Hyperspectral and Multiangular Analysis of Polarized Light in Coastal Waters

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ABSTRACT
Measurements of the underwater polarized light field were performed at different stations, atmospheric conditions, and water compositions using a newly developed hyperspectral and multiangular polarimeter during a recent cruise in the coastal areas of New York Harbor - Sandy Hook, NJ region. Angular and spectral variations of the degree of polarization are found to be consistent with theory. Maximum values of the degree of polarization do not exceed 0.4 and the position of the maximum is close to 100° scattering angle. Normalized radiances and degrees of polarization are compared with simulated ones obtained with a Monte Carlo radiative transfer code for the atmosphere-ocean system and show excellent agreement.

KEYWORDS: Remote sensing and sensors, oceanic optics, polarization, radiative transfer.

INTRODUCTION
Polarization characteristics of underwater light contain useful additional information on inherent optical properties (IOP), concentrations, and size distributions of water constituents when compared with standard reflectance data [1-5]. In particular, information on the state of the water constituents can be obtained through analysis of the spectral and geometrical angular dependence of the polarized light components. In addition, this analysis can help assess visibility in underwater environments, provide interpretation of ocean lidar signals, etc. These properties should also be taken into account in the studies of atmospheric aerosols above the ocean which employ polarization properties of atmospheric particulates [6]. Although many measurements of light scattering in the seawater have been made, the majority have not taken into consideration the changes that occur in the linear polarization of the light field. Despite the importance of polarization for marine applications, relatively few in situ observations of the oceanic polarization state of light have been carried out, owing to a lack of instrumentation and to the practical difficulties in achieving reliable measurements. Remote sensing of ocean water provides information on suspended particles. Among the different types of suspended matter in ocean water, phytoplankton play the primary role in global biological production in the ocean and, therefore, in the carbon cycle. Remote sensing measurements of ocean color are directly related to the water leaving spectral radiance which depends on the absorption and scattering properties of the suspended particles. However, phytoplankton cells exhibit only weak polarization effects (because of the small index of refraction relative to water) while inorganic particles, which are

Figure 1. Geometry of observation. θ_{sun} is the solar zenith angle; θ_{d} is the detector zenith angle; θ_{sca} is the scattering angle; φ is the detector azimuthal angle.
strong backscatters, appreciably affect the polarization signal [7]. Having this in mind, Chami [8] investigated the influence of marine particles on the polarized radiation exiting the ocean. Using theoretical modeling, he showed that an empirically based inversion approach relying on the underwater polarized radianc could retrieve the concentration of inorganic particles regardless of the phytoplankton content in coastal waters. On this basis, Chami [9] also performed in situ measurements of the polarization state of underwater oceanic radiation with the purpose of having direct estimation of suspended inorganic matter concentration from remotely sensed data in coastal waters. REFPOL, the instrument used in these measurements, was a multispectral radiometer with only four channels centered at 450, 650, 850 and 1650nm together with polarizers which rotate in front of the detectors, allowing for successive (not simultaneous) measurements of radiances values. Above water measurements of the degree of polarization were taken exclusively in the principal plane and were inevitably affected by sun glint effects. In this paper, we set out to obtain a comprehensive understanding of the changes that occur in the polarized light in coastal waters. Unlike previous multiband instruments, we obtained underwater angularly resolved hyperspectral measurements of the degree of linear polarization (DOLP or simply DOP) in coastal environments illustrating how the variability of the DOP is connected to water constituents. Measurements were also taken in different atmospheric conditions, to observe the effects of diffuse light, rather than direct sun light on the DOP and a comparison between above and under water measurements is explored. Finally, we assess the consistency between our measurements and theoretical polarized radiative transfer models regarding the influence of marine particles on the polarized signal with particular emphasis on the corresponding wavelength and angular dependence.

THEORETICAL BACKGROUND
The polarization state of the underwater light field is quantified using the Stokes vector \( \mathbf{S} = [I \ Q \ U \ V] \), where \( I \) represents the energy flux (Wm\(^{-2}\)nm\(^{-1}\)), \( Q \) and \( U \) describe the linearly polarized component of this flux, while its circular polarized component is described through the Stokes parameter \( V \). Except for circular/elliptical polarization next to the borders of Snell's window (which is the circular region above an underwater observer with an aperture equal to twice the critical angle, \( \theta_c = 48.6^\circ \), the underwater light field is essentially linearly polarized [10]. The DOP is a measure of the percentage of linear polarization and can be expressed as:

\[
\text{DOP} = \frac{\sqrt{Q^2 + U^2}}{I}
\]  

Oceanic water, especially in the coastal areas, contains many suspended particles. Scattering processes clearly modify the polarization state and the angular features of the polarized light (i.e., their dependence on the scattering angle, the angle between the incoming light and the direction of observation), are strongly related to the size, shape and composition (i.e., refractive index) of their scattering sources. Fig. 1 shows the relevant scattering and geometric angles we use in describing our measurements.

INSTRUMENTS AND METHODS
Polarization measurements were taken using a hyperspectral and multiangular polarimeter developed by the Optical Remote Sensing Laboratory at the City College of New York. The instrument consists of three Satlantic Hyperspectral radianc sensors (recording intensity at the wavelengths 350-800nm, 8.5° field of view in water) mounted on a scanning system controlled by an underwater electric stepper motor as shown in Fig. 2a. Data were collected during a cruise on the R/V “Connecticut” in the coastal areas of New York Harbor - Sandy Hook, NJ region, on July 21-23, 2008. The instrument was lowered from a winch extending from the side of the ship so that shadow effects were minimized (Fig. 2b). The entire assembly was kept 1m below the water surface using four arms.

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**Figure 2.**
The underwater instrument developed by the Optical Remote Sensing group at City College of New York. (a) detail of a Satlantic Hyperspectral sensor, (b) the instrument on the deck of R/V “Connecticut.”
DR. SAMIR AHMED is a Herbert Kayser Professor in the Department of Electrical Engineering at the Grove School. He has over 40 years of industrial and academic research experience.

Dr. Ahmed was educated at the University of Cambridge (BA) and University College of London University, where he earned a Ph.D. in electrical engineering. At RCA David Sarnoff Research Laboratories in Princeton, New Jersey, Dr. Ahmed was responsible for the first use of lasers for tunable high-resolution spectroscopy and for the invention of graphite bore ion lasers. Then, at GTE Laboratories, New York he developed multicolor ion lasers, rf-excited aperture magnetic confinement lasers, and a new type of molecular metal halogen arc true color lamp, which is now widely used.

At CCNY, Dr. Ahmed has pioneered the use of differential absorption (DIAL LIDAR) for the monitoring of molecular air pollution, under grants from the EPA, the NSF and the US Army. His research in fundamental processes explained energy transfer mechanisms in organic dye molecules, leading to the invention of energy transfer multicolor dye lasers, and to the definition of optical and refractive properties of resonantly absorbing media.

Recently, Dr. Ahmed has been a leader in environmental remote sensing research. With grants from NASA, (as Director of the University Research Center for Optical Sensing & Imaging), NOAA, and ONR, he uses atmospheric LIDARS for air quality and climate change research. This work includes the use of remote sensing to study optical properties of oceanic and coastal waters, and has led to the invention and patent pending of a fundamentally new polarization technique for separating fluorescence and elastic scattering.

Dr. Ahmed served as Chair of the Electrical Engineering Department from 1988 to 1997. Presently, he serves on the Executive Committee of the Electrical Engineering program and is the department’s Ph.D. advisor. Dr. Ahmed is a Life Member of IEEE, American Geophysical Union, AMS, and SPIE. He has numerous patents and well over 100 publications.

EXPERIMENTAL RESULTS

Figure 3 shows absorption ($a_{\text{tot}}$) and attenuation ($c_{\text{tot}}$) spectra for selected stations during the cruise. As will be shown below, a priori knowledge of these spectra is important in the analysis of the DOP.

Along with the absorption and attenuation coefficients, the volume scattering function (VSF) is one of the fundamental IOPs which governs the propagation of polarized light in aquatic environments. VSF measurements were made with a custom device called the MASCOT. Fig. 4 shows the comparison between MASCOT and standard Petzold’s phase functions for Station 1. Petzold’s phase functions were chosen to represent the phase functions of particulate matter in the Monte Carlo model.

To assess our measurements, we first note that the DOP for ocean waters typically makes a bell-shaped distribution as a function of the scattering angle, with the maximum around 90° and going to zero in proximity of 0 and 180°. Typical plots of the DOP vs. scattering angle, recorded in the main scattering plane at 1m depth are presented in Fig. 5. The maximum of the DOP reaches an upper limit of approximately 0.4 at 410nm. However,


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I graduated cum laude in 2004 from the University of Milan in Italy, where I studied physics and chemistry and wrote a thesis that explored the optical properties of nano-aggregates of hybrid organic/inorganic compounds. This formed the basis of my interest in interactions of light with matter, especially the exploration of the impact of microscopic features on the macroscopic world. After working in the semiconductor industry, I entered City College in the fall semester of 2005.

In 2007, under the mentorship of Dr. Samir Ahmed and Dr. Alex Gilerson, I joined the Optical Remote Sensing group, part of the NOAA-CREST Center. Now, I work on the challenging topic of polarized light in ocean waters. The problem is theoretically complex, and it also requires a hands-on understanding of the real ocean environment. Through several field trips to coastal areas of New York, I’ve gained a deeper understanding of how to take reliable and accurate field measurements, even in the toughest ocean situations. By the end of summer 2008, we have come a long way since the first set of sea-water polarization measurements was made.

As a complement to my oceanographic knowledge, I’ve been in touch with experts in the field, thanks to CCNY’s Remote Sensing Group and the opportunities I’ve had to participate in conferences and symposiums. The resulting exchanges of ideas and collaborations have led to the development of the custom-made polarization radio-meter and the important results obtained with it. Our report here discusses some of these results, which we have also presented at the International Ocean Optics conference in Barga, Italy in October 2008.

DR. ALEXANDER GILERSON joined the Grove School of Engineering in 2008 as a professor in the Department of Electrical Engineering. He received his BS, MS and PhD degrees from the Technical University in Kazan, Russia, where he also worked as a faculty member and research laboratory director. In 2003, Dr. Gilerson joined City College’s Optical Remote Sensing Laboratory as a research scientist. In recent years, he has led the CCNY group in multi-university campaigns in Chesapeake Bay, the waters of Georgia, Long Island Sound and New York/New Jersey areas. The aim of such trips is to measure the optical properties of coastal zone water by using state-of-the-art instrumentation and specially designed sensors. Now, Dr. Gilerson is a member of NOAA-CREST faculty and he’s a co-investigator on a grant from the Office of Naval Research.

In his current work with undergraduate and graduate students, Dr. Gilerson analyzes satellite images of water for the development, improvement and testing of bio-optical models and algorithms for future satellite missions. He works on the development of polarization probes, improvement of underwater imaging techniques as well as on expansion of the Optical Remote Sensing Laboratory’s measurement capabilities for its ocean research projects.

Dr. Gilerson’s recent work on the parameterization of chlorophyll fluorescence was welcomed by the community of researchers who study ocean color. During his work in remote sensing, he coauthored about 15 journal and more than 30 conference papers. He is a member of the Program Committee for the Coastal Waters Section of SPIE Europe Conference on Remote Sensing. Dr. Gilerson enjoys teaching electrical engineering and environmental engineering students in his course: Introduction to Remote Sensing and Satellite Imagery.

Figure 6. Plots of the DOP vs. scattering angle for Station 4: (a) 1m above water, (b) 1m below water.

we note a significant reduction of the DOP at Station 7. These can be traced to the diffuse illumination from clouds as well as an increase in mineral concentrations. We also note the shift of the maximum of the DOP towards 100° scattering angle. Chami et al. [1] predicted this effect and suggested its use to allow discrimination between biological and non-biological constituents which should be further verified.

It is worth noting that for remote sensing purposes, only scattering angles in the range 130-150° should be realistically considered. We recorded above water
measurements for Station 4 and the data are presented in Fig. 5 in comparison with underwater measurements. For angles corresponding to the scattering angle in water less than 130°, sun glint effects appear, giving abnormal values of DOP.

Comparisons between spectral dependences for measurements of the DOP taken at Station 1 are presented in Fig. 7. We observe a maximum in the DOP at lower wavelengths. This region is dominated by chlorophyll and CDOM absorptions, as can be seen in the normalized absorption spectrum reported in the top part of Fig. 7. In the top part of Fig. 7, the total absorption spectrum (atot) divided by the total attenuation spectrum (ctot) is also shown. Of course atot/ctot=1-ω, where ω, the single scattering albedo, is a good measure of the amount of multiple scattering. If ω decreases, multiple scattering events are reduced and the DOP increases. Fig. 7 also shows that the DOP reaches maximum values in the range 0.4-0.5 at 410 and 440nm. On the other side of the spectrum (i.e. 700-750nm), another maximum appears. This behavior is consistent with the absorption spectrum. After 700nm, water absorption starts increasing, minimizing again elastic scattering. The relative maximum between 600-650nm is also consistent with the absorption curve. On both sides of this relative maximum, two minima occur and the DOP reaches minimum values around 0.3. The first minimum is consistent with the minimum in the absorption; absorption decreases and multiple scattering events increase, depolarizing the underwater light field. The second minimum, however, cannot be directly related to the absorption curve. This dip in the DOP is due to the chlorophyll fluorescence in this spectral interval, which occurs in addition to elastic scattering and it is unpolarized [4, 5]. This hypothesis is confirmed by the comparison of experimental data with Monte Carlo simulations, which will be shown in the next section.

To assess the results beyond simple qualitative experiments, the polarimeter measurements were compared to the results of a Monte Carlo Vector Radiative Transfer model to simulate the complete Stokes vector. This is an updated version of the code used in Adams and Kattawar [11] and Adams et al. [12]. A plane-parallel model of the coupled atmosphere ocean system, it allows for a number of different layers in both the atmosphere and ocean. Fig. 8 shows a comparison between the measured and modeled values at Station 1, at a wavelength of 510nm for the DOP and the normalized radiance. We note that the modeled and measured values show excellent agreement with both DOP and radiance. The largest difference occurs with the radiance values in the direction of the sun, which is not surprising. The agreement between the magnitudes of the measured and modeled DOP is remarkable considering the proximity of the radiometer to the surface and waves up to 1.2m high.

Similar comparisons for wavelength 676nm for Station 1 are also presented in Fig. 9. The match in this case is poor. The Monte Carlo radiative transfer code did not include chlorophyll fluorescence which, as anticipated above, decreases the value of the DOP. This explains the significant difference in the measured and simulated values. Fig. 10 summarizes the spectral comparisons of modeled and measured DOP for four relevant scattering angles for Station 1. Again, the match is quite good except in the region of chlorophyll fluorescence as discussed before.
CONCLUSIONS
An analysis of the angular (0-180°) and spectral (400-750nm) variations of the degree of polarization was performed. It was observed that maximum values of the DOP, which occurred approximately at scattering angle of 100°, did not exceed 0.4 for all stations. In overcast conditions however, the light was still partially polarized but with the maximum DOP reduced to approximately 0.2. Spectral dependence of DOP very well correlates with the measured water absorption and single scattering albedo (ω) spectra: increase of absorption (decrease of ω) corresponds to the decrease of the number of the scattering events which means less depolarization. In the spectral area of chlorophyll fluorescence we observed significant decrease of DOP which is explained by the depolarizing effect of fluorescence. For remote sensing applications, when scattering angles are in the range of 130-150°, the DOP does not exceed 0.2. In addition, we note that the measured values above water very well correspond to the results of underwater measurements. This result suggests that, despite the effect of the water surface on the polarization of light, the contribution of the underwater polarized light field is sufficiently significant to affect the above water signal. This makes the study of polarization in the ocean promising for future improvement of retrieval algorithms in complex waters, such as those found in the coastal areas. In addition, by performing these measurements underwater, further noise sources due to the wind-roughened state can be eliminated. The excellent agreement between the Monte Carlo results and the experimental data are also shown and clearly demonstrate the success of radiative transfer simulations applied to the transmission and scattering of light in an atmosphere-ocean system. The shape of both the radiance distribution and the DOP has been correctly reproduced for dramatically different atmospheric and water conditions. It is expected that the ability of our polarimeter to provide information about the characteristics of the underwater polarized light field has great potential for application in radiative transfer problems in the earth-ocean system; hyperspectral and multiangular data can be collected very accurately and in a short time, thus changes both in the water and in the atmosphere can be avoided.

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