

APPLICATION OF RADIATIVE TRANSFER THEORY TO ATMOSPHERIC CORRECTION OF AVIRIS Data

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1. Introduction

The aim of an algorithm based on Radiative Transfer Theory (RTT) is a physical-bio-optical description of the radiative transfer process in the entire system from the solar source to the remote sensor via the hydrosols. The quantitative description provides a sound basis for the inversion of remotely sensed signals to retrieve the optical water quality parameters. AVIRIS records the integrated effects of the solar source, the atmosphere and the targeted surface. To compensate for the atmospheric effects in the AVIRIS data, an air water interface atmospheric correction algorithm based on DISORT was applied to infer the water-leaving radiance. The spectral absorption and backscattering defined as the inherent optical properties (IOP) are physically related to subsurface irradiance reflectance $R(0^-)$. The subsurface irradiance reflectance links the optical properties to the water signals recorded by AVIRIS. This paper reports on the application of physically-based algorithms for retrieval of optical properties of the coastal waters for which the near-infrared black pixel approximation is invalid. To test the retrieval algorithm the configuration of the AVIRIS bands are used. In conjunction with bio-optical models these optical properties are used to characterize such waters in terms of chlorophyll concentration, colored dissolved organic matter and inorganic material.

The study area is the Hudson/Raritan Estuary located south of the Verrazano Narrows and bordered by western Long Island, Staten Island and New Jersey. Fresh water flows into the estuary mainly from the Hudson and Raritan Rivers and ocean waters enter tidally across the Sandy Hook-Rockaway transect. The tidal water is mixing with fresh water inflows, in highly dynamic environments where there are major conflicting interests on the use of these waters. This shallow (< 8 m) and eutrophicated interface of the Hudson and Raritan Rivers and Atlantic Ocean was cruised during the field seasons in 1998-2000 with RV Walford (NJMSC) and Blue Sea (MAST). Table 1 shows the sample locations and local observations recorded during the field campaigns.

2. Materials and Methods

2.1 AVIRIS Data and Atmospheric Correction

On May 15, 2000, the AVIRIS, was flown over the study area. The AVIRIS images the earth's surface in 224 spectral bands approximately 10 nm covering the region 400-2500 nm from a NASA ER-2 aircraft at an altitude of 20 km. The ground resolution is 20m * 20m. AVIRIS records the integrated effects of the solar source, the atmosphere and the targeted surface. To compensate for the atmospheric effects in the AVIRIS data, an atmospheric and air-water interface correction algorithm based on DISORT was utilized.

DISORT is a forward radiative transfer model for the coupled atmosphere-ocean system (Jin and Stamnes, 1994; Thomas and Stamnes, 1999) which is used to determine the water constituents as well as the atmospheric parameters that in combination give rise to the reflected radiance spectra measured by the AVIRIS spectrometers. Currently, Most of the atmospheric correction algorithms are designed for case 1 (clean deep ocean) waters. Those algorithms are based on the assumption that the water-leaving radiances are close to zero in the spectral range 760 - 870 nm. Thus, an aerosol/aerosol optical depth model can be derived from the channels located in that region of the spectrum. Subsequently, the aerosol information can be extrapolated into the visible range for retrieval of the water-leaving radiance and the water constituent concentration. Unfortunately, these algorithms are not directly applicable to case 2 (turbid coastal) waters because of the presence of suspended materials which cause strong scattering in the spectral range of 760 - 870nm.

Figure 1 depicts the atmospheric reflectance ratio spectra produced from the selected pixels within the subset of the AVIRIS imagery. It is evident that the shape of these spectra covering 60 channels of AVIRIS data varied considerably; the first two spectral lines show that the two pixels provide very different information about the ocean. In the bay area, the water is very turbid due to strong absorption at 660 nm and strong scattering in the NIR region. This implies that the concentration of suspended matter is high there. On the right side of the image, the

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ocean water is of different spectral characteristics. The ratio changes smoothly with wavelength, which indicates that the difference between the two pixels is mainly due to the atmosphere. The spectra are consistently higher at the blue wavelength as is the characteristic of the molecular (Rayleigh) reflectance. At the bottom right of the image, the aerosol optical depth is much larger than the area to the top. Furthermore, we noted that ratio lines 3 and 5 are parallel, but ratio line 4 is anomalous. It is evident that pixels (523,342) and (510,49) have the same aerosol absorption and scattering characteristics, but different optical depths, while pixel (26,66) has different aerosol absorption and scattering characteristics altogether. It should be mentioned that the raw image contained distinctive patterns recognizable as surface features--e.g., swell and slicks--indicating some degree of sunglint. In addition, rough waters were observed from the shipboard and recorded by the field spectroradiometer at the time of the AVIRIS overflight. The aerosol information obtained from the ratio image were extrapolated for retrieval of water leaving radiance and estimation of water quality parameters (Table 2).

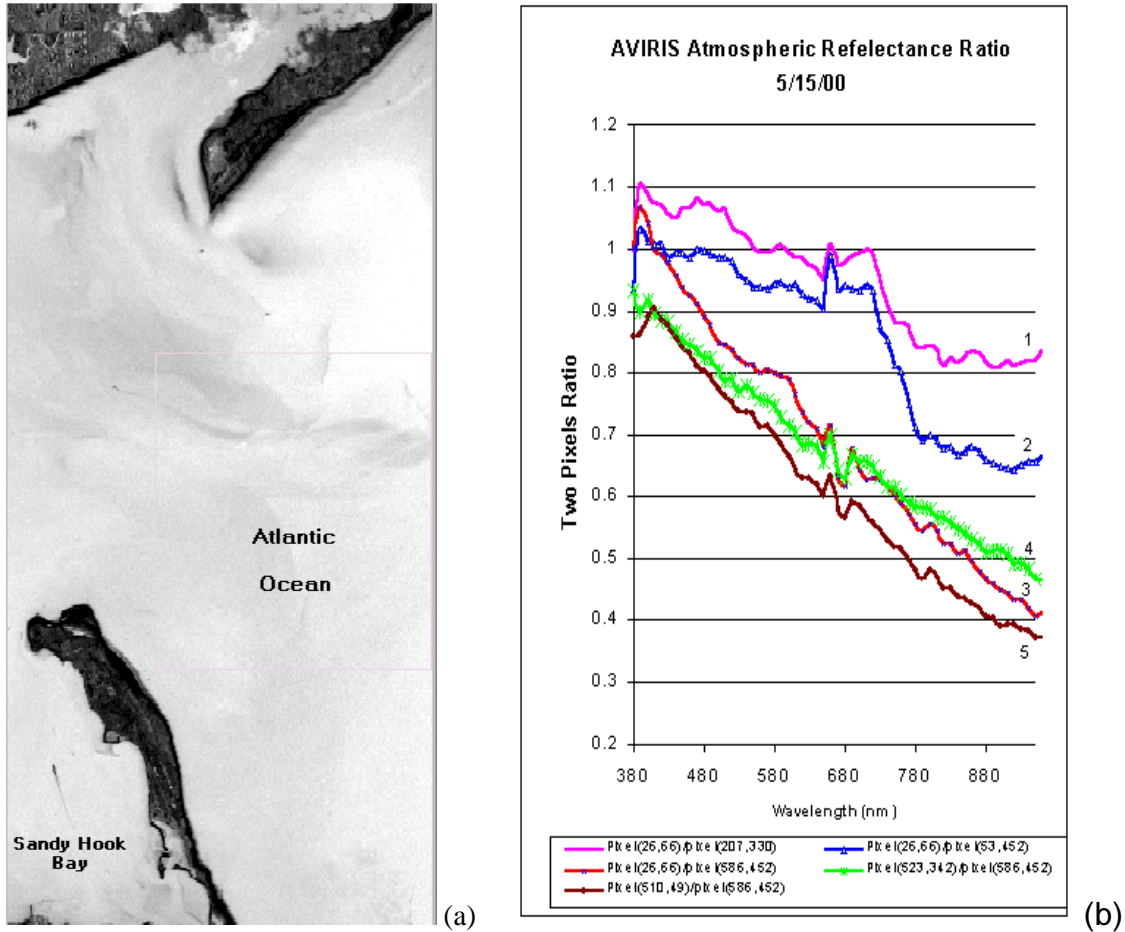


Figure 1(a) AVIRIS ratio image (13/20) of transect 1 acquired on 5/15/2000 and (b) two pixels ratio spectra of the AVIRIS showing the atmospheric variations

2.2 Subsurface Irradiance Reflectance $R(0-)$

Spectral subsurface irradiance reflectance $R(0-)$ as a ratio of upwelling to downwelling irradiance for all stations listed in Table 1 were obtained using the submersible field spectroradiometers--OL754 (Bagheri et. al., 2000). The goal is to parameterize the bio-optical model relating the colored dissolved organic matter (CDOM), total suspended matter (TSM) and algal pigment concentrations, 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 $R(0-)$ (Dekker, 1993).

2.3 Inherent optical properties (IOP)

The spectral absorption and backscattering are the inherent optical properties (IOP). The spectral absorption causes reduction in $R(0^-)$ and the spectral scattering causes an increase in $R(0^-)$. Laboratory based spectrophotometric measurements of spectral attenuation and spectral absorption was performed. From these measurements spectral scattering was deduced. Absorption spectra of seston (phytoplankton and tripton) and tripton (suspended particles excluding phytoplankton) were determined using the filterpad method (Truper & Yentsch, 1967) with 0.45 μm Whatman GF/F filters. 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 CDOM and the seston beam attenuation were determined spectrophotometrically according to the methods described in Rijkeboer et al., 1998.

2.4 Water quality Parameters (WQP)

To estimate optical water quality concentrations coinciding with the spectral reflectance measurements, subsurface water samples (0.2 to 0.5-m depth) were collected in 1-l bottles for laboratory analysis. Standard procedures as described by Rijkeboer *et al.* 1998 was 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 and TSM concentrations were determined according to the Dutch standard norm (NEN 6520, 1981 and NEN 6484, 1982) respectively.

Table 1. Sample locations and water conditions as recorded on board R/V Walford and Blue Sea

Date	St	Location	Lat	Long	S.D. (m)	TCHL (mg m^{-3})	TSM (gm^{-3})
8/14/1999	1	Comptons/PewsCreek	40.45	74.08	1.3	15	6
	2	Keyport Harbor	40.47	74.19	0.8	32	26
	3	Traid Bridge	40.50	74.28	0.9	17	13
	4	Crookes Pt State Isl.	40.54	74.14	0.6	37	15
	5	Coney Isl. Pt.	40.57	74.02	1.8	6	11
	6	Sandy Hook Tip	40.49	74.02	0.9	22	12
	7	Shrewsbury River	40.38	73.98	0.5	48	21
5/15/2000	1	Buoy 2	40.42	74.01	1.25	31	8
	2	Atlantic Highlands	40.47	74.03	1.25	46	11
	3	Horseshoe Cove	40.59	74.03	1.37	22	7

3. Bio-Optical Model Development

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 IOP to the subsurface irradiance reflectance. In this study, we used the linear backscattering albedo model (Gordon et. al., 1975), which is being considered the most appropriate model for case 2 waters (Dekker et. al. 1994).

$$R = r_1(b_b/(a+b_b)) \quad (1)$$

The use of this model implies knowledge of the IOP:

$$a = a_w + a_{dw}^*DW + a_{ph}^*CHL + a_{CDOM440}^*CDOM \quad (2)$$

$$b_b = 0.5 b_w + b_{dw}DW$$

Where a is the total absorption coefficient, b_b is the total backscatter coefficient and r is a factor that is dependent on geometry of the incoming light and the volume scattering in the water body. a and b_b are assumed to be linear functions of the constituent concentrations. This allows the introduction of the specific inherent optical properties, i.e. the IOP per unit concentration: e.g. the specific inherent absorption by phytoplankton, a_{ph}^* , is the amount of absorption caused by 1 mg m^{-3} CHL. Utilizing Beer's law enables to write the total absorption coefficient a as a superposition of the absorption by phytoplankton, tripton, CDOM and water. The concentrations of the constituents are given by CHL, DW and CDOM₄₄₀ (the absorption of coloured dissolved organic matter at 440 nm).

The asterisks denote that a and b_b are specific inherent optical properties (SIOP), i.e. per unit concentration denoted by the subscript. The factors for calculating backscattering for water itself and samples were taken from Bukata (1995) and Dekker (1997) respectively. The backscattering b_b is used here to convert the scattering coefficient to the backscattering coefficient. For pure water this ratio is 0.5 but for seston measurements depends on the composition of the water and is measured as the difference between beam attenuation and seston absorption (Pasterkamp et.al., 2000).

The absorption and scattering coefficients of the main water quality parameters collected for all stations were averaged to produce a set of representative values (Figure 2) and were used as input for calculating $R(0-)$ for different dates. No significant changes in concentrations of water quality parameters were observed in the field data collected in 1999 and 2000. The shapes of the absorption curves reflect the composition and concentration of different optical water quality parameters (i.e., phytoplankton).

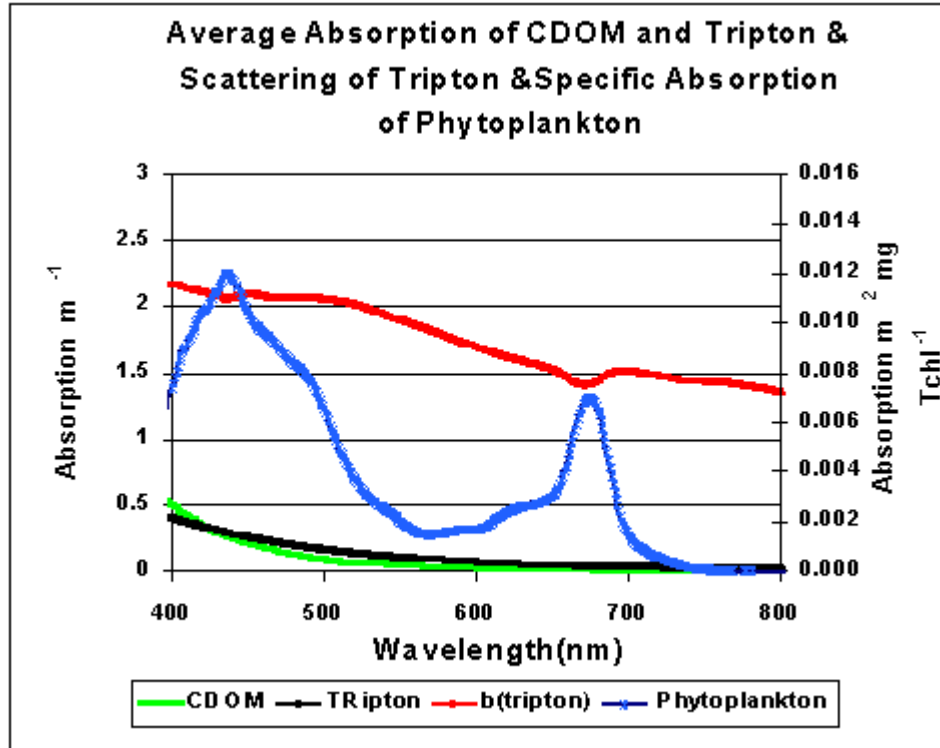


Figure 2. The average spectral absorption, specific absorption and scattering for all stations sampled

Using equation 1, the modeled $R(0-)$ were generated to represent the spectra for the range of chlorophyll-a concentrations calculated in the laboratory for the individual station sampled on May 15'00. Figure 3 depicts the modeled $R(0-)$ versus measured $R(0-)$ for station 2 (Atlantic Highlands) sampled simultaneously with the AVIRIS

overflight on May 1500. The figure demonstrates that a reasonable fit could be obtained between calculated and measured $R(0-)$ spectra using the bio-optical model. Several reflectance features are prominent in the modeled/measured spectra. These features are the absorption by humus, tripton and the first chlorophyll_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.

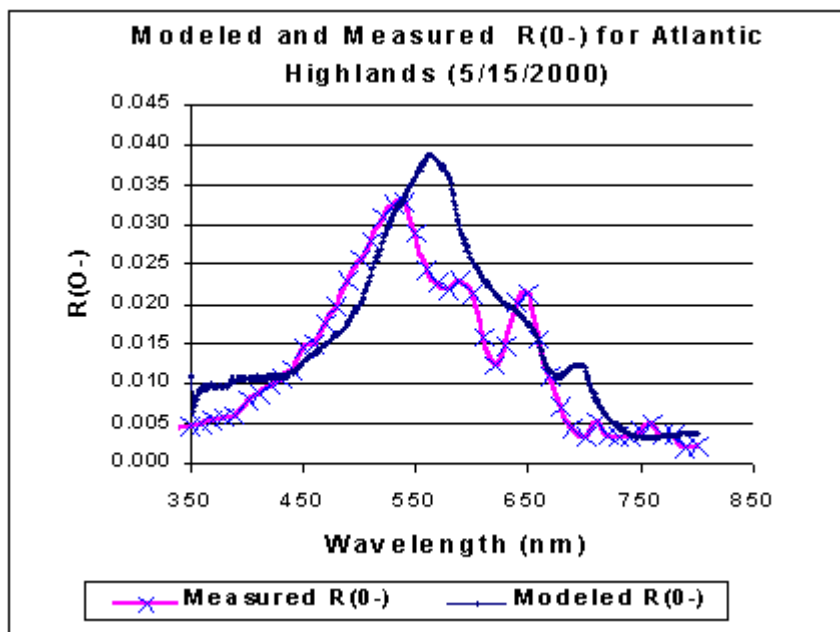


Figure 3. Modeled $R(0-)$ vs measured $R(0-)$ for Horseshoe Cove sampling station

Note that the discrepancy between the measured and modeled $R(0-)$ at the 615-645 nm region is due to the fact that the water-soluble phycobiliprotein pigments are not extracted in the pigment extraction. Thus there are cyanobacteria absorbing through cyanobacterial pigment phycocyanin (cpc) at 615-645 nm visible in the measured $R(0-)$ detected by the field spectroradiometer and not visible in the modeled $R(0-)$.

Use of all the ancillary data recorded during the flight led to a “reasonable” agreement between $R(0-)$ derived from the spectral irradiance data recorded by the field spectroradiometer and computed by the radiative transfer model. In the radiative transfer model we used a mid-latitude summer atmospheric model with an aerosol optical thickness $\tau=0.12$. Subsequently these atmospheric parameters were applied to spectra from several sampling locations where in situ measurements were collected during the AVIRIS overflight and the results are given in Table 2. The table presents a good match between the insitu measurements and the retrieved water constituents concentrations from the atmospherically corrected AVIRIS data.

Table 2. AVIRIS Retrieved Chlorophyll and Suspended Solids vs Insitu Measurements

Chlorophyll l (mg m^{-3})	31-46	34-41
TSM (g m^{-3})	7-11	7-8

4. Conclusion

We conclude that the AVIRIS spectral data provides the opportunity to distinguish the atmospheric effect from the ocean effect, and to set the estimated turbidity for chlorophyll concentration retrieval. Development of a robust algorithm for simultaneous retrieval of atmospheric aerosol optical properties, chlorophyll concentration and colored dissolved organic matter is a very challenging task. Nevertheless, such an algorithm is needed to make progress in this area. Future work will continue in this collaborative effort aimed at tying the bio-optical model derived from the field measurements to a reliable algorithm for simultaneous retrieval of water constituents and aerosol optical properties using the information content of the AVIRIS data.

Acknowledgment

This project is funded by the National Science foundation (Grant # 9806982). Support of the NASA/Headquarters-Biology and Geochemistry Program and the AVIRIS Experiment Team is greatly appreciated.

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