CenSSIS Year 7 Project Report

Project ID: S4					
Title: Multiscale Sensing for Benthic Habitat Monitoring: Remote Sensing					
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I. Brief Overview of the Project and Its Significance

Coral reefs and other benthic habitats are being increasingly threatened by the impacts of anthropogenic stressors and the effects of global change. These ecosystems play a crucial role in overall marine health and biodiversity, as well as providing significant economic, aesthetic and other ecological benefits. The management and preservation of these valuable natural resources requires a set of reliable quantitative tools for mapping and monitoring the dynamics of habitat distribution and condition.

Because of the range in water depths associated with the benthic habitats under consideration, CenSSIS efforts follow a two-pronged approach:
- Airborne and satellite ***remote sensing*** is used for monitoring habitats in depths up to a limit of 20 m;
- ***Underwater unmanned vehicles*** are used for monitoring habitats in depths exceeding 20 m.

By improving and extending the overall capabilities for benthic habitat monitoring, the resulting spatial analysis tools will contribute and essential component in resource management decisions and risk management evaluations. This report focuses on the remote sensing component of this effort. See report SeaBED-B for a description of AUV effort.

II. State of the Art, Major Contributions and Technical Approach

State of the Art

Remote sensing is increasingly being used to map and monitor the complex dynamics associated with coral reefs and other shallow coastal ecosystems. Advantages of remote sensing technology include both the qualitative benefits derived from a visual overview, and more importantly, the quantitative abilities for systematic assessment and monitoring. Advancements in instrument capabilities and analysis methods, particularly with respect to hyperspectral remote sensing, are continuing to expand the accuracy and level of effectiveness of the resulting data products.

- Most current large-scale mapping applications rely on the visual interpretation of aerial photographs and multispectral imagery (e.g., NOAA mapping of shallow habitats in U.S. marine environments [e.g, Coyne et al. 2003; Kendall et al. 2001]) or on more complex image analysis techniques using multispectral satellite data (e.g., the NASA-sponsored global Millennium Coral Reef Mapping Project [http://imars.usf.edu/corals/index.html]). Results of these efforts represent significant improvements over previously available large-scale map resources. However, because of the immense scope of each project, the maps still have limitations with respect to small-scale resource assessment. For instance, individual reefs are typically described according to general categories and spatially explicit quantitative habitat information is limited.
- Hyperspectral sensors are emerging as a more complete solution, particularly for the analysis of subsurface shallow aquatic systems. In contrast with multispectral sensors, hyperspectral instruments provide much greater spectral detail, and thus an improved ability to extract greater amounts of information from an optically complex environment. As examples, hyperspectral applications have achieved specific objectives, such as deriving information on water properties and constituents (Brando and Dekker 2003; Carder et al. 1993; Hamilton et al. 1993; Richardson 1996; Thiemann and Kaufmann 2002), extracting information on benthic habitat composition (Hochberg and Atkinson 2000, 2003; Lubin et al. 2001; Mumby et al. 2004) and estimating bathymetry (Bagheri et al. 1998; Sandidge and Holyer 1998). Additionally, more complex modeling schemes, which typically follow a physically based approach, have been used to simultaneously derive multiple layers of information from a single image (Adler-Golden et al. 2005; Dierssen et al. 2003; Durand et al. 2000; Goodman 2004; Hedley and Mumby 2003; Louchard et al. 2003; Mobley et al. 2005). Essentially, the spectral detail offered by hyperspectral instruments facilitates significant improvements in the capacity to differentiate and classify benthic habitats.

Major Contributions and Technical Approach

CenSSIS research is involved with exploring the limits of hyperspectral remote sensing technology, primarily using data from the SeaBED-A field site, Enrique Reef (Fig. 1) Efforts are focused on developing, improving and testing a diverse range of image analysis techniques, from preprocessing and enhancement to atmospheric and water column correction routines.

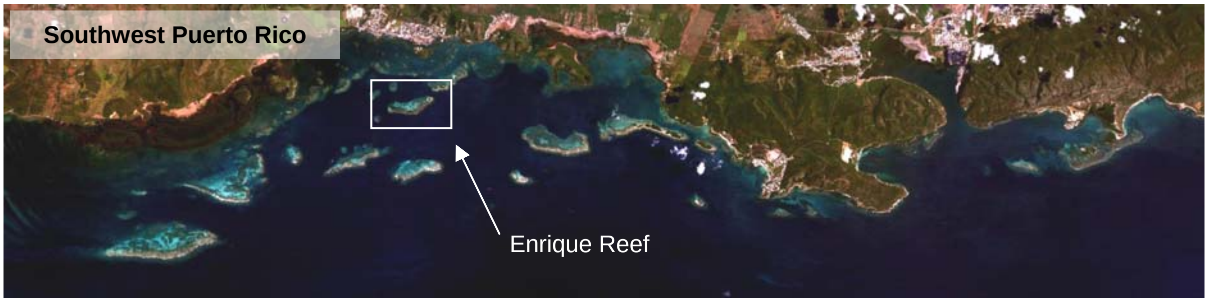

Figure 1. AVIRIS imagery of Enrique Reef.

Sensors used for this research include: hand-held spectrometers; laboratory and field-portable imaging spectrometers; NASA's HYPERION instrument, a satellite-based hyperspectral sensor; and NASA's AVIRIS instrument, which is an airborne instrument. As described in the SeaBED-A report, HYPERION data (30 m spatial resolution) is available from 2002, 2003, 2004, 2005 and 2006 and AVIRIS data is available from 2004 (17 m spatial resolution from the ER-2 platform) and 2005 (4 m spatial resolution from the Twin Otter platform). Additionally, to complement the medium resolution HYPERION and AVIRIS imagery, we are exploring the potential of acquiring high spatial resolution (~1 m) hyperspectral imagery of Enrique Reef. If feasible, the high resolution imagery will be acquired in 2007, with partial funding from a recent NOAA-CCRI grant (see below), and be accompanied by an extensive coincident field campaign to collect various levels of ground truth information. Data from each of the different sensors are being evaluated independently, and in order to take advantage of the varying levels of spatial details, also in combination.

A diverse range of image processing algorithms are being developed, tested and applied to the data collected for SeaBED on Enrique Reef. Algorithms include, but are not limited to, atmospheric correction, sunglint removal, water column correction, denoising and benthic classification. Each algorithm represents a different aspect or approach to analyzing the varying layers and complexities of subsurface sensing of shallow aquatic ecosystems. The following descriptions provide some specific examples of these research directions:

- A sequence of image processing steps are being used to resolve the complex interaction of atmospheric conditions, bathymetry, sea surface state, water optical properties and bottom composition. The overall procedure was initially developed utilizing AVIRIS imagery in the Hawaiian Islands (Goodman 2004) and is now being tested and improved using AVIRIS and HYPERION data from Enrique Reef. The analysis starts with preprocessing, which includes atmospheric correction (Gao et al. 2000; Montes et al. 2001; 2003) and sunglint removal, and then utilizes a semi-analytical optimization model to retrieve bathymetry and water properties throughout the study area (Lee et al. 1998; 1999). Using field spectra data representing the dominant benthic components (e.g., spectral endmembers for sand, coral and algae), a constrained non-linear unmixing model is then utilized to classify the benthic substrate as a function of the fractional contribution from each endmember (Goodman 2004; 2005). Preliminary analysis of the 2004 AVIRIS data from Puerto Rico (Fig. 2) indicates both the transferability of the approach to a different geographic area and demonstrates its utility for large-scale benthic habitat mapping.

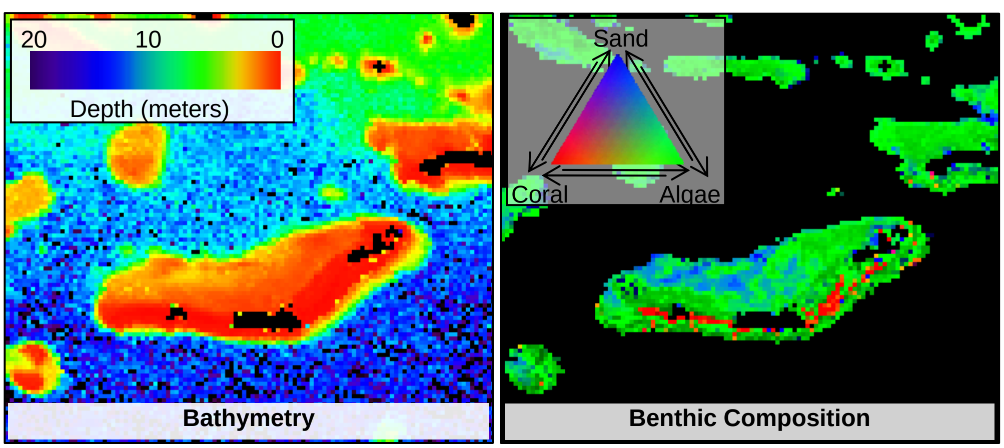

Figure 2. Example output from 2004 AVIRIS imagery: bathymetry and benthic classification for Enrique Reef.

- A new inversion approach has been developed to merge the above mentioned semi-analytical optimization model (Lee et al. 1998; 1999) with the constrained non-linear unmixing approach (Goodman 2004; 2005). By modeling the bottom albedo as a linear mixture of selected spectral endmembers (sand, coral, algae and seagrass), the new model simultaneously retrieves bathymetry, water optical properties and abundance estimates for the spectral endmembers without any *a priori* knowledge of scene composition. An MS thesis based on this approach has recently been published (Castrodad-Carrau 2005).

- The spatial resolution of most hyperspectral instruments is typically larger than the size of the objects being observed. Therefore, by leveraging the detailed spectral information available from these sensors, image analysis can be used to detect and classify subpixel objects as a function of their contribution to the total measured per-pixel spectral signal. The basis of this unmixing problem (Keshava 2003) is to decompose the measured reflectance (or radiance) into its basic elements, or endmembers, as well as a set of corresponding fractions or abundances. A common two-stage approach used for solving this problem is to first identify the spectral endmembers and then estimate abundances by solving a constrained linear least squares problem. However, the endmember identification stage typically requires significant interaction by the user. CenSSIS research in this field is focused on developing methods where the endmembers and their abundances are determined simultaneously. Current efforts are directed towards solving the constrained positive matrix factorization (PMF) problem (Lee and Seung 2001) using a penalty type method to enforce constraints. Results using HYPERION data of Enrique Reef show close agreement between the endmembers derived using the PMF approach and endmembers identified using the pixel purity index analysis function in ENVI.
- One of the significant challenges in remote sensing of benthic habitats is that the signal exiting the water is only a small component of the overall signal received at the satellite or airborne sensor. Therefore, extracting accurate physical and ecological information from benthic habitat areas requires imagery with a high signal-to-noise ratio (SNR). Although high SNR can be obtained through better sensors, another approach is to take advantage of the sampling characteristics of hyperspectral instruments and achieve improvements through signal processing. We have developed an image pre-processing scheme motivated by oversampling theory to improve the SNR in hyperspectral imagery. Oversampling implies that there is redundant information in the spectral domain that can be exploited to reduce the noise and subsequently increase classification accuracy (Hunt and Sierra 2003; Hunt and Laracuente 2004). The technique consists of using low pass filtering in the spectral dimension, with a cutoff frequency selected to remove noise in the spectral signature. The cutoff frequency is adaptively selected based on the image and any available training data. Results from applying this algorithm to both AVIRIS and HYPERION imagery reveal features in the enhanced images not evident in the original imagery. Example output from a 2002 HYPERION image is shown in Fig. 3.

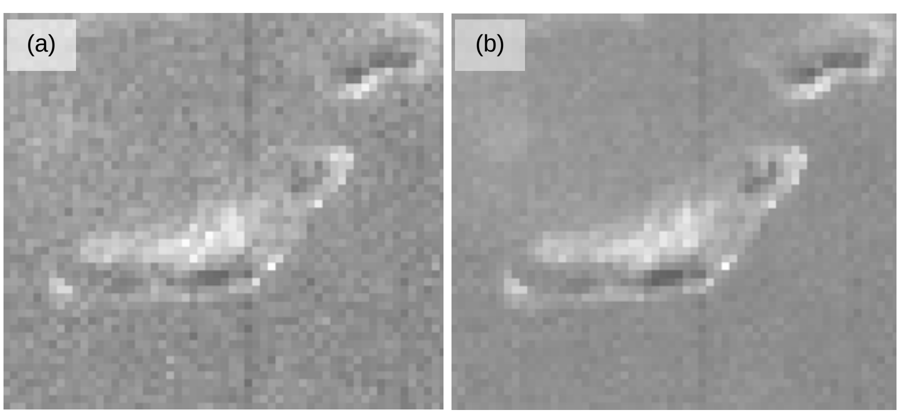

Figure 3. HYPERION data of Enrique Reef (band 8 – 427 nm) before (a) and after (b) filtering algorithm.

- As new methods and algorithms are developed within CenSSIS for subsurface image analysis, most are being made publicly available in the Hyperspectral Image Analysis Toolbox (HIAT). This is a

MATLAB based toolbox that currently includes capabilities for pre-processing, spectral unmixing, classification, and change detection. The HIAT can be downloaded from the CenSSIS website (www.censsis.neu.edu) under 'Software' and is updated as new algorithms are added.

- CenSSIS researchers are also involved with high-performance computing and the implementation of image analysis algorithms within a parallel processing framework. Current efforts include translating the Lee et al. (Lee et al. 1998; 1999) semi-analytical inversion model into a C++/MPI parallel analysis scheme (Gerardino et al. 2006). The purpose is to investigate alternative optimization schemes, perform a sensitivity analysis of the inversion model's physical parameters, identify the most significant parameters to adjust for improving model performance, and ultimately develop a more computationally efficient framework for implementing the inversion model. Further, the greater processing speed obtained with the C++/MPI implementation will provide the foundation for assessing real-time processing capabilities as well as the computation power necessary for addressing complex optimization and sensitivity questions.

III. CenSSIS Strategic Goals and Legacy

The S4 Driver applies research in subsurface sensing and imaging carried out at CenSSIS to tackle the important problem of aquatic subsurface sensing. The idea is to develop and validate algorithms for satellite and airborne remote sensing analysis, augmented by localized in-situ point measurements, to monitor the benthic habitats of shallow and deep coastal waters. A specific focus of this research is on monitoring and mapping coral reef resources to improve coral health management tools. This work is a collaboration between CenSSIS partners UPRM and WHOI. It incorporates data from SeaBED (field level measurements and remote sensing imagery) and research from R2 (multi and hyperspectral image analysis algorithms) and R3 (implementation of algorithms in high performance computing framework).

IV. Future Plans

- CenSSIS will utilize the image processing capabilities developed through R2 research and SeaBED data resources to produce an assessment of the shallow coastal resources along selected coastal areas of Puerto Rico. These research products will exceed the existing map resources of this area and provide managers with a spatially explicit indication of the distribution of existing coastal resources. This work is facilitated by a grant through the recently established Caribbean Coral Reef Institute (CCRI) located at UPRM's Magueyes Marine Laboratory in southwestern Puerto Rico.
- S4 research efforts will also be enhanced through collaboration and interaction with reef scientists and resource specialists at the Rosenstiel School of Marine and Atmospheric Research (RSMAS) at the University of Miami. This is being achieved through CenSSIS researcher J. Goodman, who has been working as a Visiting Scientist at RSMAS in 2006 and will continue in 2007. This will serve to improve the application potential and ultimate utility of benthic image analysis products by providing a stronger link with some of the intended users of these products.
- We will apply our recently developed image analysis algorithms across a greater range of imagery, specifically focusing on the hyperspectral imagery of Enrique Reef available through SeaBED-A. For instance, the image processing sequence developed by Goodman (2004; 2005), as described above, will be applied to the full collection of HYPERION images extending from 2002 to 2006. Of particular interest is that this collection of imagery spans the timeframe before and after the massive Caribbean-wide coral bleaching event occurring in fall of 2005, thus providing a unique opportunity for examining the spatial impacts of this highly significant environmental event.

V. Broader Impact

It is becoming increasingly apparent that without adequate protection and preservation, coral reef ecosystems and other associated benthic habitats face an uncertain fate. The global implications of coral decline include elevated environmental significance due to the crucial role reefs play in overall marine ecosystem health and biodiversity. Fortunately, the ecosystems themselves are incredibly resilient and have the ability to recover and thrive if adequate management and conservation measures are implemented. However, the complexity of both the natural system and the many factors involved do not lend themselves to simple solutions, particularly when human factors are included in the equation.

An essential element of any program to preserve, protect and manage coral reefs is a reliable means for quantitatively mapping and assessing the dynamics of community distribution. Also important are capabilities for identifying stressor-response relationships, incorporating multiple levels of spatial analysis and efficiently monitoring the current and future health of the ecosystem. By continuing to advance the field of hyperspectral image acquisition and analysis, CenSSIS research is facilitating a progression in the level of questions that can be addressed using remote sensing and an increase in the effectiveness of the resultant management tools. Furthermore, by linking remote sensing capabilities with traditional methods of analysis, field data, and local knowledge of site conditions, CenSSIS is creating a more robust management and analysis tool, one that encompasses site-specific information within a spatial and temporal monitoring context.

VI. Sustainability

External Funding

The following are ongoing projects in 2006 or recently awarded proposals for research using SeaBED data that are directly related to CenSSIS work in benthic habitat monitoring. In each case the projects represent a synergistic combination of existing CenSSIS resources and practical applications of image analysis techniques and habitat classification algorithms.

- *Utilizing High-Performance Computing to Investigate Performance and Sensitivity of an Inversion Model for Hyperspectral Remote Sensing of Shallow Coastal Ecosystems*

  Principal Investigator: James Goodman, UPRM
  Co-Investigator: Wilson Rivera, UPRM
  Funding Source: NASA: Puerto Rico Space Grant Consortium
  Status: Awarded
  Duration: 03/05 – 05/07 (1 year + no-cost extension)
  Award Amount: $29,940

- *Taking Coastal Mapping to a New Level: Assessing Habitat Composition and Water Properties of Shallow Coastal Ecosystems along the Coast of Puerto Rico Using Hyperspectral Remote Sensing*

  Principal Investigator: James Goodman, UPRM
  Funding Source: NOAA: Caribbean Coral Reef Institute
  Status: Awarded
  Duration: 09/06 – 08/08 (2 years)
  Award Amount: $133,296

- *Coral Reef Bleaching and Threats to Biodiversity in Puerto Rico*

  Principal Investigator: Liane Guild, NASA ARC
  Co-Investigator: Roy Armstrong, UPRM
  Co-Investigator: James Goodman, UPRM
  Co-Investigator: Brad Lobitz, NASA ARC
  Funding Source: NASA: Interdisciplinary Research in Earth Science
  Status: Awarded
  Duration: 05/07 – 04/10
  Award Amount: $731,199 (3 years)

- *Characterization of shallow and deep coral reef communities of Vieques Island, Puerto Rico*
  - Principal Investigator: Roy Armstrong, UPRM
  - Co-Investigator: Fernando Gilbes, UPRM
  - Funding Agency: NOAA
  - Status: Awarded
  - Duration: 09/06 – 08/08
  - Award Amount: $49,770
- *Characterization of Deep Hermatypic Coral Reef Biodiversity in Puerto Rico and the U.S. Virgin Islands Using Autonomous Underwater Vehicles and Advanced Diving Technology*
  - Principal Investigator: Roy Armstrong, UPRM
  - Funding Source: NOAA - Coral Reef Ecosystem Studies
  - Status: Awarded
  - Duration: 05/06 – 4/09
  - Award Amount: $1,500,000

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VIII. Documentation

A. Publications Acknowledging NSF Support (Jan. 1, 2006 to Dec. 31, 2006)

1. Armstrong, R.A. (2006) Coral Reef Bio-Optics, Southwestern Puerto Rico, *Fourth Science Meeting NOAA ICON/CREWS*, April 24-26, La Parguera, Puerto Rico.

2. Castrodad-Carrau, A., M. Vélez-Reyes and J.A. Goodman (2006) An algorithm to retrieve coastal water optical properties, bathymetry, and bottom albedo from hyperspectral imagery, In *Proceedings of SPIE: Photonics for Port and Harbor Security II*, Vol. 6204, April 17-21, Orlando, Florida.

3. Gerardino, C., Y. Rivera, J. Goodman and W. Rivera (2006) Parallel Implementation of an Inversion Model for Hyperspectral Remote Sensing, *49th IEEE International Midwest Symposium on Circuits and Systems*, August 6-9, San Juan, Puerto Rico.

4. Guild, L., R. Armstrong, F. Gilbes, J. Goodman, A. Gleason, E. Hochberg, R. Berthold, J. Torres and M. Johnston (2006) Airborne Hyperspectral Remote Sensing of Coral Reefs of Puerto Rico, Florida Keys and Oahu, *AGU Ocean Sciences Meeting*, February 20-24, Honolulu, Hawaii.

5. Vélez-Reyes, M., J.A. Goodman, A. Castrodad-Carrau, L.O. Jiménez-Rodriguez, S.D. Hunt and Roy Armstrong (2006) Benthic habitat mapping using hyperspectral remote sensing, *Proceedings of SPIE: Remote Sensing of the Ocean, Sea Ice, and Large Water Regions*, Vol. 6360, September 11-14, Stockholm, Sweden.