Remote sensing of deep hermatypic coral reefs in Puerto Rico and the U.S. Virgin Islands using the Seabed autonomous underwater vehicle

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ABSTRACT

Optical imaging of coral reefs and other benthic communities present below one attenuation depth, the limit of effective airborne and satellite remote sensing, requires the use of *in situ* platforms such as autonomous underwater vehicles (AUVs). The Seabed AUV, which was designed for high-resolution underwater optical and acoustic imaging, was used to characterize several deep insular shelf reefs of Puerto Rico and the US Virgin Islands using digital imagery. The digital photo transects obtained by the Seabed AUV provided quantitative data on living coral, sponge, gorgonian, and macroalgal cover as well as coral species richness and diversity. Rugosity, an index of structural complexity, was derived from the pencil-beam acoustic data. The AUV benthic assessments could provide the required information for selecting unique areas of high coral cover, biodiversity and structural complexity for habitat protection and ecosystem-based management. Data from Seabed sensors and related imaging technologies are being used to conduct multi-beam sonar surveys, 3-D image reconstruction from a single camera, photo mosaicking, image based navigation, and multi-sensor fusion of acoustic and optical data.

Keywords: AUV, coral reefs, biodiversity, rugosity, remote sensing, Puerto Rico, USVI

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1. INTRODUCTION

The benthic community structure, biodiversity, and condition of deep (30-100 m) hermatypic (zooxanthellate) coral communities in the U.S. Caribbean and other tropical areas throughout the world remain largely unknown. This includes ecologically-relevant parameters such as percent coral cover, reef rugosity, incidence of disease, and species richness and diversity. Coral reefs are being increasingly threatened by the impacts of anthropogenic stressors and the effects of global change. Deeper reefs appear to be healthier than their shallow water counterparts and are known habitats of commercially important fish species. As the deeper shelf and upper insular slope zone in the Caribbean Region may be up to thousands of square kilometers in area, it is impractical to rely solely on diving surveys to adequately map and characterize these deeper coral reef habitats.

Due to the exponential attenuation of light in the water column, satellite and airborne remote sensing of benthic communities, even in clear tropical waters, is limited to depths of less than 20 m, or as defined by the attenuation depth ($Z_k = 1/Kd$). Therefore, the use of *in situ* platforms, for high-resolution optical and acoustic imaging, is required for mapping and characterizing the deeper reefs.

The Seabed AUV was conceived as an inexpensive alternative to provide high resolution imaging capabilities typically associated with large remote operated vehicles (ROVs) and other tethered vehicles. Under the auspices of the National Science Foundation’s Engineering Research Center for Subsurface Sensing and Imaging Systems (CenSSIS) the Seabed was developed along with the critical imaging technologies necessary for high resolution color imaging (1). As a leading instrument in this field, the Seabed AUV has already been successfully deployed for the imaging and mapping of the deep coral reef zones in the US Virgin Islands and Puerto Rico for 1) engineering tests and initial sea trials in southwestern Puerto Rico (2002), 2) benthic surveys of the Hind Bank Marine Conservation District (MCD), St.

Remote Sensing of the Ocean, Sea Ice, and Large Water Regions 2006,
edited by Charles R. Bostater, Jr., Xavier Neyt, Stelios P. Mertikas, Miguel Vélez-Reyes,
Proc. of SPIE Vol. 6360, 63600A, (2006) · 0277-786X/06/$15 · doi: 10.1117/12.692993

Thomas, USVI (2003), and 3) deeper insular shelf and slope surveys in Vieques Island and southwestern Puerto Rico (2004).

2. METHODOLOGY

2.1 The Seabed AUV

The Seabed AUV is composed of two torpedo-like body sections fixed to each other with vertical structural members (Figure 1). Measurements of velocity over the bottom, heading, altitude, pitch, roll, and integrated position are provided by a 300 kHz Acoustic Doppler Current Profiler (ADCP), which projects four sonar beams into the water. The forward pointing beam is utilized for obstacle avoidance. The Doppler position estimate is accurate to 1-5% of the distance traveled. A Paroscientific depth sensor provides depth information that, when combined with a dedicated vertical thruster, delivers depth accuracies in the order of centimeters.

The Seabed is hover capable and passively stable in pitch and roll. This makes it ideally suited for imaging applications such as side-scan sonar surveys, photo transects and bathymetric surveys. It has an operational depth of 2000 meters and at one meter per second can operate for up to 10 hours and survey 36 km per mission. The Seabed can integrate several optical and acoustic sensors such as a pencil beam bathymetric sensor, a high-resolution CCD camera, 300 kHz side-scan sonar, Seabird conductivity and temperature sensor, and a RDI ADCP (Figure 1). The high-resolution camera used for surveying the deeper coral reefs was a 1280 x 1024 12-bit camera (Pixelfly from Cooke Corp.) in a submersible housing. A 150 watt-second strobe is used for photographic illumination. The strobe is mounted 1.4 meters aft of the camera to reduce the effects of lighting backscatter in the images. The frequency of photos is a function of strobe recharge time (2.5 seconds). The size of the images is determined based on the altitude of the vehicle to the bottom and the field of view of the camera. An Imagenex 675 kHz pencil beam sonar is used to collect fine-resolution bathymetric data. More information on Seabed components, sensors, control systems, and navigation can be found in (1).

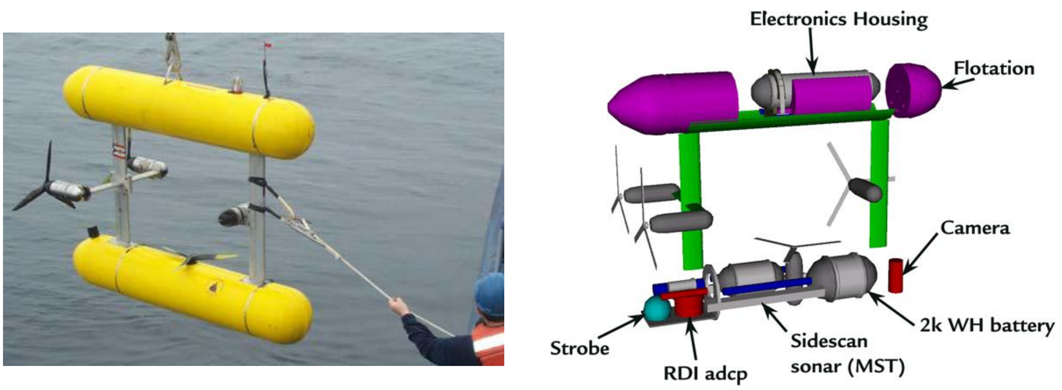
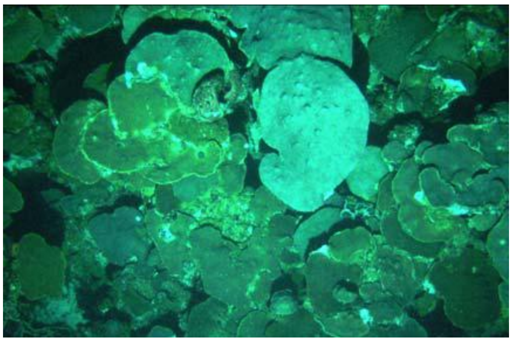


Figure 1. The Seabed AUV is a two hull hovering design with a 2000m depth capability and an endurance of 8 hours at speed ranging from 0-1.5m/s. Its present sensor suite includes a high dynamic range CCD camera, side-scan or multi-beam sonar, 675 kHz pencil beam bathymetric sonar and a 300 kHz acoustic Doppler current profiler.

2.2 Image Processing

Underwater imagery is typically characterized by low contrast and low color fidelity. The nonlinear attenuation of the visible spectrum in seawater causes parts of the visible spectrum to be preferentially attenuated. Thus most underwater images tend to be saturated in the blue-green region. The raw imagery is reprocessed to obtain three channel RGB images. The 12 bits of dynamic range provided by the camera that is part of Seabed allow us to compensate and color balance the imagery to obtain “true” color (Figure 2) and then allows us to mosaic these images into a composite view.



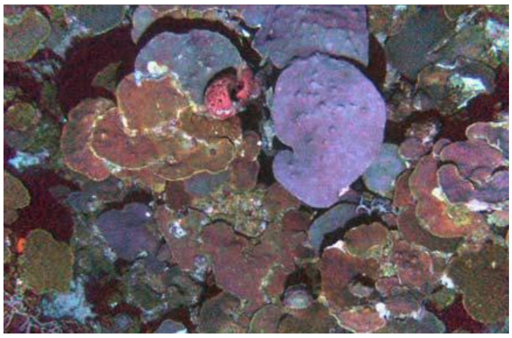


Figure 2. Original image (left) and the corresponding color compensated and normalized image (right). This image was taken on the Hind Bank MCD, south of St. Thomas, USVI at a depth of 36 m using the Seabed AUV.

3. RESULTS

For the coral reef surveys the Seabed, which runs at speeds between 0.3 m/s to 1 m/s, was programmed to run at minimum speed and to maintain a fixed distance from the bottom to avoid collisions in case sudden changes in bottom relief were encountered. As opposed to most other AUV's, the Seabed was designed to be hover capable, that is, to be able to independently drive in the X, Y and Z axes. The color-corrected imagery, in combination with precisely planned and well-navigated surveys can be used to build up composite image photomosaics of large benthic areas (Figure 3). This figure shows a mosaic of six overlapping images of the reef at the eastern side of the MCD. The area covered is approximately 2.5 m wide by 10 m long with a depth range of 44.6 to 45.4 m. This phototransect depicts the geomorphology of the deep reef at this location and some of the coral and sponge species present. The dominant coral throughout the MCD was the *Montastrea annularis* complex while the dominant sponge was the giant barrel (*Xestospongia muta*). Macroalgal cover was also abundant at these depths.

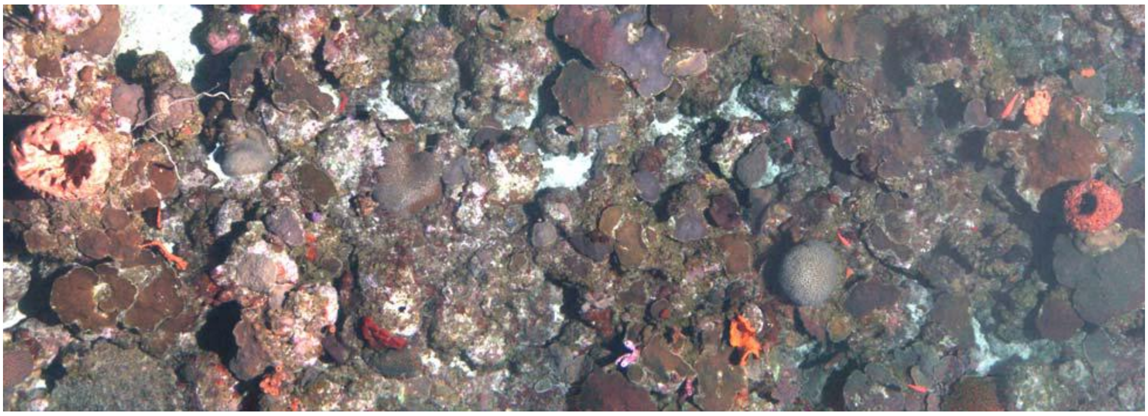


Figure 3. Photomosaic of the deep reef at the MCD showing corals, sponges, algae, some small fish, and sand.

The Seabed high-resolution color images have been used to characterize the major components of the coral reef community that includes corals, gorgonians, sponges, other macro-invertebrates, algae, and reef fish. 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 (1,2,3). We found high coral cover at depths of 40-47 m at several sites south of St. Thomas and St. John (USVI), and between 35-40 m at Black Jack Reef, Vieques Island. Each transect was approximately 1 km in length and produced over 500 images, each about 3.1 m wide by 2.5 m long, at the predetermined 4 m distance from the bottom (Figure 4).

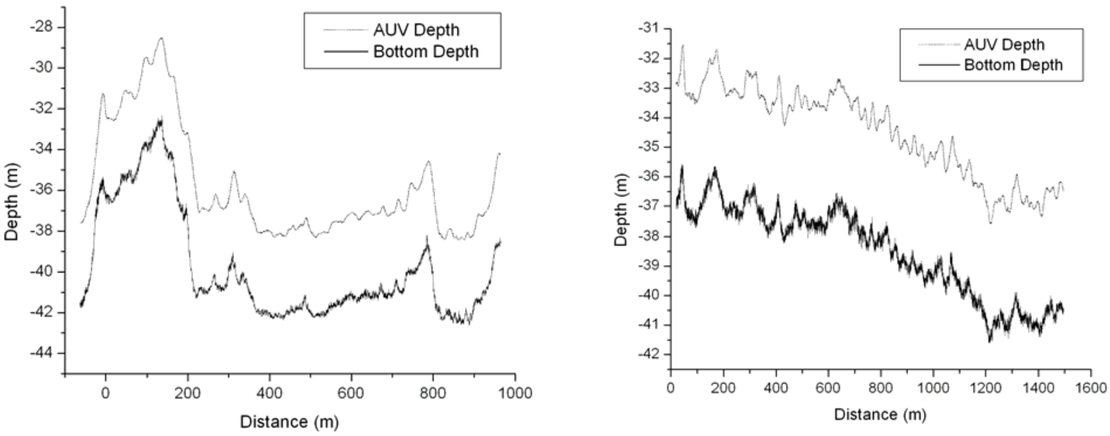


Figure 4. Bathymetry and Seabed altitude plots of two1 km transects at the western side of the MCD. These plots show that the vehicle can easily follow the bottom at the predetermined 4 m fixed altitude.

Although most of the analysis of the Seabed images for the quantification of benthic coral cover has relied on overlaying random points and visually classifying the various coral species, it is advantageous to automate recognition in order to eliminate the need for human interpretation and make the process faster (4). The dominant coral species present in most of the transects was *Montastrea annularis* complex, which occurs at these depths as flattened colonies and, with its small polyp size and smooth texture relative to other substrates, make it appealing to a texture-based recognition algorithm. An example of this image segmentation product is shown in Figure 5. Notice that only areas of living coral cover were selected in the output facilitating the quantification of corals in a large number of images.

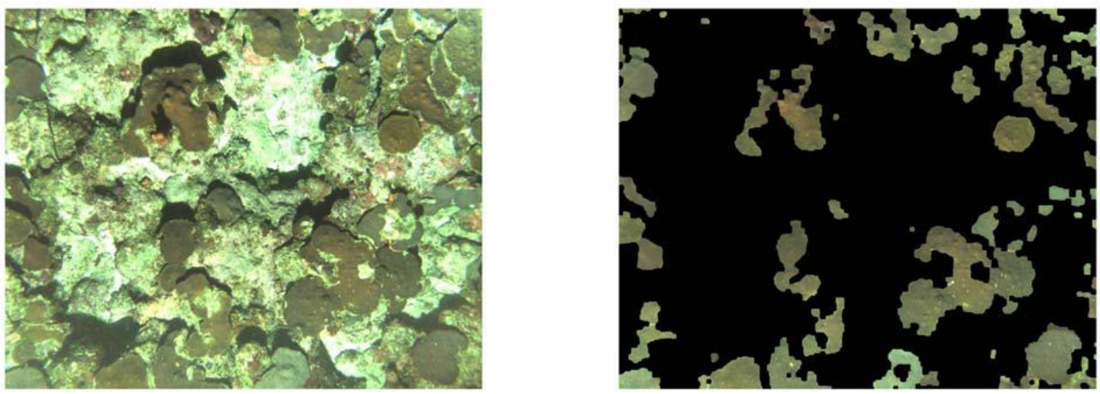


Figure 5. The reef at 40 m in the MCD (left) and the corresponding output from the segmentation algorithm showing only the benthic substrate covered by corals (right).

Very high resolution acoustic mapping, provided by the 675 kHz pencil-beam sonar, was used to derive the rugosity index of coral reefs from the Seabed AUV. Rugosity is an index of structural complexity and is an important ecological parameter that reflects the spatial distribution and density of many reef organisms. Traditionally, rugosity is obtained by measuring the length of a chain draped over the reef surface to the linear horizontal distance between the two end points using SCUBA divers. The Seabed measurements of rugosity provide, for the first time, data on this important ecological parameter beyond the depth of conventional SCUBA diving (Figure 6).

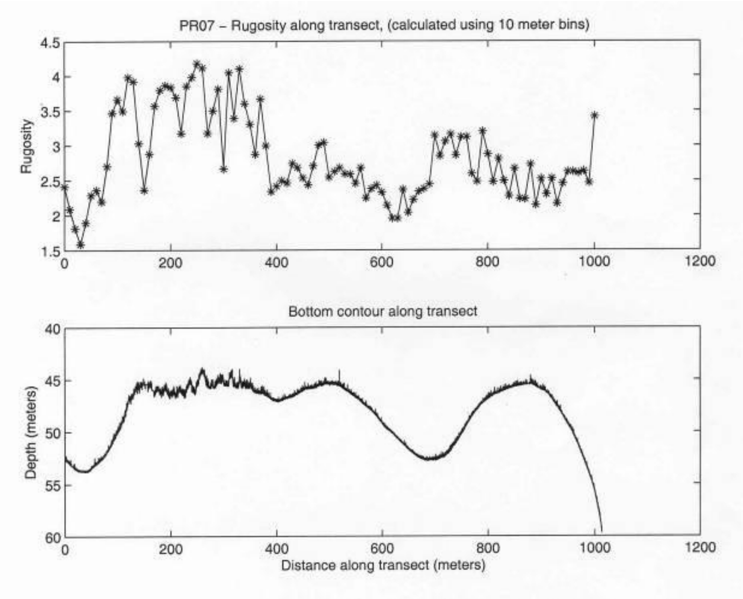


Figure 6. Acoustic rugosity from the pencil-beam sonar (top) and the corresponding bottom contour (below).

Chemical sensors have been recently added to the AUV to characterize important water biogeochemical properties that can help explain the distribution and spatial patterns of benthic organisms. The first instrument developed for the Seabed AUV for this purpose measured chlorophyll, colored dissolved organic matter (CDOM) and methane. Profiles of CDOM and chlorophyll obtained by the Seabed off southwestern Puerto Rico are shown in Figures 7 and 8, repectively.

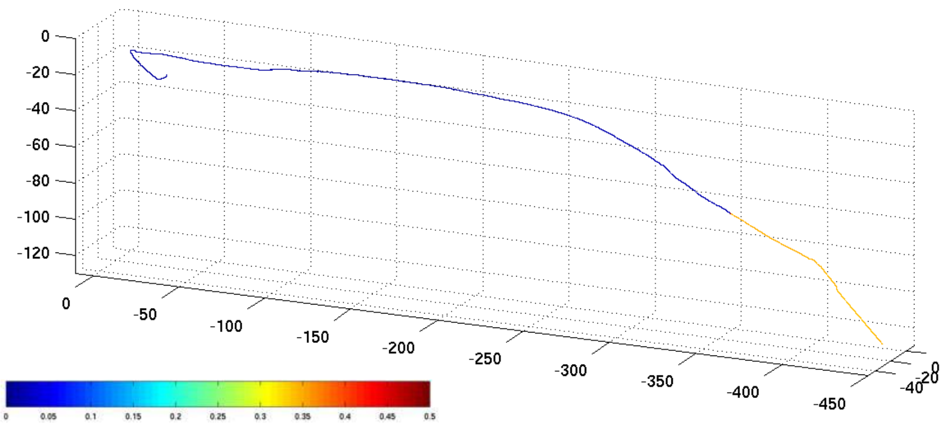


Figure 7. Profile of CDOM concentration from a Seabed transect off southwestern Puerto Rico.

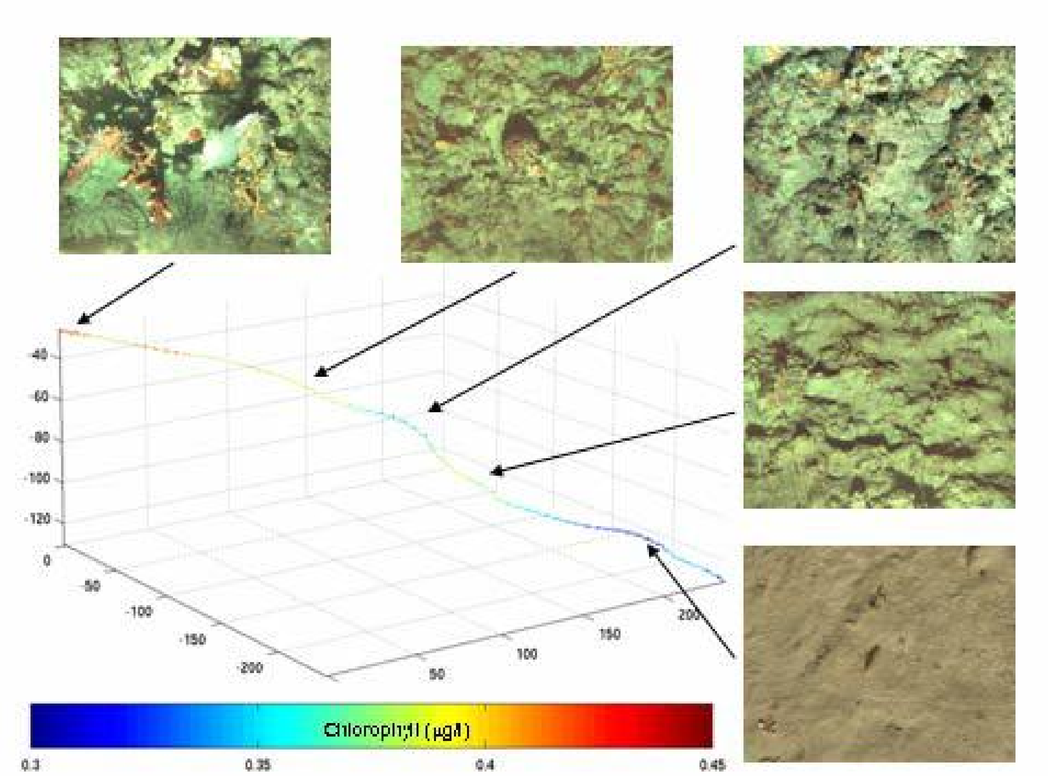


Figure 8. Chlorophyll concentration obtained from a Seabed transect off Guanica Bay, Puerto Rico and the corresponding benthic images at several depths.

The Seabed AUV is an ideal imaging platform for studies of deep-water (30-100 m) coral reefs and other benthic habitats. Fish, coral and other macro invertebrates can be identified in most cases to the species level. For most of the algae, however, only major groups could be identified. The Seabed AUV coupled with chemical sensors provides a new and optimal way of collecting information on water column biogeochemical properties overlying the marine benthos while maintaining a constant distance to the bottom. In addition to the pencil-beam sonar, the Seabed has been recently equipped with a multi-beam sonar for large-scale, high-resolution bathymetric surveys (Figure 9). The multi-beam acoustic microbathymetry data, when combined with optical data photomosaics, can provide an additional layer of information useful in coral reef benthic classifications. This is analogous in remote sensing to the fusion of visible satellite optical imagery with active sensor data such as synthetic aperture radar.

In the future, other optical imaging technologies such as fluorescence, multispectral and hyperspectral sensors could be used aboard the Seabed to provide information on ecological processes and the status of the deeper coral reef habitats. For example, fluorescence imaging can be used to identify small coral recruits that cannot be discriminated using RGB images. Multispectral and hyperspectral sensors could provide the additional data required to spectrally discriminate the various species of corals, detect coral diseases, and monitor recovery or mortality after bleaching events. A Video Plankton Recorder can also be integrated with the AUV to collect data on the distribution and abundance of zooplankton over deep reefs. Zooplankton is a critical food source for corals and could be an important food source for many fish that inhabit the deeper reef zones.

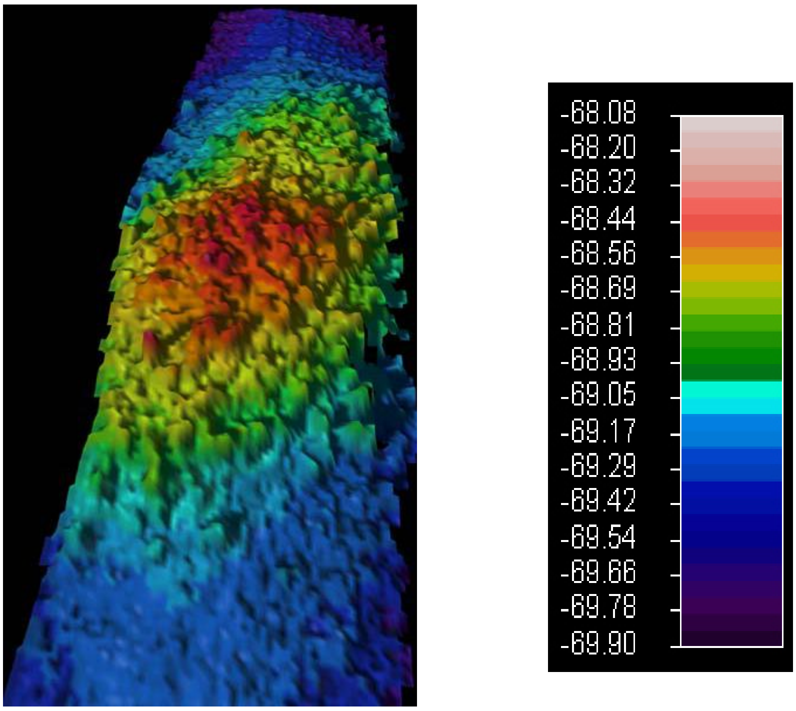


Figure 9. Acoustic microbathymetry of the seafloor using the multi-beam sonar of the Seabed AUV.

4. CONCLUSIONS

Data from the Seabed AUV sensors and related imaging technologies has provided unprecedented information on the community structure and condition of the deeper zooxanthellate coral reefs of Puerto Rico and the US Virgin Islands. The high-resolution optical images also provide useful data for inventories of the fish species present as well as lobsters, crabs and other macro invertebrates associated with these habitats. This information can be used by state and federal agencies to develop efficient management strategies to protect critical deep reef habitats. Multi-sensor data fusion, image-based navigation, 3-D image reconstruction, and chemical sensors are promising technologies that will augment the Seabed capabilities for remote sensing surveys and ecological assessments of these and other benthic ecosystems. The high-resolution imagery obtained by the Seabed AUV provided the first quantitative data of this important habitat. At more than 40 m depth, these shelf and upper insular slope reefs are beyond the limits of safe SCUBA diving operations. The high attenuation of the water column at this site also precludes the use of airborne or satellite remote sensing surveys.

ACKNOWLEDGEMENTS

Funding was provided by the CenSSIS ERC of the National Science Foundation under grant EEC-9986821 and by the Caribbean Fishery Management Council. We thank J. Kaeli for providing Figure 5 and Richard Camilli for Figures 7 and 8.

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