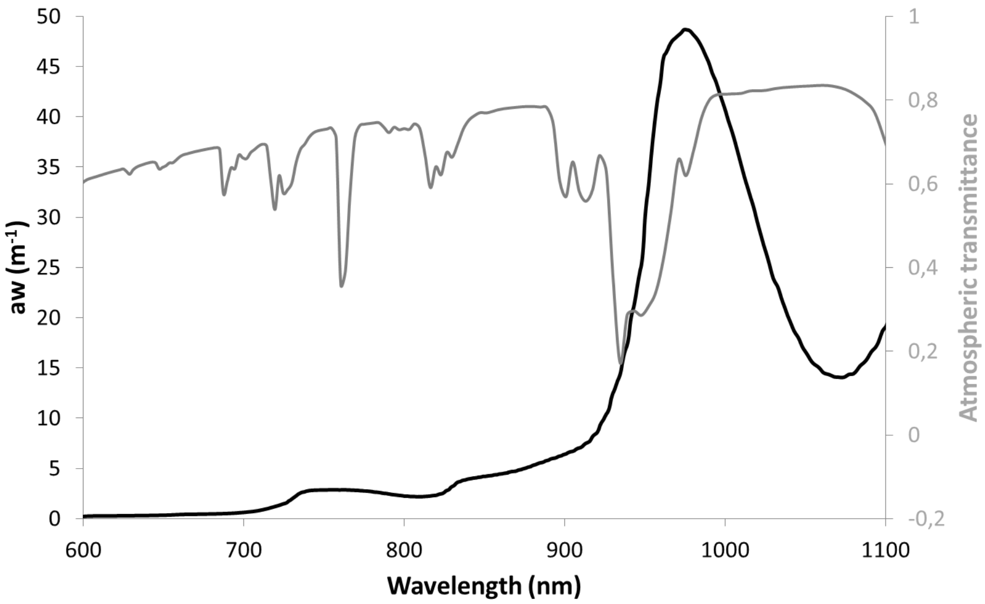


Figure 2. Pure water absorption coefficient (Pope and Fry, 1997; Kou et al., 1993) and total one-way atmospheric transmittance simulated using the Modtran radiative transfer code for a platform height of 800 km, a nadir view, a visibility of 17 km, a water vapor content of 2.5 m−1 and a rural aerosol

Single band algorithms are, however, sensitive to errors in the atmospheric correction and to the variability in reflectance due to the natural variability in the particle scattering properties. To overcome this issue, as well as to reduce the impact of atmospheric correction errors, several band ratios (Doxaran et. al., 2010; Qiu, Z. 2013; Tassan, J., 2004) models have been proposed. As the backscattering has a relatively flat spectral signature, a ratio is less sensitive to changes in the scattering properties. Doxaran et al. (2003) showed on the basis of in-situ measurements that ratio algorithms reduce the effects of variable sediment types and are also less sensitive to illumination conditions. Red-to-green and NIR-to-red band ratios have been proposed (Min et al., 2002; Doxaran et al., 2013). Band ratio algorithms may however be sensitive to the natural variability of sediment absorption properties.

Empirical algorithms are set-up for a specific region under specific conditions in time. Thus, the major drawback of empirical derived algorithms is that they can only be applied within the conditions of the calibration data (Odermatt et al.,2012, Nechad et. al., 2010). A few researchers tested the seasonal portability of their empirical algorithm to data collected from the same site later in the year. Knaeps et al. (2012) presented a seasonally robust band-ratio algorithm for the retrieval of Suspended Particulate Matter (SPM) in the Scheldt River from hyperspectral images. Doxaran et al. (2012) proposed an invariant band ratio ($\frac{850\text{ nm}}{550\text{ nm}}$) algorithm to retrieve the estuarine sediment dominated waters of the Gironde and the Loire. Both authors point to the seasonal robustness of their algorithms, however, their algorithms need recalibration when applied to different estuarine environments. It is because the characteristics of the suspended sediment (particle size and type) are highly variable in space and time (much more than the seasonal variability). Especially for estuaries these variations can be large as they depend on the upland basins, river discharge, tidal cycles, and flocculation processes. These characteristics influence the scattering behavior and, consequently, these empirical algorithms are no longer valid when applied to the other environments (Knaeps et al., 2012).

Though there are examples of seasonal portability of these empirical algorithms, but they are scarce. Geographical portability on the other hand is not possible due to geologic diversity of the upland basin, the dynamics of ocean currents, and the variety of residence times that will result in highly varying scattering and absorption properties of TSM.

4.2.2. ANALYTICAL TSM ALGORITHMS

Analytical approaches use sophisticated radiative transfer models or analytical bio-optical models to model the reflectance as function of inherent optical properties (IOP) like absorption ($a(\lambda)$) and the backscattering (b_b (λ)) coefficients. A well-known bio-optical model is the one developed by Gordon et al., 1988:

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

with $R(0-,\lambda)$the subsurface irradiance reflectance, $a(\lambda)$ the spectral total absorption coefficient at wavelength λ (m^{-1}), b_b(λ) the spectral total backscattering coefficient at wavelength λ (m^{-1}), and $f$an empirical factor which depends on solar and viewing geometry and volume scattering in the water.

The IOP $a(\lambda)$ and b_b(λ) are linear functions of the constituents' concentrations and their specific inherent optical properties (SIOPS). The subsurface irradiance can, therefore, be re-written as (omitting the wavelength dependencies of the factors),

$$R(0-) = f \cdot \frac{b_{bw} + TSM \cdot b_{b,p}^*}{a_w + g440 \cdot \tilde{a}_{CDOM} + CHL \cdot a_{ph}^* + NAP \cdot a_{NAP}^* + b_{bw} + TSM \cdot b_{b,p}^*},$$

where,

a_w the absorption of pure water (m^{-1}),

a_{bw} the backscattering of seawater (m^{-1}) ,

$\mathrm{g440}$ CDOM absorption at 440 nm (m^{-1}),

$\tilde{a}_{\mathrm{CDOM}}$ CDOM absorption normalized by the absorption at 440 nm (m^{-1}),

$\mathrm{CHL}$the concentration of chlorophyll-a ($\mathrm{mg} \cdot \mathrm{m}^{-3}$),

NAP the concentration of non-algal particles ($\mathrm{g} \cdot \mathrm{m}^{-3}$),

TSM the concentration of suspended matter ($\mathrm{g} \cdot \mathrm{m}^{-3}$) ,

$b_{b,p}^{*}$ the specific backscattering coefficient of marine particles ($\mathrm{m}^{2} \cdot \mathrm{g}^{-1}$),

$a_{p,h}^{*}$ the specific absorption coefficient of chlorophyll-a ($\mathrm{m}^{2} \cdot \mathrm{mg}^{-1}$), and

a_{NAP}^{*} the specific absorption coefficient of non-algal particles ($\mathrm{m}^{2} \cdot \mathrm{g}^{-1}$).

To retrieve the water constituents the models are inverted through neural networks, use of LUTs, matrix inversion or curve fitting techniques using the different spectral bands available. The matrix inversion approach is restricted to linear forward models only, in which case an analytical expression can be found with some constraints. One of the typical problems of this approach is the presence of negative concentration values when applying to real data (Kempeneers et. al, 2005). For neural networks on the other hand large data set is required for its training with field data. Collecting field data at sea is often unfeasible due to time and cost factor (Schiller et. al., 1999, Hoge et. al, 1999).

The analytical algorithm HYDROPT (van der Woerd & Pasterkamp, 2008) is often used with multispectral data (Gavin et. al., 2012). HYDROPT comprises a forward model based on the HYDROLIGHT radiative transfer model (Mobley, 1994) and an inverse model based on least-square fitting of the MERIS measured to modeled reflectance (Garver & Siegel, 1997; Maritorena et al., 2002). The forward model generates a lookup table (LUT) of water leaving reflectance as a function of the absorption and scattering properties and their constituent. Although the HYDROPT algorithm was developed and demonstrated for the MERIS band settings, the principles do apply for the ocean color instruments which have similar instrumental characteristics (number of bands, central wavelengths of the bands, atmospheric correction procedures and signal/noise ratio). Besides sensor characteristics, the HYDROPT algorithm can be applied to remote sensing data of any Case-II water if the appropriate regional optical model for the area of interest is available. The HYDROPT method, however, is not suitable to sensors like Proba-V due to limited number of bands.

Analytical approaches are based on our physical knowledge of the radiative transfer in waters and should be more robust and more widely applicable than the empirical counterparts. In practice, these algorithms are highly sensitive to errors in the atmospheric correction and sensor noise. Under the same conditions empirical single band or band ratio algorithms sometimes have surprisingly good results. For instance, a curve fitting may be unsuccessful due to a mismatch in magnitude (a white error) although the spectral shape may be correctly reproduced. In this case an empirical band difference algorithm will be insensitive to the white error.

There is a large variety in these optical properties for different coastal waters, care must be taken when applying these analytical models and to derive water quality estimates. As said by Han et al. (2016) the performance of analytical based models which theoretical link TSM with IOPs depends strongly on the representativeness of the used particulate backscattering or absorption properties which are expected to vary widely.

Finally analytical methods are not suitable for multi-spectral sensors as PROBA-V which has only 3 broad bands in the VNIR; which is not sufficient to perform proper inversion of the analytical model.

4.2.3. SEMI-ANALYTICAL ALGORITHMS

To overcome the limitations of both the simple empirical approaches and the complex analytical methods, semi-analytical approaches are gaining more and more attention (Chen et al., 2013; Doxaran et al., 2012; Nechad et al., 2010). Semi-analytical methods have a strong theoretical basis – they for instance consider the relationship between the absorption or scattering properties and TSM concentration, which they combine with statistical methods.

In this framework, Nechad et al. (2010) developed a sensor generic single band semi-analytical TSM algorithm. It has the advantages that it can be applied to any sensor with bands in the Red and NIR. Further, this method is also applicable to areas with extremely high TSM concentrations provided that the sensor has a spectral band in the SWIR region (1000-1200 nm) (Knaeps et al., 2015).

The Nechad et al. (2010) single band algorithm has the following form,

$$\mathrm{TSM} = \frac{\mathrm{A}^{\rho} \cdot \mathrm{R_w}(\lambda)}{\left(1 - \frac{\mathrm{R_w}(\lambda)}{\mathrm{C}^{\rho}}\right)},$$

where A^{ρ} (in $\mathrm{g \cdot cm^{-3}}$) and C^{ρ} (dimensionless) are wavelength depended calibration parameters, related to the IOPs,

$$\mathrm{A}^{\rho} = \frac{\mathrm{A}}{\gamma},$$

$$\mathrm{C}^{\rho} = \frac{\gamma \cdot \mathrm{C}}{(1 + \mathrm{C})},$$

with$\gamma \approx 0.216, A$ is the ratio of non-algal particulate absorption to the specific particulate backscattering coefficient $\left(\mathrm{A} = \frac{\mathrm{a_{np}}}{\mathrm{b^*_{bp}}}\right)$,

and

C the ratio of the specific particulate backscattering and the specific particulate absorption $\left(\mathrm{C} = \frac{\mathrm{a^*_{np}}}{\mathrm{b^*_{bp}}}\right)$.

As described in Nechad et al. (2010) A^{ρ} is determined by regression analysis of seaborne reflectance measurements of the North Sea and the corresponding in-situ measured TSM values . Thus, in order to apply this algorithm to other sites recalibration is needed (Han et al., 2016). Parameter C^{ρ} is calibrated using SIOPs for a selected number of sites, which might not be valid. However Nechad et al. (2010) showed that results are not very sensitive to C^{ρ} , thus, as long as the asymptotic limit is avoided recalibration of the C^{ρ} is not necessary. Tabulated A^{ρ} and C^{ρ} values (between 520 en 885 nm) are given in Nechad et al. (2010), which were used in Figure 3 to plot the variation in the water leaving radiance reflectance in PROBA-V RED and NIR bands with respect to a change of TSM concentration. The reflectance in the RED band is very sensitive to low and medium TSM concentrations where the relationship is approximately linear but saturates at higher TSM concentrations. While the NIR is less sensitive to low—medium TSM concentrations, saturation seems to occur only at very high TSM concentrations (> $100\mathrm{mg}^{-1}$).

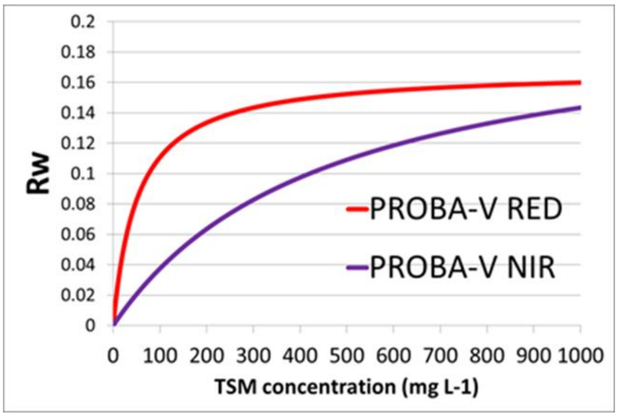


Figure 3. PROBA-V water leaving reflectance in RED and NIR bands in function of the TSM concentration, following the Nechad et al. (2010) algorithm

Because of the different sensitivity to the level of TSM concentration, wavelength switching TSM algorithms have been proposed (e.g. Han et al., 2016). The algorithms use different bands based on the turbidity and often apply a merging in between to obtain a smooth transition.

The validity of semi-analytical TSM algorithms may be restricted to a specific region. New parameterization of the algorithm might be needed for other sites due to changes in particle type and composition

4.2.4. TURBIDITY AS PROXY FOR TSM

None of the discussed TSM retrieval algorithms allow for a global operational processing of the coastal water as there is always a need for region-specific adaptation or calibration. An alternative would be the use of turbidity instead of TSM. The turbidity of a water sample is an optical measure of the extent to which the intensity of light passing through water is reduced by the particles in the water. Turbidity is therefore strongly related to TSM. Turbidity can be expressed in various units, such as Formazin Turbidity Unit or FTU, Nephelometric Turbidity Unit or NTU. Turbidity is listed by the European Union as one of the prime water quality parameters to be measured regularly. Due to the fact that turbidity is an optical property, it is more related to reflectance through the backscattering than TSM.

In-situ measurements of TSM are costly and are time-consuming as they require dedicated field campaigns in order to take water samples and these water samples need to be filtered, weighted and dried in an oven. Turbidity can be measured automatically using in situ turbidity meters which are often part of autonomous buoys like the CEFAS SmartBuoys. HACH turbidity meters can also be used on site, which allow a direct measurement of the turbidity of the water sample without much effort and specialized equipment. However care has to be taken when combining turbidity data from different instruments or sensors as they might read light scatter from suspended particles differently, outputting different measurements for the same water sample etc. Some sensors are more accurate at low turbidity levels, while others offer the ability to measure a wide turbidity range. Within the Highroc project four *in situ* sensors were tested in different tanks with Formazin in fresh water, Formazin in filtered seawater, River water, kaolin in seawater and different algae concentrations in seawater. In situ turbidity meters had 10 to 25% higher values compared to the Hach turbidity meter.

Whereas there are many remote sensing publications on TSM algorithms, there are only a few focusing on turbidity. While the existing TSM algorithms are site-specific, algorithms proposed in the literature for turbidity retrieval are more globally applicable.

Ouillon et al. (2008) proposed a global empirical–based algorithm for turbidity retrieval in tropical coastal waters on the basis of MERIS data. The algorithm uses a merging of two algorithms in: turbidity is first calculated from the reflectance in the 681 nm band following a power law and then, if < 1 FTU, it is recalculated using a three band clear algorithm i.e. based on bands at 620, 681, and 412 nm).

Nechad et al. (2009) developed a semi-analytical turbidity algorithm which links the water leaving radiance reflectance in a single band to the turbidity. The relationship was calibrated using in-situ measurements from the Southern North Sea.

Vanhellemont et al. (2013) compared the Nechad et al. (2009) algorithm with the Ouillon et al. (2008) on Meris data from the North Sea and the Irish sea using turbidity data from autonomous buoys. Although the Ouillon et al. (2008) algorithm was developed for tropical coastal waters differences between the algorithms were small, indicating the potential for global application of the Ouillon et al. (2008) algorithm.

Dogliotti et al. (2015) developed a global semi-analytical turbidity algorithm which can be used in very different regions and is almost insensitive to the sediment type and composition. It has been developed on the basis of the Nechad et al. (2009) turbidity algorithm; It includes a wavelength switching between the MERIS 645 nm and the 859 nm band. The NIR band is used to generate maps of turbidity in moderate to highly turbid waters, while the red band is more sensitive in low turbid waters. The methodology was tested for a large range of turbidity values , i.e. between 0.5 and more than 1000 FNU. Successful retrieval of the water turbidity based on the Dogliotti et al. (2015) algorithm has been reported in the literature for multiple areas. Brando et al. (2015) applied the Dogliotti et al. (2015) turbidity algorithm to Landsat8 images to characterize the turbidity in river plooms in the northern Adriatic Sea. Constantin et al. (2016) used the algorithm to retrieve the turbidity in the Black Sea based on MODIS observations.

In order to retrieve TSM, a global turbidity algorithm can be combined with a regional TSM-turbidity relationship which can be established based on a set of local field measurements of both TSM and turbidity as illustrated in Figure 4.

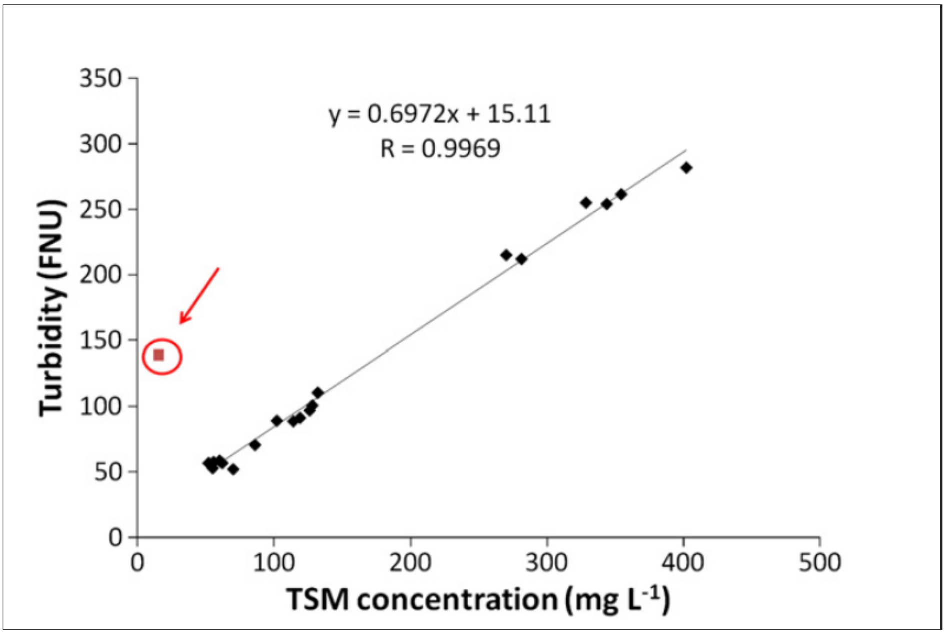


Figure 4. Calibration relationship between TSM and Turbidity as obtained by Knaeps et aL (2012) for the Scheldt river

4.3. Discussion

4.3.1. Summary table

Table 4 TSM algorithms for coastal waters: summary table

	Algorithmic approach	Applicability to PROBA-V	Main limitations	Some references
1	Empirical TSM algorithms	Yes	Empirical models always need in-situ data to set-up the empirical relationship. As these empirical relationships are site-specific, they can't be used for other areas.	Binding et al. (2005), Forget and Ouillon (1998), Doxaran et al., (2002), Miller and McKee, (2004; Wang et al., 2009), Onderka and Pekarova, (2008), (Siswanto et al., (2011), Sterckx et al. (2007)
2	Analytical TSM algorithms	No, not applicable to sensors with only 3 VNIR bands	A link between TSM with IOPs depends strongly on the representativeness of the used particulate backscattering or absorption properties which are expected to vary widely. Requires sufficient (small)	Han et al. (2016)

			spectral bands in the VNIR region.	
3	Semi-analytical TSM algorithms	Yes	The validity of these algorithms may be restricted to a specific region. New parameterization of the algorithm might be needed for other sites due to changes in particle type and composition.	Nechad et. al (2010), Han et al. (2016); Knaeps et al., (2015).
4	Turbidity based TSM retrieval	Yes	These algorithms can be used in very different regions and are almost insensitive to the sediment type and composition. However in order to derive TSM a regional TSM-turbidity relationship has to be established .	Nechad et. al (2009), Ouillon et al. (2008) , Dogliotti et al. (2015)

4.3.2. Proposed method for PROBA-V

Based on the literature review we propose to test three different algorithms:

1. The Nechad et al. (2010) single band semi-analytical TSM algorithm is selected because of its strong theoretical background and successful applications in the literature. However we should bear in mind that the algorithm might perform less in regions where particle type and composition vary significantly from the calibration region. We propose to apply a wavelength switching to include both clearer and turbid waters.
2. A band ratio algorithm combining the Proba-V red and NIR band because this algorithm might be less sensitive to changes in particle type and composition and less sensitive to errors in the atmospheric correction.
3. The Dogliotti et al. (2015) semi-analytical turbidity algorithm because several references (Brando et al.,2015; Constantin et al.,2016) have already shown that it can be applied in very different regions and that it is almost insensitive to the sediment type and composition. The Dogliotti et al. (2015) approach is based on a regional turbidity algorithm developed by Nechad et al. (2009) and uses a wavelength switching approach between RED and NIR bands depending on the turbidity. The disadvantage is that some users prefer to have TSM instead of turbidity (e.g. in many regulations thresholds are expressed in mg L-1). A TSM product can be derived from the turbidity product by combining the PROBA-V turbidity data with a regionally

calibrated Turbidity-TSM relationship. These kind of relationships are often available because they are also used to calibrate the in situ buoy turbidity meters.

CHAPTER 5 VALIDATION APPROACH FOR: A/C FOR COASTAL WATERS AND TSM RETRIEVAL METHODS

5.1. INTRODUCTION

In this chapter we discuss the validation approaches adopted for the A/C and for the TSM/T retrieval method. The purpose here is to validate the developed algorithm in order to characterize its accuracy and identify possible systematic biases, the validation procedure shall follow common used protocols and guidelines and shall be based on cross-comparison with available in-situ data and with satellite products. In this chapter we'll indicate the validation approach, the needed validation data, and test sites, allowing to assess products accuracy in a consistent way over time and at global scale.

5.2. VALIDATION APPROACH FOR A/C

5.2.1. AERONET-OC VALIDATION SITES

In this project we'll use data available from AERONET –Ocean Color (AERONET-OC) sites as validation dataset. The AERONET sites, developed to sustain atmospheric studies at various scales with measurements from worldwide CE-318 distributed autonomous sun-photometers, have been extended to support marine applications. This network component called AERONET – Ocean Color provides the additional capability of measuring the radiance emerging from the sea i.e., water-leaving radiance reflectance with CE-318 sun-photometers installed on offshore platforms. AERONET-OC is instrumental in satellite ocean color validation activities through standardized measurements a) performed at different sites with a single measuring system and protocol, b) calibrated with an identical reference source and method, and c) processed with the same code. In the following part of the section we describe the AERONET-OC sites used to obtain dataset for the preliminary and the global validation.

5.2.2. SITE FOR PRELIMINARY VALIDATION

For the verification of the basic functioning of the A/C algorithm a test dataset will be created consisting of cloud-free PROBA-V 100 m data acquired from the Belgian coastal waters and reference water leaving reflectance radiance data measured by AERONET CIMEL instruments located at the nearshore MOW1 platform (51.362°N; 3.120°E) (Figure 5) near Zeebrugge harbour and at the offshore Thornton_C-power platform (Figure 6) . Aeronet-OC station data will be obtained from the Aeronet website (http://aeronet.gsfc.nasa.gov/).

Figure 5 The coastal MOW1 validation site (51.36200° N, 3.12° E) located 5 km from the harbor of Zeebrugge.

Figure 6. The Thornton_C-power platform site (51.5329°N; 02.9549°E) located at 26 km from the coast.

5.2.3. ADDITIONAL SITES FOR GLOBAL VALIDATION

For the global validation of the PROBA-V reflectance product a more in depth performance validation will be performed through application of the A/C algorithm on a series of PROBA-V scenes acquired over the globally distributed AERONET-OC stations located in coastal waters. Some of the global validation sites shortlisted for validation purpose are depicted in Figure 7

→ **Global site – 1**

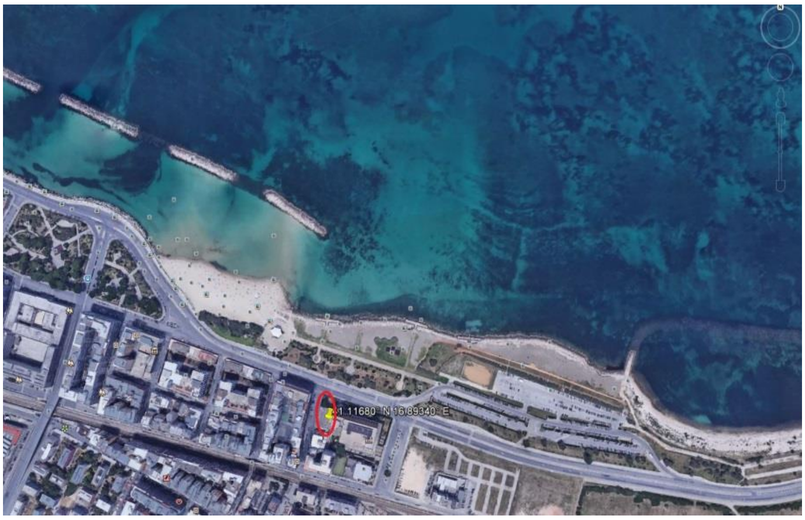


Figure 7 The global validation test site at Bari water front, Italy site with coordinates 41.11667° N 16.89333° E

For the global validation test site shown in Figure 7 the instrument is installed on the roof of ARPA (Regional Agency for environmental protection) of Bari, near the waterfront, Italy. The instrument is mounted on a platform with elevation of 50 meters and is within 200 meters range of the coast.

→ **Global site – 2**

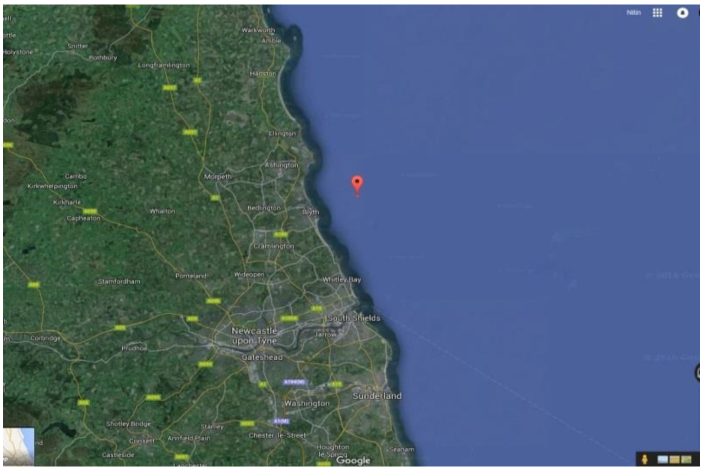


Figure 8 The global validation test site at Blyth NOAH, England with coordinates 55.14639 N 1.420833 W

The original purpose of the Blyth Narec Offshore Anemometry Hub (NOAH) is to characterize wind and ocean conditions for the Blyth Offshore Demonstrator, the demonstration offshore wind farm that Narec is developing close to Blyth. The Hub is located 3 nautical miles off the coast of north-east England in 35 m of water.

→ **Global site – 3**

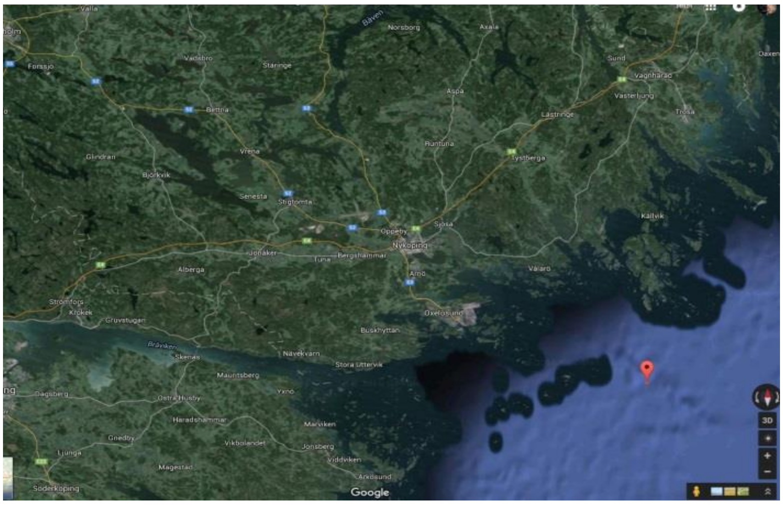


Figure 9 The global validation test site at Gustav Dalen Lighthouse (GDL) in the Baltic Sea with coordinates 58.59417 N, 17.46683 E

The Gustav Dalen Lighthouse is situated in the Baltic sea and 5 nautical miles offshore of the Swedish coast with coordinates 58.59417° N, 17.46683° E and platform elevation 25 meters.

→ **Global site – 4**

Figure 10 The global validation test site at Kaust Campus Thuwal, Saudi Arabia with coordinates 22.30472 N, 39.10278 E

For the validation test site Kaust Campus of Saudi Arabia, the instrument is placed in a rural region within the campus just at the sea shore on the roof of the building.

→ **Global site – 5**

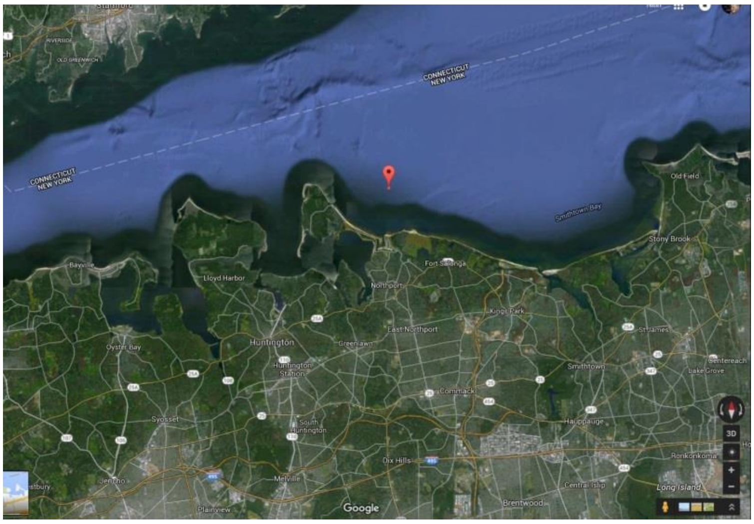


Figure 11 The global validation test site at LISCO NY, USA with coordinates 40.95444 N, 73.34167 W

The global test validation site at LISCO is on western Long Island Sound 2 miles offshore at New York, USA with coordinates 40.95444° N, 73.34167° W.

→ **Global site – 6**

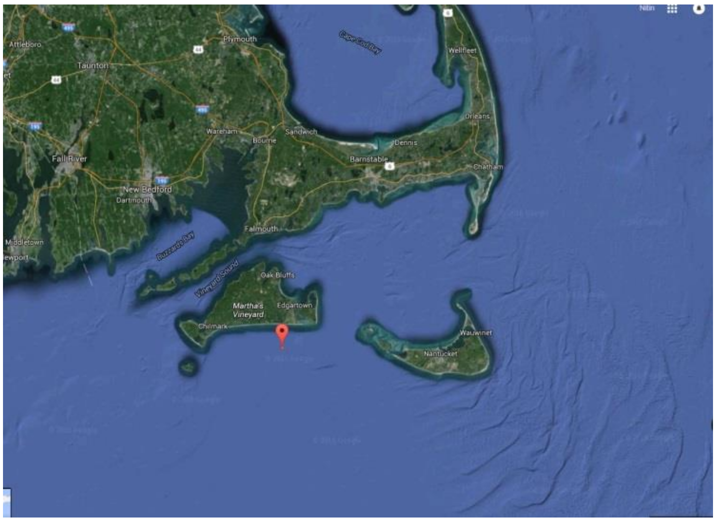


Figure 12 The global test validation site at MVCO, USA is shown with coordinates 41.3 N, 70.55 W

This global validation test site at MVCO is located 5 km off shore on the Air-Sea Interaction Tower, one node of the Martha's Vineyard Coastal Observatory (MVCO) near Rhode island, USA with platform at 10 meter elevation.

Table 5 All AERONET-OC locations. Those highlighted in red color are used. The choice is based on the offshore distance

Abu_Al_Bukhoosh (25N,53E)	Bari_Waterfront (41N,16E)	Blyth_NOAH (55N,1W)
Brussels (50N,4E)	CCNY (40N,73W)	COVE_SEAPRISM (36N,75W)
Gageocho_Station (33N,124E)	Galata_Platform (43N,28E)	Gloria (44N,29E)
GOT_Seaprism (9N,101E)	Gustav_Dalen_Tower (58N,17E)	Helsinki_Lighthouse (59N,24E)
Ieodo_Station (32N,125E)	KAUST_Campus (22N,39E)	LISCO (40N,73W)
Lucinda (18S,146E)	MVCO (41N,70W)	New_Hampshire_Univ (43N,70W)
Palgrunden (58N,13E)	Socheongcho (37N,124E)	Thornton_C-power (51N,2E)
USC_SEAPRISM (33N,118W)	USC_SEAPRISM_2 (33N,118W)	Venise (45N,12E)
WaveCIS_Site_CSI_6 (28N,90W)	Zeebrugge-MOW1 (51N,3E)	

5.2.4. Direct validation approach for A/C

In this section we elaborate the approach to validate the PROBA-V product using AERONET-OC measurements from the test sites.

To validate the A/C method a so called "direct validation approach" will be used. In the direct validation approach, the retrieved PROBA-V water leaving radiance reflectance is compared with the corresponding in-situ AERONET-OC measurements. For this the normalized water leaving radiances ($L_{wn} = \pi.\rho_w.F_0$), measured by AERONET-OC CIMEL instruments will be converted to water leaving radiance reflectance (ρ_w). The general methodology adopted for validating the PROBA-V derived water leaving radiance reflectance with the corresponding in-situ data begins with the development of a match-up database. The steps to develop the matchups database are as follows:

1. For each PROBA-V overpass the nominal 100 m pixel containing the location of the AERONET-OC measurement is extracted,
2. The PROBA-V water leaving radiance reflectance for this pixel and the AERONET-OC measurement that is temporally closest to the exact time of the satellite overpass are recorded as a matchup,
3. The threshold for the temporal offset between the time of the PROBA-V overpass and AERONET-OC measurement is set as ±15 minutes.
4. Any matchups from the PROBA-V products accompanying clouds are rejected. Indeed, only the highest quality observations will be used for matching up with the AERONET-OC measurements.

As can be seen in Figure 13 PROBA-V spectral bands are much broader than the AERONET-OC spectral bands, which complicates the "direct" comparison. In order to take into account the difference in center wavelength and band width "a spectral shift" correction should be applied before performing the "direct" comparison. For this, hyperspectral in-situ measured ρ_w spectra from the SeaSWIR project acquired from turbid waters, and simulated hyperspectral ρ_w spectra from the Coastcolour Round Robin will be used. These hyperspectral in-situ and simulated datasets will be spectrally resampled to both the PROBA-V and the AERONET-OC spectral bands. Next, a regression analysis will be performed between the resampled ρ_w data for the corresponding bands in order to define the "spectral shift" correction to be applied to the real data. For the blue band this spectral correction function will probably consider the two AERONET-OC bands at both edges of the PROBA-V blue band.

Furthermore, it should be noted that there might be an issue of spatial scale when comparing local point AERONET-OC data with 100m PROBA-V data.

Using the matchup database, scatter plots of the PROBA-V-based atmospherically corrected reflectance versus in-situ spectra will be generated. The overall relationship between the PROBA-V and in-situ reflectance will be statistically characterized for each reflective band (through slope, offset, R^2, RMSE measures). The analysis will be performed globally and per region which allows to identify the situations/areas where the A/C method fails.

The quality of the reflectance product in terms of RMSE or R^2 can be directly propagated to the TSM/T product through the TSM algorithm employed in this study.

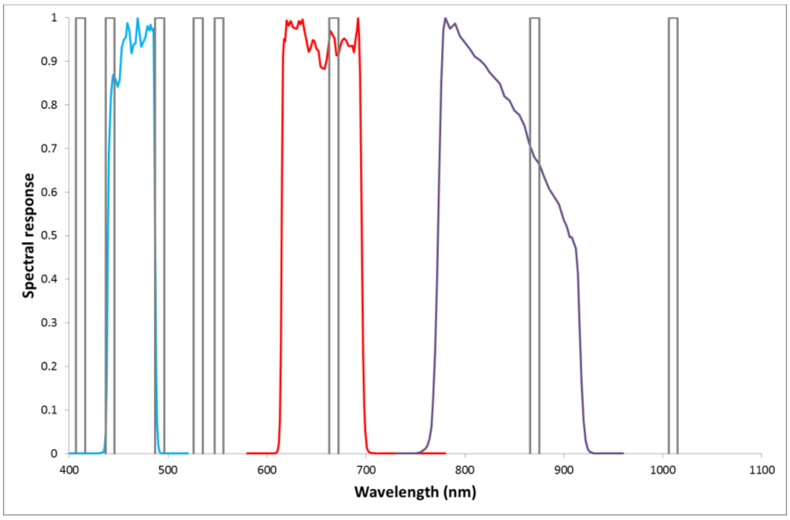


Figure 13 Comparison AERONET-OC (in grey) and PROBA-V spectral bands

5.3. VALIDATION APPROACH FOR TSM/T PRODUCTS

The performance of the selected algorithm for accurately estimating TSM/T in coastal waters on the basis of PROBA-V 100 m will be first evaluated through applications of the algorithms to bio-optical datasets containing simultaneous measurements of above-water remote sensing reflectance and TSM concentrations over coastal and estuarine waters (i.e. the test dataset). Applicable datasets are :

1) the CoastColour Round Robin datasets (Nechad et al., 2015)
2) the SEASWIR dataset (Knaeps et al, 2015)
3) the Mermaid dataset
4) the NASA bio-optical Marine Algorithm Dataset (NOMAD).

The above-water remote sensing reflectance spectra will be spectrally resampled to the PROBA-V spectral bands prior to the application of the algorithm.

To complete the performance analysis, the algorithms will also be applied to real PROBA-V scenes over coastal waters. These PROBA-V TSM/T products will be evaluated through direct comparison (using statistical measures such as slope, offset, R^2, RMSE) against in-situ measured TSM or turbidity data from:

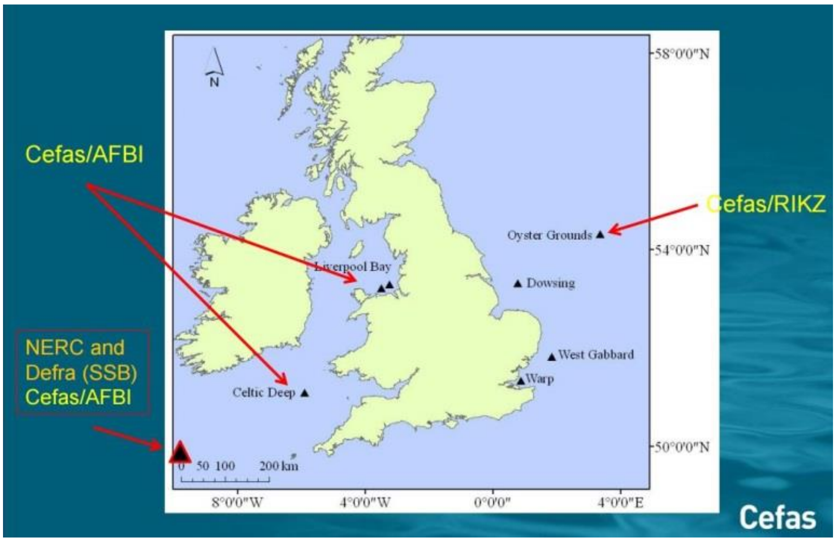
1) CEFAS SmartBuoys (Figure 14)
2) VLIZ buoys (Figure 14)
3) European ferry boxes

Besides the mentioned datasets Turbidity and TSM data which are being collected during dedicated sampling campaigns in the framework of the Belspo funded Proba4coast project and the Highroc FP-7 project might also be used.

For the direct comparison with in situ data it should be noted that differences might be due to the mismatch in the spatial scale.

It is important to note that independent validation and QC of the Smart Buoys is not planned in the project because CEFAS already calibrates the Smart Buoys and does extensive QC. The Smart Buoys each collect data every half an hour (at the start of the program this was 15 minutes) in a burst which is usually between 5 and 10 minutes in duration. This burst data has basic QA applied (min/max) and the good data in the burst is averaged. This then undergoes more thorough QA which includes flagging for biofouling, low power etc. Fouling is more prevalent in the summer months and therefore there are typically more gaps in the summer which you have observed in the data.

(a) Location of CEFAS SmartBuoys and VLIZ buoys



(b) location of all CEFAS SmartBuoys is shown

courtesy: http://www.uk-imon.info/documents/Presentations%20-%20New%20Technologies/010%20Sivyer%20UK-IMON.pdf

Figure 14 CEFAS SmartBuoys and VLIZ Buoys locations are shown

Furthermore an indirect validation will be performed by cross-comparison between MODIS and Proba-V TSM/T products, where the MODIS images are processed independently using SeaDAS. The performance evaluation will be done through :

a) Comparison of spatial patterns with those obtained from MODIS.
b) Comparison of absolute values with those obtained from MODIS.

For the cross validation with MODIS it should be noted that the time difference between image acquisitions (varies in the order of 30min. with Terra and 2h with Aqua) could cause differences in TSM concentrations in the high dynamic coastal waters which may influence the comparison against other missions. Recently, Vanhellemont and Ruddick (2014) showed that these differences exist even for a minimum time difference.

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