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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 water and 3) advanced atmospheric correction schemes.

OBJECTIVES

Enhancement of algorithms for IOP retrieval from reflectance spectra with utilization of UV, 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 through 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 blue band (412 nm) 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 UV, VIS and NIR bands

The NIR peak in reflectance spectra from coastal waters contains important information about chlorophyll concentration Chl and other parameters used in retrieval algorithms. Red-NIR algorithms for Chl retrieval were analyzed using both synthetic and field datasets for the development of the advanced, more universal versions of the algorithms (in collaboration with Dr. A. Gitelson, University Nebraska-Lincoln). Optical properties of toxic *Karenia Brevis* (*K. brevis*) algae were further analyzed with the goal of developing new approaches and algorithms for the satellite detection and distinction of *K. brevis* algal blooms (in collaboration with Dr. I. Gladkova, CS Dept, CCNY). The data from Long Island Sound Coastal Observatory (LISCO) with both multispectral SeaPRISM and hyperspectral HyperSAS instruments installed for the validation of the current and future Ocean Color satellites are analyzed in terms of impacts of the sunglint and coastal waters BRDF on the quality of the retrievals.

Utilization of underwater and above water polarization components of reflectance spectra for the improvement of in-water visibility through particle type discrimination, and algorithm development

The thrust of this part of the work is to obtain above and underwater angularly resolved hyperspectral field measurements of the degree of polarization (DOP) in wide variety of the open ocean and coastal environments using our newly developed Stokes vector spectroradiometer, and compare results with simulated data. Differences in polarization signatures for different waters can be further used in the improved interpretation of remote sensing signals and in comparisons with the polarization signatures of naval targets with the goal of improvement of visibility and detection.

Development of advanced atmospheric correction models

To incorporate lidar data from CCNY site into atmospheric correction for LISCO satellite imagery the data from AERONET CCNY site (in Manhattan) and AERONET LISCO site (on the platform) were statistically compared to estimate the validity of such approaches. In addition, we are using the LISCO site to reevaluate if retrieval errors at the shortest wavelengths can be traced to atmospheric retrieval biases in order to assess if 412nm estimator based corrections are needed.

WORK COMPLETED

- Two and three bands red-NIR algorithms for Chl retrieval were analyzed using synthetic, field and satellite data showing robustness of Rrs(665)/Rrs(708) and $R_{rs}^{-1}(665) - R_{rs}^{-1}(708)]\times R_{rs}(753)$ ratio models based on MERIS bands and advanced versions of the algorithms were developed which should be valid in the broad variety of coastal and inland waters.

- Recently developed by CCNY group algorithms for the detection and classification of K. Brevis blooms which utilize the difference signal at 2 red bands 667 and 678 nm on MODIS and similar bands on MERIS (Red Band Difference Technique) are compared to a new statistical based approach showing good matches.

- Long Island Sound Coastal Observatory (LISCO) on the offshore platform became operational in the fall 2009 as a part of NASA AERONET and AERONET-OC networks with multispectral SeaPRISM and hyperspectral HyperSAS instruments installed, the quality of the data are evaluated

through the matchups between instruments as well as with the satellite data of SeaWiFS, MODIS and MERIS. The data were also used in the validation of the HICO instrument on the International Space Station.

- Hydrodynamic model for LIS was developed for better understanding of the processes near the platform and for the further incorporation of the remote sensing data.

- The performance of the neural network algorithm which includes VIS and NIR bands for retrieving the IOP components from remote sensing reflectance was trained on synthetic and field CCNY data showed good performance for NOMAD data in a very broad range of water parameters.

- A Stokes vector spectroradiometer was used to obtain accurate and reliable *in situ* hyperspectral and multi-angular measurements of polarization characteristics of the underwater and above water light fields in the various coastal waters as well as in the open ocean "blue" waters. The angular and spectral dependence of the degrees of polarization (DOP) was analyzed, correlated to the water constituents and compared with radiative transfer models for the improved characterization of water parameters showing significant dependence on water environment. First attempts are made for the retrieval of underwater DOP from above water polarization measurements.

- The measured underwater polarized radiances were used to numerically reproduce the polarized images for underwater horizontal imaging system and to estimate the polarized components of the background veiling light. The blurring effects were modeled by point spread functions obtained from the measured volume scattering functions. The underwater imaging visibility improvement for unpolarized targets by using a polarizer oriented orthogonally to the partially polarized direction of the scattered veiling luminance was estimated for several water conditions and target reflections.

- The good correlation between aerosol optical thicknesses (AOT) at AERONET CCNY site (Manhattan) and AERONET LISCO site (Long Island Sound) has been established which opens a possibility of the incorporation of the lidar data at CCNY site for the atmospheric correction of the satellite data at the pixels which include LISCO platform.

- To optimize the 412nm estimator used to provide post-processing corrections on SWIR algorithms using Neural Networks we find the optimal channel selection is 490-510-555 and 670nm. We find that including the 443nm channel results in strong errors due to errors in operational atmospheric correction and should be left out.

RESULTS

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

Estimation of Chlorophyll-a in Coastal Waters using Red and Near Infrared Bands

Remote Sensing algorithms for retrieval of chlorophyll-a concentrations Chl from reflectance spectra and which employ the red and NIR bands are less sensitive to the absorption of the colored dissolved organic matter (CDOM) and scattering of mineral particles than traditional blue-green ratio algorithms [1]. We tested such two-band R2=Rrs(708)/Rrs(665) and three-band R3 = $[Rrs^{-1}(665) - Rrs^{-1}(708)]\times Rrs(753)$ algorithms using comprehensive synthetic datasets of reflectance spectra and inherent optical properties (IOP), related to various water parameters together with the analysis of the

dependence of the specific phytoplankton absorption on Chl. It was shown that two-band R2 and three band R3 Red-NIR algorithms almost do not depend on variations of CDOM absorption and backscattering, can be modeled as a function of water absorption coefficient at respective bands and the phytoplankton specific absorption at 665 nm $a^*_{ph}(665)$ and thus should not show significant variability in different waters. These two- and three band algorithms were established in the following forms:

$$[\mathrm{Chl}] = [35.745 * R2 - 19.295]^{1.124} \text{ and } [\mathrm{Chl}] = [113.36 * R3 - 16.45]^{1.124}.$$

Comparison of these algorithms (equation – red line) with Nebraska field data (blue circles - R^2 = 0.9588 and 0.9584 respectively) and the data in Azov Sea (Russia) determined from MERIS reflectances and in-situ Chl measurements (cyan lines) are presented in Fig. 1 below and shows a very good match. Black and green dash lines correspond to the expected boundaries of algorithms variations due to the changes in $a^*_{ph}(665)$.

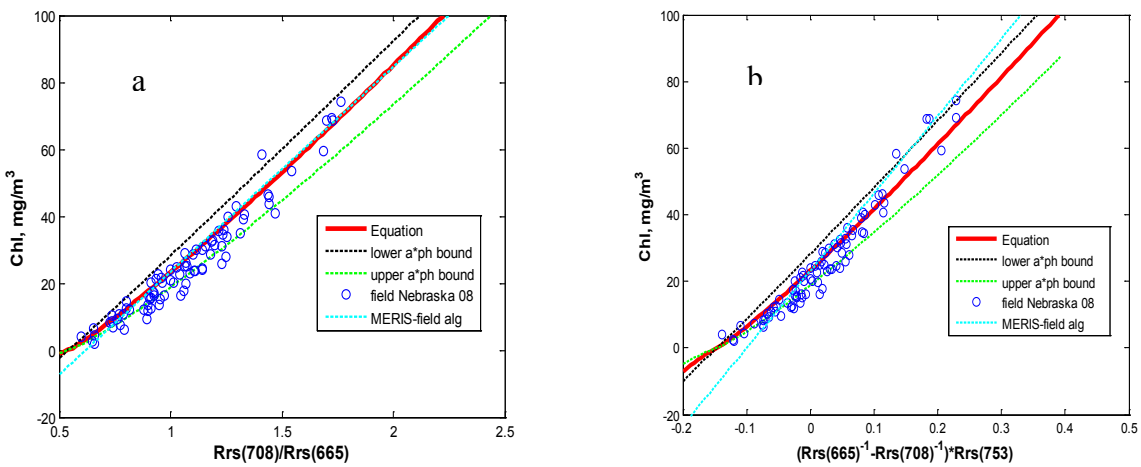

Fig. 1. Comparison of analytical relationships with the field data (Nebraska) and empirical algorithms from MERIS –field data: a) 2 bands algorithm, b) 3 bands algorithm.

On the other hand, simulations using the same datasets showed that blue-green ratio OC3M algorithm which is efficient for the open ocean has significantly lower correlations (R^2<0.4) with the simulated and field data which makes red-NIR algorithms more advantageous for coastal waters.

Novel Optical and Statistical Techniques for Detecting and Classifying Toxic Dinoflagellate Karenia brevis Blooms Using Satellite Imagery

We recently proposed a detection technique for blooms with low backscatter characteristics, which we named the Red Band Difference (RBD) and which takes advantage of the fact that because of lower backscatter characteristics in K. brevis blooms, the red peak in the reflectance signal is dominated chlorophyll fluorescence rather elastic scattering (Amin et al, 2009). Results

of the bloom detection using this technique were compared with a new statistical approach based on the development of the binary classifier for bloom conditions.

A statistical approach was applied to find K.brevis binary classifier for West Florida Shelf waters which relies on largest existing K. Brevis Harmful Algal Blooms (HAB) database from the The Fish and Wildlife Research Institute and associated with each observation a satellite product based observational vector. This vector is made up of the following variables: chlorophyll, normalized water leaving radiance at wavelengths 443, 551, and 667, and sea surface temperature, matching the time and location of the HAB database measurement. Once trained, this classifier is used to predict the HAB or no HAB state from the satellite based observation vector alone and thus detect K. Brevis blooms.

The process of creating training data set was the following. First, the entries were filtered out in the HAB database spatially if they did not fall in the Florida coastal region, and temporally if they were for a date not available in MODIS Ocean Level 3 product. Once the data for all the variables was gathered, observations that have been flagged as having cloud or land were filtered out, resulting in the final dataset used for training. That resulted in 236 positive and 778 negative observations in the training dataset, which after quadratic mapping were inputted to a fast algorithm known as the Ho-Kashyap learning rule to obtain a binary classifier of K. brevis. The initial results of this approach appear promising. They show relatively good detection of actual blooms with few false positives, and a good match up with RBD for the same blooms (Fig. 2).

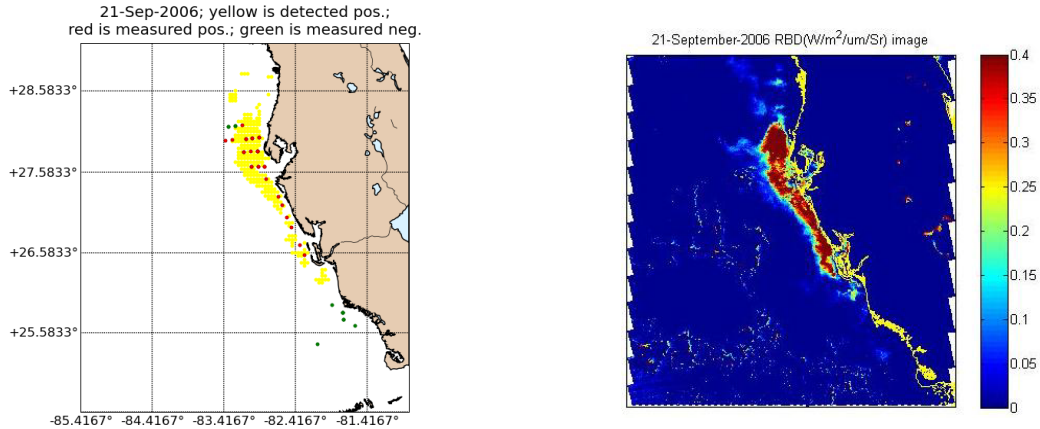

Fig. 2: a) Results for the HAB classifier. Green and red dots correspond to ground truth as given by historical database. Yellow dots correspond to the detected locations of HAB by the classifier, b) RBD retrieval for the same date.

Evaluation of the data quality on the LISCO offshore platform

The validation of the current and future Ocean Color satellite data is important for characterizing the optical environment connected with coastal waters. 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 a new, scientifically comprehensive, off-shore platform, the Long Island Sound Coastal Observatory (LISCO). This site has been designed to serve as

a venue and framework for combining multi- and hyperspectral radiometer measurements with satellite and in situ measurements and radiative transfer simulations of coastal waters, helping to and provide more effective closure for the whole measurement validation/simulation loop. Measurements from the platform are utilized for multi-spectral calibration/validation of current Ocean Color satellites (MERIS, MODIS, SeaWIFS) in coastal waters, and for evaluating future satellites missions (NPOESS, OCM2, Sentinel 2) with extension to hyperspectral calibration/validations of the hyperspectral sensors (HICO), as well as for improvements in coastal IOP retrieval and atmospheric correction algorithms.

The platform combines an AERONET SeaPRISM radiometer (CIMEL ELECTRONIQUE, France) as a part of AERONET Ocean Color Network [2], with a co-located HyperSAS (Satlantic, Canada) set of radiometers capable of hyperspectral measurements of water-leaving radiance, sky radiance and downwelling irradiance. Both instruments were installed on the LISCO platform (Fig. 3a) in October 2009 and since then have been providing data. SeaPRISM data are transferred by the satellite link to NASA, processed by the NASA AERONET group and posted on the NASA AERONET website. HyperSAS data are transmitted by broadband cellular service to the CCNY server.

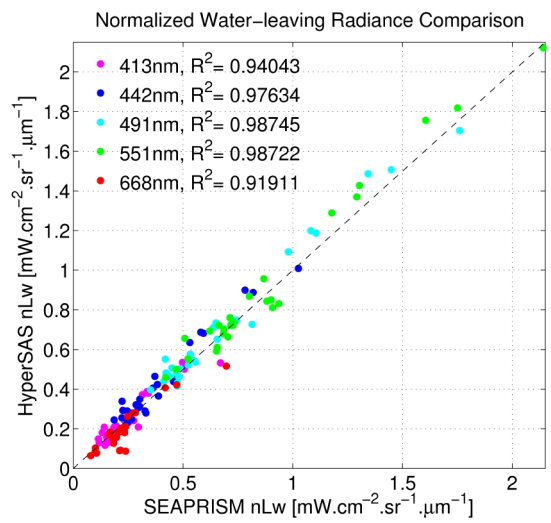

Fig. 3.a) SeaPRISM and HyperSAS instruments at the top of the retractable tower on the LISCO platform, b) Scatter plot of the comparison between HYPERSAS and SeaPRISM datasets from October 2009 up to April 2010.

The main difficulty with above-water measurements is associated with correcting the observations for the effect of surface waves that introduce significant fluctuations into the glint and reflected skylight components [3]. These fluctuations induce different geophysical noise to be removed from SeaPRISM and HYPERSAS sensors, respectively. Based on the retrieval scheme of SeaPRISM [4], a specific processing has been developed in order to derive the normalized water-leaving radiance nLw from the HYPERSAS measurements.

The comparison between HYPERSAS and SeaPRISM nLw datasets is plotted Fig. 3b for the wavelengths centered on the SeaPRISM bands from October 2009 up to April 2010. The results show a strong correlation, with R^2 greater than 0.92, between the two datasets for all wavelengths. However, a few outliers are present especially for the lowest values of nLw. This observation is consistent with

errors originating from the sky and sun glint correction of which the absolute values are independent on nLw. Thus, those collocated sensors enable us to assess the quality of different surface effect correction schemes over a long term monitoring. The achievement of such an analysis is expected for a near future. In addition, the observed dispersion between the two datasets relies also on the different techniques of measurements of the atmospheric transmittance and on the bidirectionality correction of nLw because of the different observational geometries used by SeaPRISM and HYPERSAS. The satisfactory correlations shown prove the consistency of the processing of both instrumentations. The long term monitoring as well as the comparison with satellite data is expected to determine the representativeness of each technique.

Hydrodynamic model for Long Island Sound

A circulation FVCOM model [5] is run for a region along the coast extending from the south of Massachusetts to the south of Virginia. In the simulation, 22922 nodes are used on the horizontal plane, and there are 11 layers in the vertical direction. Fig. 4a shows the region of the Long Island Sound and locations of the observation stations that measure surface elevation and current velocity. In this region, observations at four NOAA stations are used for the model calibration [6]. Predictions for surface elevation and current velocity at LISCO and Gardiners Bay are presented Fig. 4b and c. The LISCO pin indicates the location of an ocean color measurement station. This model will be further used for the better understanding of water parameters variability in the area of the LISCO platform, for the incorporation of optical remote sensing data and for the coupling with biological models.

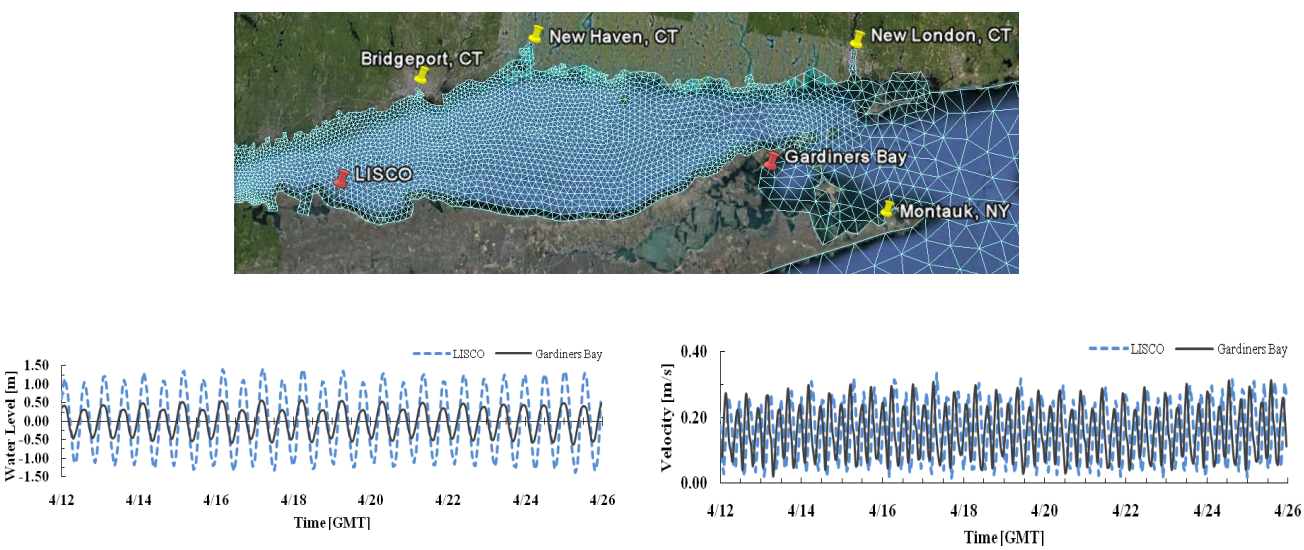

Fig. 4: Results of predictions of coastal flows in Long Island Sound in 2010. (a) Region of study and mesh. Yellow pins indicate locations of observation stations, and red pins represent locations of interest. (b) Prediction of surface elevation at LISCO and Gardiners Bay. (c) Prediction of velocity at LISCO and Gardiners Bay.

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

Two field campaigns in a variety of coastal and open ocean waters were carried out to measure polarization characteristics of light below and above water surface using the new Stokes vector spectroradiometer developed by the CCNY Optical Remote Sensing Laboratory. These measurements

were done in conjunction with additional standard instrumentation needed for comprehensive water characterization. Campaigns included: i) Gulf of Mexico in the area of Port Aransas, TX as a part of the MURI ONR project ii) Long Island Sound in the area of the LISCO platform to compare underwater polarization characteristics with above water measurements by the additional radiometers on the platform with polarization sensitivity. Polarization measurements were complemented by measurements of water optical properties (absorption, attenuation, backscattering, fluorescence, particle size distribution) and reflectances by CCNY or partner instruments. All acquired data are being processed. Typical distributions of the degree of polarization (DOP) for 3 environments are shown below in Fig. 5 where they are compared with Rayleigh scattering model. The decrease of the maximum of DOP with the increase of turbidity is clearly observed, the shift of the DOP maximum also depends on the water composition.

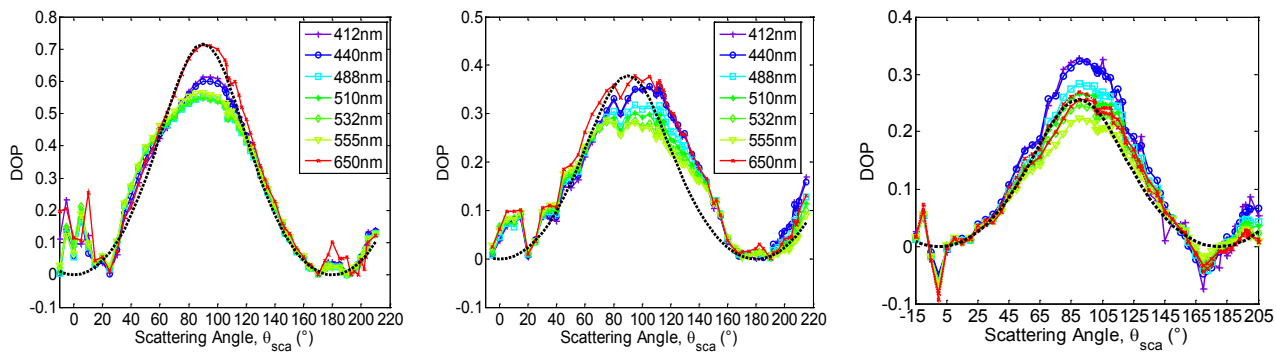

Fig. 5 Degree of polarization (DOP) as a function of scattering angle for 7 wavelengths and 3 types of waters: clear water (left), moderate (center) and turbid water (right), VA, summer 2009.

Two radiance sensors with polarizers oriented vertically and at 45º and looking at 40º down were added to the HyperSAS on the LISCO platform in June 2010. A first attempt was recently made to retrieve Stokes components I, Q, U and underwater DOP from new HyperSAS-POL observations.

The radiance measured by the sensor above water mainly originates from the reflection of the sun and sky radiances (the so-called sun and sky glint). Only a small fraction comes from the radiance emerging the water body. Thus, the sun and sky glints have to be removed from the total signal in order to retrieve strictly oceanic information. First, the sky glint contamination of the HyperSAS-POL data is minimized by taking the 20% of the minimum of the measurements acquired during a two-minute integration time. Second, the sky glint is estimated and subtracted from the Stokes parameters acquired by HyperSAS-POL. The down-welling sky radiance (noted I_{sky}) is measured by HyperSAS-POL and the corresponding Q_{sky} and U_{sky} are simulated using radiative transfer code [7] for a purely molecular atmosphere. Example of the retrieval is shown in Fig. 6.

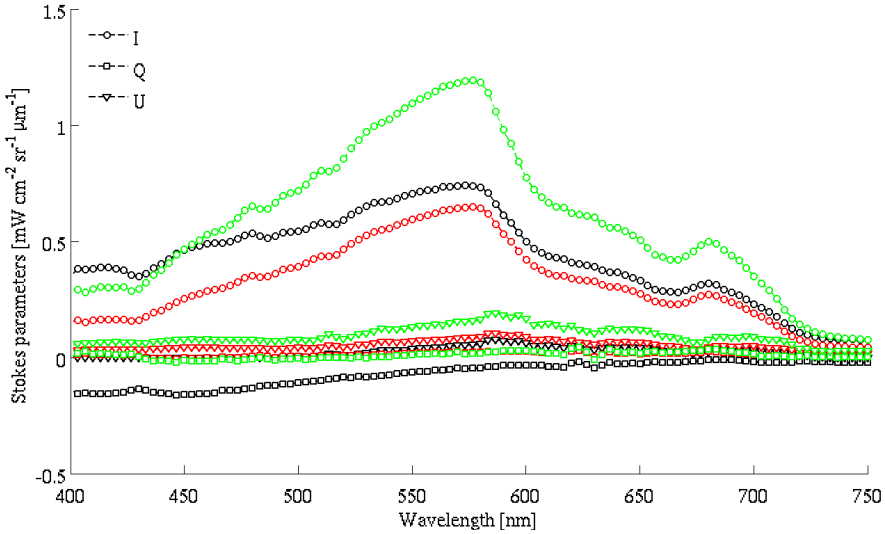

Fig. 6. Hyperspectral values of the Stokes parameters retrieved from the HyperSAS-POL measurements of August 19th 2010 at 12:30 PM local time. I, Q and U are shown for the total signal (black), signal corrected from the sky glint (red) and the below water signal (green). The scattering angle is 138.1° and 149.2° above and below water, respectively.

Development of advanced atmospheric correction models

Atmospheric correction of the satellite imagery in the coastal waters remains challenging; improvements can be made if additional information on aerosol parameters is available. That includes the data from AERONET sites and from co-located lidar measurements. To evaluate the possibility of the incorporation of the lidar data available at CCNY (usually upwind from the platform) into atmospheric correction at LISCO aerosol parameters (aerosol optical thickness AOT) are compared at AERONET LISCO and CCNY sites. Results of AOT comparison are presented in Fig. 7 showing reasonable correlations. Correlation is similar for the Angstrom coefficient.

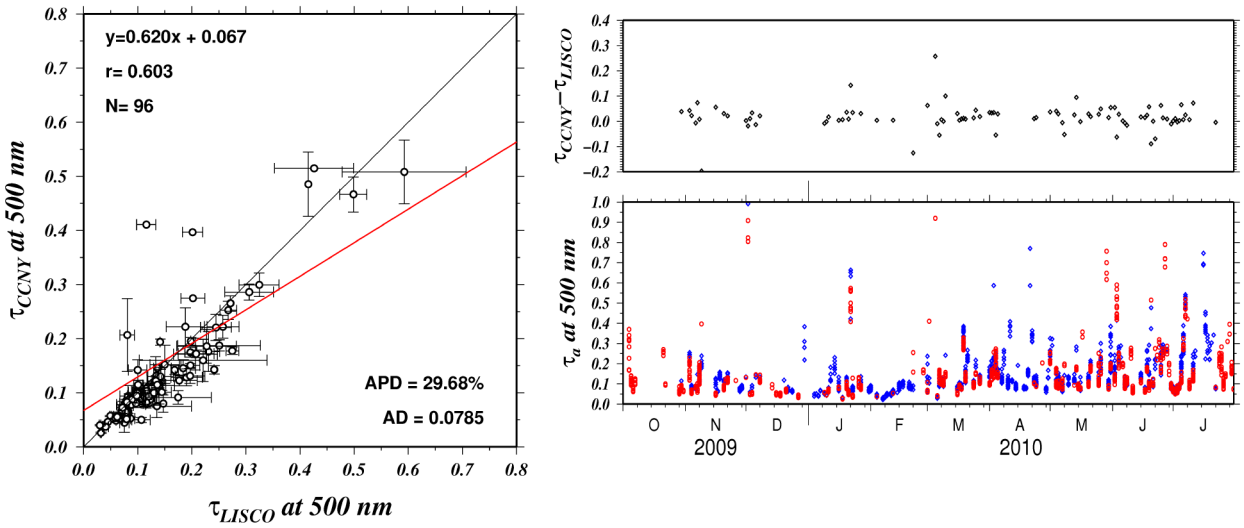

Fig. 7 Comparison of AOT at CCNY and LISCO AERONET sites: a) correlation, b) time series (blue dots – CCNY, red dots – LISCO site).

However, we do see that the optical depth from the LISCO site shows a significant high bias and if we require the AOD to be within +- .02 (AERONET sensitivity threshold) to signify the same aerosol features so that the CCNY lidar vertical structure is useful; the actual matchups that can be used are much less frequent. This might lead us to the conclusion that a Long Island Lidar is needed. On the other hand, it might be reasonable to use Air Quality Model outputs such as the NYSDEC CMAQ as a means of estimating the atmospheric correction and such models are now being evaluated to see how accurate they can be in predicting the optical properties and mixing layer height and if they can be used in conjunction with lidar.

IMPACT/APPLICATIONS

Current algorithms for the retrieval of water optical properties based primarily on the spectral features in the blue-green region produce significant errors in coastal waters. Advanced versions of the algorithms which use red-NIR bands and which are based mostly on water absorption coefficients at two or three bands will result in improved [Chl] retrievals in complex coastal waters from MERIS and hyperspectral sensors. These algorithms are also less vulnerable to atmospheric corrections. New statistical approach based on the binary classifier for the detection of K. Brevis blooms appear promising for toxic algal bloom detection and distinction.

A new AERONET and AERONET-OC sites on the LISCO platform which is operational since October 2009 will be used continuously for the validation of the ocean color satellites, water monitoring and algorithm development in coastal waters.

The successful development of new techniques for the measurement of hyperspectral water polarization characteristics, has led to important understandings of the nature and parameters of underwater polarization fields, with wide-ranging of applications. Accurate measurements of water

polarization properties on angular and spectral scales, made possible by our new instrumentation, coupled with the radiative transfer simulations, is also now proving helpful in work on the improvement of in-water visibility and detection of naval targets, as well as in the retrieval of bio-optical properties. Retrieval of Stokes vector components from the HyperSAS-POL observations on the LISCO platform will give a significant additional understanding of the potential of the availability of polarization channels on the satellite sensors.

Atmospheric correction plays a crucial role in all coastal ocean algorithms, and the work reported is advancing the development of an operational module which can be used in certain domains where the 412 reflectance is expected to be sufficiently small as well as in regionally trained areas where NN approaches or bio-optical estimators can be used.

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 studies polarization characteristics of light in water through another award from ONR N000140911054 for years 2009-2012 with the emphasis on the underwater animals vision and camouflage applications.

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