Atmospheric Corrections

Water-ForCE

Project Identification

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History of Changes

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15.12.2021	V0	Template and first outline
5.12.2022	V0.1	With major contributions by VITO, PML, CNR and 3EDATA
12.12.2022	V0.2	With additions by UTARTU and VITO
16.12.2022	V0.3	Implementing review comments

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20.12.2022	V1.0	Final editing by VITO. V1.0 for submission to EC

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List of Acronyms

AAC	Alternative Atmospheric Correction
AC	Atmospheric Correction
ACOLITE	Atmospheric Correction for OLI lite
AE	Adjacency Effect
AERONET	Aerosol Robotic Network
AERONET-OC	Aerosol Robotic Network-Ocean Colour
AOT	Aerosol Optical Thickness
ANN	Artificial Neural Network
API	Application Programming Interface
ARD	Analysis Ready Data
ASV/ROSV	Autonomous and Remotely Operated Surface Vessels
ATBD	Algorithm Theoretical Basis Document
ATCOR	Atmospheric and Topographic Correction
AWP	Adaptive Window by Proportion
BAC	Baseline Atmospheric Correction
BLR	Baseline residual
BOUSSOLE	Bouée pour l'acquisition de séries optiques à long terme
C2RCC	Case 2 Regional Coast Colour Processor
CAMS	Copernicus Atmospheric Monitoring Service
Cal/Val	Calibration and Validation
CCI	Climate Change Initiative
CCVS	Copernicus Cal/Val Solution
CDOM	Colored Dissolved Organic Matter
CEOS	Committee on Earth Observation Satellites
CF	Climate and Forecast
CGLOPS	Copernicus Global Land Service
Chl-a	Chlorophyll-a
CLMS	Copernicus Land Monitoring Service
CMEMS	Copernicus Marine Environment Monitoring Service
CSA	Coordination and Support Action
C3S	Copernicus Climate Change Service
DSF	Dark Spectral Fitting
EC	European Commission
EDMO	European Digital Media Observatory
EEA	European Environment Agency
EnPT	EnMAP Processing Tool
EO	Earth Observation
ESA	European Space Agency
FAIR	Findable, Accessible, Interoperable, Re-usable
FEM	Finite Element Model
FRM	Fiducial Reference Measurement

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GLEON	Global Lake Ecological Observatory Network
GRS	Glint Removal for Sentinel-2
HR	High Resolution
iCOR	Image Correction for Atmospheric Effects
IOCCG	International Ocean-Colour Coordinating Group
IOP	Inherent Optical Property
L1	Level 1
L2	Level 2
L3	Level 3
LR	Low Resolution
LUT	Look-up-Table
MAJA	MACCS ATCOR Joint Algorithm
Meet2C	Meet Case 2 Water
MERIS	Medium Resolution Imaging Spectrometer
MIP	Module Inversion Program
MOBY	Marine Optical Buoy
MODIS	Moderate Resolution Imaging Spectroradiometer
MSI	Multispectral Imager
NASA	National Aeronautics and Space Administration
Netlake	Networking Lake Observatories in Europe
NIR	Near Infrared
NN	Neural Network
NOAA	National Oceanic and Atmospheric Administration
OBPG	NASA Ocean Biology Processing Group
OC	Ocean Colour
OC-SMART	Ocean Colour Simultaneous Marine and Aerosol Retrieval
OLCI	Ocean and Land Colour Instrument
OWT	Optical Water Type
PFS	Product Family Specification
POLYMER	Polynomial based algorithm applied to MERIS
QA/QC	Quality Assurance/Quality Control
RGB	Red, Green, Blue
RMSD	Root Mean Square Deviation
RPAS	Remotely Piloted Aircraft Systems
Rrs	Remote Sensing Reflectance
RT	Radiative Transfer
RTD	Radiative Transfer Database
S2	Sentinel-2
S3	Sentinel-3
SeaDAS/l2gen	Seawifs Data Analysis System/l2gen
SeaWIFS	Sea-Viewing Wide Field-of-View Sensor
Sen2COR	Sentinel-2 Correction
SDG	Sustainable Development Goal

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SI	International System of units
SIMEC	SIMilarity Environment Correction
SNAP	Sentinel Application Platform
SVC	System Vicarious
SWIR	Short-Wave-Infrared
TOA	Top-of-Atmosphere
TSM	Total Suspended Matter
VIIRS	Visible Infrared Imaging Radiometer Suite
WG	Working Group
WP	Work Package

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1 Introduction

Deliverable D2.3 of the Water-ForCE Coordination and Support Action (CSA) aims to give an overview of the atmospheric corrections currently used by the Copernicus services for water products, the state-of-the-art, needs and recommendations related to atmospheric corrections for water. D2.3 serves as input for the Water-ForCE Roadmap.

IOCCG, 2018:

'The atmosphere typically contributes around 90% of the signal at Top-of-Atmosphere (TOA) over a clear ocean. Thus **the signal from the water is challengingly small in comparison to the atmosphere**. In inland waters, the water-leaving signal may be substantially larger (in the case of high concentrations of phytoplankton or suspended matter) or smaller (in the case of high CDOM) than that observed in the open ocean. This makes correcting for the atmosphere in a consistent manner in inland waters substantially more challenging, potentially requiring the use of different atmospheric correction schemes dependent on conditions. The main challenges for atmospheric correction over small to intermediate inland targets arise from contamination by atmospheric **aerosols** and **stray light (i.e. adjacency effect**).'

Montes et al., 2022:

'One of the main sources of uncertainties in Landsat-8/ Sentinel-2 data processing is the atmospheric correction (AC) (IOCCG, 2019a; Pahlevan et al., 2021a) for which inaccurate representation of aerosol radiative properties is one major weakness, particularly when **absorbing aerosols** are present (IOCCG, 2010; Pahlevan et al., 2017a; Frouin et al., 2019). This is explained by the contribution of coupled aerosol scattering and absorption and their high spatial and temporal variability (Prospero et al., 1983). Given a particular location and time,

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realistic aerosol mixtures are critical for executing a robust AC on aquatic satellite scenes to retrieve high-quality spectral remote sensing reflectance (Rrs) products (Mobley, 1999), from which bio-geophysical products are derived.'

Moses et al., 2017:

'Atmospheric correction of remotely sensed data is more challenging for inland waters than for open ocean waters due to a number of factors. The proximity of inland waters to various terrestrial sources of atmospheric pollution results in a more optically heterogeneous atmosphere, which complicates atmospheric modeling; the signal received at the sensor is often contaminated by contribution from the **adjacent land**, which is particularly problematic in cases of **raised topography** surrounding the water body and complicates atmospheric correction; non-negligible reflectance from water in the near-infrared region due to **high sediment concentrations** in inland waters (caused by agricultural and industrial discharge from terrestrial sources) makes it difficult to accurately estimate and remove the effect of atmospheric aerosol scattering on the received signal.'

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2 Atmospheric correction in Copernicus services

2.1 Copernicus Marine Environment Monitoring Service (CMEMS)

The atmospheric correction approach for the CMEMS Low Resolution (LR) and High Resolution (HR) products differs and is described in this section.

CMEMS LR

In CMEMS LR ESA Ocean Colour-Climate Change Initiative (OC-CCI) products based on MERIS (MEdium Resolution Imaging Spectrometer) from ESA, SeaWiFS (Seaviewing Wide Field-of-view Sensor) and MODIS (Moderate Resolution Imaging Spectroradiometer) from NASA, VIIRS (Visible Infrared Imager Radiometer Suite) from NOAA, and most recently the Copernicus Sentinel 3A OLCI (Ocean and Land Colour Instrument) (Volpe et al., 2019) are accessible. On the basis of round-robin analyses, the **POLYMER** atmospheric-correction processor (Steinmetz et al., 2011) was selected for the processing of MERIS data and the NASA **l2gen** processor was selected for SeaWiFS, MODIS-Aqua, and VIIRS data (Sathyendranath et al., 2019a, 2019b). Figure 1 (taken from Sathyendranath et al., 2021) shows the statistics for the matchups between OC-CCI V5.0 (top) and V4.2 (bottom) satellite Rrs and in situ MOBY (station located near Hawaii) Rrs.

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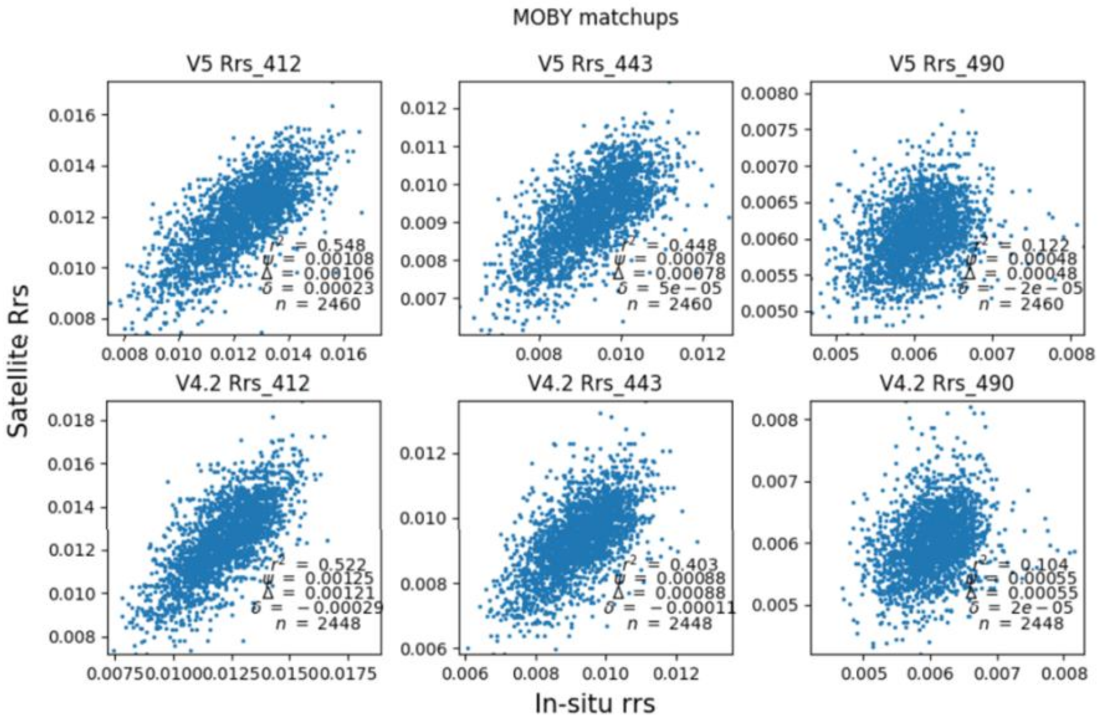

Figure 1: Matchups for data taken at MOBY station for OC-CCI V5 and V4.2. Summary statistics are correlation coefficient, RMSD, unbiased RMSD, bias and number of matchups (Sathyendranath et al., 2021).

CMEMS HR

The CMEMS HR (Sentinel-2A and B, 20 km coastal strips of all European seas, 100m spatial resolution) atmospheric correction workflow running on CREODIAS relies on a **pixel-based switching approach between two atmospheric correction algorithms: C2RCC (for clear to moderate turbid waters) and ACOLITE/DSF (for more complex optical waters)** (Van der Zande et al., 2022). A band ratio between green (Rrs at 560 nm) and NIR band (Rrs at 865 nm), defines which of both methods is selected. In doing so, the workflow focuses on the strengths of both correction methods, i.e.:

- ACs like **ACOLITE/DSF** (Vanhellemont, 2019) (and **iCOR** (De Keukelaere, 2018a)) make no assumption about the water reflectance enabling the return of unusual

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water reflectance spectra corresponding to optical properties that would not be found in a typical water reflectance model or might lead to an ill-defined mathematical problem with multiple solutions for the more usual water conditions. However, the disadvantage of this approach is that some atmospheric conditions (e.g. severely sun-glinted pixels) may be just too challenging.

- ACs like **C2RCC** (Brockmann et al. 2016, Doerffer and Schiller, 2007) (and **POLYMER** (Steinmetz et al., 2011, 2017)) have an underlying water reflectance model that assumes that water reflectance will fit some known spectral shape (albeit with a certain number of degrees of freedom). The main advantage of the latter approaches is that the additional information provided by a constraint on water reflectance enables a solution to be more easily obtained even in very challenging situations such as high sun glint. These approaches (unless they fail completely) will always produce a Rrs spectrum that looks like water. The Level 2 aquatic reflectance products can even be relatively insensitive to sensor calibration errors.

Validation results of the merged ACOLITE/C2RCC AC approach against AERONET-OC and PANTHYR in situ data are shown in Figure 2 and Figure 3 respectively.

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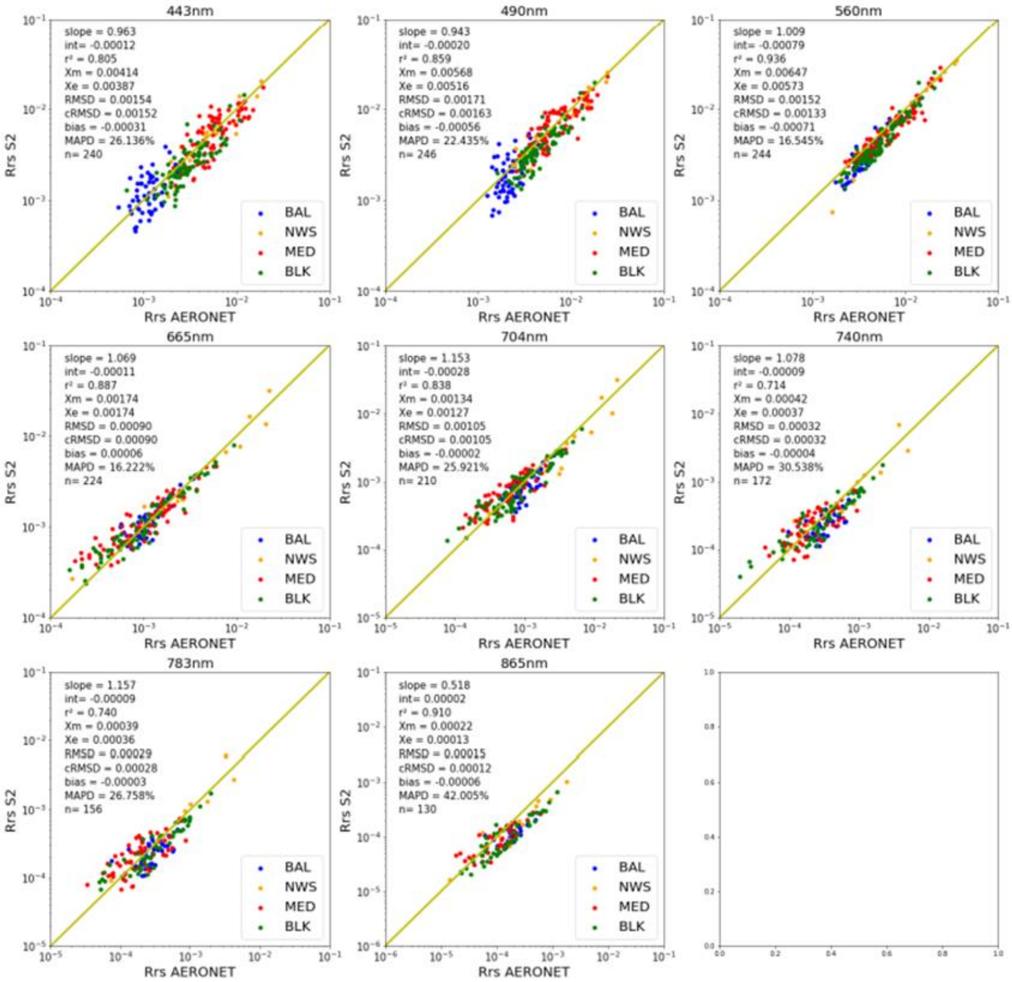

Figure 2: L3 daily MSI spectral Rrs dataset against in situ observations obtained from the AERONET-OC network for 11 stations located in 4 CMEMS regions: Baltic Sea (BAL), NW European Shelf (NWS), Mediterranean Sea (MED) and (Black Sea) BLK. (Van der Zande et al., 2022).

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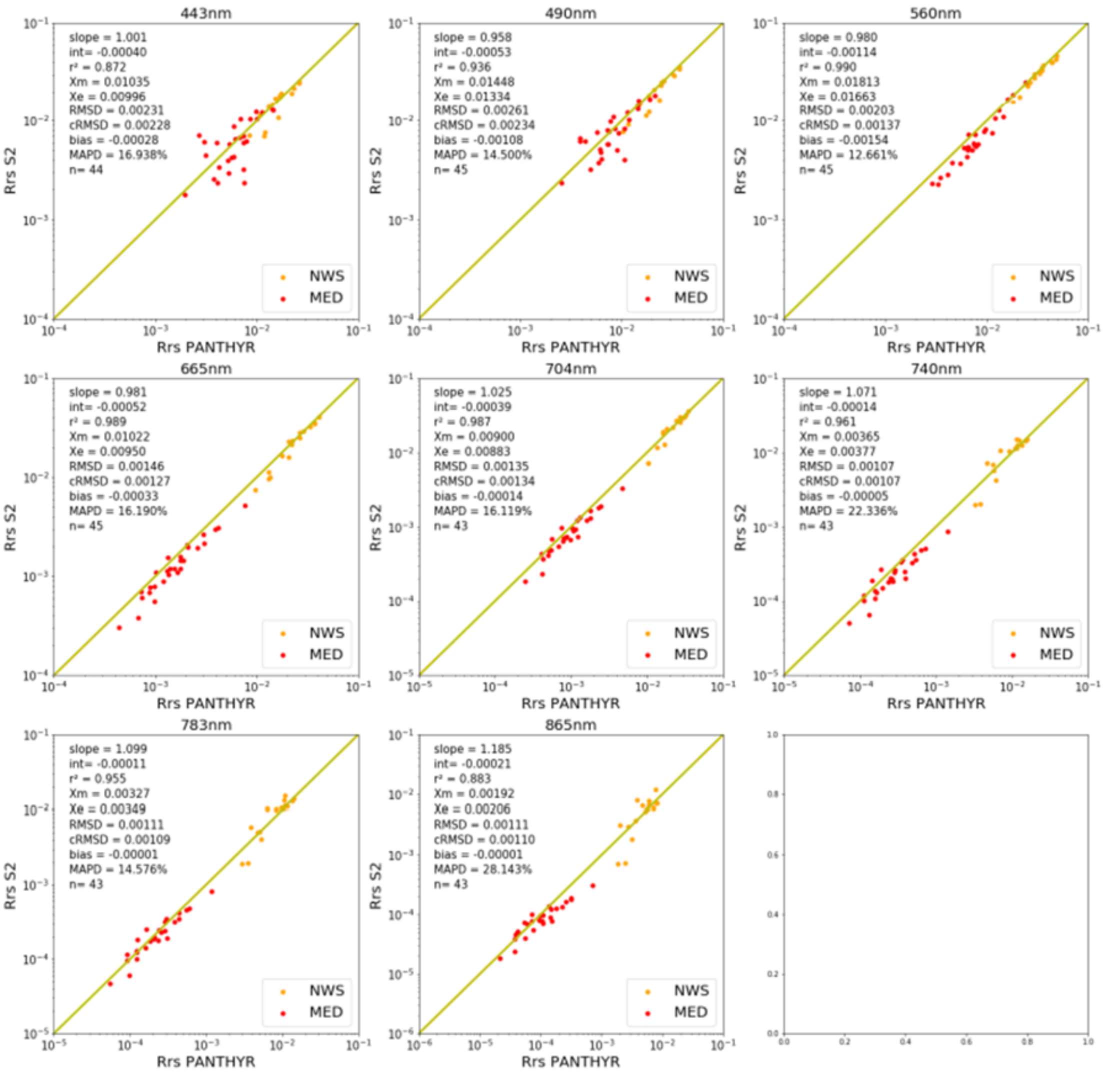

Figure 3: L3 daily MSI spectral Rrs dataset against in situ observations obtained from the PANTHYR network for 2 stations located in 2 CMEMS regions: NW European Shelf (NWS) and Mediterranean Sea (MED). (Van der Zande et al., 2022)..

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2.2 Copernicus Global Land Service (CGLS) of the Copernicus Land Monitoring Service (CLMS)

The CLMS-CGLS and ESA Lakes Climate Change Initiative (Lakes_cci)[1] production chains both use the **POLYMER** atmospheric correction processor by HYGEOS, using a configuration to circumvent common issues encountered in optically complex water and near land:

- Initialisation of the processor in 'Case-2' conditions with Chl-a concentration and the backscatter parameter f_b both initialized at 10 instead of 1.
- Re-initialisation of the model parameters when negative values are encountered.
- Internal cloud and land masking thresholds are not used. Instead, water identification is based on the Idepix module in SNAP.

A key difference between the Service and the Climate data record production is their latency, with CLMS-CGLS working operationally with all non-time-critical L1B data available in 12-day periods (delivering 10-day sequences on the 13th day) and Lakes_cci producing distinct, uncertainty-characterized datasets every few years which benefit from consistency checks between color, temperature and ice records, as well as additional characterization of land adjacency effects in the data. There is no lake water color product currently in the Copernicus Climate Change Services (C3S). CLMS-CGLS outputs are close to the native sensor resolution (300m) whilst Lakes_cci products are delivered on a 1/120 degree ('1km') grid, compatible with Lake surface water temperature products in the same merged (L3S) outputs. Thus far, CLMS-CGLS have produced versions of archive data from the MERIS and Sentinel-3 OLCI A/B sensors at 300m resolution, whilst Lakes_cci also considers MODIS-Aqua. Finally, the CLMS-CGLS includes a 100-m product derived entirely from Sentinel-2 MSI A/B, for a selection of scenes in Europe and Africa.

[1] https://climate.esa.int/en/projects/lakes/

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The lakes configuration of POLYMER (currently v4.13 at 300m and v4.14 at 100m) was selected following round-robin comparison of satellite vs in situ matchups of MERIS data, where it was one of the processors with the largest number of outputs (along with C2RCC), whilst also giving the statistically most consistent correlation between in situ and satellite. It was nevertheless found that the resulting reflectances have negative bias against the (limited) in situ reflectance observations, which is not found in coastal marine waters. As a result, the reflectance product in CLMS-CGLS have not been considered 'operational', whilst the biogeochemical products derived from reflectance (Trophic State Index, Turbidity) benefit from end-to-end algorithm tuning per Optical Water Type, so that the systematic bias is removed. The MSI processing chain also uses POLYMER based on an early evaluation of different A/C processors (Warren et al. 2019) and because no clear improvement in the available AC solutions for MSI was shown in later work (Pahlevan et al. 2021a). Whilst globally relevant in situ reflectance datasets are still largely lacking to independently assess AC performance of OLCI and MSI, products derived from the latter were tuned against OLCI products for overall consistency, instead of taking a sensor-by-sensor approach (Warren et al. 2021). In turn, the OLCI products are still assumed to perform to the same standard as MERIS, which is verified on the basis of time-series investigations.

An important difference between the operational CLMS-CGLS Lake water quality service and the Lakes_cci is that the former is designed primarily against user requirements and expected to deliver the state-of-the-art (as far as the means to assess this, are available), whereas the climate data set is first and foremost designed to fulfill the Global Climate Observation System (GCOS) set of requirements for the Lakes Essential Climate Variable. The 2022 GCOS implementation plan sets out the requirements for relative uncertainty of lake color (reflectance) from 30% at peak amplitude (Target requirement) down to 20% (Breakthrough requirement) and 10% (Goal). According to the AC round robin performed within Globolakes, the detrended normalized root-mean-square-error (dNRMSE%) ranged 15-109% across MERIS wavebands, with best performance seen in the red and NIR bands with errors of 25%, 19%, 17%, and 15% in bands 665, 709, 754, and 779 nm respectively. The

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detrending of error translates the retrieval accuracy to the remaining, random uncertainty which is decisive for retrieval of the chlorophyll-a and TSM estimates in a wide range of inland water types, whereas the absolute uncertainty in the reflectance products is (much) higher. A more recent investigation by Liu et al. (2021) shows that the detrended uncertainty at 560 nm (which is most often near the peak amplitude) was 21%, whilst the uncertainty before detrending was still in the order of 89% (Figure 4).

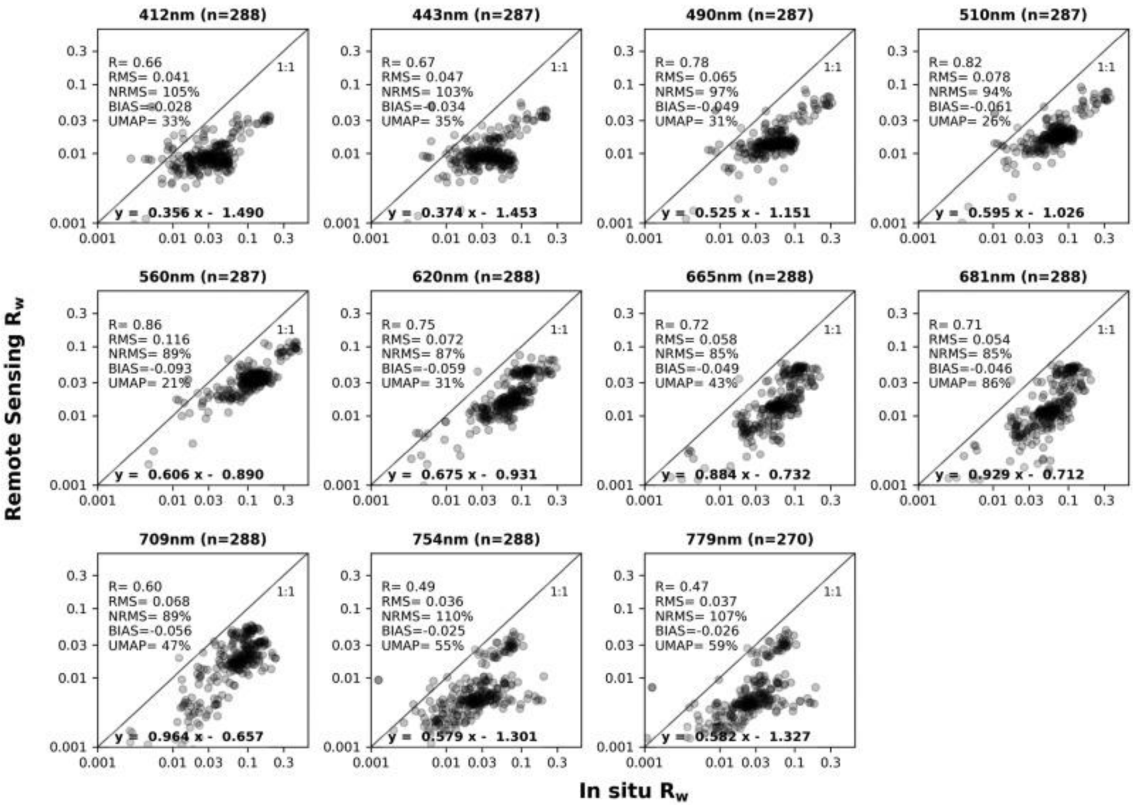

Figure 4: MERIS-derived reflectance validation using POLYMER in the Lakes_cci, from Liu et al. (2021).

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2.3 Copernicus Climate Change Service (C3S)

For the C3S Ocean Colour products (heritage of ESA Ocean Colour-Climate Change Initiative[2]), daily composites from satellite data from SeaWiFS, MERIS, MODIS Aqua, VIIRS and S3-OLCI are used. The latest data set (V6.0) is created by band-shifting and bias-correcting SeaWIFS, MODIS, VIIRS and S3 OLCI data to match MERIS data, merging the data and computing per pixel uncertainty estimates. MODIS and VIIRS is dropped from the record after 2019 due to quality concerns of the aging sensors (as described in Sathyendranath et al., 2022). The focus is on Case 1 waters. **POLYMER** (see previous section) is used for all atmospheric corrections (SeasDAS L2gen only for geometric correction). Validation results for the V6.0 data set are not yet available. For validation results of previous versions, we refer to Section 2.1.1 CMEMS LR.

3 Needs

3.1 From the Copernicus services and its end-users

At the Water-ForCE Water Quality Continuum Group Meeting 1, 23 February 2021, the Water-ForCE Copernicus Water Component Evolution-Policy Expert workshop[3], 20-21 October 2021, Copenhagen (Denmark), within the COINS[4] project (supporting the European Environment Agency (EEA) cross-cutting coordination of the Copernicus programme's in-situ data activities – Observational data Lake Water Quality In-Situ Data Requirements and

[2] https://climate.esa.int/en/projects/ocean-colour/

[3] https://waterforce.eu/workshops/copernicus-water-component-evolution--policy-expert

[4] https://insitu.copernicus.eu/library/reports/COINS_WaterQuality_FinalReport_v1.1.pdf

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Availability and the Copernicus Cal/Val Solution (CCVS[5]) project the following needs in terms of atmospheric correction and/or validation were formulated:

CMEMS-Green Ocean-HR

- Add narrow bands + 620 nm (for cyanobacteria detection) and improved SNR (see also Water-ForCE D2.5)
- Correct for sun glint
- Solve detector stripes (clearly visible and information on angles does not solve the problem)
- Lack of suitable in-situ data for some regions (Arctic, Iberia-Biscay-Ireland)

CLMS-CGLS-Water Quality:

Immediate needs:

- Focus on increased validation particularly of recent (Sentinel-2, Sentinel-3) sensors; more interaction with in situ sensor operators is needed.
- In situ data needs
    - Readily available spectroradiometry
    - Transect radiometric data to assess adjacency effects particularly on small water bodies

Further future needs:

[5] https://www.ccvs.eu/

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- Handle the overlap between inland, marine and transitional waters (water quality continuum) with a harmonized approach (prove consistency, alignment of parameters)
- Regularly repeating round robins for different algorithms (atmospheric correction (AC), in-water, cloud/pixel classification)
- In-situ database (quality controlled/harmonized + metadata) open for algorithm developers to provide comparable quality indicators

Copernicus in situ component:

- Optical data such as lake water reflectances and Inherent Optical Properties (IOPs) needed for calibrating and validating the atmospheric correction algorithm(s) and optical processes in the water (absorption and scattering). These data are needed for both – algorithm development and algorithm validation.

COINS :

- Data from more regions and optical water types are required - some parts of the world are not covered by open or public datasets.
- Smaller lakes are poorly represented (e.g. AERONET-OC only covers six very large lakes).
- Hyperspectral data is especially needed, both for improving AC models, and to be able to adjust data to more satellite sensors.

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CCVS:

- Accurate calibration is needed for the instruments developed for validation activities, and the calibration should be traceable to SI
- Need for more data simultaneously collected with satellite overpasses
- There are a lot of measurements already being conducted but there is need to help these to reach Fiducial Reference Measurements (FRM) (Ruddick et al., 2019)
- Need for an improved data sharing/distribution
- There is a need for a Standard Travelling Instrument that is maintained together with the Copernicus programme and its partner laboratory. These devices are well characterized and calibrated and will be used to compare different sites regularly to make sure that there is site-to-site consistency.
- Need for automated surface reflectance measurements
- Need for automated reflectance and IOP measurements
- Full uncertainty budget needed for reflectance measurements
- The main aim has to be to collect FRM quality data to validate Copernicus radiance/reflectance products. This means that the data have to cover a variety of conditions.
- Need to evaluate if the potential of the Research Infrastructures is used in the Cal/Val activities, as they are fully operational, long term funded and aiming for full FAIRness (Findable; Accessible; Interoperable; Reusable).
- There is need for a network of measurements covering a variety of different water sites, both marine and inland waters

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3.2 From the R&D community and its end-users

At the Water-ForCE Water Quality Continuum Group Meeting 1, 23 February 2021 and the Water-ForCE In situ calibration and validation of satellite products of water quality and hydrology workshop, 17, 18 and March 2021 (report[6]) needs from the EO and in situ community were collected. Here the needs related to atmospheric correction and/or validation are listed split over the categories Products, Processing, Cal/Val and Education/Capacity Building.

3.2.1 Products

- Atmospheric correction data need to be harmonized (protocols, data formats)

3.2.2 Processing

- Development and performance assessment of atmospheric corrections that can correct for adjacency effect
- Aerosol characterization for atmospheric correction under different atmospheric conditions

3.2.3 Cal/Val

In situ data needs for atmospheric correction validation

- Use of new autonomous hyperspectral spectroradiometers for the acquisition of Rrs information. Include Rrs in regular monitoring programmes.
- Prioritize collection and accessibility of data used for atmospheric correction validation (including nearshore)
- Lacking capacity building on sampling, protocols for Earth Observation (EO) Cal/Val

[6] https://web-waterforce-files.vercel.app/workshop-report-in-situ-calibration-and-validation-of-satellite-products-v10.pdf

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- Including more (reflectance) spectroradiometry in in situ observation networks, to improve complementary value of in situ water quality measurements and satellite observations, reducing uncertainties in atmospheric correction. Multiple solutions exist from a range of providers (hyperSAS, PANTHYR, HYPSTAR, WISPstation, HydraSpectra) although some are still prototypes. For non-static platforms the So-Rad and hyperSAS and Dalec can be considered suitable. The sensors should be networked, hyperspectral and continuous.
- The case is made to support hyperspectral in situ reflectance radiometers for fiducial Cal/Val of optical satellites. The ideal sensor system has a broad spectral range and continuous calibration features using a built-in light source. HYPERNETS develops this sensor and several prototypes are currently in place.

Metadata and interoperable data

- Create a Standard of Practise for metadata collection and data storage
    - Develop and adopt a controlled vocabulary, informed by existing services (NERC vocabulary services, GLEON/NETLAKE common vocabulary, CF conventions, EDMO codes).
    - Promote FAIR principles.
- Develop tools to help centralize: 'upload API' & forms/templates, QA/QC
- Provide platforms to explore and query in situ and satellite observation data together.
- Pursue the same level of data integration of inland waters as achieved for marine (e.g. SeaDataNet with 100 National Oceanographic Data Centres, 34 European coastal states; physical, chemical, biological, geology, to geophysics and bathymetry).
- Clarify the respective roles of EEA and Copernicus In Situ as coordinating bodies for in situ observation data.

Round robin exercises

- Atmospheric correction round robin exercises for AC validation under different

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atmospheric and water conditions

Sustainable in situ data infrastructure for atmospheric correction validation

- Provide standard procedures to maintain data quality (e.g., instrument care)
- Promote sustained long-term funding (instead of project-based short-term funding) to support data providers for network, infrastructure, data collection, Q&A and training.
    - Focus on sustainability of funding for high quality measurements - e.g., use of Research Infrastructures.
    - Build support for long-term continuous measurements in countries that may not be able to afford to do so.
    - Forge direct cooperation between in situ and EO communities through common funding support.

3.2.4 Education/capacity building

- Skilled people are needed to handle data.
- Establish wider contribution to Cal/Val:
    - Establish Cal/Val contributing activities within (national) monitoring context
    - Develop protocols for site operators to do local Cal/Val
    - Harmonize existing measurements by inter-comparison exercises (of protocols, calibrations and instruments)
    - Train in situ monitoring community to facilitate data collection for use in satellite Cal/Val (i.e sample on clear days during satellite overpass)
    - Community-driven improvement of commercial sensor offering, e.g. with radiometers and drones.
    - Provide tools (e.g. QGIS, SNAP) that allow for Cal/Val using local data
- Training
    - Training of students, globally
    - Training for citizen science programmes, including young people

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  - Training of individuals to reach the required data standard, particularly small research groups with limited expertise
  - Increase 'satellite literacy' at key agencies to promote more support for remote sensing Cal/Val (for time series of water quality data to match-up with satellite passages, including key variables, strategic locations)
- Funding
  - Seek funding for training programmes and for citizen science programmes

4 State-of-the-art in atmospheric correction for water and validation

4.1 Atmospheric correction

Removing the effects of the atmosphere from the measured remote sensing signal is an inverse problem, which by definition does not have a single solution. About 90% of the radiance measured by satellites above the water surface originates from the atmosphere and does not contain any information about water properties. Therefore, a small error in removing the atmospheric effects may actually be larger than the whole water leaving signal. Thus, atmospheric correction of satellite data collected over water bodies is a very challenging task (Kay et al. 2009).

Table 1 gives an overview of the state-of-the-art AC processors used for Sentinel-2 MSI, Sentinel-3 OLCI and spaceborne hyperspectral imaging sensors (i.e. imaging spectroradiometers) like PRISMA or EnMAP. Description of the AC processors used for Sentinel-2 MSI, Sentinel-3 OLCI and some hyperspectral imaging sensors are detailed in the next sessions.

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Table 1: Overview of AC processors (with or without adjacency correction) and applicability to Sentinel-2 MSI, Sentinel-3 OLCI and imaging spectroradiometers (hyperspectral).

AC processor	Incl. adjacency correction	Free access	S2	S3	Imaging spectro radiometer	Reference
ACOLITE/ DSF	Ongoing	Yes	Yes	Yes	Yes (PRISMA)	Vanhellemont et al., 2019
iCOR	Yes (SIMEC)	Yes	Yes	Yes	Ongoing (PRISMA)	De Keukelaere et al., 2018a
C2RCC	No	Yes	Yes	Yes	Yes (EnMAP)	Brockmann et al., 2016
POLYMER	Robust to spectrally flat adjacency effect; adjacency correction ongoing	Yes[a]	Yes	Yes	Yes (EnMAP)	Steinmetz et al., 2011
GRS	No	Yes	Yes	No	No	Harmel et al., 2018
MEETC2	No	Yes	Yes	Yes	No	Saulquin et al., 2016
SeaDAS/ l2gen	No	Yes	Yes	Yes	Yes (l2gen hyperspectral version)	Pahlevan et al., 2017b
OC-SMART	Robust and resilient to contamination due adjacency effects of land	Yes	Yes	Yes	Yes (HICO)	Fan et al., 2021

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	or cloud					
MIP	Yes	No	Yes	Yes	Yes	Heege et al., 2014
A4O	No	Yes	No	Yes	No	Hieronymi et al., 2022
BAC	No	Yes	No	Yes	No	Antoine and Morel, 1999
AAC	No	Yes	No	Yes	No	EUMETSAT, 2021
ANN	No	Yes	No	Yes	No	Schroeder et al. 2022
BLR	No	Yes	No	Yes	No	Gossn et al. 2019

[a]POLYMER is available under license for non-operational processing, please refer to the software license for detail.

4.1.1 Sentinel-2 MultiSpectral Instrument (MSI)

Sentinel-2 was not designed but has potential for monitoring water quality in inland and coastal waters (Toming et al., 2016, Gernez et al., 2017, Potes et al., 2018, Maciel et al., 2019, Page et al., 2019, Balasubramanian et al., 2020, Cao and Tzortziou, 2020, Hakimdavar et al., 2020, Huangfu et al., 2020, Peterson et al., 2020, Soomets et al. 2020, Guo, et al., 2021, Ma et al., 2021, Sent et al., 2021, Virdis et al. 2022). However, atmospheric correction in these waters is challenging, and there is no standardized approach yet, but many different atmospheric correction algorithms have been developed for Sentinel-2 in recent years. These algorithms are under continuous development:

- **ACOLITE** (Atmospheric Correction for OLI lite) (Vanhellemont., 2019): ACOLITE is a generic processor for atmospheric correction and processing for coastal and inland water applications. ACOLITE performs the atmospheric correction by default using

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the ”dark spectrum fitting” (DSF) approach. The DSF uses multiple dark targets in the subscene to construct a “dark spectrum” which is used to estimate the atmospheric path reflectance according to the best fitting aerosol model.

- **GRS** (Glint Removal for Sentinel-2) (Harmel et al., 2018). The GRS algorithm is developed to estimate the sun glint signal directly from Sentinel-2-like spectral information and viewing geometry. The GRS algorithm also allows for an atmospheric correction based on aerosol parameters provided by the Copernicus Atmospheric Monitoring Service (CAMS). The latest GRS version incorporates new aerosol models and a specific correction for absorbing aerosols. This correction is based on the separation of the scattering and absorbing properties of aerosols to perform the atmospheric correction and based on the first guess provided by the new aerosol products of CAMS .
- **MEETC2** (Meet Case 2 waters) (Saulquin et al., 2016); MEETC2 approach relies on a Bayesian inference using Gaussian Mixture Model prior distributions on reference spectra of aerosol and water reflectance. The key feature of the model is the inversion of water and atmospheric signals from TOA observations using a multi-hypothesis setting. Rather than considering a single model, linear or not, a Bayesian framework where the priors stated as mixture of models is used.
- **POLYMER** (POLYnomial based algorithm applied to MERIS); POLYMER (Steinmetz et al., 2011) employs a spectral optimization technique to retrieve atmospheric and in-water parameters simultaneously from all available spectral bands. The algorithm which now accommodates multiple sensors combines a water reflectance model that depends on two parameters, namely, the Chl-a concentration and particle backscattering, and a polynomial atmospheric reflectance model with three spectral components, which models the reflectance of the atmosphere, including aerosols and contamination by sun glint. The algorithm is configurable with respect to input bands, bio-optical model, initialisation values and bounds.
- **SeaDAS/l2gen** (SeaWiFS Data Analysis System) The SeaDAS implementation for Sentinel-2 is described in detail in Pahlevan et al., 2017b. The process begins with

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removing the Rayleigh contribution using ancillary data and pre-computed LUTs. The Rayleigh-corrected radiance in the NIR (865 nm) and SWIR bands are then used to infer an aerosol type and aerosol optical thickness. The contributions by whitecaps and sun-glint are discarded in SeaDAS.

- **iCOR** (image CORrection for atmospheric effects) (De Keukelaere et al., 2018a):; iCOR is a scene-generic processor that can handle land and water targets. The AOT retrieval and adjacency correction are specifically designed to improve retrievals over inland waters. iCOR includes the adjacency correction SIMEC (SIMilarity Environment Correction) (Sterckx et al., 2015). The aerosol optical thickness is derived above land through a TOA radiance inversion of selected end-members in the scene following the approach described in Guanter et al. (2007). Over water the AOT is retrieved through spatial extension of the derived values of neighboring land pixels assuming local spatial invariability of the aerosol.
- **Sen2Cor** (Sentinel 2 Correction) is an atmospheric correction algorithm developed for Sentinel-2 Level 2A land products. The AC module in Sen2Cor is a porting and adaptation of the ATCOR (Atmospheric/Topographic Correction for Satellite Imagery (Richter and Schläpfer, 2017)) software (Main-Knorn et al., 2017). In general, the atmospheric correction algorithm assumes that the vegetation pixels in the satellite image have adequate darkness and that the ratio of the bottom-atmospheric reflectance between the wavelengths is constant, called dark dense vegetation (DDV). Accordingly, this algorithm will require the presence of vegetation, corresponding to the dark areas in satellite images. Please note that Sen2Cor is mainly designed for land applications. Water surface effects such as sun and sky glint are neglected and therefore Sen2Cor is not included in Table 1..
- **MAJA** (MACCS ATCOR Joint Algorithm, release 4.2). MAJA is a processor for cloud detection and atmospheric correction and is specifically designed to process optical time series (Rouquié et al., 2017). The main feature of MAJA is the use of multi-temporal information contained in the time series to better estimate aerosol optical

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thickness and correct atmospheric effects (Hagolle et al., 2017). MAJA is designed for land applications and therefore not included in Table 1.

- **OC-SMART** (Ocean Color Simultaneous Marine and Aerosol Retrieval Tool) (Fan et al., 2021). The atmospheric correction (AC) and ocean IOP algorithms in OC-SMART is based on machine-learning multilayer perceptron neural networks, trained with synthetic datasets that were generated using in-water and atmospheric radiative transfer models.
- **MIP:** The L2A nominal atmospheric correction over water for EnMAP is based on the Module Inversion Program (MIP) of EOMAP. The radiative transfer model is based on a Finite Element Model (FEM), calculating the light transfer in a multi-layer system, including atmosphere, water surface, water body and seafloor. The MIP algorithm accounts and corrects a number of environmental impacts:

  - The adjacency effect is accounted for by following the procedure of Kiselev et al., 2014. It calculates and corrects the impact of lateral scattering from adjacent land targets in terms of contributing adjacency radiance.

  - The altitude of the water level is reflected as variable within the radiative transfer database (RTD) and thus accounted for and corrected for through usage of a global elevation data set.

  - Reflection of sunlight at the water surface is accounted for in different elements: (i) in form of the physical implementation of the bidirectional water surface in FEM and the RTD; (ii) the spatial variations of sun glint are still partially compensated through the retrieved aerosol content; (iii) high levels of sun glint are flagged depending on the calculated sun glint appearance.

- **C2RCC** (Case 2 Regional Coast Colour processor) (Brockmann et al., 2016) is based on a multi-sensor per-pixel artificial neural network method, built upon previous AC algorithms Case2Regional (Doerffer & Schiller, 2007) and CoastColour. C2RCC uses a large database of simulated water-leaving reflectance and related TOA radiances. It applies neural networks to both invert the water-leaving radiance from measured

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satellite TOA and to retrieve inherent optical properties of the water body. The C2RCC currently accounts for three processors (i.e., C2-Nets: C2RCC, C2X, and C2X-COMPLEX) using different training datasets within a neural network (NN) (Soriano-Gonzales et al., 2022):

- **C2RCC**-Net (here C2RCC) is the original net covering typical ranges of coastal IOPs.
- **C2X** (Case-2 Extreme Waters) C2RCC complemented with the CoastColour dataset to extend the range for coastal waters including extreme cases.
- **C2X-COMPLEX (C2XC)**: C2RCC trained with intermediate ranges of IOPs, larger than C2RCC and tighter than C2X.

C2-Nets do not include specific correction for sun glint or land adjacency.

Several inter-comparison exercises have been done (Warren et al., 2019; Renosh et al., 2020; Pahlevan et al., 2021; Bui et al., 2022; Pan et al., 2022). The most comprehensive assessment has been done in the aquatic subgroup of the second Atmospheric Correction Intercomparison eXercise (ACIX-Aqua), a joint ESA and NASA initiative under the CEOS direction. In ACIX-Aqua the performance of eight state-of-the-art AC processors was evaluated through a community-wide data sharing effort from field campaigns in freshwaters around the globe and utilizing coastal data from AERONET-OC sites. Results of the ACIX-Aqua intercomparison exercise are summarized in Pahlevan et al., 2021a. For the performance assessment the entire dataset was divided into Optical Water Types (OWTs), which allowed an assessment of processors across widely variable coastal and inland water conditions.

The main results of the ACIX-Aqua intercomparison exercise:

- For global studies of inland and coastal waters, the ACIX-Aqua results indicated that there is no single solution, and a preferred AC processor may be chosen according to the specific scientific objective and application. The OWT-specific relative performance of each AC processor allows to facilitate this choice (Figure 5)

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- Each processor has different degrees of sensitivity to varying choices of constituent retrieval algorithms. This suggests that a **switching scheme to select the optimal AC based on OWTs may be a promising approach**.

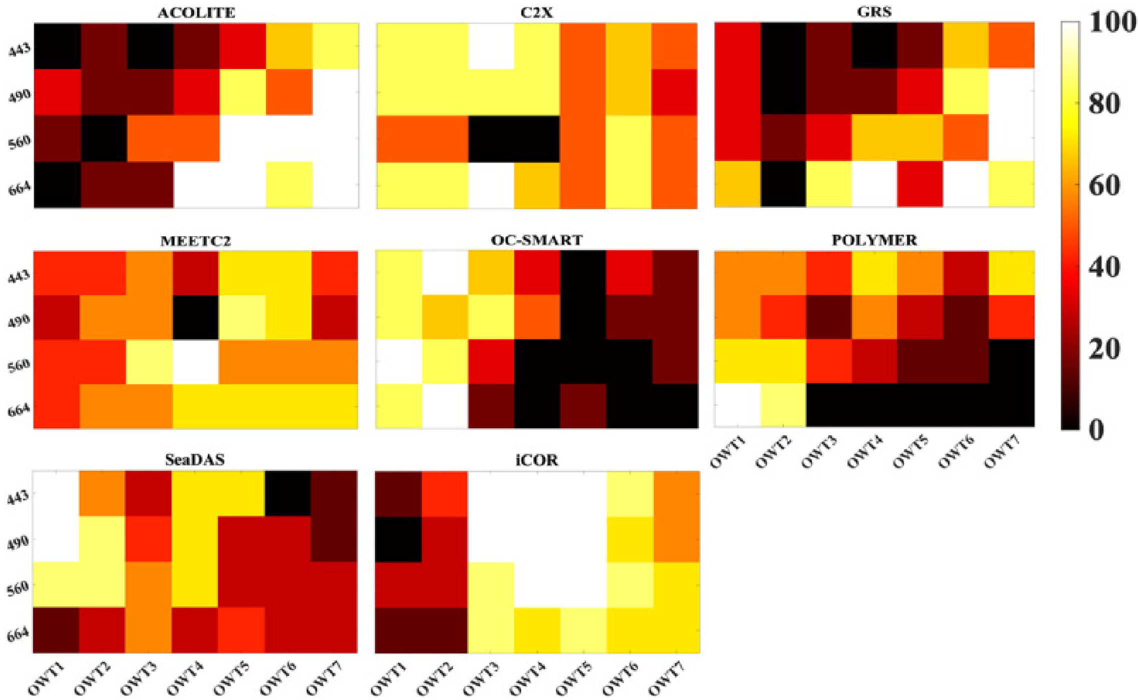

Figure 5: ACIX-Aqua OWT-specific relative performance [%] of AC processors. Relative performance assessments [%]. Processors with brighter colors (white or yellow) are likely to generate high-quality for a given OWT and band. (Figure extracted from Pahlevan et al., 2021). OWTs 1 and 2 are commonly found in the coastal waters and/or oligotrophic lakes. OWT3 is attributed to moderately eutrophic waters. Lakes or coastal estuaries with various degrees of phytoplankton blooms are represented by OWTs 4, 5 and 6. OWT7 represents sediment-rich waters. (More information about the specification for the water constituents per OWT can be found in Pahlevan et al. 2021a).

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4.1.2 Sentinel-3 Ocean and Land Colour instrument (OLCI)

OLCI is the multispectral pushbroom sensor carried on the Sentinel-3 series of platforms, guaranteed to remain operational within the ongoing Copernicus framework. It provides an extended bandset compared to its predecessor MERIS, and overlaps in bandset with SeaWiFS, MODIS and VIIRS instruments. Some multi-sensor AC processors were already listed in Section 4.1.1 for Sentinel-2 MSI, and can also be used for Sentinel-3 OLCI. Commonly available OLCI atmospheric correction algorithms include:

- **Baseline Atmospheric Correction (BAC)** is part of the standard OLCI L2 Ocean corrections (WFR, WRR products) and includes (1) glint and whitecaps correction, (2) Case-2 NIR reflectance estimation, and (3) Aerosol and Rayleigh correction.
- **Alternative Atmospheric Correction (AAC)** is also part of the standard OLCI L2 Ocean corrections (WFR, WRR products), using a neural network approach to improve corrections over turbid and highly absorbing Case 2 waters and for areas contaminated by sun glint.
- **C2RCC** - see previous section. **C2RCC-Alt(net)** (C2RCC ALTERNATIVE NN as provided in SNAP 7.0) provides an alternative solution trained on a wider range of optical water types, expected to perform better in extremely absorbing or turbid waters.
- **ACOLITE:** see previous section
- **POLYMER:** see previous section
- **MEETC2** (Meet Case 2 waters): see previous section
- **OC-SMART:** see previous section
- **iCOR**: (see also previous section). The iCOR version modified for usage on Sentinel-3/OLCI is referred to as iCOR4S3, which includes the SIMEC adjacency correction and land-based AOT retrieval whilst the AOT is bounded over water pixels. The maximum AOT is calculated as the minimum of the AOT values for which the retrieved water leaving reflectance (without adjacency correction) at Oa11 and at Oa18 would equal zero. To correct for known positive bias in the OLCI Level-1 data,

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iCOR4S3 includes the application of the OLCI System ViCarious (SVC) gains prior to this atmospheric correction step.

- **A4O** is an extensive revision of the C2RCC processor. The core of A4O is an ensemble of several neural networks that approximate fully-normalized remote-sensing reflectance at 16 OLCI bands from the top-of-standard-atmosphere reflectance spectrum. Optimized for Sentinel-3 OLCI and all Optical Water Types representing inland, coastal and ocean waters (Hieronymi et al., 2022).
- **ANN** (Schroeder et al. 2022) is also a neural network based approach, which provides pixel-based estimation of the inherent model inversion uncertainty and sensor noise propagation. The algorithm is a full-spectral model-based inversion of radiative transfer (RT) simulations in a coupled atmosphere–ocean system using an ensemble of artificial neural networks (ANN).
- **BLR (Baseline Residual,** Gossn et al. 2019) extends earlier work (Ruddick et al. 2000) on extrapolation of Red/NIR/SWIR bands to aerosol and water reflectance, from which aerosol reflectance is then extrapolated to shorter wavelengths. The procedure is suggested to address highly turbid waters.
- **SeaDAS/l2gen** - see previous section; **SeaDAS-ALT** is an alternative processing for SeaDAS/l2gen, using the 2 band 865/1020 multi-scattering algorithm

Numerous studies have comparatively analyzed the performance of subsets of the available algorithms over coastal water bodies, with varying results. Table 2 below provides an overview of some of the most recent, regional studies in coastal and inshore waters. It is noted that no single study included all listed algorithms, and performance metrics are not standardized.

Table 2: Overview of recent comparative atmospheric correction studies in coastal water environments.

Study	**Area**	**ACs compared**	**Notable results**
Mograne et al. 2019	French coast	L2 Ocean default, C2RCC	C2RCC-Altnet and

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		C2RCC-Altnet POLYMER l2gen	POLYMER performed best
Windle et al. 2022	Chesapeake Bay	C2RCC POLYMER BAC l2gen	C2RCC (most accurate) and POLYMER (more results)
Van Hellemont and Ruddick 2021	Belgian Coast	ACOLITE-DSF, L2-WFR, POLYMER, C2RCC-ALT, SeaDAS, SeaDAS-ALT	ACOLITE (VIS) and L2-WFR (NIR) performed best in high turbidity environment.
Liu et al. 2022	AERONET-OC sites	POLYMER l2gen C2RCC BAC	POLYMER best ≤443 nm, SeaDAS best for longer bands.
Tilstone et al. 2022	Baltic Sea	BAC (2 versions) POLYMER C2RCC	POLYMER gave encouraging results
Li et al., 2022	Coastal waters of Qinhungdao in Bohai Sea	BAC C2RCC C2RCC-Altnet POLYMER iCOR ACOLITE-DSF	POLYMER scored the highest based on all statistical parameters

In lakes, studies comparing the performance of AC algorithms across sites are relatively scarce, owing to poor availability of a quality controlled in situ reflectance observation set, and poor geographic distribution of the data which are available. This is expected to improve somewhat in the near future as a result of community effort to collate a larger reference dataset. At present, the largest satellite matchup datasets are still found to correspond to

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MERIS and MODIS-Aqua satellites. In the Lakes_cci, uncertainty estimates have thus far been based on the former, with POLYMER and C2RCC performing best across the 'global' data set (see Section 2.2).

Consistent, **standardized round-robin exercises using the available atmospheric correction algorithms against the pool of available in situ reflectance data are clearly still needed**, particularly as more matchup data gradually become available. These exercises should be transparent about geographical and seasonal bias, and take input from algorithm developers on the most suitable configuration of the algorithm for the type of water bodies under evaluation (lakes versus coastal or open ocean).

4.1.3 Hyperspectral satellites

PRISMA

The PRISMA Level 2 processor is in charge of processing TOA spectral radiance measurements into geophysical parameters. These parameters depend on the observed pixels and provide information on:

- The at-surface radiance/reflectance;
- The properties of the atmosphere above the surface:
    - Aerosol Optical Thickness and Angstrom Exponent;
    - Water Vapor;
    - Thin Cloud Optical Thickness.

Overall, the processing steps to transform the TOA spectral radiance (Level 1) to at-surface reflectance provide Level 2C; while the processing geocoding step brings to the Level 2D.

The general scheme of atmospheric correction for PRISMA does not depend on surface properties and hence it is not optimized for water. The high-level processing steps applied

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during the atmospheric inversion procedure, along with the set of inputs needed for this processing are shown in Figure 6 (PRISMA ATDB, 2021).

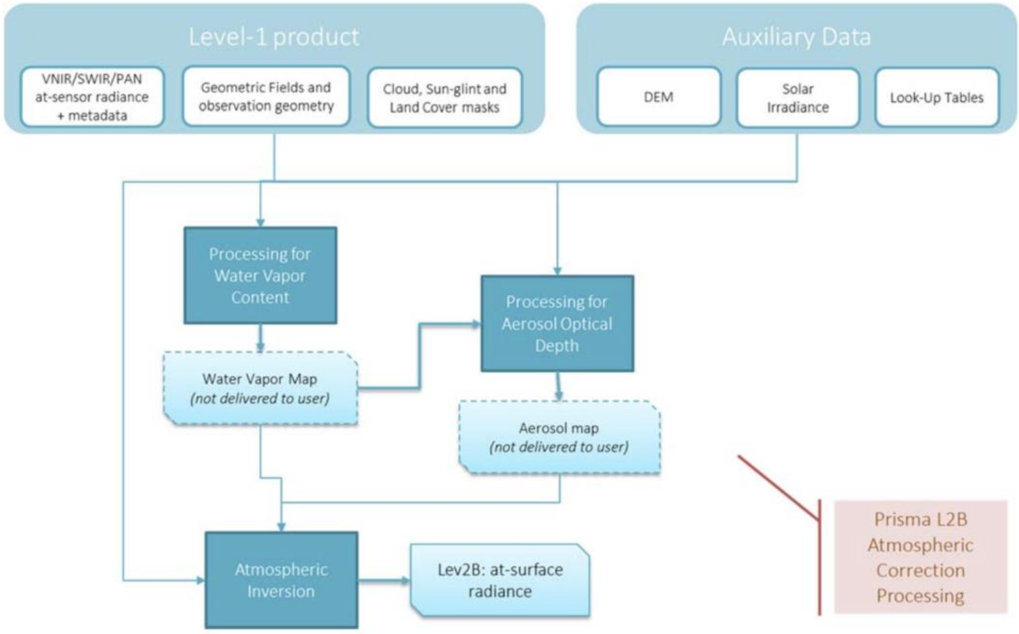

Figure 6: Workflow of the Level 2B atmospheric correction processor for PRISMA.

In particular, the atmospheric parameters, most notably an aerosol description and the column water amount, are first retrieved. As the aerosol retrieval is usually possible over a very limited set of surface types (water and dark land pixels) an average visibility is then obtained for the whole 30 km by 30 km scene. In case of water vapor, it is instead retrieved on a pixel-by-pixel basis by using the spectral band at 1.13 µm. For the given aerosol and column water vapor, the solution of the atmospheric RT equation is then performed to retrieve the surface reflected radiance. This is achieved by inverting the RT by an iterative method, by minimizing a suitable cost function representing the difference between the spectrum simulated by the RT at given surface reflectance (i.e. the simulated TOA radiance) and the one measured by the instrument (i.e. the measured TOA radiance). A standard equation for spectral radiance at a sensor pixel, in the solar wavelength range (neglecting

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thermal emission) from a flat Lambertian surface is used. To increase RT solution speed, simulated TOA radiances are stored in LUT derived by MODTRAN runs.

So far PRISMA Level 2 data have been used to demonstrate the aquatic ecosystems mapping in Bresciani et al. 2022, and Niroumand-Jadidi et al., 2020, while O'Shea et al., 2021 used PRISMA data ad hoc corrected with the ATCOR (Richter and Schlaepfer, 2002) code. Braga et at (2022) recently observed the improvement of Rrs retrieval by ACOLITE, with respect to PRISMA L2D, in moderately clear waters (by also including glint correction). An improvement that was not so evident in turbid lakes waters. In general, as PRISMA will be used to test the-state-of-the-art of the atmospheric correction over water (e.g. in ACIX- III Aqua), more general findings on atmospheric correction for spaceborne imaging spectrometry will be available in the near future.

EnMAP

The L2A nominal atmospheric correction over water for EnMAP is based on the Module Inversion Program (**MIP**) of EOMAP. See previous section on Sentinel-2 MSI for details on MIP.

Through the EnMAP-Box and the EnMAP processing tool (EnPT) users have access to alternative atmospheric correction algorithms such as **POLYMER** (Steinmetz et al., 2011) and **C2RCC** (Brockmann et al., 2016). The EnMAP-Box is a free and open source plug-in for QGIS to visualize and process satellite remote sensing data with special emphasis to the spaceborne EnMAP imaging spectrometer. EnPT provides free and open-source features to transform EnMAP top-of-atmosphere Level-1B data to bottom-of-atmosphere Level-2A products.

An **ESA-NASA AC intercomparison exercise, ACIX-III AQUA**, is currently ongoing and now includes imaging spectroscopy data from PRISMA. Data analysis and initial reporting is planned for August 2023. **The goal of ACIX-III AQUA hyperspectral is to identify viable**

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AC processors for global data processing and to give recommendations to space/operational agencies.

While the conventional approach in water remote sensing is removing the atmospheric effects first and then interpreting the water reflectance data, it should be noted that alternative, physics based, approaches where atmospheric models are used in forward mode, are sometimes also being used for specific applications. For example, Kutser et al. (2002, 2006) showed that interpreting hyperspectral Hyperion imagery with a top-of-atmosphere spectral library, created by modeling benthic reflectances through a water column with variable depth and the atmosphere, outperformed the conventional method where the imagery was first atmospherically corrected and then an above water spectral library was used for mapping coral reef benthic substrates.

4.2 Adjacency effect correction

The presence of land, ice or clouds in the vicinity of water pixels can affect the radiance detected by a sensor looking at these water pixels through the so-called adjacency effect (AE) (Tanré et al. 1979). Adjacency effect occurs when light reflected from objects surrounding the target area is added to the target-sensor path through atmospheric scattering. The adjacency effect, thus, modifies the at-sensor radiance recorded over the target. The adjacency effect is more pronounced in cases of a dark target with a bright surrounding, such as an inland water body surrounded by land. The magnitude of the adjacency effect depends on various factors, such as the aerosol optical properties and vertical distribution/scale height, land-cover type, viewing and illumination geometry, and the shape and size of water bodies.

Adjacency effects are not confined to the first km offshore, particularly for highly reflecting land covers, in the NIR and for highly sensitive sensors. Extensive theoretical simulations of land adjacency effects in typical OC observation conditions (Bulgarelli and Zibordi, 2018)

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showed that the average adjacency effect in data from MODIS-A, MERIS, S3-OLCI and from S2-MSI, are still detectable (i.e. above the sensor noise level) up to 36 km offshore (20 km for S2-MSI), except for adjacency effects caused by green vegetation at the red wavelengths. In general, the adjacency effect over lakes is stronger than that of coastal zones even when they have the same water and land reflectance, this is because the closed shape of the lake allows it to gain more photons from the land (coming from all sides) (Pan et al., 2022). In addition to the environmental adjacency effect, another effect is the "topographic" adjacency effect, which arises when large portions of the sky are blocked by the land surface (possibly covered by vegetation), such as with lakes surrounded by mountain slopes (Moses et al., 2017).

If not properly accounted for, the adjacency effect leads to spectral perturbations in the retrieved water reflectance, leading in complex ways to uncertainties in derived products. The impact of the adjacency effect however depends on the characteristics of the AC algorithm. For atmospheric correction schemes not deriving the atmospheric properties from satellite data and/or from the water pixel, simulations (Bulgarelli and Zibordi, 2017, 2018) showed that adjacency effect induced artifacts in the water reflectance are positive for all wavelengths, with biases monotonically decreasing with distance from land. For atmospheric correction schemes inferring the aerosol properties from NIR data, biases are mainly negative apart from cloud-induced adjacency effects and perturbations induced by adjacency effects at NIR and visible wavelengths might compensate each other. As a consequence, biases induced by adjacency effects on the water reflectance are not strictly correlated to the intensity of the reflectance of the nearby land.

Pan et al. (2022) inter-compared ten atmospheric correction algorithms on small lakes. All failed to meet the 30% retrieval accuracy target across all the visible bands, which was likely due to uncorrected adjacency effects. With simulations they showed that up to 60% of the top of atmosphere reflectance in the near-infrared bands over the lake is coming from the adjacent lands covered with green vegetation. It should be noted that besides the challenges due to adjacency effects, inland waters often contain algal scums, floating

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macrophytes such as water-lilies, and floating debris that cover significant portions of the water surface and produce reflectance signals that are uncharacteristic of water (Moses et al., 2017). Surface scums of algae and floating vegetation can produce very high reflectance in the NIR region that resembles the reflectance from terrestrial vegetation (e.g., Kutser, 2004). The anomalous reflectance produced by floating objects on the water surface may cause some atmospheric correction to fail.

Observations over smaller water bodies (rivers, lakes) are expected to suffer increasingly from adjacency effects, because the contrast between land and water pixels is increased within the affected area. The adjacency effect is relatively stronger when the contrast between land and water albedo increases, such that dark water bodies are particularly affected. Land vegetation is particularly disruptive because the spectral signature of the adjacent land brings additional contrast in near infra-red wavebands. In the Lakes_cci, this effect is captured using similarity to type spectra which characterize vegetated land, in the same fashion that algorithm selection for biogeochemical properties is based on similarity to a set of Optical Water Types (Jiang et al. *submitted*). This allows masking or flagging pixels which are particularly affected, whilst still resolving observations under clear atmospheres or in seasons where the land reflectance is less featured, and can sometimes be corrected for within the atmospheric correction steps (see below).

While full 3D Monte-Carlo simulations allow accurate simulation of adjacency effects, simplified formulations are needed for implementation of an operationally fast correction scheme. In spite of the challenges, several methods have been developed or are under development to account for adjacency effects:

- **SIMEC** SIMilarity Environment Correction (Sterckx et al., 2015). The SIMEC approach, which has been integrated into iCOR AC, was first proposed by Sterckx et al. (2011) for the correction of airborne imaging spectroscopy data over inland and coastal waters. The correction algorithm estimates the contribution of the background iteratively by checking the correspondence of the retrieved water reflectance with the NIR similarity spectrum defined by Ruddick et al. (2006). Therefore, no

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assumption is made on the exact value of the NIR reflectance; only its spectral shape in the NIR region is assumed to be invariable. When the surrounding vegetation contributes to the at-sensor radiance from a water pixel through scattering in the atmosphere, it not only increases the retrieved reflectance for the water pixel in the NIR region but also alters the spectral shape to something different than the NIR similarity spectrum. An a priori assumption in SIMEC is the validity of the NIR similarity spectrum. The assumption might be violated in extremely turbid waters, waters with macrophyte growth or algal blooms, and waters that are optically shallow in the NIR region.

- **AWP-Inland Water** Adaptative Window by Proportion applied to Inland Water (Paulino et al., 2022), AWP-Inland Water, is an empirical algorithm that adapts the window size to local conditions across the water body. For example, if larger window sizes are used for water pixels close to land, unrealistic adjacency effect magnitude may occur due to overestimating the adjacency contribution. On the other hand, smaller window sizes attributed to water pixels located far from the land can underestimate the adjacency effect. AWP-Inland Water minimizes these uncertainties by controlling the relationship between the distance of the water pixel from the land and the weight distribution of the Atmospheric Point Spread Function through the proportion of the targets within the range of the adjacency effect.
- **POLYMER**: As the POLYMER atmospheric correction algorithm can correct for spectrally smooth contamination, it is relatively robust to spectrally smooth adjacency contamination by snow, sand and rocks. Vegetation has however strong spectral features. Adjacency contamination by vegetation is therefore strongly wavelength dependent and might cause some anomalies in the POLYMER results of mainly the NIR bands. A mitigation methodology is currently under development through the adding of a fourth term to the POLYMER polynomial atmospheric reflectance model that allows for the modeling of vegetation introduced adjacency contamination.

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- **RADCOR:** (Castagna and Vanhellemont, 2022) A new physically based adjacency correction algorithm is under development. RADCOR is a sensor-agnostic, Dark Spectrum Fitting (DSF)-integrated adjacency correction algorithm working in the frequency domain. RADCOR is applicable to land and water pixels. As adjacency effects are accounted for during the atmospheric correction (through future integration of RADCOR in ACOLITE), it is expected that it will improve the aerosol retrieval as well.
- **MIP adjacency correction:** developed by (Heege et al., 2014). A sensor-independent adjacency correction module is integrated within the Modular Inversion and Processing (MIP) system. It is based on an analytical approximation of the atmospheric point-spread function using the primary scattering assumption (Kiselev et al. 2015).

These developments suggest that uncertainties due to adjacency effects could be reduced in the future. Until accurate adjacency effect corrections are not available, it is recommended to at least flag pixels having a risk of being contaminated by adjacency effects. Furthermore **more validation of the different adjacency effect algorithms is needed which requires the establishment of transects datasets dedicated for adjacency effect algorithm testing (including different seasons, water types, water body size, surrounding land cover types (vegetation, sand, snow).**

4.3 In situ data collection supporting AC validation

Different types of platforms and instruments exist which can be used for validation or calibration of Earth Observation aquatic products. Three categories of platforms can be distinguished: fixed stations, buoys and moving platforms (De Keukelaere et al., 2018b). Most data are available for clear oceanic waters from e.g. MOBY, BOUSSOLE but very few data

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are publicly available for coastal and inland waters. This section gives an overview of the various platforms and sensors that can be used for AC validation. For an overview of in situ data bases (e.g. LIMNADES, AERONET-OC) for AC validation and access to data, we refer to Water-ForCE D4.3.

Fixed stations

Sensors mounted on fixed platforms provide continuous data, measured in a consistent way over time. These time series of in situ data yield important information on temporal variation and dynamics taking place in the water. Once positioned, they are not intended to be relocated except for sensor calibration. Examples include:

- Aerosol Robotic Network (**AERONET**), developed by Aeronautics and Space Administration (NASA), is a worldwide network containing autonomous sun-photometer measurements to sustain and support atmospheric studies (Zibordi et al., 2009). AERONET measures, amongst other parameters, the aerosol optical thickness (AOT) at different wavelengths. This is a major asset in optical remote sensing since light detected by a satellite sensor has to pass the atmosphere twice (sun – target and target – satellite). AOT is rarely known, hard to retrieve from optical satellite imagery and has an important contribution in the atmospheric correction, particularly over water.
- The Ocean Colour extension of AERONET (**AERONET-OC**) supports marine applications, by providing additional capability of measuring the radiance emerging from the sea (i.e. water-leaving radiance) with modified sun-photometers installed on offshore platforms. AERONET-OC is instrumental in satellite ocean color validation activities through standardized measurements (i) performed at different sites with a single measuring system and protocol (IOCCG, 2019b), (ii) calibrated with an identical reference source and method, and (iii) processed with the same code.

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With the recent advances in AERONET-OC, the radiance data are measured in 12 (before 9) discrete narrow bands matching S3 OLCI bands (Zibordi, 2021).

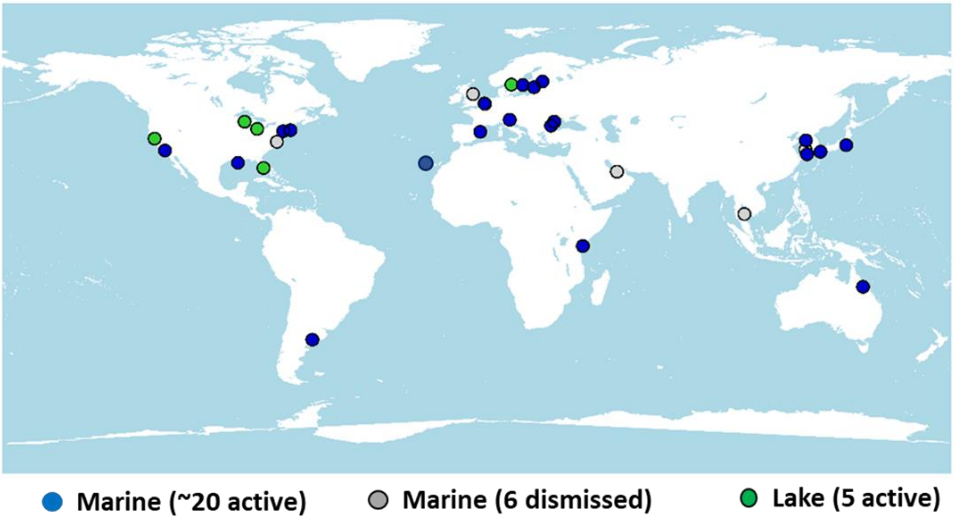

Figure 7: Marine and lake AERONET-OC, international automated measurement network, sites (Zibordi, 2021).

- The **HYPERNETS** instruments are hyperspectral radiometers (PANTHYR measuring between 400-900nm (Vansteenwegen et al, 2019) or HYPSTAR measuring between 380-1700nm (https://hypstar.eu/)) integrated in automated networks of water and land bidirectional reflectance measurements for satellite validation. HYPERNETS ensure high quality in situ measurements at all spectral bands and for a wide range of water and land types for the validation of the surface reflectance and aquatic reflectance data from Earth observation missions. The HYPERNETS Water Validation Network consists of 12 water sites (WATERHYPERNET). PANTHYR prototypes were deployed and tested at the Aqua Alta Oceanographic Tower in the Adriatic Sea (AAOT) (Zibordi et al. 2002), during the FRM4SOC intercomparison exercise (Tilstone et al., 2020), the RT1 Blue Innovation Platform outside the harbor of Oostende (Figure 8) and the Blankaart water reservoir in Belgium. A beta release of data was used for the validation of Sentinel-2A, Sentinel-2B, Landsat-8 and

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Planetscope/Dove cubesats (Vanhellemont, 2020), of Sentinel-3 (Vanhellemont and Ruddick, 2021) and for evaluation of PRISMA (Giardino et al. 2020). WATERHYPERNET is a federated network of automated hyperspectral radiometers on zenith- and azimuth- pointing systems, deployed on fixed structures. Data is acquired, processed and quality controlled according to a common protocol providing water reflectance as well as the underlying upwelling (water) radiance, downwelling (sky) radiance and downwelling irradiance data. Measurement uncertainties are estimated according to Fiducial Reference Measurement principles and will be distributed together with the measured data.

Figure 8: RT1 station outside harbor of Oostende with PANTHYR (Vanhellemont and Ruddick, 2021).

- The **WISPstation** is a high-end, affordable, extremely low power optical instrument to measure water-leaving reflectance from buoys and at fixed stations. Without any moving parts, it is still able to reliably capture the water leaving reflectance during the biggest part of the day. It uses two sets of sensors (Avantes Mini mk-1 spectrometer) in a carefully chosen configuration to measure the light reflecting from the water in the spectral range 220-1100nm (Steef Peters et al. Ocean Optics Conference, 2018).

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Moored buoy data

Similar as for fixed platforms, sensors mounted on buoys provide continuous data, measured in a consistent way over time. A non-exhaustive list of buoy measurements, used for calibration and validation of EO products:

- The **Marine Optical buoy (MOBY)** is an autonomous optical buoy moored off the island of Lanai in Hawaii, and it is supported by the National Oceanic and Atmospheric Administration (NOAA, USA) to provide vicarious calibration of ocean colour satellites. Water-leaving radiance (Lw) is calculated by propagating Lu measurements to just below and then across the surface. Additionally, above-water downwelling irradiance (Es) is measured from sensors mounted on top of the buoy. MOBY radiometry data are regularly used by the NASA Ocean Biology Processing Group (OBPG) as part of ocean color validation and vicarious calibration activities. MOBY has generated calibrated measurements of ocean color at the sea surface since 1996 and served as the primary sea surface calibration for satellite borne sensors such as the sea-viewing wide field-of-view sensor (SeaWiFS) and the moderate-resolution imaging spectroradiometer (MODIS).
- The buoy named "Bouée pour l'acquisition de Séries Optiques à Long Terme" (**BOUSSOLE**) is deployed in the Mediterranean Sea between Nice at the French Riviera coast and Corsica. Instruments on the buoy include radiometers of the Satlantic 200 series, measuring the downward irradiance E_s (at 4.5 meters above the water surface), and downward irradiance E_d, upward irradiance E_u, and upwelling radiance L_u (nadir) at 2 depths (4 and 9 m) to perform match-up analyses and vicarious calibration experiments for ocean color satellite sensors (Antoine et al., 2008).
- **Yamato Bank Optical Mooring (YBOM)** (Kishino et al. 1997**),** equipped with a fluorometer, two pairs of upwelling radiance and downward irradiance sensors at 1.2 and 6.5 m depths providing spectral data from 400-800nm and an above-water irradiance reference sensor providing data at 860nm.

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- **Thetis bio-optical profiler** is a submersible vertically profiling platform for use in coastal marine and freshwater environments (as installed in the Baltic sea and in Lake Geneva). The Thetis bio-optical profiler can measure radiance and irradiance through two Satlantic HyperOCR sensors (and many bio-optical parameters like spectral absorption and attenuation coefficient, backscattering at several wavelengths, fluorescence of chlorophyll-a, CDOM and phycocyanin, temperature, salinity, oxygen) while profiling through the water column. Thetis profiler is parked at the sea/lake bottom and is profiling through the water column at predefined times which can be synchronized with satellite overpasses.

Moving platforms

Moving platforms cover a wide range of in situ data collection, including measurements from boats, Ferry boxes, gliders, drifting profilers, drones and even sensors mounted on surfboards. These datasets do not have a fixed temporal frequency and cannot always meet the high accuracy standards of fixed platforms, but they allow a larger flexibility in sampling location, and often at much lower cost due to better accessibility for maintenance:

- Measurement by **boat, ship or research vessel** is a widely used approach for inland, coastal and marine surveys, and provides flexibility in terms of survey timing and sampling locations. A planned field campaign by boat allows for data collection during optimal environmental conditions and for dedicated experiments and testing. Sampling locations or transects can be chosen as desired, especially across gradients of change in optical-biogeochemical properties or to assess the impact of adjacency effects on remote sensing reflectance. Instruments can be either handheld (e.g. WISP-3 by Water Insight, ASD Fieldspec) or fixed to the boat (e.g. using the Solar tracking radiometry platform (So-Rad) which optimizes the measurement geometry of commercially available sensors to increase the number of successful observations of water color obtained from moving platforms) in order

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to collect measurements by the most suitable means and with varying levels of control over observation conditions. A full list of commercially available multi-spectral and hyperspectral radiometers is provided in Table 3. Another advantage with boat surveys is that power sources and laptops can remain on the boat, therefore the instruments and components do not require the same rigor in weather- and waterproofing as for permanently exposed installations. However, radiometric measurements from (small) boats are subject to errors from tilt and roll; therefore, affected data must be screened during data processing (Tilstone et al., 2012).

- **Ships-of-opportunity** use a combination of volunteer commercial and research vessels to collect data. As chartered vessels for equipment deployment are expensive and time consuming, the use of volunteer vessels, in addition to equipment especially designed to be deployed efficiently and without the need for high-level technical experience is at the core of the Ships of Opportunity Facility. The use of vessels that undertake continuous transects between ports or regions allow seasonal and annual datasets to be established. An example is FOCOS which comprises two sets of above-water hyperspectral radiometers (HyperSAS) to measure sea surface reflectance, which are mounted on two ferries crossing optically different waters of the Salish Sea. The sensors are positioned to avoid shadows, spray, and sun glitter and have an autonomous solar tracking system, developed by Satlantic to maintain ideal geometry.
- **Airborne drones,** Remotely Piloted Aircraft Systems (RPAS) or Unmanned Aerial Vehicles (UAV). Drones complement water quality monitoring activities: they observe at a high temporal frequency (e.g; hourly basis for intertidal monitoring) and acquire high spatial resolution (El Serafy et al. 2021). Different optical camera systems can be mounted on drones from RGB, to multispectral (e.g. MicaSense or Maia multispectral cameras) to hyperspectral (e.g. Headwall). Irradiance measurements can be conducted using downwelling light sensors or spectral reference panels with known reflectance in the field. When collecting in situ

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measurements for validation and/or calibration of algorithms and EO products, drone data can help to understand fine-scale dynamics (Padró et al., 2018; De Keukelaere et al., 2022).

- **Surface drones,** Autonomous and Remotely Operated Surface Vessels (ASV/ROSV) are a special case of a boat platform. An example is the water color remote sensing-oriented unmanned surface vehicle (WC-USV) designed by Li et al., 2020). The USV consisted of four parts to acquire data: a floating optical buoy (FOBY) for remote sensing reflectances, a water sample auto collection system, a water quality measurement system and meteorological sensors.

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Table 3: Most frequently used commercially available multispectral and hyperspectral radiometers, manufacturers and corresponding websites (Oubelkheir, et al., 2022).

Radiometer name	Deployment Platform(s)	Spectral range and resolution (nm)	Manufacturer	Above- or in-water
C-OPS	C-OPS Free-fall profiler	19 bands	Biospherical Instruments	In-water
OCR-500 series	Gliders, Moorings, Profiling system	4 bands	Sea-bird (Satlantic)	In-water
SEAPRISM CE318-TV12-OC	SEAPRISM system, fixed platforms	12 bands	Cimel	Above water
HyperOCR	HyperPRO free-fall profiler, Thetis moored profiler	350-900 nm, 3nm step	Sea-bird (Satlantic)	In-water
	HyperSAS system			Above-water
DALEC	Underway from ship or fixed platform (e.g., LJCO)	350-900 nm, 3nm step	In-Situ Marine Optics	Above water
RAMSES	Profiling system	350-900 nm, 3nm step	TriOS	In- and above-water
ASD FieldSpec	Portable, hand-held	350 – 2500 nm	Malvern Panalytical	In and above-water
SR-3500	Portable, hand-held	350-2500 nm	Spectral Evolution	Above-water
WISP-3	Portable, hand-held	350-800 nm	Water Insight	Above-water

One of the key findings of the MONOCLE project as described in De Keukelaere et al., 2022 is to implement a **combination of observational approaches**. This should fill the immediate data gap which exists for hyperspectral water-leaving reflectance in coastal waters, lakes and estuaries. A global network of sensors to consistently ground-truth satellite observation approaches of 100 inland water sites may already suffice to

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operationally determine the quality of atmospherically corrected satellite products, to guide appropriate use (application-specific) and thereby build trust in derived biogeochemical products. Automated data flows e.g. from the HSP1 Hyperspectral Radiometer for Global & Diffuse Irradiance (Wood et al. 2017) and Thetis are available to make these efforts sustainable. We recommend that water and atmospheric radiance signals are collected simultaneously wherever feasible. In the short term, this can aid selection of the most appropriate atmospheric correction model, for which no single ideal solution currently exists. In the longer term, this will support R&D into better performing atmospheric correction techniques or better a priori predictions of data quality. For strategic site-specific monitoring including environmental or industrial activities, drones provide a highly versatile method to map out problem areas. When collecting radiometric data from these platforms, operators need to be properly guided to record observations under suitable viewing geometry and light conditions. Following this, handling the large volumes of imagery collected from drone-mounted sensors benefits from established data flows such as those featured in the MapEO[7] cloud-based water service.

5 Recommendations

At the Water-ForCE Water Quality Atmospheric Correction Workshop[8], 20 October 2022, 36 recommendations in the categories AC processing (13 recommendations), in situ data for AC Cal/Val (14 recommendations), AC Cal/Val (4 recommendations) and future sensors to improve AC (5 recommendations) were formulated by invited experts and discussed with the participants of the workshop (55). After the workshop participants were invited to complete a questionnaire in order to score the recommendations provided during the

[7] https://monocle-h2020.eu/Sensors_and_platforms/MapEO_Water_en

[8] https://waterforce.eu/workshops/water-quality-atm

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workshop from 0 (low priority) to 10 (high priority). We received 21 valid responses (2 were incomplete) which were further analyzed, both aggregated by category as well as a whole.

Recommendations to meet the CEOS Analysis Ready Data (ARD) Product Family Specification (PFS)[9] Aquatic Reflectance (AR) Target Requirements related to atmospheric correction are included in the list of recommendations. (The AR PFS Version 1.0 has been published on ceos.org/ard and has an annual PFS update cycle).

5.1. Recommendations by category

5.1.1. Recommendations regarding AC PROCESSING

Figure 9 gives an overview of the average score for each AC processing recommendation. The 13 recommendations given by the experts are listed in the table below.

Table 4: List of recommendations regarding AC PROCESSING.

AC PROCESSING
1 - Develop an indicator to quantify adjacency effects (AE) and develop a clear definition of the parameters to quantify adjacency effects.
2 - Develop atmospheric correction (AC) algorithms that include adjacency effect correction.
3 - Flag pixels with a risk of adjacency effect contamination if NOT corrected for.
4 - Flag pixels with a risk of adjacency effect contamination if corrected for.
5 - Evaluate the impact of adjacency effects (from snow, land, vegetation) on each AC algorithm to have a better understanding of the different impact of AE on the various AC algorithms.
6 - Provide uncertainty estimates of the values in measurement units (e.g. using uncertainty propagation or characterization).

[9] https://ceos.org/ard/

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7 - Develop approaches to normalize measurements for solar and viewing conditions, including BRDF effects.
8 - Separately assess and correct for sky glint.
9 - Indicate the amount of sun glint contribution that is removed if a pixel has correctable (moderate) sun glint.
10 - Improve the representativeness of aerosol models (particularly absorbing aerosols) in AC.
11 - Improve the methodology for removing sky/sun glint.
12 - Select AC processors according to the specific scientific objective and application as there is no single solution for global studies of inland and coastal waters.
13 - Identify optimal constituent retrieval algorithms for each AC processor due to the varying sensitivities of constituent retrieval algorithms and (systematic) biases of AC processors.

The minimum average score in this category was 7.00 for recommendation 7. The maximum average score (8,81) was given to recommendation 2 (Develop atmospheric correction (AC) algorithms that include adjacency correction). Above the median value of the average score (8,05), so considered the most important in this category, were recommendation 1, 2, 3 and 12, highlighting the need and importance of the **correction for adjacency effects.**

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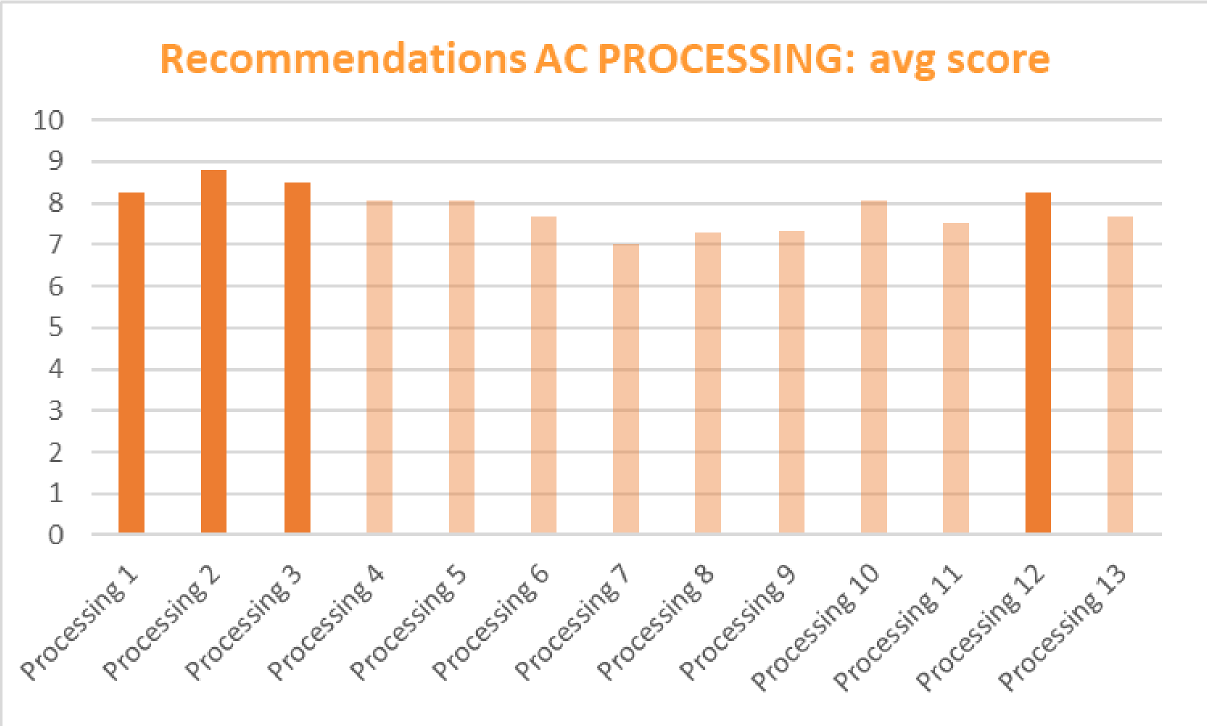

Figure 9: Average score for the recommendations regarding AC PROCESSING (recommendations with average score above the median are indicated with a darker color).

5.1.2. Recommendations regarding IN SITU DATA for AC CAL/VAL

Figure 10 gives an overview of the average score for each IN SITU DATA for AC CAL/VAL recommendation.

The 14 recommendations given by the experts are listed in the table below.

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Table 5: List of recommendations regarding IN SITU DATA for AC CAL/VAL.

IN SITU DATA for AC CAL/VAL
1 - Need for automated fixed station measurement networks, which are geographically well-distributed and represent different water types to support AC validation activities for both coastal and inland waters.
2 - Need for automated ships-of-opportunity measurements to collect in situ data along optical and shore to open water transects, for Cal/Val.
3 - Need for networks with centralized services (data calibration, handling, reduction, processing, quality control, uncertainty, archiving, distribution).
4 - Need for standardization of network components such as instruments, measurement protocols, and processing.
5 - Use of autonomous hyperspectral spectroradiometers for the acquisition of remote sensing reflectance (Rrs) to assess AC uncertainties.
6 - Include autonomous Rrs systems in regular monitoring programmes.
7 - Need for long-term funding programs to support automatic measurement networks.
8 - Space agency/Copernicus should (continue to) support measurement intercomparison exercises and radiometer calibration/characterization, e.g. FRM4SOC.
9 - Need for open-source tools and open access to in situ data (including uncertainty estimation) for validation of AC (need for improved data sharing/distribution).
10 - Establish an international data set for adjacency correction algorithm testing (seasonal, water type, water body type/size, environment type).
11 - More in situ data are needed to characterize uncertainties in AC due to algorithm, sensor, water type, observation angle, adjacency effects, atmospheric composition (need high data volume, transects to untangle effects).
12 - Measure microscale variations (e.g. in close proximity to the shore, vessels) with drones.

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13 - Measure atmospheric conditions alongside Rrs to better attribute AC correction uncertainties.
14 - Develop strategies to combine high data volumes of automated high-frequency data with low volumes of manual data collection, to avoid geographic bias.

The minimum average score in this category was 6,24 for recommendation 12. The maximum average score (8,95) was given to recommendation 7 (Need for long-term funding programs to support automatic measurement networks). Above the median value of the average score (8,55), so considered the most important in this category, were recommendations 1, 3, 4, 7, 8, 9 and 11 highlighting the need for **more open in situ data and tools to characterize uncertainties in AC due to algorithm, sensor, water type, observation angle, adjacency effects, atmospheric composition (need high data volume, transects to untangle effects) requiring in situ automated standardized networks covering inland and coastal waters with centralized data supported by long-term funding programmes and continued support by space agencies/Copernicus for intercomparison exercises and Fiducial Reference measurements.**

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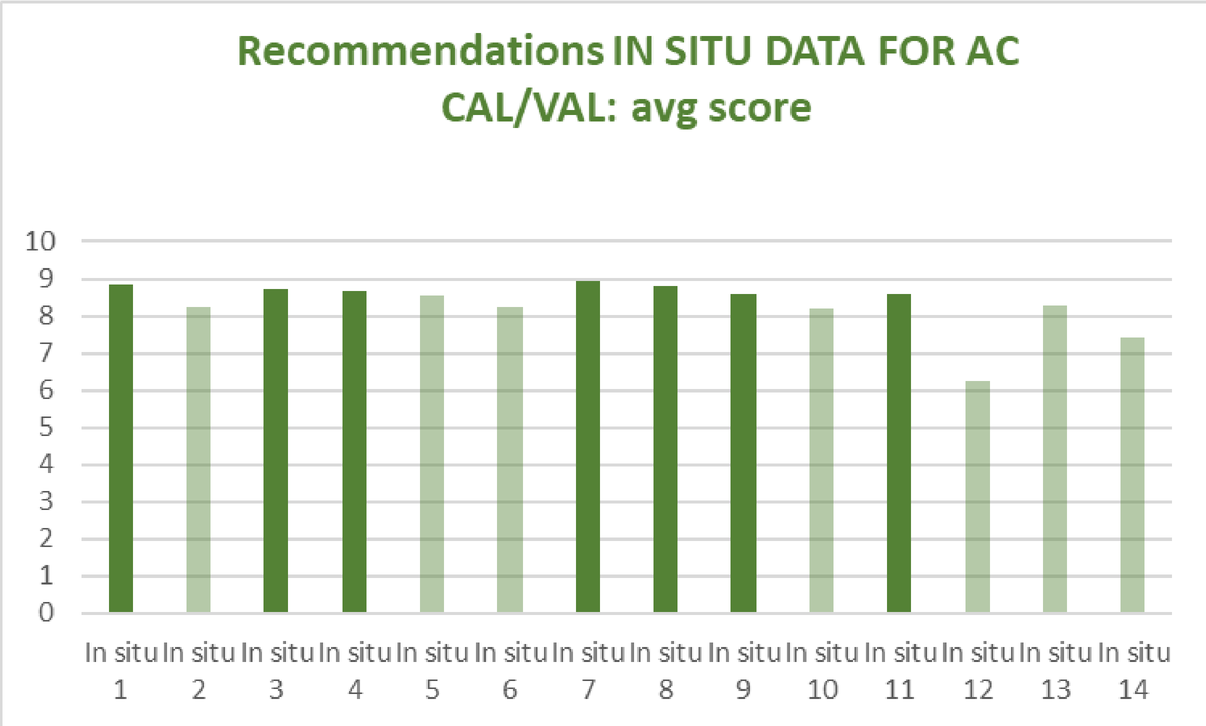

Figure 10: Average score for the recommendations regarding IN SITU DATA for AC CAL/VAL (recommendations with average score above the median are indicated with a darker color).

5.1.3. Recommendations regarding AC and CAL/VAL

Figure 11 gives an overview of the average score for each AC and CAL/VAL recommendation.

The 4 recommendations given by the experts are listed in the table below.

Table 6: List of recommendations regarding AC and CAL/VAL.

AC and CAL/VAL
1- Need for AC round robin exercises with focus on validation of AE correction using *in situ* data for validation

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2 - Need for atmospheric correction round robin exercises with focus on validation of AE correction using image-based analyses (e.g. Image based consistency analyses).
3 - Need for AC round robin exercises with focus on validation of sun glint correction using image-based analyses (e.g. Image based consistency analyses).
4 - Need for AC round robin exercises with focus on AC validation under different atmospheric and water conditions

The minimum average score in this category was 7,76 for recommendation 3. The maximum average score 8,76 was given to recommendation 1 (Need for atmospheric correction round robin exercises with focus on validation of AE correction using in situ data for validation). Above the median value of the average score (8,38), so considered the most important in this group, were recommendations 1 and 4, **highlighting the need for round-robin intercomparison exercises for AC (including adjacency effect correction validation using in situ data) for different atmosphere and water conditions.**

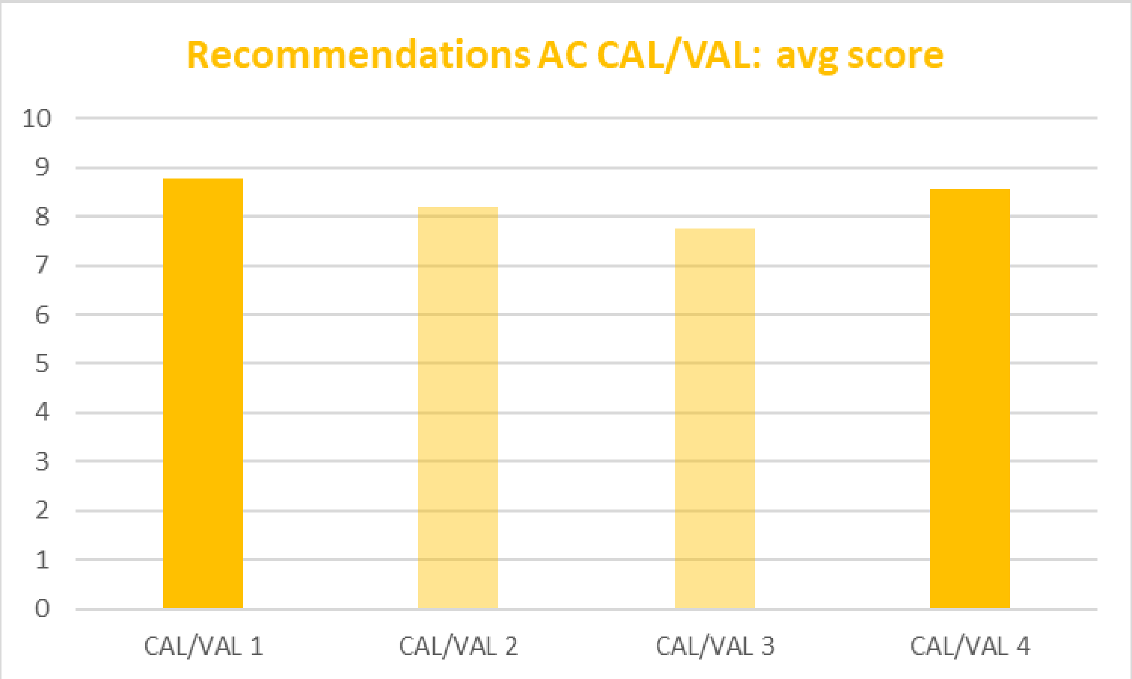

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Figure 11: Average score for the recommendations regarding AC and CAL/VAL (recommendations with average score above the median are indicated with a darker color).

5.1.4. Recommendations regarding AC and SENSORS

Figure 12 gives an overview of the average score for each AC and SENSORS recommendation.

The 5 recommendations given by the experts are listed in the table below.

Table 7: List of recommendations regarding AC and SENSORS.

AC and SENSORS
1 - Future mission concepts/designs should consider inclusion of observation modalities (polarimetry) to improve the discrimination and/or characterization of aerosol types, heights, and/or optical thickness.
2 - Future mission concepts/designs should consider inclusion of observation modalities (multiangular) to improve the discrimination and/or characterization of aerosol types, heights, and/or optical thickness.
3 - Future mission concepts/designs should consider inclusion of observation modalities (hyperspectral radiometry) to improve the discrimination and/or characterization of aerosol types, heights, and/or optical thickness.
4 - Future mission concepts/designs should consider inclusion of observation modalities (ranging/profiling) to improve the discrimination and/or characterization of aerosol types, heights, and/or optical thickness
5 - Add high-fidelity radiometric measurements in the deep blue and/or ultraviolet regions to further constrain the solution space for estimating aerosol contribution.

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The minimum average score in this category given by the experts was 7,45 for recommendation 4. The maximum average score 7,77 was given to recommendation 1 (Future mission concepts/designs should consider inclusion of observation modalities (polarimetry) to improve the discrimination and/or characterization of aerosol types, heights, and/or optical thickness). Above the median value of the average score (7,64), so considered the most important in this group, were recommendations 1 and 5, highlighting **the importance of polarimetry and hyperspectral radiometry including the blue and UV wavelength region to accurately characterize the aerosol contribution**.

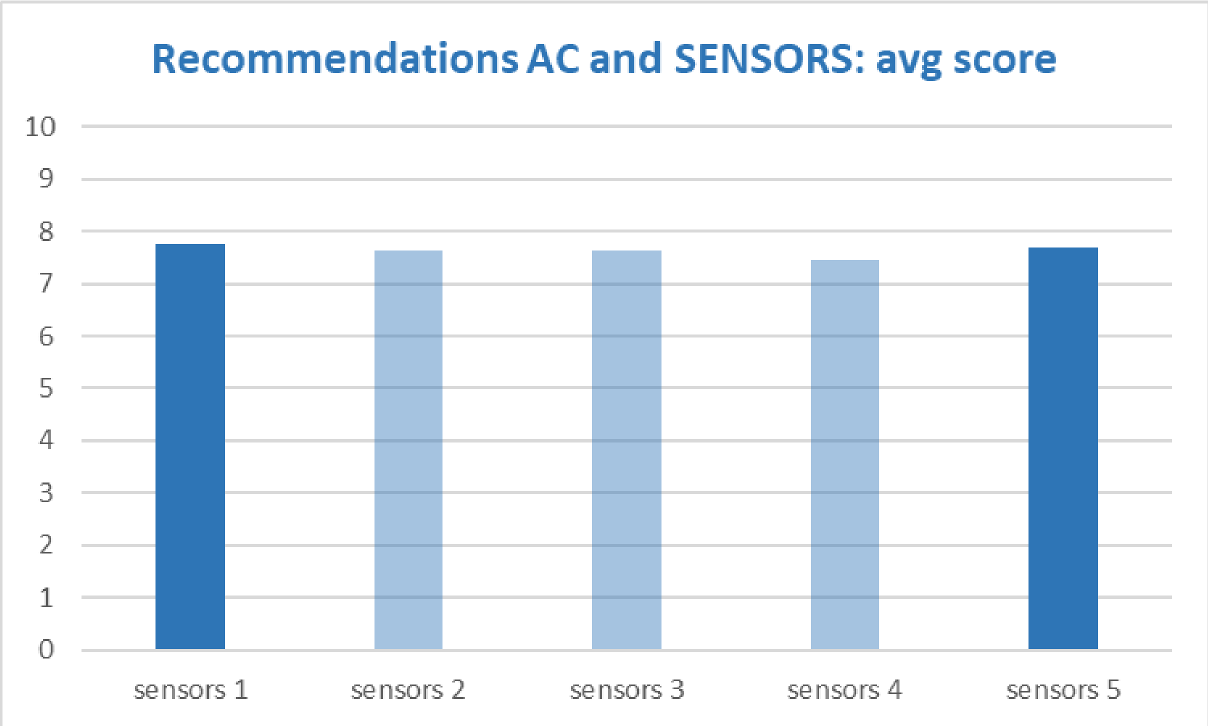

Figure 12: Average score for the recommendations regarding AC and SENSORS (recommendations with average score above the median are indicated with a darker color).

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5.2. Recommendations as a whole

When analyzing the entire list of 36 recommendations and average scores as a whole, several patterns can be distinguished (Figure 13). First, **79% of the recommendations with an average score above the median value (8,19) was related to category IN-SITU DATA for AC CAL/VAL (while this category had 39% of the total number of recommendations).**

The highest average score was given to these 10 recommendations (from high to lower priority):

- **Need for long-term funding programs to support automatic measurement networks**
- **Need for automated fixed station measurement networks, which are geographically well-distributed and represent different water types to support AC validation activities for both coastal and inland waters**
- **Develop atmospheric correction (AC) algorithms that include adjacency effect correction**
- **Space agency/Copernicus should (continue to) support measurement intercomparison exercises and radiometer calibration/characterization, e.g. FRM4SOC.**
- **Need for AC round robin exercises with focus on validation of adjacency effect correction using in situ data for validation**
- **Need for networks with centralized services (data calibration, handling, reduction, processing, quality control, uncertainty, archiving, distribution).**
- **Need for standardization of network components such as instruments, measurement protocols, and processing.**

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- **Need for open-source tools and open access to in situ data (including uncertainty estimation) for validation of AC (need for improved data sharing/distribution).**
- **More in situ data are needed to characterize uncertainties in AC due to algorithm, sensor, water type, observation angle, adjacency effects, atmospheric composition (need high data volume, transects to untangle effects).**
- **Need for AC round robin exercises with focus on AC validation under different atmospheric and water conditions.**

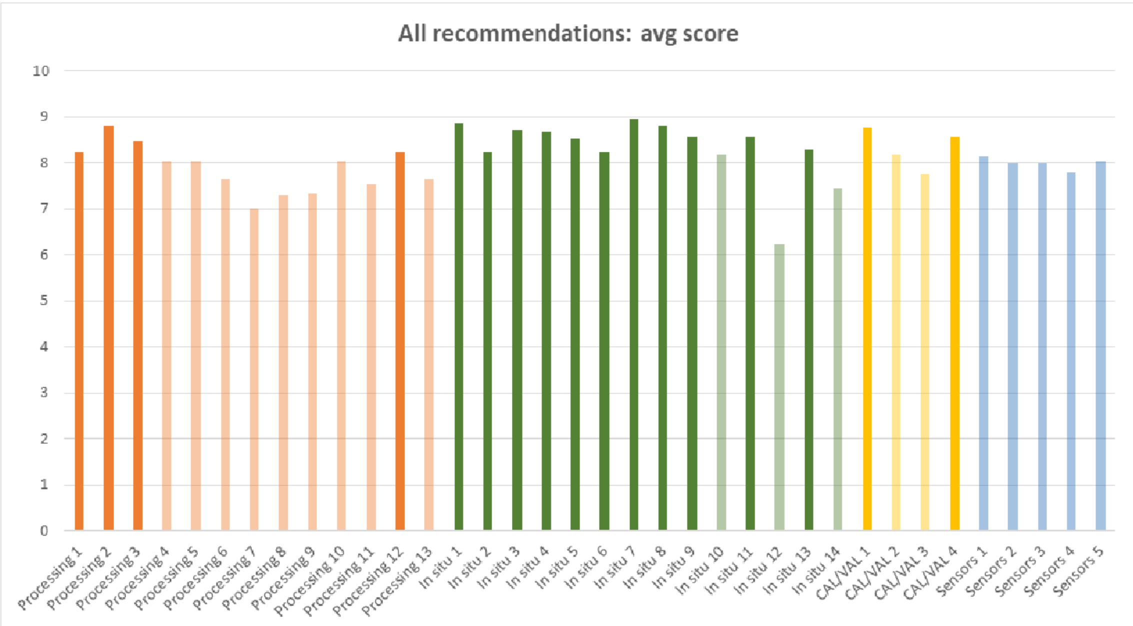

Figure 13: Average score for all recommendations (recommendations with an average score larger than the median average score (8,19) are indicated with a darker color).

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6 Conclusion

After describing the current atmospheric corrections used in the Copernicus water quality related services, collecting Copernicus services, R&D and end-user needs and describing the state-of-the-art in atmospheric correction, recommendations in categories atmospheric correction, in situ data for atmospheric correction Cal/Val, atmospheric correction Cal/Val and sensors for atmospheric correction were collected. These recommendations were scored by experts in atmospheric correction (validation) in order to prioritize the recommendations. Most high priority recommendations were related to the category **in situ data for atmospheric correction Cal/Val and to the need to develop AC algorithms for adjacency correction**. The top 3 highest priority recommendations are:

- **Priority 1: Need for long-term funding programs to support automatic measurement networks**
- **Priority 2: Need for automated fixed station measurement networks, which are geographically well-distributed and represent different water types to support atmospheric correction validation activities for both coastal and inland waters**
- **Priority 3: Develop atmospheric correction algorithms that include adjacency effect correction**

This deliverable (including all recommendations and scores received) serves as an input for the Water-ForCE Roadmap.

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