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Exploring Techniques for Improving Retrievals of Bio-optical Properties of Coastal Waters

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LONG-TERM GOALS

Development of algorithms for improved retrievals and monitoring of inherent water optical properties (IOP) from satellite imagery of coastal waters with current and future sensors for improvement of Navy electro-optical system performance utilizing: 1) VIS-NIR channels, 2) polarization characteristics of light in sea water and 3) advanced atmospheric correction schemes.

OBJECTIVES

Enhancement of algorithms for IOP retrieval from reflectance spectra with utilization of VIS and NIR bands through: a) the use of reflectance characteristics obtained from red-NIR measurements as additional constraints in basic inversion models, b) utilization of satellite data (SeaWiFS, MODIS, MERIS, etc.) and the data from the LISCO offshore platform.

Utilization of underwater and above water polarization components of reflectance spectra for the improvement of in-water visibility by particle type discrimination, and algorithm development through: a) the simulation of polarization components of reflectance for coastal water environments using polarized radiative transfer and b) measurements of polarization characteristics in field conditions to validate radiative transfer modeling and assess possibilities for the separation of organic and inorganic particulate components, improvement of underwater visibility and target detection.

Development of advanced atmospheric correction models including a) incorporation of additional constraint for atmospheric correction in coastal waters, b) development of the interface to perform retrievals based on real time radiometer and lidar observations.

APPROACH

Enhancement of algorithms for IOP retrieval from reflectance spectra with utilization of VIS and NIR bands Data from the multispectral SeaPRISM instrument on the Long Island Sound Coastal Observatory (LISCO) is used for the validation of JPSS VIIRS sensor on the coastal site and comparison with other Ocean Color satellites. A Neural Networks (NN) approach recently developed for reflectances related to IOPs is extended for more accurate retrieval of chlorophyll concentration.

Utilization of under and above water polarization components of reflectance spectra for improvement of in-water visibility by particle type discrimination and algorithm development Extensive vector radiative transfer simulations for a very broad range of ocean and coastal water parameters were used for the analysis of the underwater polarized light fields and their relationships with characteristics of water particulates, specifically retrieval of the attenuation-to-absorption ratio from below and above surface measurements of Stokes components of upwelling polarized light. A modified integrated system of the polarimeter, thrusters and full Stokes vector video camera was successfully used in various water environments for underwater polarization imaging and target characterization.

Development of advanced atmospheric correction models Combinations of instrumentation on the LISCO site measuring aerosol properties (SeaPRISM) and hyperspectral reflectances (HyperSAS) were utilized for the development of a novel approach which takes into account polarization characteristics of skylight and is aimed at the improvement of SeaPRISM data processing.

WORK COMPLETED

- The Long Island Sound Coastal Observatory (LISCO) on an offshore platform, operational since the fall 2009 as a part of NASA AERONET and AERONET-OC networks combining multispectral SeaPRISM and hyperspectral HyperSAS instruments, evolved into one of the key elements for validation of OC satellite data, especially after launch of the JPSS – VIIRS instrument. Quality of

the data is continuously evaluated through matchups between instruments on the platform as well as with the satellite data of VIIRS, MODIS and MERIS.

- Three neural networks of remote sensing reflectances for MODIS VIS and NIR bands, and related to IOP components, were trained on synthetic data and validated on the NOMAD and field CCNY data; derived IOPs, combined with measured Rrs values are then used in a final NN, to derive [Chl], thus effectively reducing the inherent non-uniqueness of solutions.
- A coastal ocean circulation model (FVCOM) was expanded for regions from the Chesapeake Bay to Boston, especially NY and NJ region where mesh at coastal regions (especially NY and NJ) is as fine as less than 10 m. The model has been set up at supercomputing centers including the National Energy Research Scientific Computing (NERSC) of DOE. The model will be used for further incorporation of the satellite data.
- Based on extensive radiative transfer simulations using the vector radiative transfer code RayXP, it is demonstrated that the underwater degree of linear polarization (DoLP) is closely related to the attenuation-to-absorption ratio (c/a) of the water body, a finding that enables retrieval of the attenuation and scattering coefficients from measurements of the Stokes components of the upwelling underwater polarized light field.
- Polarized and unpolarized targets were imaged underwater at various water conditions, depths, illumination and azimuth angle with a full Stokes vector imaging camera on the integrated polarimetric system (also part of the MURI program – PI M. Cummings, see details in the MURI report).
- Aerosol optical thicknesses (AOT) and distributions of Angstrom coefficients from MODIS, MERIS and VIIRS are estimated for the LISCO site and compared with SeaPRISM data. Aerosol characteristics obtained from the SeaPRISM instrument on the LISCO site were used for the development of a new approach for sky glint correction which takes into account polarization characteristics of the skylight reflected from the water surface.

RESULTS

Enhancement of algorithms for IOP retrieval from reflectance spectra with utilization of VIS and NIR bands

Validation of the satellite imagery using LISCO data

To support present and future multi- and hyper-spectral calibration/validation activities, as well as the development of new measurement and retrieval techniques and algorithms for coastal waters, City College (CCNY) along with Naval Research Laboratory at Stennis Space Center, has established an off-shore platform, the Long Island Sound Coastal Observatory (LISCO) which is in operation since October 2009. This site combines multi-spectral (SeaPRISM) and hyperspectral (HyperSAS) radiometer measurements, for comparisons with satellite and in situ measurements and radiative transfer simulations for coastal waters, helping to provide more effective closure for the whole measurement validation/ simulation loop. Thus, measurements from the platform are utilized for multi-spectral calibration/validation of current Ocean Color satellites (MERIS, MODIS, SeaWiFS) in coastal waters. With the launch of JPSS-VIIRS sensor in October 2011 the efforts were focused on VIIRS validation including the comparison VIIRS data with current Ocean Color satellites (MERIS, MODIS)

on the LISCO site as well as with the instruments on the platform. This comparison for normalized water leaving radiances is shown in Fig. 1 and results of matchups in Fig. 2.

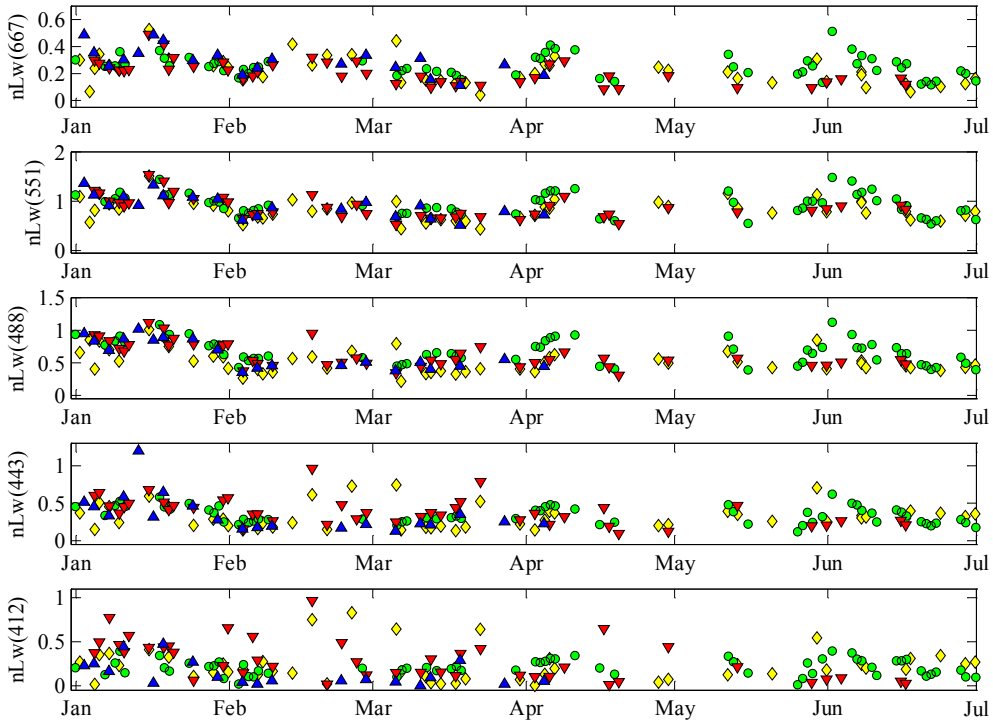

Fig. 1. Time series of normalized water leaving radiance, nLw(λ), (in mW cm^{-2} sr^{-1} nm^{-1}) retrieved from SeaPRISM (green dots), MODIS (yellow diamonds), VIIRS (red triangles) and MERIS (blue triangles) at the SeaPRISM spectral bands.

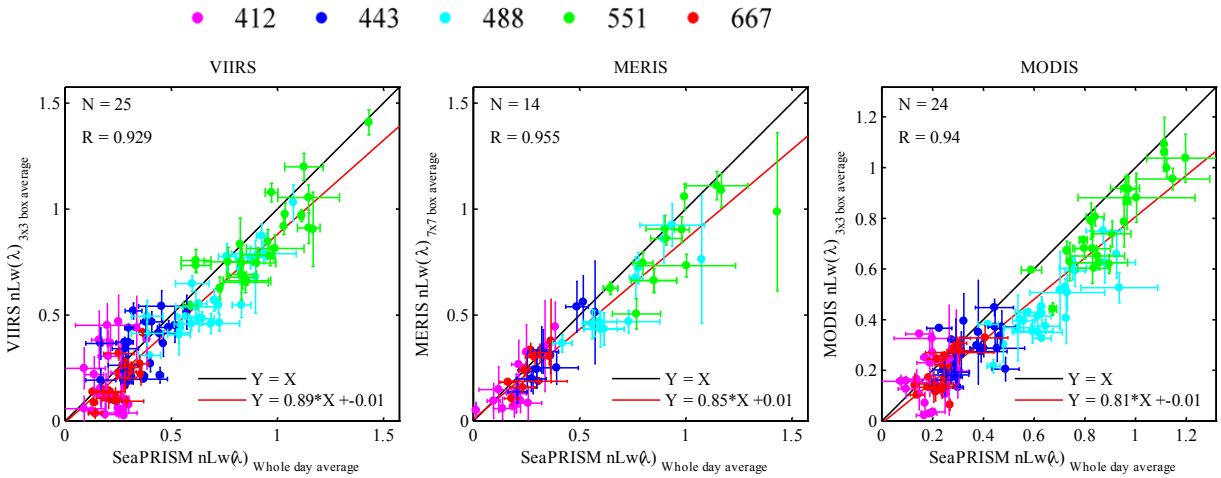

Fig. 2 Matchup comparison between the normalized water leaving radiance nLw(λ) (in mW/cm^2/um) retrieved from SeaPRISM data and (Left) VIIRS, (Middle) MERIS and (Right) MODIS data. N is the total number of satellite images considered in each matchup comparison. Horizontal and vertical error bars represent the temporal and spatial variations in SeaPRISM and satellite data respectively.

Impacts of the non-perfect cosine response of the irradiance sensor of HyperSAS and the presence of absorbing aerosols on the HyperSAS and SeaPRISM downwelling irradiance derivation are also analyzed. Further analysis of the total sea radiance and water leaving radiance intercomparisons and data filtering procedures for instruments on the LISCO site showed that the observed discrepancies between the data of the two systems are only about 1% when both instruments are pointed approximately in the same direction thereby minimizing the directional fluctuations.

Development of a neural network approach to retrieve inherent optical properties and chlorophyll concentration in sea water based on MODIS bands

Our previous work of neural network (NN) retrieval was expanded by developing two new NNs whose outputs are used to separate the non-phytoplankton absorption coefficient into dissolved and particulate components and to estimate oceanic chlorophyll concentrations from remote sensing reflectance (Rrs). The latter method shows a significant improvement in accuracy over traditional maximum band ratio (MBR) algorithm retrievals. First, a NN is trained to estimate the ratio of the absorption coefficient of non-phytoplankton particulates to the absorption coefficient of dissolved species at 443nm, from the remote sensing reflectance measurements at the MODIS visible wavelengths (412, 443, 488, 531, 547 and 667nm) thereby permitting analytical separation of the non-phytoplankton absorption at 443nm into its independent components. These two new products, in addition to parameters of total, phytoplankton, non-phytoplankton absorptions and total backscattering coefficients derived in our previous work, are further used to provide comprehensive information about the inherent optical properties (IOPs) of the water body. These derived IOPs, combined with measured Rrs values are then used in a final NN, to derive [Chl], thus effectively reducing the inherent non-uniqueness of solutions. Comparison of OC3 and NN algorithms is shown in Fig. 3

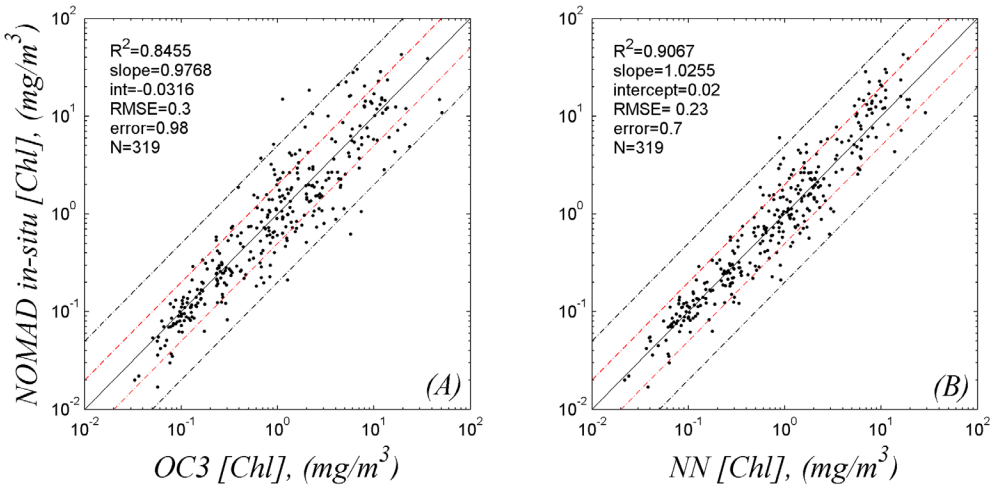

Fig. 3 Comparison between the OC3(left) and NN(right)) derived [Chl],(mg/m3) (x-axis) compared with the in-situ measured [Chl],(mg/m3) (y-axis) for the part of the dataset that was not used in the training.

Utilization of underwater and above water polarization components of reflectance spectra for improved retrievals of particle type discrimination and algorithm development

<u>*Estimation of the attenuation coefficient of the water body using polarimetric observations*</u>

The attenuation coefficient of the water body is not directly retrievable using measurements of unpolarized water-leaving radiance. Based on extensive radiative transfer simulations using the vector radiative transfer code RayXP, it is demonstrated that the underwater degree of linear polarization (DoLP) is closely related to the attenuation-to-absorption ratio (c/a) of the water body, a finding that enables retrieval of the attenuation coefficient from measurements of the Stokes components of the upwelling underwater polarized light field. The relationship between DoLP and the c/a ratio is investigated for the upwelling polarized light field for a complete set of viewing geometries, at several wavelengths in the visible part of the spectrum, and for varying compositions of the aquatic environment, whose constituents include phytoplankton, non-algal particles, and color dissolved organic matter (CDOM) as well as for varying microphysical properties such as the refractive index and the slope of the Junge-type particle size distribution (PSD). As the result this study reveals the possibility for retrieval of additional inherent optical properties (IOPs) from air- or space-borne DoLP measurements of the water-leaving radiation. The parameterized relationship was estimated using a power law fitting for the three PSD slopes of NAPs as follows (see Fig. 4):

$$\left\{\left(\frac{c}{a}\right)_{fit}\right\}_{\xi_{nap}=3.5,4.0,4.5} = \left\{\chi(DoLP)^{\gamma}\right\}_{\xi_{nap}=3.5,4.0,4.5}$$

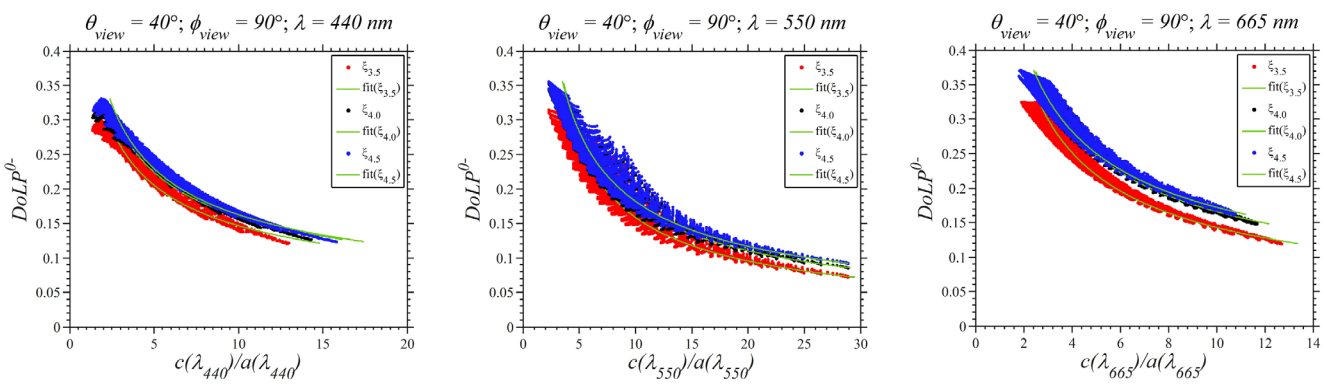

Fig. 4. Fitted Relationship between DoLP at θview = 40° and c/a ratio at 440, 550 and 665nm for three different NAP slopes of the particle size distribution (PSD).

The coefficient R^2 between the parameterized/fitted values of c/a(DoLP) and the resultant values of the radiative transfer simulations was also calculated. In order to have a synoptic view of the fitting quality, the R^2 values are plotted in Figure 5 for all the viewing geometries available for a given solar zenith angle 30° and for the detector just below water surface. In this manner, we can estimate the range of geometries that permit us to obtain the best accuracy for the retrieval of the attenuation (and the scattering, b=c-a) coefficient based on measurements of the DoLP. It can be seen that 665nm is the best band for the retrieval. Results are similar for the c/a(DoLP) simulated just above water surface.

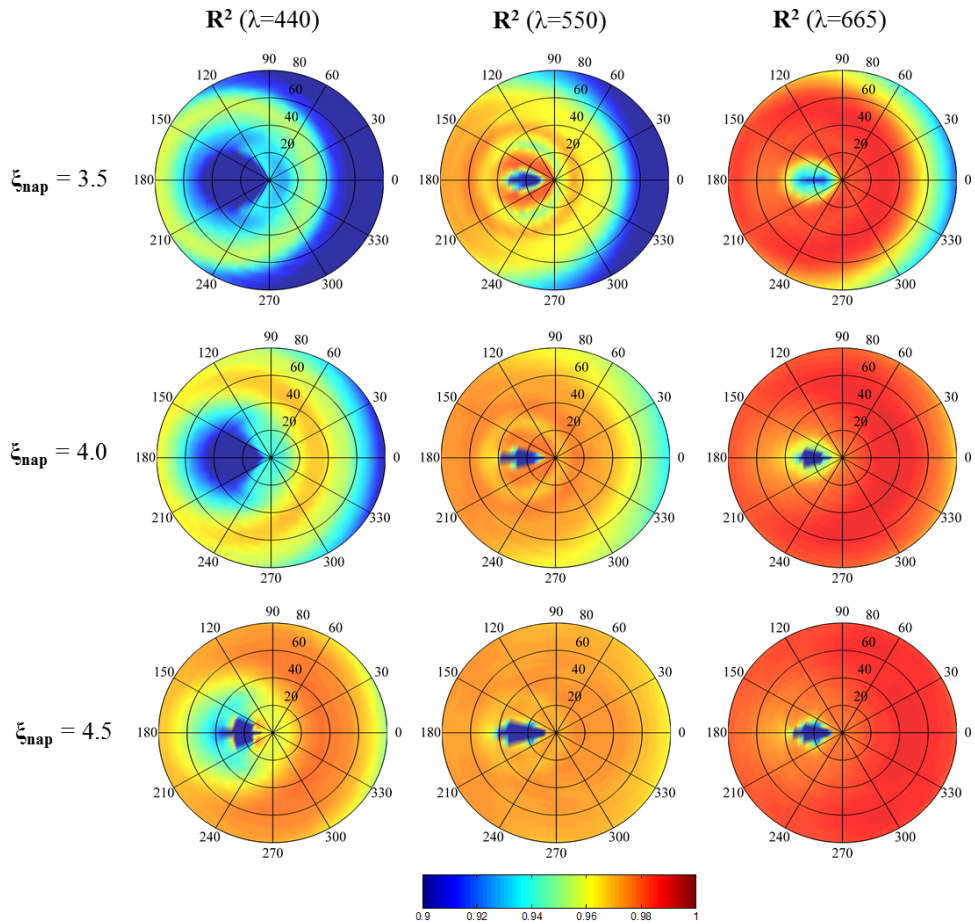

Fig. 5. Synoptic view of the coefficient of determination R^2 between the parameterized/fitted values and the resultant values of the radiative transfer simulations

<u>*Underwater polarization imaging using integrated polarimetric system*</u>

Integrated system for polarimeteric underwater measurements and imaging is shown in Fig. 6. It includes hyperspectral polarimeter for multi-angular hyperspectral polarimetric measurements, thrusters for orientation control of the system against the sun under water and a full Stokes vector imaging camera in the underwater housing for polarization imaging (up to 15frames/s, currently in the green band,520-550nm). This system was successfully used in various water environments for combined measurements of polarization light fields and polarization imaging of targets, shallow bottoms and ruffled water surfaces in various water environments (Florida Keys, August 2011, Curacao, 2012, Long Island Sound and NY Bight, 2012). Example of images of the shallow bottom from the camera without correction and with polarization correction and deconvolution with point spread function (PSF) is shown in Fig. 6.

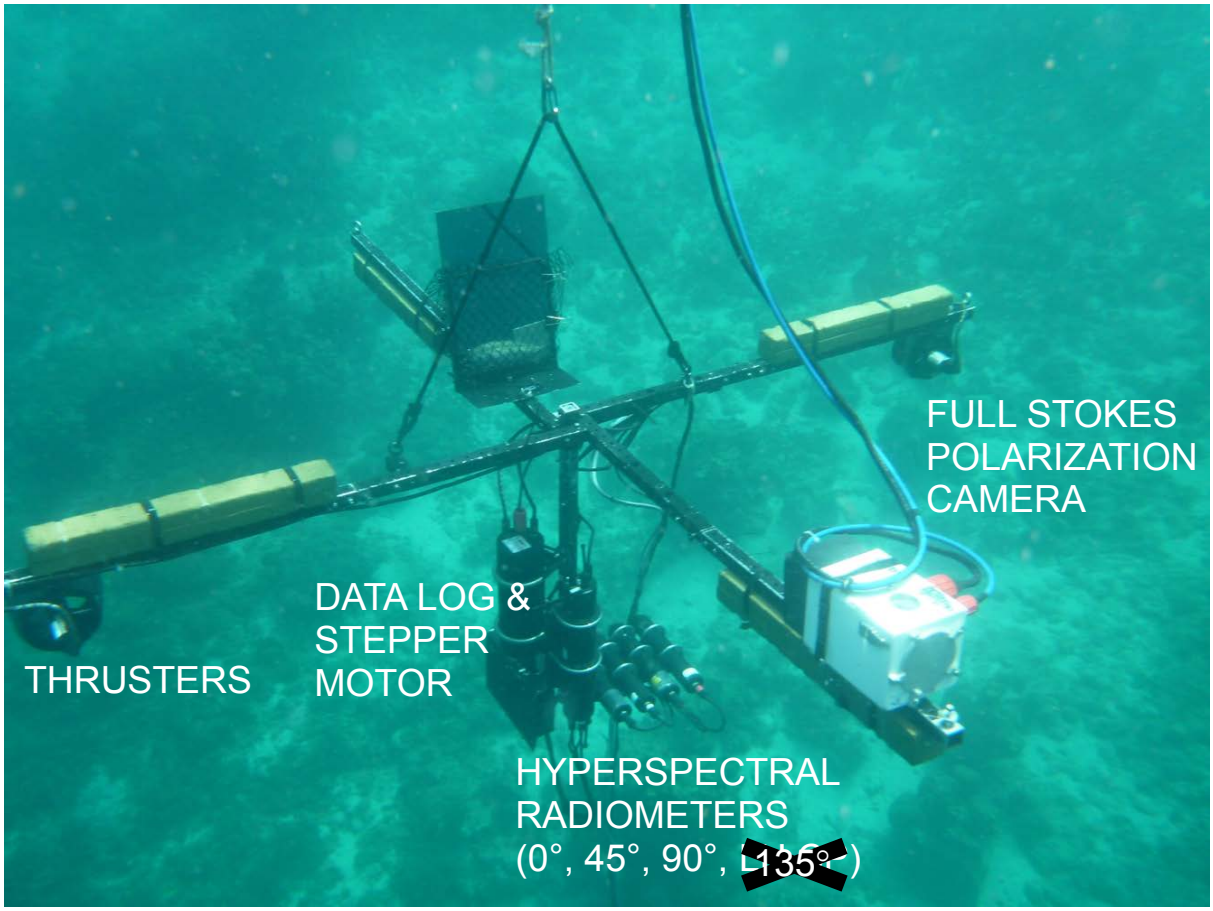

Fig. 6. Integrated underwater system for polarization measurements and imaging

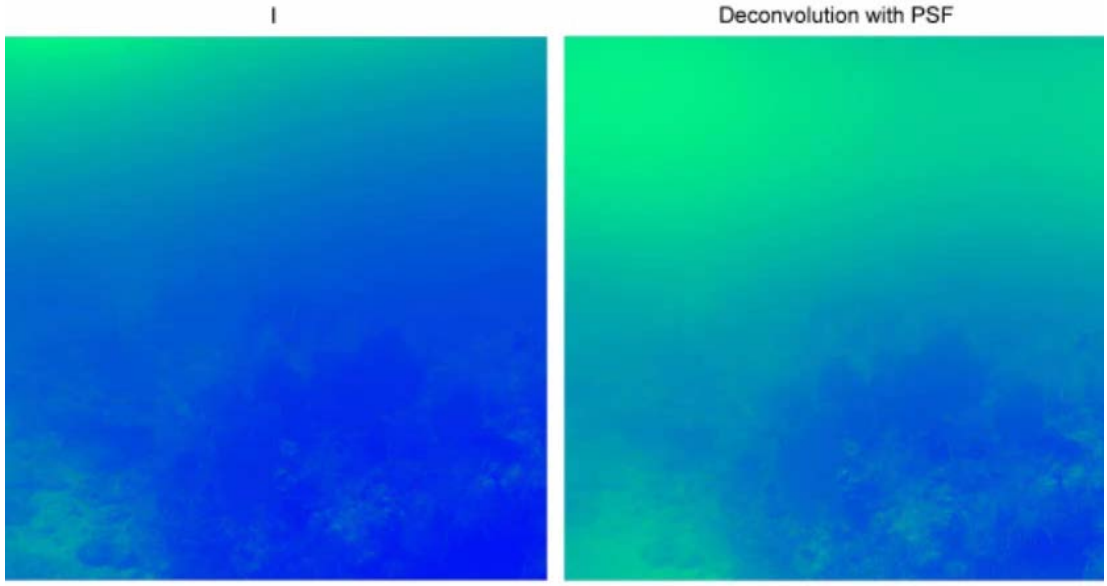

Fig. 7. Image of the bottom (left) and corrected using polarization technique and PSF deconvolution (right).

Development of advanced atmospheric correction models

Distributions of the Angstrom coefficient from ocean color satellites (MODIS, MERIS and VIIRS) and SeaPRISM at the LISCO site showed discrepancies suggesting the necessity of broader aerosol models for coastal waters as shown in Fig. 8.

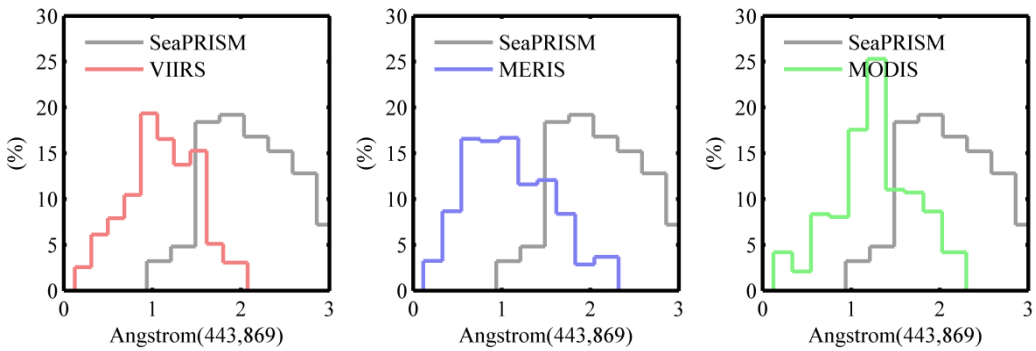

Fig. 8. Histograms of the % distribution of the Angstrom exponent plotted in grey for SeaPRISM and in red, blue and green for VIIRS, MERIS and MODIS respectively.

A newly developed algorithm based on radiative transfer simulations including polarization is described. Its application to the standard AERONET-OC and hyperspectral radiometric measurements of the 1.5-year dataset acquired at the Long Island Sound site demonstrates the noticeable importance of considering polarization for water-leaving radiance estimation. In particular, it is shown, based on time series of collocated data acquired in coastal waters, that the azimuth range of measurements leading to good quality data is significantly increased, and that these estimates are improved by more than 12% at 413 nm. Full consideration of polarization effects is expected to significantly improve the quality of the field data utilized for satellite data validation or potential vicarious calibration purposes. The sea surface reflectance in case of unpolarized and polarized reflection from RT simulations is shown in Fig. 9.

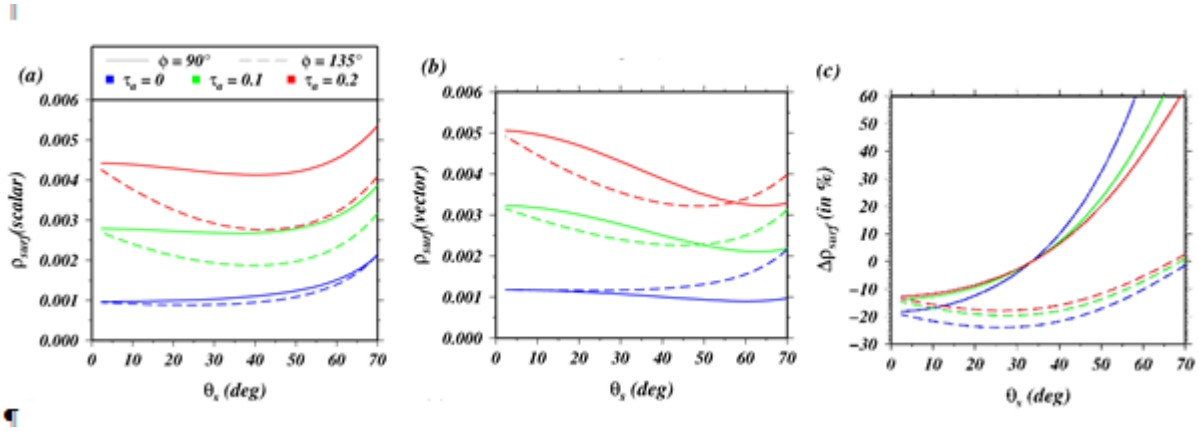

Fig. 9. Sea surface reflectance at 550 nm for no-wind conditions with respect to the solar angle computed (a) in ignoring the polarization terms of the Fresnel matrix (i.e. R12=R13=0), (b) in fully considering polarization behavior of skylight reflection at the sea surface. (c) Relative difference expressed in percent between the sea surface reflectances displayed in (a) and (b). The results are shown for two different azimuths, namely 90° (solid lines) and 135° (dashed lines), and for different aerosol optical thicknesses: 0 (blue), 0.1 (green) and 0.2 (red).

IMPACT/APPLICATIONS

AERONET and AERONET-OC data from Long Island Sound Coastal Observatory (LISCO) site is now used continuously for validation of ocean color satellites, water monitoring and algorithm development in coastal waters including JPSS-VIIRS data after sensor launch in October 2011. Distribution of Angstrom coefficient on the LISCO site suggests the necessity for broader aerosol models for coastal waters. Polarization characteristics of the skylight reflected from the water surface should be taken into account to improve AERONET-OC data quality especially in the blue part of the spectrum.

A new technique for the retrieval of the attenuation/absorption ratio from polarized measurements of upwelling radiance is proposed based on radiative transfer simulations. This technique opens a possibility of retrieval of attenuation and scattering coefficients from future aircraft and airborne instruments with polarization sensitivity. Our newly developed integrated system for underwater polarization measurements and imaging opens possibility for the precise validation of polarization techniques as well as advanced imaging of polarized and unpolarized targets and deconvolution of the targets properties from polarized images.

RELATED PROJECTS

This ONR project, on improvement of retrieval of bio-optical properties, benefits from the leveraging of funding by NOAA CREST in which remote sensing of coastal waters is an important component.

Starting 2009 the CCNY group also studied polarization characteristics of light in water through another award from ONR N000140911054 for years 2009-2014 with the emphasis on underwater animals vision and camouflage properties and applications.

PUBLICATIONS

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