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

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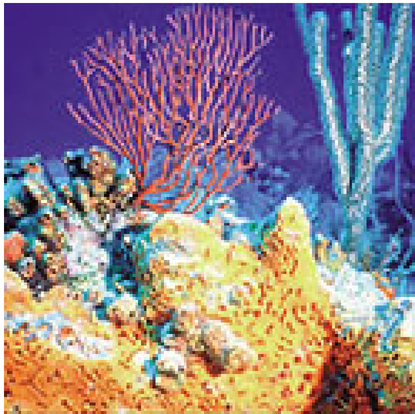
The Team

- 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

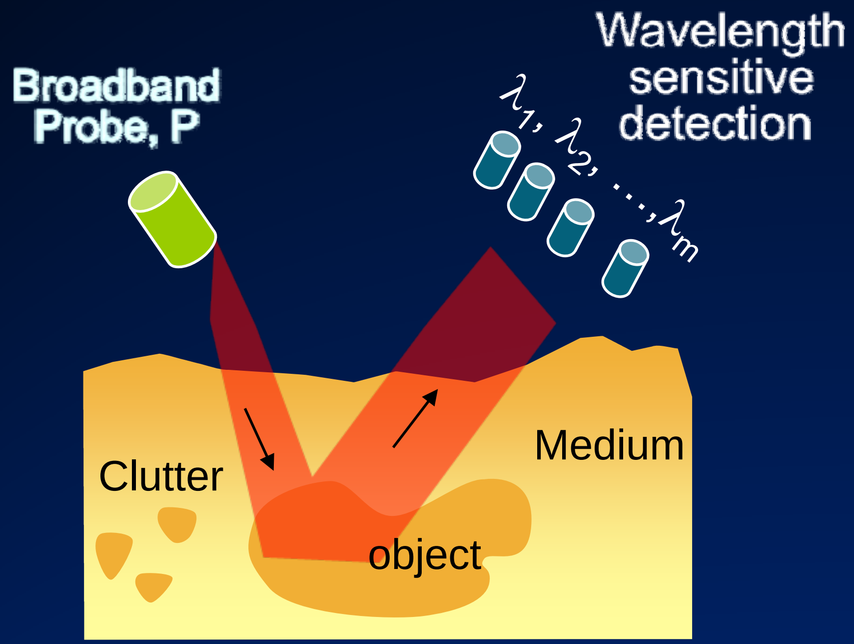
Benthic Habitat Monitoring

- 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

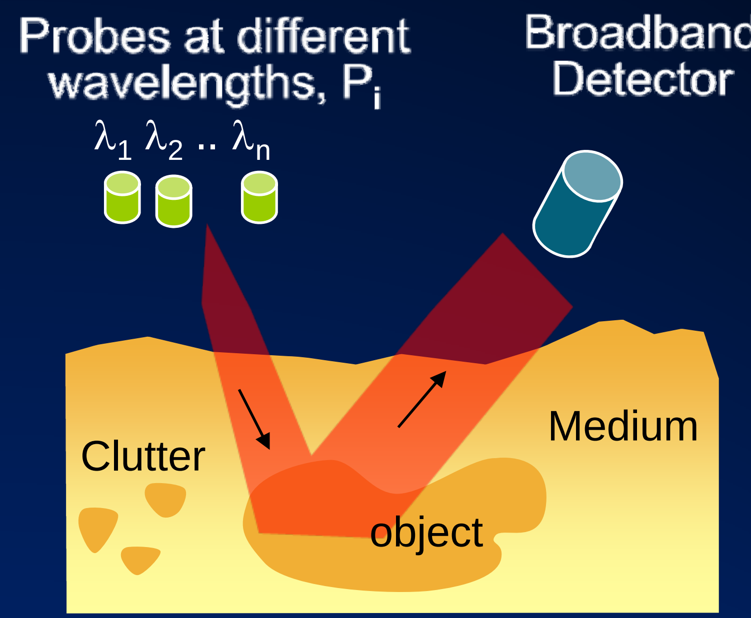


Subsurface Spectral Sensing

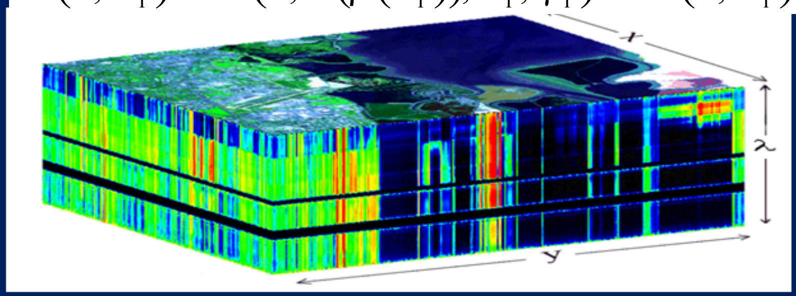
Imager-Spectrometer Configuration



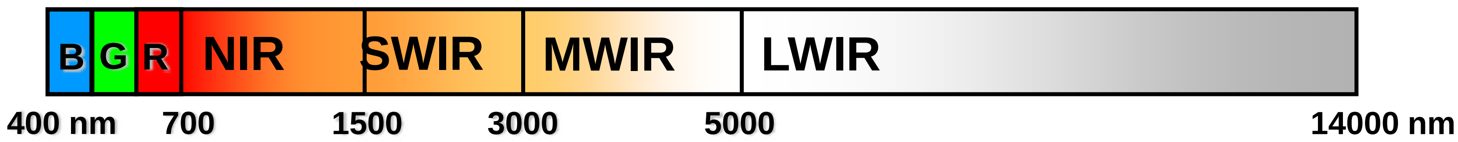
Spectrometer-Imager Configuration



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



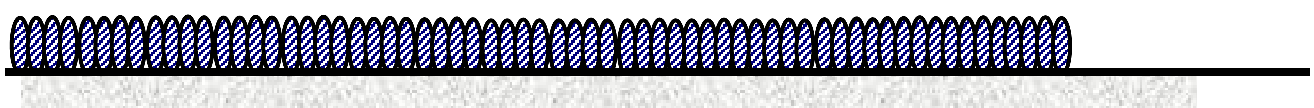
Spectral Sensing



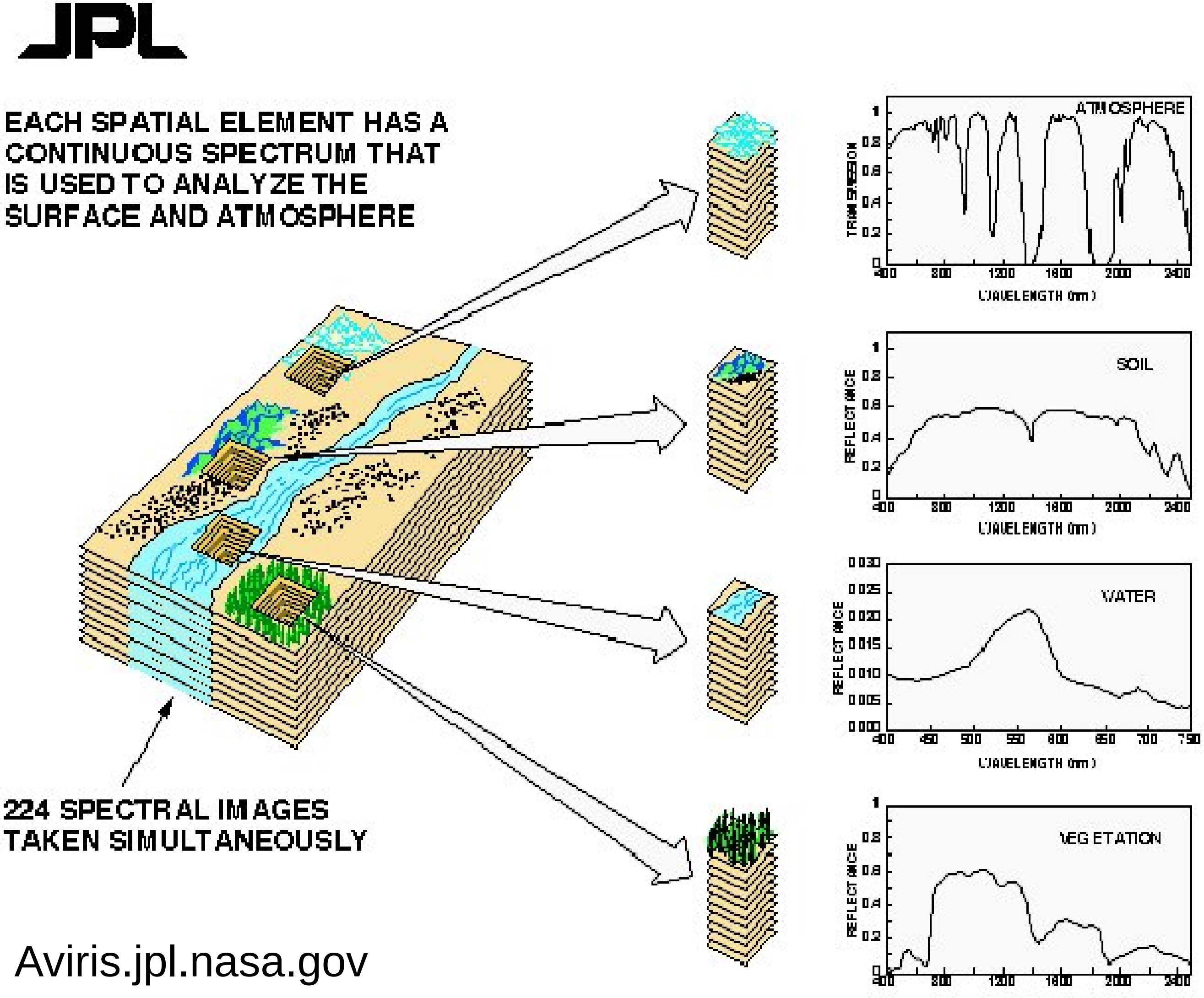
LOW **Panchromatic: one very wide band**

MED **Multispectral: several to tens of bands**

HIGH **Hyperspectral: hundreds of narrow bands**

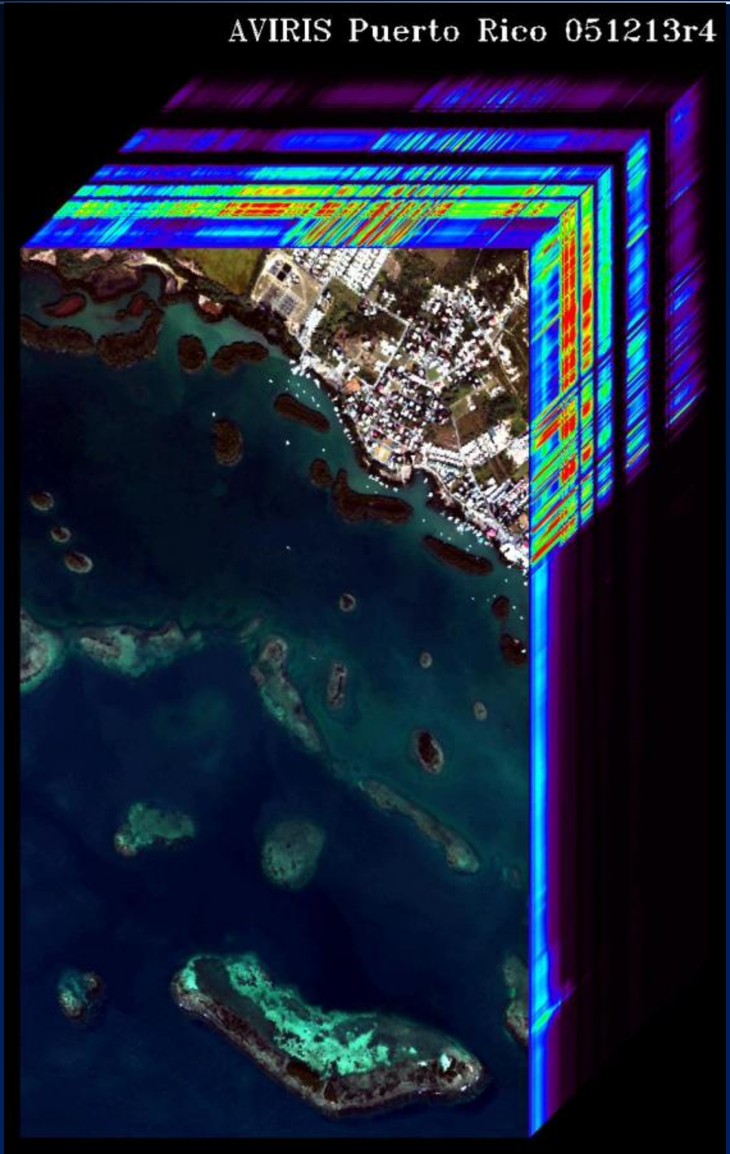


Imaging Spectrometry



Aviris.jpl.nasa.gov

Hyperspectral Imaging



- **Information Content**

  Temporal, Spatial and Spectral Domains

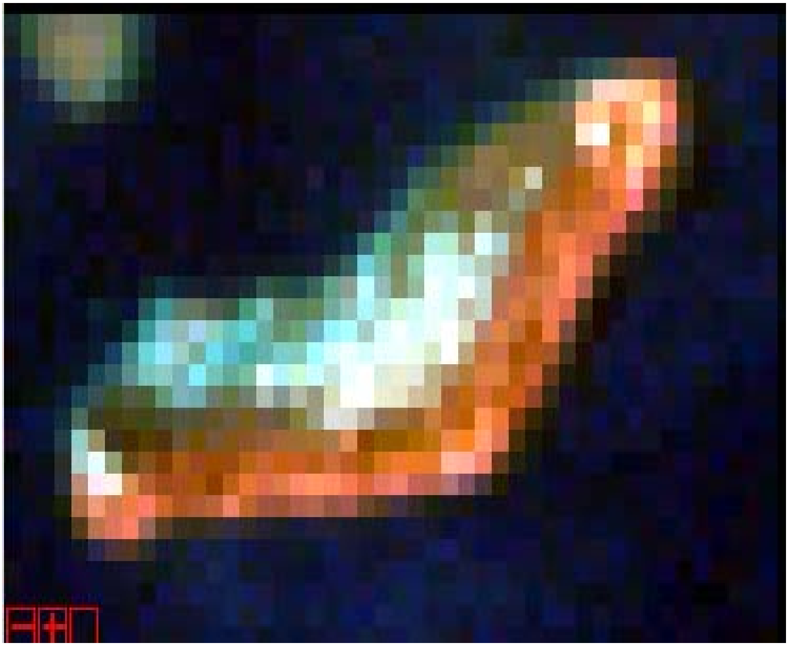
- **High Spectral Resolution**

  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

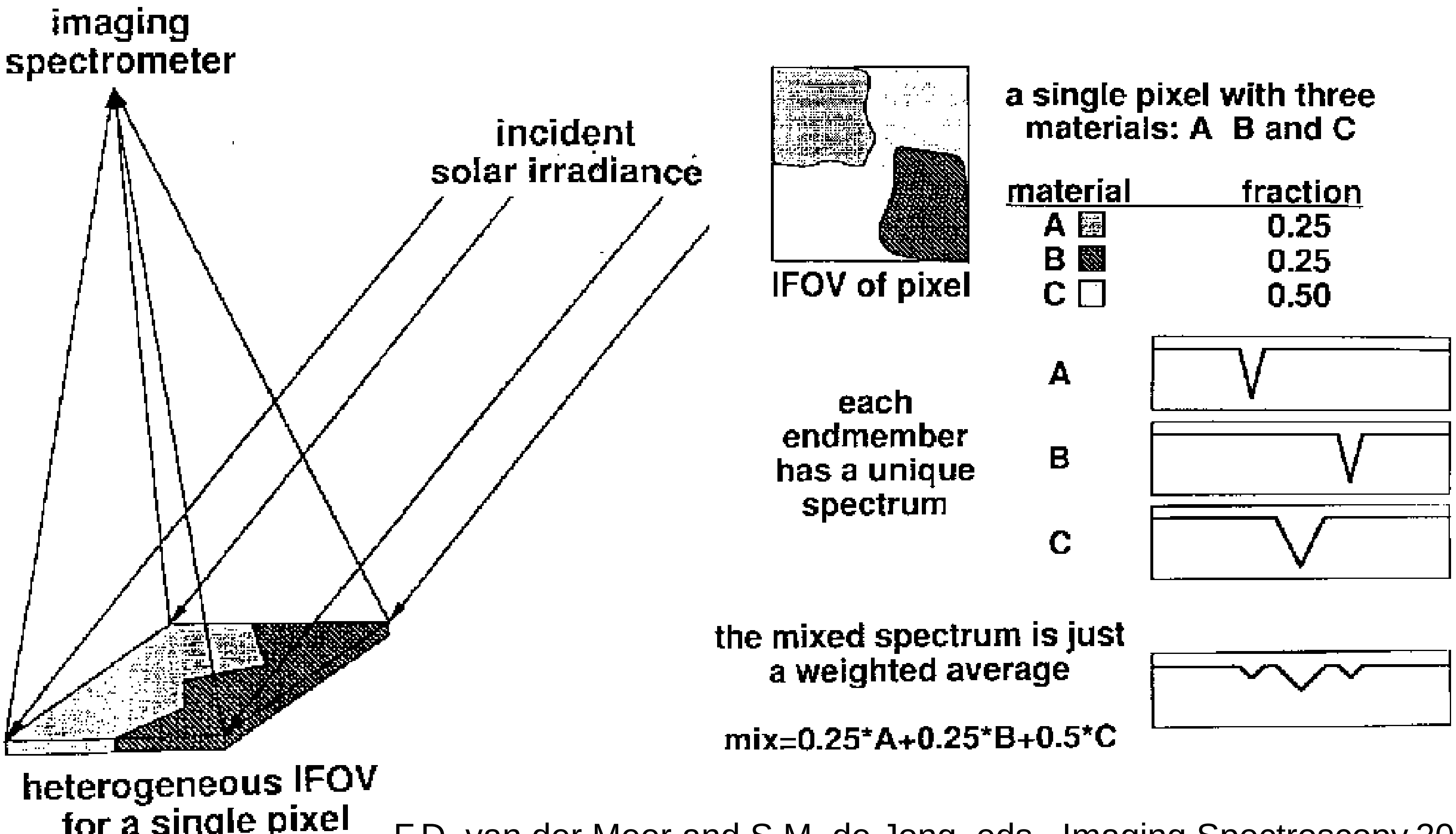


IKONOS PAN Sharpened Image
Multispectral Sensor
1m PAN, 4m/4 bands MSI

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

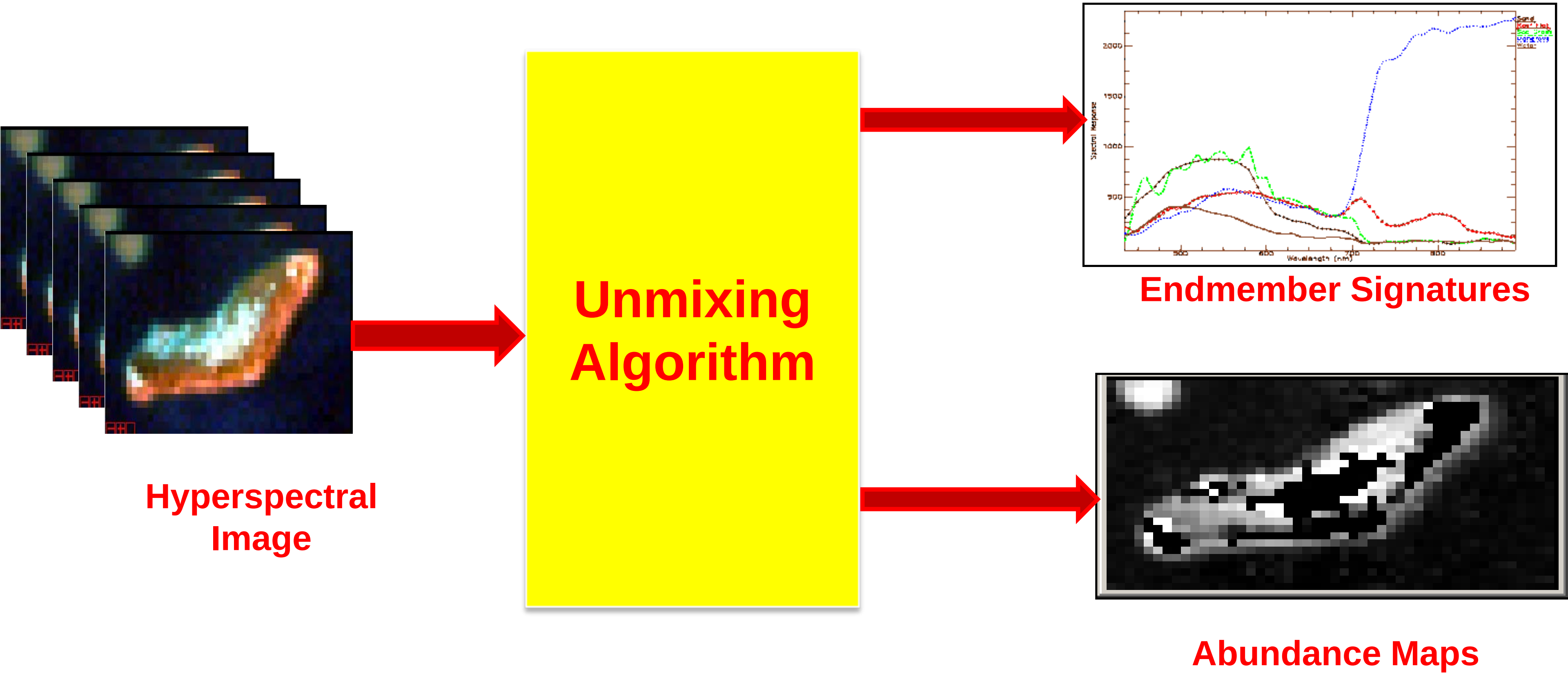
Enrique Reef in Parguera, Lajas, PR

Linear Mixing Model: Standard for Land Surface

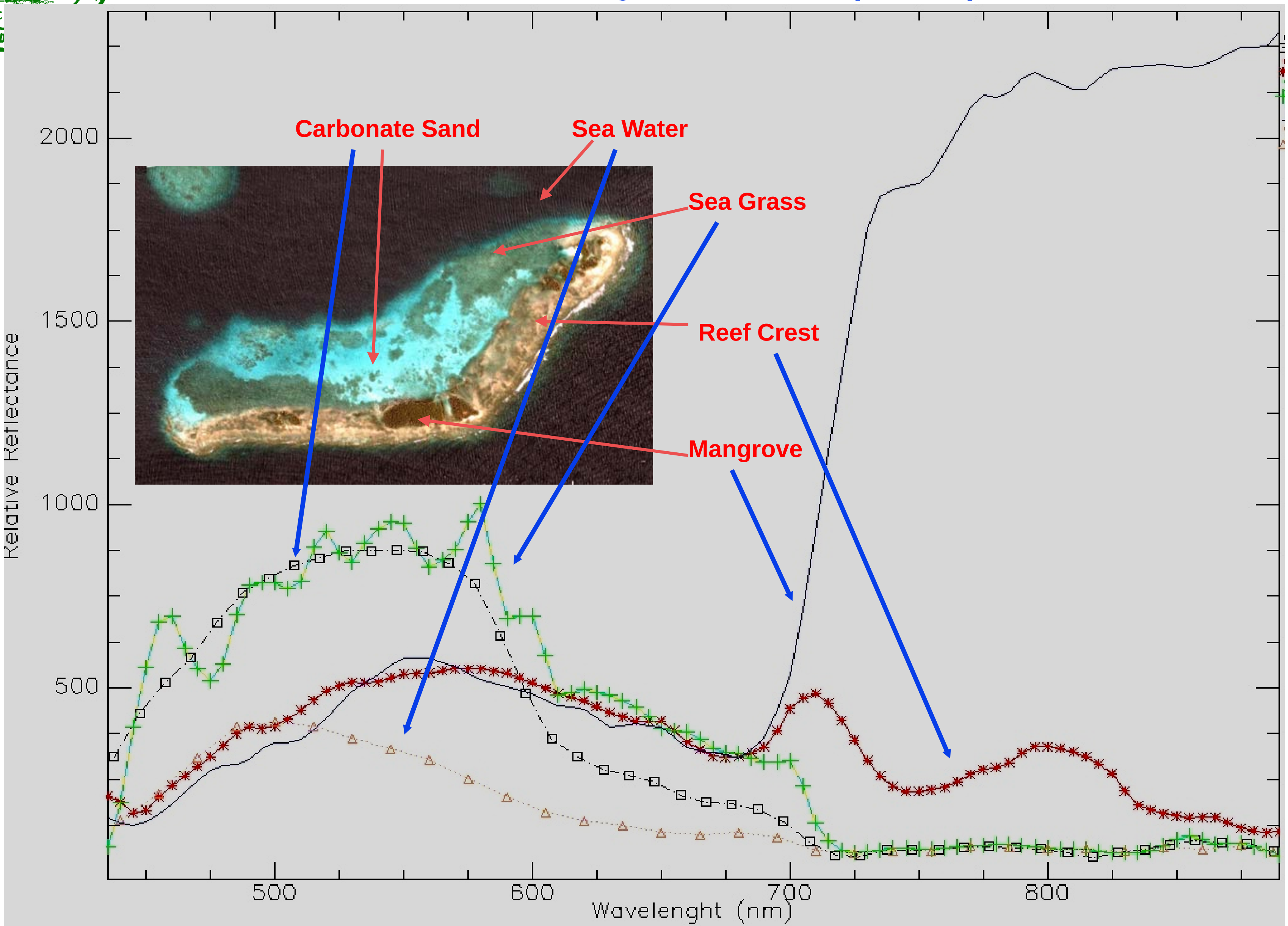


F.D. van der Meer and S.M. de Jong, eds., Imaging Spectroscopy,2003

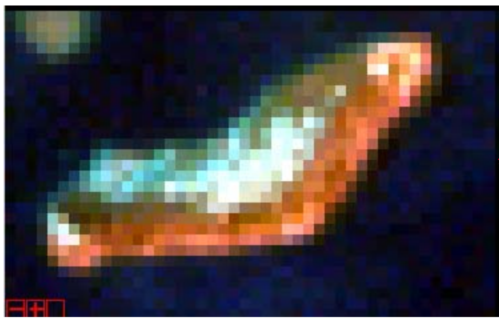
Unmixing

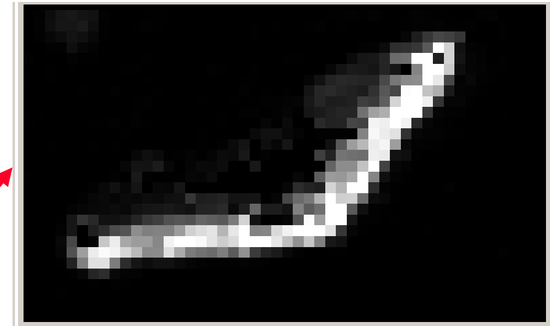

Hyperspectral
Image
Unmixing
Algorithm
Endmember Signatures
Abundance Maps

Endmembers Estimated with Pixel Purity Index (PPI)

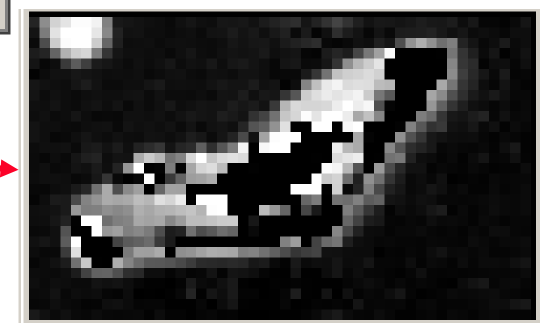


Abundance Estimation: Surface Approach

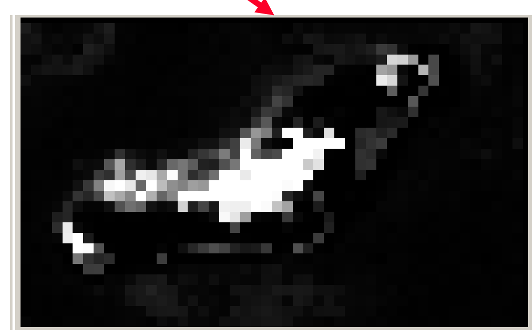




Reef Crest



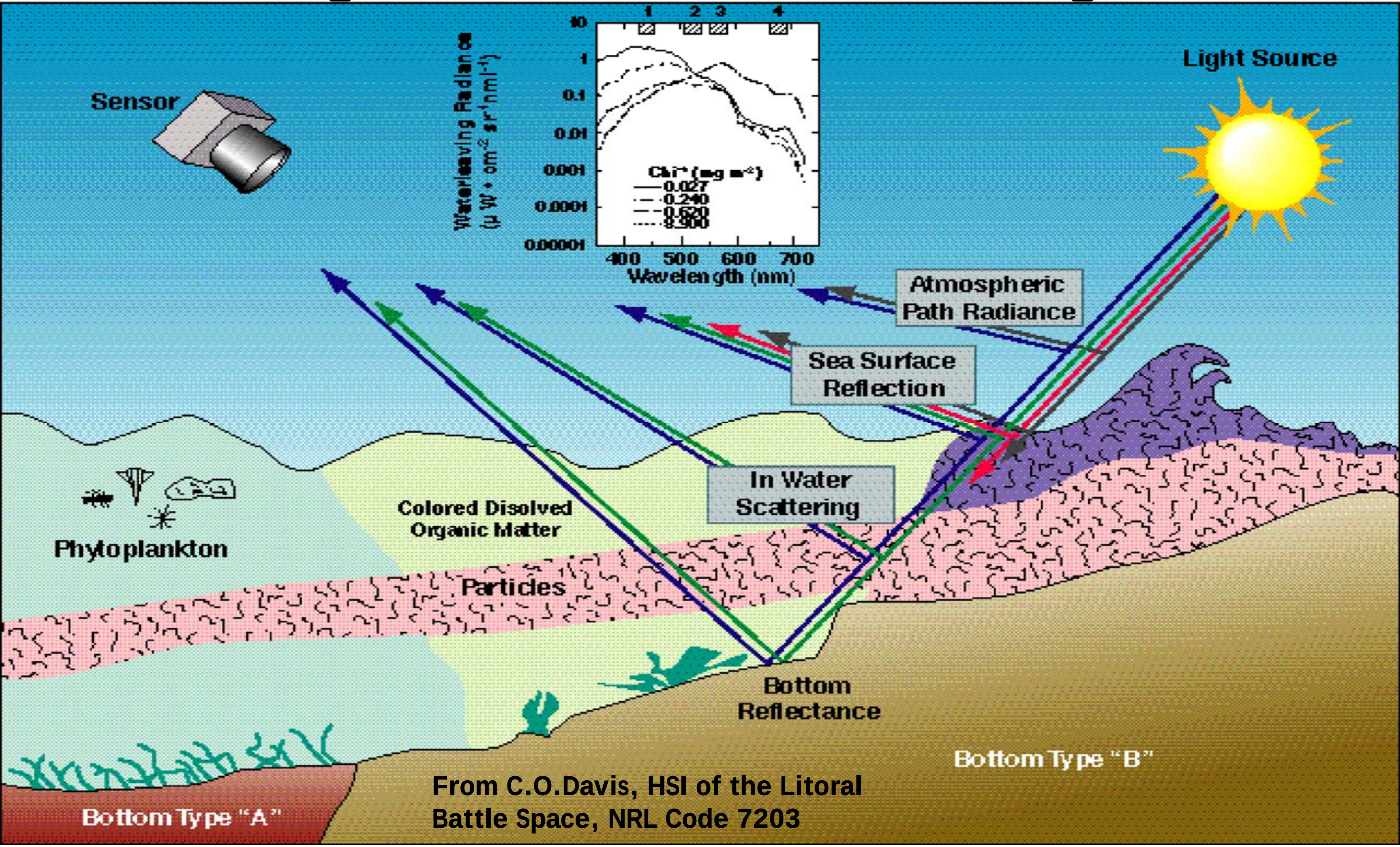
Sea Grass



Carbonate Sand

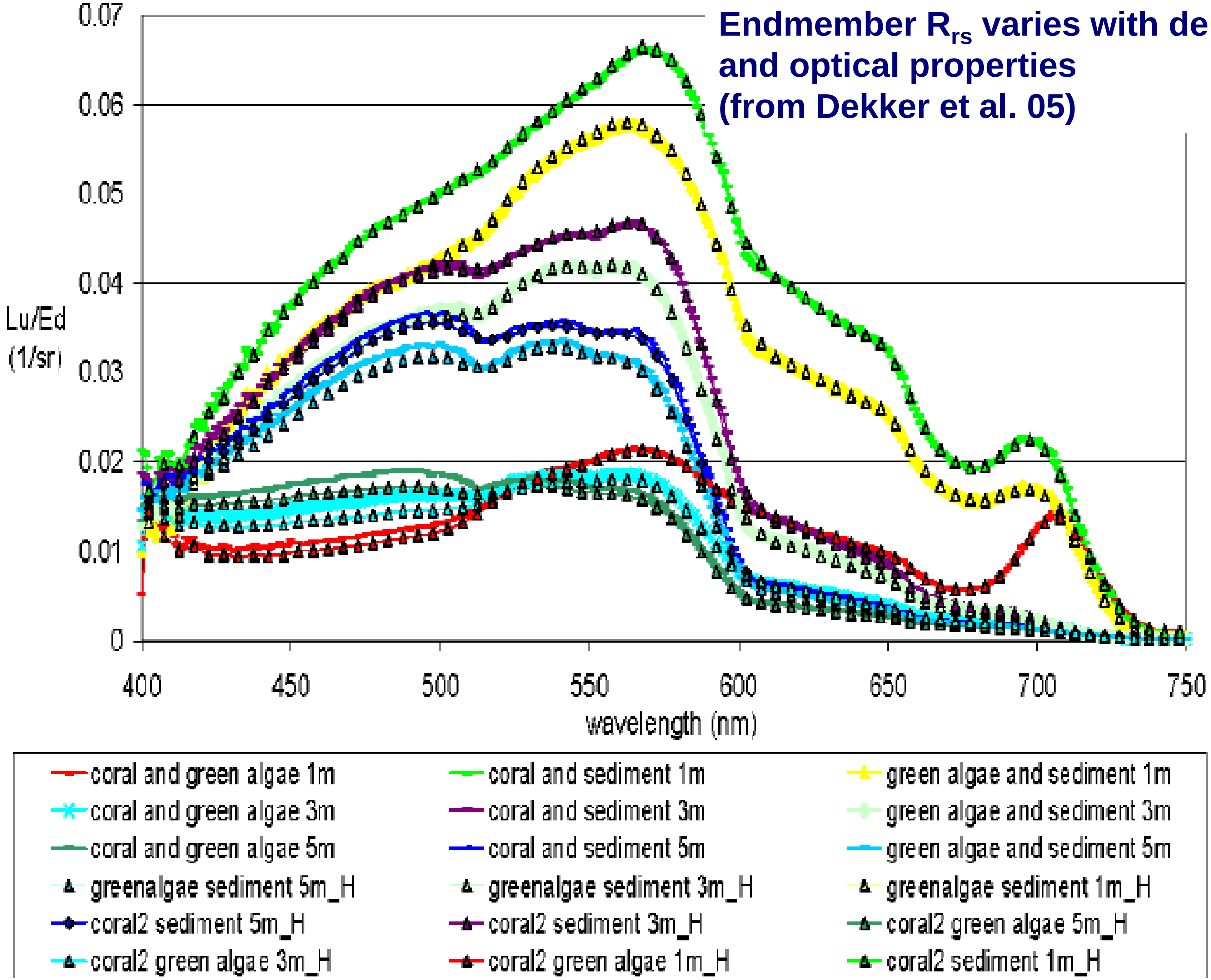
This is a Subsurface Sensing Problem

Challenge: Subsurface Unmixing

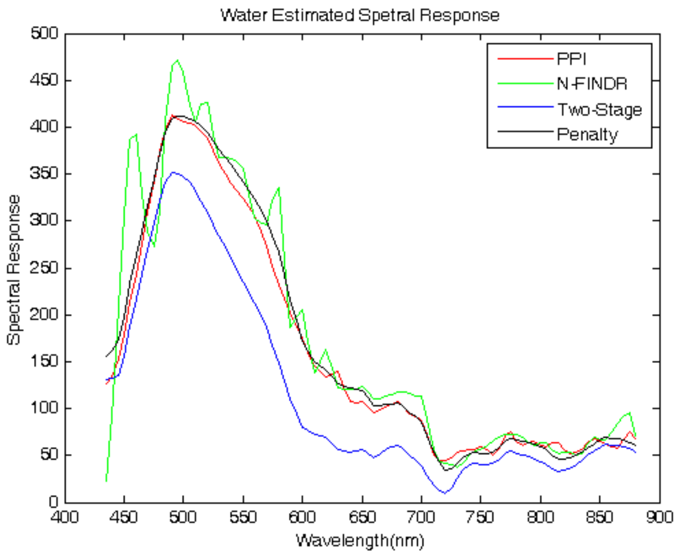


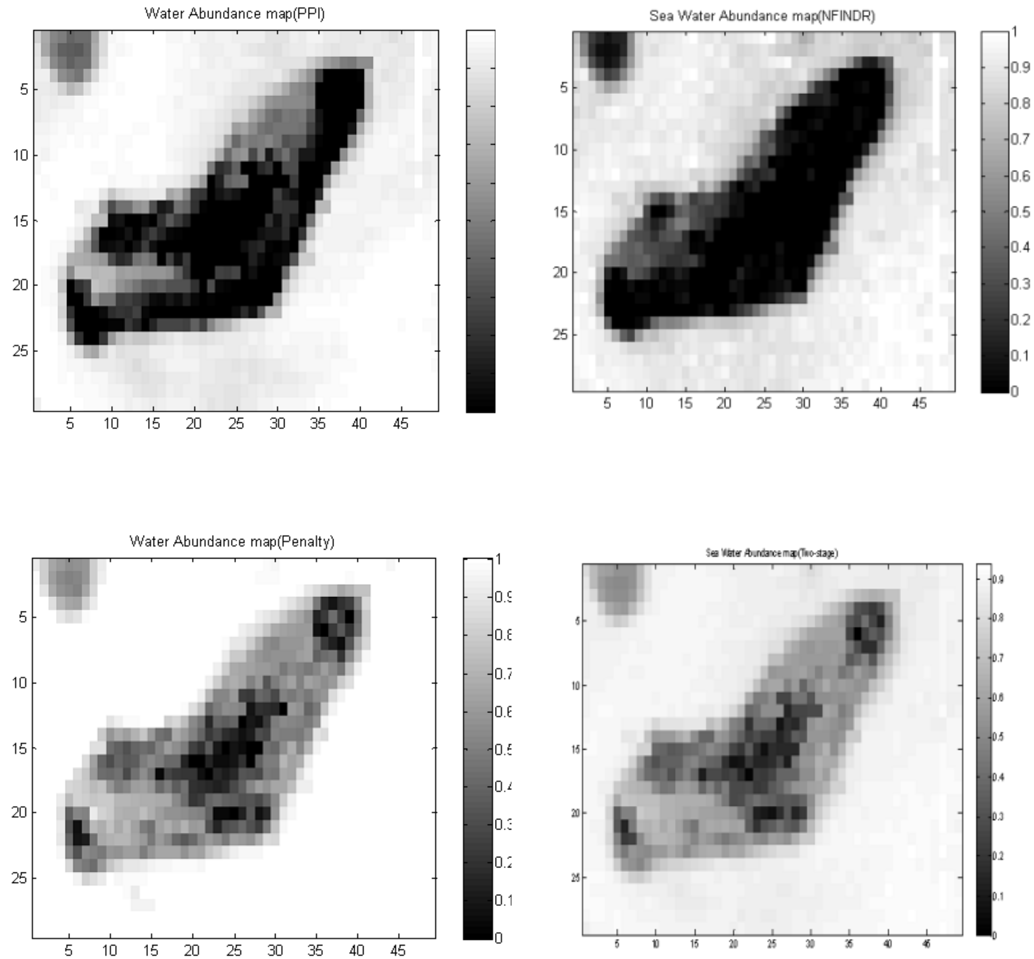
Temporal and Spatial Variability of Optical Properties and Variable Bathymetry

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

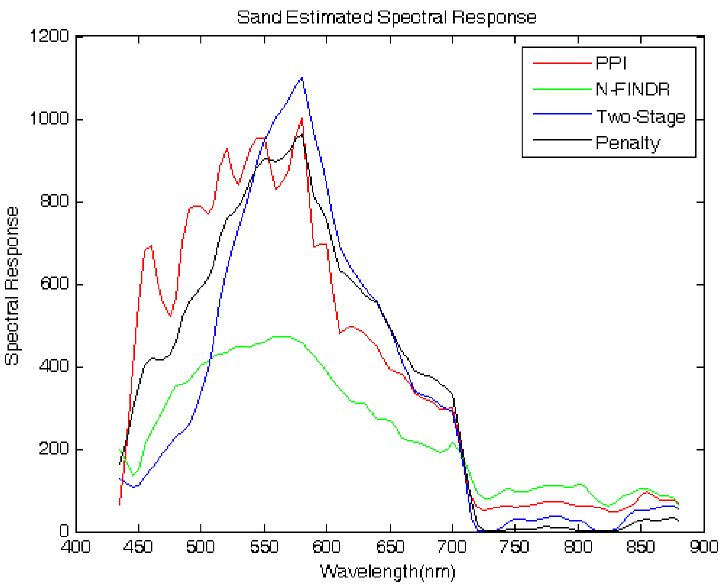


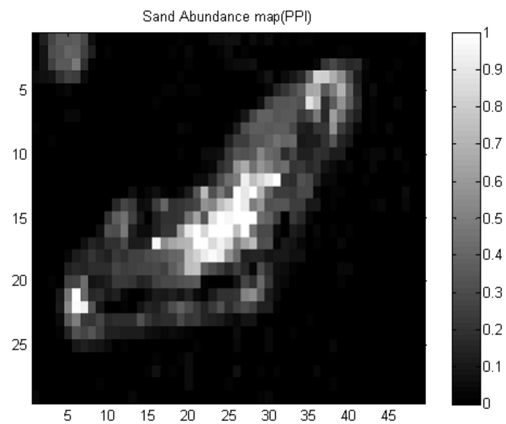
Effect of Endmember Variability: Water

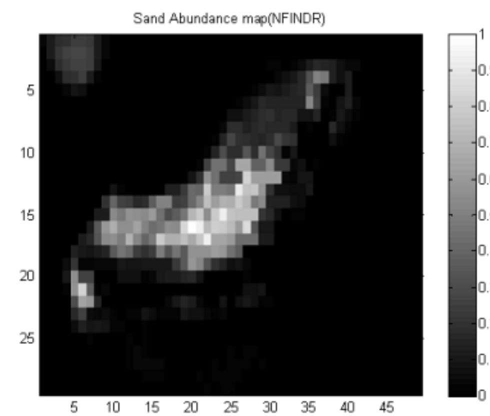


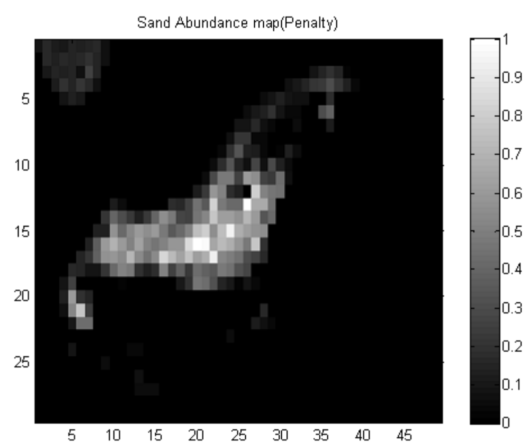


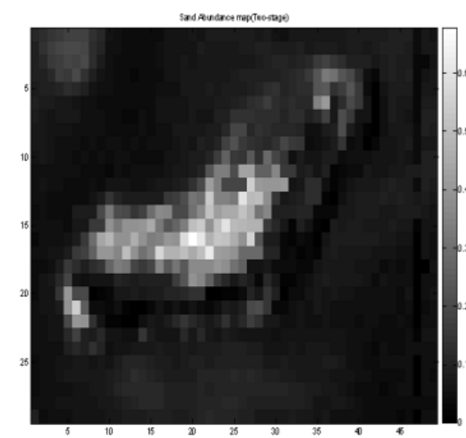
Effect of Endmember Variability: Sand











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}

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

Subsurface remote sensing reflectance, r_{rs}

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

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

- Model is parametrized by 5 parameters

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

ρ_{sand} is a 550-nm normalized sand spectra and α is a vector of nuisance parameters.

Lee's Method to Determine IOP and Bathymetry

- Nonlinear least squares optimization

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

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

and ρ_{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 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

$$\overline{\mathbf{R}}_i(x,y) = \mathbf{R}_{rs}\left(\hat{\boldsymbol{\gamma}}_{Lee}(x,y), \boldsymbol{\rho}_i\right) \quad \text{for } i = 1,2,3$$

- Step 3: Linear Unmixing at each location

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

Combined Inversion and Unmixing at the Bottom (CIUB) Approach

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

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

- Linear mixing model for the bottom albedo

$$\bar{\boldsymbol{\rho}} = \mathbf{Sf}$$

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

where **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

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

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

Partially Linear Nonlinear Least Squares Problem

Two-Stage Simple Iterative Inversion Approach

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

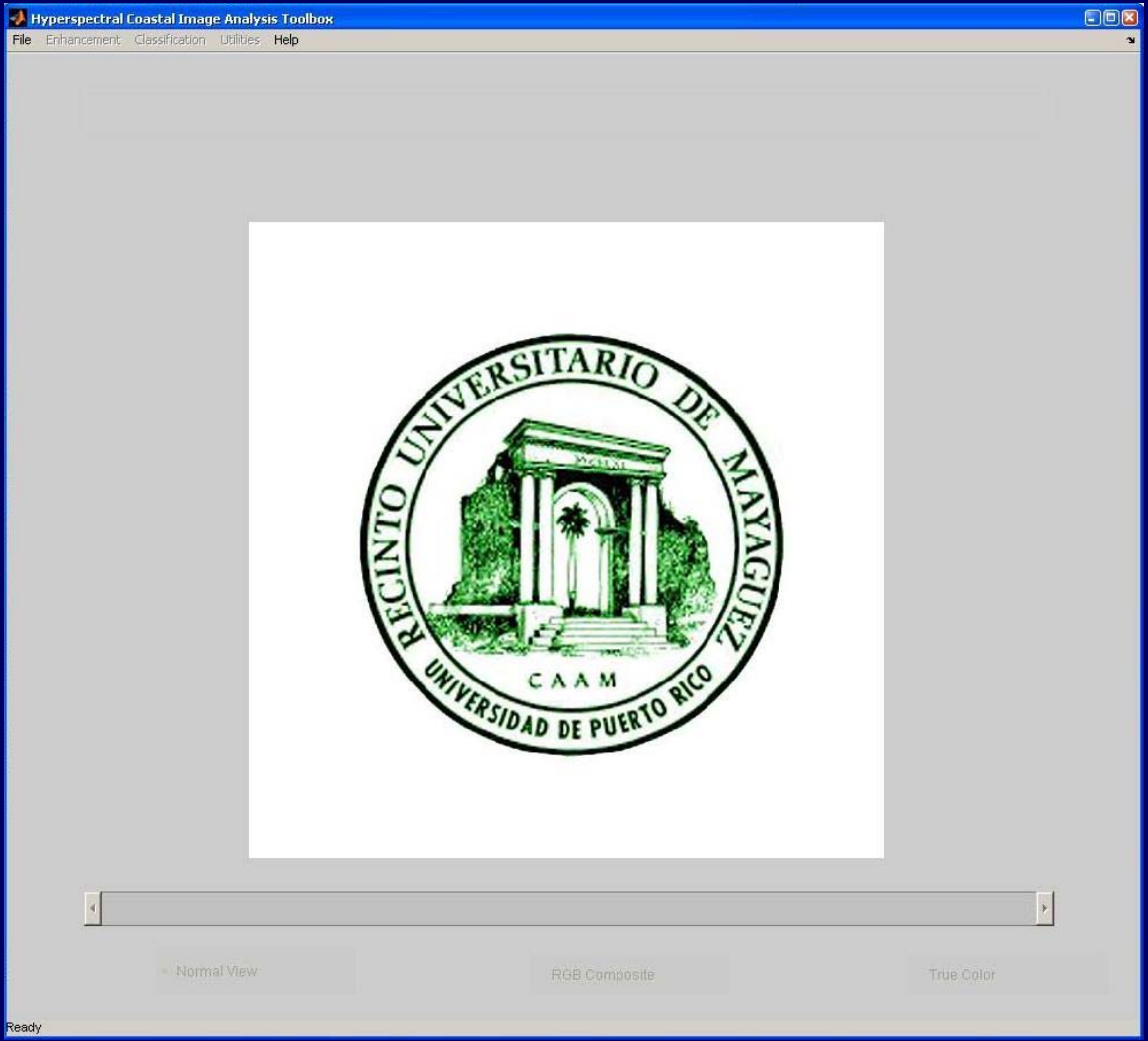
$$\hat{\mathbf{f}} = \arg\min_{\gamma,\mathbf{f}} \frac{\left\| \mathbf{b}(\hat{\gamma}) - \mathbf{A}(\hat{\gamma})\mathbf{f} \right\|_2^2}{\left\| \mathbf{r}_{\mathrm{rs}} \right\|_2^2}$$

- Step2: Update optical properties, bathymetry and bottom albedo at 550nm

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

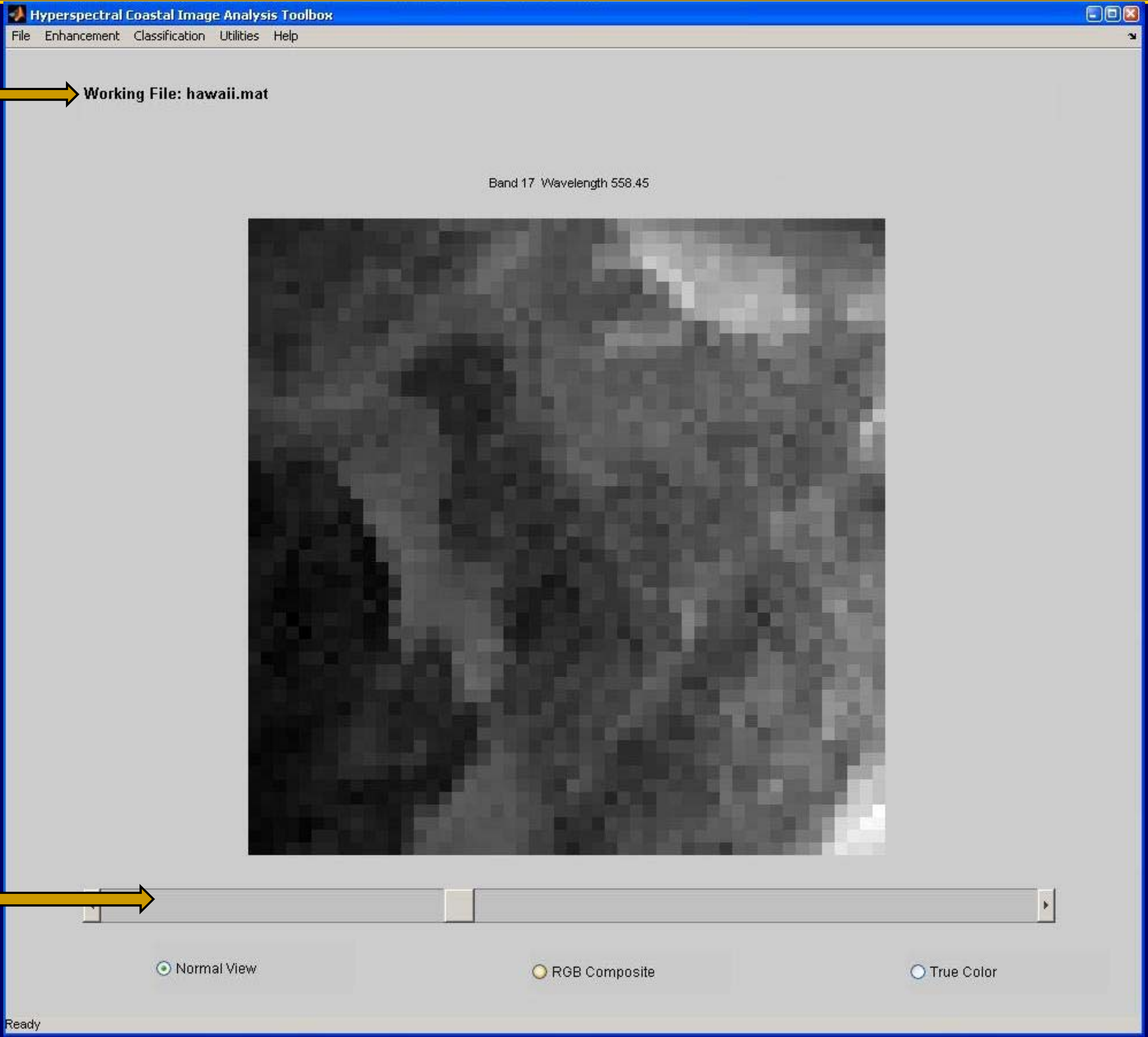
HyCIAT: A Hyperspectral Coastal Image Analysis Tool

HyCIAT Toolbox



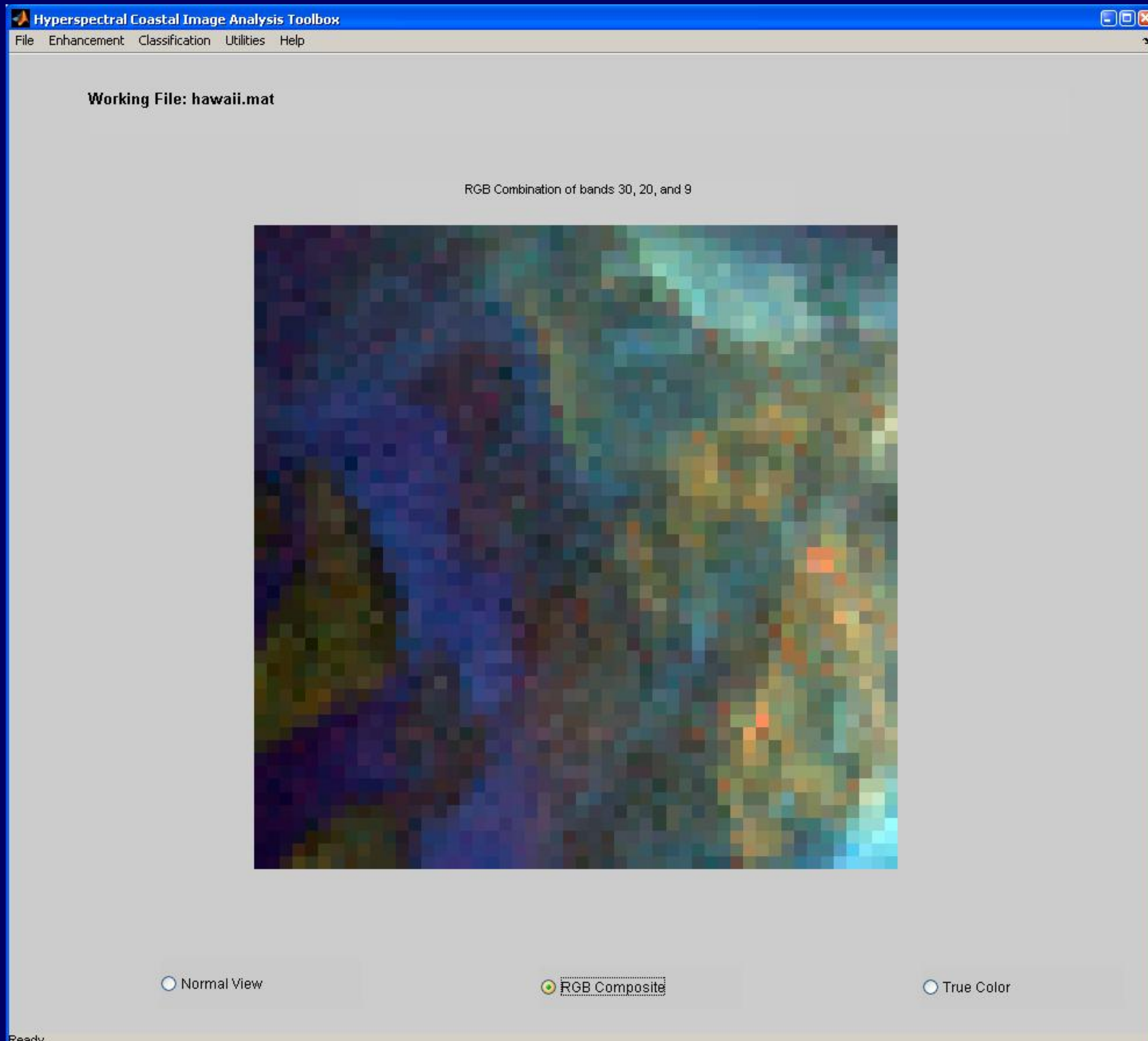
Visualization

File Name

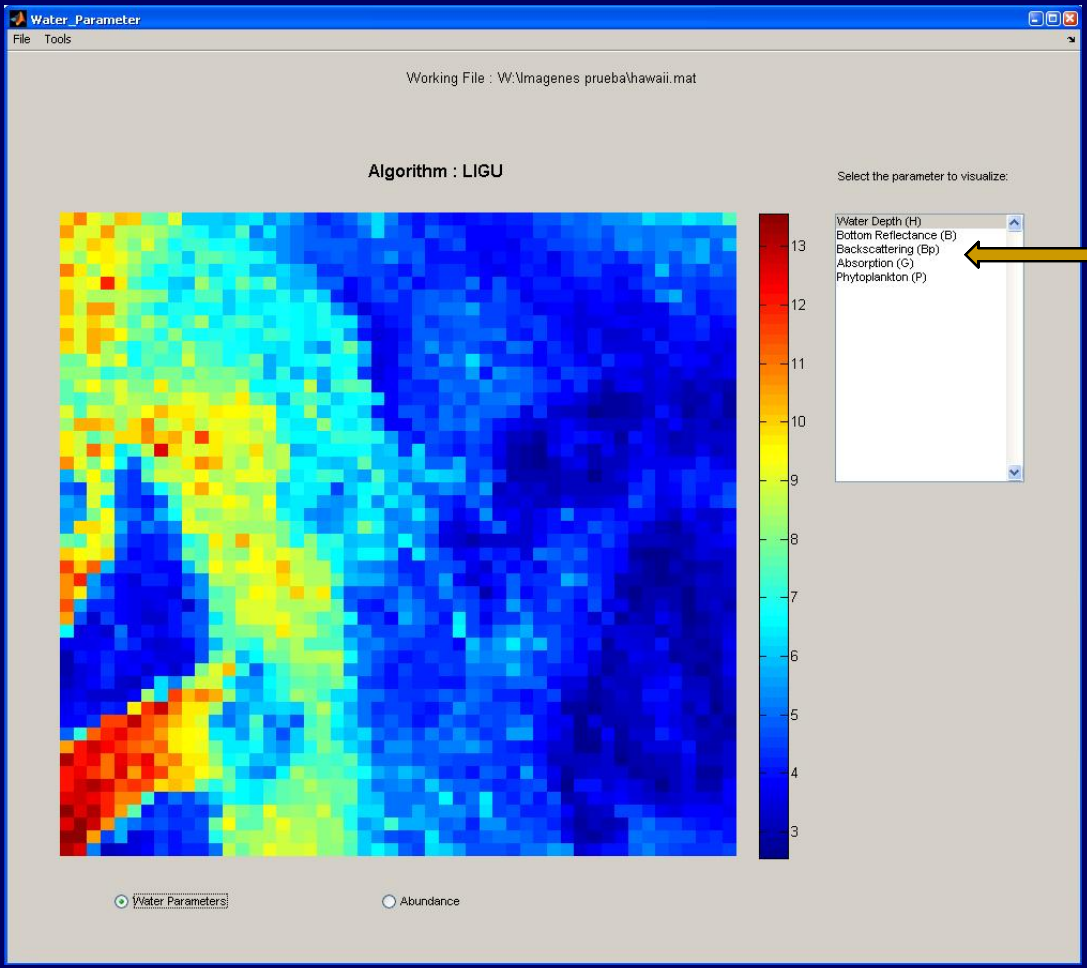


Scrolling Through Bands

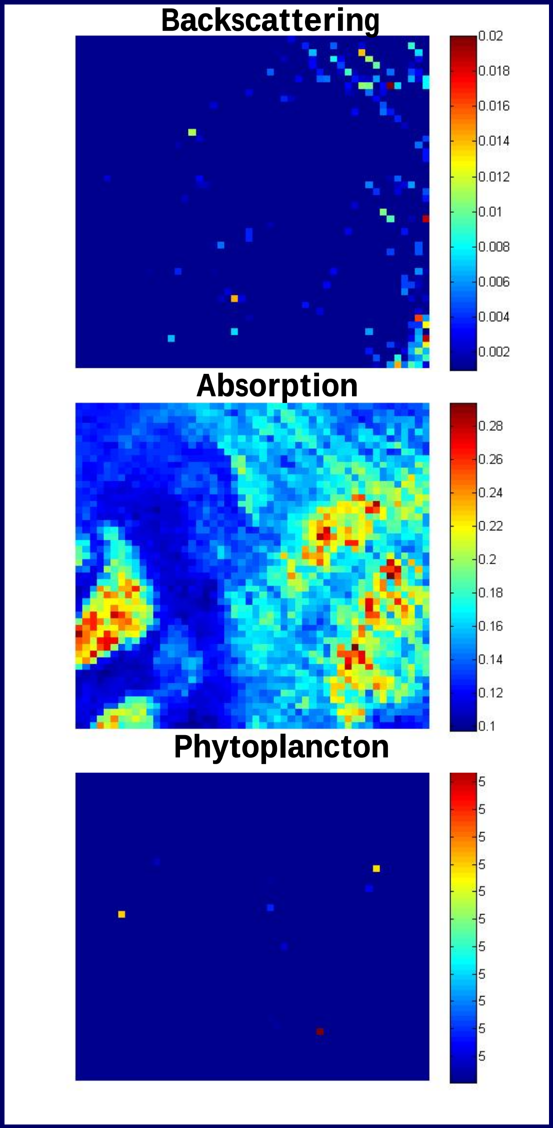
RGB Composite (30-20-9)



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

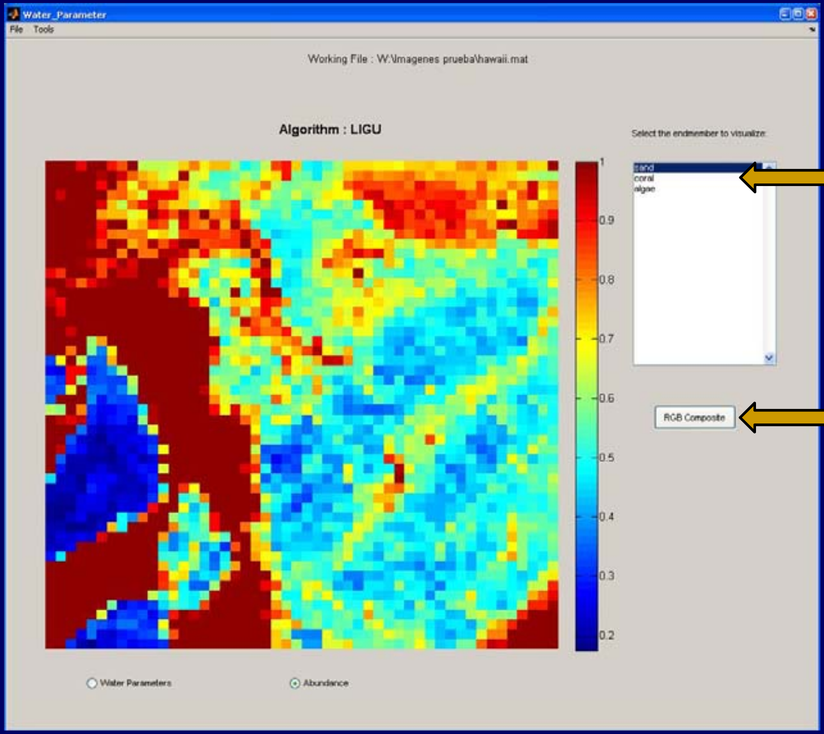


Select Parameter



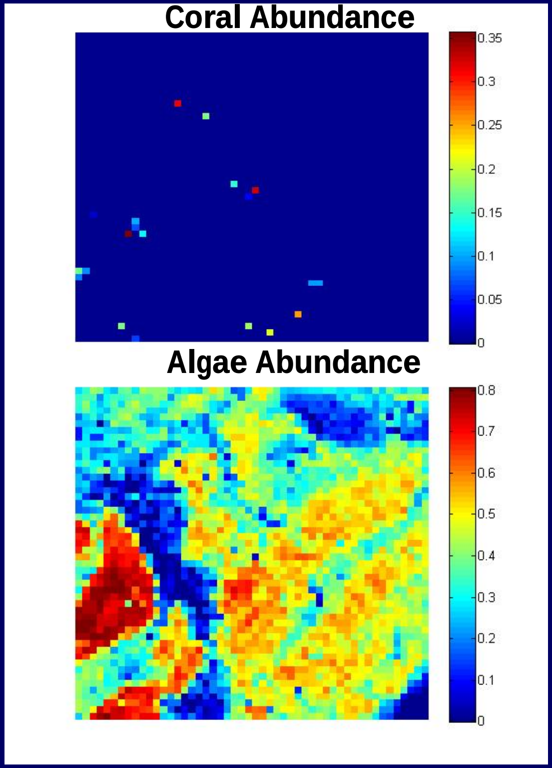
Abundance Estimates

Result Window: Sand Abundance

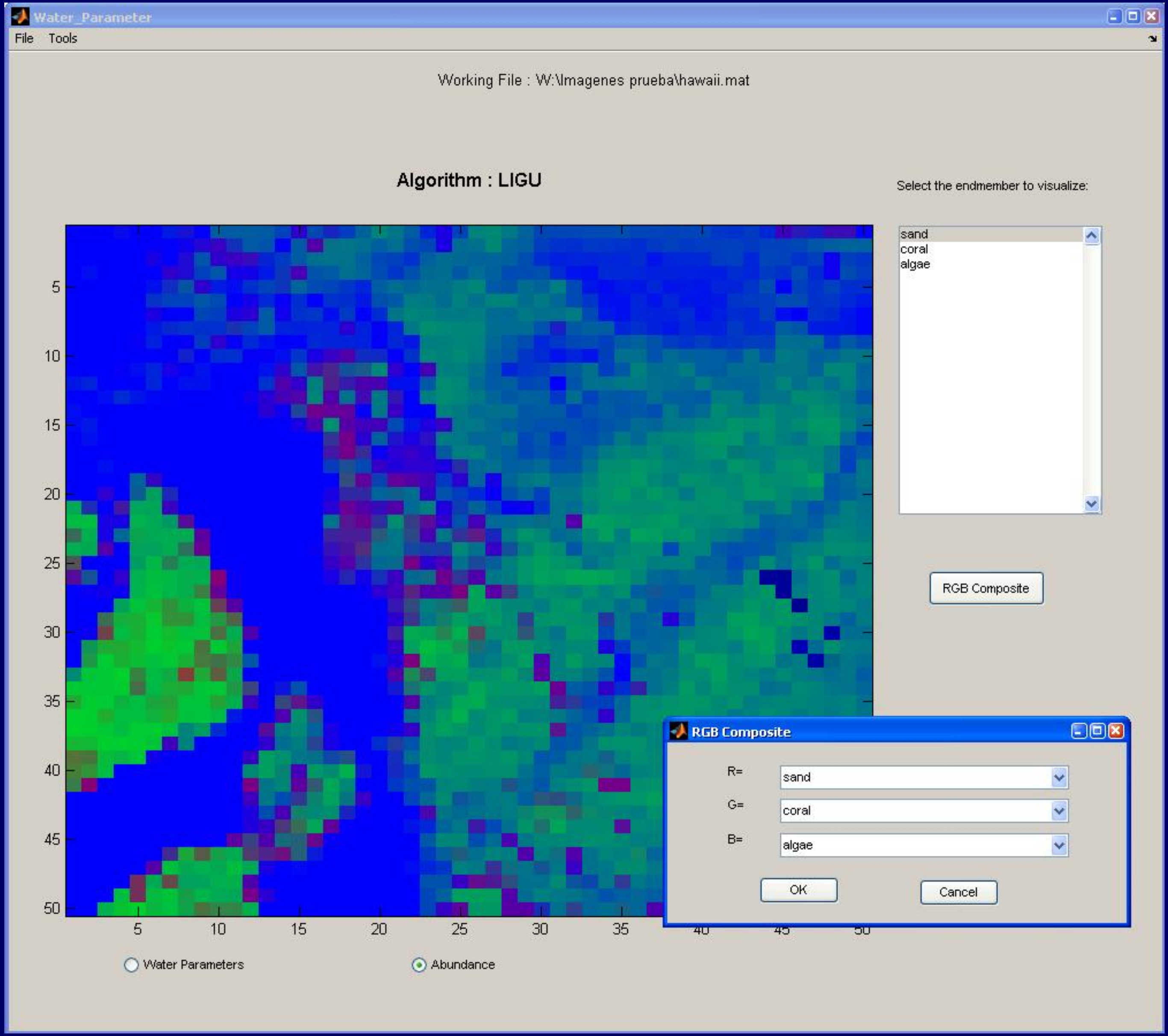


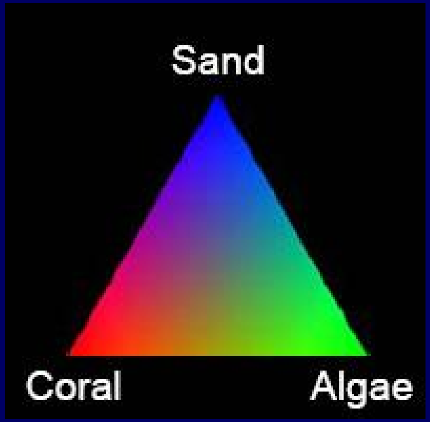
Select Endmember

RGB Composite



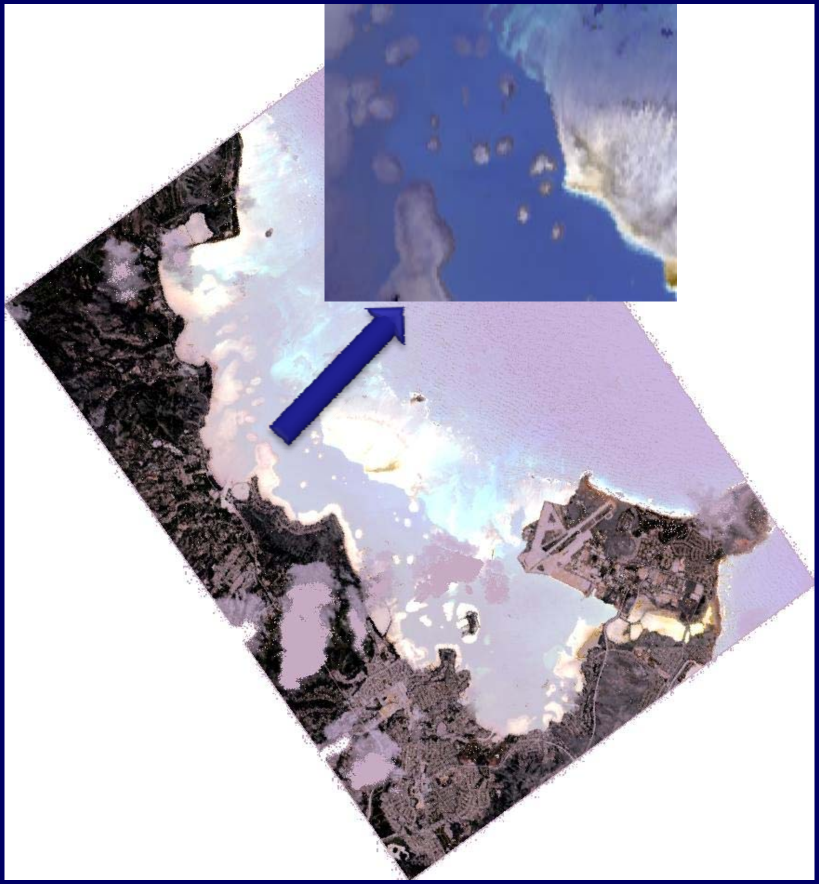
Fractional Plots: RGB Composite of Three Abundance Maps



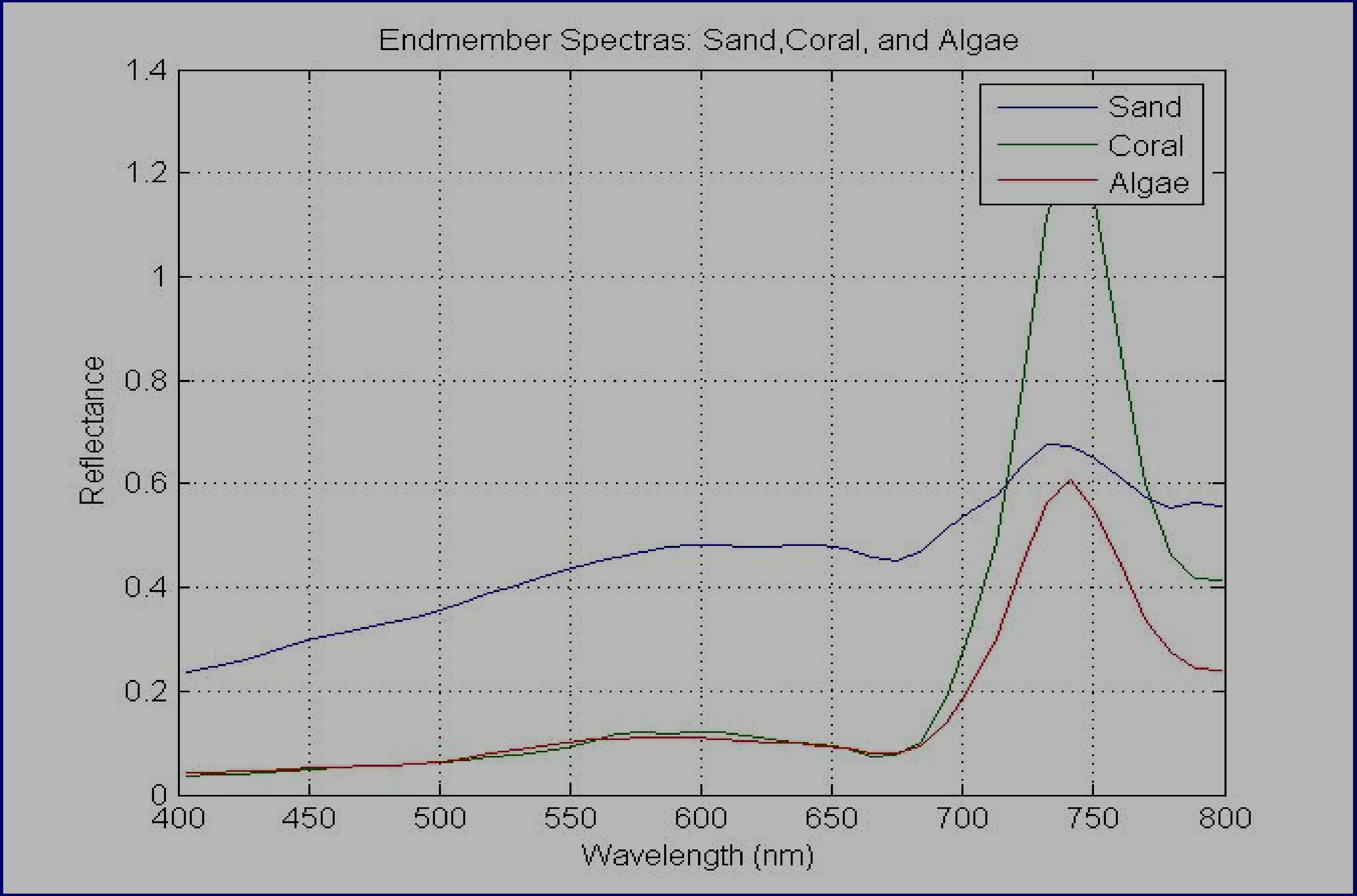


Kaneohe Bay

Kaneohe Bay: is in the north eastern side of the island of Oahu in Hawaii, is12.8 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 μm range, it consists of an image already corrected for atmospheric and sunglint effects .

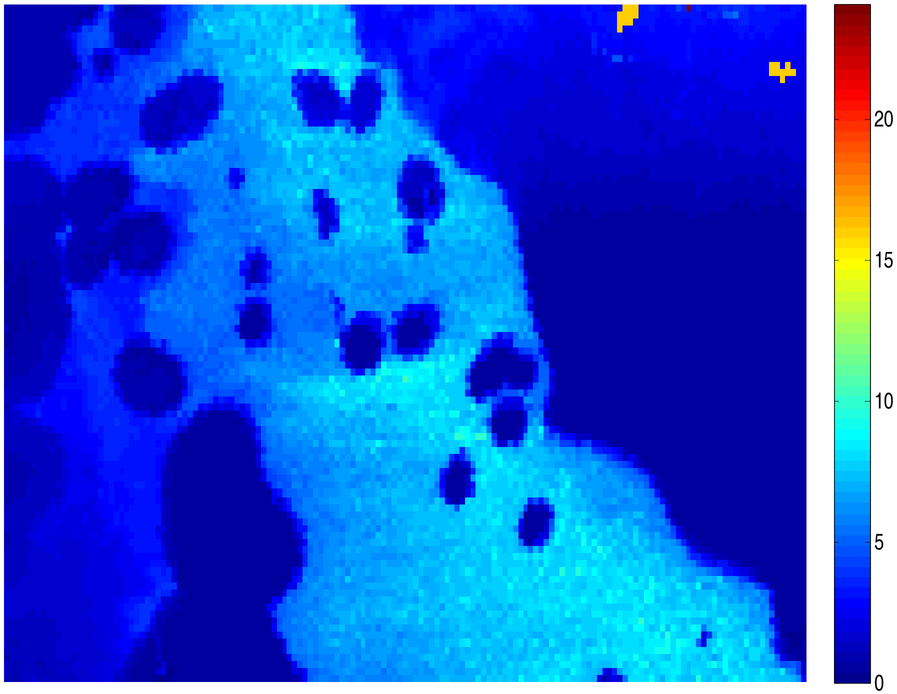


Measured Bottom Reflectance

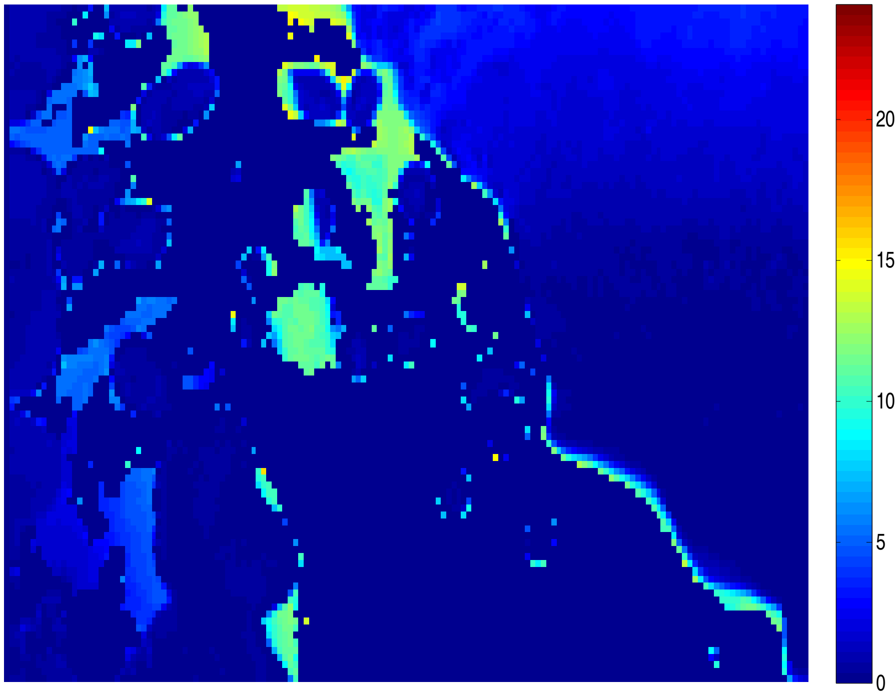


Bathymetry

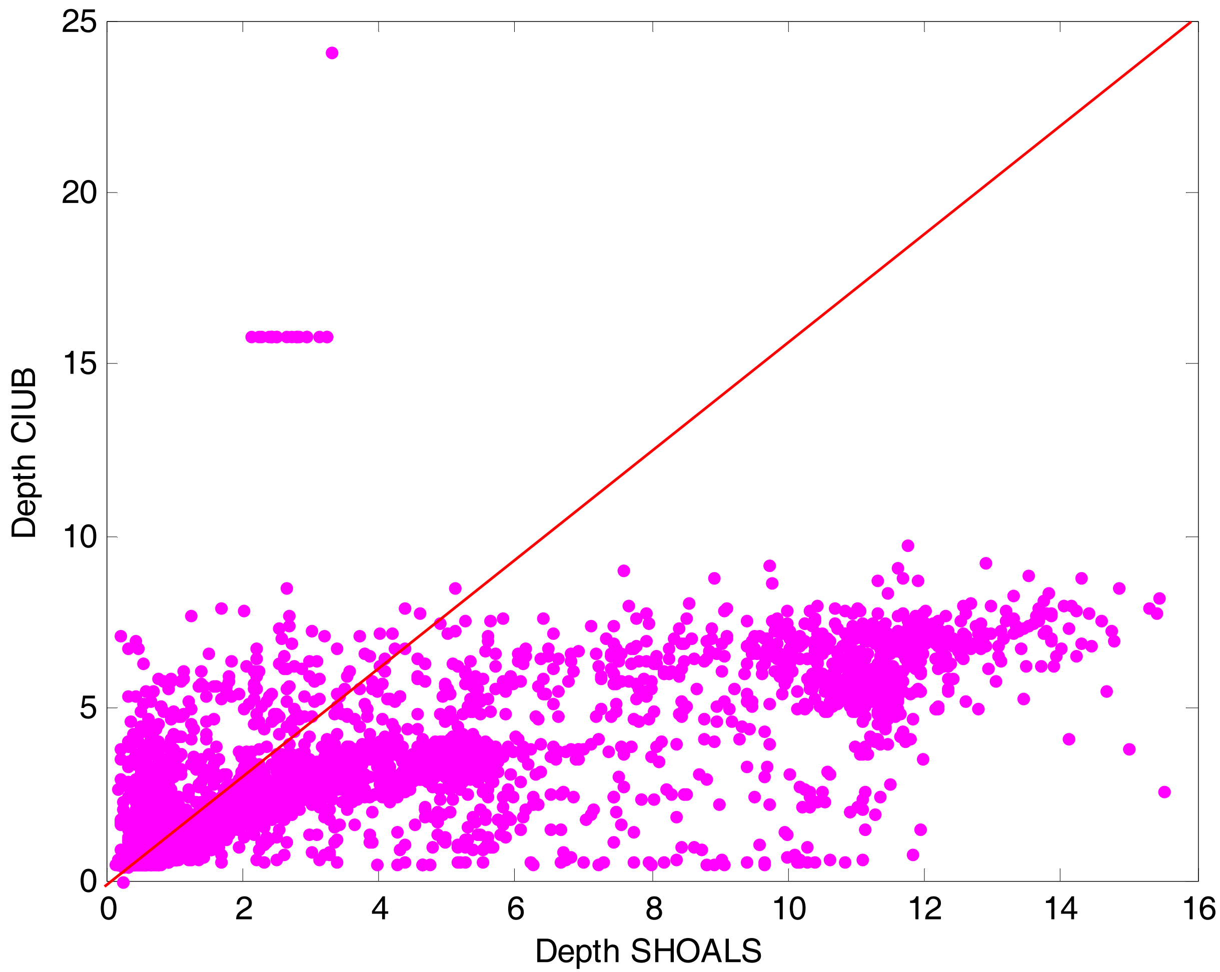
CIUB: Depth



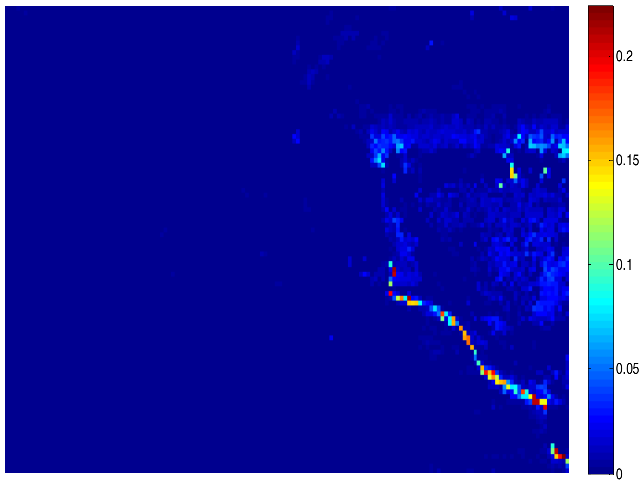
SHOALS Depth



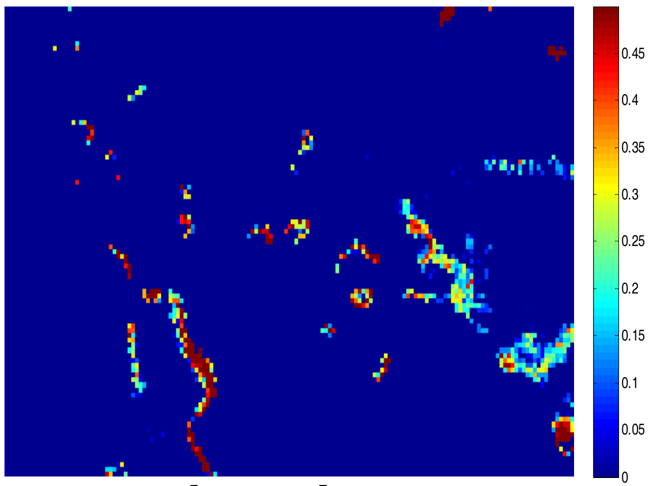
Bathymetry Comparison



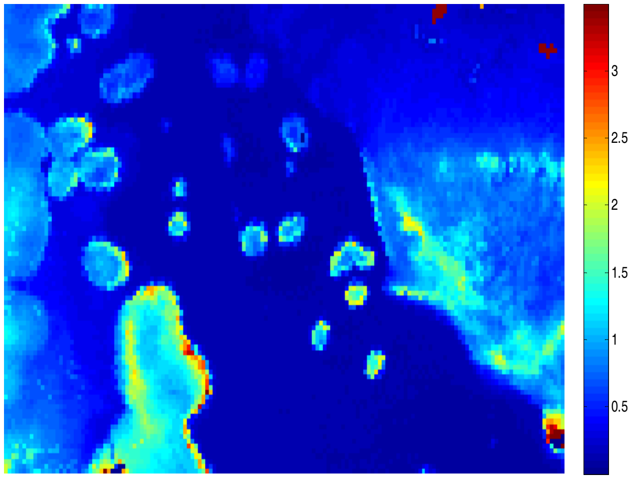
Water Parameters



Backscattering

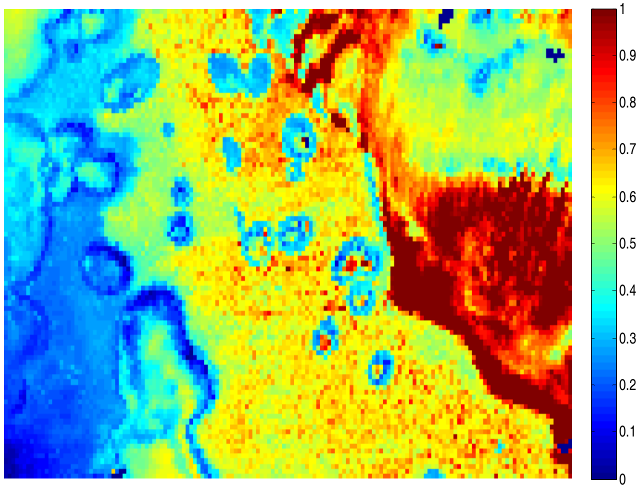


Phytoplancton

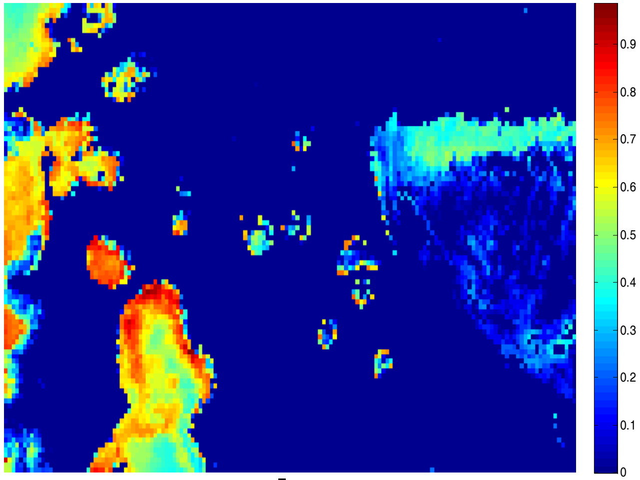


Absorption

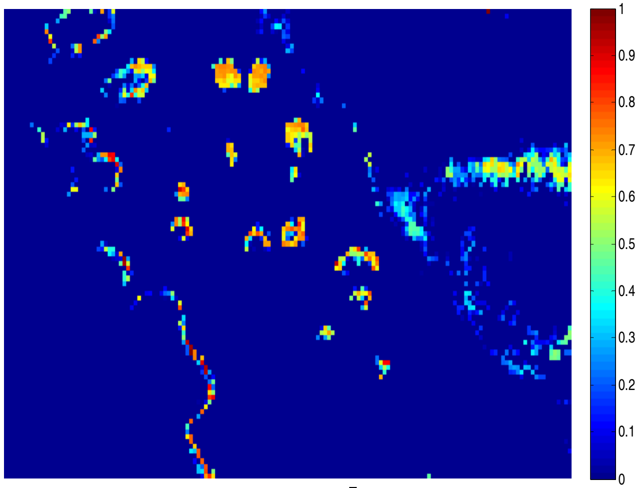
Abundance Maps



Sand

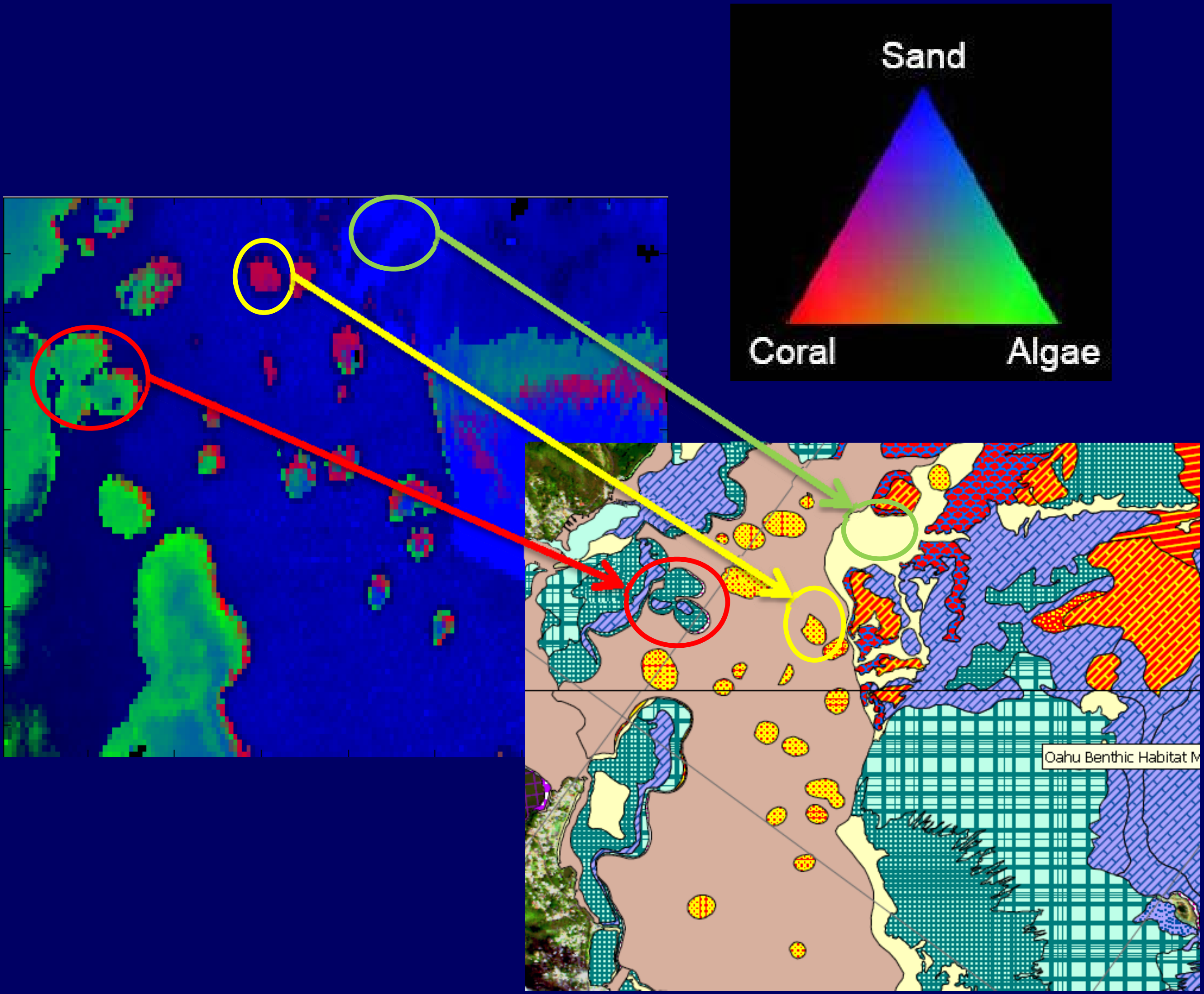


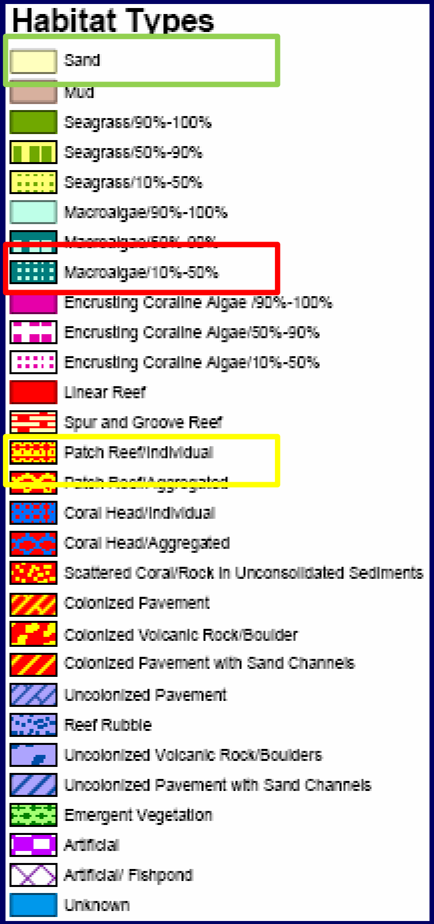
Algae



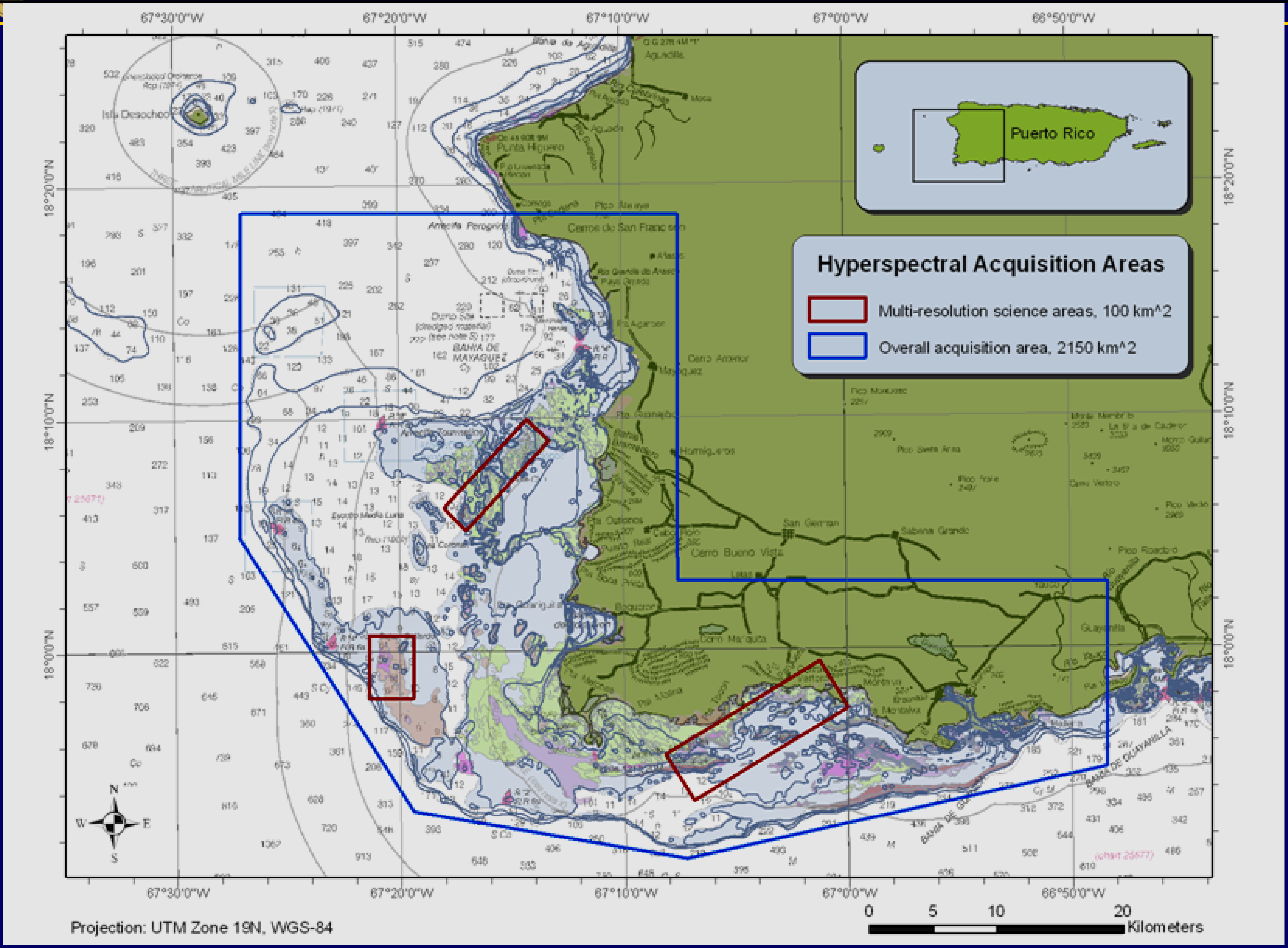
Coral

Fractional Map

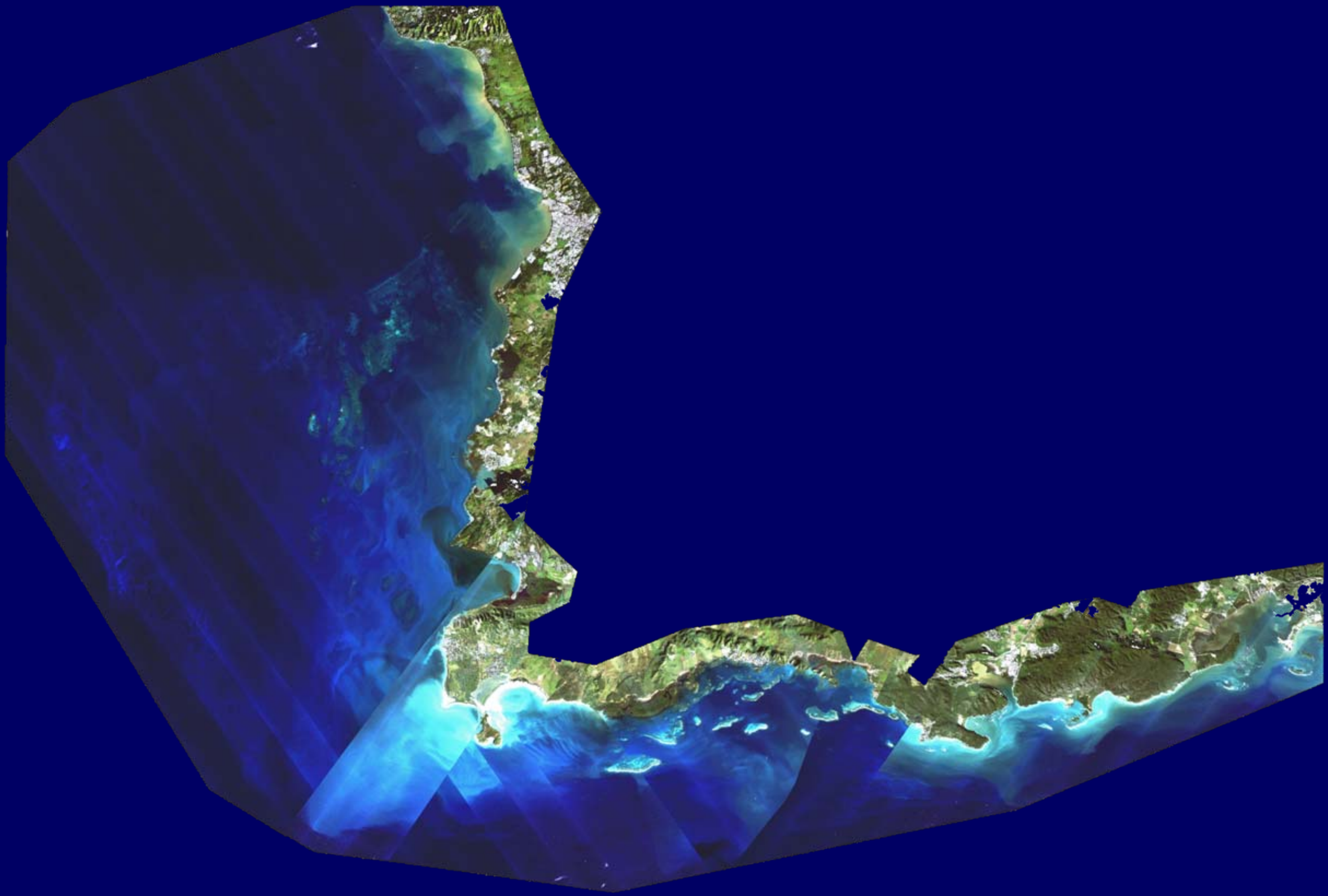




Mission Coverage: Galileo - AISA



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 throught few grants