# ATMOSPHERIC CORRECTION AND INVERSE MODELING OF AVIRIS DATA TO OBTAIN WATER CONSTITUENT ABUNDANCES

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## 1.0 INTRODUCTION

Coastal embayments and estuaries are important ecosystems containing a number of critical habitats and resources. They are currently threatened by changes to their surrounding watersheds. Although there has been a wealth of new knowledge generated over the last decade about these ecosystems, the spatial and temporal patterns of biologic and physical processes, as well as anthropogenic influences are not fully understood. Remotely sensed data offer a unique perspective on these processes because of the synoptic view and that quantitative algorithms can be used to extract geophysical and biophysical information from them. We are conducting a number of investigations using remotely sensed data to develop a better understanding of the visible-near infrared reflectance of water, substrate, and land components that will be used to develop algorithms and analytical tools for analysis of processes in the near shore and estuarine environment (patterns of productivity, spatial and temporal patterns of algal blooms, turbidity, etc.).

The study area for our work is Narragansett Bay, Rhode Island (Figure 1). The bay and coastal salt ponds are Rhode Island's premier natural resource and provide the state with numerous jobs ranging from tourism to shellfishing. The objectives of this proposal are complementary to many Bay Project initiatives and thus support a number of high quality goals. These include: effects of land use and land use change on estuarine systems, links between existing data sets for Narragansett Bay and coastal salt ponds with regional perspectives of remote sensing, and a better understanding of the relationships between physical and biological processes.

Visible-near infrared reflectance spectra of coastal and estuarine waters are a complex convolution of the optical properties of water, phytoplankton, gelbstoff, dissolved organic matter, and suspended sediment. Our long term goals are to develop quantitative methods for extraction of the physical abundances of these contributing constituents to the observed reflectance spectra. The work consists of observations with airborne sensors such as AVIRIS and insitu measurements using water samples, towed salinity, temperature, and fluorescence sensors, and field spectra obtained with portable spectrometers. In this paper, we report on results of calibration and reflectance modeling of AVIRIS data obtained on August19, 1997. The data discussed here were obtained at 10:58 and 11:22 EDT on a flight path from the north to the south along the eastern and western borders of the bay (Figure 1). The solar zenith angle was 55.5° and the solar azimuth was 141°.

## 2.0 PHYSICAL CHARACTERISTICS OF MT. HOPE BAY

The Narragansett Bay estuary runs northward from the Rhode Island Coast into Rhode Island and Massachusetts (Figure 1), and has a drainage area of 4660 $km^2$ [Kremer and Nixon, 1978]. Its 2.6 X $10^9$ $m^3$ of water are spread over an area of almost 350 $km^2$, with a mean depth of 7.8 m [Chinman and Nixon, 1985]. The mean tidal prism is much greater than the mean volume of river flow into the bay during an equivalent period of time, so that the estuary is generally well mixed, although occasionally stratified (measured by salinity gradients) in the upper bay [Kremer and Nixon, 1978]. The semi-diurnal tide ranges from 0.8 to 1.6 m [Chinman and Nixon, 1985], but the prevailing winds, northwest during the winter and southwest during the summer, frequently dominate short-term circulation patterns [Kremer and Nixon, 1978]. Water temperatures throughout the year range from below freezing up to the mid-20s (°C), and the annual water temperature cycle tends to lag solar radiation by about 40 days [Kremer and Nixon, 1978]. The Narragansett Bay ecosystem is phytoplankton based, and usually experiences a bay-wide winter-early spring bloom, several localized short term blooms throughout the summer, and a late summer bay-wide bloom [Kremer and Nixon, 1978]. The bay is inhabited by many commercially important fish species, and the benthos is dominated by clams which are harvested in limited areas. The Narragansett Bay ecosystem is significantly impacted by industrial and sewage-treatment effluents, as well as runoff from its intensely populated watershed.

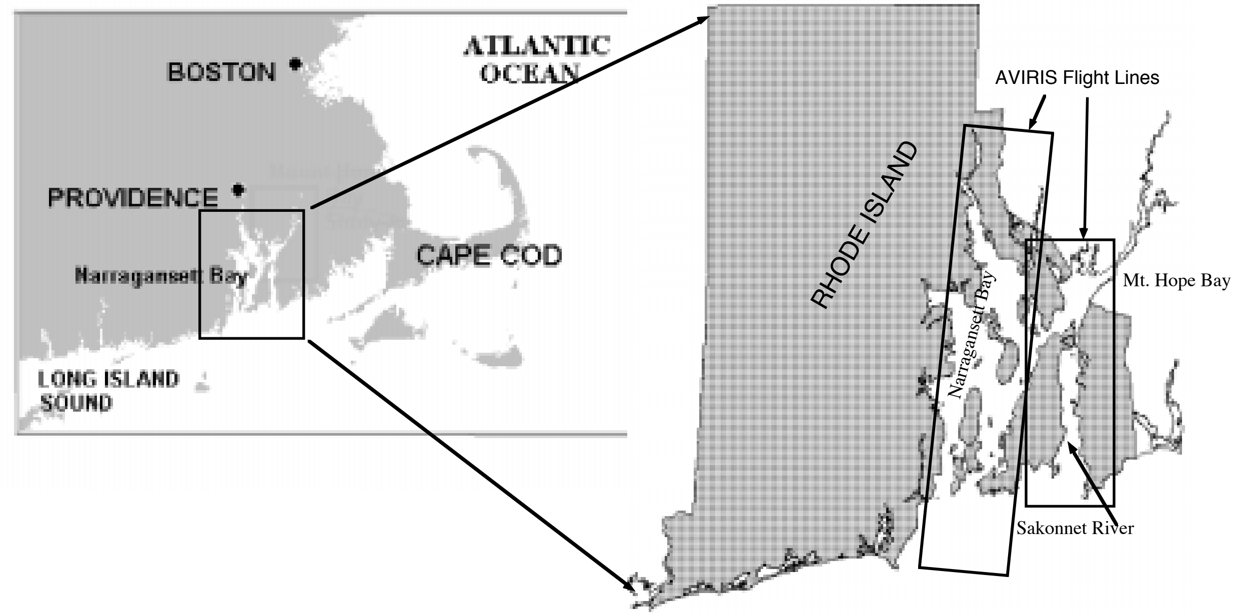

Figure 1. Location of Narragansett Bay and the AVIRIS Flight Line.

## 3.0 AVIRIS DATA CALIBRATION

The goal of calibration was to provide the best estimate of reflectance for all the AVIRIS data. Radiometrically corrected data were provided by the AVIRIS Data Facility. Data were acquired as 12-bit and converted to units of radiance in units of microwatts per square centimeter per nanometer per steradian, or uW / (cm^2 * nm * sr), using inflight and ground calibration files. AVIRIS radiometric calibration factors are calculated by measuring the response of AVIRIS to an integrating sphere (a known target illuminated by a known light source). This calibration is reported to be accurate to within 7%, absolute, over time while intra-flight accuracy is within 2%.

Accurate calibration of radiance to reflectance over water targets is challenging, since up to 90% of the measured radiance can be contributed by sources other than water. The AVIRIS radiance data over Narragansett Bay exhibited two such sources that varied spatially across the scene; one was a phase angle dependent variation in the path radiance (Figure 2) and the other a fresnel reflection off water surfaces optimally oriented with respect to the solar incidence angle and the viewing angle. Both these sources are additive to the total radiance and the spatially dependent properties need to be removed prior to the reflectance calibration. The spectral properties of these sources were characterized empirically using the fact that large regions of the scene were occupied by water with relatively homogeneous spectral properties. Thus any variations in radiance would be due to the phase angle dependent path radiance and fresnel reflections. Radiance spectra from regions that exhibited minimal effects from these sources were subtracted from radiance spectra from regions exhibiting maximum effect to derive the spectral signatures of phase-angle dependent path radiance and fresnel reflection off the water. These signatures were then used to derive magnitude coefficients on a pixel by pixel basis for the entire scene. The magnitude coefficients thus determine the amount of these sources to remove from each pixel. A representative result of this approach is shown in Figure 3.

A number of approaches were examined for reducing the AVIRIS calibrated radiance data to reflectance, including atmospheric modeling, empirical line calibration, and an empirical radiance calibration. Atmospheric modeling was performed using the ATREM model . However, due to a lack of adequate characterization of the atmosphere, the resulting spectral shapes were unsatisfactory, particularly at shorter wavelengths. Though typical land cover units exhibited realistic spectral shapes (e.g. vegetation, soils), the spectra for the estuary were unlike any field spectra that we had obtained to date. An empirical line calibration was attempted. However, this resulted in systematic features in the water spectra unrelated to the spectral properties of water. In essence, the gain and offset corrections were weighted towards the noise statistics of the low albedo calibration target. Projection to the even lower albedo properties of water resulted in the unacceptable spectral features.

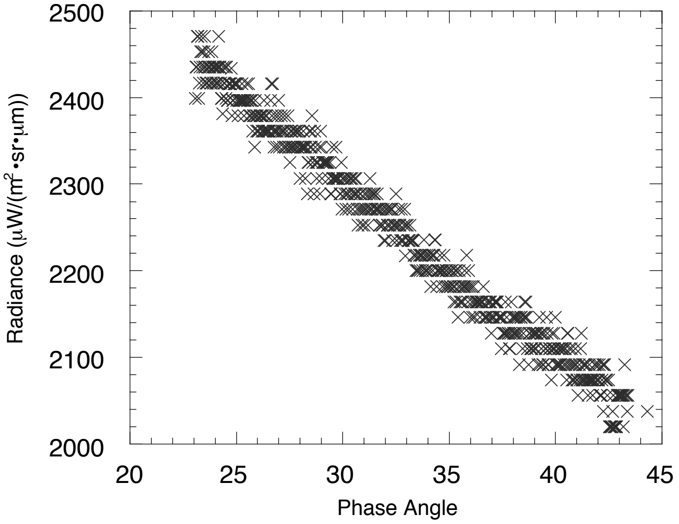

Figure 2. Phase Angle Dependence of Path Radiance.

Fortuitously, several small low altitude cumulous clouds were present in the AVIRIS flight line. These cast shadows over both land and water. Radiance spectra were extracted from shadowed and unshadowed regions of approximately similar terrain cover and analyzed. Regardless of terrain cover, all the shadowed spectra exhibited a consistent spectral shape between 0.4-0.8 µm, and ratios of the various shadowed terrains to shadowed water produced a relatively flat ratio spectrum. Furthermore, ratios of the shadowed regions to unshadowed regions produced relative spectra that exhibited a 1/_$^4$ dependence. Shadowed regions are thus dominated by the global path radiance in the scenes and we propose that shadowed water can provide a first order estimate of path radiance.

Cumulous clouds scatter light very efficiently in the 0.4-0.8 µm region without any significant absorptions. They can therefore provide a first order estimate of solar radiance. To provide a first order estimate of reflectance we therefore subtract the spectrum of shadowed water, with a small reduction to account for reflected sky irradiance (basically attenuate the spectrum by a factor of 0.95) from every pixel in the scene, and divide by the spectrum of a homogeneous cloud, which also has had the estimate of path radiance removed. Carder et al. (1992) presented an approach based on the same concept but with a more thorough development of the radiance contributions for all sources. This was used to constrain a radiative transfer model for the calculation of reflectance and they showed the cloud-shadow approach has merit in the calibration of hyperspectral data in aquatic environments.

## 3.1 ASSESSMENT OF CALIBRATION

The simple approach to calibration provided remarkably clean spectra of the estuary that are highly consistent with reflectance spectra measured insitu. This is illustrated in Figure 4. The AVIRIS spectra are 3x3 pixel averages selected from regions representative of the typical estuarine waters. The field spectra were acquired with ASD portable spectrometers using a 20% reflective Spectralon target as a standard and corrected for the absolute reflectance of the standard. We see that the AVIRIS spectra reproduce the main important characteristics of the field spectra of the estuary: strong chlorophyll absorption between 0.4 and 0.55 µm, strong drop in reflectance after 0.58 µm due to increased water absorption, the presence of a small chlorophyll absorption near 0.67 µm, and chlorophyll fluorescence between 0.67 and 0.71 µm. These spectra are also comparable to estuarine spectra collected by other researchers (e.g. Roesler and Perry, 1995).

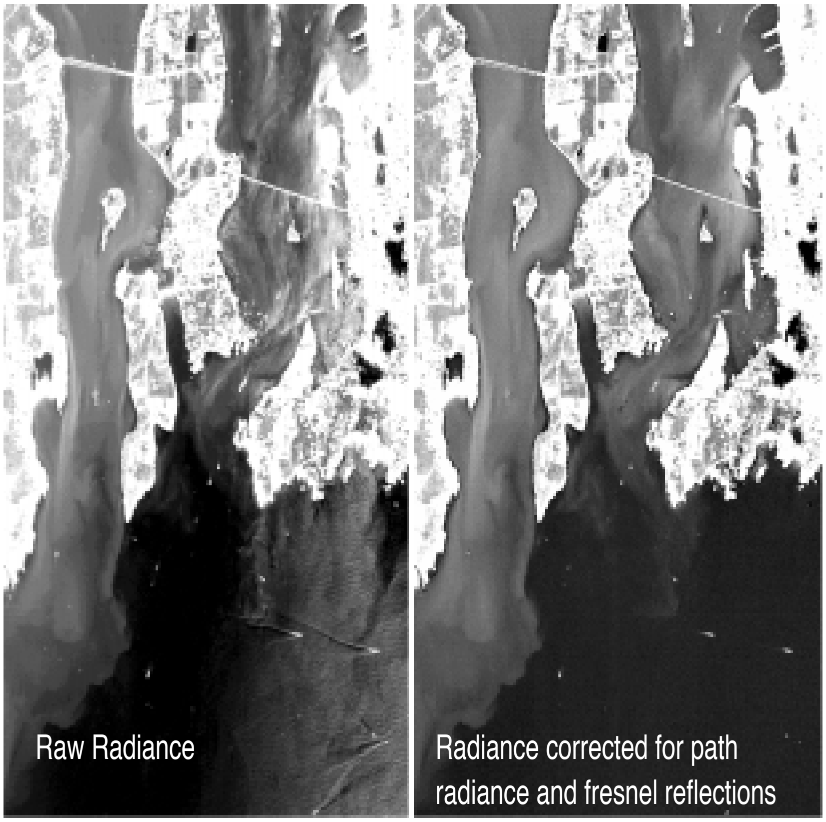

Figure 3. Example of Removal of Pixel Dependent Path Radiance and Fresnel Reflections for the 580 nm Band.

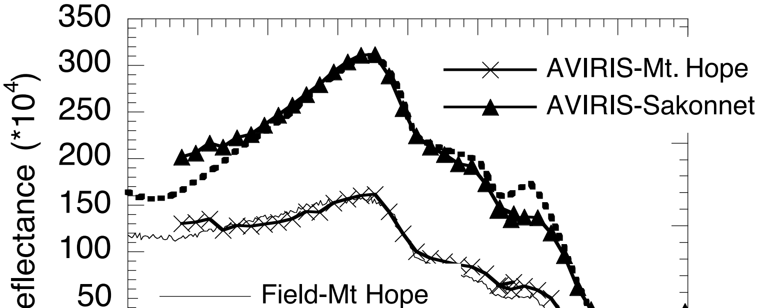

Figure 4. Comparison Between AVIRIS Apparent Reflectance Spectra and Field Spectra Acquired with an ASD FieldSpec FR.

## 4.0 INVERSE MODEL AND ANALYSIS

The high quality of the AVIRIS hyperspectral data shown here provide the opportunity to perform inverse modeling of reflectance to obtain constituent properties remotely. There have been a number of analytical algorithms developed for this purpose (e.g. Carder et al., 1994; Lee et al., 1994; Roesler and Perry, 1995; Hoge and Lyon, 1996). For this analysis we employ the approach of Roesler and Perry (1995), discussed briefly below.

Remote sensing reflectance (ratio of radiance measured in a particular solid angle to the downward irradiance) of coastal and estuarine waters is primarily governed by the optical properties of water, phytoplankton, organic matter (tripton, gelbstoff), and suspended sediment. The reflectance is defined by the ratio of the backscattering properties of these optical components to the absorbing properties. Roesler and Perry (1995) simplified the basic radiative transfer theory to arrive at the fundamental relationship:

$$R(\lambda) = G\frac{\sum_j M_j b_j(\lambda)}{\sum_i M_i a_i(\lambda)} \tag{1}$$

where __is wavelength, R is the reflectance, G accounts for the angular dependence of the upward light field, þand $a_i$ are the backscattering and absorption coefficients for the jth and ith components in the water, and $M_j$, $M_i$ are the magnitudes of the contribution of those components to the measured reflectance. To perform inverse modeling of reflectance to obtain the relative contributions of the optically active components, this equation needs to be solved for the magnitude parameters. Furthermore, some knowledge of the optical properties of these components is required.

The absorption and backscattering properties of pure water are relatively well known and most researchers use the values published by Smith and Baker (1981). The magnitude of the water contributions of backscatter and absorption are fixed to be 1.0. The optical properties of phytoplankton, dissolved organic matter, and suspended sediment vary with location, season, and over the coarse of tides. Nevertheless, the backscattering and absorption properties of organic matter vary within a relatively narrow range over the visible to near-infrared wavelength range and can be reasonably approximately by simple functions of wavelength. For this application we ignore suspended sediment. This is a reasonable approximation for some regions of Narragansett Bay which is fed by mature rivers with virtually no bedload or suspended sediment. However, in regions of strong tidal currents, sediment may be re-suspended from the bottom.

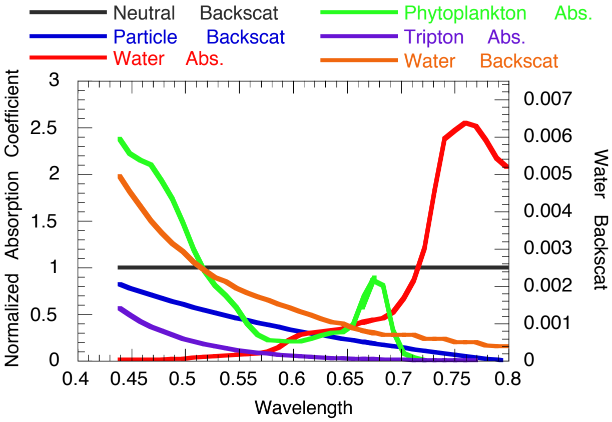

Figure 5. Basis Vectors for Absorption and Scattering Components.

Phytoplankton absorption is known to vary with pigment concentration, packing, and composition (Sathyendranath et al., 1987; Bricaud et al., 1988). In addition, solar-stimulated chlorophyll fluorescence contributes to the measured reflectance, but varies with phytoplankton production. One approach is to use known phytoplankton absorption coefficients to invert the optical model. However, this limits general application and requires a library of local phytoplankton absorption. In addition, phytoplankton species vary seasonally and spatially in estuaries, complicating the building of such libraries. The model of Roesler and Perry (1995) employs novel techniques to simultaneously account for fluorescence and variable phytoplankton absorption through a three-step model inversion.

Solutions to equation (1) are obtained by simultaneous inversion over the number of wavelengths to determine the values of M for the absorption and backscattering basis vectors. The basis vectors used are shown in

Figure 5. Because this is a nonlinear equation, we employ the Levenberg-Marquardt method (Press et al., 1986), setting the values for water equal to 1. The first set of iterations to a solution provide a first-order estimate of the reflectance, using a prescribed value for the phytoplankton absorption spectrum. We use only the wavelengths up to 660 nm to avoid contributions from chlorophyll fluorescence affecting the solutions. In the second step, contributions from chlorophyll a fluorescence are determined as the difference between the measured and modeled reflectances over the wavelength region 660-730 nm. The solutions provide values of the concentration of optical constituents and the fluorescence activity. Example solutions are shown in Figure 6 for two different water types.

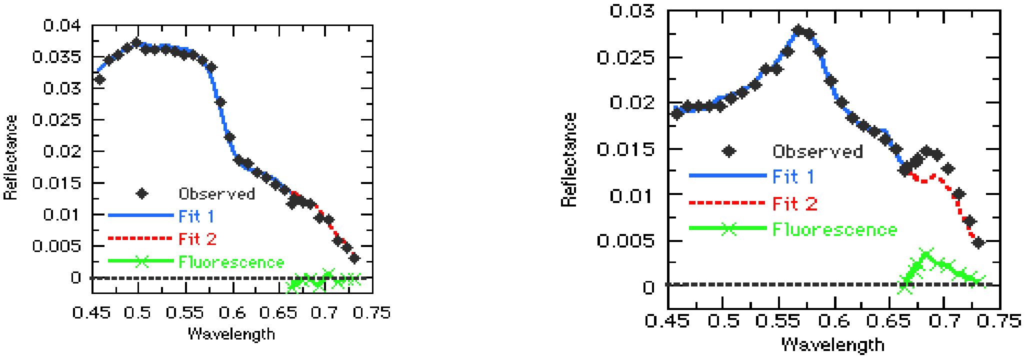

Figure 6. Example solutions of the fit of the model equation to two AVIRIS spectra. The plot on the left shows a low phytoplankton, low fluorescence solution, while the plot on the right shows a high phytoplankton, high fluorescence solution.

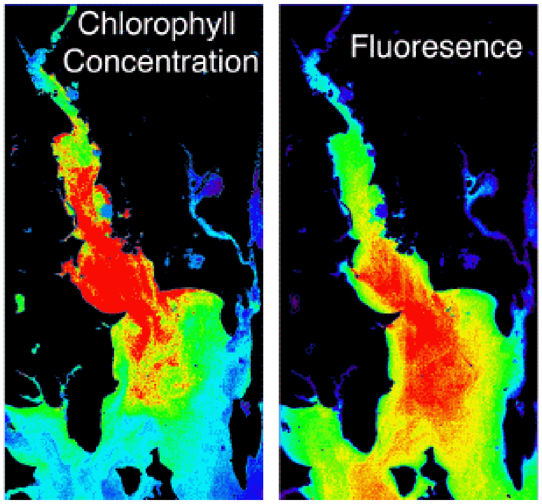

Figure 7. Concentration of phytoplankton represented as chlorophyll contrasted against the activity of the same represented as fluorescence.

Roesler and Perry (1995) demonstrated that this method allowed them to consistently invert reflectance spectra to the relative magnitudes of the various optical components, as well as an estimate of the specific phytoplankton absorption coefficient spectrum for aquatic environments ranging from open ocean to estuarine. We have successfully applied this model to AVIRIS data calibrated using the methods described in this paper. Example results for the concentration of phytoplankton and the activity of phytoplankton (fluorescence) are shown in Figure 7. While there is a general correspondence between high chlorophyll and high fluorescence, also note that there are regions where there is high fluorescence but moderate chlorophyll and vice versa. High fluorescence generally indicates very active photosynthesis and thus may be a good indicator of ecosystem health. Additional results of model applications to AVIRIS data over the Narragansett Bay will be presented at the meeting.

## 5.0 SUMMARY

The very high fidelity of AVIRIS data afford the opportunity to apply deterministic models to remote acquired data over relatively large regions. AVIRIS data acquired over Narragansett Bay, RI in August, 1997 were calibrated to reflectance, taking into account spatially variable contributions from path radiance and fresnel reflectance. A simple cloud-shadow approach was used to derive estimates of global path radiance and downward irradiance. This provided an estimate of reflectance that was highly consistent with reflectance spectra acquired with a field spectrometer. The complications of deterministic models in Case II waters has long been recognized, due to the high concentrations of chlorophyll and organic matter, suspended sediment, and highly variable phytoplankton species and optical properties. The analytical mixing model of Roesler and Perry (1995) offers the promise of simultaneous determination of the concentrations of optically active components as well as the absorption spectrum of the most dynamically variable of these components, chlorophyll. Application of this model to the calibrated AVIRIS data is very promising, offering not only the concentrations of key optically active species, but also the activity of phytoplankton through the fluorescence parameter. Our future plans are to validate the modeling through field research and to apply this model to additional AVIRIS scenes over this estuary.

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## 6.0 REFERENCES

Adams, J. B., M. O. Smith, and A. R. Gillespie. 1993, “Imaging Spectroscopy: Interpretations Based on Spectral Mixture Analysis." *Remote Geochemical Analysis: Elemental and Mineralogical Composition (C. M. Pieters and P. A. Englert, Eds.)*, 145-166.

A. Bricaud, A. Bedhomme, and A. Morel, “Optical properties of diverse phytoplankton species: Experimental results and theoretical interpretation,” *J. Plankton Res.,* Vol. 10, pp. 851-873, 1988.

K. L. Carder, S. K. Hawes, K A. Baker, R. C. Smith, R. G. Steward, and B. G. Mitchell, “Reflectance model for quantifying chlorophyll a in the presence of productivity degradation products,” *J. Geophys. Res.,* Vol. 96, pp. 7457-7466, 1994.

K. L Carder, .P. Reinersman, and A. R. F. Chen, “AVIRIS calibration using the cloud-shadow method*,” Summaries of the Fourth Annual JPL Airborne Geoscience Workshop*, (R. O. Green, ed.) JPL Publication 92-14, vol. 1, pp. 26-28, 1992

R.A. Chinman and S. W. Nixon. “Depth-Area-Volume Relationships in Narragansett Bay. Graduate School of Oceanography, the University of Rhode Island”. *NOAA/Sea Grant Marine Technical Report* 87, 1985.

Hode and R. P. Lyon, “Satellite retrieval of inherent optical properties by linear matrix inversion of oceanic radiance models: An analysis of model and radiance measurement errors,” *J. Geophys. Res.,* Vol. 101, pp. 16631-16648, 1996.

J.N. Kremer and S.W. Nixon, *A Coastal Marine Ecosystem,* New York: Springer-Verlag Berlin Heidelberg, 1978.

Z. Lee, K. L. Carder, S. K. Hawes, R. G. Steward, T. G. Peacock, and C. O. Davis, “Model for the interpretation of hyperspectral remote-sensing reflectance,” *Appl. Opt.,* Vol. 33, pp. 5721-5732.

J. F. Mustard, A. Sen, C. Swanson, D. Mendelsohn, and C. Deacutis, “Integration of remotely sensed data and hydrodynamic modeling into a GIS to assess the impacts of thermal effluent in an estuary”, in *Proc. 4th International Conference on Remote Sensing for Marine and Coastal Environments*, Environmental Research Institute of Michigan, Ann Arbor, MI, II 34-II 43, 1997.

W. H. Press, B. P. Flannery, S. A. Teukolsky, and W. T. Vetterling, *Numerical Recipes, The Art of Scientific Computing,* Cambridge University Press, New York, 1986.

C. S. Roesler and M. J. Perry, “In situ phytoplankton absorption, fluorescence emission, and particulate backscatter determined from reflectance”, *J. Geophys. Res.* v. 100, 13,279-13,294, 1995.

S. Sathyendranath, L. Lazarra, and L. Prieur, “Variations in the spectral values of specific absorption of phytoplankton,” *Limnol. Oceanogr.,* Vol. 32., pp. 403-415, 1987.

R. C. Smith and K. S. Baker, “Optical properties of the clearest natural waters (200-800 nm),” *Appl. Opt.* Vol. 20, pp. 177-183, 1981.