COMPARISON OF FIELD SPECTRORADIOMETERS IN PREPARATION FOR BIO-OPTICAL MODELLING

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INTRODUCTION

The coastal marine and estuarine waters of New Jersey are important commercial and recreational assets of the state. Extensive use is made of these waters for fishing, boating, swimming and aesthetic enjoyment. However, the beneficial uses of the waters of some coastal areas within the state are adversely impacted by municipal and industrial wastewater discharges, land runoff, and surface/groundwater inputs of leachates from sanitary and hazardous waste landfills. Currently there are numerous efforts underway to improve the understanding of physical, chemical and biological characteristics of estuarine/coastal waters including remote sensing techniques. Remote sensing offers unique advantages for the study of recurrent hydrological phenomenon (i.e., algal blooms) on regional and local scales.

In order to develop analytical algorithms for these case 2 waters it is necessary to develop an appropriate bio-optical model linking the water constituents to the inherent optical properties (IOP) and to link the inherent optical properties to the subsurface irradiance reflectance. As part of this bio-optical modeling efforts, a field campaign was carried out in the Hudson/Raritan Estuary of New York-New Jersey during August '99 to obtain in-situ measurements of subsurface irradiance reflectance R(O-), together with in situ samples, that were later analysed in the laboratory for their inherent optical properties. The subsurface irradiance reflectance R(O-) was calculated as a ratio of $E_u(\lambda)$ to $E_d(\lambda)$ irradiance. A comparison is made of different field spectroradiometers deployed simultaneously in the estuary, thus ensuring that the algorithm development, being carried out by three groups takes place on similar data. Spectral intercalibration of field spectroradiometers was performed through determining the spectral position and magnitude of subsurface reflectance peaks. Using the in situ measurements and samples (i.e., R(O-), IOP and WQP) of August 1999 the bio-optical models will be developed that will lead to remote sensing algorithms, that once applied may provide the water resource managers spatial information from air or space to enabling sound decision making concerning the protection of our coastal /estuarine environment. The fieldwork was intended to take place during an AVIRIS overflight. Unfortunately the AVIRIS flight was cancelled due to logistical reasons. AVIRIS data from 1998 is available. Through the application of case 2 water algorithms based on the 1999 in situ dataset (including the lab analyses) to the 1998 AVIRIS data the methodology previously developed in The Netherlands for groundtruth independent application of algorithms will be demonstrated.

PHYSICAL CHARACTERISTICS OF THE STUDY AREA

The study area is the Hudson/Raritan Estuary south of the Verrazano Narrows, and bordered by western Long Island, Staten Island and New Jersey. The estuary is connected to the Atlantic Ocean through the Sandy Hook-Rockaway Point transect and to Long Island Sound through the East River. (Figure 1). The partially mixed drowned river estuary is relatively shallow (< 8 m) (Oey et al., 1985). The major fresh water discharges are the Hudson, Raritan, Passaic and Hackensack Rivers. Over the last century the quality of the estuarine water has degraded in part due to eutrophication, the process of nutrient enrichment through either natural or anthropogenic processes. Eutrophication disrupts the pre-existing natural balance of the system, resulting in phytoplankton blooms of both increased frequency and intensity in response to the over-enrichment. Noxious phytoplankton blooms are among the potential negative impacts, as are shifts to less desirable species of phytoplankton, diminished aesthetics (e.g., from brown tides) and changes in phytoplankton cell size. Dense and accelerated phytoplankton blooms ultimately increase oxygen demand on the system leading to episodes of hypoxia. Phytoplankton populations in the Hudson/Raritan estuary, the Bight Apex and coastal waters of New Jersey are dominated by diatoms (>20 µm) such as Skeletonema costatum during the unstratified winter/spring months and by Nannochloris atomus (between 0.7-20 µm) during the stratified summer/fall months.

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Diatoms typically dominate at all times in the offshore waters of the Bight (EPA, 1986). Biweekly field observations throughout the summer 1999 indicated low concentration of Chlorophyll a, as indicator of phytoplankton, which is not a typical representative of the water quality condition in this area. Table 1 shows the sample locations and local observations (i.e., weather conditions) as well as water conditions recorded onboard R/V Walford on August 14, 1999 field campaign. Note: All data collected during outgoing tides.

Table 1

St	Location	Lat	Long	Bottom Depth (m)	Secchi Depth (m)	Salinity (ppt)	Temp (^{o}C)	TSM (g m^{-3})	TCHL (mg m^{-3})
1	Comptons/Pews Creek	40.45	74.08	3.4	1.3	27.8	24.2	6.44	14.75
2	Keyport Harbor	40.47	74.19	2.2	0.8	25.6	25.6	25.74	32.36
3	Traid Bridge	40.50	74.28	7.8	0.9	25.4	27.0	12.99	16.60
4	Crookes Pt State Isl.	40.54	74.14	4.1	0.6	26.9	26.9	15.47	36.88
5	Coney Isl. Pt.	40.57	74.02	7.8	1.8	28	24.1	10.45	6.33
6	Sandy Hook Tip	40.49	74.02	20.6	0.9	28.4	24.5	12.38	21.53
7	Shrewsbury River	40.38	73.98	3.1	0.5	27.4	26.6	20.53	47.79

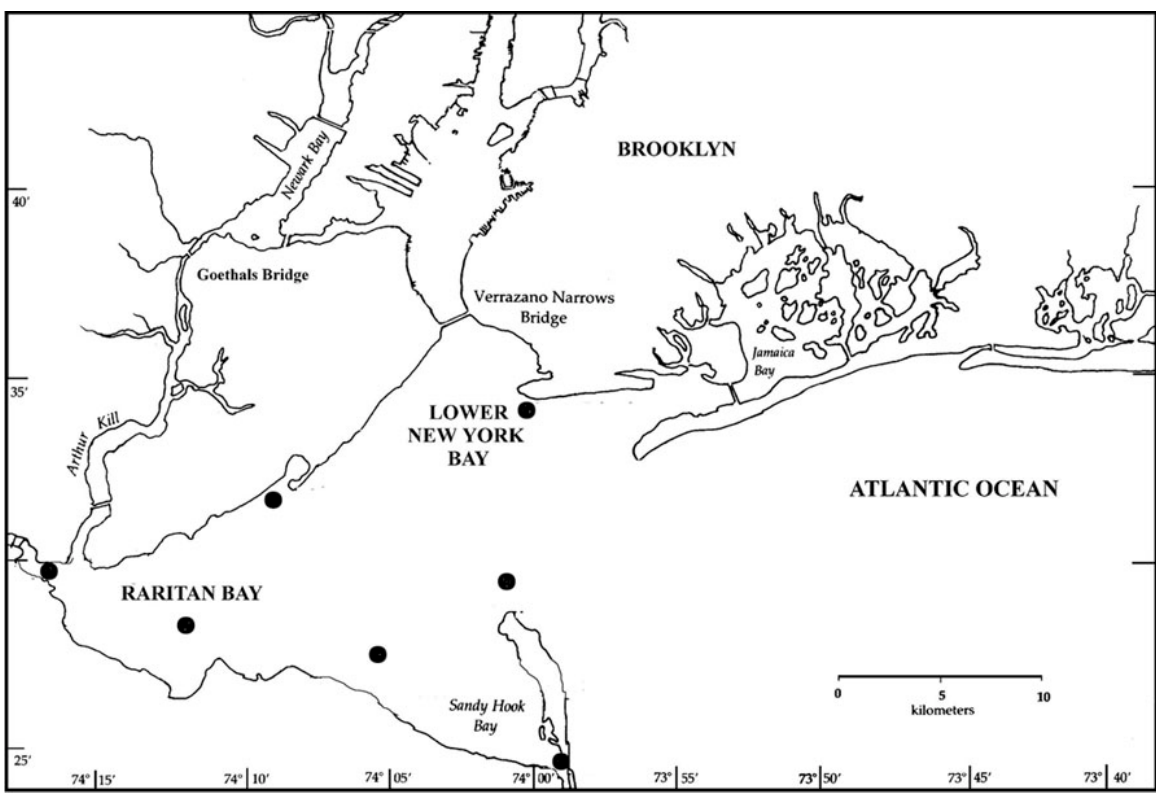

Figure 1. Map of the study area with the locations of sample points

RESEARCH MATERIAL AND METHODS

A. SUBSURFACE IRRADIANCE REFLECTANCE R(O-) MEASUREMENTS

Spectral subsurface irradiance reflectances R(O-)s for all stations listed in table 1 were obtained using the field spectroradiometers. The goal is to parameterise the bio-optical model relating the CDOM, TSM and algal pigment concentration, to the light absorption and scattering and to the water leaving radiance, through direct and laboratory based optical measurements. In short, the link between remotely sensed upwelling radiance and underwater inherent optical properties is made through R(0-). The specifications of the field spectroradiometers used in the intercomparison process are as follows:

1. OL 754

The OL 754 is a scanning submersible spectroradiometer. The OL 754-O-PMT Spectrometer Optics Head uses a double monochromator for low stray light and measures spectral data over 300nm to 850 nm. Three sets of fixed slits are provided with the PMT Optics Head enabling the user to vary the FWHM from 1 to 10 nm, for computation of normalized percentage reflectance curves. The OL IS-470-WP Submersible Sphere Assembly (4-inch integrating sphere) has dual port design with the ports located 90^{o} apart. The sphere contains an internal baffle before the exit port to permit only integrated light from exiting the sphere. The integrating sphere is connected via a waterproof fiber optic to the entrance port of the monochromator. The design of the sphere and the geometries of its components (entrance port, baffle, etc.) enable the WP submersible sphere assembly to achieve a near-perfect cosine response. The OL 730-7Q-WP Quartz Fiber Optic Probe provides a mechanism for mounting the input optics (i.e., cosine receptor, integrating sphere etc.) to the entrance port of the monochromator. Other peripherals of OL 754 includes:

1. The OL 754-C Spectroradiometer Controller links all components to a shipboard computer where the spectroradiometric data is stored.
2. The OL 752-10 is a NIST traceable lamp to calibrate the spectrometer for spectral irradiance response measurement.
3. The OL 65A is a precision current power supply, specifically designed for operation of standard lamps such as the OL 752-10.
4. The OL-752-150 Dual Check source module checks the wavelength and gain calibrations. The accuracy of these parameters is verified quickly in the lab/field to ensure that the system has not been adversely affected by shipping, handling or change in environment.

The software provides flexibility to accommodate different field conditions. The Quick Scan™ feature of the software allows scanning of sources that are changing with time by scanning much faster than conventional methods. This feature takes into account such important factors as automatic gain changes and blocking filter changes.

The necessary parameters needed to determine the irradiance of a test source (Optronics Laboratories, 1997) :

i	:	dark reading (measured while source is shuttered before scan) [A].
λ	:	wavelength [nm].
$K(\lambda)$	:	system spectral irradiance response calibration factor[Wcm^{-2} nm^{-1} A^{-1}].
$E(\lambda)$	:	standard lamp spectral irradiance [W cm^{-2} nm^{-1}].
$T(\lambda)$	:	test source irradiance [W cm^{-2} nm^{-1}].
$S_E(\lambda)$,$S_T(\lambda)$	:	average signal reading [A] with dark current (i [A]) subtracted.

The system spectral irradiance response, $K(\lambda)$, is calculated as follows:

$$K(\lambda) = E(\lambda)/S_E(\lambda)$$

The test source spectral irradiance, $T(\lambda)$, is calculated as follows:

$$T(\lambda) = K(\lambda)*S_T(\lambda)$$

Upwelling ($E_u(\lambda)$) and downwelling ($E_d(\lambda)$) irradiances were obtained by deploying the submersible sphere assembly in direct and reverse modes into the water at 3 feet below the surface (figure 2). This depth was generally deeper than the maximum wave amplitude to negate the effects of waves. The subsurface irradiance reflectance R(O-) in percentage was calculated as a ratio of $E_u(\lambda)$ to $E_d(\lambda)$ irradiance in units of (W/(cm^2 nm)) for intercomparison process .

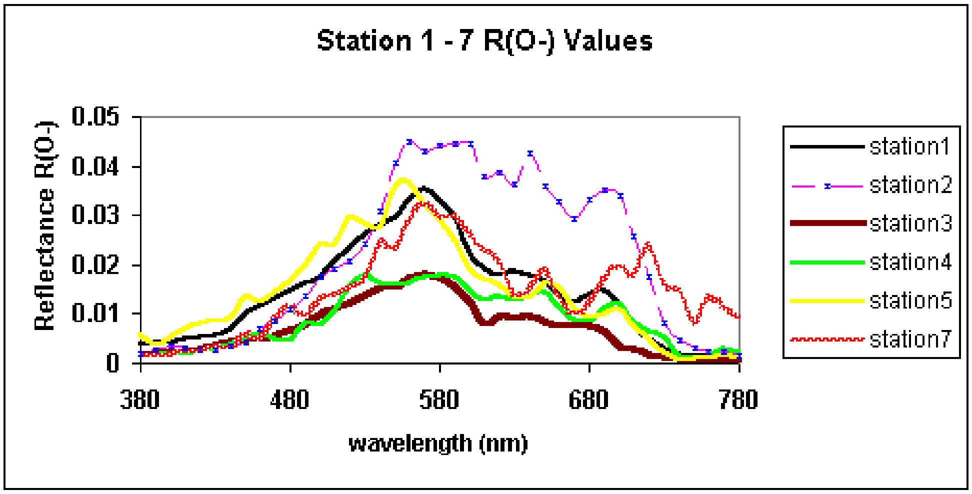

Figure 2. R(O-) Data for all Stations Using OL 754

2. PR 650

The PR-650 portable telephotometer/colorimeter (Photo Research) was used for spectral radiance measurements above the water surface, and is the instrument used by the Institute for Environmental Studies in their remote sensing related research. This instrument included 1^0 measuring optics and holographic grating, 128-element diode-array spectrometer that acquires spectra from 380 to 780 nm. The FWHM used was 8 nm. The integration time was automatically selected. At each measurement cycle a dark measurement of equal duration was automatically subtracted. The instrument was calibrated by the manufacturer. See Gons (1999) for details on the method. The method of measurement is geared fully towards above surface measurements, with the advantage of not having to deal with variable watercolumn heights due to waves, no selfshading, rapid measurements etc.

The water-leaving radiance (L_{au}) and the downward radiance of skylight (L_{sky}) were scanned at a nadir and a zenith angle of 42^0, respectively. The angle of 42^0 was used in order to avoid influence by reflection and shading from the boat. The measured water-leaving radiance includes reflected sky light, which can be subtracted after also measuring the sky radiance at the relevant angle (Equation 1). In order to calculate downward radiance (E_{ad}) and discriminate between direct sunlight and the diffuse irradiance, the radiance was measured from a calibrated reflectance panel before (L_{rp}) and after shading (Lr_{pd}) (Equation 1). For both practical and theoretical reasons the chosen direction of observation was 90^0 to the plane of the sun. Each scan involved 10 measurement cycles of which the average was filed (figure 3). Three upto 5 complete series of scans were done, which in general took less than 3 minutes.

From the light measurements obtained above the water surface, the subsurface irradiance reflectance R(0-), i.e. the ratio of upward (E_{wu}) and downward irradiance (E_{wd}) just beneath the water surface was computed, as described in Gons (1999).

where

$$R(0-) = \frac{Qf\,(L_{au} - r_{sky}L_{sky})}{\left[\left\{E_{ad} - r\Theta(1-F)E_{ad} - r_{dif}FE_{ad}\right\} + (0.5E_{wu})\right]}$$

Q = the conversion coefficient for L_{wu} to E_{wu}

f = the conversion constant of L_{au} to L_{wu} ,

L_{au} = the upward radiance above the water at nadir angle of 42^0 ,

L_{sky} = the radiance of skylight at zenith angle of 42^0 ,

r_{sky} = the Fresnel reflectance coefficient at zenith angle of 42^0,
E_{ad} = the downward irradiance just above the water,
r_θ = the Fresnel reflectance coefficient for sunlight,
r_{dif} = the Fresnel reflectance coefficient for diffuse light,
F = the fraction diffuse light of E_{ad},
E_{wu} = the upward irradiance just below the water surface.

The following values were applied. The value of the geometric parameter Q while still being a point of discussion in literature was calculated according to Gons (1999). Whereby Q depends on solar angle and the ratio between total and diffuse downwelling light. Here Q varied between 2.8 and 3.4. For the value of r_{sky} the modeled value of 0.0293 was used (Gons, 1999), only in case of a flat water surface (no waves) the theoretical value of 0.0256 (Kirk, 1994) may be used. Further the values f = 1.84 for salt water (Austin, 1980), and r_{dif} =0.06 (Jerlov, 1976) were applied. The Fresnel reflectance coefficient for sunlight (r_θ) was calculated from Julian day, time and geographical position. The downward irradiance just above the water (E_{ad}) was obtained by measuring the radiance from a calibrated reflectance panel. The fraction diffuse light (F) was the ratio between E_{ad} measurements obtained from the reflectance panel before (Lr_p) and after shading (Lr_{pd}).

The reflectance spectra were stored in a Spectral Library database only if they satisfied the following criteria:

(1) R(O-) > 0 for the spectral wavelength range between 440 nm and 780 nm, and
(2) R(O-) < 0.33 for the spectral wavelength range between 440 nm and 780 nm.

In case one of the triple R(O-) spectra differed more than the standard deviation from the average , the spectrum was rejected. The two remaining R(O-) spectra were then averaged as input into intercalibration.

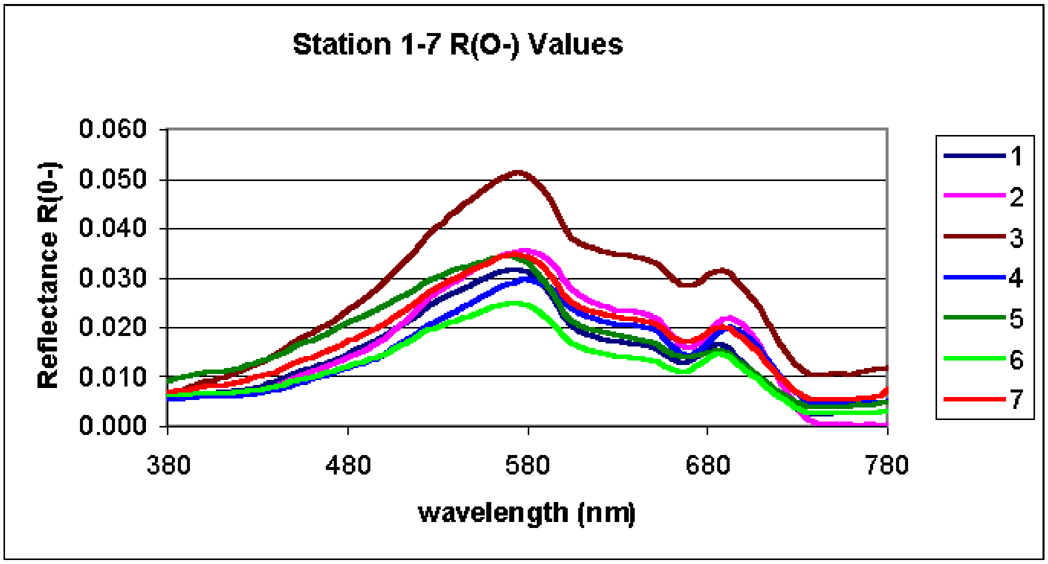

Figure 3. R(O-) Data for all Stations Using PR 650

3. OCEAN OPTICS 2000

The SD2000 Fiber Optic Spectrometer is a low-cost, high-performance system that is easily configured. The SD2000 has a high-sensitivity linear CCD array that provides high response and good optical resolution. The design is based on a S2000 grating (600 lines/mm), with an entrance slit of 50mm. The 2050 wavelength bands range from 350-900 nm, with a FWHM of approximately 1.5 nm. The spectrometer was directly linked to a laptop on-board. At all stations, measurements of the under-water irradiance reflectance were made. The downwelling and upwelling irradiance was measured simultaneously by connecting cosine collectors to the fibers. Then one sensor was directed upwards, and the fibre was connected to one channel of the Ocean Optics (Master) the other sensor was directed downwards and the fibre was connected to the other channel of the Ocean Optics (Slave). Both sensors were attached to a heavy frame and were lowered into the water using a crane, positioned at the rear of the ship, which for all stations was directed towards the sun. To avoid resuspension of bottom material, engines were shut off at all stations except station 7.

For all measurements a running average of ~10 nm was applied to reduce noise and a spectrally flat dark current correction was applied by assuming a zero irradiance for wavelengths larger then 950 nm, due to the large absorption of pure water in that spectral region. The irradiance reflectance at a certain depth was then calculated by dividing the upwelling and downwelling irradiance and applying a spectral correction for the difference in sensitivity of the two sensors. The correction was established one day before the field-campaign, using a calibration lamp, but without the cosine collectors. After rejection of inconsistent measurements the remaining measurements were averaged (figure 4).

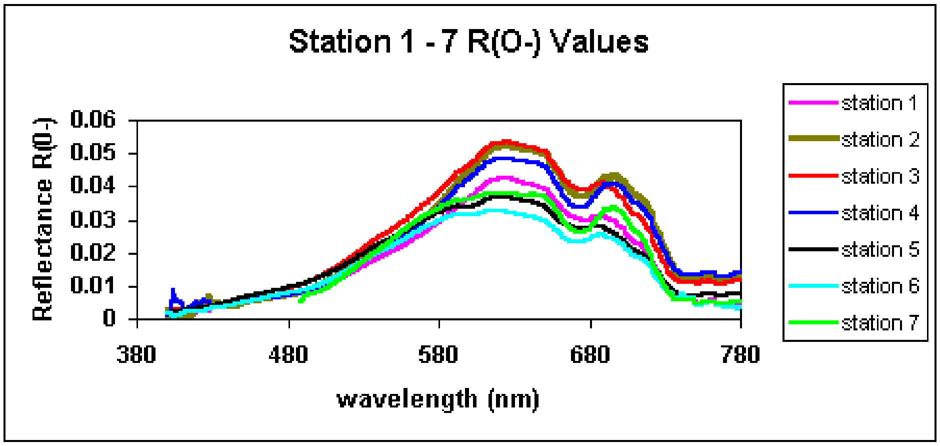

Figure 4. R(O-) Data for all Stations Using Ocean Optics 2000

B. INHERENT OPTICAL PROPERTIES MEASUREMENTS

The spectral absorption and backscattering are the inherent optical properties (IOP). The spectral absorption will cause reduction in R(O-) and the spectral scattering causes an increase in R(O-). Laboratory based spectrophotometric measurements of spectral attenuation and spectral absorption were performed. From these measurements spectral scattering was deduced. Absorption spectra of seston (phytoplankton and tripton) and tripton were determined using the filterpad method (Truper & Yentsch, 1967) with 0.45 μm Whatman GF/F filters (figures 5, 6 & 7). The absorption was calculated on a basis of a calibrated relationship between the optical density of a suspension in a sample cell and the optical density on a filter (Weidemann & Cleveland,1993). The absorption spectra of color dissolved organic matter (CDOM) and the seston beam attenuation were determined spectrophotometrically according to the methods described in Rijkeboer et al., 1998.

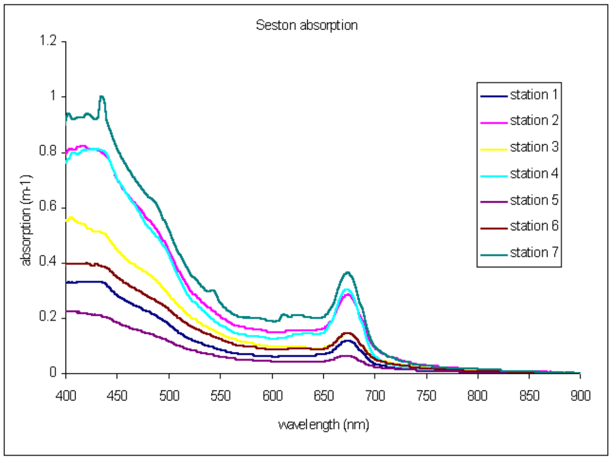

Figure 5. Absorption spectra of seston (organic and inorganic material)

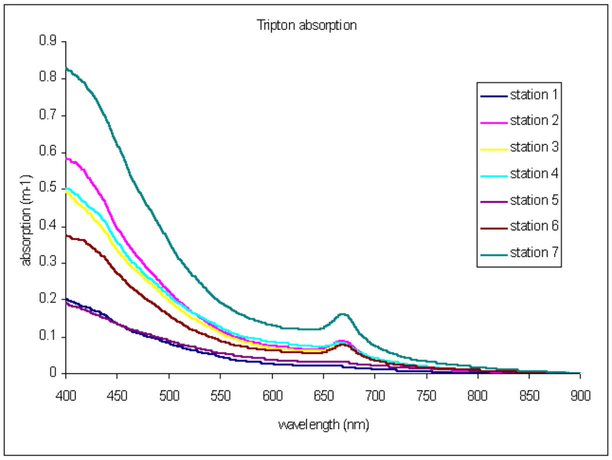

Figure 6. Absorption spectra of tripton (non-algal fraction of seston)

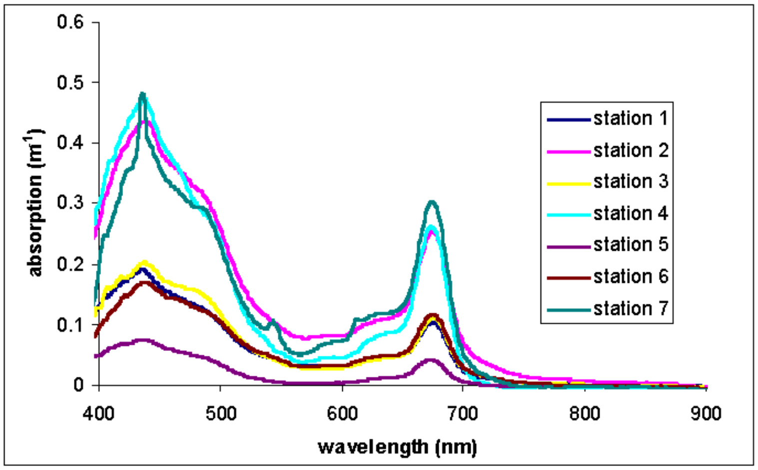

Figure 7. Phytoplankton absorption spectra calculated by subtracting the Tripton absorption spectra from the Seston absorption spectra

C. OPTICAL WATER QUALITY CONCENTRATIONS MEASUREMENTS

For the bio-optical model it is essential that the specific absorption and scattering of the major constituents of the estuarine water are known. The specific absorption and scattering are the per unit concentration absorption and scattering properties. Once these are known spectral irradiance reflectances of any range of concentrations potentially present in the waters may be modeled. To estimate optical water quality concentrations coinciding with the spectral reflectance measurements subsurface water samples (0.2 to 0.5 m depth) were taken in 1-1 bottles and placed in a cooler with melting ice before transport to the laboratory for analysis.

Standard procedures as described by Rijkeboer *et. al*. 1998 were used to determine the concentrations of total chlorophyll-a (*TCHL*) defined as the sum of chlorophyll-a and phaeopigment (as indication of concentration of phytoplankton) and total suspended matter (*TSM*). The *TCHL* concentration was determined according to the Dutch standard norm (NEN 6520, 1981). This method is based on the extraction of chlorophyll-*a* pigments from the phytoplankton using hot ethanol (80%, at 75^{0}C). The *TCHL* is then determined spectrophotometrically, using the extinction of the solvent at 665 and 750 nm. The phaeopigment concentration is determined similarly after acidification of the sample. All analysis were performed in duplicates to verify the result. Additional chlorophyll measurements have been performed using extraction in cold acetone (Strickland and Parson, 1972). The *TSM* concentrations were determined according to the Dutch standard norm (NEN 6484, 1982), by filtering samples over 0.45 μm Whatman GF/F filters and drying the filters at 80^{0}C. Ignition loss was determined by ashing the filters with TSM at 550^{0}C. The filters were flushed with 10 ml tap water to prevent overestimation of the *TSM* concentration due to remaining salt left on the filter. Filtered volumes range from 50 to 200 ml. All analyses were performed in triplicates. Both methods are reproducible within 5% (Pasterkamp *et. al.*, 1999). See table 1 for the concentrations per sampling point. The *TSM* ranges (6.44 – 25.74 g m^{-3}) are within the range expected for this time of year, but the measurements are not representative of maximum concentrations for the estuary. The *TCHL* concentrations are low (6.33 – 47.79 mg m^{-3}), since measurements did not coincide with any major outbreaks of phytoplankton blooms.

D. DISCUSSION AND THE RESULTS

Three spectroradiometers were deployed simultaneously in the Hudson-Raritan estuary in August 1999. Each spectroradiometer has a totally different design: The OL754 is purpose built for underwater measurements of up and downwelling irradiance; the PR650 is purpose built for radiance measurements in above surface applications and the Ocean Optics 2000 system is a modular spectrophotometric/spectroradiometric system relying on optical fibers and fore-optics to enable it to carry out a variety of optical measurements. The methods of dispersing the incoming lightfield is different as well as the optical detectors registering the number of photons. In many researches the results of only one system are presented and seen as " groundtruth". As the aim of this research is , amongst others, to apply a methodology developed in The Netherlands for turbid Case 2 waters to an estuary in the East Coast US, it was necessary to compare the spectroradiometric systems for consistency.

Over most of the stations measured the influence of the wave propagations were shown in the spectra acquired by OL 754. Generally, wave refraction problem result from the modulation of light by alternating focussing and defocusing cycles produced by the motion and shape of the waves. With the other systems averages of many scans were taken but, because of time constraints, only one upwelling and one downwelling scan was taken with the OL 754 at each station and the influence of waves can be seen in the results.

For direct comparison radiance data of PR650 was converted to irradiances and data from different spectrometers were plotted for all stations (see figures 2, 3 & 4). Intercomparison of different types of field spectroradiometers (i.e., OL 754, PR 650 and Ocean Optics 2000) were established using the spectral position and magnitude of subsurface reflectance peaks (Figures 8 & 9). Comparing the reflectance spectra show that there are significant differences between the results of the different spectroradiometers. The range of reflectance values, however is, quite consistent (ie 1% to 5 % R(0-) over the wavelength range of 480 nm to 700 nm). However the spectral shape varies considerably as seen in Figure 9. Several reflectance features are prominent in the spectra depicted on figures 8 & 9 which support earlier research results that information extraction in inland and turbid estuarine and coastal waters should be limited to spectral green to infrared part of the spectrum (Dekker, 1990 and Gitelson and Kondratyev, 1991). These features are the absorption by humus, tripton and the first chl_a absorption peak causing low reflectance. Beyond 500nm overall absorption decreases and reflectance increases allowing a better discrimination on local spectral features in the spectra, such as the red chlorophyll a absorption peak at 676 nm.

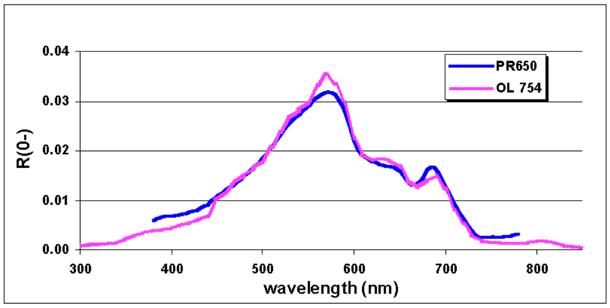

Figure 8. Comparing OL 754, PR650

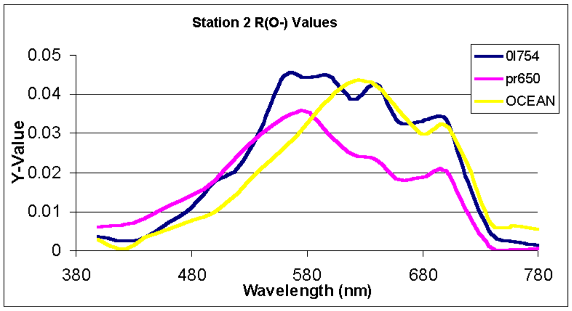

Figure 9. Comparing OL 754, PR650, Ocean 2000

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