Remote Sensing of Environment 186 (2016) 548–566

Contents lists available at ScienceDirect

Remote Sensing of Environment

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

# Retrieval of macro- and micro-physical properties of oceanic hydrosols from polarimetric observations

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ARTICLE INFO

*Article history:*
Received 1 September 2015
Received in revised form 20 August 2016
Accepted 7 September 2016
Available online xxxx

*Keywords:*
Remote sensing
Polarization
Hydrosol
Ocean color
Case-I waters
Case II waters
Bio-optics
Chlorophyll *a*
CDOM
Plankton
Minerals
Scattering
Vector radiative transfer
modeling
Aerosol
Cloud
Ocean ecosystem
PACE

ABSTRACT

Remote sensing has mainly relied on measurements of scalar radiance and its spectral and angular features to retrieve micro- and macro-physical properties of aerosols/hydrosols. However, it is recognized that measurements that include the polarimetric characteristics of light provide more intrinsic information about particulate scattering. To take advantage of this, we used vector radiative transfer (VRT) simulations and developed an analytical relationship to retrieve the macro and micro-physical properties of the oceanic hydrosols. Specifically, we investigated the relationship between the observed degree of linear polarization (DoLP) and the ratio of attenuation-to-absorption coefficients ($c/a$) in water, from which the scattering coefficient can be readily computed ($b = c - a$), after retrieving $a$. This relationship was parameterized for various scattering geometries, including sensor zenith/azimuth angles relative to the Sun's principal plane, and for varying Sun zenith angles. An inversion method was also developed for the retrieval of the microphysical properties of hydrosols, such as the bulk refractive index and the particle size distribution. The DoLP vs $c/a$ relationship was tested and validated against in-situ measurements of underwater light polarization obtained by a custom-built polarimeter and measurements of the coefficients $a$ and $c$, obtained using an in-water WET Labs ac-s instrument package. These measurements confirmed the validity of the approach, with retrievals of attenuation coefficients showing a high coefficient of determination depending on the wavelength. We also performed a sensitivity analysis of the DoLP at the Top of Atmosphere (TOA) over coastal waters showing the possibility of polarimetric remote sensing application for ocean color.

## 1. Introduction

The polarization of light is highly sensitive to chemical and physical properties of particles in the atmosphere and oceans (Hansen and Travis, 1974; Kattawar and Adams, 1989; Mishchenko et al., 2004; Chami and Platel, 2007; Lotsberg and Stamnes, 2010; Knobelspiesse et al., 2011; Chowdhary et al., 2012). The development of satellite sensors capable of measuring and quantifying the polarization of light emerging from atmosphere-ocean (AO) system is becoming increasingly important for understanding not only the macrophysics, but also the microphysics of particulate matter in AO system. The microphysical properties reveal new details about aerosol/hydrosol characteristics that make it possible to distinguish between different aerosol/hydrosol types from space observations, and to derive precise distributions of size, shape, and concentrations that can help in our understanding of the earth's radiation budget, climate change, and ocean processes (Hansen and Travis, 1974; Chowdhary et al., 2006, 2012). Consequently, NASA is considering the addition of a polarimeter onboard a future ocean color mission: the Plankton, Aerosol, Cloud, and ocean Ecosystem (PACE) (PACE, 2012). The long-term goal of this mission is essentially to assess the carbon cycle and its interrelationship with climate change. It also will extend the ocean climate data records collected since the 1990s and evaluate observed long-term changes. Polarimetric measurements from space will improve atmospheric corrections, especially over bright coastal and shallow waters (Chowdhary, 1999; Chowdhary et al., 2001; Waquet et al., 2009; Knobelspiesse et al., 2011). While polarization and

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http://dx.doi.org/10.1016/j.rse.2016.09.004

multi-angle measurements can be used to derive some key properties of aerosols, such measurements can also be useful in retrieving the optical and microphysical oceanic properties (PACE, 2012). In addition, the planned Multiviewing, Multichannel, and Multipolarization Imager - 3MI (ESA/Eumetsat) will help with understanding the composition of aerosols and clouds in the atmosphere and possibly the oceanic hydrosols and their impact on climate forcing (Marbach et al., 2015). The Second Generation Global Imager (SGLI) on-board the Japanese Global Change Observation Mission (GCOM-C) will provide atmosphere, land, and ocean color products. The two added polarization channels with 250-meter spatial resolution will help to improve aerosol and ocean color retrievals, especially in coastal regions (Honda et al., 2006). The studies and analyses performed in this work will contribute to the development of comprehensive remote sensing inversion algorithms that utilize the polarimetric signature of the ocean for the retrieval of macro- and micro-physical properties of hydrosols.

Several studies have shown the potential of utilizing the polarization characteristics of oceanic light to retrieve Inherent Optical Properties (IOPs) and biogeochemical properties (Chami et al., 2001; Chami and Mckee, 2007; Chami and Platel, 2007; Loisel et al., 2008; Lotsberg and Stamnes, 2010; Tonizzo et al., 2011; Ibrahim et al., 2012). For example, Chami and Platel (2007) studied the use of directional variations and polarization of marine reflectance in the remote sensing retrieval of IOPs. Using an artificial neural network (NN), they demonstrated that adding polarized reflectance to unpolarized reflectance at 490 and 665 nm as inputs to the NN improves the retrieval of the scattering coefficient by >75% in relative error compared to the use of scalar reflectance alone. The remote sensing reflectance $R_{rs}$ is defined as the water-leaving radiance normalized by the sum of direct and diffuse downwelling irradiances. To a first approximation, $R_{rs}$ is proportional to $b_b/a$ for open ocean waters and to $b_b/(a+b_b)$ for coastal waters, where $b_b$ is the backscattering coefficient. As such, $R_{rs}$ by itself does not contain any information on the light scattered forwardly into the water (Gordon et al., 1975, 1983, 1988; Gordon, 1989). The extraction of coefficient $b$ from coefficient $c$ retrieved from polarization data can provide this information and reduce the retrieval uncertainty of $b_b$ and $a$ from $R_{rs}$ data, especially in optically complex waters.

Studies have shown that the particulate attenuation coefficient, $c_p$, of hydrosols co-varies with the particulate organic carbon concentration (POC) as well as with phytoplankton carbon biomass (Behrenfeld and Boss, 2003; Behrenfeld et al., 2005; Cetinic et al., 2012; Graff et al., 2015). They suggest that there is a first-order relationship between the ratio of $c_p$ to chlorophyll concentration ($c_p$:Chl), as an index of phytoplankton carbon (C) biomass ratio to chlorophyll concentration (C:Chl) and phytoplankton physiology, which is important for estimating primary production of the oceans. Thus, retrieval of the attenuation coefficient from remote sensing would allow for better understanding of the carbon cycle on the global scale, a primary goal of many ocean color satellite missions (e.g., PACE mission).

In coastal waters, hydrosols are composed primarily of two types of particles: algal and non-algal. Algal particles with high water content have a low refractive index (approximately 1.06) relative to that of water and therefore produce only an indistinctive polarization signature similar to that of Rayleigh scattering (Voss and Fry, 1984; Tonizzo et al., 2009). Their impact on the fraction of polarized light is predominantly by means of their absorption, which reduces the amount of multiple scattered light. Non-algal particles (NAP), such as mineral particles, scatter light more effectively due to their high relative refractive index, typically around 1.18 (Babin et al., 2003a, 2003b). Through multiple scattering, these particles can significantly decrease the polarization of water-leaving radiance; thus, their concentration should be retrievable using polarization measurements. Although this polarization is highly sensitive to underwater light scattering (Tonizzo et al., 2011), absorbing properties of the water also significantly impact the polarized light field, since the increase in absorption also results in the decrease of the number of the multiple scattering events; in turn this leads to an increase of the fraction of light that is polarized, and therefore, the increase of water absorption in the red part of the spectrum increases the fraction of polarized light. Similarly, the presence of colored dissolved organic matter (CDOM), a strong absorber of blue light, increases the fraction of polarized light in the blue part of the underwater spectrum (Chowdhary et al., 2012).

In the open ocean, the majority of particles are algae and their by-products whose concentrations co-vary with chlorophyll *a* concentration [Chl]. These types of particles exhibit polarization patterns similar to those of molecular scattering because of their low refractive index (Chami et al., 2001). Underwater polarization for open oceans is therefore relatively simple (Voss and Fry, 1984, You et al., 2011a, 2011b). It can be reproduced well by vector radiative transfer (RT) computations and persists in the water leaving radiance even when the sea surface is ruffled by strong winds (You et al., 2011a, 2011b).

The advantage of using polarization measurements for remote sensing of oceans over scalar $R_{rs}$ measurements is that the polarized components of light intrinsically (mathematically) carry more information about the microphysical properties of scattering particles. $R_{rs}$ is dependent on only one element of the scattering matrix (i.e. scattering function) of hydrosols which is an IOP, and the absorption, while the polarized components are affected by all of the elements of the scattering matrix. Therefore, scattering and absorbing hydrosols modulate the polarization of light induced by molecular scattering of water molecules. Changes of light polarization depend on the concentration and composition of these hydrosols and thus can be related to both their absorption and scattering properties.

Timofeyeva (1970) found a relationship between the linearly polarized light in artificial milky turbid water and the parameter T, which is equal to the ratio of the attenuation coefficient of the scattered light flux to the direct light flux. Inspired by this preliminary relationship, the work presented here seeks to expand that early study and extends it to naturally complex water conditions under natural illumination. It also expands the similar analysis of Ibrahim et al. (2012) to include a more realistic vector radiative transfer model in order to retrieve the attenuation coefficient, *c*, and the microphysical properties of hydrosols in the water body. The improvements in the model are focused on the development of a *hybrid* model that relates the microphysics to the macrophysics of hydrosol particles.

## 2. Background

### 2.1. Stokes parameters

A full description of light takes the electromagnetic (EM) vector nature of light into account and includes the intensity and the polarization state. The intensity is the energy flux of an EM wave (i.e., the brightness of light), and the polarization state fully describes an oscillating EM wave. In turn, a polarized beam of light can be defined by the 4 × 1 Stokes vector $\mathbf{I} = \{I, Q, U, V\}'$ (Mishchenko, 2014). Stokes parameter $I$ is the intensity or radiance, which has the dimension of energy flux per unit solid angle (i.e. the total energy carried by the EM wave). Stokes parameters $Q$, $U$, and $V$ describe the polarization state of the EM wave. The $V$ component, which describes the amount of circular polarization, for most cases of light scattered in AO systems is negligible (Mishchenko, 2014). Therefore, one can confine the description of light scattered in AO systems to the intensity and linear polarization of an EM wave, which are given by the first three elements of the Stokes vector. A convenient measure for such cases is the degree of linear polarization (DoLP), which is defined as:

$$\mathrm{DoLP} = \frac{\sqrt{Q^2 + U^2}}{I} \tag{1}$$