Retrieving the Scattering Coefficient of Marine Particles from Polarimetric Observations

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ABSTRACT
Polarized light in the oceans carries intrinsic information that can be utilized to estimate the optical and microphysical properties of the oceanic hydrosols. It is especially sensitive to the scattering coefficient, which cannot be retrieved from the unpolarized light used in current ocean color remote sensing algorithms. Through the unpolarized remote sensing reflectance (Rrs), these classical algorithms can only estimate backscattering coefficients bb, but the total scattering coefficient b could be solely retrieved based on the characteristics of polarized light. The correlation is quantified in this paper. Based on extensive simulations using the vector radiative transfer program RayXP, the attenuation-to-absorption ratio (c/a), from which b is readily computed, is shown to be closely related to the degree of linear polarization (DoLP). The relationship is investigated for the upwelling polarized light for several wavelengths in the visible part of the spectrum, for a complete set of viewing geometries, and for varying concentrations of phytoplankton, non-algal particles, and color dissolved organic matter (CDOM) in the aquatic environment. It is shown that there is an excellent correlation between the DoLP and c/a for a wide range of viewing geometries.

KEYWORDS: Remote Sensing, Polarization, Radiative Transfer.

I. INTRODUCTION
Light scattering properties of the environment have been extensively studied, especially in the ocean color and atmospheric science communities. Numerous scientific articles within the ocean color community are being published trying to solve the inverse problem based on empirical [1], analytical/semi-analytical, and statistical algorithms to retrieve useful oceanic parameters. This includes optical, microphysical, and biogeochemical properties such as the absorption coefficient, particle sizes, and the concentration of the constituents that occupy the oceans. Retrieving the aforementioned properties of the oceans within reasonable accuracy is important to a great extent. Modeling of carbon cycles in the Atmosphere-Ocean system (AO) based on the chlorophyll concentration in the water is critical for the studies related to the understandings of the temperature anomalies in the environment. Global retrieval of the chlorophyll concentration has been erroneous especially in coastal waters. Sediments and nutrients discharge from the rivers makes the coastal water to be optically complex. The typical remote sensing retrieval algorithms are based on the measurements of the Rrs which is the summation of the polarized and unpolarized reflectances. Inherently, Rrs is dependent on the absorption coefficient (a) and the backscattered coefficient (bfs). The complexity of the significant constituents in the ocean and their relative concentrations makes this relationship between Rrs and the IOPs to be highly ambiguous. Retrieving any information about the forwardly scattering light becomes virtually impossible. On the other hand, the polarized light field in the ocean has been proven to be highly dependent on the scattering coefficient b [2, 3], where b = bfs + bff and bff is the forward scattering coefficient. Obtaining the total scattering coefficient b from the remotely measured polarized reflectance is novel. In this work, the effects of spectral and angular variations on the relationship between DoLP and the inherent optical properties (IOPs) are considered. The purpose of this study is to investigate the relationship between DoLP and IOPs for various microphysical and optical properties of the hydrosols specifically in coastal waters. The results presented here are based on a theoretical analysis encompassing a larger range of realistic parameters representative of typical coastal waters.

II. RADIATIVE TRANSFER MODELLING
The RayXP program [4] was used to simulate the transfer of radiation in homogeneously scattering, plane parallel media. The program optimizes computational time by incorporating various techniques, collectively called the Multicomponent Approach (MCA), for solving the vector radiative transfer equation. The outputs of the vector radiative transfer code are the Stokes elements of underwater radiance (at a specific optical depth). The DoLP can then be calculated as:

\[ \text{DoLP} = \frac{\sqrt{Q^2 + U^2}}{I}, \]
where I is the total radiation, Q and U are the linearly polarized components of the Stokes vector representing linearly polarized radiance. In this work, we simulated the atmosphere-ocean system assuming two simple plane-parallel homogeneous layers. The first layer is dedicated to the atmosphere, assuming Rayleigh (molecular) scattering only. No aerosols are included in this analysis for simplification. Rayleigh optical thickness values are the same as the ones used for MODIS products (0.098 at 550 nm) and the molecular optical properties (Scattering Matrix) were obtained from the standard data bank provided with RayXP. No gas absorption is included in the modeled atmospheric layer. The second layer is dedicated to the ocean, which is also composed simply of homogenous, optically deep water in order to minimize bottom boundary effects. Isotropic wind speed is assumed to be 3 m/s for the interface between the atmosphere and the ocean. The optical properties of the oceanic layer were generated using the bio-optical model detailed in Gilerson et al. [5] and references therein. The constituents included the water itself, non-algal particulates (i.e. mineral) (NAP), and chlorophyll containing particles (phytoplankton) and CDOM. We use the subscripts "w", "NAP", "ph", and "g," respectively, to identify these four components. In figure 1, the flow diagram explains the bio-optical and the radiative transfer (RT) modeling. The scattering matrices (F) are calculated with the Lorenz-Mie theory for a Junge (or hyperbolic) particle size distribution (PSD) for a specific range of particles radii using a code developed by Mishchenko et al. [6]. Although fixed refractive indices are assumed for both types of particles, the calculated scattering matrices of each particle using Mie theory are mixed based on the scattering coefficient for each NAP and Phytoplankton particles derived from the bio-optical model following the equation below [7]

\[
F_{\text{Bulk}}(\lambda) = \frac{b_{\text{nap}}(\lambda) \times F_{\text{nap}}(\lambda) + b_{\text{ph}}(\lambda) \times F_{\text{ph}}(\lambda)}{b_{\text{nap}}(\lambda) + b_{\text{ph}}(\lambda)}, \quad (2)
\]

where \(F_{\text{Bulk}}\) is the bulk scattering matrix resultant from the mixing of the NAP scattering matrix (\(F_{\text{nap}}\)) and the phytoplankton scattering matrix (\(F_{\text{ph}}\)).

The variability in the calculations of the bulk scattering matrix is directly dependent on the particulate concentrations in the bio-optical model. The radii of both phytoplankton particles and NAP were assumed between 0.1 and 50 μm with the slope (ξ) of the Junge-type particle size distribution (PSD) equals to 3.5, 4.0, and 4.5 for each type of particles. These three different slopes cover the typical range of different types of particles in the ocean. By independently varying all the parameters, for the two particle types, we were able to cover a large range of IOPs typical of both open ocean and of coastal waters. We use a permuted dataset to describe the variability of particulate concentrations in the water: 15 different cases for both

![Figure 1. Flow Diagram of the bio-optical and RT models for the generation of the data set.](image-url)
chlorophyll and NAP concentrations and 5 cases of CDOM absorption at 400 nm. To generate RayXP datasets, the different chlorophyll concentrations, NAP concentrations, CDOM absorptions, PSDs of each type of particles, and their refractive indices were permuted. 10125 different cases to be simulated were generated. For each of these cases, four main parameters were needed for the RayXP program: the spectral hydrosol's attenuation coefficient, the hydrosol's single scattering albedo, the bulk scattering matrix calculated for each case, and the dissolved matter absorption (CDOM).

III. RESULTS AND DISCUSSION

In this section, simulated radiative transfer outputs of DoLP are investigated in order to find a definitive relationship with the IOPs, in terms of the attenuation to absorption ratio ($c/a$). Such a relationship would give us the possibility of retrieving the attenuation coefficient, $c$, of the water constituents from data obtained by under- or above-water polarization radiometer measurements of the upwelling radiation, since the absorption coefficient, $a$, is routinely estimated from the remote sensing reflectance using well-established algorithms [8]. The results presented below were obtained from simulations at three wavelengths (440, 550, and 665 nm) at depths just below the air-water interface.

The range which corresponds to the aperture of Snell's window, whose border is shown by dashed lines in Fig. 2 is the one in which we are mostly interested because of the possibility of future above-water remote sensing measurements of the

Figure 2. DoLP just below water surface vs. viewing angle between -70° and 80° (0° for vertically downward), sun zenith 30° and relative azimuth plane 0°, 40°, and 90° at three wavelengths (440, 550, and 665 nm). The grey color gradation corresponds to varying values of $c/a$. Lighter grey is for lower $c/a$ ratio, while darker is for higher $c/a$ ratio. The dashed vertical lines correspond to the angles of the borders of Snell's window.
DoLP. In Fig. 2, we show the angular plot of the DoLP for three relative azimuth angles equal to 0°, 40°, and 90° at the three aforementioned wavelengths. The plot shows the dependence of the DoLP on the \( a/c \) ratio by the color gradation from light to darker grey or black. Light grey corresponds to values of the DoLP calculated for low \( a/c \) ratio, whereas dark grey represents high \( a/c \) ratios. In another sense, this color gradation could also correspond to the single scattering albedo, where higher \( a/c \) ratio means less absorption, more scattering, and higher single scattering albedo in the medium, therefore producing lower DoLP. Similarly for lower \( a/c \) ratio, it means less scattering and lower single scattering albedo producing higher DoLP. A strong relationship exists between the DoLP and \( a/c \) ratio with high variability in the broad range of both parameters for specific viewing angles (20°-50°) in the sun’s main plane, and at 40° and 90° away from it (this range of viewing angles in water corresponds to 27°-82° viewing angles in the air). As a result, it is possible to easily fit the relationship, which allows us to retrieve the attenuation coefficient given the DoLP measurements and the absorption coefficient (which can be retrieved with good accuracy using inversion algorithms) plus a prior knowledge of the slope (\( \xi \)) of the PSD of NAPs. The parameterized relationship was estimated using a power law fitting for the three PSD slopes of NAPs as follows:

\[
\left\{ \left( \frac{c}{a} \right)_{\text{fit}} \right\}_{\xi_{\text{nap}}} = \left\{ \chi \left( \text{DoLP} \right)^{\gamma} \right\}_{\xi_{\text{nap}}},
\]

where \( a \) and \( c \) are the absorption and attenuation coefficients, respectively; \( \chi \) and \( \gamma \) are the fitting coefficients. The power law fitting is believed to be a good method because of its simplicity in representing the bio-optical properties of the water (\( c/a \)) using only two parameters; this also agrees with the results shown by Timofeyeva [9]. In Fig. 3, the relationship between the IOPs (\( c/a \) ratio) and the DoLP is parameterized as a power law as in Eq. (3) with a good coefficient of determination \( R^2 \) (squared correlation) opening the possibility for an accurate retrieval technique of the attenuation coefficient. While deriving a final semi-analytical or analytical relationship between DoLP and \( c/a \) are not the main goals of this work, nevertheless it is important to show that a relationship exists between the polarization signature of the ocean and its bio-optical, microphysical, and geo-chemical properties. An interesting result shown in Fig. 3 is that the fits for both \( \xi_{\text{nap}} \) of 4.0 and 4.5 are similar for the all three wavelengths. In coastal waters, the slope \( \xi_{\text{nap}} \) of PSD of NAP largely falls in the range 4.0-4.5, where these particles are small in size.

Since the relationship weakly depends on the PSD of chlorophyll particles, a rough estimate of \( \xi_{\text{nap}} \) to be in its typical range may not induce large errors in, for example, retrieval analysis. The quality of the fitting of Eq. (3) can be estimated by calculating the root mean squared error (RMSE) or the coefficient \( R^2 \) between the parameterized/fitted values and the resultant values of the radiative transfer simulations. A high correlation or a low RMSE value indicates a good quality of the fitting and vice-versa. The coefficient of determination is calculated as follows:

\[
R^2 = \frac{\text{SSR}}{\text{SST}} = \frac{\sum_{i=1}^{10125} \left[ \left( \frac{c}{a} \right)_{\text{DoLP},i} - \left( \frac{c}{a} \right)_{\text{fit},i} \right]^2}{\sum_{i=1}^{10125} \left[ \left( \frac{c}{a} \right)_i - \left( \frac{c}{a} \right)_{\text{fit},i} \right]^2},
\]

where SSR is the sum of squared differences between the regression predictions or fit \( (c/a(\text{DoLP})_{\text{fit}}) \) and the sample

![Figure 3](image-url)

**Figure 3.** Fitted relationship between DoLP at \( \theta_{\text{view}} = 40° \) and \( \varphi_{\text{view}} = 90° \) and \( c/a \) ratio at three wavelengths for three different NAP slopes of the particle size distribution (PSD). Figure 3(a) is for 440 nm, 3(b) is for 550 nm, and 3(c) is for 665 nm.
mean of \((c/a)\) with the over bar in Eq. (4), where ‘i’ iterates from 1 to 10125 different cases of IOPs in the RT simulations. The SST term stands for sum of squares total which means the sum of squared deviations of the \((c/a)\) values around their mean. In order to have a synoptic view of the fitting quality, the \(R^2\) values are plotted in Fig. 4 for all the viewing geometries available for a given solar angle (i.e. \(\theta_{sun}=30^\circ\)). In this manner, we can estimate the range of geometries that permits one to obtain the best accuracy for the retrieval of the attenuation (and the scattering, \(b=c-a\)) coefficient based on measurements of the DoLP. Similar results were found from RMSE distributions. In Fig. 4, the coefficient of determination \((R^2)\) for most of the viewing geometries below the water surface is higher than 0.9. That indicates a good and consistent relationship between the simulated data set and the fitting obtained using the power law function in Eq. (3). It is also noticeable that \(R^2\) degrades in the backscattering direction where the DoLP is theoretically minimal (DoLP \(\approx\) 0). That region is in the anti-solar plane (180° relative azimuth, between 150° and 210°) and between viewing angles ranging from 0° to just slightly higher than 40° for \(\xi_{nap}\) of 3.5 and 4.0 at 440 nm and between 0° to 20° for \(\xi_{nap}\) of 3.5, 4.0 and 4.5 at 550 and 665 nm. Less steep slopes of NAP PSD are not typical in the ocean; they correspond to higher density of large NAP, which can have a highly depolarizing effect on the upwelling radiance. As a result, degradation in the relationship between DoLP and \(c/a\) is probably due to the decrease in the sensitivity of the DoLP. It can be seen from Fig. 4 that waters with larger-sized NAP (\(\xi_{nap}\) of 3.5) exhibit lower \(R^2\) compared to other slopes of NAP PSD.

The high (squared) correlation in Fig. 4 is very promising when considering future air- or space-borne measurements of the polarized water-leaving radiance, since it does not limit the range of viewing angles at which this type of sensors operate. For example, the good correlation that exists at the meridian...
plane away (90° away, for instance) from the sun's main plane (and therefore away from sun glint contaminations), makes the measurements of polarized water-leaving radiance easier and more accurate and opens the possibility of a direct estimation of the attenuation coefficient, otherwise physically impossible, using above water sensors. It is obvious from Fig. 4 that the best $R^2$ values can be achieved at 665 nm for a broad range of azimuth and viewing angles. This is most likely due to the moderate absorption (usually dominated by the water absorption) which reduces the number of the scattering events and increases DoLP in comparison with 550 nm case. Details of these effects should be further studied.

IV. CONCLUSION

While attenuation and scattering coefficients are not retrievable from the scalar reflectance measurements, a relationship between the degree of linear polarization (DoLP) and the attenuation to absorption coefficients ratio ($c/a$) has been investigated using vector radiative transfer simulations for a large range of viewing geometries, wavelengths, and bio-optical and microphysical parameters typical of ocean and coastal waters for conditions just below the air-water interface. We showed that it is possible to fit, using a power law function, the relationship between the DoLP and the $c/a$ ratio with a satisfactory coefficient of determination $R^2$ and with a relatively weak dependency on the particle size distribution. These results open a possibility for the retrieval of the attenuation and, further, the scattering coefficients of the water medium from the DoLP measurements assuming given absorption coefficient, which is routinely retrieved from remote sensing reflectance data. The relationship was also tested for above the air-water interface and showed high $R^2$ values for a broad range of viewing angles. Dependence of the relationship on the sun zenith angle was analyzed as well. The best viewing geometries for below water polarization measurements call for a viewing angle between 20° and 40° from the nadir direction, which is within the borders of Snell's window, and a relative azimuth of 90° with respect to the sun and for above the water viewing angles from 40° to 60° with relative azimuth of 90°. Established relationships can be tested in the future for many of the illumination and viewing conditions considered here, together with varying water properties at the LISCO site. Applications to above water polarization measurements, such as those provided by the LISCO instrumentation set are one of the main potential follow-ons of this work and of future validation studies.

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REFERENCES


AMIR IBRAHIM  I earned my bachelor of Electrical Engineering degree at the City College of New York in 2009. Currently, I am pursuing the Ph.D. degree from the Electrical Engineering department, while my thesis topic is on the remote sensing of the ocean based on polarimetric observations of light. I was given the opportunity by my current mentors to join the optical remote sensing laboratory after they advised me to take the remote sensing satellite imaging class with Dr. Gilerson. That opportunity allowed me to understand that research is an interdisciplinary world; physics, mathematics, and engineering skills, all together orchestrate to expand our knowledge about the environment and how to perceive it. Therefore, my current goal in my study is to use the aforementioned skills to develop a new retrieving algorithms of ocean’s optical, microphysical, and biogeochemical characteristics that utilizes the information of one of the hidden properties of light that the human eyes cannot perceive: polarization. I would like also to acknowledge Dr. Samir Ahmed and Dr. Alex Gilerson for their dedicated support and guidance. Their mentorship allowed me to conduct quality research that is highly regarded throughout the scientific community of ocean color remote sensing.