CENSSIS SEABED: DIVERSE APPROACHES FOR IMAGING SHALLOW AND DEEP CORAL REEFS

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The main task of the Center for Subsurface Sensing and Imaging Systems (CenSSIS), funded by the National Science Foundation, is to develop appropriate techniques to separate complex subsurface signals. This multi-university Engineering Research Center aims to revolutionize the existing technology for detecting and imaging objects under different layers, including underwater. The University of Puerto Rico at Mayaguez (UPRM), a main partner of CenSSIS, has created SeaBED for the development of improved remote sensing techniques for monitoring coral reefs. SeaBED includes both controlled laboratory facilities and a field test environment in the southwest coast of Puerto Rico that is being used to validate sensors, improve algorithms, understand physical models, and develop extraction tools and classification methods for underwater sensing. Multiple sensors with different spatial and spectral resolutions, such as Landsat TM, IKONOS, Hyperion, and AVIRIS, have been tested. In terms of image processing, different pattern recognition algorithms (e.g., image classification and spectral unmixing) and time series analyses for change detection have been used. Bottom reflectance and remote sensing reflectance have been measured from several coral reef zones, different species, and coral health conditions with a submersible spectroradiometer. Furthermore, for optical imaging of coral reefs present below one attenuation depth (approximately 20 m in oligotrophic waters), which defines a practical limit for effective airborne and satellite remote sensing, we have used an autonomous underwater vehicle (AUV) as an *in situ* platform for acquiring measurements. High-resolution optical imaging from the AUV is used for mapping and characterizing deeper reefs present between 30 to 100 meters.

DESCRIPTION OF CENSSIS SEABED

SeaBED is a testbed used for the collection of hyperspectral data and other modalities of underwater imaging. It is composed of three separate facilities: a lab based set-up, an outdoor tank set-up, and a coral reef field site, Enrique Reef, in southwestern Puerto Rico (Figure 1).

(a) (b) (c)

Figure 1: SeaBED Facilities: (a) Indoor tank, (b) Outdoor tank, (c) Enrique Reef as shown using IKONOS.

The indoor and outdoor tanks served as controlled environments to validate physical models, feature extraction tools, dimensionality reduction approaches, inversion modeling, and detection/classification algorithms for hyperspectral data, as well as multi-modal approaches for data fusion. These parts of SeaBED provide the flexibility to manipulate various parameters and thus provide control over critical ground truth information. Data produced in these tanks includes hyperspectral images, spectral signatures, temperature, salinity, chlorophyll fluorescence, inherent optical properties, above-surface downwelling irradiance, water-leaving radiance, and bottom albedo.

SeaBED generates calibrated data with associated ground truth for subsurface sensing algorithm validation and testing. While the indoor and outdoor tanks provide fully controlled testbeds, Enrique Reef offers a well characterized field site where airborne and spaceborne data have been collected. This imagery is being used to study atmospheric impact, spatial resolution effects, and higher level of uncertainty in water and atmospheric parameters in the performance of subsurface analysis algorithms. It also serves as a natural test site to demonstrate the usefulness of these approaches. The diverse SeaBED components provide CenSSIS with real data in realistic environments obtained with multiple sensors. The Center has become a repository of valuable data to validate algorithms in collaboration with other researchers worldwide.

INDOOR TANK

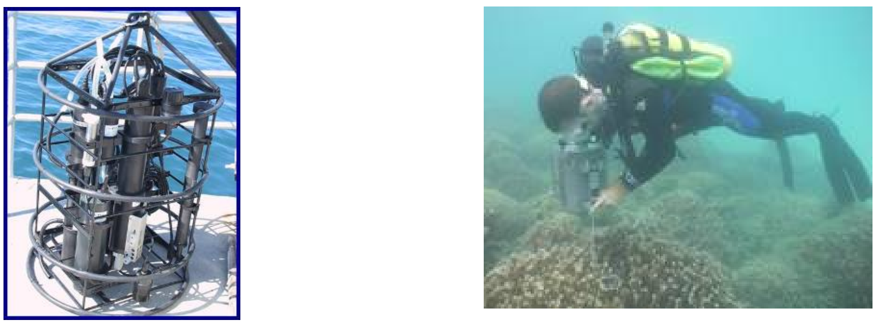
The laboratory-based testbed is composed of a small tank, light sources and sensors as shown in Figure 1a. Currently available sensors include a hyperspectral imager and a spectrometer. The hyperspectral imager consists of a 640x480 resolution CCD camera along with two tunable VariSpec filters. One filter covers the range from 400 to 720 nm, the other from 700 to 1100 nm. This combination of camera and tunable filter allows the collection of hyperspectral data at any desired spectral resolution down to 1 nm increments. The spectrometer is a GER 1500 with a spectral range from 300 to 1100 nm and a FWHM of 2.8 nm. The primary light source for the tank are two halogen quartz lamps with fiber optic cables. Incandescent lights are available for less critical experiments or for when uniform light over a wider area is required. Outdoor measurements with available sunlight can also been performed.

OUTDOOR TANK

The outdoor tank, shown in Figure 1b, is located on Magueyes Island, the field station of the UPRM Department of Marine Sciences, located in southwestern Puerto Rico. The tank uses filtered seawater from two filters that remove organic and inorganic dissolved components. A SOC700 Hyperspectral Imager, which is a field portable imaging spectrometer, is utilized for this tank. This instrument is radiometrically calibrated and includes software for both analysis and viewing. The imager acquires 640 by 640 pixel images with 120 bands. The outdoor facility is a large tank illuminated by direct sunlight that provides an environment more similar to natural conditions while still retaining control over numerous variables. Experiments are being conducted using objects with different shapes and spectral responses, at different depths, and with and without clutter effects. This enables more extensive validation of algorithms than is possible with the indoor tank alone.

ENRIQUE REEF FIELD SITE

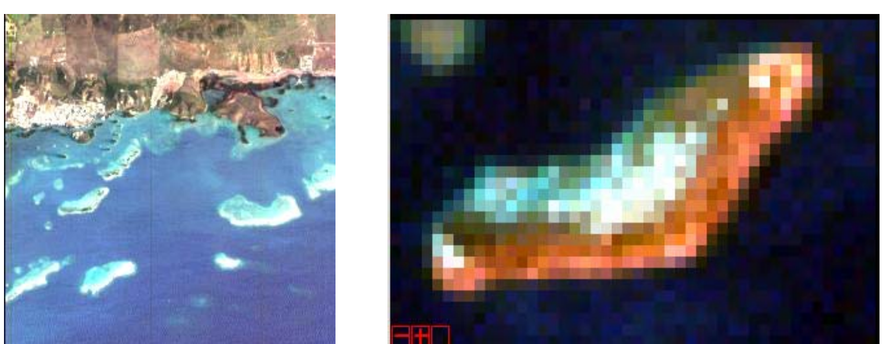
Enrique Reef is one of the many reefs located near the UPRM Marine Science Research facilities. An IKONOS image of the reef is shown in Figure 1c. Having an ocean based facility allows testing and validation of the developed algorithms and methodologies in a natural environment. Enrique Reef is a well-characterized system containing sand, coral and seagrass habitats. The bio-optical properties of the water column are measured at the reef using a bio-optical profiler (Figure 2a) consisting of: 1) CTD (Seabird SBE-19 with pump) that measures temperature and salinity, 2) A fluorometer (WetStar from Wet Labs) that measures chlorophyll fluorescence, 3) AC-9 meter (from Wet Labs) that measures spectral transmittance c(λ) and spectral absorption a(λ) at nine wavelengths, 4) HydroScat-6 (from Hobi Labs) that measures the backscattering coefficient, $b_b(\lambda)$ at six wavelengths, and 5) OCR-200 submersible radiometer (from Satlantic) that measures upwelling radiance $L_u(0\text{-},\lambda)$ and downwelling irradiance $E_d(0\text{-},\lambda)$. In addition, the water-leaving radiance, $L_w(\lambda)$, and the above-surface downwelling irradiance, $E_d(0+,\lambda)$, are measured using a GER 1500 portable spectroradiometer. $R_{rs}(\lambda)$ is calculated from the ratio between $L_w(\lambda)$ and $E_d(0+, \lambda)$. The GER 1500 spectroradiometer is also used for underwater spectral measurements (Figure 2b) to develop spectra libraries of reflectance properties of different bottom types.



(a) (b)

Figure 2: (a) Bio-optical profiler; (b) Diver using the GER-1500 Spectroradiometer with underwater housing.

Hyperspectral imagery of the region around Enrique Reef has been collected using the NASA HYPERION sensor, which is located onboard the Earth Observing-1 satellite. The HYPERION instrument was designed as a technology demonstration instrument and provides calibrated hyperspectral data for evaluating image analysis applications. The sensor has 242 channels in the 900-2500 nm region of the spectrum with a 10 nm spectral resolution. It has a spatial resolution of 30 m and a swath width of 7.7 km. Two images of La Parguera were obtained for the years 2002, 2003, 2004, 2005 and 2006. A Hyperion image of the study area is shown in Figure 3a. An enlargement of Enrique Reef (Figure 3b) depicts the differing spatial resolution of this sensor when compared to



(a) (b)

Figure 3: HYPERION images: (a) La Parquera area, (b) Enrique Reef.

IKONOS (Figure 1c). We have employed various remote sensing techniques to study the benthic habitats at this location, including a comparison of the effects of spatial and spectral resolution using IKONOS (1 m) and HYPERION (30 m) (Figure 4a and 4b). Image processing of IKONOS included atmospheric correction, sun glint removal, water column correction, and supervised classification of the dominant benthic categories of seagrass, sand, and coral. HYPERION data analysis included atmospheric correction with ACORN, minimization of noise and determination of data dimensionality (Minimum Noise Fraction), location of the most spectrally pure pixels (Pixel Purity Index), extraction and identification of spectra with an N-dimensional visualization, and spatial mapping with a Spectral Angle Mapper classification. The results of the supervised classification after the images were processed are shown in Figure 4c and 4d. Field data collection for image validation was performed by the establishment of three transects with ten quadrants for each habitat class.

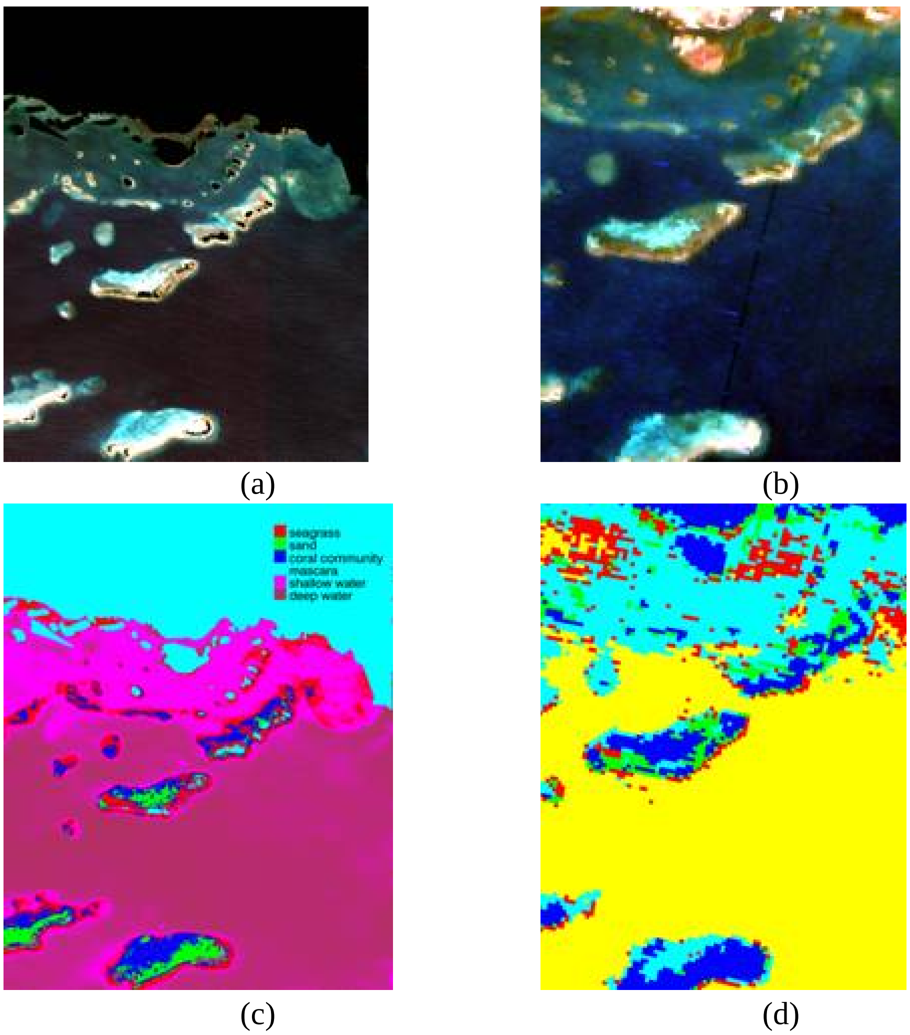


Figure 4: Atmospherically corrected IKONOS (a) and HYPERION (b) and results of supervised classification of IKONOS (c) and HYPERION (d)

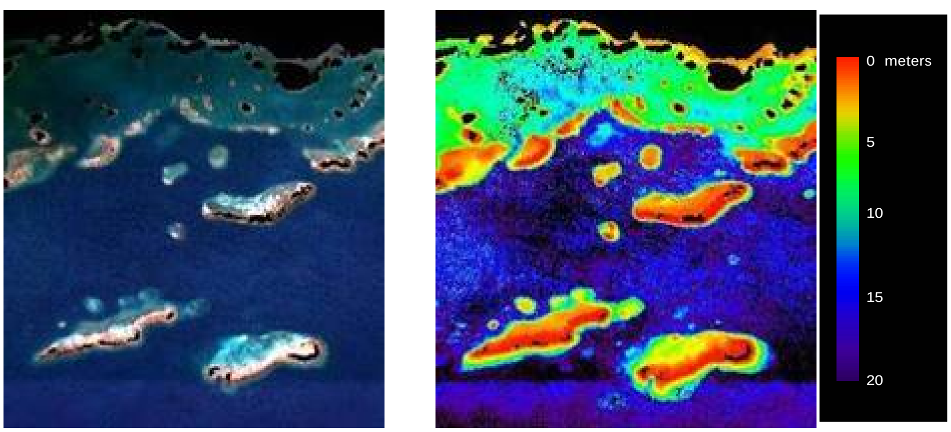
NASA's Airborne Visible/InfraRed Imaging Spectrometer (AVIRIS), operated by the Jet Propulsion Laboratory, is considered to be at the forefront of hyperspectral technology. Several AVIRIS flightlines over Puerto Rico were collected on August 19, 2004 covering much of the coastal areas of the island at 17 m spatial resolution, including the La Parguera study site (Figure 5a). Bottom types (Figure 5b) and bathymetry (Figure 6b) were obtained by processing the AVIRIS image according to

(a) (b)

Figure 5: AVIRIS image collected during August 19, 2004 over La Parguera (a) and benthic composition of Enrique Reef after image processing (b).

the following procedure (Goodman 2004):

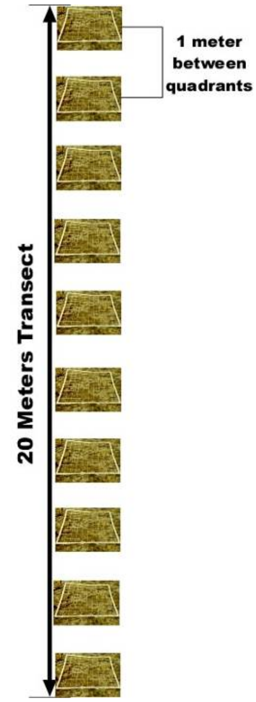
> <u>Preprocessing:</u> atmospheric correction and sunglint removal.
> <u>Inversion model:</u> semi-analytical optimization model used to retrieve bathymetry and water properties.
> <u>Forward model:</u> output from inversion model used as input to forward semi-analytical model to translate spectral endmembers (sand, coral and algae) to pixel-specific surface endmembers.
> <u>Unmixing model:</u> constrained non-linear unmixing model utilized to classify the benthic substrate as a function of the fractional contribution from each endmember.

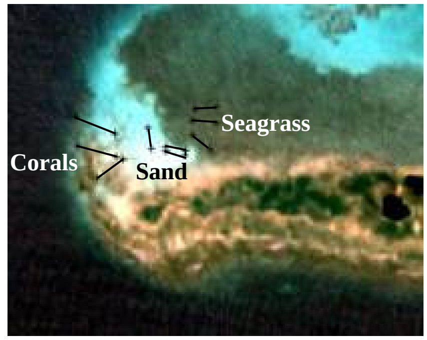


(a) **(b)**

Figure 6: AVIRIS color composite with land mask (a) and estimated bathymetry after image processing (b).

Field data collection for image validation was performed using standard methods of quadrants and transects (Figure 7a). Three 20-meter-long transects were located at random on each Enrique Reef benthic habitat (coral, sand, seagrass) (Figure 7b). Each transect included ten quadrants of 1 meter separated by a distance of 1 meter (Figure 7c). GPS locations and pictures were taken of each quadrant in order to locate ground points in the images and determine the bottom type.





(b)

(a) **(c)**

Figure 7: Field sampling at Enrique Reef. (a) Design of transects and quadrants, (b) IKONOS image showing the transect location according to bottom type in Enrique Reef, (c) Quadrant used to characterize bottom type.

AUTONOMOUS UNDERWATER VEHICLE

Remote sensing from airborne and satellite sensors becomes limited with increasing water depth due to the exponential attenuation properties of water. Therefore, autonomous underwater vehicles (AUVs), or other *in situ* platforms, are required to study the benthic habitat below approximately 20 m depth. As a leading instrument in this field, the CenSSIS Seabed AUV has been successfully deployed for the imaging and mapping of the deep coral reef zones (30-100 m) in the US Virgin Islands and Puerto Rico. The Seabed AUV is composed of two torpedo-shaped sections joined by vertical structural members (Figure 8a).The main sensor on the AUV is a high resolution digital camera (Figure 8b),

(a)

(b)

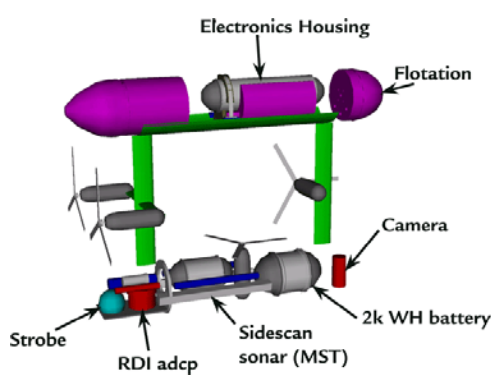


Figure 8: The Seabed AUV at the surface (a) and schematic diagram of the major components (b).

which was used to collect approximately 6000 images at the Hind Bank Marine Conservation District (MCD), U.S. Virgin Islands, at depths of approximately 30-54 meters. At the MCD, the AUV images were obtained at a constant distance of 4 m above the substrate covering an area of 7.75 m^2.Well-developed coral reefs with 43% mean coral cover were found at depths of 40 m (Armstrong et al., 2006). These AUV transects have provided the first comprehensive data set of the deep coral reef habitat of Puerto Rico and the U.S. Virgin Islands. This information is required by resource managers for selecting unique reef habitat areas for their protection and management.

The large number (in the order of thousands) of digital images acquired by the Seabed AUV requires an automated analysis procedure in order to extract quantitative coral information in a timely manner. The images acquired by the AUV usually have low contrast, can be noisy, and are extremely rich in both spectral variability and texture (Figure 9a). A classification algorithm developed for this analysis uses the Local Homogeneity Coefficient Segmentation Algorithm (Figure 9b) to automatically segment each image. The classification results are validated with the results of a manual classification using Canvas (Figure 9c).

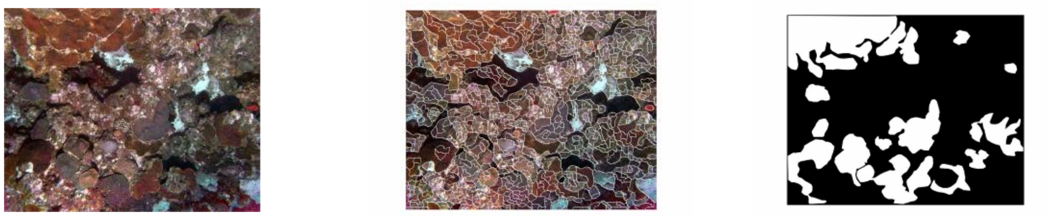


Figure 9: (a) Original image, (b) Enclosed areas are the result of segmentation using the LHC method, (c) Binary image classified using Canvas software.

CONCLUSIONS AND FUTURE WORK

As a core academic partner in CenSSIS, we are developing algorithms using hyperspectral, multispectral and other sensing modalities to extract subsurface information in aquatic environments. As part of this effort, SeaBED has been created as an algorithm validation testbed. SeaBED is composed of four different facilities: a lab based set-up, an outdoor tank facility, a field site located on a nearby reef in southwestern Puerto Rico, and an AUV for deep coral studies. SeaBED involves the collection of multiple levels of image, field and laboratory data needed to validate physical models, inversion algorithms, feature extraction tools and classification methods for subsurface aquatic sensing. In addition, the CenSSIS-developed AUV technology allows us to extend the study of coral reefs beyond the depth limit of effective airborne and satellite remote sensing. As SeaBED continues to evolve, we are working towards: (1) improving the indoor tank testbed using new illumination sources, (2) collecting new data sets for algorithm testing and validation using a SOC-700 HSI camera (3) developing a web-based interface for SeaBED to make it accessible to the general community, (4) organizing an airborne hyperspectral campaign over Puerto Rico, including La Parguera, to gather high spatial resolution hyperspectral imagery (<5 m) with well characterized underwater targets for spatial and temporal analyses, (6) assembling a spectral library describing the reflectance characteristics of specific targets (i.e., coral, algae and seagrass) and substrates (i.e., sand, rubble and mud) present in coastal Puerto Rico, (7) quantifying the spectral variability of water conditions (i.e., due to changing water constituents) in coastal areas, (8) continuing the field effort by CenSSIS students to perform a detailed field survey of habitat composition of Enrique Reef, and (9) expanding the current field work, image data collection, and algorithms development efforts to other benthic communities that are optically more complex.

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