Remote Sensing of Environment 216 (2018) 586–597

Contents lists available at ScienceDirect

Remote Sensing of Environment

journal homepage: www.elsevier.com/locate/rse

Atmospheric correction of metre-scale optical satellite data for inland and coastal water applications

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ARTICLE INFO

Keywords:
Remote sensing
Metre-scale resolution
Water colour
Water quality
Aerosol correction
Automation

ABSTRACT

A new atmospheric correction (AC) method for aquatic application of metre-scale resolution (MR) optical satellite imagery is presented in this article, and demonstrated using images from the Pléiades constellation. MR satellites are typically operated privately and imagery can be costly. However in recent years, the price of individual acquisitions has dropped and their revisit times have improved, making them promising tools for remote sensing of inland and coastal waters. Due to the spatial resolution requirements of these satellites, the bands on the sensors are relatively wide (60–140 nm on Pléiades) in order to achieve an acceptable signal to noise ratio. This bandwidth and the limited number of bands can pose problems for the AC as the water signal may not be negligible in any band, especially over turbid waters. Since the MR sensors have a relatively narrow swath (20 km for Pléiades) the atmosphere can generally be assumed to be homogeneous over a scene or sub-scene. This assumption allows the atmospheric path reflectance (ρ_{path}) to be estimated from multiple targets in the scene, which are selected according to the lowest observed top-of-atmosphere reflectances (ρ_{TOA}) in all bands. Rather than using pre-defined "dark" bands (e.g. in the NIR and SWIR) such as is common in other water-focused AC methods, the best band is selected automatically, i.e. the one yielding the lowest ρ_{path}. This criterion avoids unrealistic negative ("overcorrected") reflectances after the AC. Furthermore, for inland waters the NIR bands are usually affected by scattering from adjacent land and vegetation pixels, resulting in unrealistic ρ_{path} when used in the AC. The spatial resolution of the sensors is used as an advantage here, since ground-level object shadows (e.g. from trees and buildings) can be spatially resolved and are usually the pixels selected by the automated procedure for the determination of ρ_{path}. In fact, it is proposed that using these shadow pixels gives better performance than using any kind of water pixel for these broad-band MR sensors. The method is demonstrated using several Pléiades images, showing good performance in retrieval of the aerosol optical thickness (τ_a) for an urban (Brussels) and a coastal (Zeebrugge) site. Match-ups with water reflectances measured at the Zeebrugge AERONET-OC station show promising performance, although there is a significant spectral mismatch between the bands on the satellites and the CIMEL radiometer. Pléiades imagery of Zeebrugge reveals a turbid wake associated with the MOW1 measurement station, which opens perspectives of using MR satellites for the characterisation of monitoring and validation sites. Future work includes the application to other MR satellites (e.g. WorldView) and the evaluation for mass processing of open access high resolution (10–60 m) satellite data from Landsat and Sentinel-2.

1. Introduction

In the last few years the impacts of human activities on the coastal environment such as offshore construction and dredging have been directly observed from space with imagery from Landsat 8 (2013-present) and Sentinel-2 (2015-present). These missions were designed for land applications, but they sparked a new interest from the water quality remote sensing community for high resolution imagery, not only due to the improved radiometric quality compared to older comparable missions (Pahlevan et al., 2014; Franz et al., 2015), but also thanks to the open data policies employed by the space agencies. Landsat data are well-suited for turbidity mapping in the coastal zone (Vanhellemont and Ruddick, 2014), and has shown some promise for mapping chlorophyll-a concentration in phytoplankton dominated systems (Franz et al., 2015). Sentinel-2 has an additional band in the red-edge (at 705 nm), which allows for the estimation of chlorophyll-a absorption in the red band, and hence chlorophyll-a concentration in turbid waters (Chen et al., 2017; Toming et al., 2016; Vanhellemont

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https://doi.org/10.1016/j.rse.2018.07.015
Received 12 March 2018; Received in revised form 9 July 2018; Accepted 12 July 2018
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and Ruddick, 2016), at unprecedented resolution. With the capability of retrieving chlorophyll-a concentration in the first nautical mile from the coast, Sentinel-2 can significantly contribute to the monitoring requirements of the European Union's Water Framework Directive and amendments (European Commission, 2000).

At the spatial resolution provided by these sensors (10–60 m) "new" processes can be resolved from space, such as dredging activities (Barnes et al., 2015; Vanhellemont and Ruddick, 2015a) and impacts of offshore construction (Vanhellemont and Ruddick, 2014). In the southern North Sea, shipwrecks were detected in Landsat 8 imagery by analysing turbid tidal wakes (Baeye et al., 2016). Turbid river plumes and estuaries can be analysed in more detail thanks to the high spatial resolution and robust atmospheric correction using shortwave-infrared bands (Brando et al., 2015; Ody et al., 2016; Novoa et al., 2017), and retrieval of various optically active constituents is possible (Concha and Schott, 2016; Olmanson et al., 2016). Intense cyanobacterial blooms have been widely studied using remote sensing data from MERIS (Kutser et al., 2006; Matthews et al., 2010; Wynne et al., 2010) and Landsat (Ho et al., 2017; Vincent et al., 2004). Recently, Landsat data were used to propose a link between the proximity to waters experiencing regular cyanobacterial blooms and the occurrence of Amyotrophic Lateral Sclerosis (ALS) (Torbick et al., 2017). The improved spatial resolution allows for analysis of aquaculture performance and perhaps impacts on the local environment (fish cages and their effects become spatially resolved). Using a combination of the optical and thermal bands on OLI, Landsat 8 data were used to assess suitability for oyster cultivation in estuaries in Maine (Snyder et al., 2017). Similarly, Sentinel-2 derived turbidity and chlorophyll-a concentration were used for studying the physiological response of oyster farms in the Bay of Bourgneuf (Gernez et al., 2017).

Metre-scale resolution (MR, < 1–5 m) satellite imagery (e.g. SPOT, IKONOS, RapidEye, WorldView) has been used for aquatic studies such as coral reef and bathymetry mapping (Stumpf et al., 2003; Hedley et al., 2016), dredging activities, sediment transport applications (Doxaran et al., 2006), and mapping of underwater vegetation (Mumby and Edwards, 2002; Roelfsema et al., 2014; Fritz et al., 2017). There is significant interest from the sediment transport modelling community for high resolution turbidity maps for model validation (Vanlede and Dujardin, 2014), and also from the ocean colour community for validation site characterisation (Vanhellemont and Ruddick, 2015b). Dorji and Fearns (2017) have shown that in regions of high variability and high turbidity the spatial resolution of the sensor is crucial to retrieve accurate estimates of the total suspended solids concentration (TSS). They observed a near seven-fold difference between the maximum TSS derived from WorldView-2 and Aqua/MODIS imagery (spatial resolution respectively 2 and 250 m). With their very high spatial resolution, MR satellites may bridge the gap between in situ, in essence point measurements, and larger scale pixel-averaged satellite observations. Imagery from MR sensors used to be very expensive, but it has dropped significantly in price in the last few years. It is expected to become more and more affordable, especially with the advent of commercial nanosatellite swarms (e.g. the "flocks" of Dove satellites by Planet Labs Ltd.), allowing for broader scale applicability to various problems, including remote sensing of water quality. The high resolution allows for the monitoring of small water bodies with which humans are in regular close contact (recreational or occupational).

The atmospheric correction (AC) of MR images often relies on external measurements of aerosol optical thickness (τ_a), or inputs of manual estimates of τ_a and a typical aerosol model (e.g. FLAASH, harrisgeospatial.com/docs/FLAASH.html). Other relatively crude methods are sometimes used, for example only correcting for Rayleigh scattering, or dark object subtraction (Chavez, 1988). Empirical Line methods estimate a linear relationship between satellite observations and the surface reflectance by using bright and dark (unvegetated and invariant) objects in the scene with known (i.e. measured) or modelled reflectance (Moran et al., 2001). The use of AC methods based on spectral relationships for Dark Dense Vegetation (Kaufman et al., 1997) is not possible for sensors that lack SWIR bands. Recently, a method using cast shadows has been proposed (Schläpfer et al., 2018) showing promise for MR imagery. In several cases, top-of-atmosphere imagery is used as-is. At present, no generic, automated and reliable atmospheric correction tools exist for water applications of MR imagery.

In this paper an automated AC scheme for MR optical satellite imagery is introduced, with good performance over turbid coastal and inland waters in mind. The scheme is entirely image based, and hence does not require external inputs such as τ_a estimates or measurements. The scheme was developed for the Pléiades constellation in particular, but is in essence generic, and can easily be adapted to other MR sensors. MR sensors usually do not have bands where the surface reflectance (ρ_s) is known for certain targets in contrast to Landsat and Sentinel-2 for example, which have SWIR bands (at 1.6 and 2.2 μm), where $\rho_s = 0$ for water, facilitating the AC of extremely turbid waters (Gao et al., 2007; Wang, 2007; Vanhellemont and Ruddick, 2015a). In the algorithm presented here, no band is selected a priori for the AC, and for each scene the "best" band is selected for determining the atmospheric path reflectance (ρ_{path}). Although in first instance good performance for water is the aim, reflectances for both land and water pixels are retrieved. Next to the description of the method, a first validation of the aerosol optical thickness retrieval with AERONET data, and of marine reflectance spectra from an AERONET-OC station is presented using several Pléiades images. The retrieval of water turbidity at very high spatial resolution in and around the port of Zeebrugge is demonstrated, as well as the capability of the method to retrieve spatial variability of τ_a for larger "full swath" images.

2. Data and methods

2.1. Satellite imagery

Pléiades is a two-satellite constellation that provides multi-spectral imagery at 2.8 m spatial resolution in four broad bands, and at 0.7 m in a panchromatic band (Table 1 and Fig. 1). Imagery is typically resampled to 2 m and 0.5 m by the satellite operator. The sensor has a swath width of 20 km, and due to pointability of the satellite, the constellation can offer near-daily revisit time with two satellites in orbit. Six images were used in this paper (see Table 2): two images covering Brussels, obtained from the Belgian Pléiades Archive (pleiades.busoc.be) and four images covering Zeebrugge ordered by RBINS from Airbus Defence and Space (intelligence-airbusds.com). Although this manuscript focuses on Pléiades imagery, the proposed

Table 1
Details on the Pléiades sensor bands. Note that the multispectral bands are typically resampled to 2 m and the panchromatic band to 0.5 m. The SNR lists the Pléiades A/B separately. The relative spectral responses are given in Fig. 1.

Band	Wavelength (nm)	Resolution (m)	F0 ($W\,m^{-2}\,\mu m^{-1}$)	SNR (at 100 $W\,m^{-2}\,sr^{-1}\,\mu m^{-1}$)
Pan	450–900	0.7	1915	152/161
Blue	450–520	2.8	1830	148/150
Green	520–600	2.8	1594	146/165
Red	630–690	2.8	1060	149/156
NIR	760–900	2.8	1548	188/183

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