VARIATIONS IN THE SPECTRAL SIGNATURE OF A SUBTROPICAL ESTUARINE INLET[1]

M. John Thompson
Remote Sensing Services
Harbor Branch Foundation, Inc.
R. R. 1, Box 196
Fort Pierce, Florida 33450

BIOGRAPHICAL SKETCH

M. John Thompson received his B.S. in Biological Sciences from the University of Tampa in Tampa, Florida, and his M.S. in Marine Biology from Florida Atlantic University in Boca Raton, Florida. He is currently employed by the Harbor Branch Foundation in Fort Pierce, Florida, and his primary field of research is the application of remote sensing technology to environmental monitoring problems in estuarine and marine habitats.

ABSTRACT

Two predictive upwelling radiance models are tested as potential aids for interpreting seasonal and/or event related shifts in the upwelling spectral signature of estuarine waters. Predicted upwelling radiance values at 445 nm (blue), 542 nm (green) and 630 nm (red) from the Fort Pierce Inlet on Florida's east coast are tested for correlation with observed changes in optical properties of the water column. Upwelling radiance values predicted by both models decreased substantially during the summer sampling period. At the same time, a significant shift in distribution of predicted upwelling radiance values toward longer wavelengths was noted. These changes in spectral signature are attributed to decreasing concentration of hard-scattering inorganic materials within the water column during the calm summer months and a corresponding increase in soft-scattering and selectively absorbing organic compounds being carried into the estuary by upland run-off during the rainy season.

INTRODUCTION

In recent years, many papers have been published, attempting to relate remotely monitored spectral signatures to aquatic environmental quality parameters (Kloaster and Scherz, 1974; McCluney, 1975b; Klemas and Polis, 1977; and Lawson et al., 1977). As Morel and Prieur (1977) point out, there are two major problems in extracting qualitative or quantitative information on water quality from remotely sensed spectral signatures: (1) separating the meaningful information from inherent "noise" detected by the remote sensor and (2) interpreting the spectral composition of a filtered signal with respect to the water's optical properties, which in turn relate to concentrations of dissolved and suspended materials. This paper deals with the second of these problems and discusses the application of two predictive models in interpreting variations of upwelling spectral signatures from estuarine waters.

---

[1] Harbor Branch Foundation Technical Report #23

Estuaries, as transition zones, are extremely diverse in terms of species and concentrations of dissolved and suspended material in the water column. Conditions can change drastically over short periods of time as a result of such factors as wind, rainfall, tidal stage and human activity. Fort Pierce Inlet, site of this study, lies on Florida's east coast and is one of three major connections between the southern portion of the Indian River lagoon system and the Atlantic Ocean (Figure 1). Predicted upwelling radiance/reflectance signatures at three visible wavelengths were calculated for this inlet based on optical measurements made during January and February 1976-77 (Lawson et al., 1977) and July 1977.

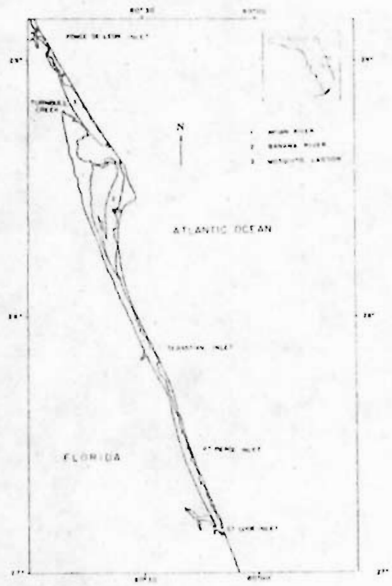

Figure 1 - Indian River Lagoon System

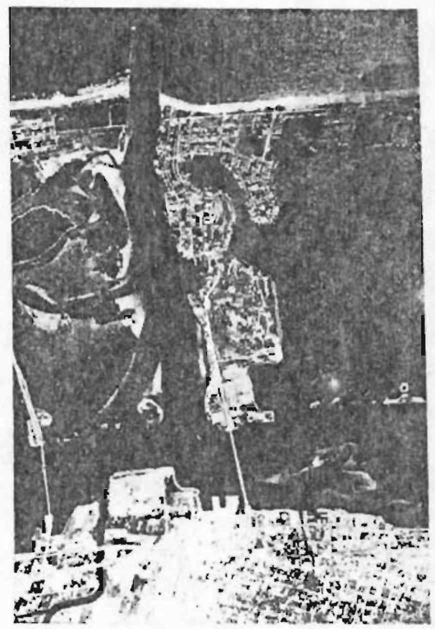

Figure 2 - Fort Pierce Inlet

PREDICTIVE MODELS

Upwelling radiance/reflectance signatures were calculated using two previously developed models. These models are the "Single Scattering Model" (SS), originally suggested by Jerlov (1968) and subsequently modified by McCluney (1974), and the "Quasi-Single Scattering Model" (QSS) described by Gordon (1973). Derivation of both these models has been extensively reviewed elsewhere (Gordon, 1973; McCluney, 1974) and will not be presented here.

The major difference between these models is that the SS model assumes any light scattering event reduces the total downwelling radiant energy field. The QSS model, based on the strong forward scattering tendencies of natural waters, assumes that none of the incident irradiance is lost as the light energy propagates downward.

For an infinitely deep, homogenous ocean, the single-scattered upwelling spectral radiance is given by:

$$N_a^\circ(\lambda,\theta_a,\phi_a) = \frac{T(\theta_a)T(\theta_a^\circ)H_o(\lambda)\beta(\lambda,\theta_w,\phi_w,\theta_w^\circ)}{\eta^2 c(\lambda)[\cos_w - \cos_w^\circ]}$$

where:

- $N_a^\circ(\lambda,\theta_a,\phi_a)$ = the upwelling spectral radiance in air at wavelength λ, detected at solar nadir angles θ_a, ϕ_a.
- $T(\theta_a)$ = transmittance at the air-sea interface for upwelling light.
- $T(\theta_a^\circ)$ = transmittance at the air-sea interface for downwelling light.
- $H_o(\lambda)$ = the spectral irradiance incident on a horizontal sea surface due to sunlight.
- $\beta(\lambda,\theta_w,\phi,\theta_w^\circ)$ = the spectral volume scattering function for wavelength λ at solar nadir angles θ_w, ϕ_w.
- η = water column index of refraction.
- $c(\lambda)$ = single scattering extinction coefficient.

The subscripts "a" and "w" refer to light rays traveling in air and in water respectively. The superscript $^\circ$ indicates we are considering the sun-only component of the light in this equation.

Transforming this equation for use in an ocean of finite depth, but with zero bottom reflectivity yields:

$$R(\lambda) = \frac{T_o\ T(\theta_a)\beta(\lambda,\theta_w^\circ)\beta[1-e^{-c[1-\sec\theta_w^\circ]Z}]}{\eta^2[1-\cos_w^\circ]c}$$ [2]

where R (λ) has replaced $N_a(\lambda,\theta_a,\phi_a)$ as denoting the upwelling radiance, T_o replaces $T(\theta_a^\circ)$, and Z equals depth.

The QSS model requires calculations of a quasi-single scattering coefficient (c^*), which is defined as:

$$c^* = c(1-w_oF)$$

where:

$w_o = \frac{b}{c}$ = the single scattering albedo (b = total scattering coefficient)

F = the forward scattering coefficient

Diffuse reflectivity $[r_o(\lambda)]$ of the bottom is defined as the ratio of upwelling to downwelling light energy just above the bottom (McCluney, 1974). Discounting potential multiple reflections between the bottom and the air-water interface, contribution to the upwelling light field due to light

[2] In this equation, source and sensor surfaces are assumed to be in the same vertical plane, thus eliminating angles θ_w and ϕ_w from the calculations.

reflected by the bottom may be given as:

$$R(\lambda) = \frac{T_o\ T(\theta)}{\pi \eta^2} \left[r_o(\lambda) e^{-c^*(\lambda)[1-\sec\theta]Z} \right]$$

Substituting the quasi-single scattering coefficient and this bottom reflectance calculation into the SS model gives us the QSS model approximation:

$$R(\lambda) = \frac{T_o\ T(\theta)}{\eta^2} \left[\frac{\beta(\lambda, \theta_w^\circ)\ [1-e^{-c^*[1-\sec\theta_w]Z}}{c^*[1-\cos\theta_w]} + \frac{r_o(\lambda) e^{-c^*[1-\sec\theta_w]Z}}{\pi} \right]$$

Both the SS and QSS modeling approaches are over-simplifications and can be expected to introduce considerable error into exact calculations of downwelling or upwelling energy fields. Their simplicity, however, suggests that they may be useful as analytical tools for relating remotely observed upwelling spectra to water quality conditions.

METHODS

Four stations in Florida's Fort Pierce Inlet (Figure 2) were sampled during January-February of 1977 (Lawson et al., 1977). These same four stations were resampled in July of 1977.

Each station was occupied a total of six times during the winter study, and five times in the summer sampling. In order to preserve their optical integrity, samples were placed in light tight containers, transported to the laboratory and analyzed less than two hours after collection.

All optical measurements were taken at three wavelengths, blue (445 nm), green (542 nm) and red (630 nm). These wavelengths were chosen because they encompass the visible range of the electromagnetic spectrum and are considered to be in the range consistent with absorption maxima and minima of organic compounds (Morel and Prieur, 1977).

In situ bottom reflectivity was determined at each studied station, using a reflectance panel calibrated to National Bureau of Standards specifications by the Remote Sensing Division of the Kennedy Space Center. During the winter study, extinction coefficients were determined from percentage transmission data taken *in situ* using a Hydro Products Transmissiometer equipped with narrow band-pass filters. Summer extinction coefficients were determined using a Varian 635 dual beam spectrophotometer. This instrument was operated at the maximum spectral band width of 2 nm using a 5 cm sample cell.

Volume scattering functions were calculated using a Brice Phoenix light scattering photometer, which has an angular measuring range from 35° to 150°. A 75 watt, tungsten-halogen light source was used in this study, replacing the standard mercury light source of the instrument. The tungsten-halogen source produced light over the entire visible spectrum, thus permitting use of spectral band-pass filters having peak transmittances in the previously stated wavelength ranges. Volume scattering functions were determined at 45°, 90° and 135° for each wavelength studied.

The angular range of backscattered light, upwelling from a water column and available for detection by an airborne remote sensor, is assumed to be $120° \leq \theta_i \leq 150°$. Volume scattering functions at the specific θ_i occupied by a theoretical remote optical sensor directly overhead, were interpolated from the measured volume scattering functions and Petzold's (1972) emperically derived volume scattering curve for turbid waters (Lawson, 1977).

Calculation of the quasi-single scattering extinction coefficient (c^*) requires values for the single scattering albedo (w_o) and the forward scattering coefficient (F). Since instrumentation necessary to directly measure w_o and F <u>in situ</u> was not available, a predictive function for w_oF, based upon the measurements of extinction (c) and scattering (β_θ) was developed. Petzold's (1972) values for w_oF relate linearly to $\frac{\ln\beta_{45}}{c}$ with a correlation coefficient of .89 ($p \geq .05$). Solving for the regression coefficients produced the function:

$$w_oF = .876 - .0282 \frac{\ln\beta_{45}}{c} \quad \text{(Lawson, 1977)}$$

This extrapolation showed an average error of 9% when tested against all sampled water masses (Petzold, 1972). More turbid waters evidenced less error between predicted and measured w_oF than did oceanic waters (Lawson, 1977).

RESULTS

Scattering and extinction functions for natural waters are well documented (Tyler, 1961; Duntley, 1963; Jerlov, 1968; and Kullenberg, 1974). Although there are local variations, scattering functions consist of smooth curves showing dominant forward scattering, a broad minimum between 90° and 130°, and a slight increase in backscatter at angles greater than 130° (Figure 3; a, b and c). Extinction functions, based upon percent transmission of the incident irradiance, slope downward and become horizontally asympotic as depth increases (Figure 4; a, b and c).

Volume scattering functions were lower during the summer months at all wavelengths (Figure 3; a, b and c), indicating a reduction in concentrations of inorganic (so called "hard scattering") material in the water column. Extinction coefficients were slightly lower at the green wavelength and considerably lower at the red wavelength during the summer sampling period, but higher for the blue wavelength (Figure 4; a, b and c).

The upwelling spectral signature predicted by both the SS and QSS models for the Fort Pierce Inlet changed dramatically between sampling periods (Figure 5; a and b). Upwelling radiances predicted during winter months exceed that predicted for summer months at all wavelengths tested. January and February upwelling radiance values predicted by both models were fairly uniform among the three wavelengths. Predicted spectral signatures for July clearly reflected the increased absorption of blue light within the water column. Ratios of upwelling red versus blue wavelength radiance ranged from 1.26:1 in winter to 2.09:1 in summer.

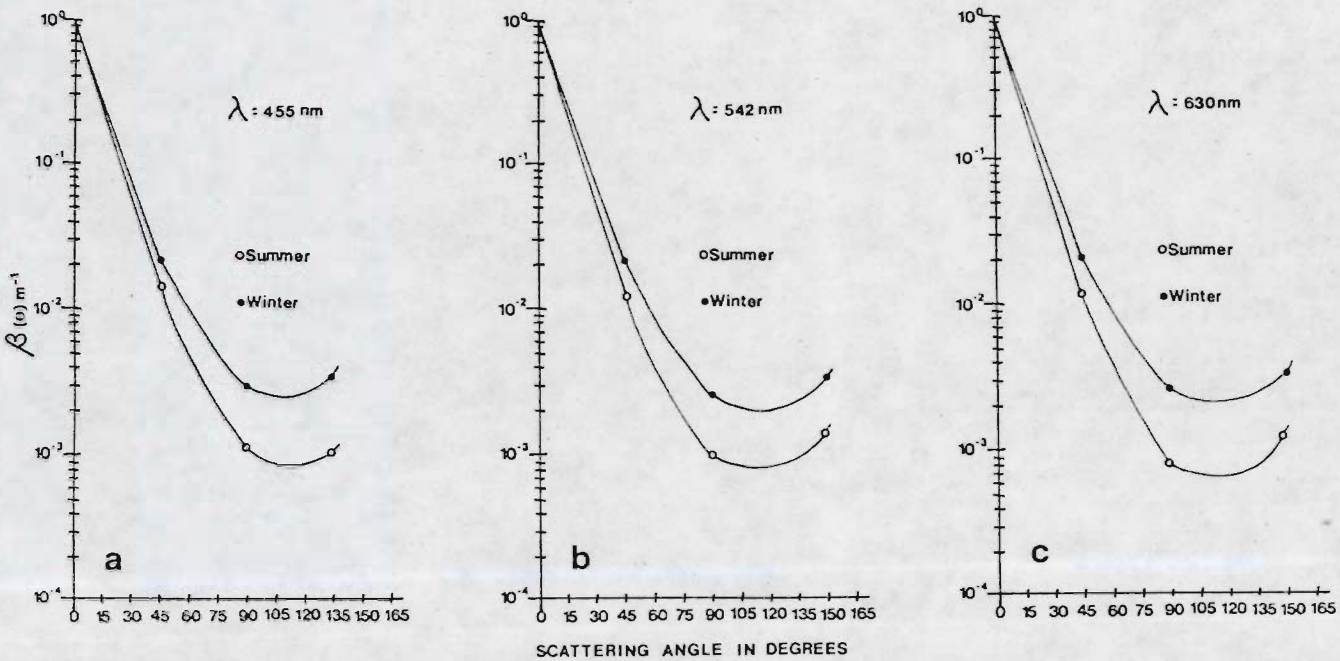

Figure 3 - Averaged volumn scattering functions from Fort Pierce Inlet during winter and summer samplings.
a) VSF for 445 nm
b) VSF for 542 nm
c) VSF for 630 nm

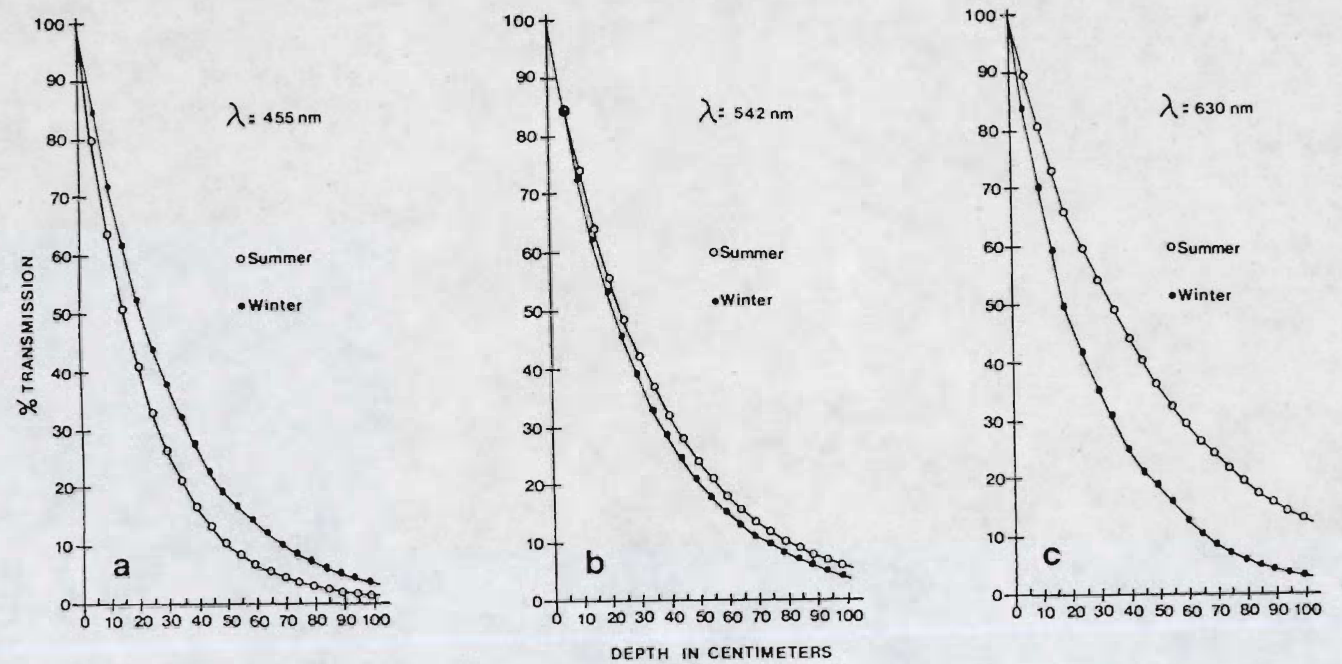

Figure 4 - Averaged extinction functions from Fort Pierce Inlet during summer and winter samplings.
a) Extinction 445 nm
b) Extinction 542 nm
c) Extinction 630 nm

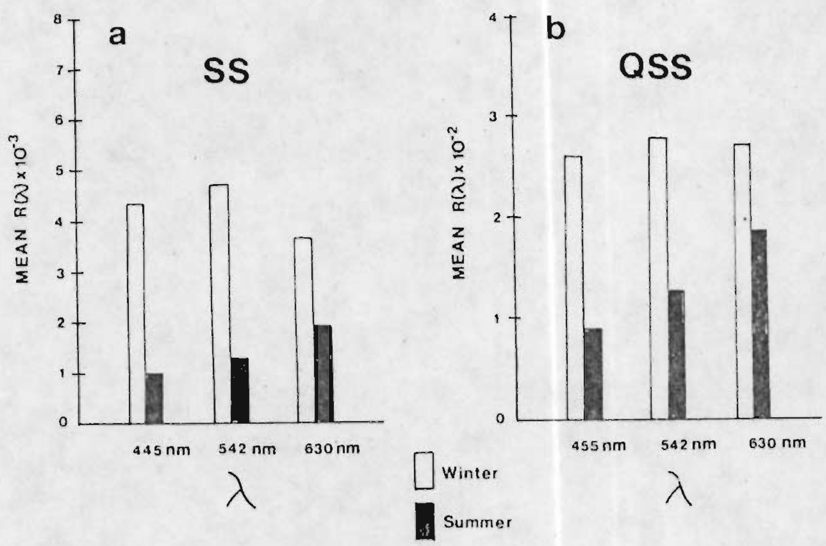

Figure 5 - Predicted upwelling radiance/reflectance values from Fort Pierce Inlet during summer and winter sampling periods.
a) SS model predictions
b) QSS model predictions

The uniformity in predicted upwelling radiance/reflectance values, characteristic of the January-February sampling period, can be interpreted as indicating a high concentration of inorganic light scattering material in the water column. This assumption is supported by the fact that winter months are traditionally the most stormy along Florida's southeastern coast, and increased wave action can be expected to resuspend large quantities of inorganic sediments into the water column.

Reduced upwelling radiance in the 445 nm wavelength range predicted by both the SS and QSS models for the July sampling period, points to substantial increases in selectively absorbing material within the water column. This fact correlates with known increases in yellow humic substances, tannins and lignins observed in Florida estuaries during the rainy season (April through October) (Maynard, et al., 1975).

Both models reflected actually occurring changes in the mechanism of radiant energy transfer in Fort Pierce Inlet. Upwelling radiance/reflectance values predicted by both models should correlate well with the upwelling radiance values detected by a remote sensor, assuming a sufficiently high signal to noise ratio.

Incident light energy produces a much stronger return signal in predictions by the QSS model than those of the SS model. This results from the introduction of the bottom reflectivity factor. Since bottom reflectivity makes an important contribution to upwelling radiance in shallow coastal areas, the QSS model can be expected to yield a more radiometrically accurate prediction for this environment. In areas of very clear, shallow water, multiple reflections between the bottom and the surface introduce additional errors into predicted upwelling radiance values, but these errors are more pronounced with the QSS model.

It is generally accepted that the peak of the color spectrum of natural waters shifts toward red in regions of high organic loads. The reflectance of longwave spectral radiance also increases as a function of the amount of suspended inorganic sediments in the water column (Clarke and Ewing, 1974; McCluney, 1975). Unfortunately, conflicting optical mechanisms are responsible for these observed spectral shifts, thus preventing the formulation of a direct relationship between changes in reflectance and concentration of organic material or suspended sediments without first performing specific optical and chemical measurements on the waters in question.

Spectral signature shifts seen during this study indicate that ratioing upwelling radiance of various specific wavelengths is the best approach to remote water quality analysis. Shifts in the relative spectral composition of the upwelling energy field may be used as indicators for such seasonal and/or event related water column changes as increased upland run-off, intense storm surges or planktonic blooms.

CONCLUSIONS

Fidelity of both modeling approximations in reflecting chemical and physical changes of the dominant light attenuating substances in Fort Pierce Inlet, shows considerable reliability for both approximations as analytical tools. Predicted upwelling radiance values should correlate closely with those detected by a remote sensor, assuring a sufficiently high signal to noise ratio.

Clarke and Ewing (1974), among others, have shown that there is an easily detectable difference in the spectral signatures of organically rich versus organically poor oceanic waters. This research shows that seasonal variations in concentrations of organic and inorganic substances may alter the spectral signatures of highly productive estuarine or nearshore waters. The existence of such seasonal and/or event related variations in the upwelling spectral radiance emerging from estuaries and coastal inlets is an important consideration in any attempts to relate nearshore water quality to remotely monitored spectral data.

values detected by a remote sensor, assuming a sufficiently high signal to noise ratio.

Incident light energy produces a much stronger return signal in predictions by the QSS model than those of the SS model. This results from the introduction of the bottom reflectivity factor. Since bottom reflectivity makes an important contribution to upwelling radiance in shallow coastal areas, the QSS model can be expected to yield a more radiometrically accurate prediction for this environment. In areas of very clear, shallow water, multiple reflections between the bottom and the surface introduce additional errors into predicted upwelling radiance values, but these errors are more pronounced with the QSS model.

It is generally accepted that the peak of the color spectrum of natural waters shifts toward red in regions of high organic loads. The reflectance of longwave spectral radiance also increases as a function of the amount of suspended inorganic sediments in the water column (Clarke and Ewing, 1974; McCluney, 1975). Unfortunately, conflicting optical mechanisms are responsible for these observed spectral shifts, thus preventing the formulation of a direct relationship between changes in reflectance and concentration of organic material or suspended sediments without first performing specific optical and chemical measurements on the waters in question.

Spectral signature shifts seen during this study indicate that ratioing upwelling radiance of various specific wavelengths is the best approach to remote water quality analysis. Shifts in the relative spectral composition of the upwelling energy field may be used as indicators for such seasonal and/ or event related water column changes as increased upland run-off, intense storm surges or planktonic blooms.

CONCLUSIONS

Fidelity of both modeling approximations in reflecting chemical and physical changes of the dominant light attenuating substances in Fort Pierce Inlet, shows considerable reliability for both approximations as analytical tools. Predicted upwelling radiance values should correlate closely with those detected by a remote sensor, assuming a sufficiently high signal to noise ratio.

Clarke and Ewing (1974), among others, have shown that there is an easily detectable difference in the spectral signatures of organically rich versus organically poor oceanic waters. This research shows that seasonal variations in concentrations of organic and inorganic substances may alter the spectral signatures of highly productive estuarine or nearshore waters. The existence of such seasonal and/or event related variations in the upwelling spectral radiance emerging from estuaries and coastal inlets is an important consideration in any attempts to relate nearshore water quality to remotely monitored spectral data.

LITERATURE CITED

Clarke, G. L. and G. C. Ewing. 1974. Remote spectroscopy of the sea for biological production studies. In: Optical Aspects of Oceanography, N. G. Jerlov and E. S. Nielsen (eds.). Academic Press, N.Y. 389-413.

Duntley, S. Q. 1963. Light in the sea. J. Opt. Soc. Am. 53: 214-233.

Gordon, H. R. 1973. Simple calculation of the diffuse reflectance of the ocean. Applied Optics. 12(12): 2803-2804.

Jerlov, N. G. 1968. Optical Oceanography. Elsevier Publishing Co., New York. p. 194.

Klemas, V. and D. F. Polis. 1977. Remote sensing of estuarine fronts and their effects on pollutants. J. Photogram. Engin. Rem. Sens. 43(5): 599-612.

Kullenberg, G. 1968. Scattering of light by Sargasso Seawater. Deep Sea Res. 15: 423-432.

__________. 1974. Observed and computed scattering functions. In: Optical aspects of oceanography, N. G. Jerlov and E. S. Nielsen (eds.). Academic Press, N.Y. 25-49.

Lawson, R. A. 1977. The application of remote sensing techniques to determine the spectral radiance reflectance in the Fort Pierce Inlet area. Master's Thesis, Florida Institute of Technology, Melbourne, Florida. 125 p.

__________, M. J. Thompson, and W. R. McCluney. 1977. Determination of upwelling spectral radiance in Fort Pierce Inlet, Florida. Proc. Fall Tech. Meeting, Amer. Soc. Photogrammetry. 204-216.

Maynard, V. I., L. A. Barnard, and R. R. Jolley. 1975. Water quality measurements in the Anclote River Estuary during 1974. In: Anclote Environmental Project Report 1974. Ed. by G. F. Mayer and V. I. Maynard. University of South Florida, St. Petersburg, Florida. 177-198.

McCluney, W. R. 1974. Ocean color spectrum calculations. Applied Optics. 13(10): 2422-2429.

__________. 1974. Remote measurement of "Turbidity" and other water quality parameters. NASA/Goddard Space Flight Center, Greenbelt, Maryland. 20771. 61 p.

Morel, A. and L. Prieur. 1977. Analysis of variations in ocean color. Limno. Oceanog. 22: 709-722.

Petzold, T. J. 1972. Volume scattering functions for selected ocean waters. SIO Ref. 72-78, Visibility Laboratory, San Diego, California.

Tyler, J. E. 1961a. Scattering properties of distilled and natural waters. Limno. and Oceanog. 6: 451-456.