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.

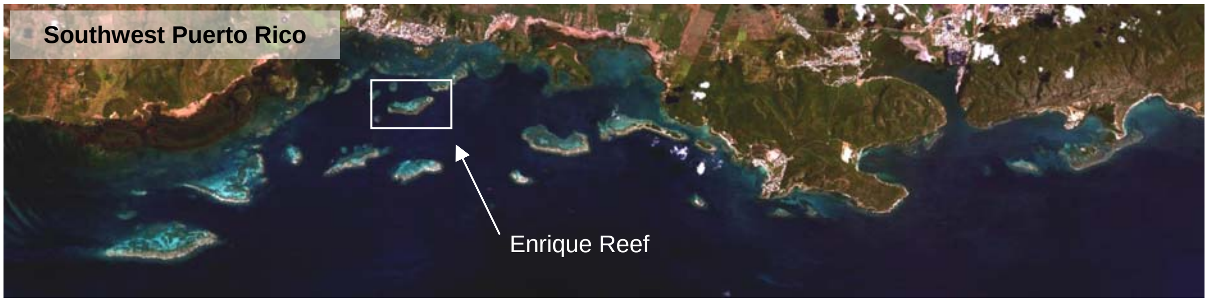

Figure 1. AVIRIS imagery of Enrique Reef.

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.

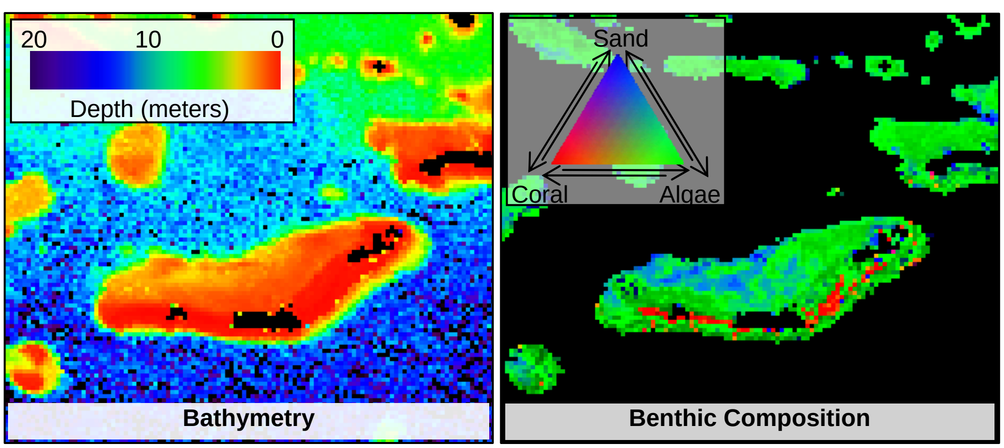

Figure 2. Example output from 2004 AVIRIS imagery: bathymetry and benthic classification for Enrique Reef.

- 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.

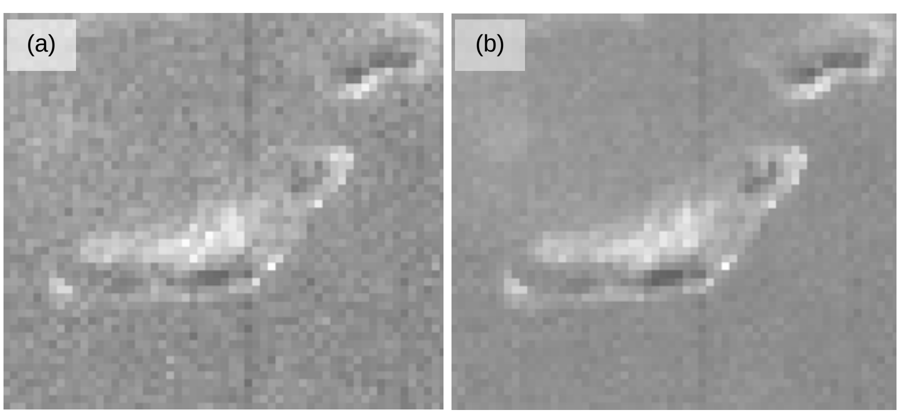

Figure 3. HYPERION data of Enrique Reef (band 8 – 427 nm) before (a) and after (b) filtering algorithm.

- 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

VII. References Cited

Adler-Golden, S.M., P.K. Acharya, A. Berk, M.W. Matthew and D. Gorodetsky (2005) Remote bathymetry of the littoral zone from AVIRIS, LASH, and QuickBird imagery. *IEEE Transactions on Geoscience and Remote Sensing*, 43(2):337-347.

Bagheri, S., M. Stein R. and Dios (1998) Utility of hyperspectral data for bathymetric mapping in a turbid estuary. *International Journal of Remote Sensing*, 19:1179-1188.

Brando, V. E. and A.G. Dekker (2003) Satellite hyperspectral remote sensing for estimating estuarine and coastal water quality. *IEEE Transactions on Geoscience and Remote Sensing*, 41:1378-1387.

Carder, K.L., P. Reinersman, R.F. Chen, F.E. Muller-Karger, C.O. Davis and M. Hamilton (1993) AVIRIS calibration and application in coastal oceanic environments. *Remote Sensing of Environment*, 44:205-216.

Castrodad-Carrau, A. (2005) *Retrieval of Bottom Properties on Shallow Waters from Hyperspectral Imagery*. Master of Science Thesis, University of Puerto Rico at Mayagüez.

Coyne, M.S., T.A. Battista, M. Anderson, J. Waddell, W. Smith, P. Jokiel, M.S. Kendall and M.E. Monaco (2003) *Benthic Habitats of the Main Hawaiian Islands*. (CD-ROM), National Oceanic and Atmospheric Administration, Silver Spring, Maryland.

Dierssen, H.M., R.C. Zimmerman R.A. Leathers, T.V. Downes and C.O. Davis (2003) Ocean color remote sensing of seagrass and bathymetry in the Bahamas Banks by high-resolution airborne imagery. *Limnology and Oceanography*, 48(1, part 2):444-455.

Durand, D., J. Bijaoui and F. Cauneau (2000) Optical remote sensing of shallow-water environmental parameters: a feasibility study. *Remote Sensing of Environment*, 73:152-161.

Gao, B.-C., M.J. Montes, Z. Ahmad and C.O. Davis (2000) Atmospheric correction algorithm for hyperspectral remote sensing of ocean color from space. *Applied Optics*, 39:887-896.

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*, San Juan, Puerto Rico.

Goodman, J.A. (2004) *Hyperspectral remote sensing of coral reefs: deriving bathymetry, aquatic optical properties and a benthic spectral unmixing classification using AVIRIS data in the Hawaiian Islands*. PhD Dissertation, University of California, Davis.

Goodman, J. (2005) Hyperspectral remote sensing of shallow coral ecosystems using AVIRIS and HYPERION. *8th International Conference on Remote Sensing for Marine and Coastal Environments*, Halifax, Nova Scotia.

Hamilton, M.K., C.O. Davis, W.J. Rhea, S.H. Pilorz and K.L. Carder (1993) Estimating chlorophyll content and bathymetry of Lake Tahoe using AVIRIS data. *Remote Sensing of Environment*, 44:217-230.

Hedley, J.D. and P.J. Mumby (2003) A remote sensing method for resolving depth and subpixel composition of aquatic benthos. *Limnology and Oceanography*, 48(1, part 2):480-488.

Hochberg, E.J. and M.J. Atkinson (2000) Spectral discrimination of coral reef benthic communities. *Coral Reefs*, 19:164-171.

Hochberg, E.J. and M.J. Atkinson (2003) Capabilities of remote sensors to classify coral, algae, and sand as pure and mixed spectra. *Remote Sensing of Environment*, 85:174-189.

Hunt, S. and H. Sierra (2003) Spectral oversampling in hyperspectral imagery. *Algorithms and Technologies for Multispectral, Hyperspectral, and Ultraspectral Imagery IX*, Proceedings of SPIE Vol. 5093.

Hunt, S. and J. Laracuente (2004) Determining noise in hyperspectral imagery for the application of oversampling to supervised classification. *Algorithms and Technologies for Multispectral, Hyperspectral, and Ultraspectral Imagery X*, Proceedings of SPIE Vol. 5425.

Kendall, M.S., M.E. Monaco, K.R. Buja, J.D. Christensen, C.R. Kruer, M. Finkbeiner and R.A. Warner (2001) *Benthic Habitats of Puerto Rico and the U.S. Virgin Islands*. (CD-ROM), National Oceanic and Atmospheric Administration, Silver Spring, Maryland.

Keshava, N. (2003) A survey of spectral unmixing algorithms. *MIT Lincoln Laboratory Journal* 14(1).

Lee, Z.P., K. Carder, C.D. Mobley, R. Steward and J. Patch (1998) Hyperspectral remote sensing for shallow waters. 1. a semi-analytical model. *Applied Optics*, 37:6329-6338.

Lee, Z.P., K. Carder, C.D. Mobley, R. Steward and J. Patch (1999) Hyperspectral remote sensing for shallow waters: 2. deriving bottom depths and water properties by optimization. *Applied Optics*, 38:3831-3843.

Lee, D.D. and H.S. Seung (2001) Algorithms for non-negative matrix factorization. *Advances in Neural Information Processing*, 556-562.

Louchard, E.M., R.P. Reid, F.C. Stephens, C.O. Davis, R.A. Leathers and T.V. Downes (2003) Optical remote sensing of benthic habitats and bathymetry in coastal environments at Lee Stocking Island, Bahamas: a comparative spectral classification approach. *Limnology and Oceanography*, 48(1, part 2):511-521.

Lubin, D., W. Li, P. Dustan, C.H. Mazel and K. Stamnes (2001) Spectral signatures of coral reefs: features from space. *Remote Sensing of Environment*, 75:127-137.

Mobley, C.D., L.K. Sundman, C.O. Davis, J.H. Bowles, T.J. Downes, R.A. Leathers, M.J. Montes, W.P. Bissett, D.D.R. Kohler R.P. Reid, E.M. Louchard and A. Gleason (2005) Interpretation of hyperspectral remote-sensing imagery by spectrum matching and look-up tables. *Applied Optics*, 44(17):3576-3592.

Montes, M.J., B.-C. Gao and C.O. Davis (2003) Tafkaa atmospheric correction of hyperspectral data. In (S.S. Shen and P.E. Lewis, eds.) *Imaging Spectrometry IX*, Proceedings of the SPIE 5159.

Montes, M.J., B.-C. Gao and C.O. Davis (2001) A new algorithm for atmospheric correction of hyperspectral remote sensing data. In (W. Roper, ed.) *Geo-Spatial Image and Data Exploitation II*.

Mumby, P.J., W. Skirving, A.E. Strong, J.T. Hardy, E. Ledrew, E.J. Hochberg, R.P. Stumpf and L.D. David (2004) Remote sensing of coral reefs and their physical environment. *Marine Pollution Bulletin*, 48:219- 228.

Richardson, L.L. (1996) Remote sensing of algal bloom dynamics. *BioScience*, 46:492-501.

Sandidge, J.C. and R.J. Holyer (1998) Coastal bathymetry from hyperspectral observations of water radiance. *Remote Sensing of Environment*, 65:341-352.

Thiemann, S. and H. Kaufmann (2002) Lake water quality monitoring using hyperspectral airborne data – a semiempirical multisensor and multitemporal approach for the Mecklenburg Lake District, Germany. *Remote Sensing of Environment*, 81:228-237.

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.

Year Eight Project Report

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I. Brief Overview of the Project and Its Significance

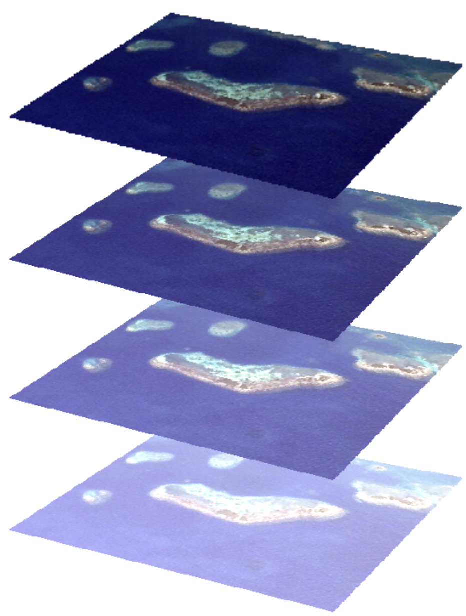
The main objective of the SeaBED-A effort is to develop an open testing infrastructure and set of publicly available data for researchers to validate subsurface aquatic remote sensing algorithms. The testBED is currently composed of two distinct analysis systems: a laboratory-based tank configuration and a field site located on nearby Enrique Reef, in southwest Puerto Rico. The purpose behind developing SeaBED-A is to collect multiple levels of image, field, and laboratory data with which to validate physical models, inversion algorithms, feature extraction tools and classification methods for subsurface aquatic sensing. Data produced from the testBED environment currently includes airborne, satellite, and field-level hyperspectral and multispectral images, *in situ* spectral signatures and water bio-optical properties. The laboratory testBED provides a controlled environment for examining subsurface spectral behavior as a function of varying illumination conditions, viewing geometry, water optical properties and target composition. The field site, which includes a heterogeneous mixture of both coral reef and seagrass habitats, offers a system for evaluating analysis techniques under natural environmental conditions. Together, these test facilities provide the flexibility and control to acquire a valuable combination of sensing imagery and fully characterized ground truth information.

As highlighted below, a major milestone was accomplished for SeaBED-A in 2007. An extensive airborne hyperspectral mission was successfully conducted in southwestern Puerto Rico to collect high quality, high resolution hyperspectral imagery over the SeaBED-A field site: Enrique Reef. The image data from this mission will be available in early 2008.

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

A. State of the Art

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. Fortunately, advances in remote sensing instrument capabilities and analysis methods are expanding the accuracy and effectiveness of applications directed at classifying habitat composition in shallow aquatic environments. This includes improvements in both multispectral and hyperspectral passive remote sensing investigations, as well as active remote sensing technologies such as bathymetric lidar. Although extensive data sets exist, e.g., Kaneohe Bay, Hawaii and Heron Island, Australia, the lack of readily available, publicly accessible ground truth information makes it difficult to perform algorithm validation and testing. SeaBED was developed to address this shortcoming by providing a multi-level aquatic test environment for creating, refining and evaluating subsurface aquatic remote sensing algorithms (Fig. 1). The resulting analysis capabilities are facilitating enhanced spatial analysis tools for algorithm development, resource management decisions, conservation planning and risk management evaluations.



Hyperspectral Image Data

- Low Res. (30m): HYPERION
- Moderate Res. (4m, 16m): AVIRIS
- High Res. (1m): AISA

Surface Measurements

- Environmental (tide, wind, rain, etc.)
- Aquatic Surface Reflectance
- Terrestrial Surface Reflectance

Water Column Measurements

- Water Optical Properties
- Water Attenuation
- Bathymetry (depth)

Benthic Measurements

- Benthic Composition (habitat)
- Spectral Library
- Benthic Reflectance

Fig. 1. SeaBED multiple level data collection concept.

B. Major Contributions and Technical Approach

SeaBED addresses the deficiency in available validation data by providing the needed framework to assess physical models, inversion algorithms, feature extraction tools and classification methods for subsurface aquatic sensing. SeaBED is focused on coral reef and seagrass habitats, but is nevertheless applicable across a broad range of shallow aquatic ecosystems. The laboratory tank provides controlled environments for experimentation, while the field site offers the physical reality of a complex natural system for evaluating analysis techniques.

Southwest Puerto Rico Hyperspectral Mission

The major accomplishment in 2007 was the collection of extensive high-resolution hyperspectral imagery over the nearshore reefs and coastal ecosystems in southwest Puerto Rico. Imagery was collected by the Galileo Group Inc. using the AISA Eagle sensor system (http://galileo-gp.com/aisa_eagle.html) as contracted with funding from Gordon-CenSSIS and the Caribbean Coral Reef Institute (CCRI). The total area included in this mission was over 2000 km^2, with enhanced coverage of four science areas, three aquatic and one terrestrial. Although the project was originated to support ongoing research at Gordon-CenSSIS related to hyperspectral remote sensing, the overall mission was significantly expanded to involve additional collaborators with added sensors and instruments that together are addressing an increasing number of scientific questions and application driven objectives.

Mission Study Area

The study area included the following (Fig. 2):

- The overall acquisition area covers 2150 km^2 and includes both land and shallow aquatic habitats. This area was acquired at 4 m GSD;
- Three additional aquatic multi-resolution science areas, totaling 100 km^2, were also included. They include three separate coral reef areas representing different environmental characteristics. These smaller subsets were acquired at multiple spatial resolutions, including 1 m, 2 m, 4 m and 8 m GSD;
- The Guánica Dry Forest, totaling 35 km^2, was also acquired at 1 m and 4 m GSD to facilitate more detailed analysis of this important ecological area. This area is both a UNESCO Biosphere Reserve and monitoring site for the proposed National Ecological Observatory Network (NEON).

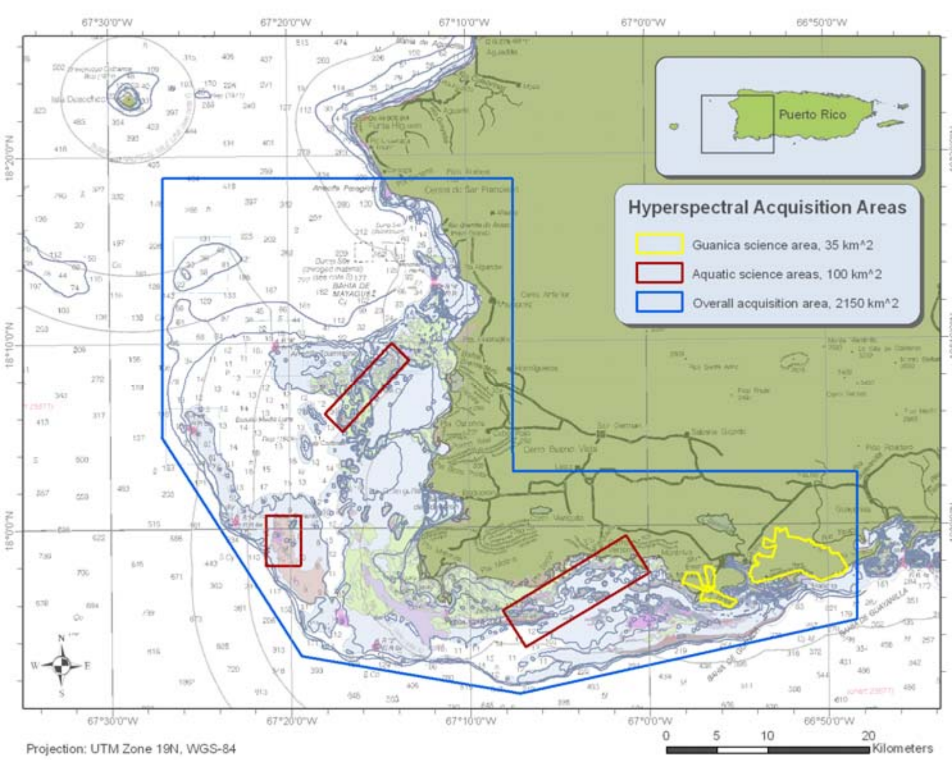


Fig. 2. Mission study area: blue polygon represents data at 4m GSD, red polygons represent science areas at 1m, 2m, 8m GSD and yellow polygons represent terrestrial science area at 1m GSD.

Hyperspectral Imagery

The Galileo Group Inc. (http://galileo-gp.com/) was selected as the commercial hyperspectral image provider. Galileo provides end-to-end image hyperspectral services, from planning and acquisition logistics to data collection and image processing. The company is experienced with both commercial and research oriented clients. Following a competitive bid process, Galileo was selected as the most appropriate company to meet our specific data requirements.

Mission specifications and deliverables provided by Galileo include the following:

- Sensor system used for acquiring hyperspectral data was an AISA Eagle manufactured by Spectral Imaging Limited (http://www.specim.fi/);
- Spectral range was from 400-1000 nm, with 128 bands at a resolution of 3-5 nm FWHM;
- The 4 m and 8 m GSD data was collected from an altitude of 2900 m with 40% spatial overlap between adjacent flightlines;
- The 2 m GSD data was collected from an altitude of 2600 m with 30% spatial overlap between adjacent flightlines;
- The 1 m GSD data was collected from an altitude of 1200 m with30% spatial overlap between adjacent flightlines;
- Flightline orientation and scheduling was independently optimized for terrestrial and aquatic areas, where aquatic flightlines were acquired in the morning and afternoon to minimize the effects of sunglint and terrestrial flightlines were acquired near mid-day to minimize shadowing effects;
- Imagery delivery from Galileo will occur in early 2008. This will include radiometrically corrected at-sensor upwelling radiance (geocorrected and non-geocorrected), atmospherically corrected surface reflectance (geocorrected and non-geocorrected), geographic lookup tables (GLTs) for performing geocorrection and a natural color mosaic of the hyperspectral imagery;
- Digital aerial photography was also acquired over the Guanica Dry Forest using a Nikon D200 camera system. This will be delivered as individual frames.

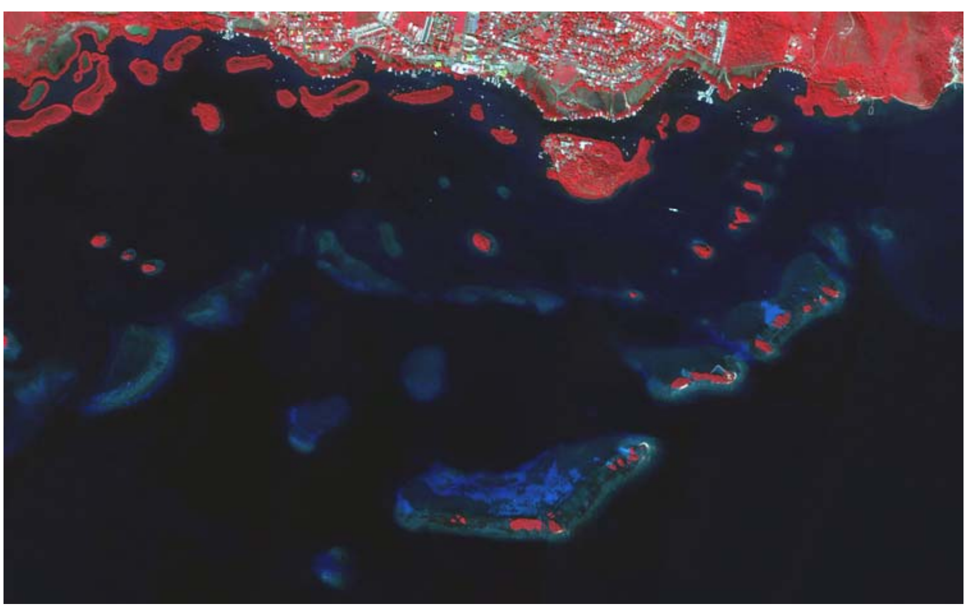


Fig. 3. Example 1 m false-color hyperspectral composite showing the reef systems near La Parguera, including Enrique Reef.

Associated SeaBED Hyperspectral Imagery

Remote sensing image acquisition for Enrique Reef has focused primarily on hyperspectral sensor systems, whose spectral detail provides a greater capacity for resolving the complexities of subsurface aquatic image analysis. Three different hyperspectral sensor systems have been utilized to acquire remote sensing data over Enrique Reef, including both satellite and airborne acquisitions. The aim is to compile a diverse set of imagery with differing spectral, spatial and temporal resolutions covering the same geographic location. As such, in addition to the imagery described below, future plans include incorporating both different sensor systems as well as repeat acquisitions using the same sensors.

A temporal summary of all the hyperspectral imagery currently available for Enrique reef is illustrated in Fig. 4. Of particular interest is that this collection of imagery spans the timeframe before and after the 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. Additionally, the spatial and temporal resolutions represented in this collection allow for comparative analysis of various image classification and change detection techniques.

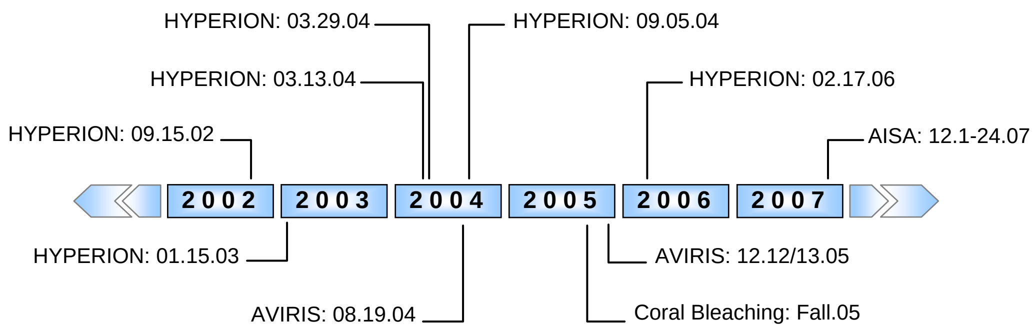


Fig. 4. . Timeline of hyperspectral image acquisition for Enrique Reef.

Coincident Field Data Collection Efforts

A variety of different field data collection efforts were performed before the mission and during the mission coincident with the airborne image acquisition Instrumentation being utilized for the field measurements included two GER-1500 spectrometers (terrestrial), a SVC HR-1024 spectrometer (terrestrial), three custom underwater GER-1500 spectrometers (aquatic), an underwater DiveSpec spectrometer (aquatic), a Satlantic HyperPro (aquatic), a bio-optical rosette with various instruments (CTD, AC-9, HS-6, OCR-200 and a fluorometer) for measuring water properties (aquatic), GPS units and cameras. The data collection efforts included:

- Reflectance characteristics of terrestrial (land) and aquatic (benthic) spectral calibration targets;
- Spectral library of dominant species and substrate types of reef and seagrass communities;
- Spectral profiles and bio-optical properties of the water column;
- Surface reflectance over representative shallow habitats and deep water locations;
- Video mosaics of 10m x 10m areas of the benthic substrate;
- GPS polygons, points and photos of reef, seagrass and mangrove features;
- Linear benthic transects, with GPS locations, measuring detailed reef community characteristics;

- Spectral library of dominant coastal and dry forest vegetation species;
- GPS polygons, points and photos of terrestrial vegetation features.

Mission Collaborators

A number of collaborators were identified and invited to participate in this project, including involvement in mission planning, field data acquisition, image processing and the utilization of image products. This has served to both expand the utility of the image acquisition efforts, as well as develop exciting new research relationships. Additionally, all involved will mutually benefit from the collective expertise and diversity of researchers involved in the mission. Collaborators include:

- University of Puerto Rico at Mayaguez (UPRM) CenSSIS/CCRI (team leaders)
- UPRM Geology Department
- UPRM Biology Department
- UPRM Agronomy and Soils Department
- NASA Ames Research Center
- USDA Forest Service Puerto Rico
- USGS Center for Coastal and Watershed Studies
- NOAA Atlantic Oceanographic and Meteorological Laboratory
- University Miami Rosenstiel School of Marine and Atmospheric Science
- Nova Southeastern University National Coral Reef Institute

Fig. 5. Field team members pictured above (left to right): (*standing*) Randy Berthold (NASA), Miguel Velez-Reyes (UPRM), Roy Armstrong (UPRM), Brad Lobitz (CSU MB); (*seated*) Ricardo Rosado (UPRM), Miguel Goenaga (UPRM), Meghan Dick (Miami), Wilma Pabon (UPRM), Brooke Gintert (Miami), Gwilym Rowlands (NSU); (*floor*) Orian Tzadik (UPRM), Samuel Rosario (UPRM), Carmen Zayas (UPRM), James Goodman (UPRM), Liane Guild (NASA).

Other Accomplishments

In addition to the hyperspectral mission, other work related to SeaBED also made significant progress:

- Work continued on refining the high-resolution basemap for Enrique Reef. This is a project initiated in 2006 to create a high spatial resolution classification map of Enrique Reef using IKONOS imagery (1 m panchromatic; 4 m multispectral). This was accomplished primarily through an intensive manual classification procedure, with the intent of producing a carefully constructed high-resolution basemap for validating image classification algorithms. This map will also serve as the spatial foundation for cataloging field data and observations acquired on Enrique Reef. Work completed in 2007 included an extensive field survey to confirm and refine polygons of reef features previously identified through image classification. Most recently, the map was used to determine the unmixing abundances for a lower spatial resolution Hyperion image. This allowed for first time an objective measure to be used in comparing the unmixing algorithms using real field data. Fig. 6 shows Hyperion image overlaid on the high resolution basemap.

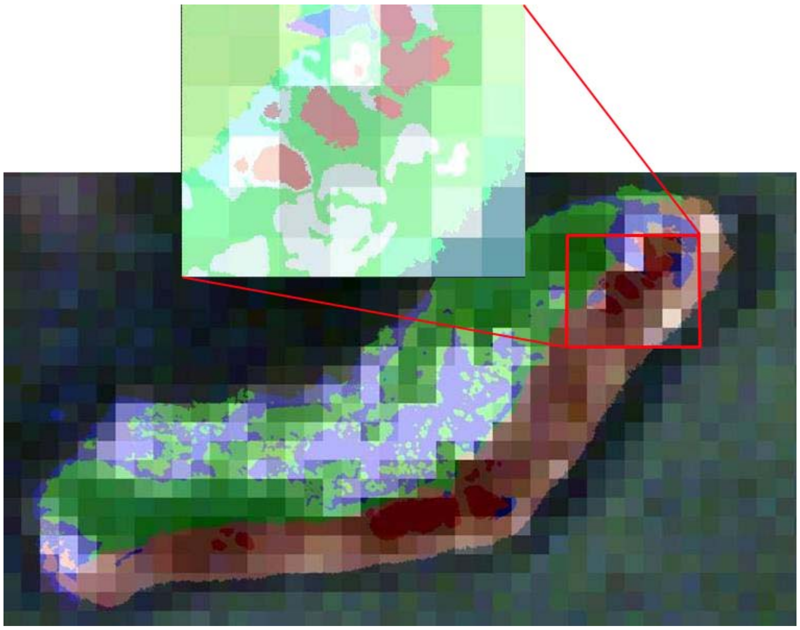


Fig. 6. Low resolution Hyperion pixels overlaid on high resolution basemap.

- Efforts continued on processing the hyperspectral AVIRIS imagery from 2004 and 2005. AVIRIS imagery was acquired over Enrique Reef in both 2004 (17 m spatial resolution from the ER-2 platform) and 2005 (4 m spatial resolution from the Twin Otter platform). The 2004 data were acquired with funding from NASA's Ocean Biology and Biogeochemistry Program through an award to Liane Guild at NASA Ames Research Center, and are currently being utilized in Gordon-CenSSIS research projects. The 2005 data were funded by NASA as part of a multi-agency response headed by the U.S. Coral Reef Task Force (USCRTF) to assess the impacts of the aforementioned massive 2005 coral bleaching event. Center researchers participated in the ground-data collection efforts for this campaign and full image access will become available following the USCRTF investigation. Note that the 2004 and 2005 imagery unfortunately contain an unwanted spectral anomaly that has greatly hindered the effective use of these data. A correction was recently devised by Dr. Liane Guild and her team from NASA Ames and the data are expected to be available in early 2008.

- Fieldwork continued for generating a spectral library of the dominant reef components. Underwater *in situ* reflectance measurements of the benthic substrate (e.g., sand, rubble, mud, etc.) and associated species (e.g., coral, algae, seagrass, sponges, etc.) were acquired using a GER-1500 handheld spectroradiometer contained within a custom underwater housing. The main instrument being utilized for this work is a GER-1500 spectrometer, which collects spectra at 512 bands from

283–1091 nm. The individual field spectra are first visually inspected for quality control, and then combined to generate average spectra for each target type. To facilitate this process, we developed the Spectral Data Analyzer (SDA) software to both visualize the spectral data and to create the average reflectance data (Fig. 7). SDA was developed in Java to increase cross-platform portability of the application and also allow rapid inclusion of future improvements. Future work for SDA includes adding capabilities for other spectral data formats, flexible data input formats, and adding database capabilities.

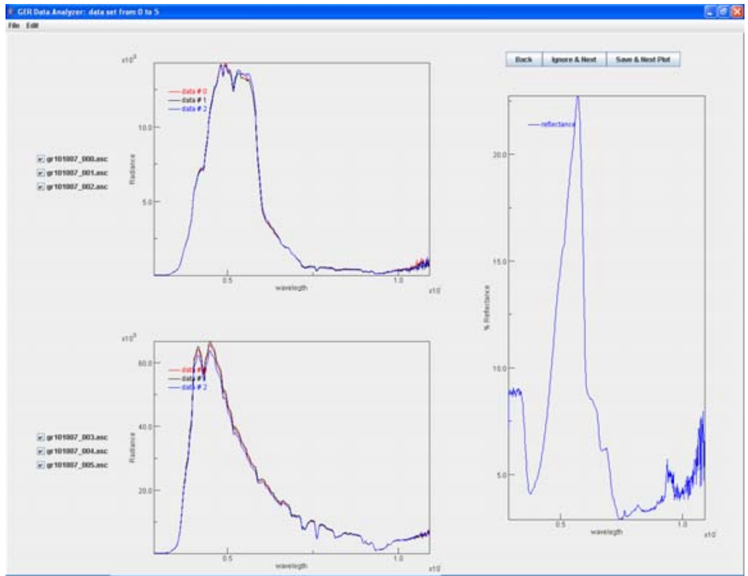


Fig. 7. Screenshot of Spectral Data Analyzer.

- Fieldwork also continued for collecting GPS polygons and point samples defining homogeneous areas of different reef habitats. Data on habitat composition and benthic cover is being collected extensively on Enrique Reef as well as on other nearby shallow reef systems. Data collected for each specific area included benthic reflectance, GPS location and a photograph to assist in both identifying benthic cover and as a permanent record of the conditions at the time of measurement. Benthic cover and GPS location of numerous randomly selected points throughout the study area are also being collected for use in accuracy assessments of image classification algorithms.

Fig. 8. Students collecting GPS on the Enrique Reef.

- Work continued towards developing capabilities for acquiring field-level hyperspectral imagery. This is being accomplished using a portable SOC-700 hyperspectral imaging camera mounted on a 3 m tall tripod, which measures 640x640 pixel images (~1-2 mm spatial resolution) in 120 bands from 400-900 nm at a 4 nm spectral sampling interval. Previous field tests performed by students illustrated the difficulties associated with compensating for the inherent environmental variations (i.e., water surface movement, current, winds and changing solar illumination angle) when acquiring very high spatial resolution data in the field. Developments in 2007 included building a submersible viewport to be placed in the water below the hyperspectral instrument in order to eliminate the effects of a variable water surface.
- In order to improve the remote sensing techniques for estimation of water quality parameters and benthic habitat mapping in coral reef systems it is necessary to determine the spatial and temporal variations of water column bio-optical properties. Therefore, a new effort has been directed toward evaluate such variability in the La Parguera coral reef system. The first bio-optical sampling was performed on May 21, 2007, incorporating a diversity of expected water and reef (e.g,, different oceanographic processes, depth, bottom type, and distance from the coast). These same stations (Fig. 9) were sampled again during October 18, November 20, and December 6 of 2007. This last date coincided with the high spatial resolution AISA mission described above. Quality control analyses and filtering processes are now underway with all data collected. Similar field work and data analyses will be performed during additional monthly samplings already scheduled for 2008.

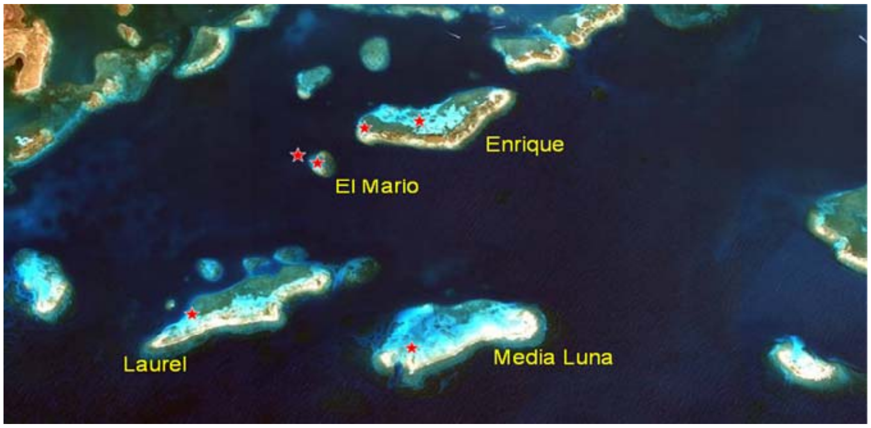


Fig. 9. Sampling stations (red stars) in La Parguera.

III. Gordon-CenSSIS Strategic Goals and Legacy

The focus of SeaBED is to provide facilities and data resources for use in the development, testing and validation of image analysis algorithms applied to subsurface sensing of benthic environments. Data with detailed groundtruth will help Gordon-CenSSIS researchers in R2C (multi and hyperspectral image analysis algorithms) and R3 (implementation of algorithms in high performance computing framework) to test and validate information extraction algorithms developed for subsurface sensing and imaging using spectral information. Furthermore, the testBED will enable the demonstration of the relevance of the Center-developed technology to solve benthic habitat mapping and assessment from remote sensing imagery.

The development of SeaBED represents a valuable component in research relating to the subsurface sensing of shallow aquatic environments. By providing a comprehensive set of imagery and accompanying ground truth data, SeaBED facilitates an improved ability for testing and validating the accuracy of image analysis algorithms. As evident from the above descriptions, much has been accomplished and numerous valuable data sets have already been acquired. Nevertheless, SeaBED represents an ongoing project that is evolving as it progresses. Further, the concept behind SeaBED is to not only develop a facility for Gordon-CenSSIS efforts, but also to provide an open testing infrastructure and set of freely available data. Accordingly, the SeaBED database will soon be available publicly and thus serve as a valuable data repository for researchers worldwide. Efforts are currently underway to develop an appropriate data distribution framework. This will be a valuable legacy to the remote sensing community.

IV. Future Plans

We expect to continue *in situ* data collection efforts over the next year and continue the analysis work in R2C and S4 until year 10.

- Continue assembling a spectral library describing the reflectance characteristics of specific species (i.e., coral, algae and seagrass) and substrates (i.e., sand, rubble and mud) present in coastal Puerto Rico.
- Quantify the spectral variability of bio-optical properties (i.e., due to changing water constituents) in coastal Puerto Rico.
- Continue efforts from 2007 by Gordon-CenSSIS students to perform a detailed field survey of habitat composition of Cayo Enrique and surrounding reefs using the high-precision Trimble GPS Pathfinder Pro XRS receiver system and an underwater camera.
- Expand current field work, image data collection, and algorithms development efforts to other benthic communities that are optically more complex (for example Mayaguez Bay).
- Finalize the IKONOS classification basemap of Enrique Reef. This will entail collecting detailed habitat information from numerous random locations throughout the reef and subsequently using this data to perform an accuracy assessment of the basemap.
- Process hyperspectral imagery and ground truth data collected in December 2007 and perform testing and validation of R2C algorithms.
- Develop website SEAWEB for dissemination of imagery and ground data from SeaBED.

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 (achieved through Gordon-CenSSIS researcher James Goodman, who has been working as a Visiting Scientist at RSMAS in 2007 and will continue in 2008). 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.

V. Broader Impact

Remote sensing is increasingly being used as a tool to quantitatively assess the location and relative health of coral reefs and other shallow aquatic ecosystems. These assessments are providing scientists and managers important spatial information on not only habitat distribution but also on the proximity of environmental stressors. It is expected that as image analysis procedures and detector capabilities continue to improve, so too will the effectiveness and efficiency of aquatic remote sensing applications. However, as the use of subsurface aquatic remote sensing continues to grow and the analysis products become more sophisticated, there is an increasing need for comprehensive ground truth data as a means to assess the algorithms being developed, particularly in the field of hyperspectral remote sensing. Thus, to address this need for validation data, we have developed SeaBED, a multi-level aquatic testBED for evaluating remote sensing information extraction algorithms. Furthermore, the data sets being generated by SeaBED will soon be made available to the remote sensing community via the internet, thus providing a unique opportunity for researchers to have access to a collection of well characterized data sets.

VI. Project Budget and Sustainability

Project Budget

The SeaBED budget for Year 8 was $150k of which a significant component was directed towards the high resolution AISA hyperspectral campaign. In years 9 and 10, funding will be primarily geared towards processing the data collected in 2007. We expect funding levels around $100k for years 9 and 10.

Industrial Collaborations

Collaboration with Spectra Vista Corp. [Tom Corl, President; Poughkeepsie, NY] continued in 2007 with respect to developing improved field equipment for the collection of underwater spectral measurements. Spectra Vista is "*dedicated to the manufacturing, delivery and support of airborne imaging spectrometers and field portable spectroradiometers for the remote sensing community*." The collaboration with Spectra Vista includes designing and testing enhanced capabilities for their GER-1500 underwater spectrometer (extending the initial design completed with Center researcher J. Goodman), as well as developing plans for utilizing southwestern Puerto Rico, including Enrique Reef, as a test area for the deployment and validation of a new airborne imaging spectrometer (sensor system still under development). Note that these collaborations benefit both the S4 driver and data development for SeaBED.

We are exploring the possibility of developing collaborations with ITT (http://www.itt.com) in the area of coastal remote sensing hyperspectral image processing. We are in conversations with them about how to establish such collaboration.

External Funding

The following are ongoing projects in 2007 or recently awarded proposals for research using SeaBED data that are directly related to Gordon-CenSSIS work in benthic habitat monitoring. In each case, the projects represent a synergistic combination of existing Center resources and practical applications of image analysis techniques and habitat classification algorithms.

1. *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

2. *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)

3. *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

VII. <u>Documentation</u>

A. Publications Acknowledging NSF Support (Jan. 1, 2007 to Dec. 31, 2007)

1. Goodman, J.A. and S.L. Ustin, 2007, *Classification of Benthic Composition in a Coral Reef Environment Using Spectral Unmixing*, Journal of Applied Remote Sensing, Vol. 1, 011501.

2. Guild, L., B. Lobitz, R. Armstrong, F. Gilbes, A. Gleason, J. Goodman, E. Hochberg, M. Monaco and R. Berthold, 2007, *NASA Airborne AVIRIS and DCS Remote Sensing of Coral Reefs*, 32nd International Symposium on Remote Sensing of Environment, San Jose, Costa Rica.

3. Vélez-Reyes, M., S. Rosario-Torres, J.A. Goodman, E.M. Alvira-Concepcion and A. Castrodad-Carrau, 2007, *Hyperspectral Image Unmixing Over Benthic Habitats*, SPIE Defense & Security Symposium: Algorithms and Technologies for Multispectral, Hyperspectral, and Ultraspectral Imagery XIII, Proceedings of SPIE Vol. 6565, Orlando, Florida.

4. Vélez-Reyes, M., J.A. Goodman, S. Rosario-Torres and A. Castrodad-Carrau, 2007, *Subsurface Unmixing with Application to Underwater Classification,* (invited paper), SPIE Europe Remote Sensing: Remote Sensing of the Ocean, Sea Ice and Large Water Regions 2007, Proceedings of SPIE Vol. 6743, Florence, Italy.

B. List of Presentations (not in conference proceedings) (Jan. 1, 2007 to Dec. 31, 2007)

1. Velez-Reyes, M., 2007, *Comparison Of Methods For Unmixing Of Hyperspectral Imagery InLitoral Zones,* 32nd International Symposium, on Remote Sensing of the Environment, San José, Costa Rica.

2. Vélez-Reyes, M., J. Goodman, S. Rosario, E.M. Alvira and A. Castrodad, 2007, *Hyperspectral Unmixing Over Benthic Habitats: A Comparison of Two Algorithms*, 15th AVIRIS Airborne Earth Science Workshop, Pasadena, California.

C. List of Relevant RICC 2007 Posters:

1. Zayas-Santiago, Carmen, C. Rivera Borrero, A. Mundorf, S. Cardona, J. Goodman, R.A. Armstrong, F. Gilbes, S. Hunt, M. Vélez-Reyes and S. Rosario, 2007, *Enrique Reef: A Spectral Library, Habitat Map and Hyperspectral Mission in Southwestern Puerto Rico*, Center for Subsurface Sensing and Imaging Systems, Research and Industrial Collaborations Conference, Northeastern University, Boston.

Year Nine Project Report

Project ID: SeaBED-A
Title: Testbed Development at UPRM

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Orian Tzadik	Marine Sci.	UPRM	otzadik@yahoo.com	M.S.	Dec 2009
Carmen Zayas	Marine Sci.	UPRM	c_castula@hotmail.com	M.S	May 2009
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I. Brief Overview of the Project and Its Significance

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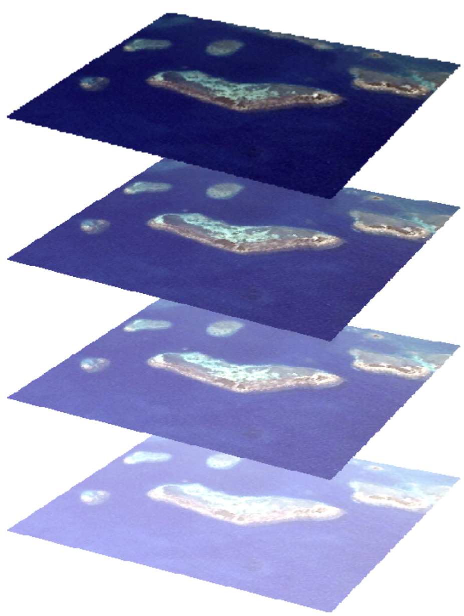
As highlighted below, work on SeaBED-A in 2008 focused on organizing, cataloging and pre-processing the extensive field data and airborne hyperspectral imagery collected in late 2007. Additional field data also continued to be collected in 2008 on Enrique Reef and other nearby reefs in southwestern Puerto Rico. Pre-processing steps included georeferencing, atmospheric correction and sunglint suppression of imagery for Enrique Reef, thus producing the necessary input format for implementing subsurface remote sensing algorithms.

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

A. State of the Art

Coral reefs and other benthic habitats are being increasingly threatened by 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 require a set of reliable quantitative tools for mapping and monitoring the dynamics of habitat distribution and condition. Fortunately, advances in remote sensing instrument capabilities and analysis methods are expanding the accuracy and effectiveness of applications directed at classifying habitat composition in shallow aquatic environments. This includes improvements in both multispectral and hyperspectral passive remote sensing investigations, as well as active remote sensing technologies such as bathymetric lidar. Although extensive data sets exist, e.g., Kaneohe Bay, Hawaii and Heron Island, Australia, the lack of readily available, publicly accessible ground truth information makes it difficult to perform algorithm validation and testing. SeaBED was developed to address this shortcoming by providing a multi-level aquatic test environment for creating, refining and evaluating subsurface aquatic remote sensing algorithms (see Figure 1). The resulting analysis capabilities facilitate enhanced spatial analysis tools for algorithm development, resource-management decisions, conservation-planning and risk-management evaluations.



Hyperspectral Image Data

- Low Res. (30m): HYPERION
- Moderate Res. (4m, 16m): AVIRIS
- High Res. (1m): AISA

Surface Measurements

- Environmental (tide, wind, rain, etc.)
- Aquatic Surface Reflectance
- Terrestrial Surface Reflectance

Water Column Measurements

- Water Optical Properties
- Water Attenuation
- Bathymetry (depth)

Benthic Measurements

- Benthic Composition (habitat)
- Spectral Library
- Benthic Reflectance

Figure 1. SeaBED multiple level data collection concept.

B. Major Contributions and Technical Approach

SeaBED addresses the deficiency in available validation data by providing the needed framework to assess physical models, inversion algorithms, feature extraction tools and classification methods for subsurface aquatic sensing using hyperspectral remote sensing. SeaBED is focused on coral reef and seagrass habitats, but is nevertheless applicable across a broad range of shallow aquatic ecosystems. The laboratory tank provides controlled environments for experimentation, while the field site offers the physical reality of a complex natural system for evaluating analysis techniques.

1. High Resolution Hyperspectral Imagery

UPRM conducted an airborne hyperspectral mission in southwest Puerto Rico in late 2007. The total area included in this mission was over 2000 km^2, with enhanced coverage of four science areas, three aquatic and one terrestrial. Although the project was originated to support ongoing research at Gordon-CenSSIS related to hyperspectral remote sensing, the overall mission was significantly expanded to involve additional collaborators with added sensors and instruments that together are addressing an increasing number of scientific questions and application driven objectives. The hyperspectral imagery from this mission was delivered to researchers at UPRM by the Galileo Group Inc. (http://galileo-gp.com/) in April 2008, and major tasks completed in 2008 included reviewing completeness of the data to identify missing files, assessing the overall quality of the data, cataloging the data in a mission summary report (Goodman, 2008), and organizing the data into a logical directory structure.

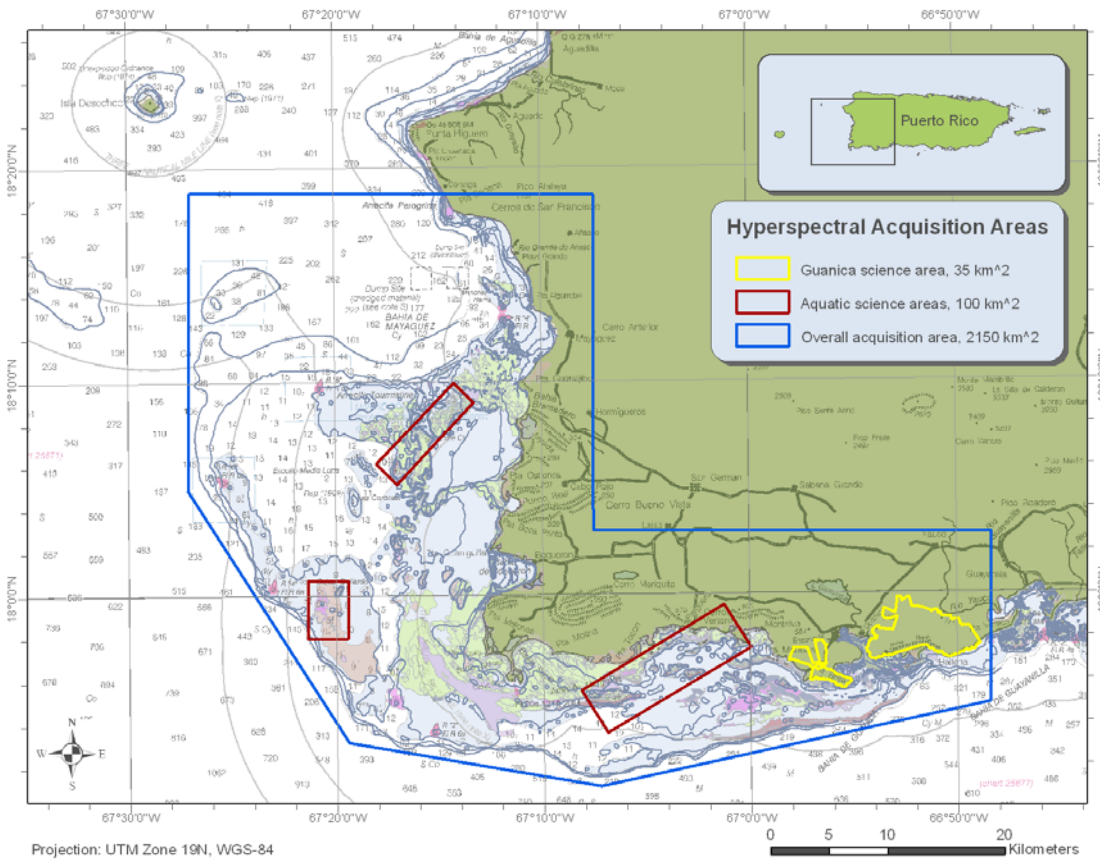


Fig. 2. Mission study area: blue polygon represents data at 4m resolution, red polygons represent science areas at 1, 2, 4, 8m resolution, and yellow polygons represent terrestrial science area at 1m resolution.

The study area for the hyperspectral mission is shown in Figure 2. The overall acquisition area covers 2150 km^2 and includes both land and shallow aquatic habitats. This area (large blue polygon) was acquired at 4 m spatial resolution. Three additional aquatic multi-resolution science areas, totaling 100 km^2, were also included (smaller red polygons). They include three separate coral reef areas representing different environmental characteristics. These smaller subsets were acquired at multiple spatial resolutions, including 1, 2, 4 and 8 m. The Guánica Dry Forest, totaling 35 km^2, was also acquired at 1 m spatial resolution to facilitate more detailed analysis of this important ecological area (yellow polygons). This area is both a UNESCO

Biosphere Reserve and the neotropical site for the proposed National Ecological Observatory Network (NEON)[1].

Data delivery from Galileo included radiometrically corrected at-sensor upwelling radiance (geocorrected and non-geocorrected), atmospherically corrected surface reflectance (geocorrected and non-geocorrected), geographic lookup tables (GLTs) for performing geocorrection and a preliminary natural color mosaic of the hyperspectral imagery (Fig. 3).

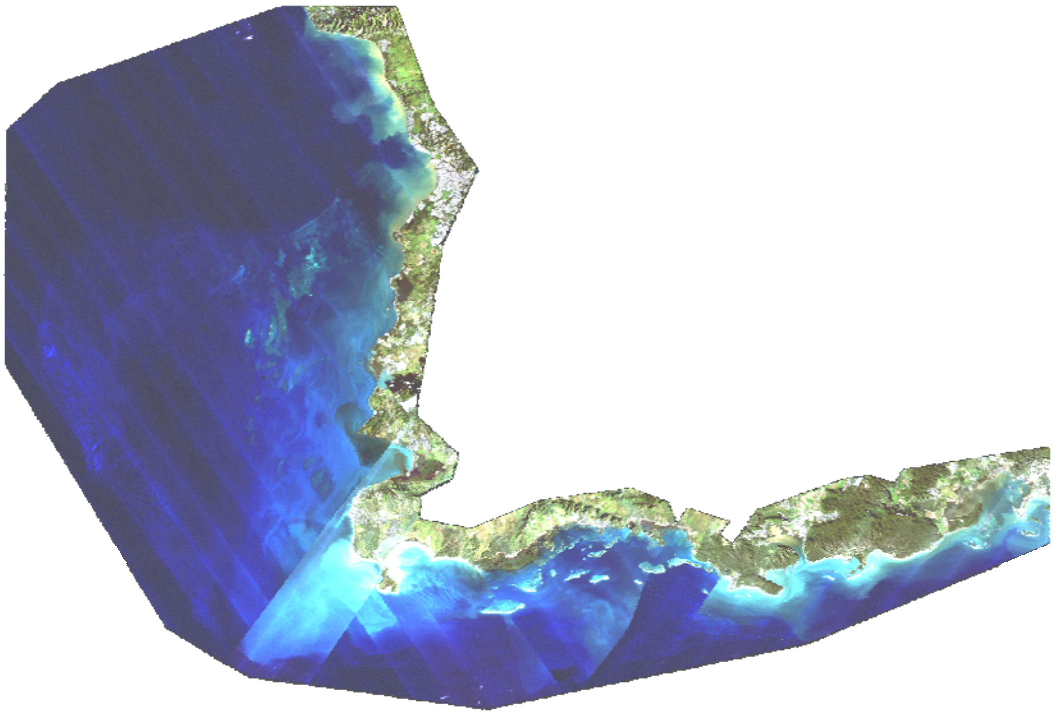


Fig. 3. Preliminary color mosaic of overall study area at 4 m spatial resolution.

A quantitative summary of the imagery follows below:

- Sensor system used for acquiring hyperspectral data was an AISA Eagle manufactured by Spectral Imaging Limited (http://www.specim.fi/);
- Spectral range is from 400-1000 nm, with 128 bands at a resolution of 3-5 nm FWHM;
- The delivered hyperspectral imagery includes 161 flightlines totaling over 1.5 TB (44 flightlines for the overall study area, 99 flightlines for the three aquatic science areas, and 18 flightlines for the Guanica Dry Forest – or alternatively – 15 flightlines at 8 m resolution, 59 flightlines at 4 m resolution, 26 flightlines at 2 m resolution, and 61 flightlines at 1 m resolution);
- The 4 m and 8 m spatial resolution data was collected from an altitude of 2900 m with 40% spatial overlap between adjacent flightlines;
- The 2 m spatial resolution data was collected from an altitude of 2600 m with 30% spatial overlap between adjacent flightlines;
- The 1 m spatial resolution data was collected from an altitude of 1200 m with 30% spatial overlap between adjacent flightlines;
- Flightline orientation and scheduling was independently optimized for terrestrial and aquatic areas, where aquatic flightlines were acquired in the morning and afternoon to minimize the effects of sunglint and terrestrial flightlines were acquired near mid-day to minimize shadowing effects;

[1] http://www.neoninc.org/

- Digital aerial photography was also acquired over the Guanica Dry Forest using a Nikon D200 camera system;
- Aerial photography was acquired over 18 separate flightlines, generating 1230 individual photos at two different exposure settings.

2. Field Data Collection

A variety of different field measurement were performed in the timeframe surrounding the 2007 hyperspectral mission, including a series of optical measurements acquired coincident with the airborne image collection. The objective behind collecting this data directly parallels the concept behind developing SeaBED-A, which is to provide a multi-level array of field data and remote sensing imagery to be used for the development and validation of subsurface remote sensing algorithms. The field data associated with the 2007 mission was collected in late 2007 and early 2008. In addition to supporting algorithm development using the 2007 hyperspectral imagery, this data also adds valuable additional field measurements to the existing SeaBED-A database. A summary of the primary 2007-2008 data follows below:

Underwater Calibration Targets. A total of seven large uniform sand areas were used as underwater calibration targets (Fig. 4). Each of the selected sand areas was a minimum of 100 m^2 in spatial extent, contained homogeneous benthic composition, and was level over the extent measured (i.e., uniform depth). The different sand areas were distributed among five different reefs in La Parguera (Enrique, Media Luna, Laurel, Caracoles, and San Cristobal), and located in a range of water depths (3-40 ft). Reflectance data from these areas were acquired simultaneous with the hyperspectral image acquisition. Two separate GER-1500 spectrometers, contained in identical underwater housings, were utilized for acquiring *in situ* underwater reflectance measurements. The GER-1500 measures 512 spectral channels from 350-1050 nm at a FWHM of 3 nm. One GER-1500 performed measurements using natural direct illumination, while the other utilized a test version of a new attachment to perform measurements using artificial illumination.

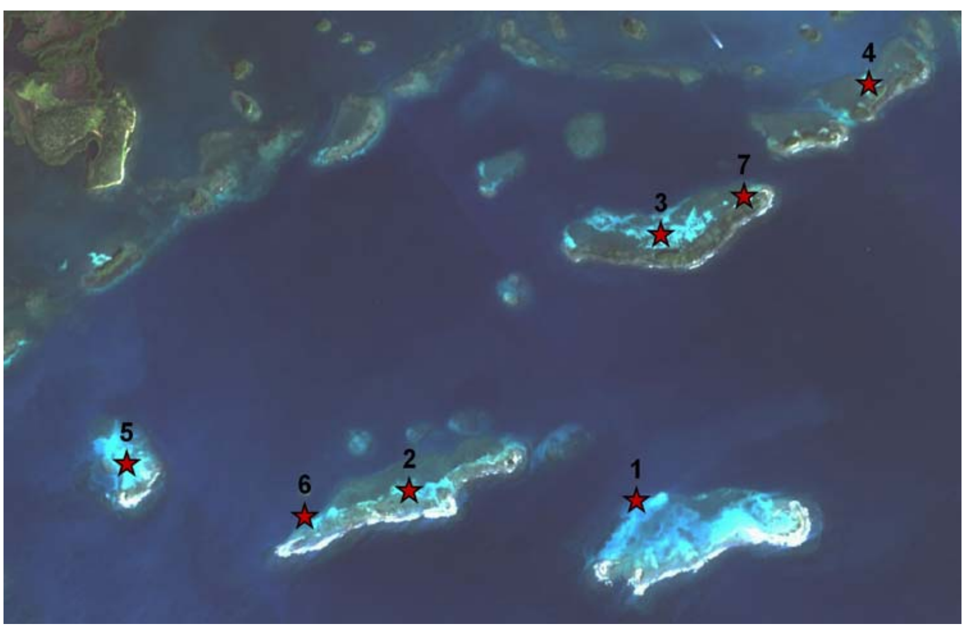


Fig. 4. Locations of underwater sand calibration targets.

Terrestrial Calibration Targets. Terrestrial calibration target areas consisted of three large uniform surfaces, as well as two commercially manufactured calibration tarps. As with the underwater calibration targets, each of the terrestrial surfaces was a minimum of 100 m^2 in spatial extent, contained homogeneous surface composition, and was level over the extent measured. The surfaces included a rooftop on the UPRM campus (measured both in the morning and afternoon), a parking lot, and a beach in Boqueron. The two tarps, one bright (56% reflectance) and one dark (2.5% reflectance), were provided courtesy of Galileo. Both were approximately 4m x 4m in dimension and thus only applicable for the 1m hyperspectral imagery. These tarps were measured on two different occasions coincident with the high resolution image acquisition. The primary instrument used for collecting reflectance measurements from the terrestrial calibration targets was a SVC HR-1024. This instrument measures 1024 spectral channels from 350-2500 nm (FWHM of 3.5 nm for 350-1000 nm, 8.5 nm for 1000-1850 nm, and 6.5 nm for 1850-2500 nm). Additionally, for consistency with the underwater measurements, a secondary set of measurements for the calibration tarps was performed using the GER-1500 spectrometers.

Spectral Library. Spectral library measurements (i.e., *in situ* reflectance measurements of the dominant species and substrate types) were acquired prior to and during the mission. This data adds to existing spectral library information collected in past years as part of the SeaBED-A efforts. Data was acquired using two different instruments, a GER-1500 and a DiveSpec. The GER-1500 measurements used natural illumination and followed the same procedure as used for the sand calibration targets. Use of the DiveSpec, which utilizes LED artificial illumination, was part of a collaborative project with NOVA Southeastern University. Measurements using each instrument were repeated for numerous individuals of different species (e.g., coral, seagrass, gorgonian, etc...) and at various locations for different substrates (sand, rubble, mud, etc...). Results from each different protocol were grouped according to species and substrate type, and processed to provide the average and standard deviation of all measured spectra.

Benthic Habitat Information. Two closely related GIS benthic habitat data layers were developed for this project, one layer delineating polygons of reef features and one layer containing *in situ* benthic photos. The polygons depict spatially distinct areas of homogeneous habitat types, and the photos represent a random sampling of points from these different habitats. Data collection began in July 2007 and continued through June 2008, thus covering a broad period surrounding the hyperspectral acquisition in November/December 2007. General fieldwork focused on nine areas in La Parguera, with an intensive field effort performed on Enrique Reef (totaling over 600 individual points/photos), which is the primary study area for the SeaBED-A project (Fig. 5). All GPS measurements were obtained using a Trimble Pro XRS and photos were acquired with a SeaLife DC600. Polygons were delineated by collecting a series of GPS points while circumnavigating visually homogeneous habitat areas. In shallow areas this was performed on foot with the GPS antenna attached to a PVC pole, while in deeper water this was performed using a snorkeler in the water with the GPS remaining on the boat (positioning achieved through careful coordination between the snorkeler and boat). As such, there is greater confidence in positional accuracy for the shallower depths (≤ 1.5m). The photos were collected from random locations within different habitats (not limited to just the polygon areas), and GPS measurements were acquired for each photo.

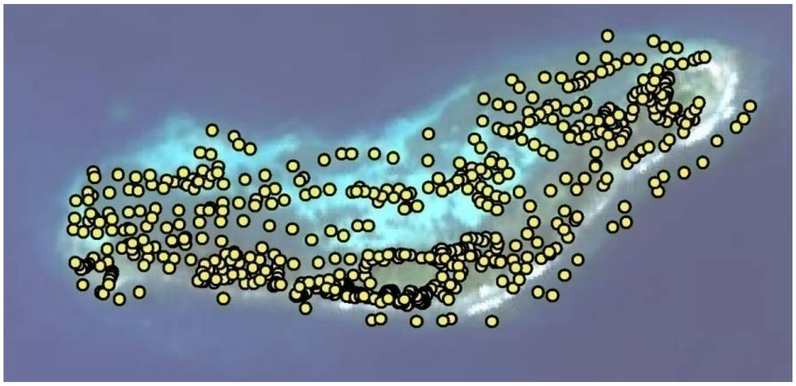


Fig. 5. Location of benthic habitat GPS points/photos for Enrique Reef.

3. Spatial and Temporal Variability of Water Optical Properties

Monthly samplings of six permanent stations located in Media Luna, Laurel, Mario, and Enrique reefs were started in May 2007 in order to evaluate, for the first time, the spatial and temporal variability of inherent and apparent optical properties of La Parguera coral reef system. The selected sites covered diverse bio-optical conditions and habitats affected by different oceanographic processes, depth, bottom type, and distance from the coast. All these stations are sampled with a rosette containing a CTD to measure temperature and salinity, a WetStar fluorometer for chlorophyll fluorescence, an ac-9 for adsorption and attenuation, a HydroScat-6 for backscattering, and an OCR-200 radiometer for upwelling radiance and downwelling irradiance. Water-leaving radiance and the above-surface downwelling irradiance are measured using the GER 1500 spectroradiometer to calculate the remote sensing reflectance. The deep station located in Mario Reef is also sampled with a Satlantic hyperspectral radiometer. Quality control analyses and filtering processes are now underway with all data collected. Similar field work and data analyses will be performed during other monthly samplings scheduled for 2009. This first-time comprehensive study of the water optical properties of La Parguera Reef System will establish the basics for further improvement of the remote sensing techniques for monitoring benthic habitats. All data collected during these samplings will be incorporated into a Geographic Information System (GIS) using ArcGIS. These layers of information will be published in the internet using the recently created database system called GERSVIEW. Examples of other databases already on-line can be found at: http://gersview.uprm.edu.

4. External Collaborative Research

A number of ongoing and newly initiated external collaborative research projects associated with SeaBED-A and involving Gordon-CenSSIS researchers were conducted in 2008. Summaries of some of the more significant projects are provided below.

NASA. This is an ongoing 3-year project funded through the National Aeronautics and Space Administration (NASA) Interdisciplinary Research in Earth Science program (PI: L. Guild; Co-I B. Lobitz, J. Goodman, R. Armstrong). The objective of this project is to utilize hyperspectral imagery to assess the biological and physical properties of reefs as related to degradation in biodiversity following coral bleaching events. Analysis uses the AVIRIS hyperspectral imagery acquired in southwestern Puerto Rico in 2005, which was funded by NASA as part of a multi-agency response headed by the U.S. Coral Reef Task Force (USCRTF) to assess the impacts of the massive 2005 coral bleaching event. The project study area covers a similar area as utilized for SeaBED-A, and one of the focus areas for analysis is the primary SeaBED-A reef site, Enrique Reef. The project leverages the field data resources and expertise in subsurface aquatic image processing of Gordon-CenSSIS and applies these capabilities towards answering important ecological questions regarding coral reef health.

NIST. This is a collaborative project with researchers at the National Institute of Standards and Technology (NIST) involving the newly developed Hyperspectral Image Projector (HIP). The HIP allows the projection of spectrally and spatially complex scenes that can be used for system level validation of hyperspectral imagers and algorithms. Scene projection facilitates examination of spectral mixing and unmixing at different spatial scales. Hyperspectral imagery from the SeaBED-A 2007 hyperspectral mission was selected as one of the first scenes to be implemented and tested on the HIP. The first phase of this research, which began in 2008, was to address functional considerations for formatting the imagery for the HIP, including identification of representative endmembers that characterize the scene. Work in 2009 is expected to progress towards improving the understanding of the optical scene components associated with coral reef imagery, which will ultimately advance the ability to monitor coral reefs using remote sensing.

NOAA. This is a collaborative project with researchers from the National Oceanic and Atmospheric Administration (NOAA), National Centers for Coastal Ocean Science (NCCOS), Biogeography Branch directed towards developing novel approaches for mapping coral reefs using an integration of hyperspectral and lidar remote sensing capabilities. The primary study area for development of these approaches is southwest Puerto Rico, and SeaBED-A data from the 2007 hyperspectral mission is playing a critical role in the project. The Biogeography Branch is largely responsible for mapping all reefs in U.S. water, which includes coastal areas in the continental U.S., the Caribbean, Hawaii, and numerous other territories throughout the Pacific. Thus, there is enormous potential for expansion as the project progresses. Work in 2008 focused on pre-processing hyperspectral imagery and establishing project goals. Efforts in 2009 will involve integrating both lidar and hyperspectral imagery into a classification scheme and producing preliminary mapping proeducts.

III. Gordon-CenSSIS Strategic Goals and Legacy

The focus of SeaBED-A is to provide facilities and data resources for use in the development, testing and validation of image analysis algorithms applied to subsurface sensing of benthic environments. Data with detailed groundtruth will help Gordon-CenSSIS researchers in R2-C (multi- and hyperspectral image analysis algorithms) and R3 (implementation of algorithms in high performance computing framework) to test and validate information extraction algorithms developed for subsurface sensing and imaging using spectral information. Furthermore, the testbed will enable the demonstration of the relevance of the Center-developed technology to solve benthic habitat mapping and assessment from remote sensing imagery.

The development of SeaBED-A represents a valuable component in research relating to the subsurface sensing of shallow aquatic environments. By providing a comprehensive set of imagery and accompanying ground truth data, SeaBED-A improves our ability to test and validate the accuracy of image analysis algorithms. As evident from the above descriptions, much has been accomplished and numerous valuable data sets have already been acquired. Nevertheless, SeaBED-A represents a project that is evolving as it progresses. Further, the concept behind SeaBED-A is to not only develop a facility for Gordon-CenSSIS efforts, but also to provide an open testing infrastructure and set of freely available data. Accordingly, the SeaBED-A database will soon be available publicly and thus serve as a valuable data repository for researchers worldwide. Efforts are currently underway to develop an appropriate data distribution framework. This will be a valuable legacy to the remote sensing community.

IV. Future Plans

We expect to continue *in situ* data collection efforts and continue the analysis work in R2-C and S4 in year 10. Other plans include:

- Expand the existing spectral library describing the reflectance characteristics of specific species (i.e., coral, algae and seagrass) and substrates (i.e., sand, rubble and mud) present in coastal Puerto Rico. Data collection will utilize the beta version of a newly designed active illumination system for the GER-1500 underwater spectrometer, which significantly reduces measurement errors due to fluctuating natural illumination conditions and also provides spectral acquisition over a larger wavelength range than previously possible.
- Finalize organization of field data and airborne imagery from the 2007 hyperspectral campaign into a single geospatially integrated dataset. This task includes finalizing remaining data pre-processing tasks required to transform the raw field and image data into formats that are consistent with input requirements of subsurface remote sensing algorithms.
- Process the hyperspectral imagery collected in the 2007 hyperspectral campaign for Enrique Reef and perform testing and validation of R2-C algorithms using the available ground truth information.
- Continue to collect and analyze data quantifying the spectral variability of bio-optical properties (i.e., due to changing water constituents) in coastal Puerto Rico.
- Develop website SeaWEB for dissemination of imagery and ground data from SeaBED-A.

Gordon-CenSSIS researcher James Goodman will also continue working as a Visiting Scientist in 2009 at the Rosenstiel School of Marine and Atmospheric Research (RSMAS) at the University of Miami. This appointment serves to enhance collaboration and interaction with reef scientists and resource specialists located at RSMAS.

V. Broader Impact

Remote sensing is increasingly being used as a tool to quantitatively assess the location, relative health and biodiversity of coral reefs and other shallow aquatic ecosystems. These assessments are providing scientists and managers with important spatial information on not only habitat distribution but also on the proximity of environmental stressors. It is expected that as image analysis procedures and sensing capabilities continue to improve, the effectiveness and efficiency of aquatic remote sensing applications will also improve. However, as the use of subsurface aquatic remote sensing continues to grow and the analysis products become more sophisticated, there is an increasing need for comprehensive ground truth data as a means to assess the algorithms being developed, particularly in the field of hyperspectral remote sensing. To address this need for validation data, we have developed SeaBED-A, a multi-level aquatic testBED for evaluating remote sensing information extraction algorithms. Furthermore, the data sets being generated by SeaBED-A will soon be made available to the remote sensing community via the internet, thus providing a unique opportunity for researchers to have access to a collection of well characterized data sets.

VI. Technology Transfer

Industrial Collaboration

Collaboration to develop improved field equipment for the collection of underwater spectral measurements continued in 2008 with Spectra Vista Corp. (Poughkeepsie, NY). The collaboration with Spectra Vista is focused on designing and testing an active illumination system for their GER-1500 underwater spectrometer (extending the existing GER-1500 design completed with Center researcher J. Goodman). Following laboratory development and testing in 2007, and field testing during the 2007 AISA hyperspectral campaign, work in 2008 progressed towards generating detailed engineering schematics in preparation for beta testing a commercial version of the instrument in 2009. The initial test version of this instrument is illustrated in Figure 6. This collaboration benefits data acquisition efforts for SeaBED-A, as the beta version of the instrument will be utilized for collecting in situ underwater spectra of dominant species and substrate types around Enrique Reef in 2009.

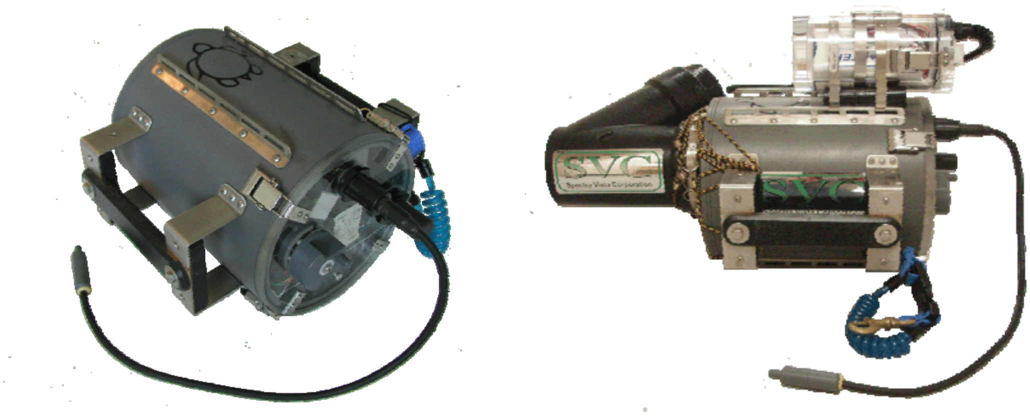


Fig. 6. GER-1500 underwater spectrometer: (left) existing design; and (right) with initial test version of the artificial illumination attachment (battery is on top and illumination guide is in the front).

We are also continuing to explore possibilities for developing collaborations with ITT (http://www.itt.com) in the area of coastal remote sensing hyperspectral image processing. We are in conversations with them about how to establish such collaboration.

VII. Project Budget and Sustainability

Project Budget

The SeaBED-A budget for Year 9 was $46k, which was used primarily to catalogue, organize and pre-process data from the 2007 high resolution AISA hyperspectral campaign and to collect additional field data in the SeaBED-A study area. In year 10, funding will be oriented towards further data pre-processing of the AISA data and developing an integrated geospatial library of field data and hyperspectral imagery for SeaBED-A. The objective in year 10 is to fulfill the overall goal of the SeaBED-A project legacy by generating a coherent multi-level dataset of all SeaBED-A data for Enrique Reef. We expect a funding level around $40k for year 10. Salaries for all researcher except Dr. Gilbes came from R2C and administrative funding.

Student Support

There were 3 graduate and 2 undergraduate students participating in the SeaBED-A project in 2008. Support for the graduate students was shared between Gordon-CenSSIS and grant funding from associated external projects (described below). M. Goenaga received funding from Gordon-CenSSIS and the NOAA project; O. Tzadik was fully supported from the NOAA project; and C. Zayas received partial funding from Gordon-CenSSIS and was recently awarded a Puerto Rico NASA Space Grant Fellowship for the 2008-2009 academic year. Support for undergraduates S. Cardona and A. Cruz was provided by Gordon-CenSSIS UPRM internal REU in 2008.

External Funding

The following are ongoing projects in 2008 contributing to SeaBED-A data acquisition, and that are also directly related to Gordon-CenSSIS work in benthic habitat monitoring. These projects leverage existing Center expertise and demonstrate collaborative research applications derived from the SeaBED-A resources. Additional external sustaining funding is being pursued through collaborations and funding opportunities with NOAA, NASA and NRL.

1. *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 + no-cost extension for 2009)
Award Amount:	$133,296

2. *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)

VIII. References Cited

Goodman, J. (Ed.), 2008, "2007 Puerto Rico Hyperspectral Mission: Image Acquisition and Field Data Collection", University of Puerto Rico at Mayagüez, 56pp.

IX. Documentation

A. Technology Transfer (Jan. 1, 2008 to Dec. 31, 2008)

None

B. Publications Acknowledging NSF Support (Jan. 1, 2008 to Dec. 31, 2008)

1. Carter, A., S. Purkis and J. Goodman, 2008, "A Spectral Linear Mixing Model and Analyses of Mixed Pixels, Broward County (Florida)", *11th International Coral Reef Symposium*, Fort Lauderdale, Florida.
2. Gerardino-Neira, C., J. Goodman, M. Vélez-Reyes, W. Rivera, 2008, "Sensitivity Analysis of a Hyperspectral Inversion Model for Remote Sensing of Shallow Coastal Ecosystems", *IGARSS 2008 Geoscience and Remote Sensing: The Next Generation*, Boston, Massachusetts.
3. Goodman, J., 2008, "New Image Analysis Method Improves Assessment of Coral Reefs", *SPIE Newsroom*, 2pp.
4. Goodman, J., 2008, "Advanced Benthic Mapping of Reef Environments in Southwestern Puerto Rico", *Caribbean Coral Reef Institute 2008 End of the International Year of the Reef Symposium*, San Juan, Puerto Rico.
5. Goodman, J.A., Z. Lee and S.L. Ustin, 2008, "Influence of Atmospheric and Sea-Surface Corrections on Retrieval of Bottom Depth and Reflectance Using a Semi-Analytical Model: A Case Study in Kaneohe Bay, Hawaii", *Applied Optics*, Vol. 47, F1-F11.
6. Goodman, J.A., M. Velez-Reyes, and S. Rosario-Torres, "An Update on SeaBED: A TesBED for Validating Subsurface Aquatic Hyperspectral Remote Sensing Algorithms." In Proceedings of SPIE: Remote Sensing of the Ocean, Sea Ice, and Large Water Regions 2008.
7. Goodman, J., M. Vélez-Reyes, S. Rosario, S. Hunt and F. Gilbes, 2008, "Development of a Field Test Environment for the Validation of Coastal Remote Sensing Algorithms: Enrique Reef, Puerto Rico", *11th International Coral Reef Symposium*, Fort Lauderdale, Florida.
8. Goodman, J., C. Zayas, S. Rosario and O. Tzadik, 2008, "A Hyperspectral Remote Sensing Campaign in Southwestern Puerto Rico with Multiple Environmental Applications", *11th International Coral Reef Symposium*, Fort Lauderdale, Florida.
9. Guild, L., B. Lobitz, R. Armstrong, F. Gilbes, A. Gleason, J. Goodman, E. Hochberg, M. Monaco, R. Berthold and J. Kerr, 2008, "Coral Reef Ecosystem Assessment Using NASA Airborne AVIRIS and DCS imagery", *AGU Ocean Sciences Meeting*, Orlando, Florida.
10. Guild, L., B. Lobitz, R. Armstrong, F. Gilbes, A. Gleason, J. Goodman, E. Hochberg, M. Monaco, R. Berthold and J. Kerr, 2008, "NASA Airborne AVIRIS and DCS Remote Sensing of Coral Reefs", *11th International Coral Reef Symposium*, Fort Lauderdale, Florida.

11. Lobitz, B., L. Guild, M. Montes, R. Armstrong and J. Goodman, 2008, "Pre-Processing of 2005 AVIRIS Data for Coral Reef Analysis", *11th International Coral Reef Symposium*, Fort Lauderdale, Florida.

12. Rowlands, G.P., J.A. Goodman, B.M. Riegl, P.G. Renaud and S.J. Purkis, 2008, "Habitat mapping in the Farasan Islands (Saudi Arabia) using CASI and QuickBird imagery", *11th International Coral Reef Symposium*, Fort Lauderdale, Florida.

13. V. Manian and M. Velez-Reyes, "Support vector classification of land cover and benthic habitat from hyperspectral images," In *International Journal of High Speed Electronics and Systems*, Vol. 18, No. 2, June 2008, pp. 337-348.

C. Relevant 2008 Site Visit and RICC Posters

1. Torres, M.C., S. Rosario, M. Vélez-Reyes and J. Goodman, 2008, *Hyperspectral Coastal Image Analysis Toolbox*, Center for Subsurface Sensing and Imaging Systems, NSF Site Visit, Boston University, Boston.

2. Tzadik, O., C. Zayas, J. Goodman, S. Rosario and M. Vélez-Reyes, 2008, *A Hyperspectral Remote Sensing Campaign in Southwestern Puerto Rico with Multiple Environmental Applications*, Center for Subsurface Sensing and Imaging Systems, Research and Industrial Collaborations Conference, Northeastern University, Boston.

3. Yilmazer, A., J.A. Goodman and D. Kaeli, 2008, *Using CUDA for Remote Sensing Applications*, Center for Subsurface Sensing and Imaging Systems, NSF Site Visit, Boston University, Boston.

4. Zayas-Santiago, C., O. Tzadik, J. Goodman, M. Vélez-Reyes and S. Rosario, 2008, *Field Spectral Measurements Acquired in Support of the 2007 Puerto Rico Hyperspectral Mission*, Center for Subsurface Sensing and Imaging Systems, NSF Site Visit, Boston University, Boston.

D. Relevant Seminars, Workshops and Short Courses (Jan. 1, 2008 to Dec. 31, 2008)

1. Chinea, J.D., S. Van Bloem, J. Goodman, S. Rosario and R. Rosado, 2008, "The Guánica Forest Reserve: A Component of the 2007 Puerto Rico Hyperspectral Mission", National Ecological Observatory Network, Puerto Rico Planning Meeting.

2. Zayas-Santiago, Carmen, C. Rivera Borrero, A. Mundorf, S. Cardona, J. Goodman, R.A. Armstrong, F. Gilbes, S. Hunt, M. Vélez-Reyes and S. Rosario, 2008, "Enrique Reef: A Spectral Library, Habitat Map and Hyperspectral Mission in Southwestern Puerto Rico", National Ecological Observatory Network, Puerto Rico Planning Meeting.

3. M. Vélez-Reyes, "Unmixing of Hyperspectral Imagery." Presented at MIT Lincoln Laboratories, Lexington, MA, April 15, 2008.