Remote Sensing of Environment 135 (2013) 202–212

Contents lists available at SciVerse ScienceDirect

Remote Sensing of Environment

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

Unattended processing of shipborne hyperspectral reflectance measurements

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ARTICLE INFO

Article history:
Received 6 June 2012
Received in revised form 14 February 2013
Accepted 4 April 2013
Available online 8 May 2013

Keywords:
Reflectance
Sky radiance
Hyperspectral
Case-2 water
Shipborne monitoring

ABSTRACT

Hyperspectral remote-sensing reflectance (R_{rs}) from above-surface (ir)radiance measurements is derived using a new, automated method that is suitable for use on moving platforms. The sensors are mounted on a rotating platform that compensates for changing solar and ship azimuth angles, optimizing the sensor azimuth for minimal contribution of sky radiance to measured water-leaving radiance. This sea-surface reflectance (ρ_s) lies in the order of 2.5–8% of sky radiance, and is determined through spectral optimization, minimizing the propagation of atmospheric absorption features to R_{rs}. Up to 15 of these gas absorption features are frequently recognized in (ir)radiance spectra under clear and overcast skies. R_{rs} was satisfactorily reproduced for a wide range of simulated Case 2 waters and clear sky conditions. A set of 13,784 in situ measurements collected with optimized viewing angles on the high-absorption, low-scattering Baltic Sea was collected in April and July 2010–2011. The processing procedure yielded a 22% retrieval rate of ρ_s for the field data. The shape of the subsurface irradiance reflectance measurements ($R(0^-)$) measured at anchor stations was well reproduced in above-surface R_{rs} in those cases where the algorithm converged on a solution for ρ_s, except under unstable or weak illumination conditions. Clear-sky conditions resulted in the best correspondence of R_{rs} and $R(0^-)$ and gave the highest (>50%) retrieval rates of ρ_s. Two indices, derived from the available sensor data, are given to describe illumination conditions, and are shown to predict the ability of the algorithm to retrieve R_{rs}.

1. Introduction

Reflectance or water color, measured from submerged (ir)radiance sensors, from poles, rafts, or ships, or from remote (air- or spaceborn) platforms, can be a cost-effective solution for monitoring water quality and aquatic biogeochemical processes. Spectral features in reflectance can be related to the concentrations and inherent optical properties of optically active water constituents (Gordon et al., 1975; Kirk, 1994; Morel, 1980; Preisendorfer, 1976; Tyler, 1960). Satellite-born sensors allow the interpretation of the reflectance properties of the oceans in terms of global biogeochemical cycles (Behrenfeld & Falkowski, 1997; Falkowski et al., 1998). In coastal waters, lakes, and estuaries, remote sensing algorithms for water quality parameters often need to be regionally tuned and validated to yield meaningful results. In these 'optically complex' waters *a priori* knowledge of the reflectance properties of the water body and transmission properties of the atmosphere can be a great asset, helping reduce uncertainties in remote sensing algorithms and atmospheric correction.

Hyperspectral reflectance can be measured from fixed offshore platforms (Zibordi et al., 2006, 2009), moored buoys, or ships, to aid data assimilation with remote sensors and to provide continuous observations under cloud cover. Ship-based installations provide some advantages over stationary platforms: they allow easy access in the home harbor which reduces operational cost, and the wider spatiotemporal coverage from ships compared to stationary platforms yields an attractive diversity in observations to compare against satellite data. However, ship-based systems also face significant platform-specific problems. Whereas stationary platforms allow quality control based on statistics over subsequent recordings, this is not strictly possible from moving platforms where the same water mass is less likely to be observed in consecutive measurements (commercial ferries easily travel at 20 kn $\approx$ 10 m s^{-1}). Further, in order to avoid sun glitter, spray, and ship shadows, close-range reflectance measurements have to be carried out at viewing zenith angle (θ_v) that projects away from the ship, and a viewing azimuth angle φ_v away from the solar azimuth (φ_s) that is sufficiently large to avoid sun glint (Fig. 1). Angles of $\theta_v = 40°$ and $\varphi_v > 90°$ (ideally 135°) are considered suitable (Hooker & Morel, 2003; Mobley, 1999; Mueller et al., 2003). Even under optimized viewing angles, however, sun and sky radiance reflected at the sea surface shows a theoretical variation in the order of 2–6% of the downwelling radiance with varying sea surface roughness (Cox and Munk, 1954a, 1954b; Mobley, 1999). This reflected sky radiance can be of similar magnitude as the upwelling radiance in clear and moderately turbid waters and therefore constitutes the main error source in R_{rs} calculations (Doxaran et al., 2004). To correct for the reflection of sky radiance at the water

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http://dx.doi.org/10.1016/j.rse.2013.04.001

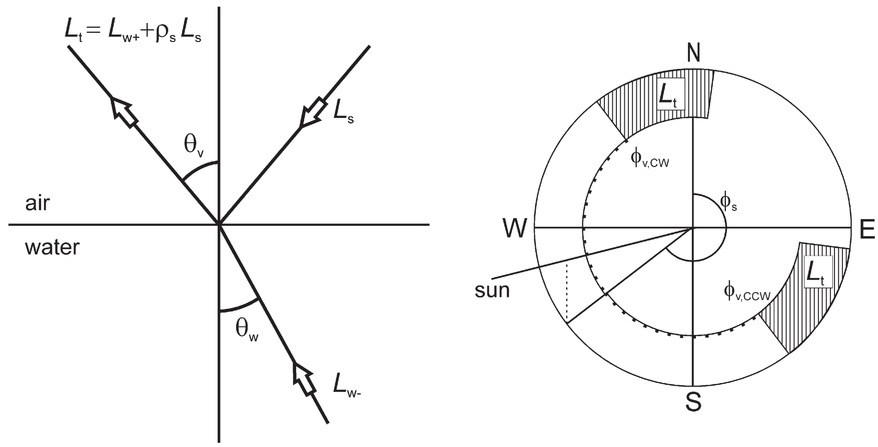

Fig. 1. Measurement geometry and used symbols in close-range remote sensing reflectance measurements (Eqs. 1a and 1b). The shaded areas in the second diagram indicate the angles under which L_t should be obtained ($90 \leq \varphi_v \leq 135°$ from solar azimuth φ_s).

surface, the following expression for close-range (above-surface) remote sensing reflectance is used:

$$R_{rs}(\lambda) = L_{w+}(\lambda)/E_d(\lambda) \tag{1a}$$

$$L_{w+}(\lambda) = L_t(\lambda) - \rho_s L_s(\lambda) \tag{1b}$$

where L_{w+} is water-leaving radiance just above the water surface, originating from subsurface upwelling radiance and altered by transmissivity of the sea-air interface. E_d is downwelling irradiance above the water surface. L_t is the radiance received by the sensor pointed at the water surface and collects L_{w+} and a fraction ρ_s of the sky radiance L_s. The symbol λ is used for wavelength. Dependence of the radiances and ρ_s on zenith and viewing angles is not explicit in Eqs. (1a) and (1b). We only consider the case where φ_v is identical for L_s and L_t, while θ_v of the two radiance quantities is mirrored in the horizontal plane, as drawn in Fig. 1.

The two largest challenges in shipborne reflectance measurements are to maintain optimal viewing geometry (Aas, 2010; Hooker & Morel, 2003) and to determine an accurate value of ρ_s under variable illumination and surface roughness conditions (Aas, 2010; Mobley, 1999; Ruddick et al., 2006). Should these problems be overcome, shipborne $R_{rs}(\lambda)$ could prove a highly valuable complement to remote sensing imagery, while also contributing hyperspectral monitoring under clear and clouded conditions. The Methods section provides a brief description of the method used to maintain an angle close to $\varphi_v = 135°$, compensating the azimuth angle of our spectroradiometers for ship course and sun position. The main topic of this study is to describe and validate a new approach to estimate the sky radiance reflectance ρ_s, particularly for relatively clear coastal waters for which no current solutions exist.

Existing approximations of ρ_s have been based on sea surface roughness (or wind speed as a proxy), sensor viewing geometry, and the direct and diffuse fractions of downwelling irradiance (Aas, 2010; Mobley, 1999). The values of ρ_s predicted from these models hold true in general but are often suboptimal for individual measurements taken under continuously changing conditions (wave and ship motion, illumination). Alternatively, assumptions can be made on the spectral shape of reflectance. Ruddick et al. (2006) showed that R_{rs} in the near-infrared (NIR) has a highly conserved shape in moderately to highly turbid waters caused by the dominant absorption properties of water. This information can be used to validate, or optimize, R_{rs} spectra in turbid waters. For clear waters where NIR L_{w+} is too weak to discern the similarity spectrum a solution has not yet been presented. Lacking a more appropriate method, we may default to $\rho_s = 0.0256$, the value of the Fresnel reflection coefficient for a flat sea under fully diffuse light. For clear-sky conditions, dependence of ρ_s on waves has been modeled on wind speed W (m s^{-1}) such as described in Ruddick et al. (2006), switching to the clear-sky case when $L_s(750)/E_d(750) < 0.05$:

$$\rho_w = 0.0256 + 0.00039W + 0.000034W^2. \tag{2}$$

Alternatively, in optically deep (clear) waters the so-called 'black pixel assumption' can be used to determine ρ_s. R_{rs} is assumed to approximate zero at wavebands where $a >> b_b$ so that Eq. (1a) and (1b) can be solved for ρ_s which assumes the value of $L_t(\lambda)/L_s(\lambda)$ in the 'black' channels. The zero-reflectance condition is only met in the NIR where absorption by water is high, and in the ultraviolet-to-blue spectrum in clear waters with high humic substances absorption (e.g. Berthon & Zibordi, 2010).

Coastal waters exhibit wide variability in backscattering intensity due to the presence of suspended minerals from river sources and shallow banks. Neither of the above approaches will be consistently valid in such waters. We present an alternative method to estimate ρ_s designed to work with hyperspectral radiometric measurements of both clear and turbid waters. The method is based on the observation that downwelling and reflected upward (ir)radiance contain a multitude of narrow spectral features that originate from gas absorption in the outer layers of the sun and the Earth atmosphere (Fig. 2A). R_{rs} is given shape by the inherent optical properties of the water, and the spectral pattern or 'fingerprint' of the downwelling light should therefore not be observed in R_{rs}. In field measurements, when an unsuitable value for ρ_s is applied to calculate R_{rs}, the atmospheric features can be recognized in R_{rs}. Reciprocally, we can optimize ρ_s so that the presence of the atmospheric features in R_{rs} is minimized. This method is detailed in this paper and referred to as the 'fingerprint' method.

Isolation of the atmospheric fingerprint from water-leaving radiance requires that their spectral signatures are distinct. To illustrate that this is a realistic expectation, absorption shapes of optically active substances are shown in Fig. 2B for comparison against the (ir)radiance spectra in Fig. 2A. The distinct absorption peaks from pigments (simulated from Baltic Sea spring bloom measurements) are dampened by the broad absorption features of water in the NIR and by colored dissolved organic matter (CDOM) in the ultraviolet (UV). In conditions of phytoplankton bloom we may expect pigment absorption and fluorescence features to mask the distinct fingerprint of the atmospheric absorption in the visible spectrum, where atmospheric absorption features are already less prominent. However, even in those situations we expect that UV and NIR channels can be used to distinguish the atmospheric influence in water-leaving radiance. This hypothesis is tested using radiance data simulated with the radiative transfer approximation software Hydrolight 5.0 (Sequoia Scientific Inc.,