Simultaneous Retrieval of Aerosol Optical Properties and Marine Constituents in Coastal Waters

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Outline

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⇒ Current aerosol retrievals

⇒ Aerosol retrievals using coupled models

– Over ocean

– Over land and snow/ice

⇒ Improved approach using MODIS data

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Motivation

Improved aerosol retrieval algorithms for turbid waters are motivated by

– Problems with current atmospheric correction algorithms

– Improved spectral capabilities of new satellite instruments

– Possibility of accurate retrievals of multiple in-water constituents

– Near-shore environmental monitoring and resource management

Motivation (cont.)

– **Problems with current atmospheric correction algorithms:**

Current attempts to retrieve aerosol information over turbid waters face difficulties because

* The so-called black pixel approximation (BPA) fails for the channels usually employed for this purpose
* Only an algorithm accounting for radiative transfer in the coupled atmosphere-ocean system can yield an answer that is radiometrically correct in all cases

Motivation (cont.)

– **Improved spectral capabilities of new satellite instruments:**

Recent and future satellite instruments have greatly improved temporal and spectral characteristics

* Additional wavelengths carrying extra information have become available and should be exploited
* Increased information content should allow for retrieval of additional state parameters

Motivation (cont.)

– Possibility of accurate retrievals of multiple in-water constituents:

Additional spectral information provided by multi- and hyperspectral sensors will allow for retrieval of several in-water parameters, BUT:

* Accurate removal of the atmospheric contribution to the TOA radiance over turbid waters is needed
* Aerosol retrieval should also determine aerosol absorption

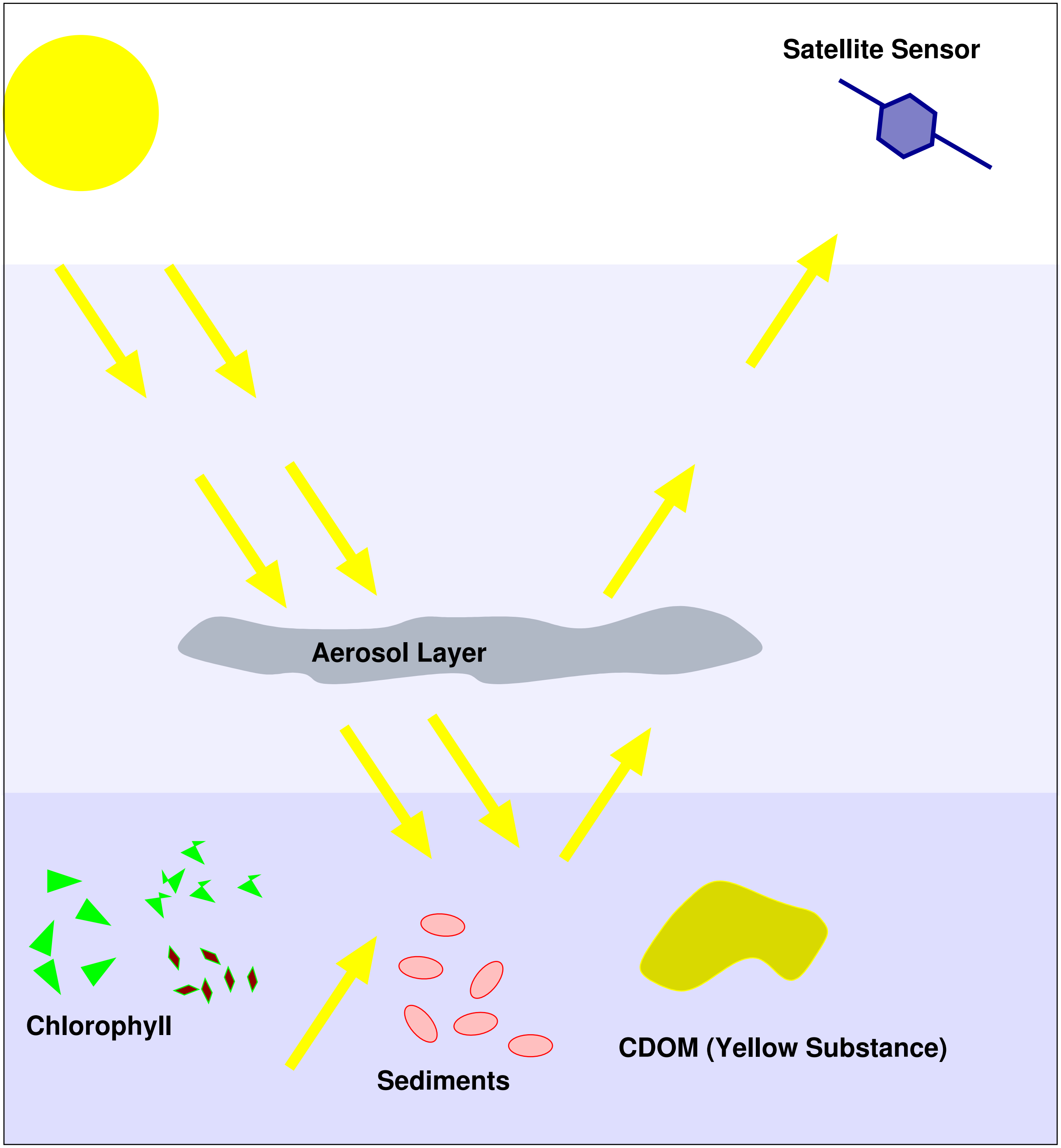

Figure 1: **A schematic illustration showing aspects of the retrieval problem.**

Current aerosol retrievals

Three major sources of uncertainty still remain in current ocean color/atmospheric correction algorithms:

1. **The aerosols are usually assumed to be non-absorbing;**
2. **A simple empirical model is used to quantify ocean reflectance $\Longrightarrow$ the water-leaving radiance is assumed to be isotropic;**
3. **The decoupling of the atmospheric and oceanic radiative transfer problems makes it difficult to quantify the retrieval error.**

Retrievals based on CAO models

* An accurate radiative transfer model (RTM) for the coupled atmosphere ocean (CAO) system becomes an essential tool when the BPA fails

* The RTM-CAO approach is needed to quantify the dependence of the TOA radiance on marine constituents:

* The RTM-CAO approach provides a Forward Model for standard inversion methods

Retrievals based on CAO models (cont.)

A RTM-CAO constitutes an essential tool for the retrieval because:

* it can be used in inversion methods as a reliable and accurate forward model required to:
* compute accurate weighting functions (Jacobians) or cost functions.

Thus, the RTM-CAO approach allows for:

* construction of robust inversion algorithms using state-of-the-art optimization methods including optimal estimation theory, simulated annealing, and neural networks;
* quantification of retrieval errors and their sources.

Retrievals based on CAO models (cont.)

We make extended use of simulated or synthetic data in addition to real data, because we have found that this approach:

⇒ **is very useful for evaluation purposes**

⇒ **makes it easy to run benchmark comparisons between different algorithms**

We will also use a variety of inversion tools:

√ **to explore the number of independent pieces of information retrievable from a given set of TOA radiances, and**

√ **to determine degrees of freedom and correlations between retrieved parameters**

Retrievals based on CAO models (cont.)

Areosol retrievals over land and snow/ice are also possible because, as shown in the next slide:

- **the TOA reflectance increases with aerosol optical depth for dark surfaces**
- **the TOA reflectance decreases with aerosol optical depth for bright surfaces.**

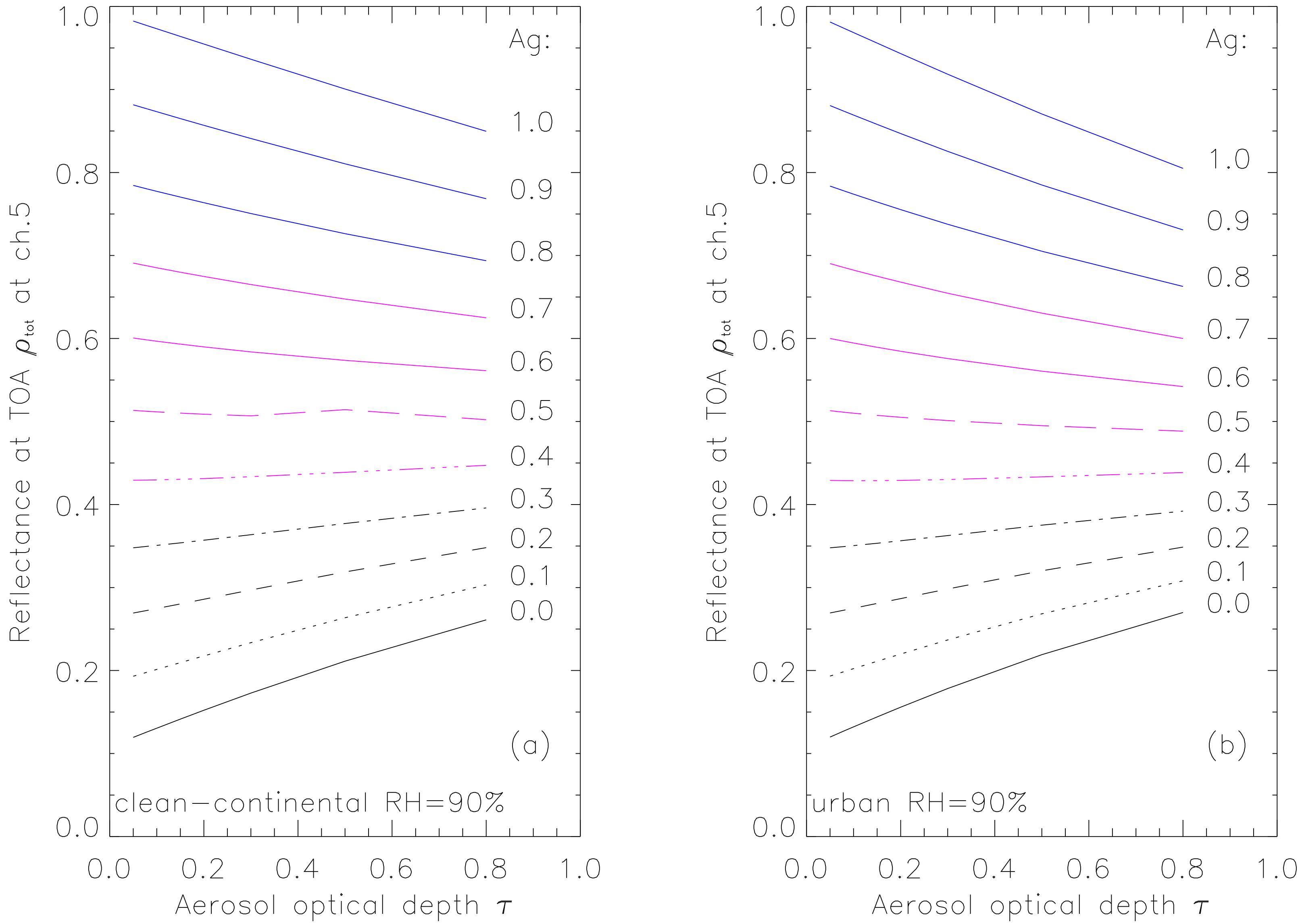

Figure 2: **The TOA reflectance at 460 nm as a function of aerosol optical depth (τ) and surface reflectance (A_g). Panel (a) is for a non-absorbing aerosol model (clean-continental, relative humidity, RH = 90%); and (b) for an absorbing aerosol model (urban, RH = 90%).**

Improved approach for MODIS channels

Compared to most ocean color instruments (*e.g.* SeaWiFS) MODIS has channels at longer wavelengths that are useful for atmospheric correction, because:

⇒ **At the longer wavelengths even very turbid water has negligible reflectance due to the shallow penetration depth (BPA holds)**

⇒ **yet these channels are sensitive to aerosol properties, and**

⇒ **can easily discriminate land and cloud areas.**

Available MODIS channels for NIR aerosol retrievals over water:

- **1.24μm**
- **1.64μm**
- **2.13μm**

Improved approach for MODIS channels (cont.)

Retrieval of aerosols using the longer NIR wavelengths are advantageous because:

* even turbid waters will work as "black pixels"
* we may use the information thus retrieved as a "first-guess" in an iterative approach to explore the validity of extrapolating aerosol information retrieved at longer NIR wavelengths into the visible
* an accurate description of the atmospheric contribution allows us to retrieve multiple in-water parameters, and to do so more accurately

Improved approach using MODIS channels (cont.)

The following figure illustrates the rationale behind the aerosol retrievals

(a) **Left Panel:** **the factor $\gamma_{\mathbf{diff}}(1240\text{nm}, 1640\text{nm})$ vs aerosol optical depth (τ_{865}) for the 16 different aerosol models used in our algorithm**

(b) **Right Panel:** **the factor $\epsilon_{\mathbf{ms}}(1240\text{nm}, 1640\text{nm})$ vs aerosol optical depth (τ_{865}) for the 16 different aerosol models in our algorithm**

$$\epsilon_{\mathbf{ms}}(\lambda_1, \lambda_2) = [\rho_{\mathbf{atm}}(\lambda_1) - \rho_{\mathbf{ray}}(\lambda_1)]/[\rho_{\mathbf{atm}}(\lambda_2) - \rho_{\mathbf{ray}}(\lambda_2)]$$

$$\gamma_{\mathbf{diff}}(\lambda_1, \lambda_2) = \gamma(\lambda_1) - \gamma(\lambda_2) \qquad ; \qquad \gamma(\lambda) = \rho_{\mathbf{atm}}(\lambda)/\rho_{\mathbf{ray}}(\lambda)$$

The two factors γ_{diff} and ϵ_{ms} form the basis for our aerosol retrieval routine.

Our aerosol model has 4 types of aerosols, maritime, tropospheric, coastal, and oceanic, at RH = 50%, 70%, 90%, 99% ⇒16 aerosol models.

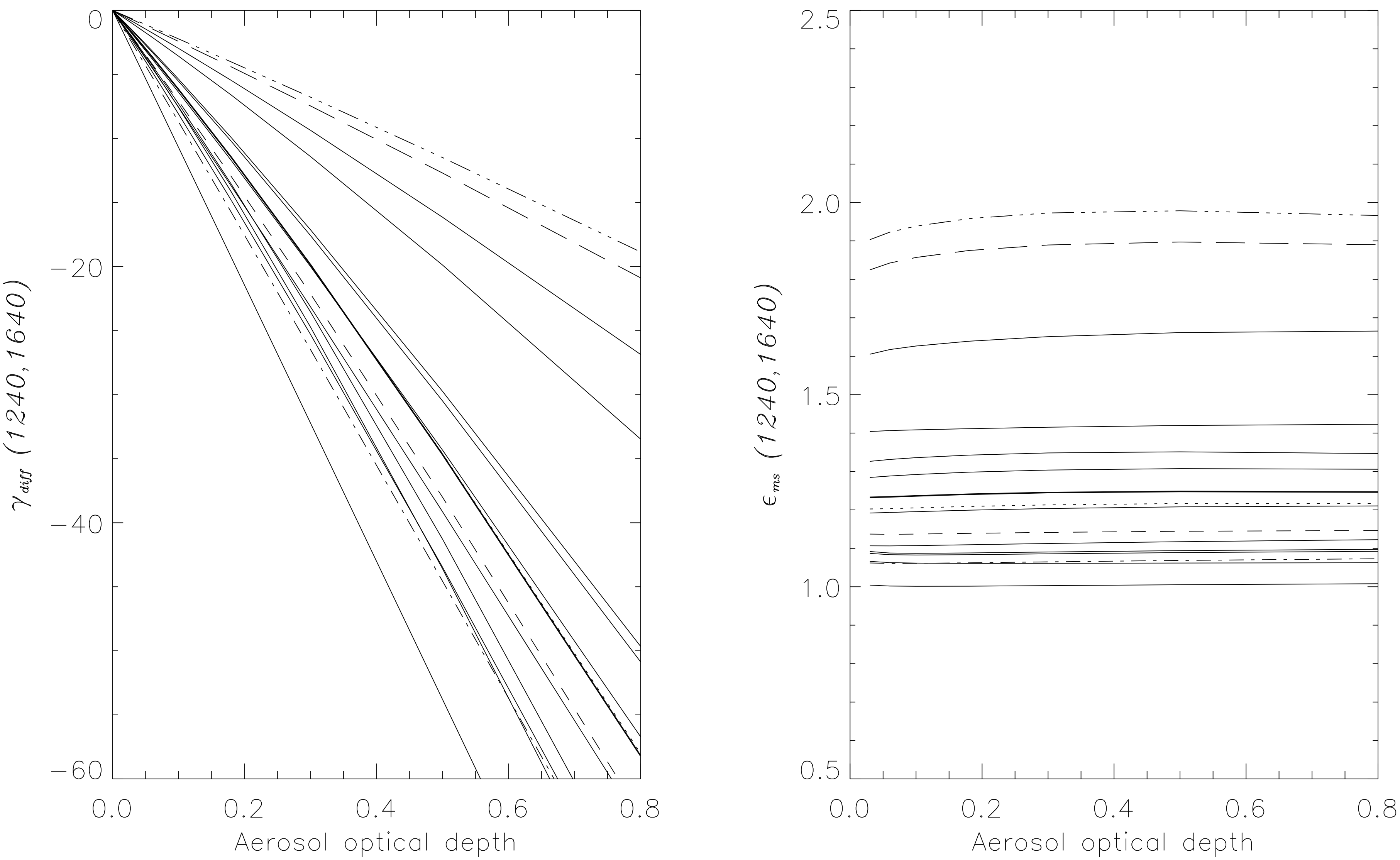

Figure 3: **Simulated values of $\gamma_{\text{diff}}(1240/1640)$ and $\epsilon_{\text{ms}}(1240/1640)$ as a function of aerosol optical depth τ_{865}. The different lines correspond to our 16 aerosol models.**

Improved approach using MODIS channels (cont.)

The following three slides show three portions along the same image scene. The scene contains clear water, turbid water, land areas, and cloudy pixels.

Each slide contains three images:

(a) Left: reference image using visual channels RGB (559nm, 518nm, 447nm)

(b) Middle: false color image using the SeaWIFS "atmospheric correction channels" at 864nm, 762nm, and 671nm

(c) Right: false color image using the MODIS "atmospheric correction channels" at 2133nm, 1648nm, and 1245nm

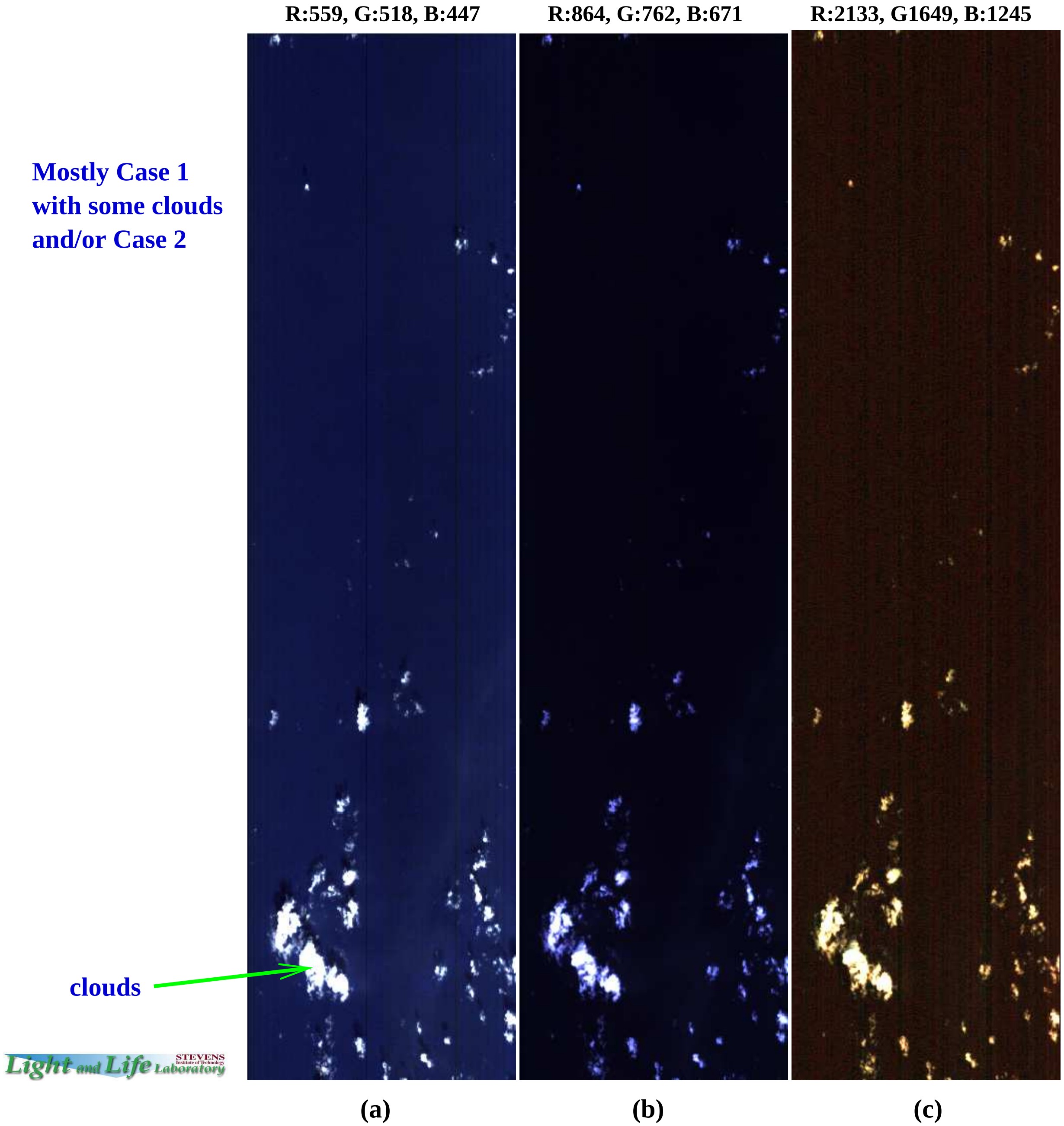

Figure 4: **Reference image made from visual channels (a), image made from the SeaWIFS atmospheric correction channels (b), and image made using the longer wavelength channels available with MODIS and Hyperion (c). The wavelengths are indicated on top of each figure.**

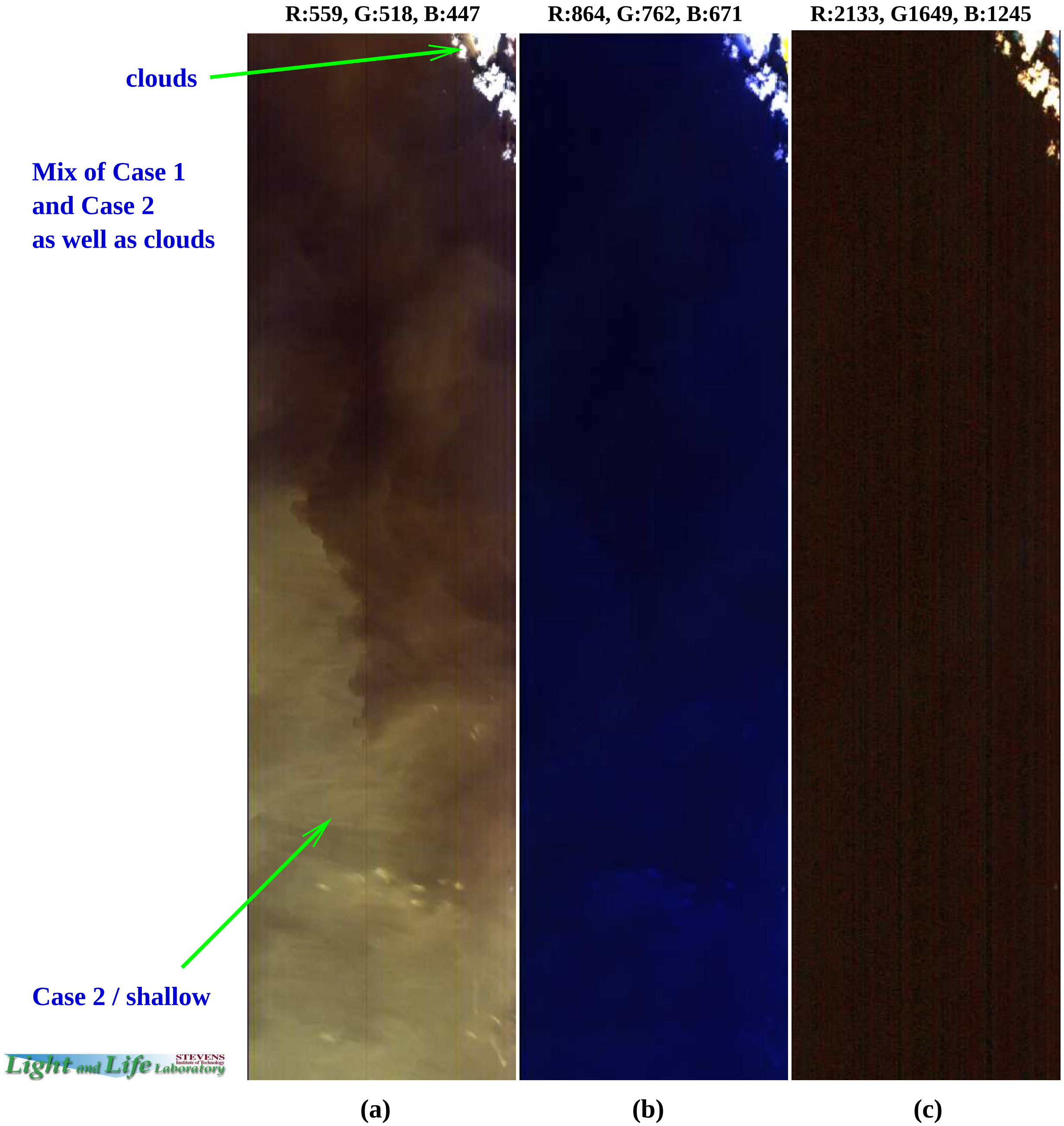

Figure 5: **Reference image made from visual channels (a), image made from the SeaWIFS atmospheric correction channels (b), and image made using the longer wavelength channels available with MODIS and Hyperion (c). The wavelengths are indicated on top of each figure.**

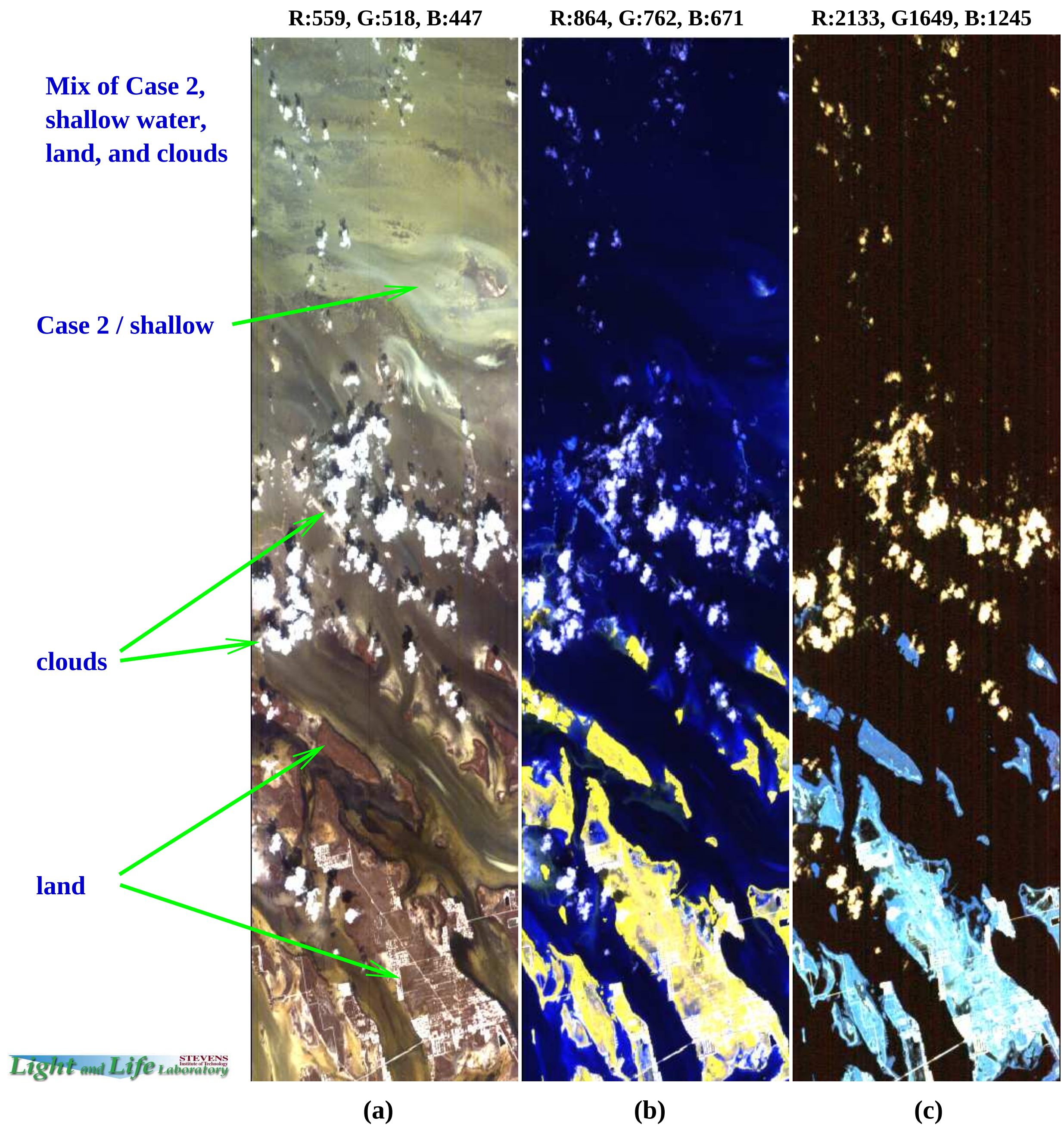

Figure 6: **Reference image made from visual channels (a), image made from the SeaWIFS atmospheric correction channels (b), and image made using the longer wavelength channels available with MODIS and Hyperion (c). The wavelengths are indicated on top of each figure.**

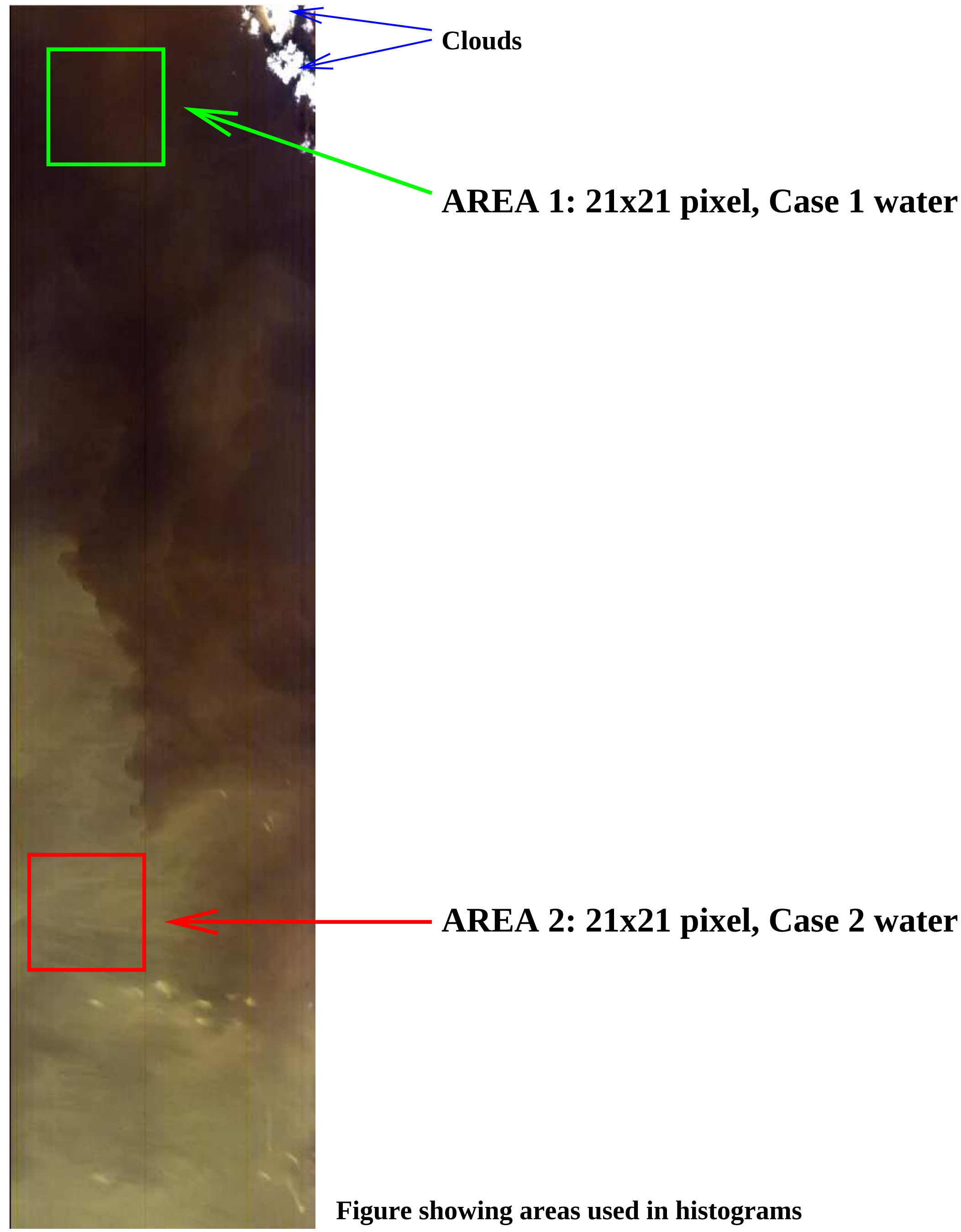

Figure 7: We will study the areas marked in the image more closely. Area 1 is (nearly) clear water, while area 2 clearly has a lot of sediments and/or shallow water.

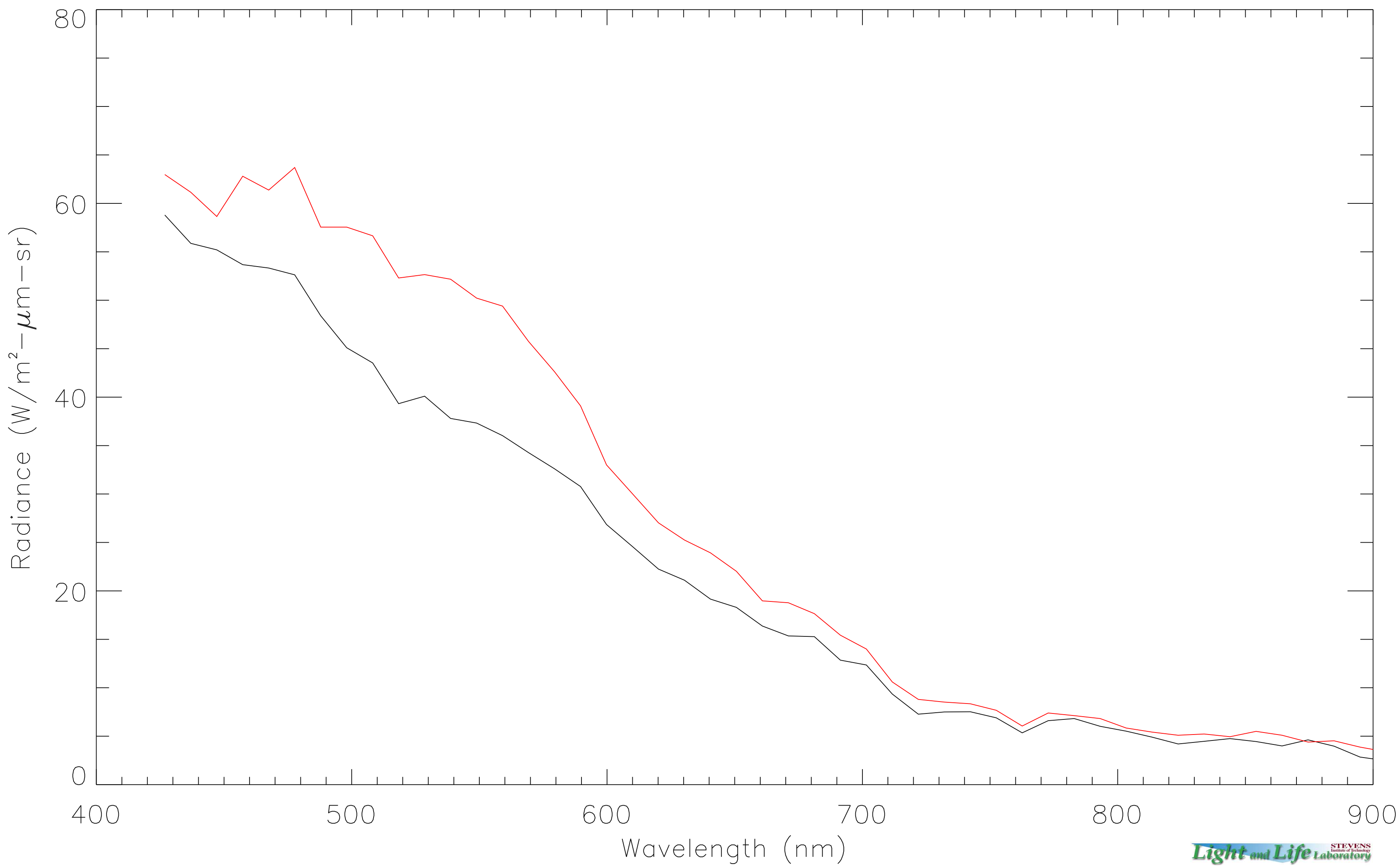

Figure 8: **Spectral radiances at the center of area 1 (clear water, black line) and at the center of area 2 (turbid water, red line). Note that area 2 (turbid water) has a higher radiance than area 1 (clear water) especially at the shorter wavelengths.**

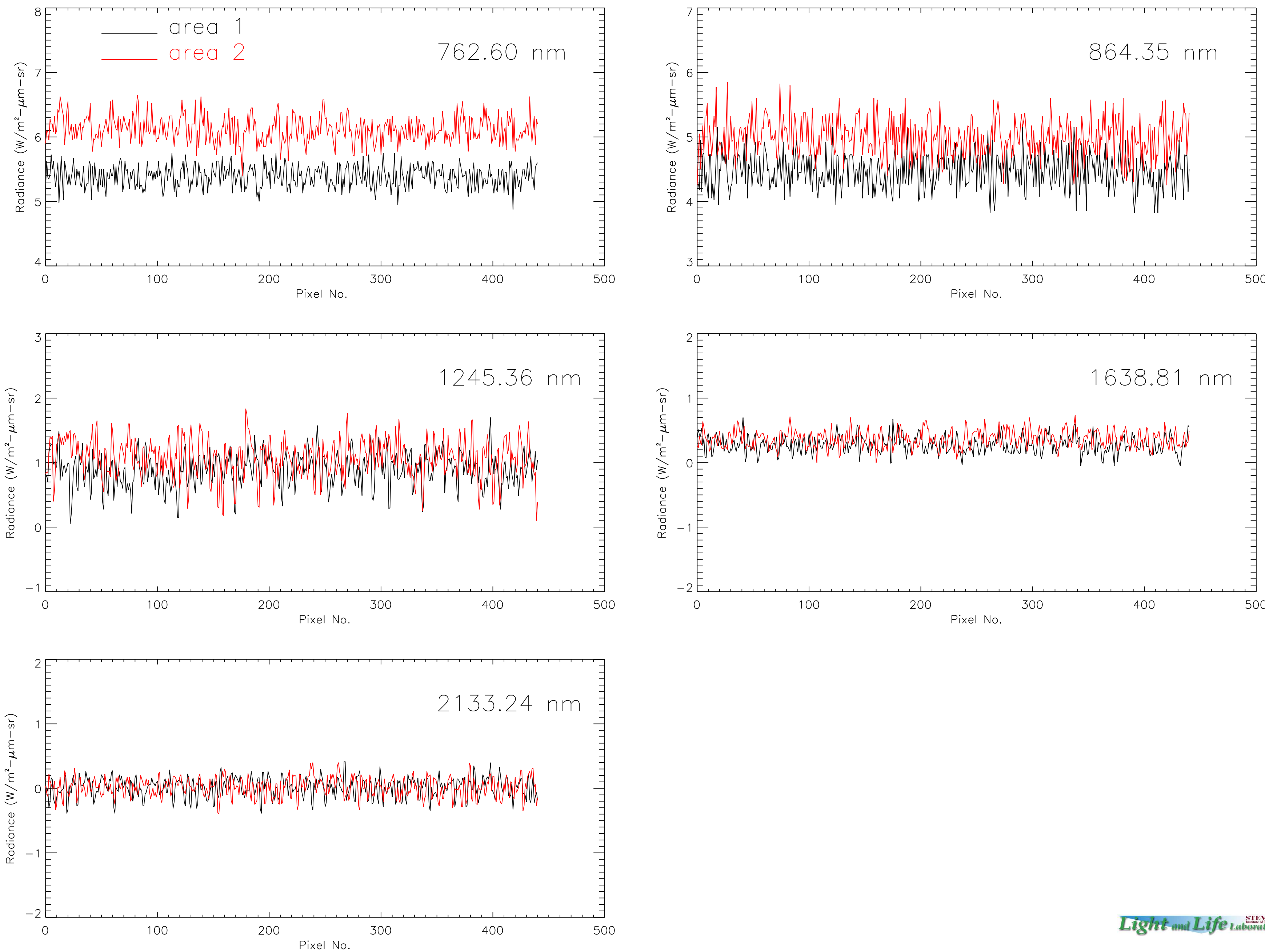

Figure 9: **Measured pixel radiance at each of the selected wavelengths for area 1 (Case 1 water, black lines) and area 2 (turbid water, red lines).**

Improved approach using MODIS channels (cont.)

From the previous figures we see that

- ⊕ the longer wavelengths discriminate water from land and clouds better (*i.e.* the BPA holds)
- ⊕ there are hardly any problems with shallow or highly sediment-loaded water

The problem of aerosol retrieval and atmospheric correction over turbid water seems to be largely solved, but

- ⊖ low signal to noise levels for the longer NIR channels might necessitate averaging over areas greater than the pixel size resolution

Preliminary results

* We have used synthetic data to test the performance of our aerosol retrieval algorithm ⇒ Full closure has been obtained
* Tests carried out on real (Hyperion) data look very promising as well, but we need to pay attention to low S/N values for the longer NIR channels
* Fortunately, the noise is Gaussian ⇒ the S/N ratio can be improved by averaging over a few adjacent pixels
* It appears feasible to achieve aerosol retrievals and atmospheric corrections over turbid water using the longer wavelengths

Preliminary results (cont.)

The following figure shows histograms from the result of the aerosol retrieval using data displayed in the images shown earlier:

(a) **Upper Left Panel:** pixel histogram of the retrieved aerosol optical depth in area 1

(b) **Upper Right Panel:** histogram of the retrieved aerosol model in area 1

(c) **Lower Left Panel:** pixel histogram of the retrieved aerosol optical depth in area 2

(d) **Lower Right Panel:** histogram of the retrieved aerosol model in area 2

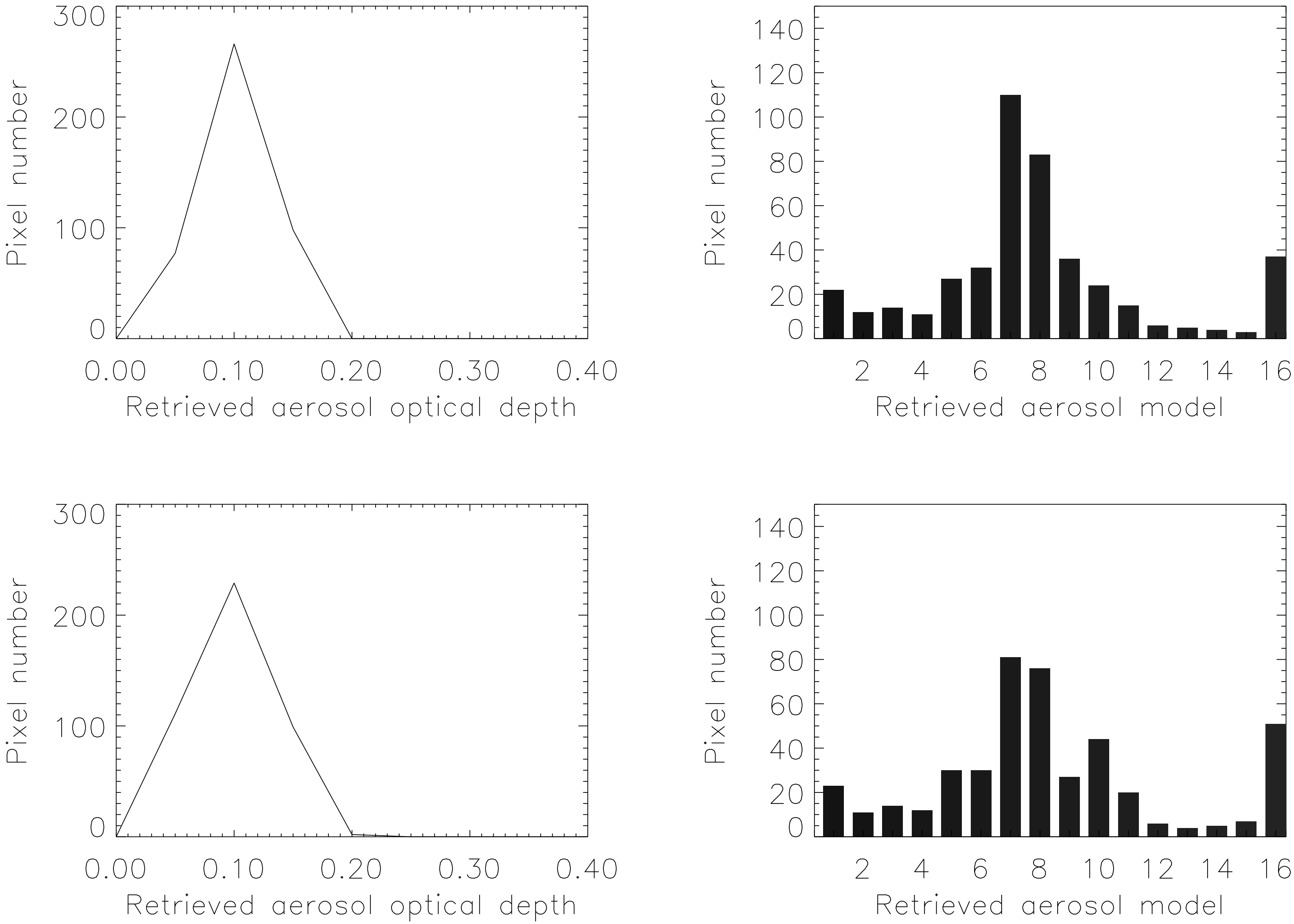

Figure 10: **Retrieval results from 21×21 pixel areas (roughly 600×600 meters). The upper row is for clear water (area 1), the lower row is for turbid water (area 2). Averaging over the 21×21 pixel areas there are no problems selecting aerosol model and associated optical depth.**

Outlook: Retrievals of multiple components in turbid water

Having determined the atmospheric contribution over turbid water, we are now poised to do retrievals of the in-water constituents

- ◇ we might start out by simply investigating retrievals of chlorophyll and sediment (one extra parameter)
- ◇ a suitable bio-optical model may be constructed from published materials
- ◇ using the bio-optical model and the coupled forward model we can model the TOA reflectances arising from various mixtures of sediment and chlorophyll

Outlook: Retrievals of multiple components in turbid water (cont.)

Using a linearized forward model for the coupled atmosphere-ocean system we have available a whole suite of tools for attacking turbid water retrievals

* principal component or singular vector decomposition analysis to quantify
  - ⇒ degrees of freedom for signal and noise
  - ⇒ information content
* optimal estimation theory ⟵ Bayesian approach
* error analysis tools
* algorithm development based on optimal estimation, simulated annealing, neural networks, etc.

Summary

- √ We have illustrated how aerosol retrievals (i.e. atmospheric correction) can be performed adequately over clear as well as turbid waters using NIR channels (for which the BPA holds) available on satellite instruments such as MODIS
- √ Utilizing a linearized forward model for the coupled atmosphere-ocean system, we are proceeding to retrieve multiple components from turbid waters using rigorous inversion methods and analysis

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