

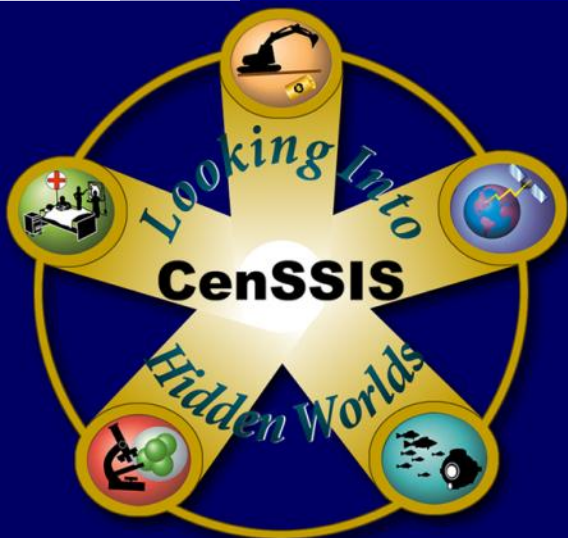


# Hyperspectral Remote Sensing of Coastal Environments

**Miguel Vélez-Reyes, Ph.D.**

Laboratory for Applied Remote Sensing and Image Processing  
Center for Subsurface Sensing and Imaging Systems  
University of Puerto Rico at Mayaguez

**2008 PRSIG**





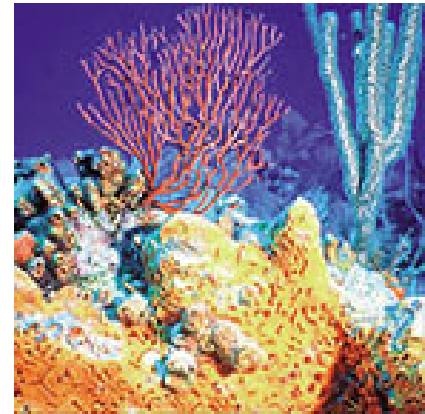
# The Team

## ■ Faculty and Staff

- Miguel Velez-Reyes, ECE
- Shawn D. Hunt, ECE
- James A. Goodman, LARSIP
- Fernando Gilbes, Geology
- Roy A. Armstrong, Marine Sciences
- Samuel Rosario, LARSIP

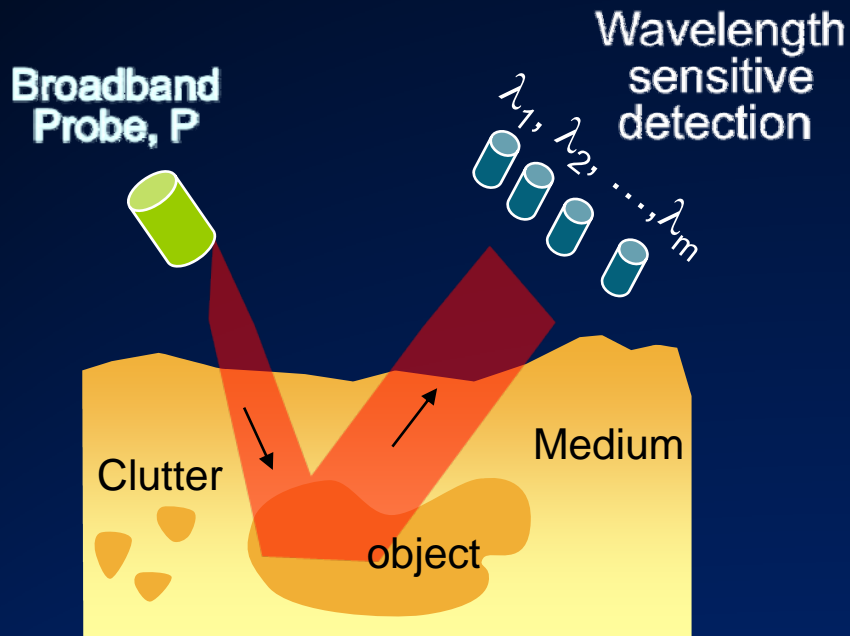
# Benthic Habitat Monitoring

- Benthic habitats are places on or near the sea floor where aquatic organisms live.
  - These beds of seagrass, areas of mud and sand, and coral reefs provide food and shelter to a rich array of animals.
- The preservation of this ecosystem, especially its coral reefs, is a National priority.
  - Need to establish an ongoing and consistent national database of coastal benthic data that document changes and trends over time.
- This ecosystem is an attractive environment for many recreational, commercial and scientific activities, and is critical to the tourist economy

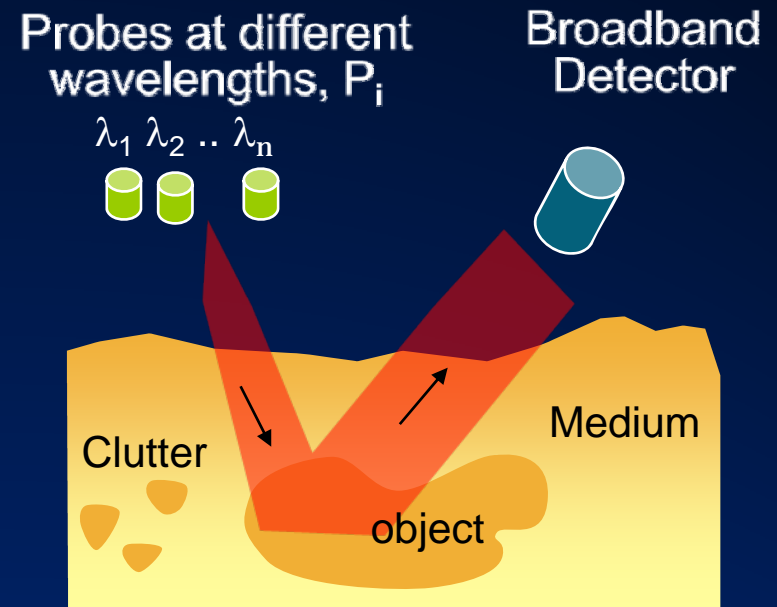


# Subsurface Spectral Sensing

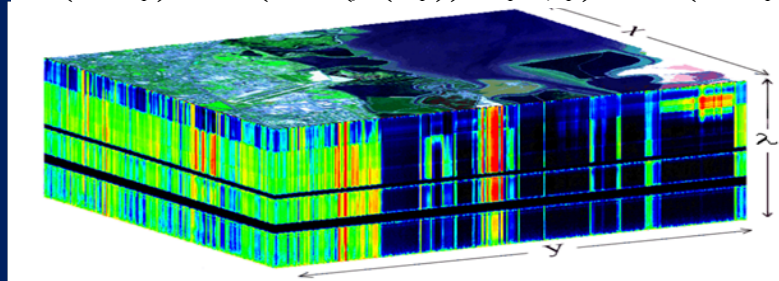
## Imager-Spectrometer Configuration



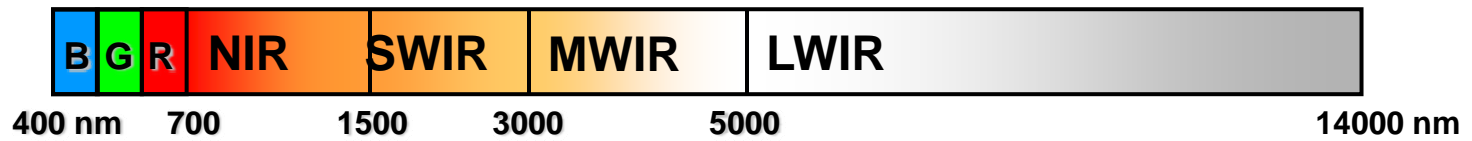
## Spectrometer-Imager Configuration



$$Y(\mathbf{r}, \lambda_i) = T(\mathbf{r}, \alpha(\beta(\lambda_i)), S_i, \gamma_i) + w(\mathbf{r}, \lambda_i)$$



# Spectral Sensing



LOW

**Panchromatic:** one very wide band



MED

**Multispectral:** several to tens of bands



HIGH

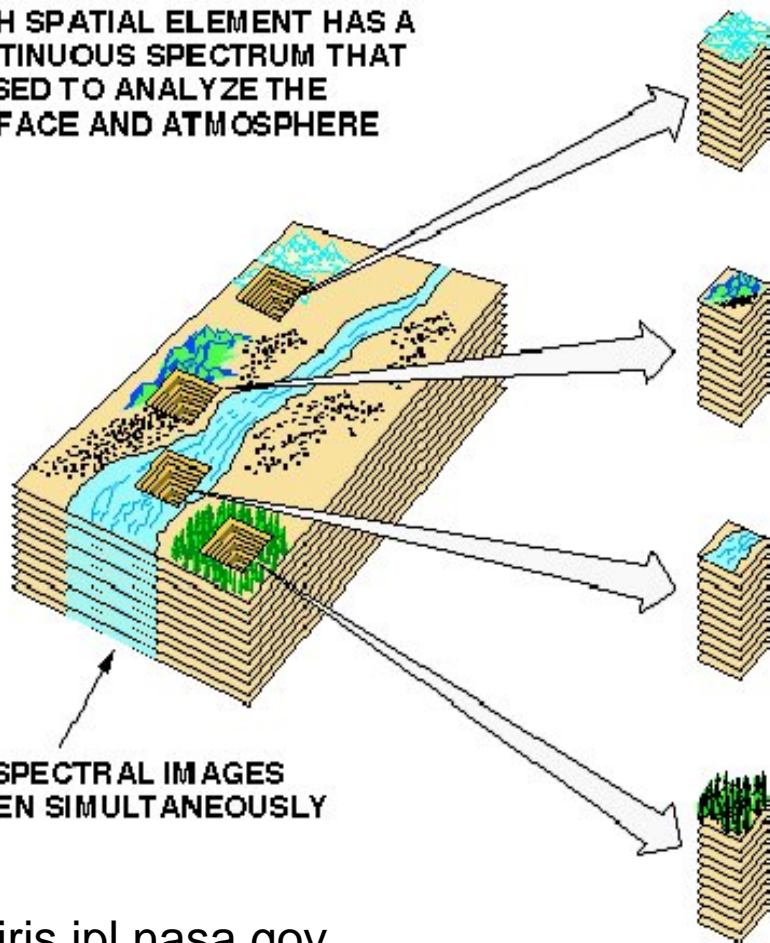
**Hyperspectral:** hundreds of narrow bands



# Imaging Spectrometry

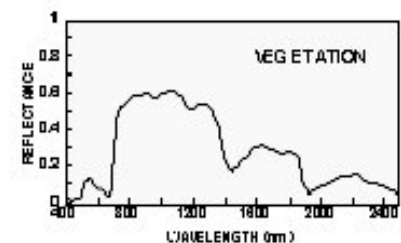
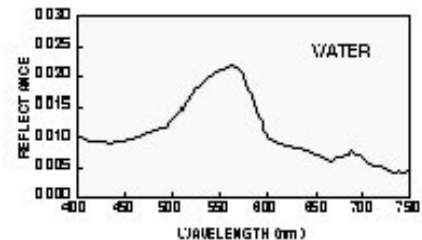
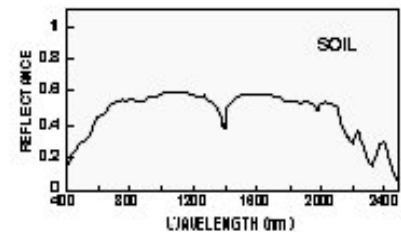
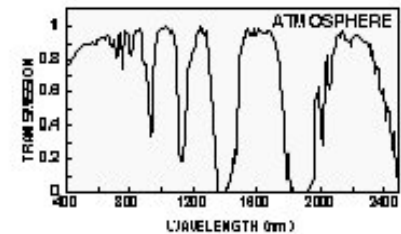
**JPL**

EACH SPATIAL ELEMENT HAS A CONTINUOUS SPECTRUM THAT IS USED TO ANALYZE THE SURFACE AND ATMOSPHERE



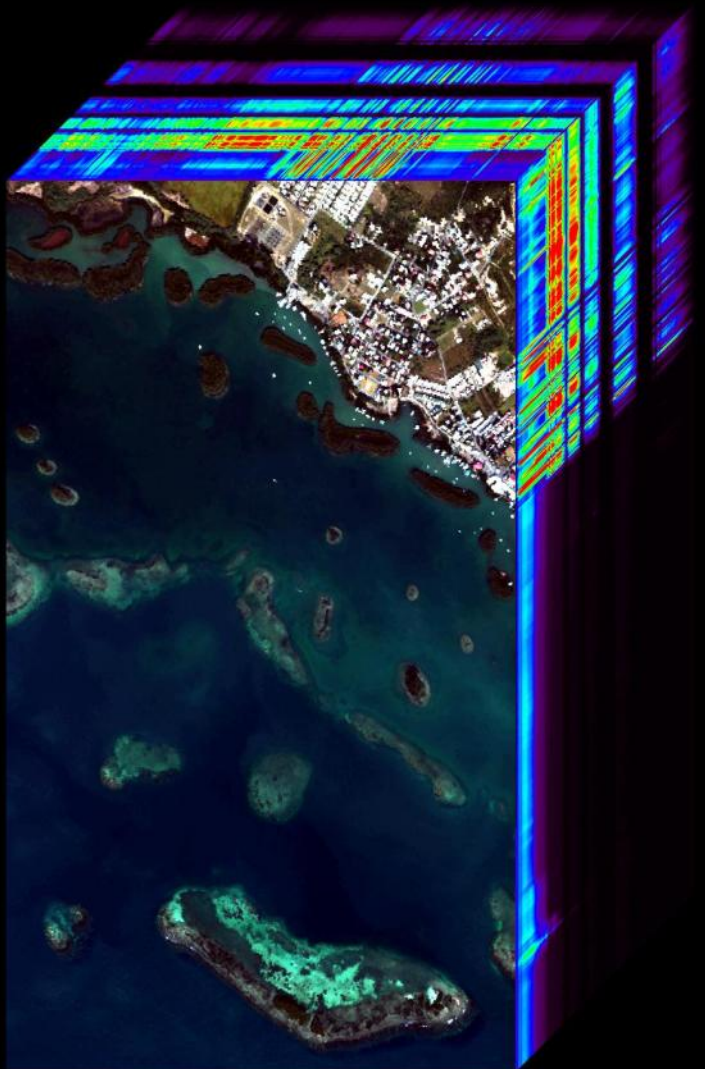
224 SPECTRAL IMAGES  
TAKEN SIMULTANEOUSLY

[Aviris.jpl.nasa.gov](http://Aviris.jpl.nasa.gov)



# Hyperspectral Imaging

AVIRIS Puerto Rico 051213r4



- **Information Content**  
Temporal, Spatial and Spectral Domains
- **High Spectral Resolution**  
Separation of Atmospheric, Bottom and Water Column Contributions



# HSI is a Key Technology

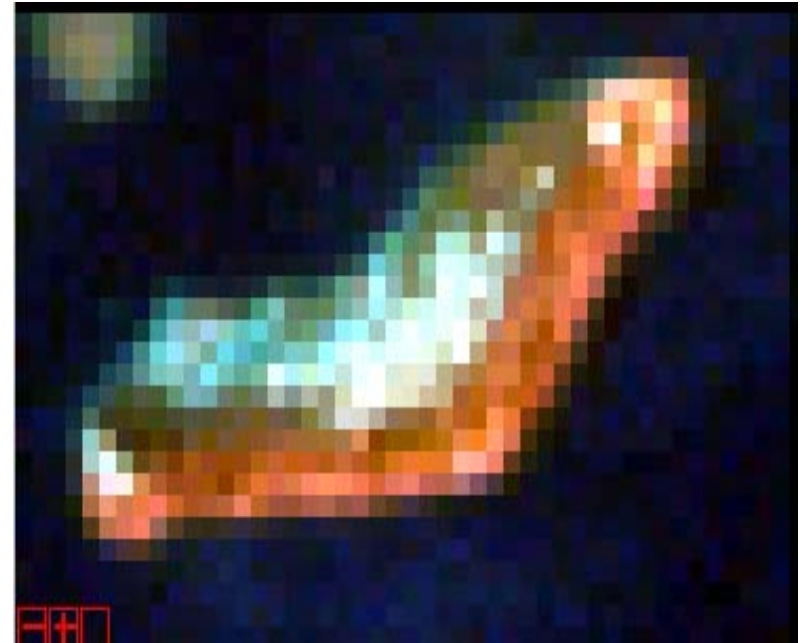
- Environmental monitoring
  - NASA Flora
  - CHRIS (Compact High Resolution Imaging Spectrometer)
  - Proba (ESA),
  - HERO (Canadian),
  - SPECTRA (ESA), and
  - EnMAP (German) missions.
- DoD Situational Awareness
  - AFRL/Raytheon TacSat 3 ARTEMIS
- Space Exploration
  - NASA MRO Compact Reconnaissance Imaging Spectrometer for Mars (CRISM)
  - NASA Moon Mineral Mapper (M3) mission



# Challenge: Low spatial resolution of hyperspectral sensors



IKONOS PAN Sharpened Image  
Multispectral Sensor  
1m PAN, 4m/4 bands MSI



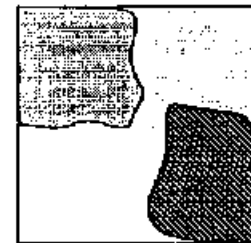
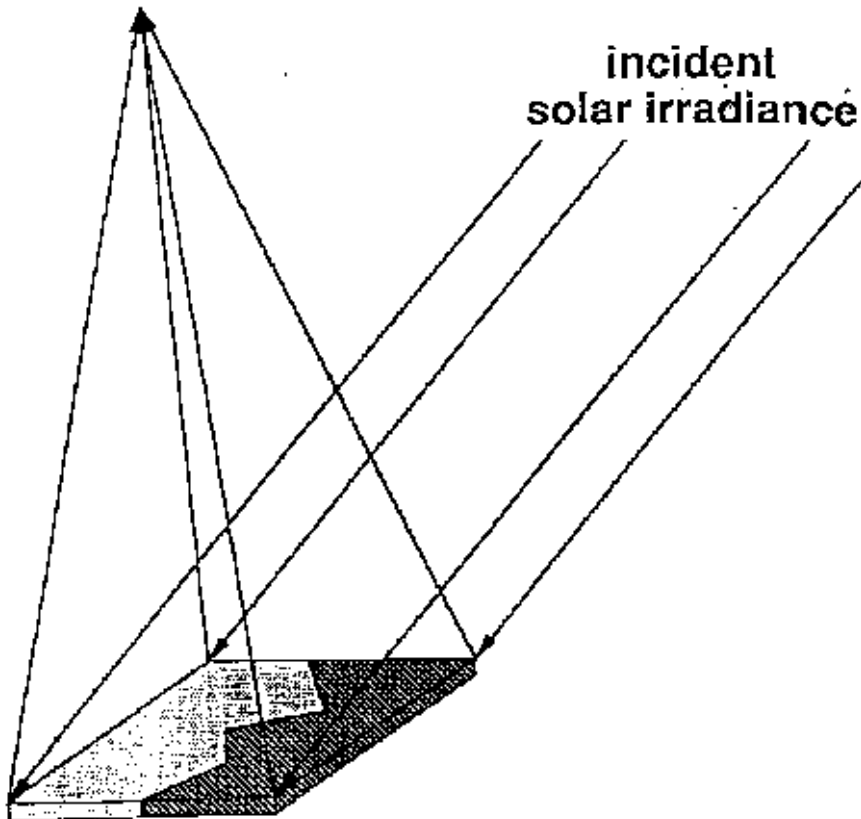
Hyperion Image  
Hyperspectral Sensor  
30 m, 220 bands, 10nm

Enrique Reef in Parguera, Lajas, PR

# Linear Mixing Model: Standard for Land Surface




imaging spectrometer

incident solar irradiance



IFOV of pixel

a single pixel with three materials: A B and C

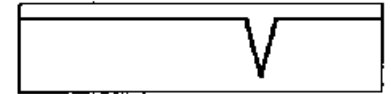
material	fraction
A 	0.25
B 	0.25
C 	0.50

each endmember has a unique spectrum

A



B



C



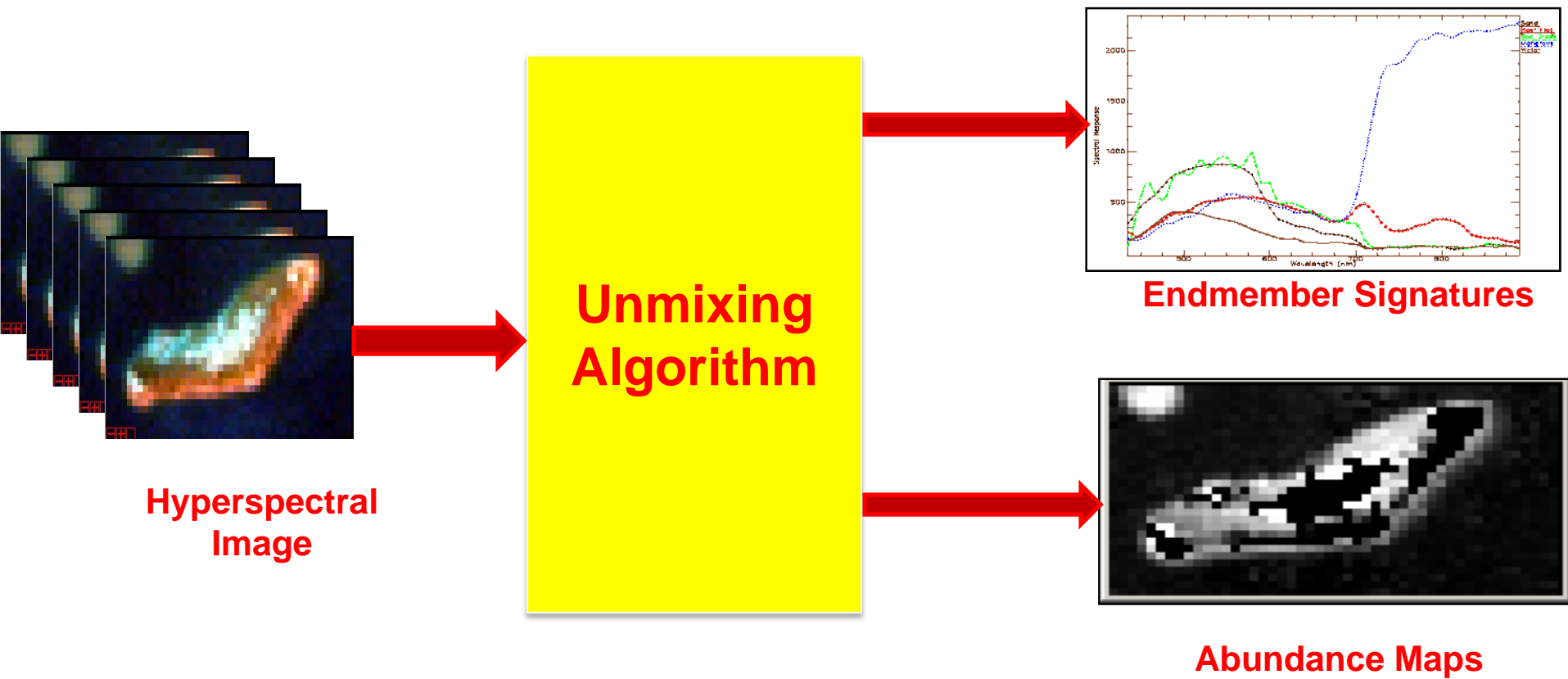
the mixed spectrum is just a weighted average

$$\text{mix} = 0.25 \cdot A + 0.25 \cdot B + 0.5 \cdot C$$



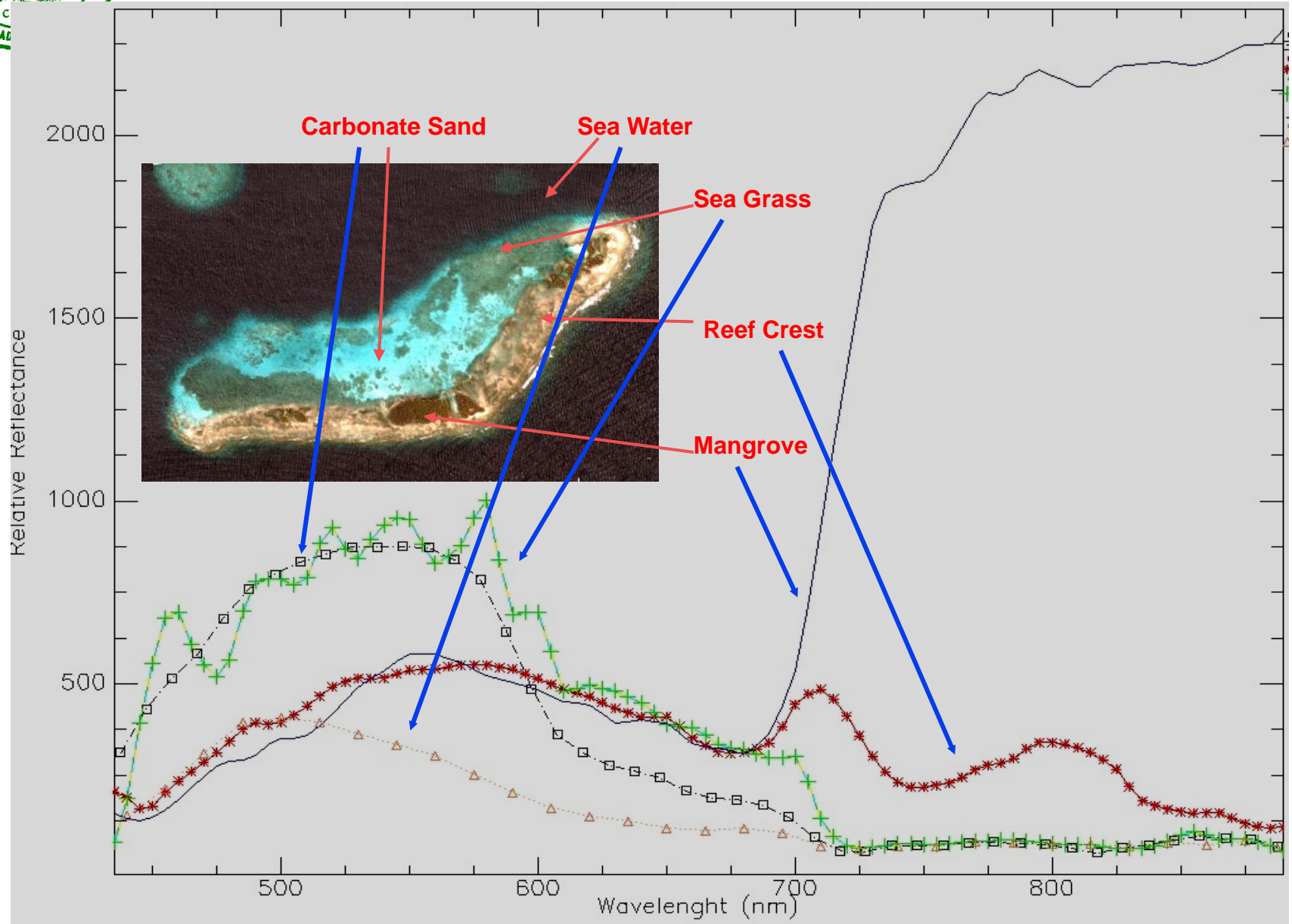
heterogeneous IFOV  
for a single pixel

# Unmixing



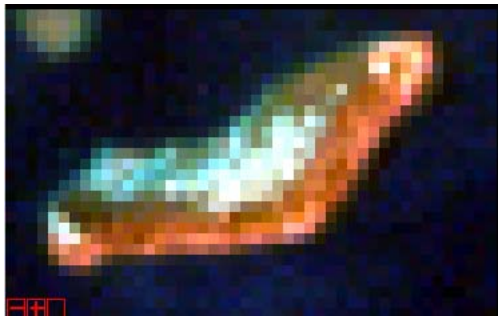


# Endmembers Estimated with Pixel Purity Index (PPI)

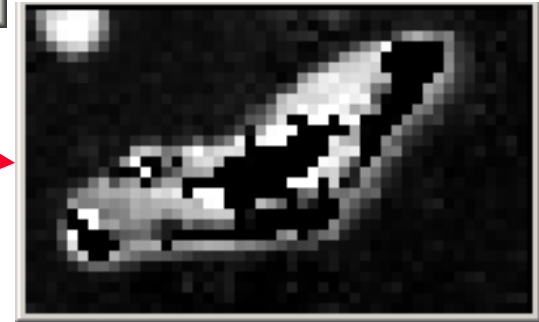




# Abundance Estimation: Surface Approach



Reef Crest



Sea Grass

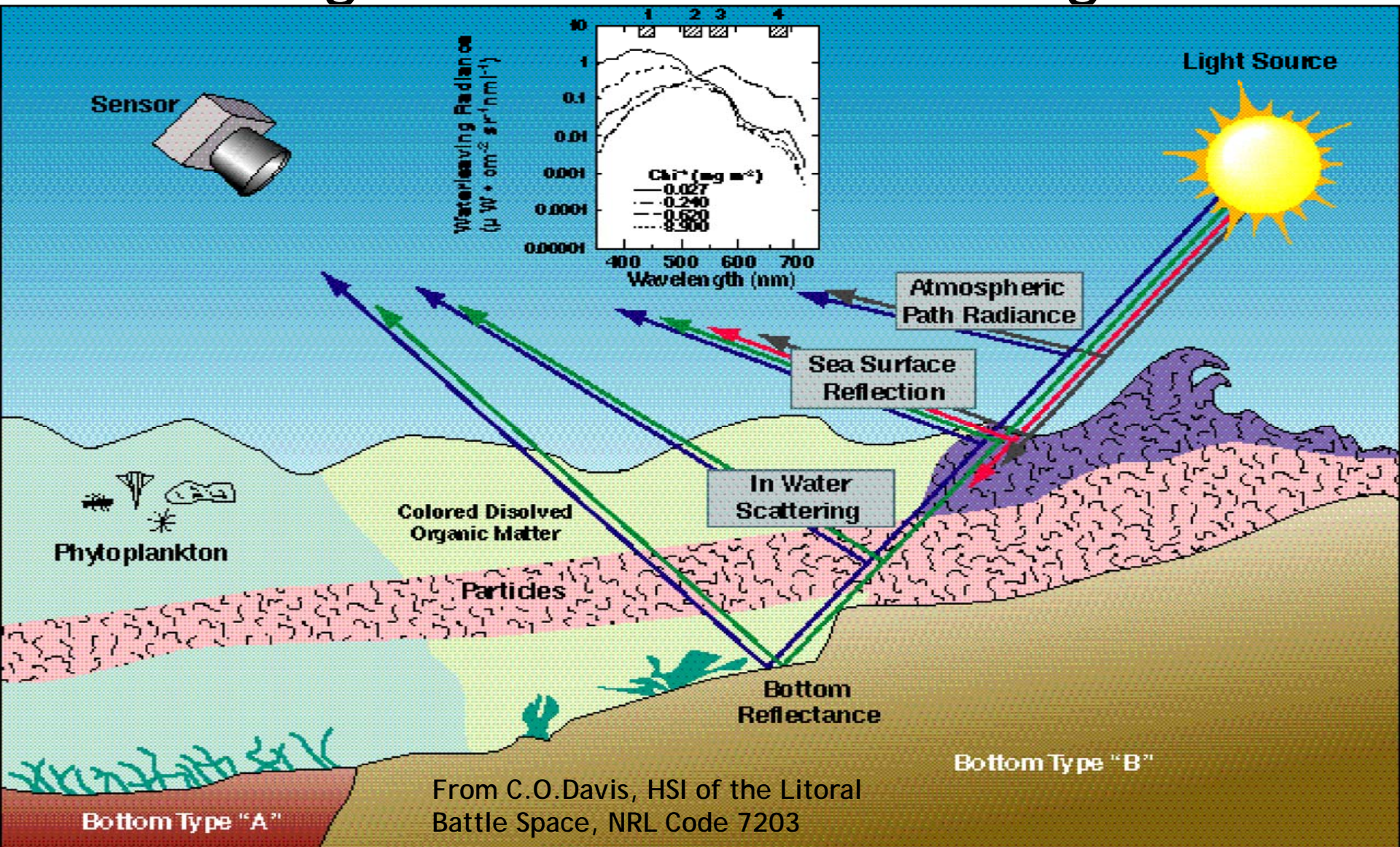


Carbonate Sand

# This is a Subsurface Sensing Problem

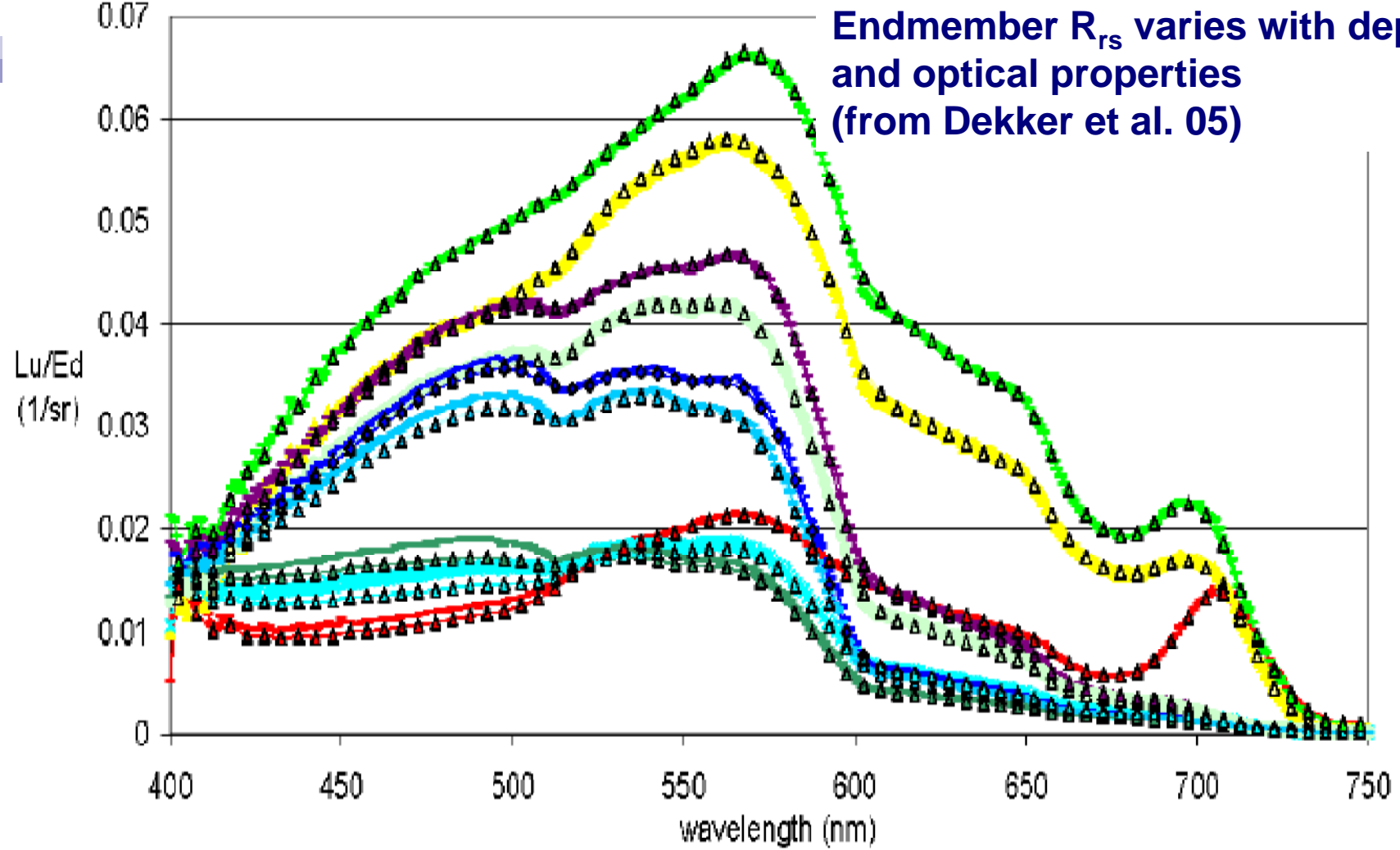


# Challenge: Subsurface Unmixing



Temporal and Spatial Variability of Optical Properties and Variable Bathymetry

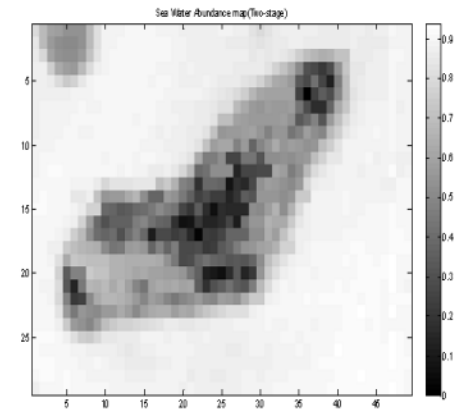
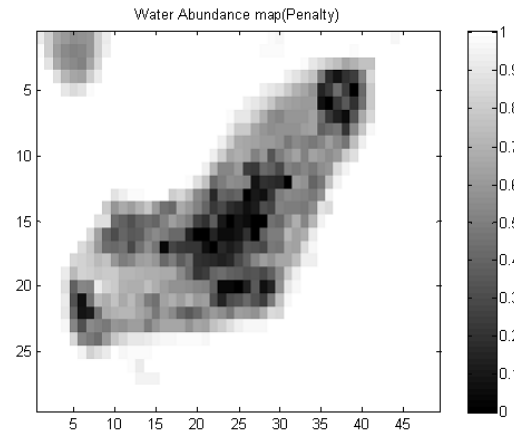
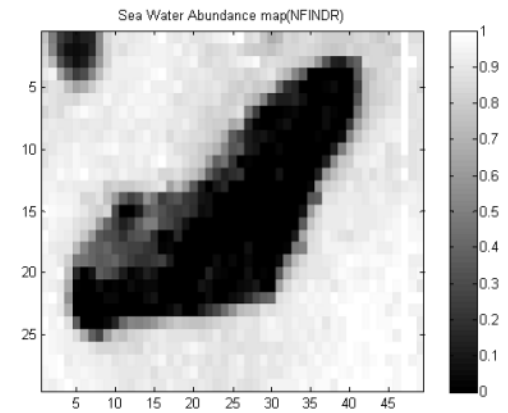
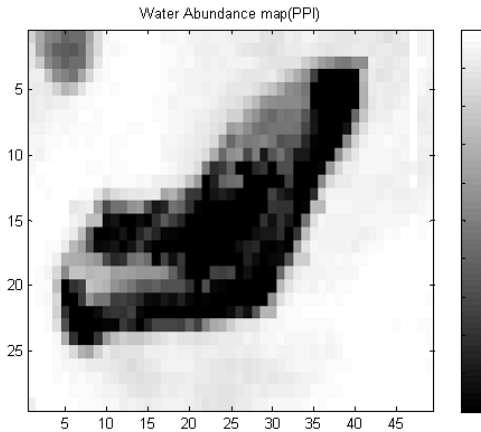
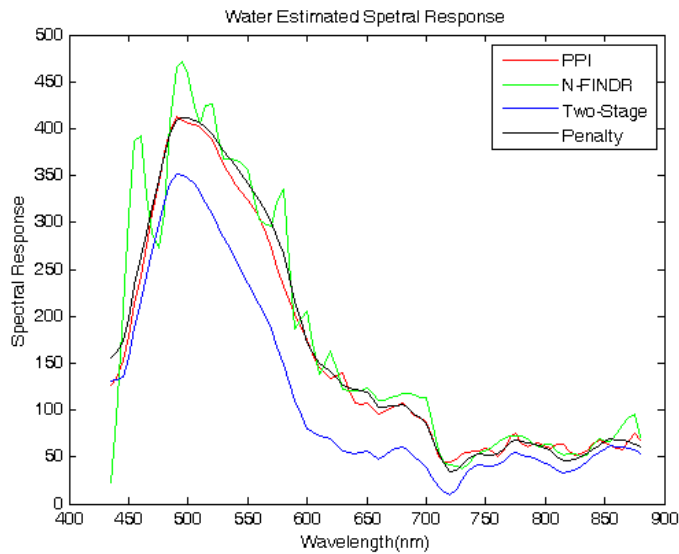
Endmember  $R_{rs}$  varies with depth and optical properties (from Dekker et al. 05)



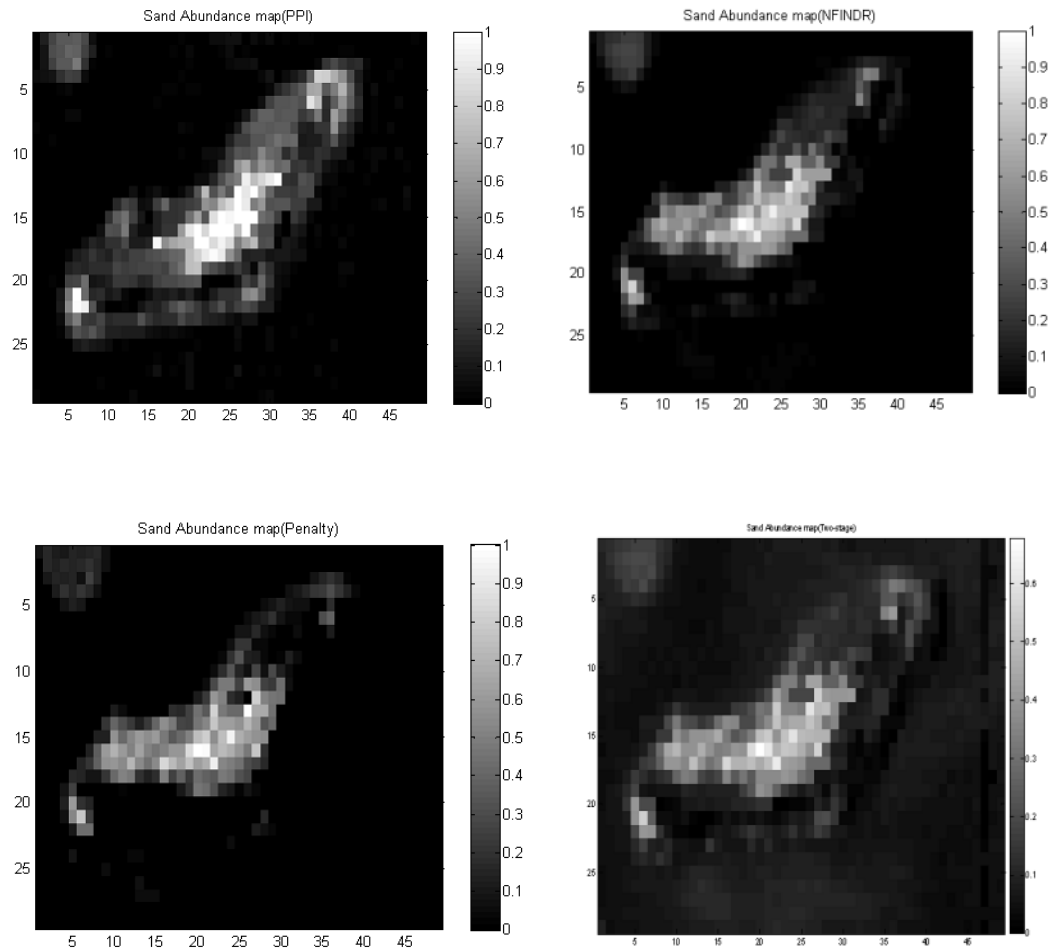
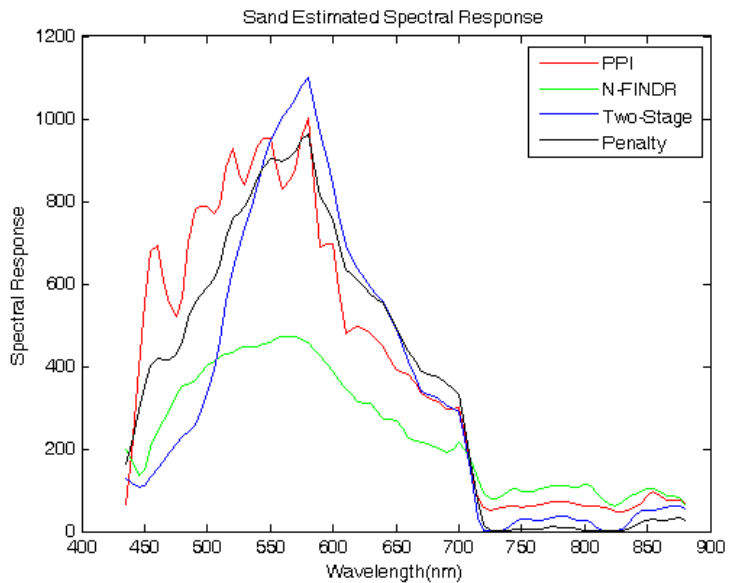
- |                            |                            |                               |
|----------------------------|----------------------------|-------------------------------|
| — coral and green algae 1m | — coral and sediment 1m    | — green algae and sediment 1m |
| — coral and green algae 3m | — coral and sediment 3m    | — green algae and sediment 3m |
| — coral and green algae 5m | — coral and sediment 5m    | — green algae and sediment 5m |
| ▲ greenalgae sediment 5m_H | ▲ greenalgae sediment 3m_H | ▲ greenalgae sediment 1m_H    |
| ◆ coral2 sediment 5m_H     | ◆ coral2 sediment 3m_H     | ◆ coral2 green algae 5m_H     |
| ▲ coral2 green algae 3m_H  | ▲ coral2 green algae 1m_H  | ▲ coral2 sediment 1m_H        |



# Effect of Endmember Variability: Water



# Effect of Endmember Variability: Sand



# Unmixing for Benthic Habitat Mapping

- Removal of the Water Column
  - Want to do it unsupervised
  - Nonlinear optimization problem
  - Nonlinear interaction of the optical properties, bathymetry and bottom albedo.
- Need of good inversion model
  - Hydrolight is a good forward radiative transfer model  
→ too detailed for inversion
  - Lee's Semianalytical Model is an inversion model
    - Other possibilities are described in the literature

# Model for $R_{rs}$ and $r_{rs}$ (Maritorena, et al. 1994)

Remote sensing reflectance,  $R_{rs}$

$$R_{rs} = \frac{L_w}{E_d} \approx \frac{0.5r_{rs}}{1 - 1.5r_{rs}}$$

Subsurface remote sensing reflectance,  $r_{rs}$

$$r_{rs} = \underbrace{r_{rs}^{dp} (1 - \exp\{-(k + \kappa_C)H\})}_{\text{Water Column Component}} + \underbrace{\frac{\rho}{\pi} \exp\{-(k + \kappa_B)H\}}_{\text{Bottom Component}}$$

# Lee's Bio-optical Semi-analytical Model (cont.)

- Model is parametrized by 5 parameters

$$\hat{R}_{rs} = f(P, B, G, BP, H, \bar{\rho}_{sand}, \alpha)$$

$\rho_{sand}$  is a 550-nm normalized sand spectra and  $\alpha$  is a vector of nuisance parameters.

# Lee's Method to Determine IOP and Bathymetry

- Nonlinear least squares optimization

$$\hat{\gamma}_{\text{Lee}} = \arg \min_{\gamma} \frac{\left\| \mathbf{R}_{\text{rs}} - \hat{\mathbf{R}}_{\text{rs}}(\gamma, \bar{\rho}_{\text{sand}}) \right\|_2^2}{\left\| \mathbf{R}_{\text{rs}} \right\|_2^2}$$

where  $\gamma = [P, B, G, BP, H]^T$

and  $\rho_{\text{sand}}$  is a 550-nm normalized sand spectra.

Model originally intended for the estimation of optical properties not for bottom mapping.

# Goodman's Linear Unmixing Variable Endmember Approach (LIGU)

- Step 1: Retrieval of water optical properties and bathymetry using Lee's approach
  - Spatial distribution of OP's
- Step 2: Compute the endmembers at each location (x,y) for a sand, coral, and algae forwarded to the surface

$$\bar{\mathbf{R}}_i(x, y) = \mathbf{R}_{rs}(\hat{\gamma}_{\text{Lee}}(x, y), \rho_i) \quad \text{for } i = 1, 2, 3$$

- Step 3: Linear Unmixing at each location

$$\mathbf{R}_{rs}(x, y) = \sum_{i=1}^3 f_i \bar{\mathbf{R}}_i(x, y)$$

# Combined Inversion and Unmixing at the Bottom (CIUB) Approach

- Use of subsurface remote sensing reflectance,  $r_{rs}$

$$r_{rs} = r_{rs}^{dp} \underbrace{\left( 1 - \exp \left\{ - \left[ \frac{1}{\cos(\theta_w)} + \frac{D_u^C}{\cos(\theta_o)} \right] \kappa H \right\} \right)}_{\text{Water Column Contribution}} + \underbrace{\exp \left\{ - \left[ \frac{1}{\cos(\theta_w)} + \frac{D_u^B}{\cos(\theta_o)} \right] \kappa H \right\} \frac{1}{\pi} B \bar{\rho}}_{\text{Bottom Contribution}}$$

- Linear mixing model for the bottom albedo

$$\bar{\rho} = \mathbf{S} \mathbf{f}$$

$$\mathbf{S} = \left[ \bar{\rho}_{\text{sand}} \quad \bar{\rho}_{\text{algae}} \quad \bar{\rho}_{\text{reef}} \right]$$

where  $\mathbf{x}$  is the vector of abundances and all endmembers are normalized to 1 at 550nm



# CIUB Approach (cont.)

- Work with the subsurface remote sensing reflectance

$$(\hat{\boldsymbol{\gamma}}, \hat{\mathbf{f}}) = \arg \min_{\boldsymbol{\gamma}, \mathbf{f}} \frac{\|\mathbf{r}_{\text{rs}} - \hat{\mathbf{r}}_{\text{rs}}(\boldsymbol{\gamma}, \mathbf{S}\mathbf{f})\|_2^2}{\|\mathbf{r}_{\text{rs}}\|_2^2}$$

$$= \arg \min_{\boldsymbol{\gamma}, \mathbf{f}} \frac{\|\mathbf{b}(\boldsymbol{\gamma}) - \mathbf{A}(\boldsymbol{\gamma})\mathbf{f}\|_2^2}{\|\mathbf{r}_{\text{rs}}\|_2^2}$$

Partially Linear  
Nonlinear  
Least Squares  
Problem

# Two-Stage Simple Iterative Inversion Approach

- Initialization using Lee's approach
- Step 1: Abundance estimation

$$\hat{\mathbf{f}} = \arg \min_{\gamma, \mathbf{f}} \frac{\|\mathbf{b}(\hat{\gamma}) - \mathbf{A}(\hat{\gamma})\mathbf{f}\|_2^2}{\|\mathbf{r}_{rs}\|_2^2}$$

- Step 2: Update optical properties, bathymetry and bottom albedo at 550nm

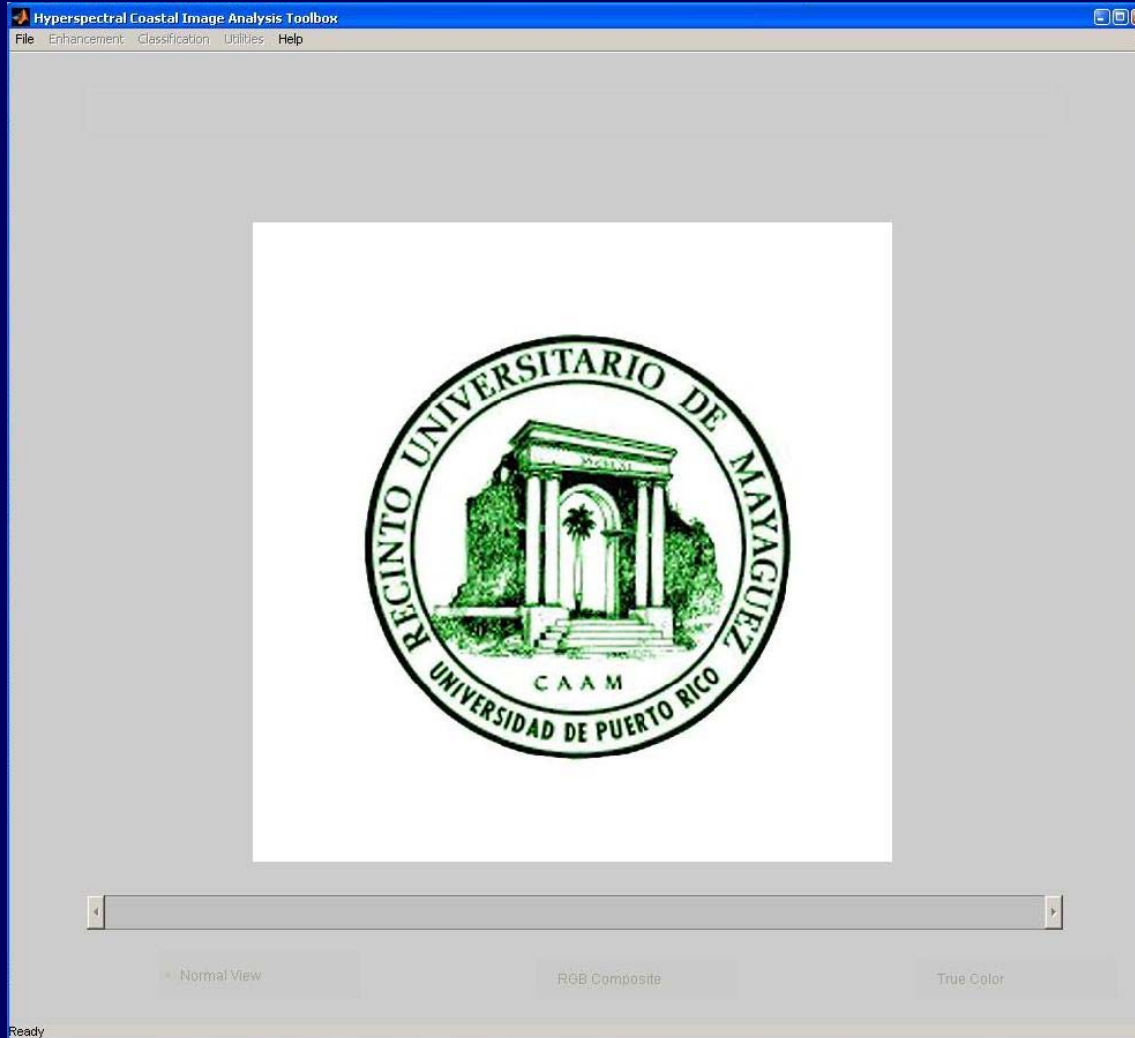
$$\hat{\gamma} = \arg \min_{\gamma} \frac{\|\mathbf{b}(\gamma) - \mathbf{A}(\gamma)\hat{\mathbf{f}}\|_2^2}{\|\mathbf{r}_{rs}\|_2^2}$$



# HyCIAT: A Hyperspectral Coastal Image Analysis Tool



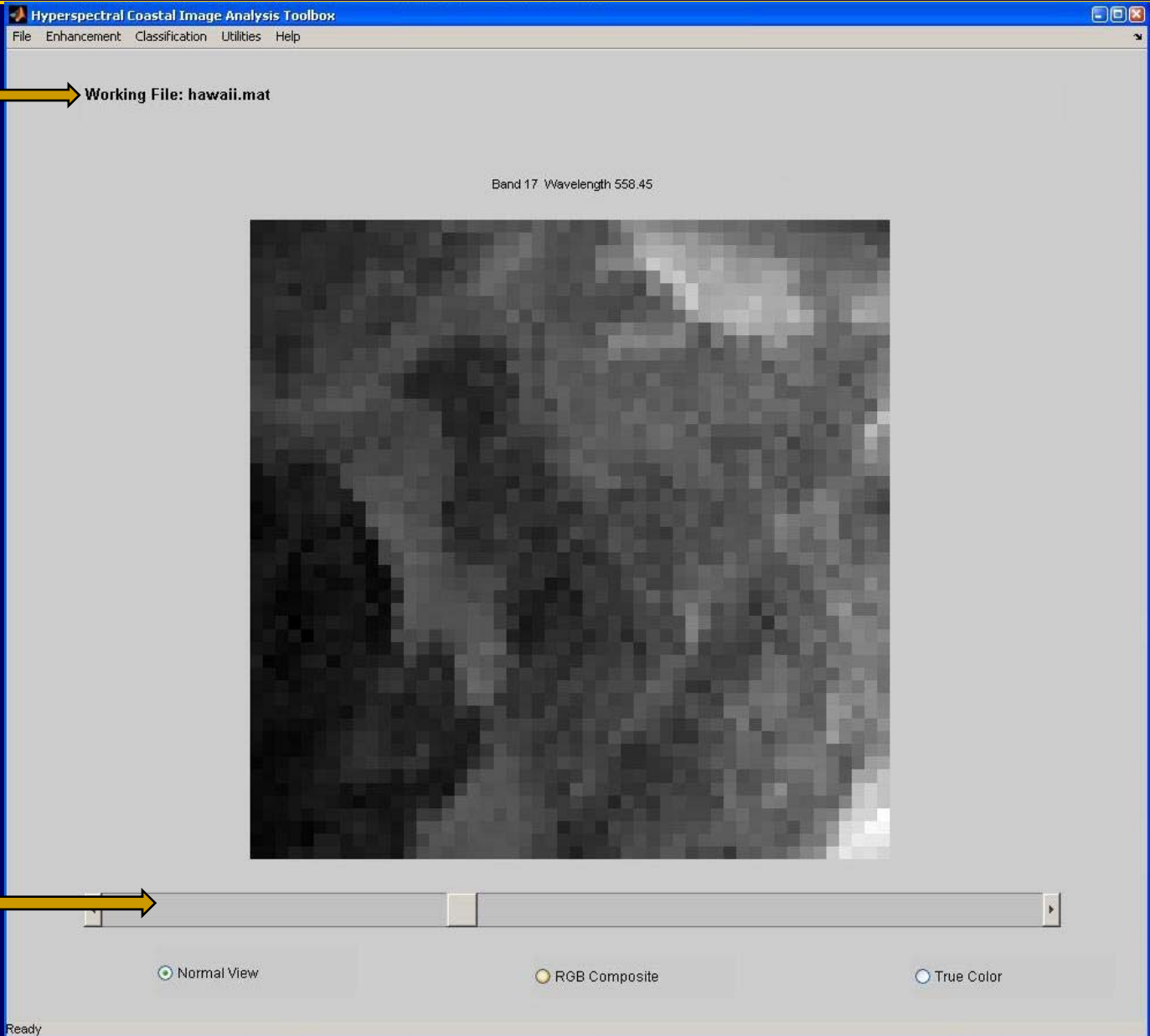
# HyCIAT Toolbox





# Visualization

File Name



Scrolling Through Bands





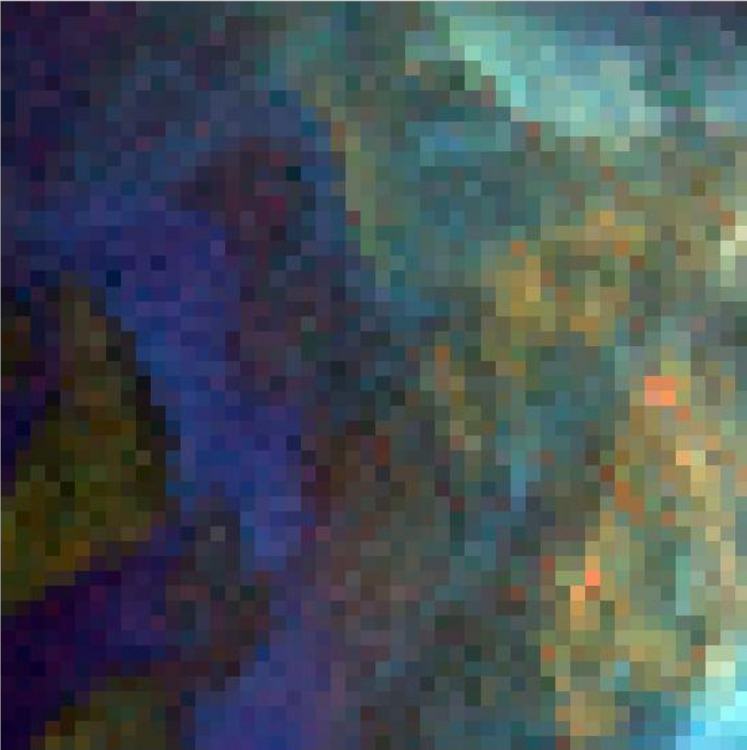
# RGB Composite (30-20-9)

Hyperspectral Coastal Image Analysis Toolbox

File Enhancement Classification Utilities Help

Working File: hawaii.mat

RGB Combination of bands 30, 20, and 9

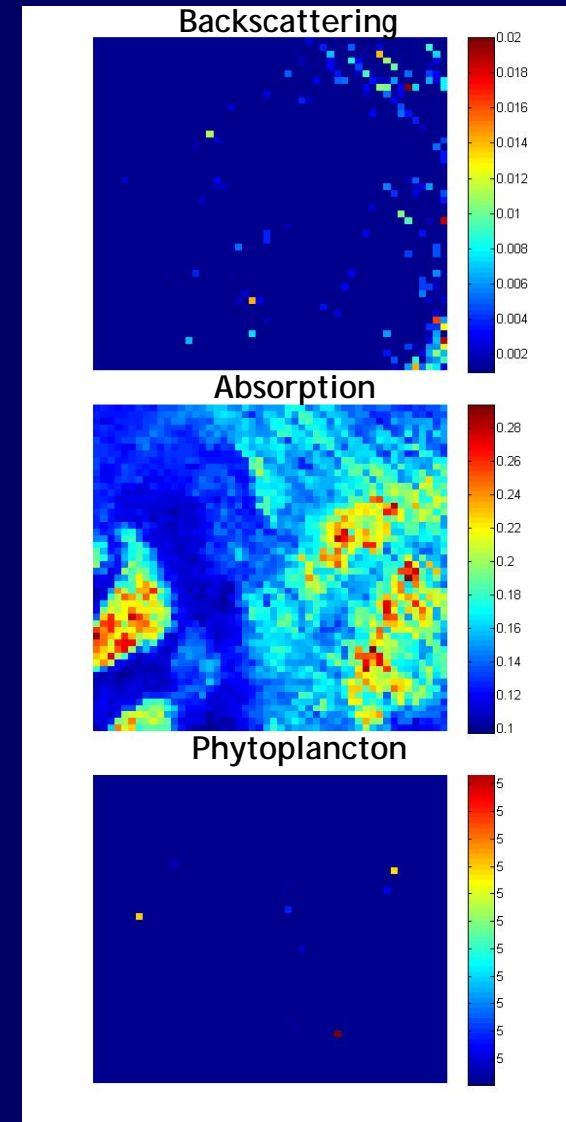
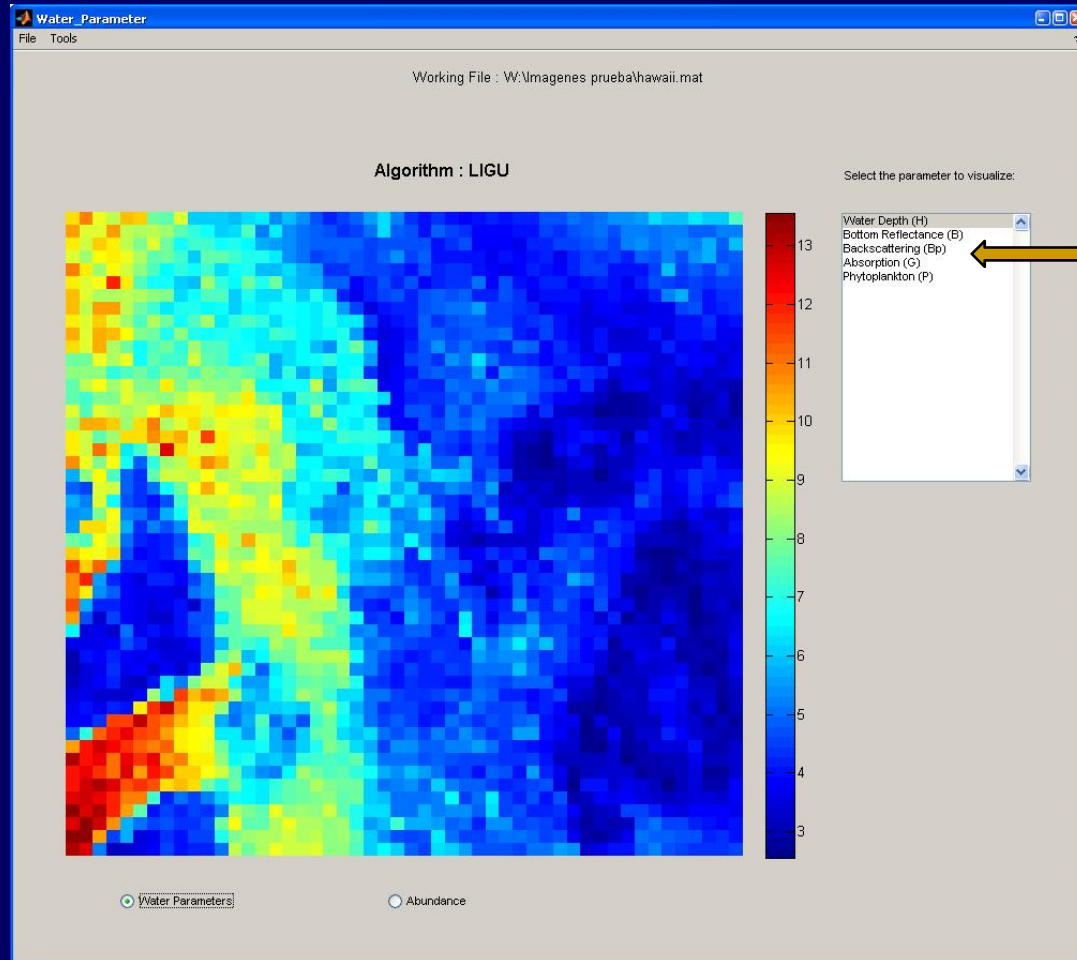
A rectangular image showing a coastal scene. The left side is dominated by dark blue and purple tones, likely representing water. The right side shows a mix of green, yellow, and orange, representing land and vegetation. The image has a pixelated, low-resolution appearance.

Normal View       RGB Composite       True Color

Ready



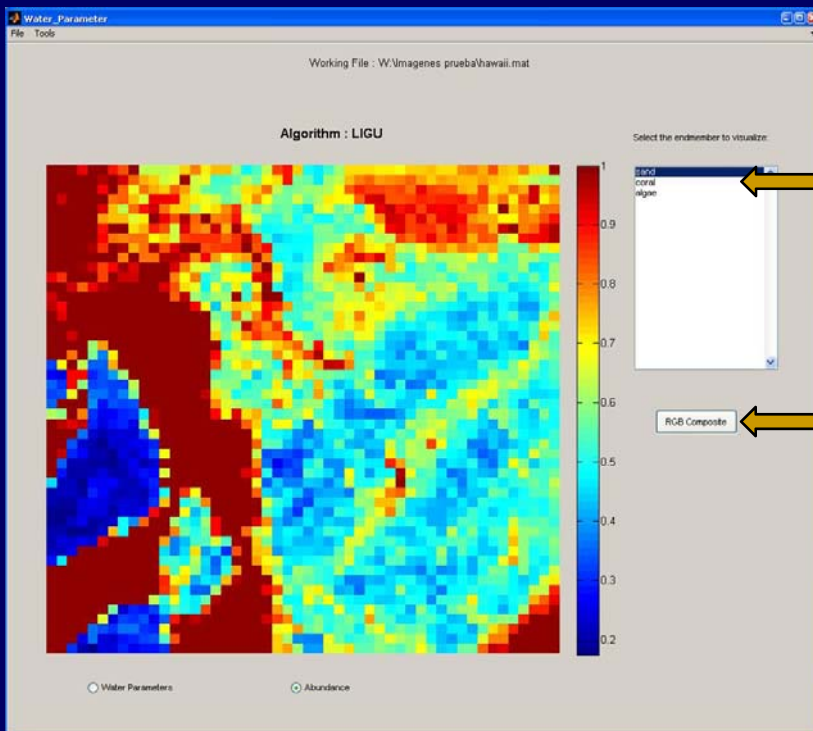
# Results Optimization: Water Optical Properties, Bathymetry and Albedo at 550nm





# Abundance Estimates

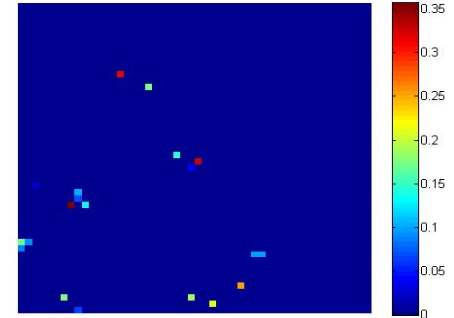
Result Window: Sand Abundance



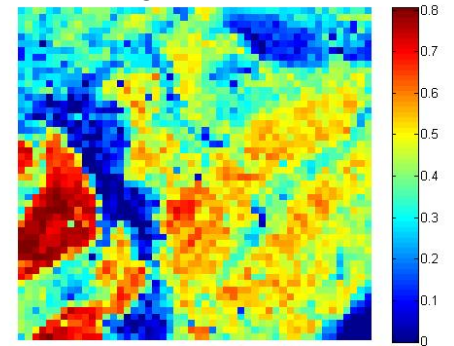
Select Endmember

RGB Composite

Coral Abundance



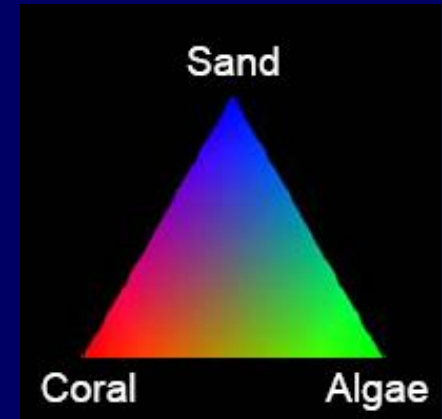
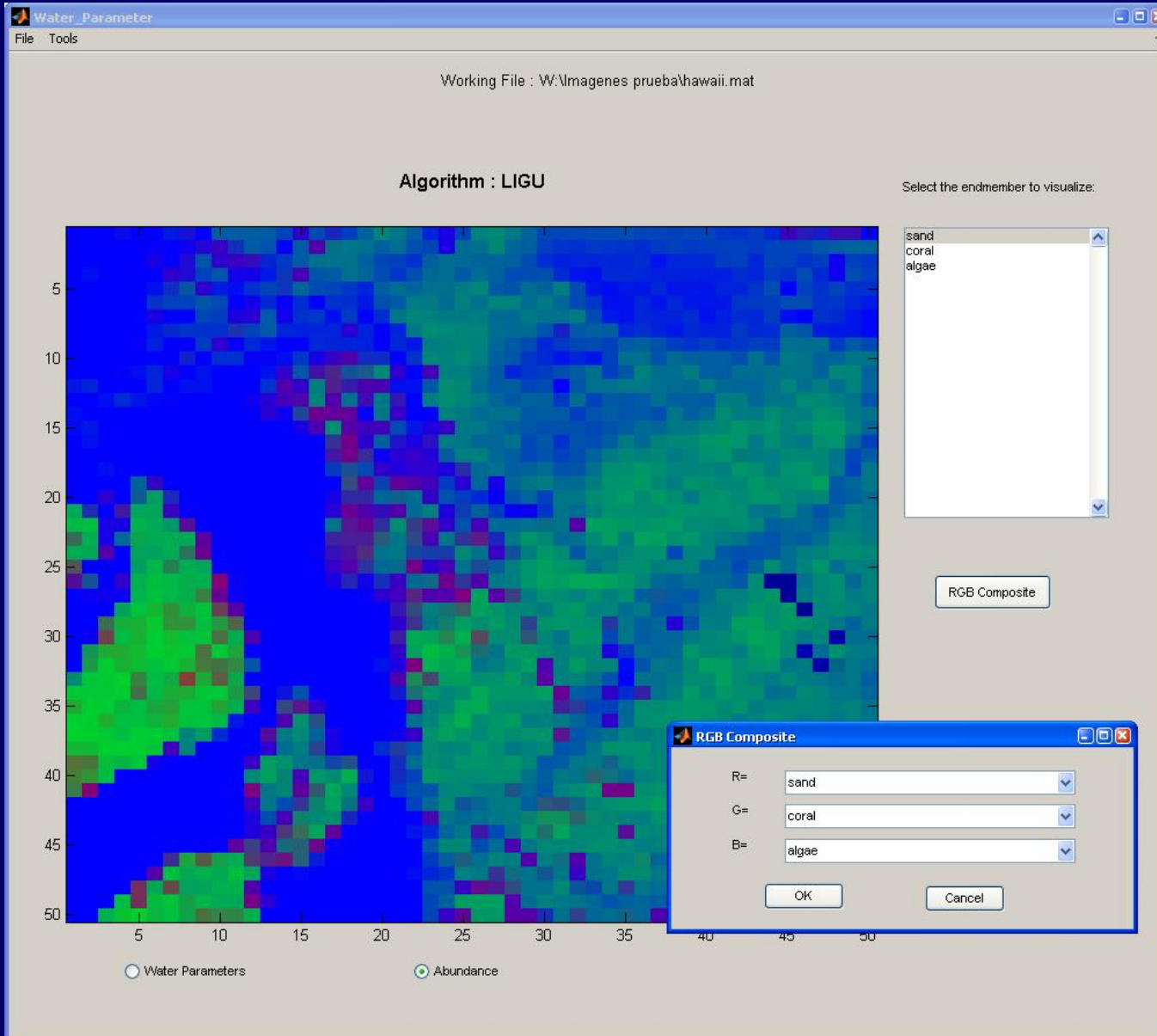
Algae Abundance







# Fractional Plots: RGB Composite of Three Abundance Maps



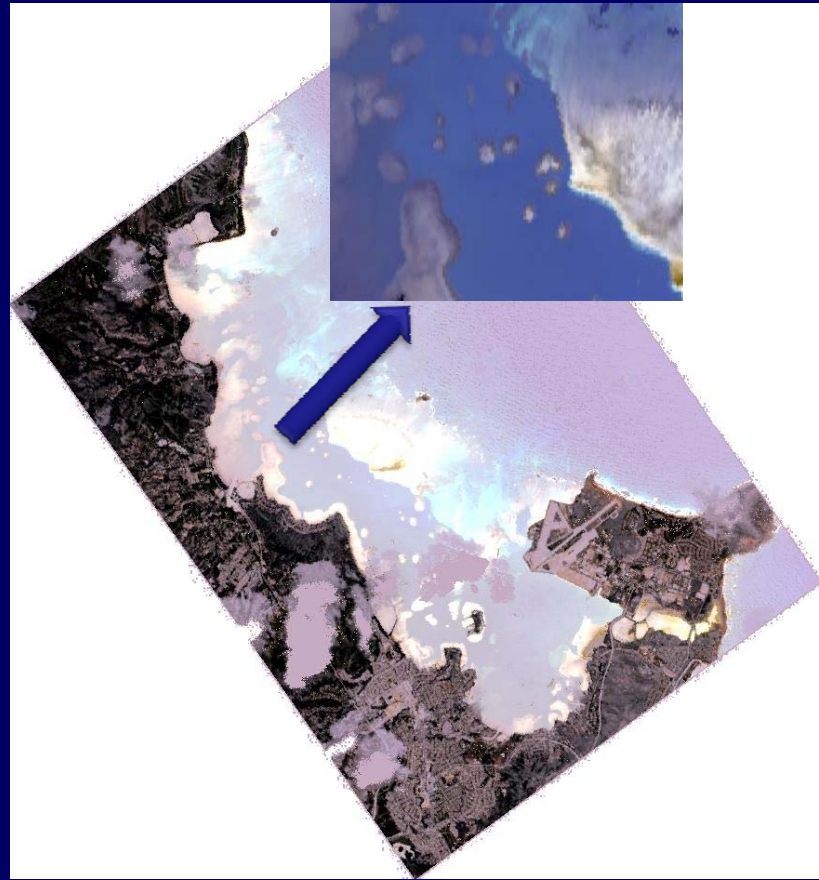


# Kaneohe Bay

**Kaneohe Bay:** is in the north eastern side of the island of Oahu in Hawaii, is 12.8 Km long and 4.3 Km broad, with a maximum depth in the bay of 12 m.

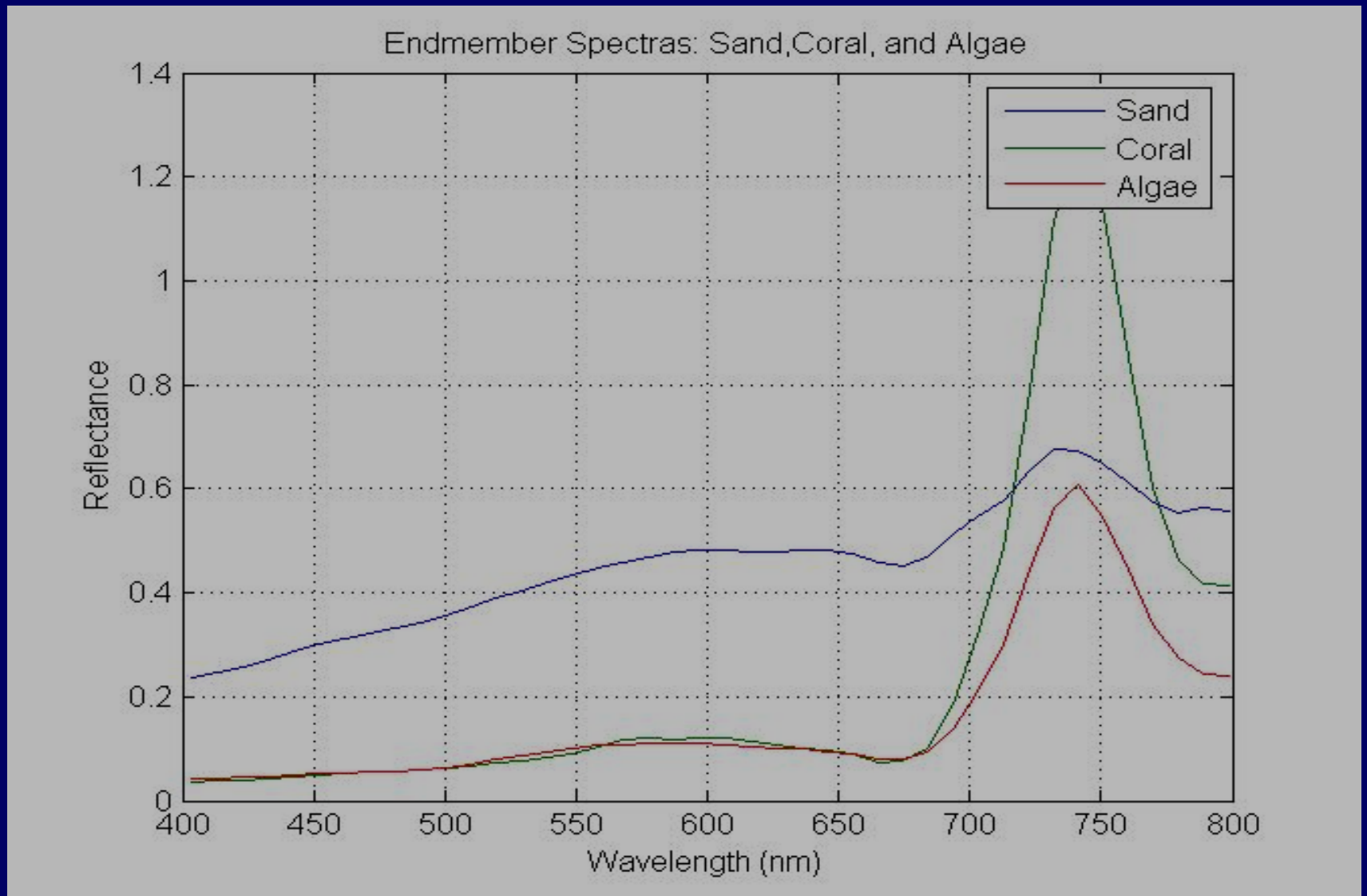
Hyperspectral imagery was acquired in April of 2000 by AVIRIS.

Hyperspectral image acquired using AVIRIS with 224 spectral bands was subset to 42 bands in the 0.4 to 0.8  $\mu\text{m}$  range, it consists of an image already corrected for atmospheric and sunglint effects .





# Measured Bottom Reflectance

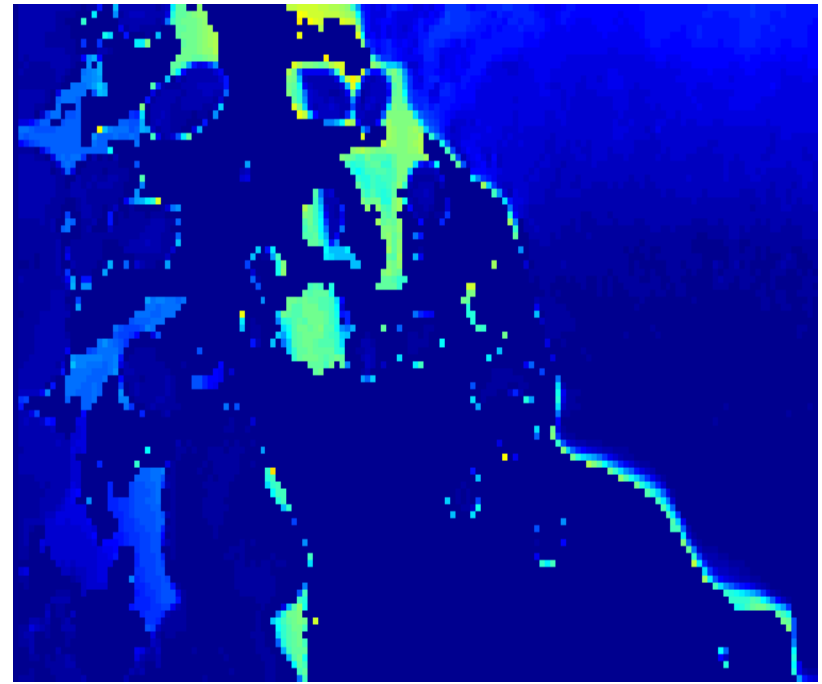
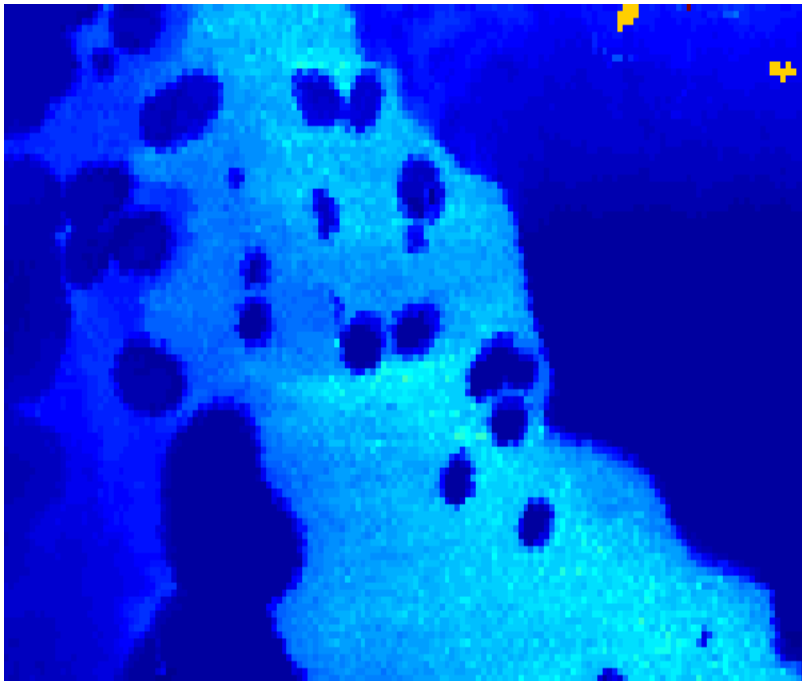




# Bathymetry

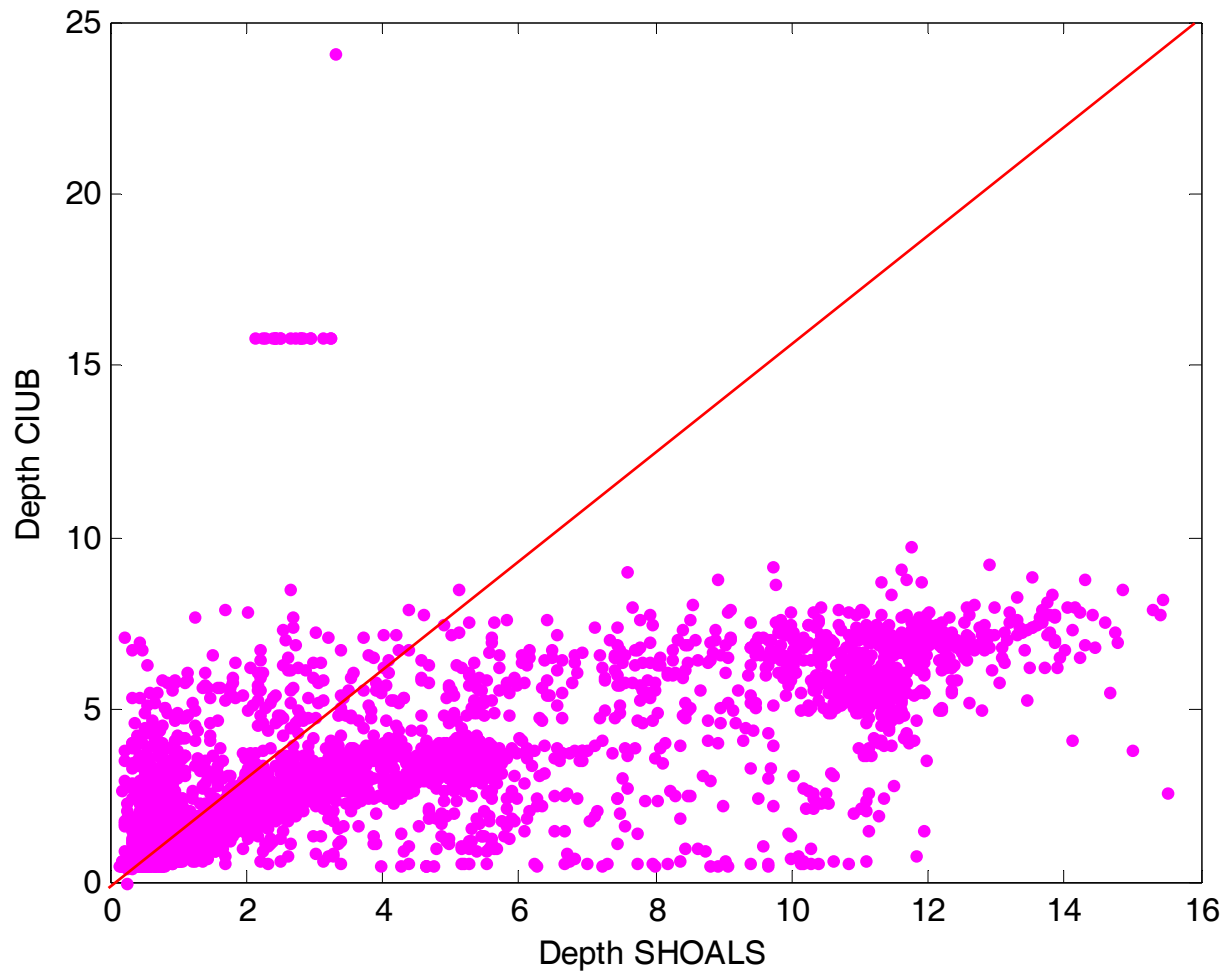
CIUB: Depth

SHOALS Depth



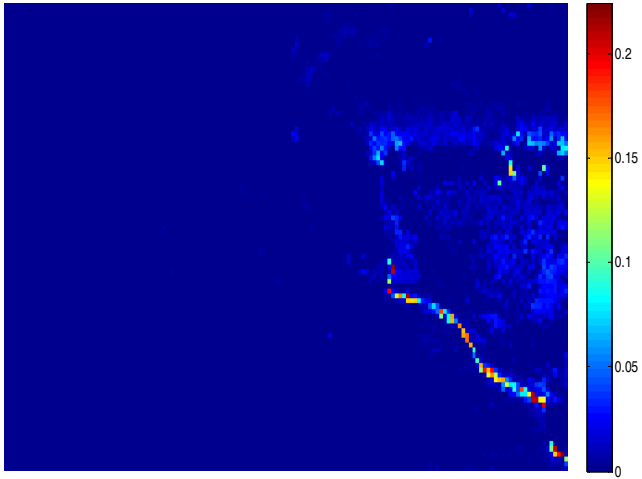


# Bathymetry Comparison

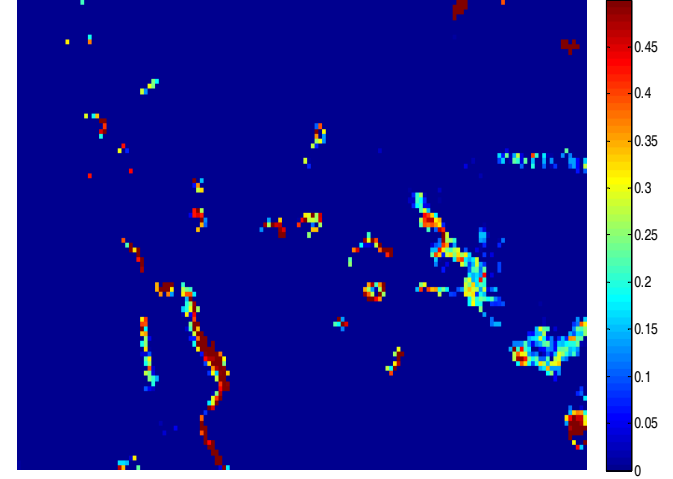




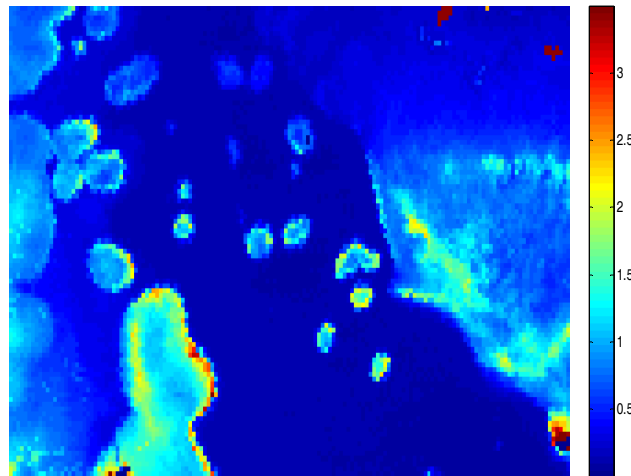
# Water Parameters



Backscattering



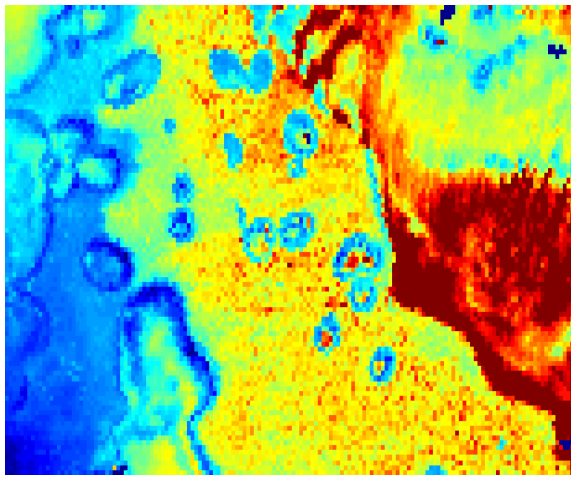
Phytoplankton



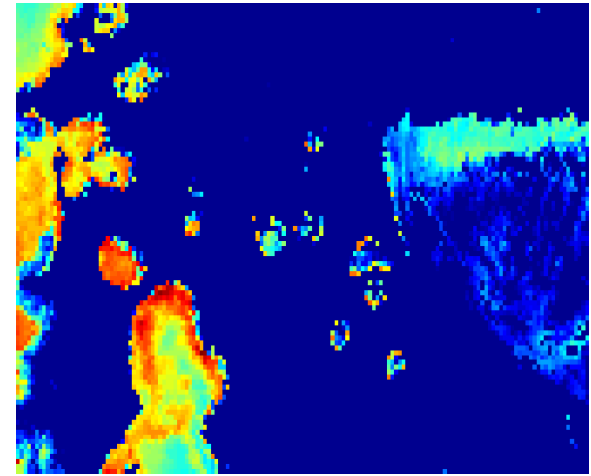
Absorption



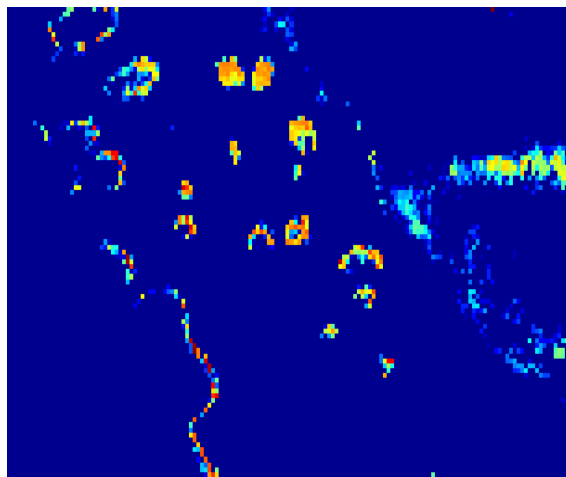
# Abundance Maps



Sand



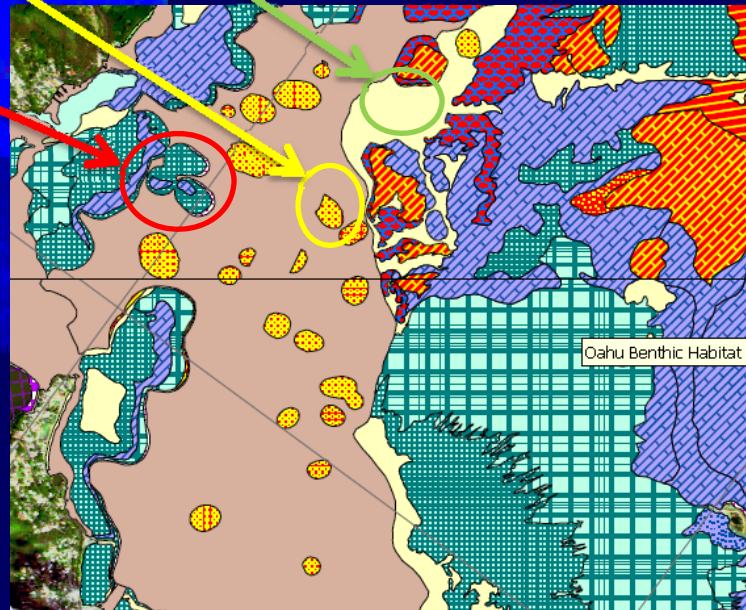
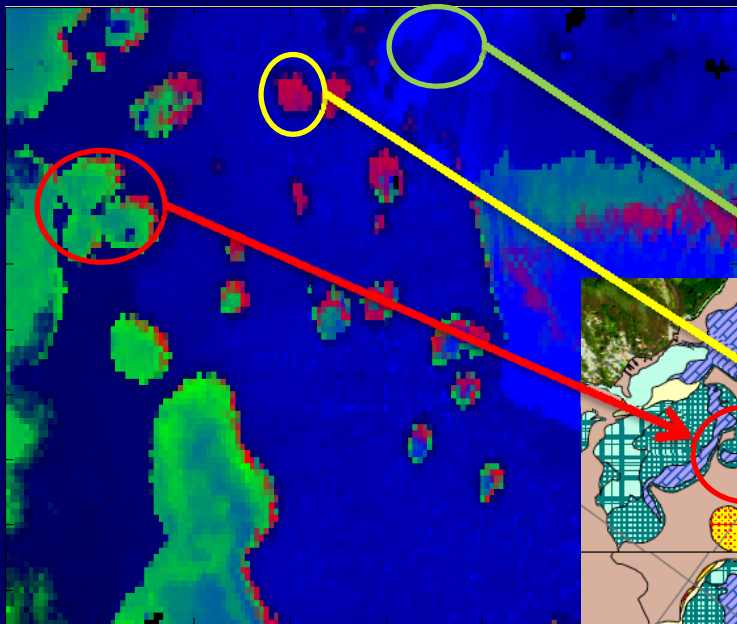
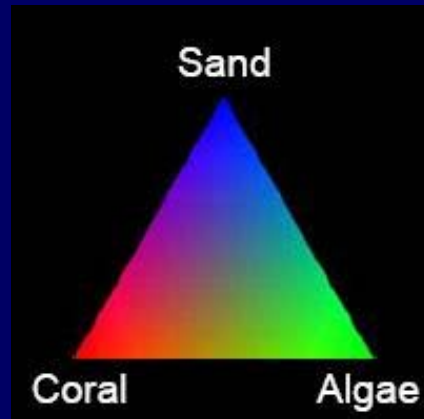
Algae



Coral



# Fractional Map



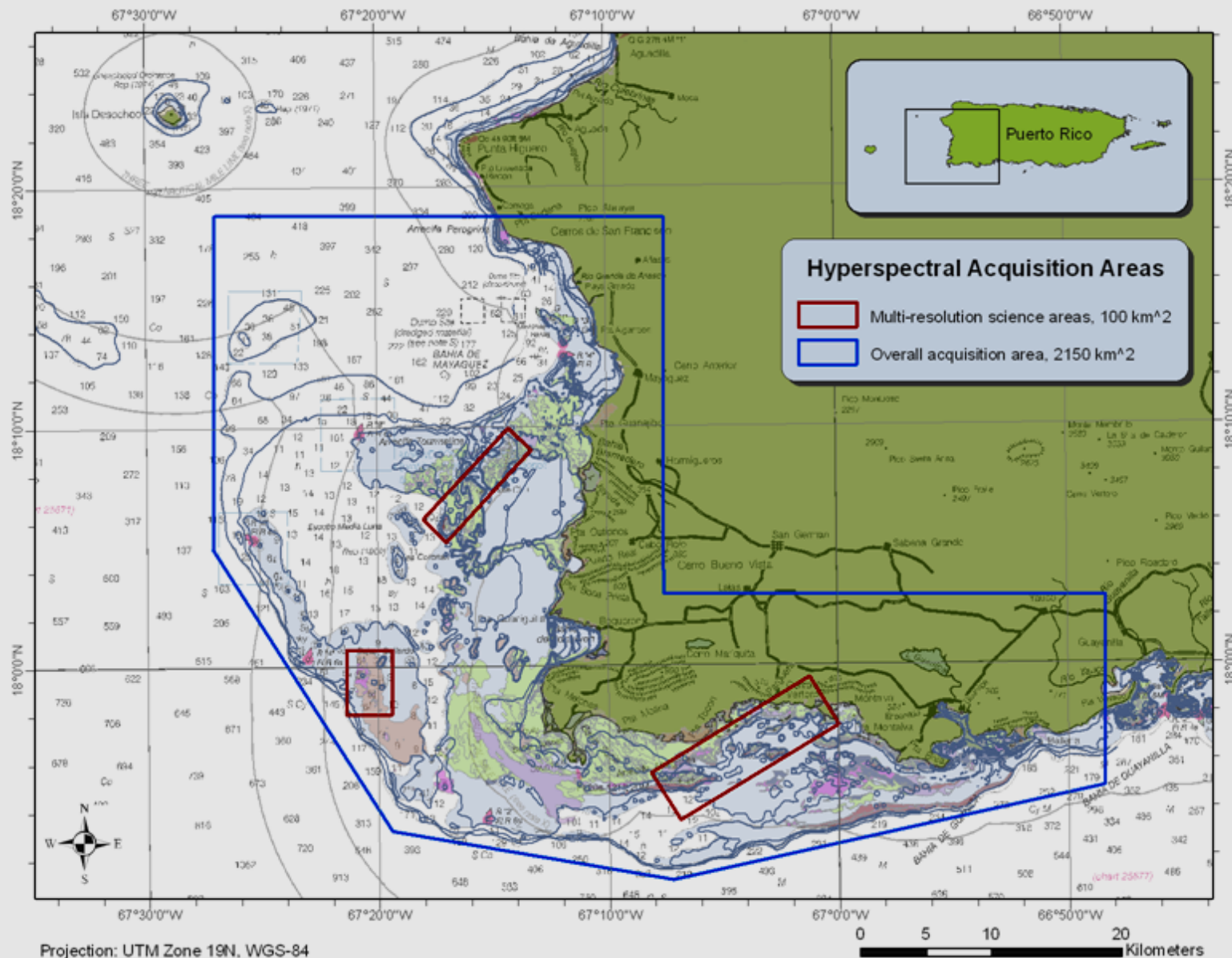
### Habitat Types

[Yellow box]	Sand
[Brown box]	Mud
[Green box]	Seagrass/90%-100%
[Green with vertical lines box]	Seagrass/50%-90%
[Green with horizontal lines box]	Seagrass/10%-50%
[Light blue box]	Macroalgae/90%-100%
[Dark blue box]	Macroalgae/50%-90%
[Dark blue with dots box]	Macroalgae/10%-50%
[Pink box]	Encrusting Coralline Algae/90%-100%
[Pink with vertical lines box]	Encrusting Coralline Algae/50%-90%
[Pink with horizontal lines box]	Encrusting Coralline Algae/10%-50%
[Red box]	Linear Reef
[Red with vertical lines box]	Spur and Groove Reef
[Yellow with dots box]	Patch Reef/Individual
[Yellow with horizontal lines box]	Patch Reef/Aggregated
[Blue with vertical lines box]	Coral Head/Individual
[Blue with horizontal lines box]	Coral Head/Aggregated
[Orange with dots box]	Scattered Coral/Rock In Unconsolidated Sediments
[Orange with vertical lines box]	Colonized Pavement
[Orange with horizontal lines box]	Colonized Volcanic Rock/Boulder
[Orange with diagonal lines box]	Colonized Pavement with Sand Channels
[Blue with diagonal lines box]	Uncolonized Pavement
[Blue with dots box]	Reef Rubble
[Blue with vertical lines box]	Uncolonized Volcanic Rock/Boulders
[Blue with horizontal lines box]	Uncolonized Pavement with Sand Channels
[Green with dots box]	Emergent Vegetation
[Purple with dots box]	Artificial
[Purple with diagonal lines box]	Artificial/ Fishpond
[Blue box]	Unknown



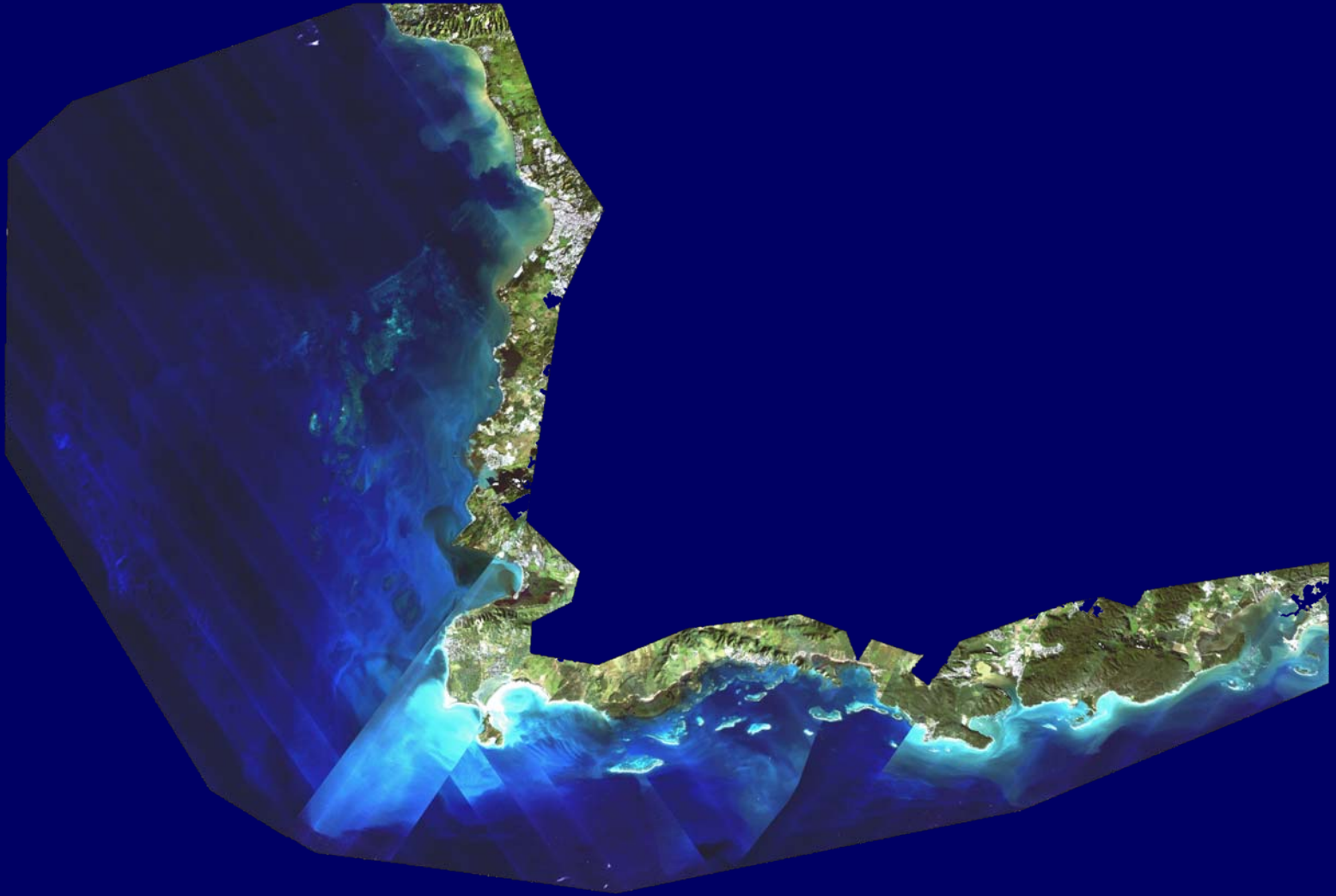


# Mission Coverage: Galileo - AISA





# Preview of New Data Set





# Conclusions

- **Hyperspectral Remote Sensing has great potential to address problems in coastal remote sensing**
- **A software tool for coastal analysis has been developed**
  - **MATLAB GUI tool provides simple environment for fast analysis**
- **Simple GUI makes algorithms accessible to a wider community**



# Acknowledgements

- This work was primarily supported by the Engineering Research Center Program of the National Science Foundation under Award Number EEC-9986821.
- Partial support was also received from NASA through few grants