Description and Access to AERONET-OC data

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Introduction

The fundamental satellite ocean color data product is the spectral normalized water-leaving radiance $L_{WN}^{\lambda}$ determined as a function of wavelength $\lambda$ in the visible and near-infrared spectral regions after removing the atmospheric perturbations from top-of-the-atmosphere radiance. *In situ* $L_{WN}^{\lambda}$ is essential for the indirect calibration of space systems (i.e., system vicarious calibration), the validation of satellite data products, and the development of bio-optical models for determining high-level data products (e.g., the concentration of chlorophyll-a). *In situ* $L_{WN}^{\lambda}$ is generally produced from optical radiometers deployed on platforms like buoys (e.g., Clark et al. 1997, Clark et al. 2002, Antoine et al. 2008), towers (e.g., Zibordi et al. 2006), and research vessels (e.g., Werdell and Bailey 2005).

Field radiometric measurements of $L_{WN}^{\lambda}$ rely on both above–water and in–water methods (Zibordi and Voss, 2010). Above–water radiometry has become a consolidated measurement methodology after the theoretical works of Mobley (1999) and Fougnie et al. (1999), and the following experimental activities of Toole et al. (2000), Hooker et al. (2002a), Zibordi et al. (2002), and Deschamps et al. (2004). Most of the published above–water methods require determining the spectral water–leaving radiance $L_w^{\lambda}$ from measurements of the total radiance, $L_T^{\lambda, \theta, \phi}$, (which includes water–leaving, sky–glitter and sun–glint radiance contributions) and of the diffuse radiance from the sky, $L_d^{\lambda, \theta', \phi}$ (i.e., sky radiance). Current measurement protocols define the relative azimuth with respect to the sun $\phi$, and viewing angles $\theta$ and $\theta'$ (Zibordi et al. 2004, Hooker et al. 2004, Deschamps et al. 2004) chosen to minimize environmental perturbations (e.g., wave effects). The equivalence of in– and above–water methods was shown and discussed with the support of data collected from ships and fixed platforms (e.g., Hooker et al. 2004 and Zibordi et al. 2004).

The Ocean Color component of the Aerosol Robotic Network (AERONET-OC) is a component of AERONET (Holben et al. 1998), a federated instrument network and data archive managed by the Goddard Space Flight Center (GSFC) of the U.S. National Aeronautics and Space Administration (NASA), and specifically conceived to support aerosol investigations through standardized instruments and methods (Holben et al. 2001). Similar to AERONET, AERONET-OC relies on NASA’s commitment for field instruments calibration, data processing and archiving. These activities are complemented by independent actions focused on establishing and maintaining CE-318 modified sun-photometers at coastal sites of interest for individual investigators or research institutions. These modified sun-photometers, called SeaWiFS Photometer Revision for Incident Surface Measurements (SeaPRISM), have the capability of performing autonomous above–water radiometric measurements in addition to the usual atmospheric measurements.

Key features of AERONET-OC are: *i.* near-real time data collection and processing (i.e., within a few hours); *ii.* use of standardized instruments, calibration procedure and data processing; *iii.* open access to measurements and products through a specified data policy. The primary data product of AERONET-OC is $L_{WN}$ at wavelengths suitable for satellite ocean color applications. An additional product is the aerosol optical thickness, $\tau_a$, complemented by phase function, particle size distribution and single scattering albedo of aerosols, all having potential importance to assess the performance of the atmospheric correction process applied to satellite data.
The quality assurance of $L_{WN}$ includes checking for: \textit{i.} cloud contamination; \textit{ii.} high variance of multiple sea- and sky-radiance measurements utilized for computing $L_{WN}$; \textit{iii.} elevated differences between pre- and post-calibrations of SeaPRISM sun-photometers; and \textit{iv.} spectral inconsistency of $L_{WN}$ data \citep{DAlimonte2006}. Estimated uncertainties of \textit{in situ} $L_{WN}$ data are 4-5\% in the blue-green spectral regions and \textasciitilde{}8\% in the red, for moderately turbid waters \citep{Zibordi2009}. These have been determined accounting for contributions from: \textit{i.} absolute calibration; \textit{ii.} change in instrument sensitivity during each deployment period; \textit{iii.} corrections for the off-nadir viewing geometry and the anisotropy of the seawater light field; \textit{iv.} variability in specific parameters required for the determination of $L_{WN}$ \citep[e.g., wind speed, surface reflectance, diffuse atmospheric transmittance]{Zibordi2009}; and finally, \textit{v.} environmental perturbations \citep[e.g., wave effects, changes in illumination and seawater optical properties during measurements]{Zibordi2013}.

The material included in this summary aiming at introducing AERONET-OC data and accessibility, was mostly published in \cite{Zibordi2009,Zibordi2010}, and, \cite{Gergely2013}.

\textbf{The Measurements}

The CE-318 autonomous sun-photometer measures: \textit{i.} the direct sun irradiance $E(\lambda, \theta_{o}, \phi_{o})$ as a function of wavelength $\lambda$, sun zenith angle $\theta_{o}$, and sun azimuth angle $\phi_{o}$, for the retrieval of the atmospheric optical thickness; and \textit{ii.} the sky-radiance $L(\lambda, \theta', \phi)$, in a wide range of directions identified by the viewing angle $\theta'$ and relative azimuth angle $\phi$, for the retrieval of the atmospheric scattering phase function. In addition to these atmospheric observations, SeaPRISM systems perform radiance measurements with a full angle field of view of 1.2\° to determine the total radiance from the sea, $L_{T}(\lambda, \theta, \phi)$, and the sky-radiance, $L_{S}(\lambda, \theta', \phi)$, at relative azimuth angle, $\phi$, and with $\theta = \pi \cdot \theta'$ (see Fig. \ref{fig}). The most recent SeaPRISM system configuration performs ocean color measurements at the 412, 443, 488, 531, 551 and 667 nm center-wavelengths. Additional measurements are performed at 870 and 1020 nm for quality checks, turbid water flagging, and for the application of alternative above-water methods \citep{Zibordi2002}. These center-wavelengths and additionally that at 940 nm, were selected to guarantee basic AERONET atmospheric aerosol and water vapor monitoring capabilities, and to support essential validation activities for current ocean color Earth Observation (EO) systems.

In agreement with assessed measurement schemes, $L_{T}(\lambda, \theta, \phi)$ and $L_{S}(\lambda, \theta', \phi)$ values are determined at $\theta = 40^\circ$ and $\phi = 90^\circ$. Larger $\phi$ values \citep[e.g., $\phi = 135^\circ$;][]{Mobley1999}, which are considered more appropriate than $\phi = 90^\circ$ for above-water observations, might lead to perturbations in radiometric measurements due to the deployment superstructure itself or its shadow. Details on the SeaPRISM sea-viewing measurement sequence were already given elsewhere \citep{Zibordi2004,Zibordi2009}. However, a summary is also provided here for the benefit of completeness.

Each SeaPRISM sea-viewing measurement sequence, which is executed every 30 minutes within \pm{} 4 hours around the local noon, comprises:

\begin{itemize}
  \item \textit{i.} A series of direct sun measurements $E(\lambda, \theta_{o}, \phi_{o})$ acquired at all channels for the determination of the aerosol optical thickness $\tau(\lambda)$, a quantity required for the computation of $L_{WN}(\lambda)$;
  \item \textit{ii.} A sequential set of $N_{T}$ sea-viewing radiance measurements for determining $L_{T}(\lambda, \theta, \phi)$ and of $N_{S}$ sky-radiance measurements for determining $L_{S}(\lambda, \theta', \phi)$, serially repeated for each $\lambda$.
\end{itemize}

The sky and sea measurements for determining $L(\lambda, \theta', \phi)$ and $L_{T}(\lambda, \theta, \phi)$ are performed with $N_{T}=3$ and $N_{S}=11$, respectively: the larger number of $N_{T}$ measurements, compared to $N_{S}$, is suggested by the higher environmental noise (mostly produced by wave perturbations) affecting the former measurements during clear-sky.
Data processing for the determination of $L_{\text{sw}}(\lambda)$ is only applied to measurement sequences fulfilling the following criteria: i. there is no missing value; ii. dark values are below a given threshold; iii. measurements are performed with $\phi_0$ values included within site-dependent limits to minimize superstructure perturbations in $L_{\text{s}}(\lambda, \theta, \phi)$; iv. aerosol optical thickness data have been determined and v. wind speed is lower than 15 m s$^{-1}$.

For each measurement sequence qualified for the data processing, $L_{\text{s}}(\lambda, \theta', \phi)$ is determined by simply averaging the $N_{\text{s}}$ sky-radiance data. Differently, $L_{\text{s}}(\lambda, \theta, \phi)$ is determined from the average of a fixed percent of the $N_{\text{T}}$ sea-radiance measurements exhibiting the lowest radiance levels (i.e., 2 out of 11 in the case of SeaPRISM). This approach has been suggested by independent studies (Hooker et al. 2002, Zibordi et al. 2002) which highlighted the need for an aggressive filtering of above-water measurements to minimize the perturbing effects of sea surface roughness in $L_{\text{s}}(\lambda, \theta, \phi)$.

The water-leaving radiance $L_{\text{w}}(\lambda, \theta, \phi)$ (i.e., the radiance emerging from the sea quantified just above the sea surface) is computed from $L_{\text{s}}(\lambda, \theta, \phi)$ and $L_{\text{s}}(\lambda, \theta', \phi)$ as

$$L_{\text{w}}(\lambda, \theta, \phi) = L_{\text{s}}(\lambda, \theta, \phi) - \rho(\theta, \phi, \theta_0, W) L_{\text{s}}(\lambda, \theta', \phi) ,$$

where $\rho(\theta, \phi, \theta_0, W)$ is the sea surface reflectance as a function of the measurement geometry identified by $\theta$, $\phi$, $\theta_0$, and of the sea state conveniently expressed through the wind speed $W$ (Mobley 1999).

The normalized water-leaving radiance $L_{\text{wn}}(\lambda)$ is determined from $L_{\text{w}}(\lambda, \theta, \phi)$ as

$$L_{\text{wn}}(\lambda) = L_{\text{w}}(\lambda, \theta, \phi) C_{\text{Q}}(\lambda, \theta, \phi, \theta_0, \tau_a, \text{IOP}, W) C_{\text{A}}(\lambda, \theta_0, \tau_a, D)$$

where the term $C_{\text{Q}}(\lambda, \theta, \phi, \theta_0, \tau_a, \text{IOP}, W)$ is introduced to remove the dependence from the viewing geometry and the bidirectional effects in $L_{\text{w}}(\lambda, \theta, \phi)$, while the term $C_{\text{A}}(\lambda, \theta_0, \tau_a, D)$ removes the basic dependence on sun zenith, atmosphere and sun-earth distance.

Specifically

$$C_{\text{Q}}(\lambda, \theta, \phi, \theta_0, \tau_a, \text{IOP}, W) = \frac{\mathcal{R}_0}{\mathcal{R}(\theta, W)} \frac{Q(\lambda, \theta, \phi, \theta_0, \tau_a, \text{IOP})}{Q(\lambda, \theta, \tau_a, \text{IOP})} \left( \frac{f(\lambda, \theta_0, \tau_a, \text{IOP})}{Q(\lambda, \theta_0, \tau_a, \text{IOP})} \right)^{-1}$$

and

$$C_{\text{A}}(\lambda, \theta_0, \tau_a, D) = \left( D^2 t_d(\lambda) \cos \theta_0 \right)^{-1} .$$

The quantities $\mathcal{R}(\theta, W)$ and $\mathcal{R}_0$ (i.e., $\mathcal{R}(\theta, W)$ at $\theta=0$) account for sea surface reflectance and refraction, and primarily depend on $\theta$ and $W$. The quantities $Q(\lambda, \theta, \phi, \theta_0, \text{IOP})$, $Q(\lambda, \theta_0, \tau_a, \text{IOP})$ and $Q_d(\lambda, \tau_a, \text{IOP})$ are the so-called $Q$-factors at viewing angle $\theta$, at nadir (i.e., $\theta=0$) and at nadir with sun

\[\begin{align*}
E_s(\lambda, \theta_0, \phi_0) \\
L_s(\lambda, \theta, \phi) \\
L_T(\lambda, \theta, \phi)
\end{align*}\]
at the zenith (i.e., $\theta=0$ and $\theta_b=0$), respectively. The $Q$-factor describes the anisotropic distribution of the in-water radiance field and mostly depends on $\theta, \varphi, \theta_b$, the aerosol optical thickness ($\tau_a$), and the seawater inherent optical properties (IOPs). The quantities $f(\lambda, \theta_b, \tau_a, \text{IOP})$ and $f(\lambda, \tau_a, \text{IOP})$ for the sun at the zenith, relate the apparent optical properties (and specifically the irradiance reflectance) to IOPs (Morel et al. 2002). It is recalled that for optically complex coastal waters the quantity $f$ is generally replaced by $f'$ (Loisel and Morel 2001). The term $D^2$ in Eq. 4 accounts for the variations in the Sun-Earth distance as a function of the day of the year, while the quantity $t_{a}(\lambda)$ is the atmospheric diffuse transmittance (Deschamps et al. 2004) computed utilizing $\tau_a(\lambda)$ determined from SeaPRISM measurements.

The values of $\mathcal{Q}(\theta, W)$, $Q(\lambda, \theta, \varphi, \theta_b, \tau_a, \text{IOP})$ and $f(\lambda, \theta, \tau_a, \text{IOP})/Q(\lambda, \theta, \tau_a, \text{IOP})$ applied in (3) and (4) are determined from look-up tables produced for oceanic waters, and clear sky conditions with $\tau_a=0.2$ at 550 nm, for various discrete values of $\lambda, \theta, \varphi, \theta_b$, and chlorophyll $a$ concentration ($\text{Chla}$) expressing the dependence on IOPs (Morel et al., 2002). It is anticipated that the center-wavelengths included in the look-up tables are $\lambda=412.5, 442.5, 490, 510, 560, and 660$ nm.

The Chla value is first assumed equal to $1$ mg m$^{-3}$ and successively estimated through an iterative procedure making use of regional band-ratio algorithms based on remote sensing reflectance $R_a(\lambda)$ (where $R_a(\lambda) = \text{L}_{\text{WN}}(\lambda) / \text{E}_{\text{d}}(\lambda)$ with $\text{E}_{\text{d}}(\lambda)$ extra-atmospheric sun irradiance). The process, which requires successive re-computations of equations 2–4, generally provides a convergence better than $0.1\%$ on the Chla value at the first iteration. It is finally pointed out that, due to the current lack of look-up data at center-wavelengths close to 870 and 1020 nm, the related measurements are processed assuming $C_{\Omega}(\lambda, \theta, \varphi, \theta_b, \tau_a, \text{IOP}, W)$ equal to 1.

Actual measurements of $W$, when available, are used for the data processing. Alternatively, data from National Centers for Environmental Prediction (NCEP) are applied.

The use of Chla to express the dependence of bi-directional effects on IOPs is mostly suitable for Case-1 waters (i.e., chlorophyll dominated waters). Nevertheless it is applied to all AERONET-OC data due to the lack of an alternative consolidated correction scheme for Case-2 waters (i.e., sediment or yellow substance dominated waters). Implications on the adoption of such a correction scheme are addressed in the uncertainty analysis (see Zibordi et al 2009 and, Zibordi and Gergely 2014).

**The Measurement sites**

AERONET-OC sites are located in coastal regions to take advantage of available and accessible offshore grounded structures. Deployment requirements for the collection of measurements suitable for ocean color validation activities are summarized as follows: i. fixed deployment platforms allowing for measurement of the direct sun irradiance through accurate sun-tracking; ii. superstructures with height and shape minimizing contamination of the measuring system by seaspray; and iii. deployment positions allowing unobstructed sea observations at the maximum possible distance from the superstructure at the time of satellite overpass. Recalling that the minimization of superstructure perturbations in above-water radiometric measurements requires observations of the sea surface at distances at least equal to the superstructure height (Hooker and Zibordi 2005), the measurement systems are generally deployed from dedicated extensions of the main structure.

Any AERONET-OC site should ideally be at a distance from the mainland suitable to assume that the adjacency effects are negligible in remote sensing data. It is recalled that the adjacency effects (Bulgarelli and Zibordi 2013) are produced by the different reflectance of nearby surfaces, and the magnitude of the related perturbations in remote sensing data is a function of the spectral reflectance of surfaces and of the optical properties of the atmosphere (mostly the aerosol type and load). As a rule of thumb, any distance greater than 5-10 nautical miles is considered suitable. This has been confirmed by analysis on adjacency effects performed at various AERONET-OC sites with synthetic transects of satellite derived $\tau_a(870)$ and $\text{L}_{\text{WN}}(670)$ climatological values (Zibordi et al. 2009b).

However, provided that the adjacency effects are accounted for during the analysis of remote sensing data, sites at close distance from the main land (i.e., less than 5 nautical miles) are still relevant for the validation of remote sensing products.
A further requirement for ideal AERONET-OC sites, is a water depth sufficient to neglect the bottom effects. A simple scheme for quantifying these effects has been proposed by Zibordi et al. (2009c) accounting for the seawater optical properties as defined through the diffuse attenuation coefficient $K_d$ and the irradiance reflectance $R$.

Table 1. Current AERONET-OC sites. The years in brackets indicate the operation period. The AAOT, GDLT, HLT, AABP, GLR and GLT are commonly indicated as Venise, Gustav Dalen Tower, Helsinki Lighthouse and Abu-Al-Bukhoosh, Gloria and Galata within the AERONET Ocean Color web page (http://aeronet.gsfc.nasa.gov). MVCO, COVE, Palgrunden, LUCINDA, LISCO, WaveCIS_Site_CSI_6, USC, GOT, Gageocho, Ieodo and Zeebrugge indicate the homonymous sites.
Applications

AERONET-OC, a network of standardized instruments operating at sites representative of different water types, relying on a consistent and assessed measurement protocol, calibration source, and processing code, provides an excellent solution to the validation of satellite ocean color data products (Zibordi et al. 2006). Still, additional regional applications are the vicarious calibration of satellite data (Mélin and Zibordi 2010), and the minimization of cross-mission uncertainties and biases (D’Alimonte et al. 2008, Zibordi et al. 2009b).

Figure 3. Scatter plots of MODIS-A (MOD-A) versus AERONET-OC (PRS) $L_{WN}$ match-up values at selected center-wavelengths for the AAOT site. $N$ indicates the number of match-ups, $L_{WN}$ and $rmsd$ are in units of mW cm$^{-2}$ μm$^{-1}$ sr$^{-1}$, $|\psi|$ is the mean of absolute percent differences while $\psi$ is the mean of percent differences, and $r^2$ is the determination coefficient. The right panel in the second row displays all the AERONET-OC $L_{WN}$ spectra collected at the AAOT site between 2002 and 2014.
Figure 3 illustrates the application of in situ AERONET-OC radiometric data to the validation of satellite ocean color derived spectral normalized water-leaving radiance $L_{WN}(\lambda)$. Specifically, it displays scatter plots of MODIS and in situ $L_{WN}$ matchups for the AAOT in the northern Adriatic Sea for the period 2002-2014. Plots show larger biases between satellite and in situ data at the red wavelength likely due to larger uncertainties introduced by the atmospheric correction process in the specific coastal area.

**Data handling and access**

AERONET-OC makes full use of the existing AERONET data acquisition, processing, archiving, and distribution infrastructure managed by NASA at GSFC (Holben et al. 1998). Data acquisition mechanisms primarily include transmitters for relaying measurements to geostationary meteorological satellites (GOES, METEOSAT or GMS) or the internet for direct transfer of data to the AERONET system. The latter then processes SeaPRISM measurements in near real-time along with ancillary data input (e.g., NO$_2$, O$_3$, surface pressure and $W$). Raw data and derived products at the various levels are stored in a specific database for each instrument on a hourly basis and are publicly available through the AERONET web interface (http://aeronet.gsfc.nasa.gov) under a specified data policy (i.e., Due to the research and development phase characterizing AERONET-Ocean Color, use of these data requires offering co-authorship to the Principal Investigator. Additionally, the original source of data, i.e. http://aeronet.gsfc.nasa.gov/new_web/ocean_color.html, needs to be acknowledged).

The AERONET web site provides aerosol microphysical and optical property products (e.g., optical thickness, size distribution, phase function and single scattering albedo), together with $L_{WN}$ data for each SeaPRISM site. Product map browsers provide a geospatial perspective of the available AERONET data for each site. Web interfaces provide site information, data plots, and support data download. Aerosol and ocean color derived products are displayed in daily, monthly, and yearly plots. Each data product may be browsed and downloaded by product type, date, and quality level. Additional related Earth science data products, such as atmospheric and oceanic satellite retrievals and 7-day back-trajectory analysis products, are also available for most AERONET sites.

Fully quality-assured (i.e., level 2.0) AERONET-OC data imply: (i) existence of complete sequences of $L_T(\lambda)$, $L_i(\lambda)$ and $E_s(\lambda)$ spectral measurements; (ii) wind speed $W<15$ m s$^{-1}$; (iii) existence of cloud-screened level 2 AERONET $\tau_a(\lambda)$ data; (iv) exclusion of $L_{WN}(\lambda)$ spectra exhibiting negative values; (v) low variance in measurement sequences of $L_i(\lambda)$ indicating stable illumination conditions and of $L_T(\lambda)$ indicating small wave and foam perturbations; (vi) differences lower than 5 % between pre- and post-deployment absolute radiometric calibration coefficients; (vii) self-consistency of the shape of $L_{WN}(\lambda)$ spectra; (viii) finally, exclusion of dubious data as a result of a spectrum-by-spectrum screening by an experienced scientist. These criteria lead to acceptance rates of $L_w(\lambda)$ and $L_{WS}(\lambda)$ data varying between 3 % and 17 % (Zibordi et al. 2009). The different rates are mostly due to site-specific factors like restrictions imposed by the instrument set-up, cloudiness or quality of data transmission.

Metadata for AERONET-OC Level-2 data from sites maintained by the Joint Research Centre, are available at:

- Discovery Client: [http://data.jrc.it/discovery/AERONET-OC](http://data.jrc.it/discovery/AERONET-OC)
- Resource Browser: [http://data.jrc.it/proxybrowser/AERONET-OC](http://data.jrc.it/proxybrowser/AERONET-OC)

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References


