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

- Broadband Probe, $P$
- Wavelength sensitive detection

Clutter, Medium, Object

Spectrometer-Imager Configuration

- Probes at different wavelengths, $P_i$
- $\lambda_1, \lambda_2, \ldots, \lambda_n$
- Broadband Detector

Mathematical model:

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

LOW  Panchromatic: one very wide band

MED  Multispectral: several to tens of bands

HIGH Hyperspectral: hundreds of narrow bands
Imaging Spectrometry

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
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)

- Mangrove
- Carbonate Sand
- Reef Crest
- Sea Grass
- Sea Water

Relative Reflectance vs. Wavelength (nm)
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

From C.O. Davis, HSI of the Litoral Battle Space, NRL Code 7203
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, $R_{rs}$

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

Subsurface remote sensing reflectance, $r_{rs}$

$$r_{rs} = r_{rs}^{dp} \left(1 - \exp\left\{- (k + \kappa_C)H\right\}\right) + \frac{\rho}{\pi} \exp\left\{- (k + \kappa_B)H\right\}$$

Water Column Component

Bottom Component
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

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

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

\[
\overline{R}_i(x, y) = R_{rs}(\hat{\gamma}_{Lee}(x, y), \rho_i) \quad \text{for } i = 1, 2, 3
\]

- **Step 3**: Linear Unmixing at each location

\[
R_{rs}(x, y) = \sum_{i=1}^{3} f_i \overline{R}_i(x, y)
\]
Combined Inversion and Unmixing at the Bottom (CIUB) Approach

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

$$r_{rs} = r_{rs}^{dp} \left(1 - \exp \left\{ - \left[ \frac{1}{\cos(\theta_w)} + \frac{D_u^C}{\cos(\theta_o)} \right] \kappa H \right\} \right) + \exp \left\{ - \left[ \frac{1}{\cos(\theta_w)} + \frac{D_u^B}{\cos(\theta_o)} \right] \kappa H \right\} \frac{1}{\pi} B \rho$$

- Linear mixing model for the bottom albedo

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

$$S = \begin{bmatrix} \bar{\rho}_{sand} & \bar{\rho}_{algae} & \bar{\rho}_{reef} \end{bmatrix}$$

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

\[
(\hat{\gamma}, \hat{f}) = \arg \min_{\gamma, f} \frac{\|r_{rs} - \hat{r}_{rs}(\gamma, Sf)\|^2}{\|r_{rs}\|^2}
= \arg \min_{\gamma, f} \frac{\|b(\gamma) - A(\gamma)f\|^2}{\|r_{rs}\|^2}
\]

Partially Linear Nonlinear Least Squares Problem
Two-Stage Simple Iterative Inversion Approach

Step 1: Initialization using Lee’s approach

- Abundance estimation

\[
\hat{f} = \arg \min_{\gamma, f} \left\| b(\gamma) - A(\gamma)f \right\|_2^2
\]

- Optical properties, bathymetry and bottom albedo at 550 nm

\[
\hat{y} = \arg \min_{\gamma} \left\| r_{rs} - \frac{b(\gamma)(\gamma)\hat{f}}{2} \right\|_2^2
\]

Step 2: Update optical properties, bathymetry and bottom albedo at 550 nm
HyClAT: A Hyperspectral Coastal Image Analysis Tool
Visualization

File Name

Scrolling Through Bands

Working File: hawaii.mat

Band 17: Wavelength 558.45
RGB Composite (30-20-9)
Results Optimization: Water Optical Properties, Bathymetry and Albedo at 550nm

- Backscattering
- Absorption
- Phytoplankton

Select Parameter
Abundance Estimates

Result Window: Sand Abundance

Select Endmember

RGB Composite

Coral Abundance

Algae Abundance
Fractional Plots: RGB Composite of Three Abundance Maps
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

Endmember Spectras: Sand, Coral, and Algae

- Sand
- Coral
- Algae

Reflectance vs. Wavelength (nm)
Bathymetry Comparison
Water Parameters

Backscattering

Phytoplankton

Absorption
Abundance Maps

Sand

Algae

Coral
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.