Reference measurements from AERONET-OC to assess Earth Observation data

Activity Report 2023

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Annex 1. Academic impact of AERONET-OC (source www.dimensions.ai)

Annex 2. Uncertainties associated with measurements
Abstract

Ocean colour remote sensing provides a diverse suite of data products of relevance for monitoring marine ecosystems and understanding their dynamics and role in ecology and climate. Reference field measurements of the primary ocean colour product, the remote sensing reflectance $R_{\text{rs}}$, are required to characterize its uncertainties. In support of the Copernicus programme, the collection of reference field measurements of $R_{\text{rs}}$ is among the objectives of the Fiducial Ocean and Land Earth Observations (FOLEO) JRC project. For that purpose, the JRC is currently managing, in close collaboration with Member States, the operations of autonomous radiometers part of the Ocean Color component of the Aerosol Robotic Network (AERONET-OC) on off-shore structures at nine sites (six in European seas, one in a Swedish lake, one in the Canary Islands and one offshore Kenya). After a brief description of the sites, the measurement protocol and the data processing are described. The data collection relies on a significant logistical effort, including shipping instruments and installations on the distributed sites, as well as laboratory work like calibration of instruments; the related activities are summarized for the years 2022 and 2023. Then, the data collected and their application for the validation of Copernicus Sentinel-3 $R_{\text{rs}}$ data are illustrated, again with a focus on the period 2022-2023. Considering the last year of operation for each site, more than 250 validation points were obtained for both Sentinel-3A and -3B.
Acknowledgements

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Authors

P. Sciuto, F. Mélin, I. Cazzaniga, B. Bulgarelli
## Introduction

Ocean colour (OC) remote sensing has become a powerful asset for the understanding and monitoring of marine ecosystems (IOCCG 2008). In the context of climate science, its primary product (the spectrum of water-leaving radiance $L_w$, or equivalently the remote sensing reflectance $R_{rs}$) is recognized as an Essential Climate Variable (GCOS 2011). Remote sensing reflectance $R_{rs}$ data are at the basis of almost all OC applications. Quantifying their uncertainties is thus key to the creation of comprehensive uncertainty budgets for OC products. Much of what is known about uncertainties of OC data still relies on comparison with field measurements, a process termed validation. Reference field observations are also required to verify uncertainty estimates derived from other methods (IOCCG 2019).

The Aerosol Robotic Network (AERONET) was born at the end of the 1990’s to collect autonomous measurements of aerosol optical properties with sun photometers (Holben et al. 1998). Later on, in the context of a collaboration between the US National Aeronautics and Space Administration (NASA) and the Joint Research Centre (JRC) of the European Commission, the measurement protocol was extended to include the capability of determining the radiance emerging from the sea (or water-leaving radiance) from suitable off-shore structures (Zibordi et al. 2002a). The first marine measurements took place in April 2002 at the site of the Acqua Alta Oceanographic Tower (AAOT) located in the North Adriatic Sea. In the following years, additional sites became operative and in 2006 the Ocean Color component of the Aerosol Robotic Network (AERONET-OC) (Zibordi et al. 2006, 2009a, 2021) was officially constituted. AERONET-OC has then extended to include 40 sites (26 of which were active in 2023) and provide globally-distributed standardized measurements of the water-leaving radiance accompanied by aerosol optical properties, with data available to the community in near-real time (see [https://aeronet.gsfc.nasa.gov/new_web/ocean_color.html](https://aeronet.gsfc.nasa.gov/new_web/ocean_color.html) for data access and site location). Today, AERONET-OC is a major source of data for the validation of satellite ocean color products from a variety of missions (e.g., Zibordi et al. 2009b, 2022b, Mélin et al. 2011, 2012, Pahlevan et al. 2021, McCarthy et al. 2023), while providing unique time series of aquatic surface optical properties, mostly for coastal and inland waters. These have been useful for various applications. Examples are the assessment of detection methods for specific types of phytoplankton (Cazzaniga et al., 2021, 2023a), the testing of multi-mission merging techniques (Mélin & Zibordi 2007, Mélin et al., 2009), system vicarious calibration (Mélin & Zibordi, 2010) or the investigation of adjacency effects (Bulgarelli et al., 2014, 2017, 2018a, 2018b). An analysis of the academic impact of AERONET-OC can be found in Annex 1.

The Fiducial Ocean and Land Earth Observations (FOLEO) JRC project supports the description of uncertainties for data from the Copernicus programme, and has among its objectives the collection of reference measurements required for the validation of the Sentinel optical missions. By documenting this activity, this report is a deliverable of FOLEO. It briefly describes the sites where JRC AERONET-OC systems operate and the measurement protocol. It then reviews the actual operations associated with these systems (deployments, calibration) and the data collected. Finally, it illustrates the main purpose of the activity, the validation of the Sentinel-3 radiometric products.
2 The AERONET-OC Sites operated by the JRC

AERONET-OC systems managed by the JRC in close collaboration with Member States, operate in various European waters (Fig. 2.1) and cover a wide variety of optical properties. One site is also operating in a European lake (Vänern, Sweden) while a site has been established offshore Kenya in 2020. JRC is also operating the AERONET site located within the precinct of the JRC of Ispra. The following sub-sections are providing some details about each site and related operations.

Figure 2.1. Locations of AERONET-OC sites managed by JRC. In italic: sites not currently operated (HLT, GLR). PGD is managed by Stockholm University with a JRC system. JRC is also managing the San Marco Platform (SMP) site offshore Kenya (lat. 2.942°S, lon. 40.215°E).

2.1 Acqua Alta Oceanographic Tower (AAOT)

The Acqua Alta Oceanographic Tower (AAOT, Fig. 2.2) is located in the Northern Adriatic Sea, 8 nautical miles out of the Venice lagoon. This structure dedicated to research and monitoring activities is owned by the Italian National Research Council (Consiglio Nazionale delle Ricerche, CNR). AAOT is the precursor site for AERONET-OC with measurements starting on the 19th April 2002. In AERONET naming, this was the “Venise” site from 2002 to March 2023 when the instrument was removed. In 2017, an additional improved instrument was installed that is currently providing the data stream for the “AAOT” site.

- Period of operations: April 2002 – present (with 2 instruments operating simultaneously from Oct. 2017 to Mar. 2023), without interruptions (except July-September 2017 for substitution of the infrastructure);
- Location (4 corners, in bold is the location of the instrument):
Latitude | N 45° 18.856' | N 45° 18.858' | N 45° 18.856' | N 45° 18.853'
--- | --- | --- | --- | ---
Longitude | E 12° 30.494' | E 12° 30.500' | E 12° 30.502' | E 12° 30.500'

Figure 2.2. Acqua Alta Oceanographic Tower (AAOT) site

2.2 Casablanca Platform (CSP)

The Casablanca Platform (CSP) is found in the Western Mediterranean near the edge of the Spanish coastal shelf (Fig. 2.3).

- Period of operations: April 2019 – present, without interruptions;
- Location of the instrument: N 40° 43.01664’; E 1° 21.49572’

Figure 2.3. Casablanca Platform (CSP) site

2.3 Gustaf Dalén Lighthouse Tower (GDLT)

The Gustaf Dalén Lighthouse Tower (GDLT) is located in the Baltic Proper, 5 nautical miles offshore the Swedish coast (Fig. 2.4). As a Baltic site, the instrument is deployed only in the spring-summer period and dismounted typically in September-October: low Sun and adverse meteorological conditions do not justify the maintenance of the instrument in winter.

- Periods of operations:
  Jun.-Oct. 2005
May-Aug. 2006
May-Sep. 2007
Apr.-Sep. 2008
Apr.-Aug. 2009
May-Oct. 2010
May-Sep. 2011
May-Sep. 2013
May-Jul. 2014
May-Oct. 2015
Apr.-Sep. 2016
Apr.-Aug. 2017
May-Sep. 2018
Apr.-Sep. 2019
Jun.-Sep. 2020
Apr.-Sep. 2021
May-Sep. 2022
May-Sep. 2023

- Location (4 corners, in bold is the location of the instrument):

<table>
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<tr>
<th>Latitude</th>
<th>N 58° 35.6451'</th>
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<td>E 17° 28.0525'</td>
<td>E 17° 28.0554'</td>
<td>E 17° 28.0484'</td>
</tr>
</tbody>
</table>

Figure 2.4. Gustaf Dalén Lighthouse Tower (GDLT) site

2.4 Helsinki Lighthouse (HLT)

The Helsinki Lighthouse (HLT) is located at the entrance of the Gulf of Finland, near Helsinki (15 nautical miles from the Finnish coast). The site has not been maintained since 2019; it is nonetheless included here for completeness as it has been operating for a long period.

- Periods of operations:
2.5 Irbe Lighthouse (IRL)

The Irbe Lighthouse (IRL) site is situated at the entrance to the Gulf of Riga, off the Latvian coast (Fig. 2.6). As GDLT, the instrument is deployed only in the spring-summer period (in 2023 the instrument was removed only in December because of adverse weather conditions).

- **Periods of operations:**
  - Jul.-Aug. 2018
  - Apr.-Sep. 2019
  - Jul. 2020
  - Jun.-Nov. 2021
  - May-Sep. 2022
  - Jun.-Dec. 2023

- **Location (4 corners, in bold is the location of the instrument):**
2.6 Section-7 Platform (S7)

The Section-7 Platform (S7) is in the Northwest Black Sea shelf, 12 nautical miles from Romania, south of the Danube River mouth. This site substituted the Gloria platform located nearby (N 44° 35.998', E 29° 21.58') in August 2019 where operations started in January 2011.

- Period of operations: August 2019 – present, without interruptions;
- Location: N 44° 32.75'; E 29° 26.816'

2.7 Galata Platform (GLT)

The Galata Platform (GLT) is also located on the Northwest Black Sea shelf in a more southerly position (~13 nautical miles offshore Bulgaria, Fig. 2.7).

- Period of operations: April 2014 – present, without interruptions;
- Location (4 corners, in bold is the location of the instrument):

<table>
<thead>
<tr>
<th>Latitude</th>
<th>N 43° 2.668'</th>
<th>N 43° 2.670'</th>
<th>N 43° 2.676'</th>
<th>N 43° 2.675'</th>
</tr>
</thead>
</table>
2.8 **PLOCAN Tower (PLT)**

The Plataforma Oceánica de Canarias (PLOCAN) is a research infrastructure located 1.5-km north-east of the Gran Canaria Island (Fig. 2.8).

- Period of operations: April 2014 – present, without interruptions;
- Location (4 corners, in bold is the location of the instrument):

<table>
<thead>
<tr>
<th>Latitude</th>
<th>N 28° 2.4748’</th>
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<th>N 28° 2.4622’</th>
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<tbody>
<tr>
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<td>W 15° 23.0995’</td>
<td>W 15° 23.0882’</td>
</tr>
</tbody>
</table>

*Source: [https://plocan.eu/instalaciones](https://plocan.eu/instalaciones)*

2.9 **San Marco Platform (SMP)**

The San Marco Platform (SMP) is located offshore Kenya (Fig. 2.9).

- Period of operations: Oct. 2020 – present, without interruptions;
2.10 Pålgrunden (PGD)

The site of Pålgrunden (under responsibility of the Stockholm University) is the only site operating a JRC system monitoring in-land waters, i.e., the Lake Vänern (Sweden). As the Baltic sites, it operates only in spring-summer.

- Periods of operations:
  - Jun.-Sep. 2009
  - May-Sep. 2010
  - May-Aug. 2011
  - May-Oct. 2013
  - May-Sep. 2014
  - May-Oct. 2015
  - May-Sep. 2017
  - May-Nov. 2018
  - Jun.-Aug. 2019
  - May-Oct. 2020
  - Apr.-Jul. 2021
  - May-Aug. 2022
  - May-Aug. 2023
- Location: N 58° 45.3198; E 13° 9.09
Figure 2.10. Pålgrunden site (Lake Vänern, Sweden).

Source: https://aeronet.gsfc.nasa.gov/new_web/photo_db_v3/Palgrunden.html
### 3 Measurements and data processing

AERONET-OC data are produced following a rigid measurement protocol, including a strict quality control procedure, to assure their fitness-for-purpose for OC satellite validation.

#### 3.1 Measurement protocol

AERONET-OC network provides water-leaving radiance values $L_W$ at various centre-wavelengths $\lambda$ deploying above-water autonomous photometers on fixed platforms. Cimel photometers CE-318 and CE-318T SeaPRISM (PRS) systems are employed. The water-leaving radiance $L_W$ is quantified from PRS measurements in the following way (Zibordi et al. 2021, and references therein):

$$L_W(\lambda, \theta, \theta_0, \phi) = L_T(\lambda, \theta, \theta_0, \phi) - \rho(\theta, \theta_0, \phi, w)L_i(\lambda, \theta', \theta_0, \phi) \quad (\text{Eq. 1})$$

where $L_T$ is the total radiance measured by the instrument pointing towards the sea surface with a geometry defined by zenith viewing angle $\theta = 40^\circ$ (measured from the nadir) and relative azimuth $\phi = 90^\circ$ with respect to the solar plane; the term $\theta_0$ indicates the solar zenith angle. $L_i$ is the sky radiance measured in sky-viewing mode with viewing angle $\theta' = 180^\circ - \theta$. The term $\rho$ is the sea-surface reflectance factor computed through radiative transfer simulations as a function of the illumination geometry and the sea state for wind speed $w$. Values of $\rho$ as provided by Mobley (1999) are currently used. Recent investigations evidenced systematic underestimates of $\rho$ factors computed by Mobley (1999) (D’Alimonte et al., 2021) and additionally suggested to account for atmospheric and spectral dependences (Bulgarelli et al., 2022).

**Figure 3.1.** Three-dimensional rendering of a SeaPRISM system, with the Cimel Sun-photometer, the robot ensuring the movement of the instrument and a holding structure.
Figure 3.2. Above-water measurements (a) side- and (b) top-view geometry supported by protocols and adopted at AERONET-OC sites.

For each measurement sequence, \( N_T \) measurements of \( L_T \) and \( N_i \) measurements of \( L_i \) are performed (with \( N_T = 11 \) and \( N_i = 3 \)). Selected values of \( L_T \) and \( L_i \) are then obtained by averaging all \( L_i \) measurements and the lowest 2 out of the 11 measurements of \( L_T \), aiming at minimizing the impact of wave perturbations (Zibordi et al. 2021, 2022a).

The measurement function (Eq. 1) associated with the determination of \( L_W \) is displayed in an uncertainty analysis diagram (also called uncertainty tree) following Mitaz et al. (2019) (Fig. 3.2, Mélin et al. 2024). This diagram documents all the influence quantities and related error sources and are useful to set up a comprehensive uncertainty budget. Appendix 2 provides an updated description of the uncertainties associated with the AERONET-OC data as described in Gergely & Zibordi (2014) and Cazzaniga & Zibordi (2023) and following metrological practices (JCGM 2008). These uncertainty estimates have been further analysed in Mélin et al. (2024).

Figure 3.2. Uncertainty tree diagram describing the AERONET-OC \( L_W \) measurement function (associated with Eq. 1). The measurement function is in the grey rectangle, expressing the measurand as a function of its influence quantities (or input quantities). For each input, the associated error sources are traced with various colors to their contributing factors. Rounded black rectangles indicate the sensitivity factors (expressed as partial derivatives), i.e., the extent to which an error in an input impacts the measurand. For all equations in the diagram, \( q_0 \) is a generic notation indicating a possible model error. \( \Omega \) is a short notation for the geometry of observation and illumination.

The conversion from \( L_W \) to the normalized water leaving radiance \( L_{WN} \) is performed through:
\[ L_{WN}(\lambda) = \frac{L_W(\lambda, \theta_0, \phi)}{d^2 \cos \theta_0 t_d(\lambda, \theta_0)} C_Q(\lambda, \theta, \theta_0, \phi, OP, w) \] (Eq. 2)

where \( d \) is the inverse normalized Earth-Sun distance, and \( t_d \) is the diffuse atmospheric transmittance (Deschamps et al. 1983). \( C_Q \) is a factor correcting for bidirectional effects associated for non-nadir illumination and observation conditions. It is here modelled as a function of geometry, wind speed and the optical properties of the water (labelled \( OP \)), represented either by chlorophyll-a concentration (Chl) according to Morel et al. (2002) or by Inherent Optical Properties (IOP) according to Lee et al. (2011). Both correction methods are provided for AERONET-OC data and corresponding \( L_{WN} \) values are referred to as \( L_{WN}^{Chl} \) and \( L_{WN}^{IOP} \), respectively.

Finally, the remote sensing reflectance \( R_{RS} \) can be expressed as:

\[ R_{RS}(\lambda) = \frac{L_{WN}(\lambda)}{E_0(\lambda)} \] (Eq. 3)

with \( E_0 \) being the mean extra-terrestrial solar irradiance (Thuillier et al. 2003).

These steps (conversion from \( L_W \) to \( R_{RS} \)) are illustrated with associated error sources by the uncertainty diagram of Fig. 3.3 (Mélin et al. 2024). Again Appendix 2 discusses the data uncertainties in more details.

In the last years, all JRC AERONET-OC CE-318 systems were substituted by the upgraded CE-318T. CE-318 and CE-318T differ mainly in the number of measurement sequences performed and the number of the centre-wavelengths at which measurements are acquired, which are both higher for CE-318T. Every hour, whereas CE-318 instruments perform two sequences of measurements, CE-318T instruments perform two triplets of measurement sequences. Each triplet is composed of three complete measurement sequences typically completed within 10 minutes. Whereas CE-318 acquires measurements at 8 bands, CE-318T acquires measurements at 11 bands with nominal center-wavelengths matching most of those of the Ocean and Land Colour Imager (Donlon et al. 2012), at 400.0, 412.5, 442.5, 490.0, 510.0, 560.0, 620.0, 665.0, 779.0, 865.0, and 1020.0 nm.

**Figure 3.3.** Uncertainty tree diagram for the conversion from \( L_W \) to \( R_{RS} \) (associated with Eqs. 2 and 3). Its construction is similar to Fig. 3.2. Bold notations indicate a spectrum of values for \( R_{RS} \) or for optical properties \( OP \). \( t_d,r, t_d,a, t_d,o \) are transmittance associated with air molecules (Rayleigh), aerosol and ozone. \( \tau_r \) is the Rayleigh optical thickness (dependent on tabulated values at the standard atmospheric pressure and the actual atmospheric pressure).

### 3.2 Instrument Calibration

The various systems managed by the JRC benefit from calibrations traceable to standards at the Goddard Space Flight Center (GSFC) of NASA (Johnson et al. 2021) as all AERONET instruments. In addition, JRC also performs
calibration and tests on its systems in its Marine Optical Laboratory, which allows cross-checking with results obtained by NASA-GSFC. More details about calibration operations are given in Section 4.

### 3.3 Quality Control

While quality assurance (QA) actions guarantee the correct execution of measurements, the quality control (QC) procedure includes all post-generation actions in support of the provision of high-quality data.

QC is often implemented as a process to include or exclude data according to successive quality levels. Specifically, the AERONET-OC product-oriented QC process is targeted to remove $L_{\text{ww}}$ spectra that are affected by (i) substantial environmental perturbations caused by clouds or heavy sea state, (ii) elements of the deployment structures observed within the sensor field of view, (iii) perturbations in the light field due to proximity of the sensor footprint to the deployment structure, and also (iv) significant changes in sensor responsivity during the deployment period (Zibordi et al. 2022a).

AERONET-OC normalized water-leaving radiance $L_{\text{ww}}$ spectra are delivered at incremental levels of accuracy identified as Level 1.0, Level 1.5, and Level 2.0. These incremental levels offer the possibility of real-time applications of data not yet benefitting of full quality control through Level 1.5, and of deferred applications requiring higher-quality measurements through Level 2.0.

Specifically (Zibordi et al., 2022a):

- **Level 1.0** denotes unscreened data subject to basic QC. For each measurement sequence passing QC:
  
  i. $\tau_s(\lambda)$ has been determined;
  
  ii. there are no missing data in the N$_1$ sea-viewing radiance measurements and in the N$_1$ sky-viewing radiance measurements;
  
  iii. dark values are below a defined threshold;
  
  iv. absolute viewing azimuth angle $\phi_v$ is within site-dependent limits to minimize superstructure disruptions in L$_{\text{r}}$ measurements;
  
  v. the wind speed is below the maximum threshold of 15 m s$^{-1}$.

- **Level 1.5** data, mostly proposed for real-time applications, are derived from level 1.0 data ensuring:
  
  i. the presence of cloud-screened AERONET $\tau_s(\lambda)$ at Level 1.5 in the AERONET database (Giles et al. 2019),
  
  ii. the satisfaction of a series of empirical thresholds (e.g., absence of exceedingly negative values at any $\lambda$),
  
  iii. $L_{\text{ww}}$(412) lower than $L_{\text{ww}}$(443) at coastal sites,
  
  iv. $L_{\text{ww}}$(1020) not exceeding 0.1 mW cm$^{-2}$ \(\mu\)m$^{-1}$ sr$^{-1}$ in regions not affected by very turbid waters to exclude measurements perturbed by the presence of obstacles in the sight of the sea-viewing sensor;
  
  v. low variance in the N$_1$ sea-viewing radiance measurements and in the N$_1$ sky-viewing radiance measurements, indicating low wave effects and negligible cloud contamination, respectively.

- **Level 2.0** data, supporting deferred applications, are based on level 1.5 products, ensuring:
  
  i. the existence of Level 2 AERONET $\tau_s(\lambda)$;
  
  ii. variance thresholds of the sea-viewing radiance measurements and sky-viewing radiance measurements lower to those applied for level 1.5 data;
  
  iii. differences between pre and post-deployment calibration coefficients for the AERONET-OC radiometer smaller than 5% (see Zibordi et al., 2022);
  
  iv. absence of questionable values in the $L_{\text{ww}}$ spectra.
Starting in July 2023, an automated QC process (Zibordi et al., 2022a) raises data from Level 1.5 to Level 2.0. Previously, an expert-based QC procedure (Zibordi et al., 2021) was applied to qualified data.

The AEREONET-OC QC procedure inherently limits quality-checked data to measurement conditions that exclude relatively high wind speeds (w≤4 m s⁻¹) and low sun zeniths (θ₀>20°). Recent investigations demonstrated that these measurement conditions ensure negligible spectral and atmospheric dependences of the sea-surface factor, which affect retrieval of $L_w$ only for extremely low values of the water signal (as for CDOM dominated waters in the blue, and oligotrophic waters in the red) (Bulgarelli et al., 2022).
4 Logistics and Laboratory Activities

The JRC validation activities supporting satellite ocean color missions rely on various components of the Marine Optical Laboratory infrastructure to perform absolute radiometric calibrations, testing and logistic tasks for field instruments operated within the framework of the Copernicus Program.

A robust logistical component is imperative to support operations for the JRC AERONET-OC network. The annual operation cycle for Cimel CE-318T instruments involves several steps including their absolute calibration at the JRC Marine Optical Laboratory and intensive tests on the JRC Testing Tower. Subsequently, the instruments are meticulously packaged in dedicated boxes together with tools and any component essential for their field installation and operation. Following shipment to national collaborating institutes, radiometers are installed on dedicated offshore structures for approximately one year (limited to 4-5 months for Nordic sites). At the end of each annual deployment, the instruments are replaced with newly calibrated and tested ones. Each radiometer completing the deployment process is returned to the Marine Optical Laboratory for recalibration and successively sent to the Goddard Space Flight Center of NASA for further calibration, testing, and recalibration before returning to the JRC Marine Optical Laboratory.

Absolute radiance calibrations of each AERONET-OC radiometer are conducted at NASA using an integrating sphere while at the JRC Marine Optical Laboratory they are performed using 1000 W FEL lamps traceable to standards and certified 99% reflectance plaques.

The repeated JRC-NASA inter-comparisons constitute a long-term exercise that already demonstrated the importance of continuous verifications to promptly address issues that may arise in any laboratory in view of ensuring radiance absolute calibrations within approximately 1-2% (Johnson et al. 2021).

4.1 Calibrations

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4.2 Installations

Table 4.2. List of installations performed in 2022 and 2023. The various instruments (SeaPrism) are labelled by their network number. AAOT and Venice refer to the same site where 2 instruments were operating simultaneously until March 2023.

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</tr>
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4.3 Shipments JRC-NASA

Table 4.3: List of shipments to NASA for calibration of the instruments labelled by their network number.

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5 Data Collection

This Section documents the data collection performed at the various sites. The use of the data is here restricted to fully quality-controlled Level 2 data (except in the case of the PLOCAN site). This explains why the time series are up-to-date to varying extents as they are completed when the latest Level-1.5 data are qualified to Level 2. For each site, 2 figures are displayed: i) the time series of \( R_{RS} \) at 443 nm illustrated by daily and monthly averages, and ii) the spectrum of median \( R_{RS} \) (±1 standard deviation) computed over all data collected since the CE-318T system has been in place at the site, together with all daily averaged spectra collected over the last year of Level-2 data.

5.1 Acqua Alta Oceanographic Tower (AAOT)

AAOT is the longest operating AERONET-OC site with a series exceeding 20 years (3155 days of measurements, Fig. 5.1). This site has been particularly well studied: 176 campaigns were performed at the AAOT between 1995 and 2016 within the Coastal Atmosphere and Sea Time Series (CoASTS) program to deliver time series of seawater apparent and inherent optical properties, in addition to the concentration of major optically significant water constituents (Zibordi et al., 2002b; Berthon et al., 2002; Zibordi et al., 2020). The site is characterised by moderately turbid, optically complex waters with \( R_{RS} \) maxima usually observed in the spectral interval 490-560 nm (Fig. 5.2). \( R_{RS} \) values cover a fairly large dynamic range with short-term variability (mostly dictated by regional river inputs) superimposed on an annual cycle showing larger values in winter-spring. The site has been fully characterized for the adjacency effects from nearby land (Bulgarelli et al., 2014, 2018b), and the impact of adjacency effects on satellite-derived radiometric products and their validation procedure has been additionally addressed (Bulgarelli et al., 2017, 2018a).

**Figure 5.1.** Time series of daily averages (circles) and monthly averages (blue curve) of \( R_{RS}(443) \) Level-2 data at the AAOT site. \( N_m \) is the total number of measurements performed at the site while \( N_d \) is the number of days with at least one valid Level-2 measurement.
Figure 5.2. For the AAOT site, median and ±1 standard deviation (dashed line) of $R_{RS}$ computed over data collected by CE-318T systems, and individual $N_d$ daily averaged spectra collected over the last year of Level-2 data (computed from $N_m$ measurements).
5.2 Casablanca Platform (CSP)

The Casablanca Platform CSP, located in the western Mediterranean Sea near the edge of the Spanish coastal shelf, exhibits fairly low turbidity and often Case-1 water conditions (i.e., with optical properties defined by phytoplankton and derivatives), with $R_{\text{rs}}$ generally decreasing from the blue to low values in the red (Fig. 5.4). The series (Fig. 5.3) shows a clear annual cycle with minima in winter-spring associated with phytoplankton growth and maxima in summer when phytoplankton is at its lowest abundance. Influence from the coastal and shelf region is also possible. The current Level-2 time series is only approximately 3-year long but the last year of operation added 227 days of valid measurements.

**Figure 5.3.** Time series of daily averages (circles) and monthly averages (blue curve) of $R_{\text{rs}}(443)$ Level-2 data at the CSP site. $N_m$ is the total number of measurements performed at the site while $N_d$ is the number of days with at least one valid Level-2 measurement.

**Figure 5.4.** For the CSP site, median and ±1 standard deviation (dashed line) of $R_{\text{rs}}$ computed over data collected by CE-318T systems, and individual $N_d$ daily averaged spectra collected over the last year of Level-2 data (computed from $N_m$ measurements).
5.3 Gustaf Dalén Lighthouse Tower (GDLT)

The Gustav Dalén Lighthouse Tower (GDLT) in the Baltic Proper started data collection in 2005 (Fig. 5.6). As the other Baltic sites, the site operates only in the spring-summer time for a period of variable length when illumination and meteorological conditions are favourable. Baltic waters are optically complex with a markedly strong influence of Chromophoric Dissolved Organic Matter (CDOM) leading to high levels of absorption. The waters are therefore associated with generally low values of $R_{rs}$, particularly in the blue. The $R_{rs}$ spectra show maxima around 560 nm and significant values in the red (e.g., Zibordi et al. 2009). The levels of $R_{rs}$ can largely increase during cyanobacteria blooms in the summer (Zibordi et al. 2006, Cazzaniga et al. 2023a).

Figure 5.5. Time series of daily averages (circles) and monthly averages (blue curve) of $R_{rs}(443)$ Level-2 data at the GDLT site. $N_m$ is the total number of measurements performed at the site while $N_d$ is the number of days with at least one valid Level-2 measurement.

Figure 5.6. For the GDLT site, median and ±1 standard deviation (dashed line) of $R_{rs}$ computed over data collected by CE-318T systems, and individual $N_d$ daily averaged spectra collected over the last year of Level-2 data (computed from $N_m$ measurements).
5.4 Helsinki Lighthouse (HLT)

The Helsinki Lighthouse (HLT) is located in the Gulf of Finland and clearly shares clear spectral properties with GDLT (Fig. 5.8). The operations at this site could not be continued after 2019 so that the last year of operations refer to 2019.

**Figure 5.7.** Time series of daily averages (circles) and monthly averages (blue curve) of $R_{\text{RS}}(443)$ Level-2 data at the HLT site. $N_m$ is the total number of measurements performed at the site while $N_d$ is the number of days with at least one valid Level-2 measurement.

**Figure 5.8.** For the HLT site, median and ±1 standard deviation (dashed line) of $R_{\text{RS}}$ computed over data collected by CE-318T systems, and individual $N_d$ daily averaged spectra collected over the last year of Level-2 data (computed from $N_m$ measurements).
5.5 Irbe Lighthouse (IRL)

The Irbe Lighthouse site is the second active Baltic site at the entrance to the Gulf of Riga. Located at the confluence of three basins (the Baltic Proper, the Gulf of Finland, the Gulf of Bothnia), IRL is characterized by varying concentrations of CDOM and sediments. After its first irregular operations (Fig. 5.9), it has operated on a regular basis for the last 3 years (including 2023 not shown as the data are still at Level 1.5). Again it shows spectral properties comparable to the previous 2 Baltic sites (Fig. 5.10).

Figure 5.9. Time series of daily averages (circles) and monthly averages (blue curve) of $R_{SS}(443)$ Level-2 data at the IRL site. $N_m$ is the total number of measurements performed at the site while $N_d$ is the number of days with at least one valid Level-2 measurement.

Figure 5.10. For the IRL site, median and ±1 standard deviation (dashed line) of $R_{SS}$ computed over data collected by CE-318T systems, and individual $N_d$ daily averaged spectra collected over the last year of Level-2 data (computed from $N_m$ measurements).
5.6 Section-7 Platform (S7)

The Section-7 platform substituted the Gloria location in August 2019. The two locations are sufficiently close to aggregate the data into one time series starting in 2011 (Fig. 5.11). The site is situated on the western shelf of the Black Sea associated with optically complex waters, with $R_{\text{rs}}$ maxima typically seen in the interval 490-560 nm (Zibordi et al. 2015, Fig. 5.12). The site can intermittently feel the influence of the Danube River (Cazzaniga et al. 2021). It can also undergo the influence of coccolithophore blooms typically observed in summer in the region and can be responsible for large increases in the magnitude of $R_{\text{rs}}$ (e.g., Cazzaniga et al. 2021, Fig. 5.11).

Figure 5.11. Time series of daily averages (circles) and monthly averages (blue curve) of $R_{\text{rs}}(443)$ Level-2 data at the Gloria and S7 sites. $N_m$ is the total number of measurements performed at the site while $N_d$ is the number of days with at least one valid Level-2 measurement.

Figure 5.12. For the S7 site, median and ±1 standard deviation (dashed line) of $R_{\text{rs}}$ computed over data collected by CE-318T systems, and individual $N_d$ daily averaged spectra collected over the last year of Level-2 data (computed from $N_m$ measurements).
5.7 Galata Platform (GLT)

The Galata Platform is also situated on the western shelf of the Black Sea and share common properties with the S7 site. It is however situated further south on the shelf and does not feel the direct influence of the Danube or rivers further north.

**Figure 5.13.** Time series of daily averages (circles) and monthly averages (blue curve) of $R_{RS}(443)$ Level-2 data at the GLT site. $N_m$ is the total number of measurements performed at the site while $N_d$ is the number of days with at least one valid Level-2 measurement.

**Figure 5.14.** For the GLT site, median and ±1 standard deviation (dashed line) of $R_{RS}$ computed over data collected by CE-318T systems, and individual $N_d$ daily averaged spectra collected over the last year of Level-2 data (computed from $N_m$ measurements).
5.8 PLOCAN Tower (PLT)

The PLOCAN Tower located northeast of Gran Canaria Island is a recent site operating a JRC system under the responsibility of the Consejo Superior de Investigaciones Científicas (CSIC). For completeness, it is here documented with Level 1.5 data covering 161 days of operations (Fig. 5.15). First results show $R_{\text{RS}}$ spectra with maxima in the blue characteristic of clear waters found in the open Atlantic Ocean (Fig. 5.16). More observations will be needed to further characterize the site.

**Figure 5.15.** Time series of daily averages (circles) and monthly averages (blue curve) of $R_{\text{RS}}(443)$ Level-1.5 data at the PLT site. $N_m$ is the total number of measurements performed at the site while $N_d$ is the number of days with at least one valid Level-1.5 measurement.

**Figure 5.16.** For the GLT site, median and ±1 standard deviation (dashed line) of $R_{\text{RS}}$ computed over data collected by CE-318T systems, and individual $N_d$ daily averaged spectra collected over the last year of Level-1.5 data (computed from $N_m$ measurements).
5.9 San Marco Platform (SMP)

The San Marco Platform is in the coastal region of Kenya (offshore Malindi). The current record (limited to 184 days of measurements, Fig. 5.19) suggests optical properties associated with turbid water, with low $R_{RS}$ in the blue, peak values at 560 nm and significant values often seen in the red (Fig. 5.18).

**Figure 5.17.** Time series of daily averages (circles) and monthly averages (blue curve) of $R_{RS}(443)$ Level-1.5 data at the SMP site. $N_m$ is the total number of measurements performed at the site while $N_d$ is the number of days with at least one valid Level-2 measurement.

![Graph of $R_{RS}(443)$](image)

**Figure 5.18.** For the SMP site, median and ±1 standard deviation (dashed line) of $R_{RS}$ computed over data collected by CE-318T systems, and individual $N_d$ daily averaged spectra collected over the last year of Level-2 data (computed from $N_m$ measurements).
5.10 Pålgrunden (PGD)

Under responsibility of the Stockholm University, this is the only JRC system operating in in-land waters, in the Lake Vänern (Sweden). As the Baltic sites, it operates only in spring-summer but has been documenting the site for the past 15 years (Fig. 5.19). As expected, $R_{\text{RS}}$ spectra are well representative of turbid lake water, with very low values in the blue associated with dissolved organic matter, maxima usually seen at 560 nm and significant magnitude in the red (Fig. 5.20).

**Figure 5.19.** Time series of daily averages (circles) and monthly averages (blue curve) of $R_{\text{RS}}(443)$ Level-1.5 data at the SMP site. $N_m$ is the total number of measurements performed at the site while $N_d$ is the number of days with at least one valid Level-2 measurement.

**Figure 5.20.** For the PGD site, median and ±1 standard deviation (dashed line) of $R_{\text{RS}}$ computed over data collected by CE-318T systems, and individual $N_d$ daily averaged spectra collected over the last year of Level-2 data (computed from $N_m$ measurements).
6 Application to Validation of Satellite Data

The major application of the AERONET-OC data is the validation of the Copernicus satellite data products, mostly from the Ocean & Land Colour Instruments (OLCI) on board Sentinel-3 (Donlon et al. 2012). This role in the evaluation of Sentinel-3 products is recognized as prominent by the European Organization for the Exploitation of Meteorological Satellites (EUMETSAT) (e.g., EUMETSAT 2021) and by the Copernicus Marine Service (CMEMS) (CMEMS, 2022b, 2023a,b). The near-real time evaluations of OLCI radiometric products by CMEMS currently rely on AERONET-OC for 87% and 96% of the in-situ data in the case of Sentinel-3A (operating since 2016) and -3B (operating since 2018), respectively (see https://octac.acri.fr/index.php?action=octacplots). The role of AERONET-OC is similarly important for the assessment of aquatic products associated with Sentinel-2 (e.g., Pahlevan et al. 2021, CMEMS, 2022a) or with third-party missions. In that context, the JRC is managing most of the systems operating in Europe (all sites active in 2023 but one) and is the institution providing the largest contribution to the global effort together.

The following Sections focus on the validation results obtained for Sentinel-3 with the data collected by JRC systems at each of the sites described above, except SMP and PLT for which few data are available and a further characterization of the site is required. No results are shown for the Pålgrunden site (PGD) since specific procedures are needed for validating Sentinel-3 products on a lake. However, some validation of satellite data has been achieved with the data collected at that site (e.g., Cazzaniga et al. 2023b).

6.1 Satellite products

The satellite products considered here are the standard Sentinel-3 Level-2 reduced-resolution (RR) reflectance products released by EUMETSAT (EUMETSAT, 2021, Zibordi et al. 2022b). The data products are associated with the Operational Baseline 3 Collection OL_L2M.003.01 generated with the processor IPF-OL-2 version 07.01 applied to data collected by OLCI. For comparison with the AERONET-OC data, the reflectance satellite products are corrected for bi-directional effects according to Morel et al. (2002).

For each Sentinel-3 image, the satellite macro-pixel of 3x3 elements closest to each site location was extracted from the processed satellite data to become a candidate match-up (i.e., satellite data coincident with an in-situ observation). In each case, AERONET-OC data collected less than 2 hours from the satellite overpass were then selected. The AERONET-OC record to be compared with the satellite match-up data was the result of a weighted average of the field observations computed at the time of the satellite overpass using data collected just before and after this overpass if available; otherwise, the AERONET-OC record used for comparison was the closest to (either before or after) the overpass. If any element within the 3x3 macro-pixel was marked by one of the standard excluding flags of the atmospheric correction algorithm (EUMETSAT, 2019, 2021), the macro-pixel was rejected from the match-up selection. These flags document conditions adverse to the atmospheric correction, such as clouds, high glint or large zenith angles for solar illumination and observation. The validation process compares data collected on different spatial scales (point measurements versus pixel-size data) and can be affected by heterogeneous conditions; these were here filtered out by excluding cases with a Coefficient of Variation (CV, ratio of standard deviation and average over the macro-pixel) larger than 0.2 for any Rs between 490 and 560 nm. To further reduce a potential representation error, the final match-up satellite value was computed from the four pixels closest to the AERONET-OC site with a bilinear interpolation applied to its precise location.

To perform the comparison between field and satellite data, the AERONET-OC Rs data were aligned to the satellite centre-wavelengths using a band-shifting approach that relied on regional bio-optical relationships (Zibordi et al., 2009, 2015), with most of the corrections applied to small spectral intervals (i.e. less than 5-10 nm). As the JRC systems were upgraded to the CE-318T standard with centre-wavelengths matching those of OLCI, this correction is no longer necessary for the recent operations.

6.2 Validation statistics

Validation is the process of comparing satellite products \(y_i\),\(i=1,N\) with reference data \(x_i\),\(i=1,N\), here represented by the AERONET-OC field observations. Among the metrics used to characterize differences (Mélin & Franz, 2014), the following are computed:

- the mean absolute relative difference |\(\psi\)| (in %):
\[ |\psi| = \frac{100}{N} \sum_{i=1}^{N} \left| \frac{y_i - x_i}{x_i} \right| \quad \text{(Eq. 4)} \]

- the mean relative difference \( \psi \) (in %):
\[ \psi = \frac{100}{N} \sum_{i=1}^{N} \frac{y_i - x_i}{x_i} \quad \text{(Eq. 5)} \]

- the root-mean-squared difference (RMSD) \( \sigma \) (in unit of \( R_{RS} \), \( \text{sr}^{-1} \)):
\[ \sigma = \sqrt{\frac{1}{N} \left( y_i - x_i \right)^2} \quad \text{(Eq. 6)} \]

- the Pearson coefficient of determination \( r^2 \).

### 6.3 Validation results

Validation results for \( R_{RS} \) (for both Sentinel-3A and -3B) are illustrated in the form of scatter plots with associated statistics for the main OLCI bands 412, 443, 490, 510, 560, 665 nm. The match-ups obtained with the last year of operations qualified to Level-2 (and their number) are indicated in orange (except for HLT where operations stopped in 2019). The number of match-ups varies as a function of the duration of deployment of the AERONET-OC systems and the characteristics of the sites (mostly the occurrence of cloud-free conditions).

The highest number of match-ups is found at AAOT (338 and 260 for Sentinel-3A and -3B, respectively). For the non-Baltic sites with a continuous operating record during the year (and more favourable atmospheric conditions), 40-60 additional match-ups were obtained during the last year of operations, while 16-20 additional match-ups were found for GDLT and IRL.

Results are in line with those documented in Zibordi et al. (2022b) and show great coherence between Sentinel-3A and -3B in general. At the Casablanca site characterized by clear waters, the agreement between field and satellite data is good in the interval 490-560 nm (|\( \psi \)| of ~11% and a small bias \( \psi \)) but is degraded in the blue even though the signal is usually high in this part of the spectrum. It can be noted that the match-ups obtained in the last year of operation for Sentinel-3B tend to be on the high end of overestimates at 412 and 443 nm, a feature that should be monitored as more match-ups are collected. The large values of |\( \psi \)| at 665 nm (~60%) can be explained by the low signal observed at this wavelength at this site.

At coastal sites with moderately turbid waters (AAOT, S7, GLT), the best agreement is seen at 560 nm with |\( \psi \)| of 10-13% and is degrading (higher |\( \psi \)| and lower \( r^2 \)) for decreasing wavelength. For instance, at AAOT, |\( \psi \)| is 14% at 490 nm, 23% at 443 nm, and 38% at 412 nm. Values are higher with positive biases at the two sites in the Black Sea. At 665 nm, |\( \psi \)| is of the order of 30-45% with a large negative bias. As for CSP, a few outliers with large overestimates are seen at 412 and 443 nm for Sentinel-3B.

The Baltic sites (GDLT, HLT, IRL) show very large discrepancies in the blue bands, with |\( \psi \)| that can exceed 100% and \( r^2 \) close to 0. This behaviour is also observed for products from other missions (Zibordi et al. 2009b, Mélin 2022, Cazzaniga et al. 2023a). Differences decrease with wavelength at ~25-30% at 490 nm, ~20% at 510 nm, and ~12% at 560 nm, and increase again at 665 nm but at a level lower or comparable to the other sites (~30-35%).

The relative agreements observed between sites may actually change when considering differences in absolute (in units of \( R_{RS} \)) instead of relative terms (in %). For instance, at 443 nm the RMS difference \( \sigma \) is larger than 0.0012 \( \text{sr}^{-1} \) for the moderately turbid sites (AAOT, S7, GLT) but lower than 0.001 \( \text{sr}^{-1} \) at the Baltic sites, which is explained by the much lower amplitude of \( R_{RS} \) at the latter sites.
6.3.1 Acqua Alta Oceanographic Tower (AAOT)

Figure 6.1. Scatter-plots of matching $R_{\text{RS}}$ AERONET-OC and satellite Sentinel-3A values at AAOT for the bands 412, 443, 490, 510, 560, and 665 nm. Symbols of statistics are defined in Section 6.2. $|\psi|$ and $\psi$ are in %, $\sigma$ is in sr$^{-1}$ (multiplied by 100). Match-ups obtained during the last year of operations are in orange.

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6.3.2 Casablanca Platform (CSP)

Figure 6.3. Scatter-plots of matching $R_{\text{RS}}$ AERONET-GC and satellite Sentinel-3A values at CSP for the bands 412, 443, 490, 510, 560, and 665 nm. Symbols of statistics are defined in Section 6.2. $|\psi|$ and $\psi$ are in %, $\sigma$ is in sr$^{-1}$ (multiplied by 100). Match-ups obtained during the last year of operations are in orange.

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6.3.3 Gustaf Dalén Lighthouse Tower (GDLT)

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**Figure 6.6.** As Fig. 6.5 for Sentinel-3B.
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Figure 6.7. Scatter-plots of matching $R_{412}$ AERONET-OC and satellite Sentinel-3A values at HLT for the bands 412, 443, 490, 510, 560, and 665 nm. Symbols of statistics are defined in Section 6.2. $|\psi|$ and $\psi$ are in %, $\sigma$ is in sr$^{-1}$ (multiplied by 100).

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Figure 6.13. As Fig. 6.12 for Sentinel-3B
7 Conclusions

In the context of its support to the Copernicus programme, the Fiducial Ocean and Land Earth Observations (FOLEO) JRC project supports the determination of uncertainties associated with satellite products derived from the Sentinel optical missions. A key component of this activity is the collection of reference measurements by autonomous radiometric systems operating on several offshore structures in European seas (with the addition of a site in African waters) in the framework of AERONET-OC. In the last year, JRC systems operated in 9 locations, 3 in the Baltic area (including one in a Swedish lake), 1 in the Adriatic Sea, 1 in the western Mediterranean Sea, 1 in the Atlantic waters close to the Canary Islands, 2 in the Black Sea and 1 offshore Kenya. This ensemble allows the collection of data representative of a large set of optical properties, from clear waters to turbid waters of various nature. This diversity is a powerful element to guarantee a comprehensive validation of satellite products.

Operating these sites entails a significant effort in terms of logistics (installations and de-installations at the measurement sites, shipments) and in the JRC Marine Optical Laboratory (calibration, testing). In practise, 11 installations of instruments by JRC staff or local collaborating institutions were performed in 2022 and 10 in 2023, while 13 instruments were shipped to NASA-GSFC for calibration in 2022 and 7 in 2023. Finally, 53 calibrations were performed in the period 2022-23.

This effort is translated into a substantial flow of data that varies according to deployment periods and atmospheric conditions. Considering the last year of Level-2 data collection, valid measurements have been made on usually more than 200 days (with a total number of measurements of the order of 2000) for Mediterranean and Black Sea sites, while this is true for 80-85 days for the Baltic sites GDLT and IRL. This makes the operation of the JRC AERONET-OC sites by far the main source of \( R_{\text{ref}} \) reference measurements in European seas. The role of AERONET-OC for the evaluation of Sentinel-3 products is consequently recognized by EUMETSAT (e.g., EUMETSAT 2021) and by the Copernicus Marine Service (CMEMS, 2022b, 2023a,b). This also applies to aquatic products associated with Sentinel-2 (e.g., Pahlevan et al. 2021, CMEMS, 2022a) or with third-party missions. Again, considering the last year of Level-2 data collection, 40-60 additional match-ups were obtained at each non-Baltic sites (AAOT, CSP, GLT, S7), while 16-20 additional match-ups were found for each of the two active Baltic Sea sites (GDLT and IRL), which means more than 250 match-ups identified for both Sentinel-3A and -3B. This ensures a significant flow of validation data allowing the monitoring of the performance of the Sentinel-3 and all other optical missions.
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Annex 1. Academic impact of AERONET-OC (source www.dimensions.ai)

Figure A1 shows the number of publications in each year containing AERONET-OC in the title and in the abstract, for a total of 124 publications. Figure A2 shows the yearly number of citations, for a total of 3101 citations. In the sole year 2023 publications related to AERONET-OC were cited 655 times.

**Figure A1.** Number of publications in each year containing AERONET-OC in the title and in the abstract.

**Figure A2.** Number of citations in each year to publications containing AERONET-OC in the title and in the abstract.
Annex 2. Uncertainties associated with measurements

AERONET-OC $L_{\text{wn}}(\lambda)$ uncertainties were evaluated applying metrology principles, following the “Guide to the Expression of Uncertainty in Measurement” (GUM; JCGM 2008). According to the GUM, the standard uncertainty associated with a measured quantity $y$ indirectly determined from other quantities through a measurement model $y = f(x_1, ..., x_n)$ can be obtained propagating the uncertainties of each model input quantity through the first-order expansion of Taylor series (omitting all correlations):

$$u^2(y) = \sum_{i=1}^{N} \left( \frac{\partial f}{\partial x_i} \right)^2 u^2(x_i).$$

For AERONET-OC $L_{\text{wn}}(\lambda)$, the main uncertainty sources affecting the quantities included in the measurement equations in Section 3 were taken into account, i.e.:

- absolute radiometric calibration ($u_{\text{ac}}$) affecting $L_i(\lambda)$ and $L(\lambda)$
- instrument sensitivity change during its deployment ($u_{\text{ac}}$) affecting $L_i(\lambda)$ and $L(\lambda)$
- data reduction minimizing the impact of wave perturbations and wave perturbation representation affecting $\rho$ factor ($u(\rho)$)
- environmental variability ($u_{\text{env}}$) affecting $L_i(\lambda)$ and $L(\lambda)$
- corrections for illumination conditions $u(C_i)$ and bidirectional effects $u(C_{\text{bd}})$ affecting $L_{\text{wn}}(\lambda)$

The total uncertainties affecting $L_{\text{wn}}(\lambda)$ values ($u(L_{\text{wn}})$), were thus calculated at relevant all centre-wavelengths $\lambda$ according to:

$$u^2(L_{\text{WN},i}) = (C_{\text{Q,i}} C_{\text{A,i}})^2 u^2(L_{\text{W},i}) + (L_{\text{W},i} C_{\text{A,i}})^2 u^2(C_{\text{Q,i}}) + (L_{\text{W}} C_{\text{Q}})^2 u^2(C_{\text{Q}});$$

where $u(L_{\text{WN},i})$ is the spectral uncertainty value affecting $L_{\text{wn}}(\lambda)$ values, i.e.,

$$u^2(L_{\text{W},i}) = u^2(L_{T}) + u^2(L_i) \rho^2 + u^2(\rho)L_i^2$$

where $u(L_{T,i})$ and $u(L_{i})$ are the uncertainty values affecting $L_{T}(\lambda)$ and $L_i(\lambda)$ respectively, which include $u_{\text{ac}}, u_{\text{sc}}$ and $u_{\text{wn}}$. The uncertainty values were calculated for both $L_{\text{Chla}}^{\text{OCT}}$ and $L_{\text{IRL}}^{\text{OCT}}$ data, taking into account alternatively the uncertainties affecting the two methods used for the BRDF effects correction (Talone et al., 2018).

Both absolute and relative values calculated for $u(L_{\text{Chla}}^{\text{OCT}})$ and $u(L_{\text{IRL}}^{\text{OCT}})$ are shown for a few sites (for which long enough time-series were available) in the following tables. Level-2 quality data from CE-318T instruments only were included in the calculation. The methodology is further detailed and discussed in Gergely & Zibordi (2014) and Cazzaniga & Zibordi (2023).

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Table A1. Relative $u_{\text{rel}}(L_{\text{wn}})$ and absolute $u(L_{\text{wn}})$ (in units of mW cm$^{-2}$ sr$^{-1}$ μm$^{-1}$) uncertainties values for $L_{\text{Chla}}^{\text{OCT}}$ and $L_{\text{IRL}}^{\text{OCT}}$. 
Table A2. Relative $u(\%)(L_{WN})$ and absolute $u(L_{WN})$ (in units of mW cm$^{-2}$ sr$^{-1}$ μm$^{-1}$) uncertainties values for $L_{WN}^{top}$

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