Polarization measurements in coastal waters using a hyperspectral multiangular sensor

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ABSTRACT

The polarized underwater light field contains information about the intrinsic nature of various water constituents and can be used in retrieval algorithms for the separation of organic and inorganic particulates and other applications. To study underwater polarization characteristics a new Stokes vector spectroradiometer has been developed by the Optical Remote Sensing Laboratory at CCNY. Results of measurements of water polarization properties using this instrument during a recent cruise on R/V "Connecticut" in the coastal areas of New York Harbor - Sandy Hook, NJ region are presented for waters with chlorophyll concentrations 2-8 µg/l, minerals concentrations 1-2 mg/l. 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 while the position of the maximum is shifted from 90º towards higher scattering angles. Total reflectances and degrees of polarization are then compared with simulated ones using a Monte Carlo radiative transfer code for the atmosphere-ocean system showing excellent agreement.

INTRODUCTION

Underwater polarized reflectance contains useful additional information on inherent optical properties (IOP), concentrations and size distributions of water constituents when compared with unpolarized data [1-4]. Study of polarized light components includes information about spectral dependence, impacts of the illuminating and viewing angles, relationships with IOP, surface roughness, etc., both for the ocean itself and for the ocean-atmosphere system. The potential use of multi-angle polarimetry can be analyzed in the context of optical water properties, including the choice of appropriate sensor orientations. Recently, Chami [5] using theoretical modeling showed that an empirical-based inversion approach relying on the underwater polarized reflectance could retrieve the concentration of inorganic particles regardless of the phytoplankton content in coastal waters. On this basis, measurements of the polarization state of underwater oceanic radiation might allow direct estimation of suspended inorganic matter concentration from remotely sensed data in coastal waters. 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. The purpose of this paper is to exploit underwater angularly resolved measurements of the degree of polarization (DOP) obtained in a coastal environment. Other goals of this paper are to validate some of the theoretical findings about the
influence of marine particles on the polarized signal and to analyze its wavelength dependence. First, the field experiment will be described. Then, measurements of the DOP, obtained through a newly developed Stokes vector spectroradiometer, will be presented and discussed together with in situ standard optical measurements, including total reflectance spectra (GER Spectroradiometer) and water absorption and attenuation spectra (WET Labs AC-S instrument). Field data are compared with simulations using Monte Carlo radiative transfer code of the atmosphere-ocean system.

EXPERIMENTAL RESULTS

Measurements were taken during a recent cruise on R/V "Connecticut" in the coastal areas of New York Harbor - Sandy Hook, NJ region, on July 21-23 2008. The wind speed according to the ship instrument measurements was in the range 3 to 7 m/s. The ocean surface wave amplitude did not exceed 1m. The sky was clear blue with no clouds during the data acquisition time for the first two days (Stations 1-5) and it was overcast during the last day (Stations 6-8). Polarization measurements were taken using a Stokes vector spectroradiometer developed by the Optical Remote Sensing Laboratory at the City College of New York, NY. The instrument consists of three Satlantic Hyperspectral radiance 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. 1. The motor rotates the sensors in a vertical plane in a specific angular range which was adjusted according to the solar altitude angle in order to cover the full 0-180° range of scattering angles. Measurements were taken every 5°. Linear polarizers are attached in front of the sensors; the polarizers are oriented at 0° (vertical), 90° (horizontal) and 45°. By rotating the sensors relative to the nadir direction, the instrument scanned the angular features of the underwater DOP in a vertical plane defined by its azimuth angle relative to the sun. The azimuth angular orientation of the instrument could be easily controlled by hand. The initial azimuth angular position usually corresponds to the principal plane, which is defined by the sun and the zenith. During this cruise all measurements were done only in the principal plane. We exploited all the features of our instrumentation (i.e. the possibility of measurements at different azimuth angles and at different depths) during its initial testing in chlorophyll rich waters [6]. Downwelling irradiance was controlled by the irradiance sensor on the deck of the boat. Instrument was kept at 1m below the surface by attached 4 horizontal arms 1m long each with buoys at the top of it.

Fig. 1. The underwater instrument developed by the Optical Remote Sensing group at City College of New York.
Water optical properties were measured at the same stations by an AC-9 instrument (WET Labs, Inc.). Attenuation and absorption data are currently available for stations 1, 4, 5 and 7. Concentrations of mineral particles and chlorophyll were not measured directly in the field, but they can be estimated by analyzing absorption and attenuation spectra measured with our AC-9 instrument. Specifically, TSS (Total Suspended Sediments) concentration can be estimated from the difference between total attenuation and total absorption values at 550 nm, which is equal to the total scattering and numerically roughly equal to TSS concentration [7], mineral concentration then equals TSS concentration multiplied by 0.5-0.7; chlorophyll concentration, on the other hand, can be estimated as the elevation from the baseline at 675 nm on the absorption spectrum divided by 0.0146 [8]. Understanding that these assumptions can differ strongly for different regions and waters, we used them only as a rough approximation for chlorophyll and mineral concentrations. Attenuation (c) and absorption (a) curves with and without water are shown in Fig. 2, where mineral concentration estimated using the above approximation was 1.3 mg/l for Stations 1, 4 and 5, and 2.0 mg/l for Station 7. Chlorophyll concentration was 8.2 µg/l for Stations 1, 4 and 7, and 2.0 µg/l for Station 5. In Fig. 2b total absorption spectra are shown which include water absorption together with the spectra from Fig. 2a. As it will be shown below total absorption spectra are important in the analysis of the spectra of the DOP.

Fig. 2. Absorption and attenuation spectra recorded with the WetLabs package.

We also recorded total reflectance spectra just below the water surface, using a GER Spectroradiometer (Fig. 3). The sky was clear with no clouds at Stations 1-5. At Stations 6-8 the sky was overcast with mostly diffuse light rather than direct sun light. Station 8 was located in the Hudson River which explains the strong increase of reflectance due to an expected increase of mineral scattering.

Fig. 3. GER total reflectance spectra.
Fig. 4a shows that there’s no difference in readings between the three polarization directions when the instrument is positioned at one of the neutral points (0°), showing that at least in our case, the impact of atmospheric particles and air-water interface on underwater polarization was minimal, while for scattering angles away from neutral points (90°, for example) the situation changes dramatically (Fig. 4b).

Fig. 4. Spectral dependence of the signal recorded by the Satlantic Hyperspectral sensors when the scattering angle is 0° (a) and when it’s 90° (b). The instrument is positioned in the main scattering plane, 1m below water.

One important aspect of polarization measurements is the repeatability of a set of recordings; sometimes this is not possible due to the ever changing ocean environment and the intrinsic low intensity level of the polarization signal. Fig. 5 shows all data points acquired in a set of measurements. Note the low variability of the experimental data points for most of angles underline the high accuracy of the detection method.

Fig. 5. Spread of the data points acquired during a set of measurements. Data are shown for λ=550nm.

Typical polarization phase functions (i.e. DOP vs. scattering angle), recorded in the main scattering plane at 1m depth are presented in Fig. 6. Evidently, the maximum of the DOP is lower than the theoretical Rayleigh prediction by 50% (i.e. it reaches a maximum value of approximately 0.4 at
410nm). Results for stations 1-5 are very similar due to similar water compositions (results for stations 1 and 2 are shown in Fig. 6. Note the reduction of the DOP at Station 7 and 8 (Fig. 6c and d) due to the diffuse illumination because of clouds and in addition for the Station 8 due to the increase in mineral concentrations. At Station 8, which was located in the Hudson River the maximum value of the DOP is approximately 0.2. Also note the shift of the maximum of the DOP towards 100º scattering angle for Station 1. 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. In fact, according to [9], as the real part of the refractive index increases (mineral particles) the absolute maximum of the DOP decreases in value and shifts towards higher scattering angles. As the imaginary part of the refractive index (phytoplankton particles) increases, the opposite occurs: the absolute maximum of the DOP increases in value and shifts towards lower scattering angles, because absorption depresses the scattering and interference.

![Fig. 6. Polarization phase functions. The instrument is located in the principal plane 1m below water.](image)

It’s worth noting that for remote sensing purposes only scattering angles in the range 130-150º should be realistically considered. We recorded above water measurements for Station 4 and the data are presented in Fig. 7 in comparison with underwater measurements. For angles corresponding to the scattering angle in water less than 130º, sun glint effects appear, giving abnormal values of DOP. It is clear that the DOP corresponding to the range 130-150º will not exceed 0.1-0.2. Taking into account the fact that Station 4 presented a low value of minerals concentration and DOP decreases for higher concentration of minerals, we can expect this value of the DOP to be close to the upper limit which can be expected for remote sensing measurements. Values of DOP measured above and below water surface (Fig. 7a and b) for this range of angle well correspond to each other.
The DOP was also found to vary with wavelength. This dependence varies with the sun’s position, but at small solar zenith angles, maxima in the percent polarization generally appear at both ends of the measured spectrum. Comparisons between spectral dependences for measurements of the DOP taken at different stations are presented in Fig. 8. In Fig. 8a (which corresponds to Station 1), we observe a maximum in the DOP on the left side of the spectrum. This region is dominated by chlorophyll and CDOM absorptions, as can be seen in Fig. 2. In fact, if the absorption coefficient increases (i.e. the imaginary part of the refractive index increases), multiple scattering events are reduced and the DOP increases. Fig. 8a 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. 750-800nm), another maximum appears. This behavior is consistent with the plots in Fig. 2. After 700nm, water absorption starts increasing, minimizing again elastic scattering. The relative maximum between 600-650nm is also consistent with the absorption curve of Fig. 2. On both sides of this relative maximum, two minima occur; the DOP reaches minimum values around 0.3. The first minimum is consistent with the minimum in Fig. 2; absorption decreases and multiple scattering events increase, depolarizing the underwater light field. The second minimum, however, cannot be related to the absorption curve of Fig. 2. At the present time we relate this dip in the DOP with the occurrence of chlorophyll fluorescence in this spectral interval, which replaces the elastic scattering, and which is unpolarized. [3, 4]. This assumption is confirmed by the data recorded at Station 8 (Fig. 8b). In the Hudson River, in fact, the concentration of chlorophyll is very low, and the dip in the DOP is barely noticeable. After 700-720nm, because of the increasing water absorption, the absolute values of radiance become very small, leading to big uncertainties in the calculation of the DOP and noise in the right edges of the spectra in Fig. 8.

Fig. 9 shows plots of the DOP for two specific wavelengths, i.e. 510nm (a) and 670nm (b) for all stations. Fig 10 shows the three different reflectance components (i.e. vertical, horizontal and 45º) as a function of the scattering angle with the maximum differences around 100º which correspond to the maximum of the DOP.
MODEL DESCRIPTION AND COMPARISON OF MODELED AND MEASURED DATA

The measurements were compared to the results of a vector radiative transfer model that uses the Monte Carlo method to solve for the complete Stokes vector. This is an updated version of the code used in Adams and Kattawar [10] and Adams et al. [11], and is a plane-parallel model of a coupled atmosphere ocean system and allows for a number of layers in both the atmosphere and ocean. Sea
Surface roughness is described using the sea-slope statistics of Cox and Munk [12]. For each station where comparisons are made, the measured and observed values of the solar zenith angle, wind speed, and absorption and scattering coefficients in the ocean are input into the code. The water column is assumed to be homogenous, but depth-dependent optical properties are easy to incorporate. The largest unknowns in these simulations are the atmospheric conditions. The modeled atmosphere consists of two layers, with the top layer chosen to be Rayleigh-scattering only and the bottom layer corresponding to a marine haze, similar to that described in Adams [11]. The atmospheric optical depth of the haze layer was then varied until the modeled sea-surface irradiance matched the measured values. The radiance values at 1m under the surface are normalized to the surface irradiance. Fig. 11 shows a comparison between the measured and models values at Station 1, at a wavelength of 510nm for the radiance reflectance and the DOP. The modeled and measured values show reasonable agreement with both radiance and DOP. 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. At this close distance, one of the largest sources of uncertainty is the effect of the wind-blown surface. Though generally small in other azimuthal planes, in the principal plane, on the side containing the direct beam of the sun, increased wind speed will cause the direct solar beam to spread into more angles and in general reduce the maximum DOP. Modeled results for the same optical properties show a smooth sea surface give a maximum DOP of approximately 10% higher than the wind-blown surface for this station. Fig. 12 shows the comparisons at Station 7, also at a wavelength of 510nm. Again, the agreement is good, which is quite remarkable due to the overcast skies and very windy conditions. The radiance reflectance values at 1m below the surface agree very well, and this time the modeled radiance values are slightly lower than the measurements at the peak. Also note the diffuse nature of the radiance under the surface, with the maximum very close to the zenith direction. The DOP again agrees very well, though there is quite a bit of statistical noise in the Monte Carlo simulations due to the large atmospheric depth and very windy conditions. Similar comparisons for wavelength 412nm for Station 1 are also presented in Fig. 13.

![Fig. 11. Comparison of modeled and measured data for 510 nm, Stations 1, a) DOP, b) total reflectance.](image-url)
CONCLUSIONS

Polarization characteristics of coastal waters were measured with high accuracy hyperspectrally for scattering angles 0-180°, using a newly developed polarization instrument. Maximum DOP, which occurred approximately at scattering angle of 90-100°, did not exceed 0.4 for all stations. For remote sensing purposes, when scattering angles are in the range of 130-150° DOP does not exceed 0.2. Measured values above water very well correspond to the results of underwater measurements. In overcast conditions light was still partially polarized with the maximum DOP reduced to approximately 0.2. Measured dependences of reflectances and degrees of polarization on the scattering angle very well matched simulated ones, using Monte Carlo atmosphere-ocean polarized radiative transfer model.
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