Advanced guidance to atmospheric correction for use over coastal and inland waters

In order to estimate key parameters linked to water quality from remotely sensed images, two steps need to be considered: 1/ Atmospheric correction and 2/ Application of bio-optical algorithms. We focus here on the first step: atmospheric correction. Introductory guidance on the basis of atmospheric correction and the different types of methods, intended for a less experienced audience, can be found in our companion document.

The purpose of the atmospheric correction process is to remove the contribution of the atmosphere to the signal measured by the remote sensor, leading to the estimation of the remote sensing reflectance, i.e. the ratio of the water-leaving radiance over downwelling plane irradiance. The contribution of the atmosphere includes the scattering and absorption of sunlight by air molecules (Rayleigh scattering), aerosols and trace gases, as well as the coupling between air molecules and aerosols. Rayleigh scattering and the absorption by atmospheric gases can be estimated from ancillary data (Mobley et al., 2016).

Note that we do not consider the contribution of the air-water interface (from foams and the reflection of the Sun and skylight) in this user's guide. Those contributions can also be estimated from ancillary data and viewing geometry (Mobley et al., 2016).

Over open ocean waters (or bodies of water with low to moderate concentration of chlorophyll-*a*), the water can be considered totally absorbing (black pixel assumption) in the near-infrared (NIR) bands so the measured signal at the top-of-the atmosphere is only due to aerosols (after removing the influence of the gases, the scattering due to the air molecules and the contribution of the air-water interface). Using the NIR bands allows aerosol models and optical properties to be estimated, while these can in turn be used to estimate the atmospheric contribution to the measured signal in the visible bands. But in more optically-complex waters, such as turbid waters found in near-coastal and inland locations, the black pixel assumption is not valid, as the water cannot be considered totally absorbing in the NIR because backscattering by suspended particles often results in non-zero water-leaving reflectance in these bands (IOCCG, 2010).

To overcome this challenge, many atmospheric correction algorithms were developed in the past two decades for dedicated ocean color (SeaWiFS, MODIS-AQUA, MERIS, VIIRS, OLCI) and high-spatial resolution space-borne sensors (OLI, MSI). The following table provides a classification of these algorithms:

Table 1. Overview of atmospheric correction algorithms based on their main hypothesis and inversion methods

Family of algorithms	Description	Advantages	Disadvantages	References
Correction of the NIR contribution of the water bodies	Estimation of the contribution of the water in the NIR through an iterative process	Based on semi-analytical models of the atmosphere and water bodies, fast processing	Needs a bio-optical model in the NIR, needs aerosol models, often based on radiative transfer simulations, processing of the images on a pixel-per-pixel basis, i.e. the neighborhood context is not considered (per-pixel method)	Ahn et al., 2016; Bailey et al., 2010; Ibrahim et al., 2019; Jaelani et al., 2015; Lavender et al., 2005; Moore et al., 1999; Stumpf et al., 2003
Homogeneity of the aerosol and/or water components	Use of sub-region of the images to determine the aerosol component with the hypothesis of the homogeneity of the atmosphere (and/or of the water component) over the sub-region	Based on simple relations to determine the aerosol component, the sub-region is considered as a whole	Hypothesis of homogeneous atmosphere not always true over coastal or inland waters, several steps to get the water component can be needed, extrapolation of aerosol contribution can be wrong, ratios of aerosol and/or water components at two bands not always constants for very turbid waters and/or absorbing aerosols	De Keukelaere et al., 2018 ; Hu et al., 2000; Ruddick et al. 2000, 2006; Sterckx et al., 2015; Vanhellemont and Ruddick, 2021; Wang et al., 2021; Zhao et al., 2021
Use of Short-Wave-Infra-Red bands (SWIR: 1000-2400 nm)	Based on the black pixel assumption, i.e. the water body is fully absorbent in the SWIR so the total signal measured at the top of the atmosphere is only equal to the aerosol component, estimation of the aerosol models and properties, use of this information to estimate the water component in the visible bands	Based on historical AC for open ocean waters, no assumption of the water bodies component, easy to implement	The Signal-to-Noise ratio of current space-borne sensors is not designed for ocean applications, needs aerosol models, based on Look-Up-Tables or radiative transfer simulations, per-pixel based	Chen et al., 2014; He and Chen, 2014; Wang and Shi, 2005; Wang and Shi, 2007; Wang, 2007; Shi and Wang, 2009

Neural-Networks-based (NN)	Direct inversion of the total signal measured by the remote sensor to estimate the water component by artificial neural networks	Direct inversion, fast inversion (once the training of the network is over)	Limited to range of validity of the data used to train the NN, per-pixel based, needs simulations of the top-of-atmosphere signal, i.e. needs aerosol and bio-optical models	Doerrfer and Schiller, 2007; Fan et al., 2006, 2020; Schroeder et al., 2007
Use of Ultra-Violet bands (UV)	Use of UV bands (<400nm) to estimate the aerosol component, hypothesis that the water body is totally absorbing in UV bands, empirical relationships used to estimate the aerosol component in the visible from UV bands white spectrum of the aerosol component	Based on historical AC for open ocean waters, no assumption of the ocean component, easy to implement	Only OLCI has a band at 400 nm, no past and current space-borne sensors have bands below 400 nm (PACE will have bands between 350 and 400 nm), valid only if CDOM- or TSM-dominated waters, empirical relationships between UV and visible bands, per-pixel based	Oo et al., 2008; He et al., 2012; Wang and Jiang, 2018
Coupled ocean/atmosphere inversion	Based on spectral optimization techniques, aerosol and water optical properties are iterated to match the exact total signal, usually the radiance measured at sensor level, calculation is based on empirical, semi-analytical or physical models to relate optical properties with the sensor signal	This method is applied over the largest range of sensors (no requirements on e.g. specific bands), and over a large range of environmental conditions, in dependency on the level of physical implementation and supported range of optical properties, up to neighborhood context is considered, output can be directly validated by inherent measurements without approximations	Labor-intensive to develop high levels of implementation, and may require more processing time in dependency on realization, lower physical implementation results in restriction	Brajard et al., 2006, 2012; Chomko and Gordon, 1998, 2001; Jamet et al., 2004; Kuchinke et al., 2009; Pan et al., 2017; Shi et al., 2016; Stamnes et al., 2003; Steinmetz et al., 2011

Statistical relationships to estimate the aerosol and water components	Based on different statistical relationships, such as PCA, the aerosol component is modelled	No need of aerosol and/or bio-optical models	Validity of the statistical relationships, per-pixel based	Gossn et al., 2019, 2021; He and Chen, 2014; Ibrahim et al., 2019; Saulquin et al., 2016; Shanmugam, 2014; Singh and Shanmugam, 2014
Dark pixel	Target in the scene of interest for which the water signal is negligible at least in one band, use of the signal from this target to estimate the atmospheric component of the signal	Image-based	Needs aerosol models, no dark pixel can be found in the region of interest	Vanhellemont, 2019; Vanhellemont and Rudidck, 2018, 2021
Multi-observations	Use of two or more images acquired on the same day to estimate aerosol optical properties, use of polarimetry from several observation angles	More accurate estimation of the aerosol properties	Need of a polarimeter, assumption that the ocean doesn't change over the day	Gao et al., 2021; Stamnes et al., 2018; Xu et al., 2016; Wang et al., 2020

Other issues can occur over coastal and inland waters that need to be considered or at least to be aware of. These main issues are not considered in the standard processing of the images. The corresponding pixels are usually flagged. The two main issues are:

1) **Absorbing aerosols and trace gases** such as from urban pollution or terrigenous dust and black or biogenic carbon (Al Shehhi et al., 2017; Banzon et al., 2009; Brajard et al., 2008; Chomko and Gordon, 1998, 2001; Frouin et al., 2019; Kuchinke et al., 2009; Mao et al., 2020; Moulin et al., 2001a, 2001b; Nobileau and Antoine, 2005; Shehhi et al., 2017; Zhang et al., 2019; Tzortziou et al. 2014; 2018). Absorbing aerosols, especially dust, are not detectable using only NIR bands as they have a spectral dependency and as an aerosol model cannot be exactly identified using only NIR bands (Frouin et al., 2019; Gordon et. al. 1997). Atmospheric NO_2 pollution can be high and highly variable near urban coastal regions, and NO_2 absorption peaks at 412 nm, complicating retrievals of Chl*a* and CDOM in coastal waters (Ahmad et al. 2007; Gao et al, 2009; Tzortziou et al 2018).

2) **Adjacency effects** (Bulgarelli et al., 2014, 2017, 2018a, b, 2020; Kiselev et al., 2015; Santer and Schmechtig, 2000; Sterckx et al., 2015). The proximity of land when observing coastal and inland waters adds a component to the signal measured by a satellite sensor. This leads to an over-estimation of the aerosol component and so to an under-estimation of the contribution of the water bodies (Frouin et al., 2019; IOCCG report #18).

Studies providing comparisons of AC over coastal and inland waters can be found. They provide evaluations based on *in-situ* measurements and guidance for using AC:

- For ocean color sensors: Goyens et al. (2013), IOCCG report #10 and in preparation, Jamet et al. (2011)
- For high-spatial resolution sensors: Pahlevan et al. (2021), Xu et al. (2020)

Codes and softwares are available: SeaDAS (https://seadas.gsfc.nasa.gov/), SNAP (https://step.esa.int/main/download/snap-download/), ACOLITE (https://odnature.naturalsciences.be/remsem/software-and-data/acolite), Polymer (https://www.hygeos.com/polymer), iCOR (https://remotesensing.vito.be/case/icor), OC-SMART (http://wPOtherww.rtatmocn.com/oc-smart/).

Authorship information

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