Modeling of spectral signatures of the littoral waters

Vladimir I. Haltrin †
Naval Research Laboratory, Ocean Sciences Branch, Code 7331,
Stennis Space Center, MS 39529-5004, USA

ABSTRACT

The spectral values of remotely obtained radiance reflectance coefficient (RRC) are compared with the values of RRC computed from inherent optical properties measured during the shipborne experiment near the West Florida coast. The model calculations are based on the algorithm developed at the Naval research Laboratory at Stennis Space Center and presented here. The algorithm is based on the radiation transfer theory and uses regression relationships derived from experimental data. Overall comparison of derived and measured RRCs shows that this algorithm is suitable for processing ground truth data for the purposes of remote data calibration. The second part of this work consists of the evaluation of the Predictive Visibility Model (PVM). The simulated three-dimensional values of optical properties are compared with the measured ones. Preliminary results of comparison are encouraging and show that the PVM can qualitatively predict the evolution of inherent optical properties in littoral waters.

Keywords: Modeling, Diffuse Reflectance, Spectral Signatures, Littoral waters.

1. INTRODUCTION

To improve aerospace algorithms for retrieval seawater content from remotely measured imagery it is very important to create models for restoring apparent reflective properties of the sea from *in situ* measured profiles of beam attenuation and scattering coefficients. In theory this set of parameters is not sufficient for restoring such reflection properties as diffuse reflection and/or radiance coefficients of the sea. To accomplish this retrieval a set of additional parameters should be employed. This includes a profile of scattering phase function or some of its integral characteristics, and the angular distribution of natural light.

Section 2 of this paper give a brief description of the experimental data gathering. The results of the spectral measurements of radiance reflectance coefficient are compared with the results of the retrieval of these values from *in situ* measurements of inherent optical properties. These data are obtained simultaneously during the ground truth experiment near the West Florida coast (see Fig. 1) in August 1994. Upwelling spectral radiances from the water surface and *in situ* inherent optical properties are measured concurrently at the same locations. Values of spectral radiance reflectance coefficients are derived from *in situ* data and compared with those obtained from spectral radiance data. A model for estimating reflectance coefficients based on attenuation and absorption data is proposed in section 3.

Prediction of inherent optical properties in littoral waters is critically dependent on the spatial and temporal distributions of optically significant constituents such as suspended sediment and biological populations. These distributions depend on hydrodynamic transport in the coastal region and photosynthetically available radiation. In the section 4 of this paper we compare the three-dimensional (3-D) optical field generated by the Predictive Visibility Model (PVM), a computer model capable of predicting diurnal and episodic changes in near-coastal water optical properties, with the results of *in situ* measurements of inherent optical properties obtained during the experiment in West Florida coastal waters. Finally, a few preliminary conclusions are given in section 5.

† For further information: e-mail: <haltrin@nrlssc.navy.mil>, phone: 228-688-4528, fax: 228-688-5379.

2. EXPERIMENTAL DATA

In situ data, from the experiment near the West Florida coast, are collected at nine stations, that range in depth from 2 meters to 23 meters. The two types of devices are used.

The spectral radiometer (model FieldSpec™ VNIR), with sensor bandwidth of 350-1000 *nm* and a one-degree acceptance angle, was manufactured by Analytical Spectral Devices, Inc. It has a CCD-based detector with the spectral range between 350 and 1000 *nm*. The foreoptic of the radiometer has a one degree acceptance angle. The radiometer reflectance measurements are made at 30° from nadir and in the opposite from the sun direction. The examples of relative measurements of radiance are shown in Fig. 2. The data from this spectral radiometer is processed according to the algorithm given in section 3.

The vertical profiles of inherent optical properties are collected with two beam absorption-and-attenuation meters (WETLabs, Inc. model A/C-9). These 25-*cm*-path length instruments measure beam absorption and attenuation coefficients at nine wavelengths ranging from 412 *nm* to 715 *nm*. The first AC-9 was anchored as a moored unit at a depth of approximately 6.8 meters and distance of 50 meters from the shoreline. The second transmissometer was configured as a vertical profiling unit, and data was collected at nine stations transecting perpendicularly from the shoreline. The absorption and attenuation coefficients are collected at nine stations transecting perpendicularly from the shoreline. The data from both these instruments are post-processed according to the algorithm developed by Weidemann and Bowers [1], and approved by WETLabs, Inc. The data are first corrected for instrument drift by applying pertinent field calibrations. A correction is then applied to the near-infrared band to correct for differences in the instrument’s initial calibration temperature and the water temperature at the time of the experiment. Next, the absorption measurements were corrected for scattering error with the formula proposed by Zaneveld [2]. This is necessary due to the instrument’s inherent design that causes the data to be overstated. Pure water absorption values for each wavelength are added then to the data according to values proposed by Pope [3] and Pope and Fry [4]. Pure water scattering values are considered negligible and are not included. The data are then separated into individual time steps and the Kriging approximation is used to create data suitable for surface generation and visualization.

Figures 3 and 4 illustrate the depth variation of measured inherent optical properties. Depth dependence is only one of the many predictive capabilities of the PVM. In section 4, the overall goal and purpose of the PVM are explained and the temporal and spatial predictive capabilities of the PVM are illustrated.

Figure 5 shows two examples that are representative of the type of experimental data accumulated at the experiment and post-processed. Figure 5a is a plot of the absorption coefficient as a function of depth at station 7 for all nine wavelengths, while figure 5b is a similar plot for the scattering coefficient.

3. PROCESSING OF SPECTRAL DATA

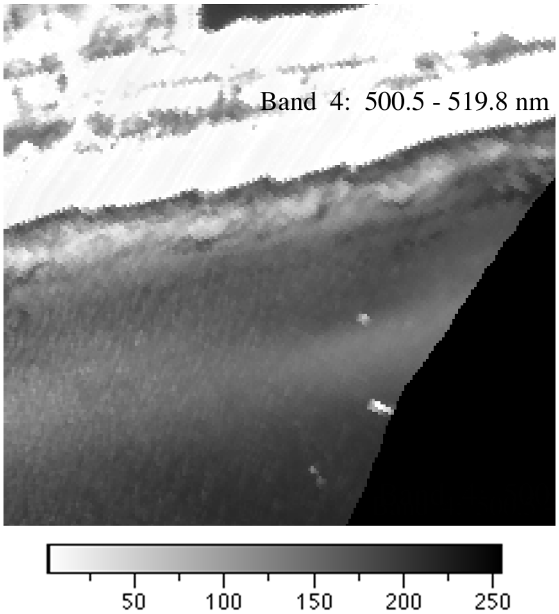
The experimental values of radiance reflection coefficient ρ_{mes} were calculated from three relative measurements of the sea N_{sea}, sky N_{sky}, and gray reference reflector N_{ref}:

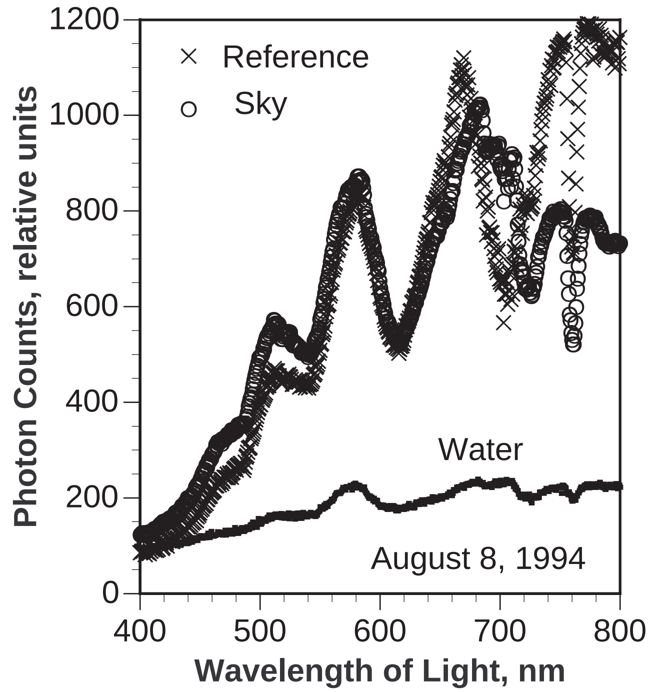
$$\rho_{mes} = \frac{A_{ref}\left(N_{sea} - R_F N_{sky}\right)}{\pi\, N_{ref}}, \tag{1}$$

here A_{ref} is the reference albedo, and R_F is the Fresnel reflection coefficient of skylight [6]. Examples of measured radiance coefficients ρ_{mes} are shown in Fig. 4.

The radiance reflection coefficients ρ_{res} derived from the profiles of absorption $a(z)$ and scattering $b(z)$ coefficients are calculated according to the equation:

$$\rho_{res} = T_d\, T_u\, R \equiv R\, \frac{\left(1 - R_F\right)^2}{n_w^2}, \tag{2}$$





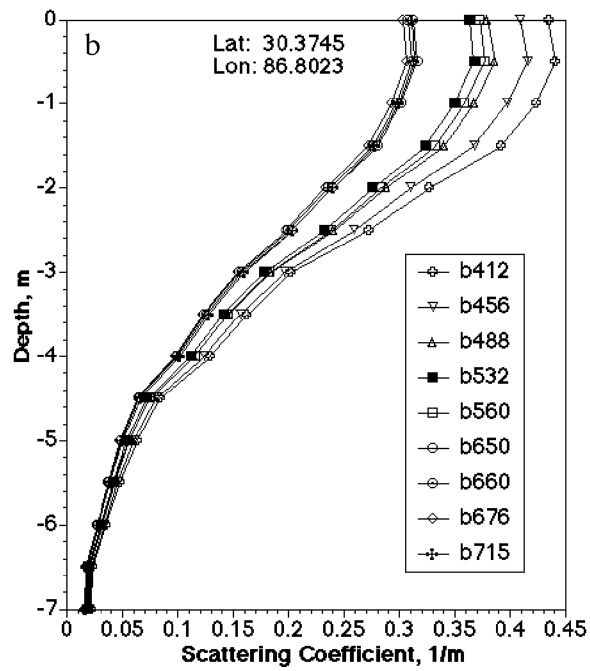


Fig. 3. Experimental values of the absorption coefficient measured August 8, 1994, in the area shown in Fig. 1.

Fig. 4. Experimental values of the scattering coefficient measured August 8, 1994 in the area shown in Fig. 1.

here T_d and T_u are, respectively, downward and upward transmission coefficients of the sea surface, $n_w \cong 1.34$ is the water refractive index, and R is the diffuse reflectance of the sea including effects of reflection from the bottom. The diffuse reflectance of a stratified shallow sea was computed using the formula proposed in Ref. [7]:

$$R = 4\int_0^{z_B} R_\infty(z)\exp\left\{-4\int_0^{z}\left[a(z')+b_B(z')\right]dz'\right\}\left[a(z)+b_B(z)\right]dz + A_B\exp\left\{-4\int_0^{z_B}\left[a(z')+b_B(z')\right]dz'\right\}. \qquad (3)$$

Here A_B is the bottom albedo and z_B is the sea depth. All other parameters – $R_\infty(z)$ and backscattering coefficient $b_B(z)$ – are optical properties of the sea calculated through the absorption and scattering profiles $a(z)$ and $b(z)$ (see Figs. 3 and 4) measured during the experiment. They are expressed through those profiles as:

$$R_\infty(z) = \left[\frac{1-\bar{\mu}(z)}{1+\bar{\mu}(z)}\right]^2, \qquad (4)$$

$$b_B(z) = a(z)\frac{g(z)}{1-g(z)}, \qquad g(z) = \frac{\left[1-\bar{\mu}^2(z)\right]^2}{1+\bar{\mu}^2(z)\left[4-\bar{\mu}^2(z)\right]}. \qquad (5)$$

$$\bar{\mu}(z) = 2.6178398\,\eta - 4.6024180\,\eta^2 + 9.0040600\,\eta^3 - 14.59994\,\eta^4 + 14.83909\,\eta^5 - 8.117954\,\eta^6 + 1.8593222\,\eta^7, \qquad \eta(z) = \sqrt{\frac{a(z)}{a(z)+b(z)}}. \qquad (6)$$

Eqns. (3)–(5) are based on the theory presented in Refs. [8, 9]. The empirical Eqn. (6) is derived by the author from the experimental and *in situ* measurements published by Timofeyeva [10].

Figure 6 shows a sample of the measured radiance reflection coefficients, while Fig. 7 displays the comparison of the measured and restored – through the algorithm presented in this section – radiance reflection coefficients. The overall error of restoration of the spectral radiance reflection coefficients with our algorithm does not exceed 20% for the experiment.

4. PREDICTIVE VISIBILITY MODEL

The Predictive Visibility Model was jointly developed by Science Applications International Corp. and the Scripps Oceanographic Institution [11-13] for the Office of Naval Research and the Naval Research Laboratory.

The PVM was designed to predict the optical properties of coastal waters from first principles using forecasts of waves, currents, river discharge, coastal geomorphology and land use. The model estimates the spatial and temporal distributions of environmental drivers required to predict subsurface scattering, absorption, and diffuse attenuation coefficients within a factor of two. It also forecasts episodic changes of environmental significance. Such drivers include river discharge, tidal currents, ocean swell, bottom resuspension, plankton growth and episodic changes in storm related land runoff.

Optically important constituents in the PVM are presently limited to sediments, phytoplankton and colored dissolved organic materials. The spatial and temporal variability in the concentrations of each constituent is driven by mixing and advection in the dynamic coastal environment. Inherent optical properties of the water were calculated with the help of Mie scattering over particle size distributions of each constituent [14, 15]. In calculations of scattering on sand and clay particles we used index of refraction data proposed in Ref. [16]. Visibility assessment was performed through the inherent optical properties. Estimation of the light fields was made according to approach published in Ref. [9].

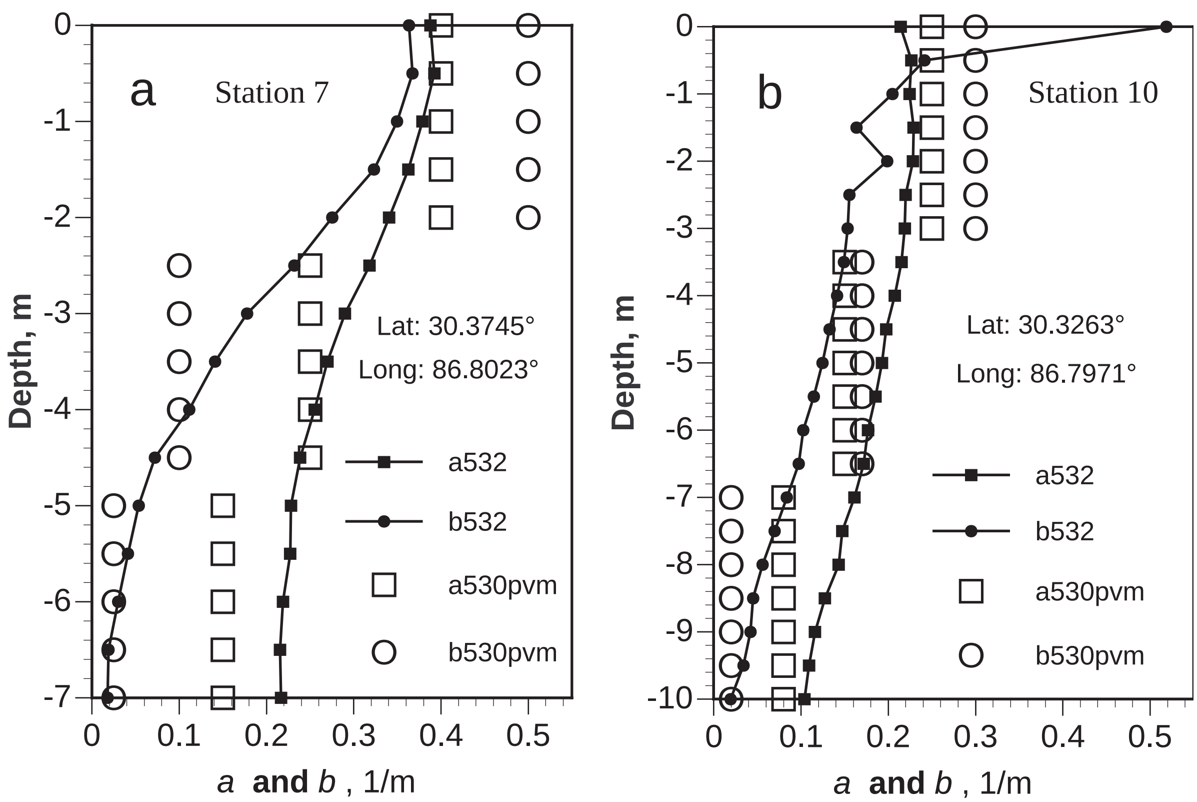


Figure 5. Experimental and simulated values of absorption and scattering coefficients at two stations.

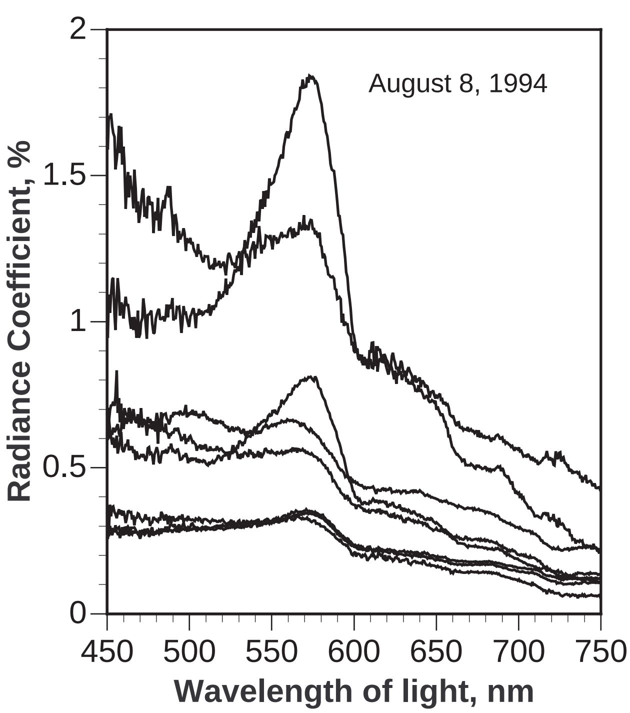


Fig. 6. Examples of the restored with Eqn. (1) radiance reflection coefficients for different shallow water stations near the West Florida coast.

Fig. 7. Experimental (lines) and restored (symbols) are values of radiance reflection coefficient for August 8, 1994, West Florida coastal waters.

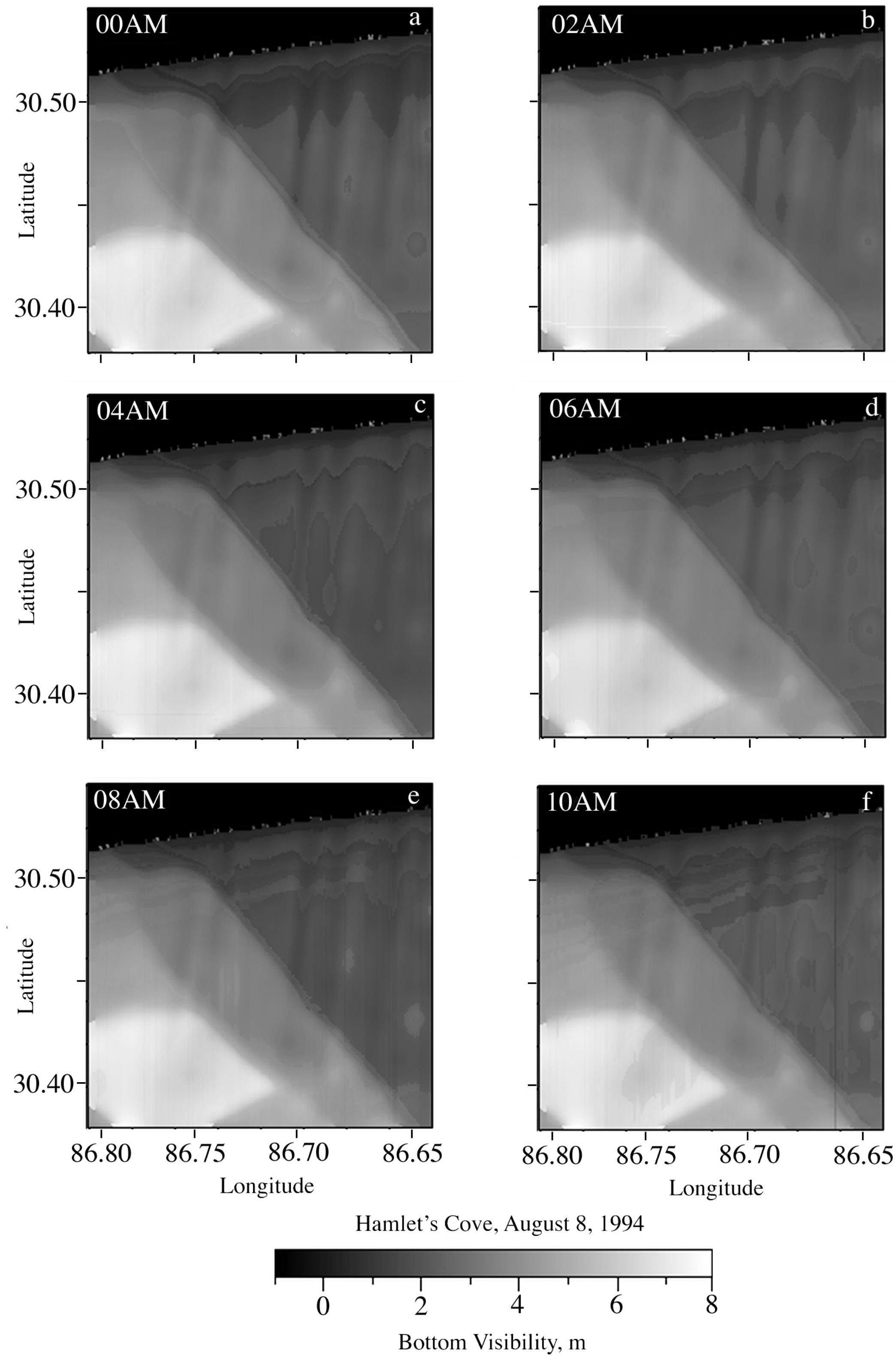


Fig. 8. Catalog of the PVM time-dependent bottom visibility v in time steps starting from the midnight to 10 PM August 8, 1994. The displayed areas lie between 30.375 and 30.55 degrees of Western Latitude and 86.5 and 86.88 of Northern Longitude.

A typical PVM run begins with an initialization. This step includes the generation of a 200×200, 3 *arcsec* resolution bathymetry grid, information about water elevation relative to mean sea level, offshore tidal current and direction for each 2-hour time step, and solar irradiance over the 24-hour simulation period. The other time-varying parameters – such as cloud cover, air temperature, sea surface temperature, pressure and direction, sea height, swell period, direction and height, offshore current velocity – are linearly interpolated at each 2-hour time step between their now-cast and 24-hour forecast values.

For each time step, one of the outputs of the PVM is the 3-D spatial variation of the inherent optical properties. In the PVM, visibility v is defined as $v = 3/c$, where $c = a + b$ is a total beam attenuation coefficient. In Fig. 8 we present a catalog of the PVM bottom visibility predictions over 5 successive two-hour time steps, from midnight to 10 AM, August 8, 1994, for the area of experiment.

5. CONCLUSIONS

The results of the spectral measurements of the radiance reflectance coefficient measured remotely from a small ship are compared with the results of the retrieval of these values through the *in situ* measured profiles of absorption and scattering coefficients obtained simultaneously during the ground truth experiment near the West Florida coast.

The presented algorithm for retrieval of the radiance coefficient using observed depth profiles of the absorption and scattering coefficients is stable. The derived values, in the worst cases, have error less then 20%. The overall comparison of the derived and measured radiance coefficients shows that this algorithm is suitable for the calibration remote data using *in situ* observations.

Because the Predictive Visibility Model incorporates the major environmental drivers responsible for the variability of inherent optical properties in littoral waters, it should be capable of predicting the concentrations of optically important substances from the driving physical, chemical and biological forcing functions. Although it is not expected that the PVM predictions will be as accurate as those achievable for open ocean waters, predictions of inherent optical properties within a factor of two are foreseeable. Comparison with the some of the collected data shows that, in spite of some discrepancies between prediction and ground truth fields, the PVM can be used for qualitative predictions and may serve as a basis for development of more robust predictive visibility models.

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