Detecting fish aggregations from reef habitats mapped with high resolution side scan sonar imagery

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Abstract—As part of a multibeam and side scan sonar (SSS) benthic survey of the Marine Conservation District (MCD) south of St. Thomas, USVI and the seasonal closed areas in St. Croix—Lang Bank (LB) for red hind (*Epinephelus guttatus*) and the Mutton Snapper (MS) (*Lutjanus analis*) area—we extracted signals from water column targets that represent individual and aggregated fish over various benthic habitats encountered in the SSS imagery. The survey covered a total of 18 km^2 throughout the federal jurisdiction fishery management areas. The complementary set of 28 habitat classification digital maps covered a total of 5,462.3 ha; MCDW (West) accounted for 45% of that area, and MCDE (East) 26%, LB 17%, and MS the remaining 13%. With the exception of MS, corals and gorgonians on consolidated habitats were significantly more abundant than submerged aquatic vegetation (SAV) on unconsolidated sediments or unconsolidated sediments. Continuous coral habitat was the most abundant consolidated habitat for both MCDW and MCDE (41% and 43% respectively). Consolidated habitats in LB and MS predominantly consisted of gorgonian plain habitat with 95% and 83% respectively. Coral limestone habitat was more abundant than coral patch habitat; it was found near the shelf break in MS, MCDW, and MCDE. Coral limestone and coral patch habitats only covered LB minimally. The high spatial resolution (0.15 m) of the acquired imagery allowed the detection of differing fish aggregation (FA) types. The largest FA densities were located at MCDW and MCDE over coral communities that occupy up to 70% of the bottom cover. Counts of unidentified swimming objects (USOs), likely representing individual fish, were similar among locations and occurred primarily over sand and shelf edge areas. Fish aggregation school sizes were significantly smaller at MS than the other three locations (MCDW, MCDE, and LB). This study shows the advantages of utilizing SSS in determining fish distributions and density.

Introduction

Ideally, fishery biologists dream of a sensor that, when placed in a water body, provides all density and meristic information of the fishes present in the water body. Even better, the sensor would also identify the fish species. In addition, all this information would be available synoptically for a large water area. In reality, such a sensor exists taking the shape of a single beam fish finder with a very narrow search cone extending from the surface to the bottom of the water body. Availability of acoustic sensors such as side scan sonar (SSS) and multibeam bottom sounders incorporating very fast processor capabilities are beginning to actualize the fishery biologist's dream (Fish and Carr, 1990).

Remote sensing techniques offer a viable option for mapping marine habitats, determining not only the location and amount of distinct benthic habitats, but also how these habitats are distributed and their degree of connectivity. In tropical regions, specifically in coastal waters, the use of traditional passive sensors (Ikonos or Landsat 7 satellites, aerial photographic camera) is restricted because light is exponentially absorbed by the water column, phytoplankton minimize remote benthic reflectance, and colored dissolved organic matter alters measured wavelengths (Roesler and Perry, 1989; Gordon and Wang, 1994; Lee et al., 1994; Arono and Gould, 1998). Even in clear water, the bottom signature can be inconclusive because it is the result of mixed spectra, which becomes more complicated with depth (Mumby et al., 1998). Existing passive sensors are also limited by low spatial resolution and lack of information from deep or turbid areas with high cloud cover. Additional problems result from back scattering from inorganic suspended particles, which add noise and may modify the bottom signal reaching the sensor. To avoid confusion between water and bottom signatures, bathymetry measurements and knowledge of water attenuation is required. Elevation models for reef areas, when available, are often inaccurate because they do not include a complete coverage of depth and they lack precise positioning. Lizenga (1978, 1981) developed the depth-invariant bottom index, which is widely applied when mapping benthic habitats regardless of algorithm limitations. Despite the above limitations, passive sensors are currently the preferred mapping tool.

An alternative to passive sensors is the use of active remote sensors. Active sensors emit a signal and detect the intensity of the signal reflected from an object. Active remote sensing in the oceanic environment is feasible using acoustic or optical techniques. An optical sensor (using a laser) can have excellent spatial resolution (cm or mm, depending on the altitude of the sensor), but accuracy falls off rapidly with increasing range; therefore its use is limited to a swath of 3–5 m (Klepsvik et al., 1994). At this time, laser sensors are too expensive and time-consuming to be an option for mapping large areas (10s km^2 or larger).

The remaining alternative, the use of acoustic technology such as SSS, is a promising approach for mapping coral reefs. By selecting an appropriate SSS system it is possible to obtain images of features as large as seamounts or as small as sand ripples. SSS images can be combined to generate mosaics over large areas, showing all structures and their position in a planimetric manner. To solve this limitation, SSS data can be combined with high resolution multibeam echo sounder, which adds depth data as a third dimension to the SSS images. The merging of these technologies has rapidly become the preferred mapping tool for accurate positioning and navigation.

SSS technology was used for the first time in 1963 in England and has been routinely used by hydrographers to help determine the characteristics of the ocean bottom in the making of nautical charts. SSS is especially valuable in identifying bottom objects in turbid waters. Historically, SSS has been used to map seabed configuration and predominant bottom targets for petroleum industry applications, dredging, and mine hunting. Geologists and geophysicists see fish and other water column signals as interference that affects the interpretation of the ocean bottom features. Such signals are eliminated from the sonar record during either acquisition or post processing. The utilization of SSS for environmental and fisheries applications is more recent (Siljestrom et al., 1996; Friedlander et al., 1999; Karl et al., 1994).

The advantage of using SSS over conventional single beam fish finders to locate fish echoes is the added volume sampled per transducer signal or ping. Typically, SSS can sample out to a range of 10–100 m on each side of a transducer, depending on the range setting and transducer frequency. The single beam transducer sampling area depends on depth and transducer beam geometry. The shallower the depth, the smaller the area sampled. All SSS systems marketed today are designed for working in relatively deep water (>10 m depth). This limitation is primarily due to the mechanical design for transducer deployment and recovery and the undesirable interaction of the transmitted sound wave with the water surface and the propeller wash. In deeper water, this problem is avoided by submerging the SSS transducer to the lower 30% of the water column.

In October 1996, Congress re-authorized the Magnuson-Stevens Fishery Conservation and Management Act (Public Law 94-265) with amendments (Kantor et al., 1996). One amendment in Title III, section 305 mandates Fisheries Management Councils to revise all Fisheries Management Plans (FMP) to include delineation of “essential fish habitat” (EFH) by October 1998. Although some FMPs will benefit from existing information portrayed in map format, other FMPs will not have such information. Information for these FMPs will be collected and relevant maps produced. The main objective of our work was to contribute to the formulation of EFH maps for the Caribbean Fishery Management Council (CFMC) in the United States Virgin Islands Exclusive Economic Zone (EEZ). The aim of the marine surveys was to provide high resolution bathymetry and SSS maps of the seabed and detailed maps of the benthic habitat at three designated conservation areas. The survey areas were designated as follows: Marine Conservation District (MCD, south off St. Thomas), and Lang Bank and Mutton Snapper (LB and MS, east and south west off St. Croix respectively). The work reported concentrates on the fish signals encountered in the SSS mapping of the seabed.

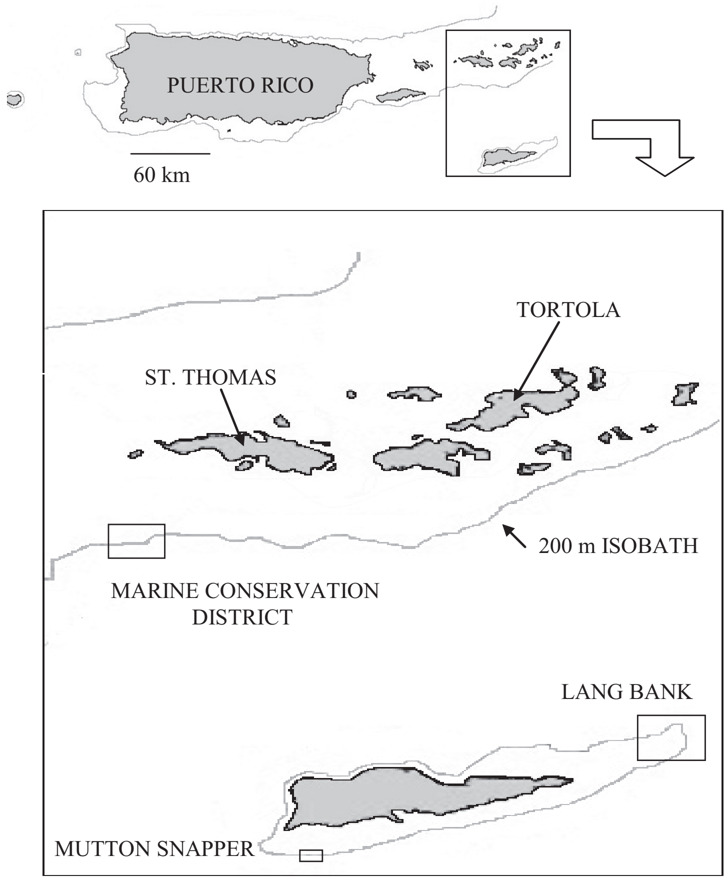
Materials and methods

Survey region and equipment deployment

Surveys were conducted on St. Thomas, USVI in the recently developed Marine Conservation District East (MCDE) and West (MCDW, Fig. 1). The data acquisition was carried out from a chartered 17 m Grand Banks wood cruiser, with dual inboard motors, Onan service generator, Raytheon autopilot, and GPS navigation system. Several remote sensing technologies were deployed from this single vessel for navigation and hydroacoustic surveying (Fig. 2). The vessel cruising speed is 8 knots.

Positioning

The survey extended from 9 April to 31 May 2003. Vessel positioning was achieved using a Trimble Series 5700 Real-time Kinematic Global Positioning System (RTK GPS). The transmission of positional corrections from a base station transmitter on shore allowed horizontal and



MARINE CONSERVATION DISTRICT

1.	18º 13.2í N	65º 06.9í W
2.	18º 13.2í N	64º 59.0í W
3.	18º 11.8í N	64º 59.0í W
4.	18º 10.7í N	65º 06.9í W

LANG BANK

1.	17º 49.3í N	64º 27.9í W
2.	17º 49.3í N	64º 26.8í W
3.	17º 48.3í N	64º 25.9í W
4.	17º 48.3í N	64º 26.8í W
5.	17º 47.3í N	64º 28.0í W
6.	17º 47.3í N	64º 26.8í W

MUTTON SNAPPER

1.	17º 37.8í N	64º 53.0í W
2.	17º 39.0í N	64º 53.0í W
3.	17º 39.0í N	64º 50.5í W
4.	17º 38.1í N	64º 50.5í W
5.	17º 37.8í N	64º 52.5í W

Figure 1

Location of three mapped areas.

vertical accuracy of the order of 5 cm to be achieved. A Pacific Crest PDL radio modem on the survey vessel received the positional corrections.

A laptop computer ran the Hypack Max (version 2.12, Coastal Oceanographics, Inc., Middletown, CT) navigation software aboard the survey vessel. Latitude and longitude measured by the RTK GPS system were stored at the rate of five readings per second on the laptop's hard drive. These were converted into Cartesian (X, Y) coordinates of the local grid used for surveying. The Universal Transverse Mercator (U.T.M.) projection system (Zone 20-N), with the WGS-84 datum was used for horizontal positioning. Current vessel position relative to the local grid was displayed on a screen dedicated for use by the vessel captain. The Sonarwiz (version 1.65, Chesapeake Technology, Inc., Mountain View, CA) SSS data acquisition software system was linked to Hypack Max via multiple RS232 interfaces. During data acquisition, the SSS output data were attached to the (X, Y) grid position and stored on hard disk. The various instrument offsets relative to the GPS antenna were entered into the data acquisition systems, allowing real-time positional corrections to be carried out. The vessel was also equipped with a Meridian Surveyor gyrocompass from S. B. Brown Ltd., which was used to provide precise heading information during surveying.

Swath bathymetry

We use a Geoacoustics, Ltd., Geoswath 250 kHz phase comparison system to conduct the swath bathymetry. Complete equipment specifications can be found in Appendix A. The transducer V-plate was installed in a position directly off the port side of the vessel, 0.91 m from the stern. The V-plate mounting contains a motion reference unit (MRU) and the port and starboard trans-

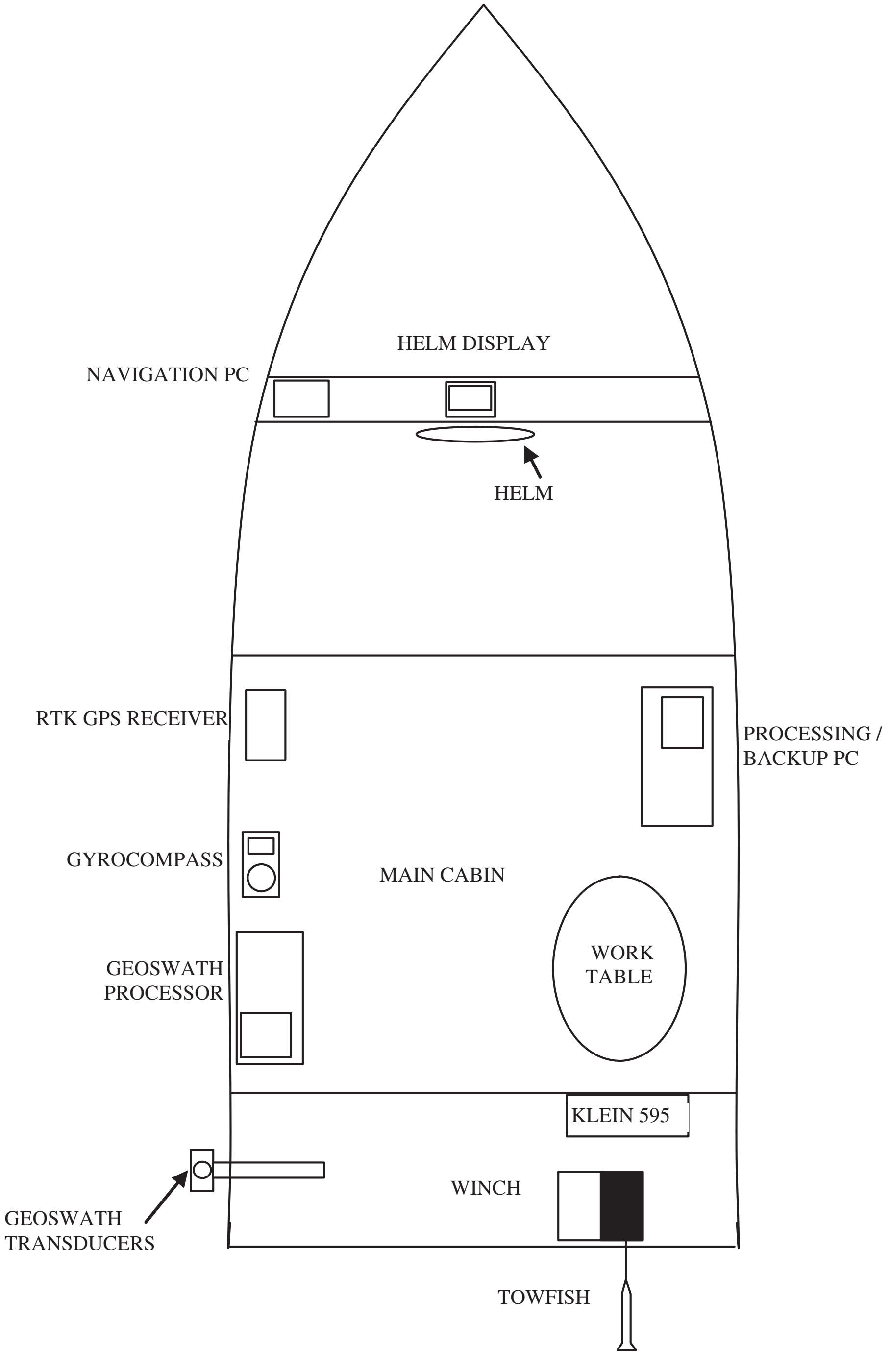


Figure 2

Survey vessel equipment layout diagram.

ducers. The V-plate assembly was fixed at approximately 1.1 m beneath the waterline, and was secured using an anodized aluminum mounting pole attached to a swivel over the side mount. The vertical pole was locked at the top end, and steel guy wires were run from the V-plate to the amidships and the stern of the vessel to ensure the V-plate was stable. Signals from the transducers and MRU were sent to the Geoswath processing unit, located in the main cabin of the vessel. This PC-based system ran proprietary software (version 2.07s, Swath32, Geoacoustics, Ltd., Norfolk, UK) on the Microsoft Windows® 98/Me operating system.

Correction for survey vessel heave, pitch, and roll was performed through the use of a dynamic motion sensor (DMS) from TSS Limited, located in the V-plate assembly between the transducers. The DMS from TSS Limited is the MRU. The DMS was connected to the Geoswath system via an RS-232 connection, enabling correction of the bathymetric data for heave, roll, and pitch in real time.

Sound velocity profiles

For the Geoswath system to accurately survey the seabed, precise information on the water column sound speed profile is required. This information was acquired by lowering a Valeport DigiBar sound velocity probe through the water column at approximately 1 m intervals. The sound speed profile was entered into the Geoswath software to accurately convert the raw data into depths.

Side scan sonar

The side scan sonar system utilized was a Klein Model 595. Data was captured using a Klein 590 Digital Graphic Recorder unit, and subsequently transferred to a PC running Sonarwiz data acquisition software. Although the tow fish was a dual frequency fish, capable of acquiring data at 100 kHz and 500 kHz, only the 500 kHz data was analyzed. The instrument range was set at 50 m on each side of the sonar transducer. During data acquisition, the vessel speed was maintained between 2 and 5 knots, while the tow fish was kept between 5 and 10 m off the seabed. The length of cable out was controlled by an electric winch. This length was entered into the SonarWiz program, which allowed a layback calculation to be applied to the sonar image navigation coordinates. Navigation was supplied to the SonarWiz system through serial communication of the NMEA GLL data string generated by Hypack Max at the rate of two readings per second. The navigation string was corrected for the offset between the vessel reference position and the winch tow-block position.

Side scan sonar data processing

The raw side scan sonar data consisted of a digital file in standard XTF format. SonarWeb software (version 3.15G, Chesapeake Technology, Inc., Mountain View, CA) was used to process the XTF file into mosaic form. Before utilization of SonarWeb, some pre-processing of the side scan data was necessary. This was accomplished using GPR's proprietary dedicated software to smooth the navigation data and correct for the slowly varying amount of cable out. Once the navigation data was corrected, the XTF files were partitioned into separate blocks of 1.86 km^2. This was necessary due to the scale requirements for the maps, and due to file size limitations in creating the mosaics using SonarWeb. Once the XTF files were correctly partitioned, they could be imported into SonarWeb. Each 1.86 km^2 area was processed as a separate project.

The underlying purpose of each project was to produce finished sonar mosaics at high resolution for display and analysis. The most critical and time-consuming task was tracking the return from the seabed (bottom-track) for all the SSS data (Fig. 3). Bottom-tracking had to be carried out by manually digitizing the return since the automated tracker provided in the software was not sufficiently accurate. Bottom-tracking allowed the water column to be accurately measured and its influence removed, so as to provide slant range corrected data. Once all the files in a project were accurately bottom-tracked, the mosaic was generated using a set resolution and color scheme.

No beam angle corrections were made to the mosaic data in order to obtain maximum signal contrast. The mosaics were exported in geotiff format, and then imported into a separate software package for visualization/map preparation. These mosaics were subsequently used to perform habitat mapping.

Delineation of habitat from SSS mosaics

A total of 28-1.86 km^2 mosaics in geotiff format from SSS imagery processed at 0.2 m resolution were used to generate detailed benthic habitat maps through visual interpretation and delineation. Interpretation was aided by the availability of geotiff mosaics from multibeam bathymetry processed at 1 m resolution, which provided a three dimensional perspective when assigning a habitat class to an area. Habitat maps were created using ArcView (version 3.2, Environmental Systems Research Institute, Inc., Redlands, CA) and projected in Universal Transverse Mercator (UTM) coordinates for UTM-83 Zone 20. Digitization utilized the ArcView extension Habitat.avx v 1.2 developed by the NOAA/NOS/Biogeography Team[1].

A modified version of the hierarchical habitat classification scheme developed by Prada (2002) was used to run the Habitat extension, which contained a total of 23 different habitat types (one more than originally defined (Table 1)). The hierarchical classification scheme was developed after qualitative observations were conducted at 107 sites in fifteen 1.86 km^2 areas

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[1] NOAA/NOS Biogeography Team. 2002. Benthic habitats of Puerto Rico and the U.S. Virgin Islands. CD-ROM, Silver Spring, Md. Available from http://ccmaserver.nos.noaa.gov/products/biogeography/benthic/order.shtml

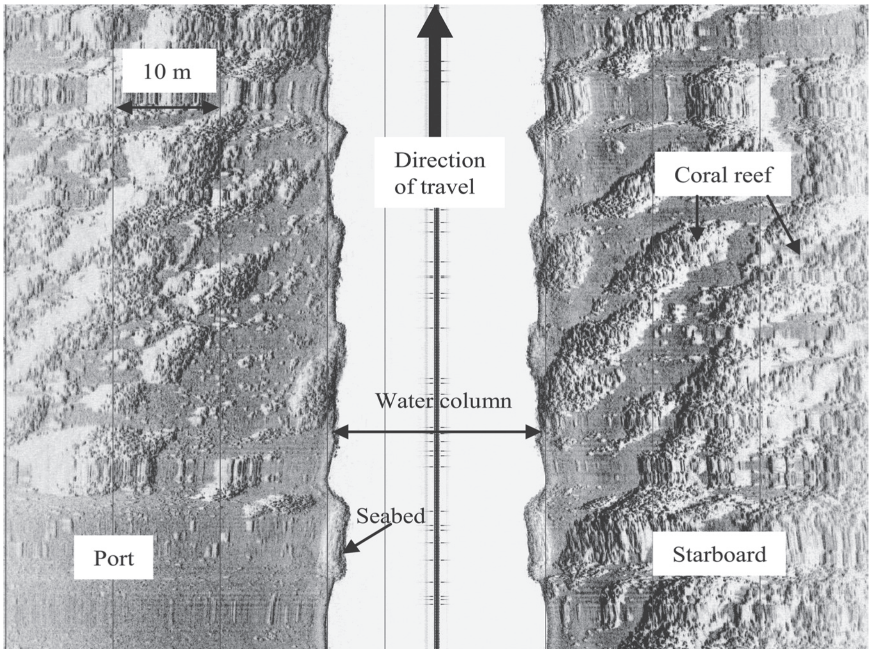

Figure 3
Example side scan sonar record with water column (before slant range correction).

corresponding to their respective SSS mosaics. Each habitat type was visited at least three times within a SSS depicted habitat. Habitat types were based on detailed observations of the SSS mosaics performed at a series of spatial scales (1:500, 1:1000, 1:2500, and 1:5000). The qualitative observations were obtained by videotaping through an underwater drop video camera an average of three minutes per location from a small boat while slowly transiting. Quantitative measurements were conducted at an additional 59 sites. The quantitative data were taken in 5–6 replicates within each sampled habitat type by a team of 4–5 divers. At each location, four quadrants of $1m^2$ were randomly placed along a 48 m metric tape. Within each quadrant, divers estimated the percent cover of sand, rubble, live coral, dead coral, gorgonians, sponges, macro algae, sea grass, and Cyanophyta. Number and size (length, height, and width) of each live colony of hard corals, gorgonians, and sponges within the quadrant were also recorded. Additionally, twelve rugosity estimates were taken at each location using a 3 m (2 cm link) chain laid along the metric tape. Percent cover and presence or absence data were then analyzed utilizing the Ochiai Index (Ochiai, 1957) and detrended correspondence analysis (DCA) to ordinate the habitat types by levels of complexity. The scheme was organized into four levels of complexity. The first level grouped habitats in three meta-communities designated: corals and gorgonians on consolidated sediments, submerged aquatic vegetation (SAV) on unconsolidated sediments (algae and sea grasses), and unconsolidated sediments (Fig. 3).

Map colors were similar to the palette defined in Prada (2002) to easily identify habitat types. The new category was included within variations of the color green. Most habitat maps overlap 100–200 m in every direction, with the exception of the MS area that had no overlap. Small areas (hundreds of meters) in the MS area, and a larger (thousands of meters) area at LB had no SSS information, which consequently resulted in gaps in the habitat maps.

Quantitative determination of habitat classification map accuracy at the MCDW and MCDE areas by using existing ground truth video was not performed because available video lacked precise frame specific time or geo-positioning. However, a general idea of habitat classification map accuracy was obtained by comparing underwater benthic pictures obtained from an Autonomous Underwater Vehicle (AUV)[2] and drift transects from a digital video underwater camera with

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[2] Autonomous Underwater Vehicle Expedition. 2003. Caribbean Fisheries Management Council AUV Expedition to the MCD south of St. Thomas, USVI. Collection of digital photo transects. Caribbean Fisheries Management Council, 268 Muñoz Rivera Ave., Suite 1108, San Juan, PR 00918-2577.

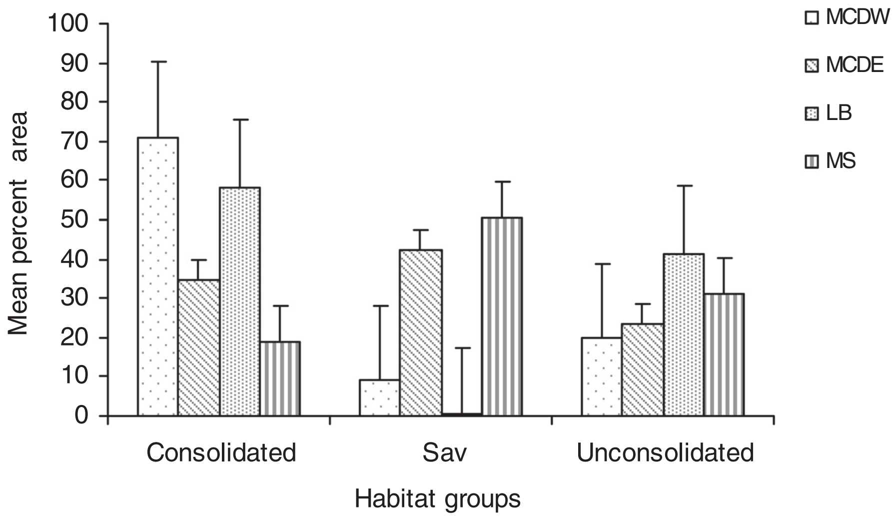


Figure 4

Mean percent area for the three habitat groups in the mapped area. Error bars indicate one standard error.

Table 1

Hierarchical classification scheme of benthic habitats used to generate detailed habitat maps (Modified from Prada, 2002).

Meta-community	Community	Sub-community	Habitat types	Habitat Codes
Coral and gorgonians on consolidated sediments	corals	coral high relief	Continuous Corals	COCO
		coral patch	Coral Patch	COPA
		coral low relief	Coral Limestone	COLI
		gorgonian patch	Gorgonian Patch	GOPA
	gorgonians	Plains	Gorgonian Plains	GOPL
		elevated plains	Elevated Gorgonians	ELGO
Submerged Aquatic Vegetation (SAV) on unconsolidated sediments	seagrass	Seagrass	Dense Grass	DEGR
			Sparse Grass	SPGR
			Grass-Invertebrates	GRIN
			Grass Halo & Coral Patch	HALO
	macro-algae	algae on sand	Dense Algae	DEAL
			Sparse Algae	SPAL
			Algae & Invertebrates	ALIN
		algae on silt	Shallow Algae	SHAL
			Deep Algae	DEEP
Bare or mixed invertebrates on unconsolidated sediments	sand	coarse sand	Sand Invertebrates	SAIN
		Sand no Ripple	SANR	
			Sand Ripple	SARI
		fine sand	Fine Sand	FIMU
	silt	mud	Mud-Invertebrates	MUIN
			Mud Bare	MUBA
			Mud Reef	MURE

habitat classification maps at presumed AUV transect lines. Estimation of habitat classification accuracy for maps for the MS and LB areas could not be conducted, even at the qualitative level, due to lack of ground truth; consequently these maps may need correction.

Habitat polygons were visually delineated from a Viscon FV170, 40.8 cm LCD monitor with high contrast ratio (350:1). Habitat polygon classification is based on the texture, brightness, and shape of the benthic habitat features on the high resolution SSS imagery.

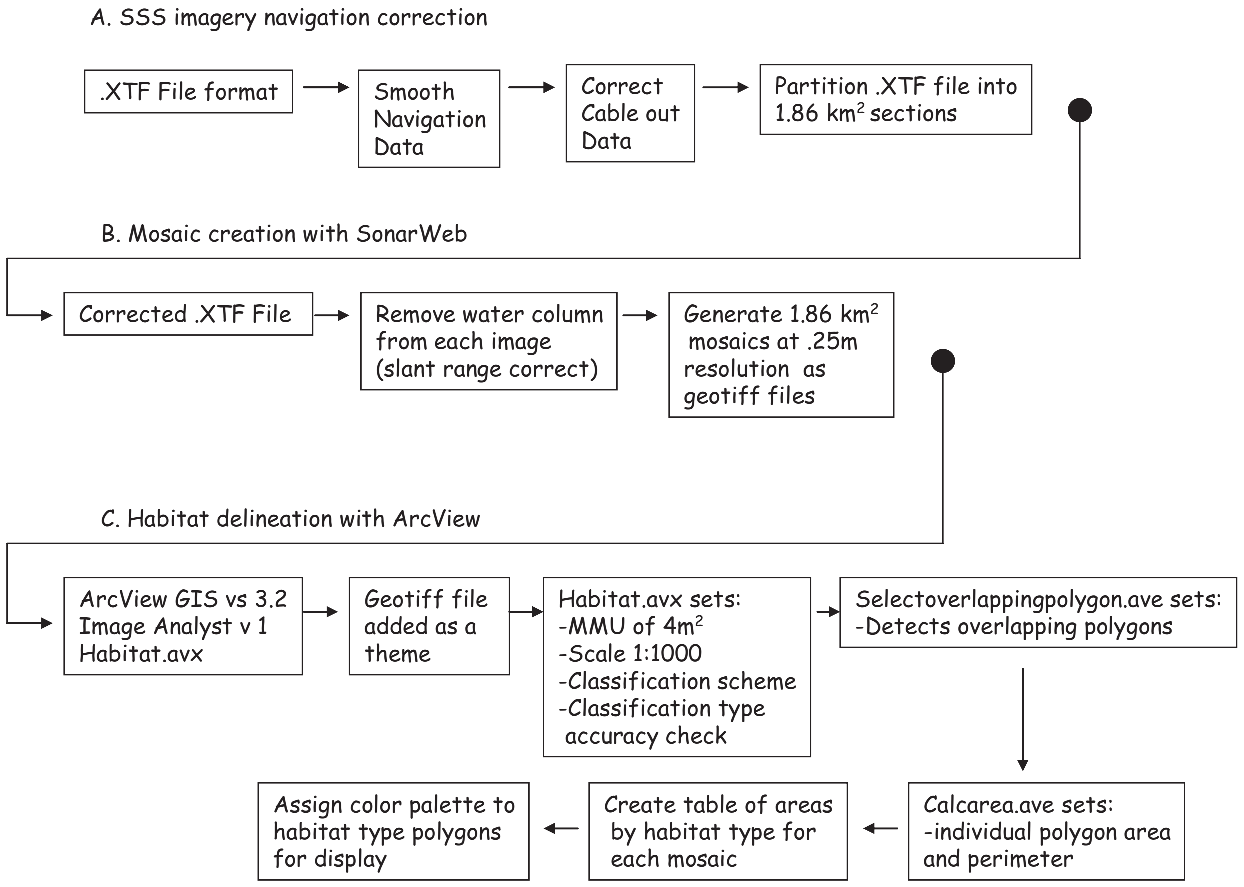


Figure 5

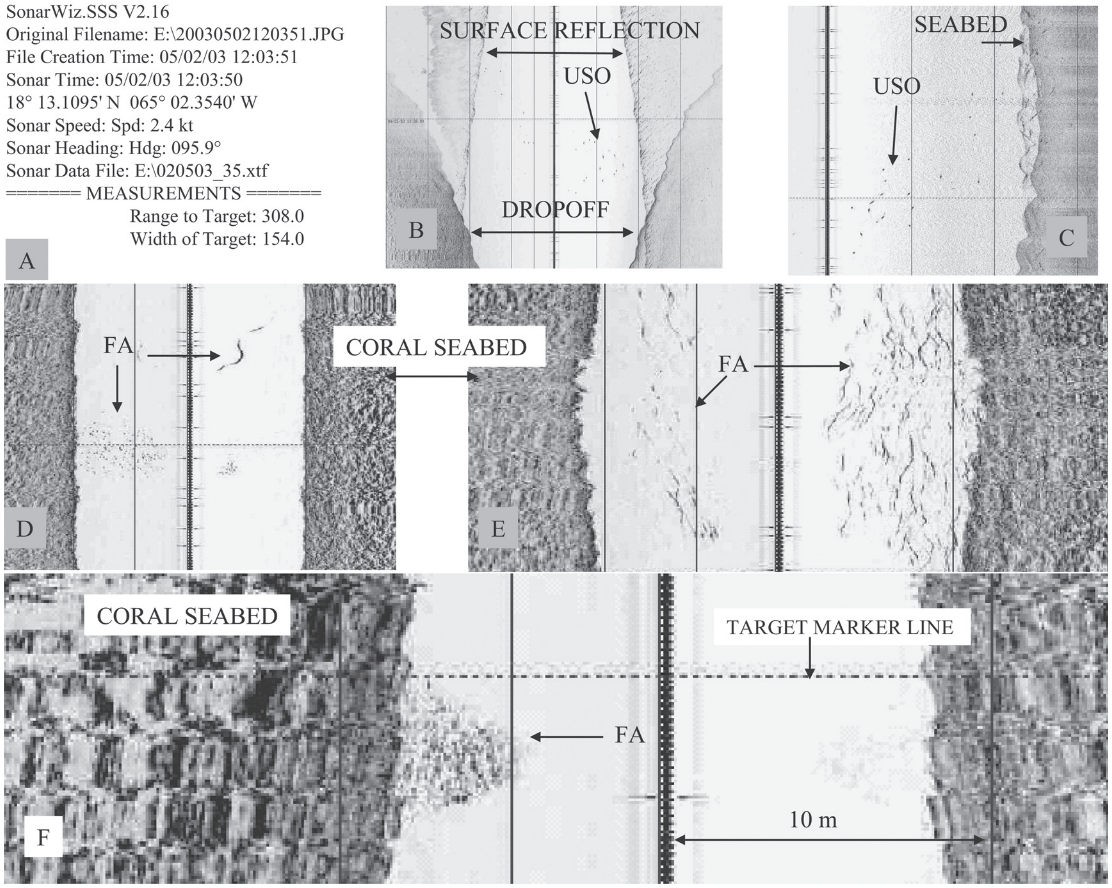
Flow diagram of SSS data processing procedures. A) SSS imagery navigation correction. B) Mosaic creation with SonarWeb. C) Habitat delineation with ArcView.

The interpreter's accumulated experience and ground truth information were also taken into account. Ground truth information consisted of a 1.10 hour digital video available for drift transects for MCDW (mosaics 2, 3, 4, 5, 6) and MCDE (mosaics 2, 3) which covered a total length of approximately 2.3 km. In addition, high resolution underwater pictures (foot print of 2 × 2 m) taken by an AUV were provided by the CFMC for four 1 km transect lines at MCDW (mosaics 1, 2, 10) and MCDE (mosaics 6, 7).

Data processing of the SSS habitat survey data involved a series of events in order to differentiate habitat types according to prescribed classifications and to isolate water column signals that would represent individual fish or aggregations of fish (Fig. 5). Prior to initiating the digitizing process, within the Habitat extension a Minimum Mapping Unit (MMU) of 4 m and an image scale of 1:1000 was defined. At the end of digitization of each image mosaic, resulting small polygons were joined if they shared a boundary and had the same classification type. Habitat type classification accuracy was checked utilizing the Habitat extension routine. Overlapping polygons (generated after polygon junction) were detected by running the ArcView script SelectOverlappingPolygons2.ave. Once detected, overlapping polygons were separated to ensure the correct habitat type classification. The use of the Calcacre.ave ArcView script allowed inclusion of individual polygon area and perimeter into the map's attribute table.

Processing of fish signals

As the SSS data was being displayed and acquired by SonarWiz, two viewers made a visual inspection of all water column echo returns. Every time an echo suggesting fish was detected in the water column, the signal was saved as a target image in "jpg" format. In addition to the raster image, an ancillary text file was also saved simultaneously containing image position, name and saved location information (e.g., Fig. 6).



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SonarWiz.SSS V2.16
Original Filename: E:\20030502120351.JPG
File Creation Time: 05/02/03 12:03:51
Sonar Time: 05/02/03 12:03:50
18° 13.1095' N  065° 02.3540' W
Sonar Speed: Spd: 2.4 kt
Sonar Heading: Hdg: 095.9°
Sonar Data File: E:\020503_35.xtf
======= MEASUREMENTS =======
                Range to Target: 308.0
                Width of Target: 154.0
```

Figure 6

Example of unidentified swimming objects (USO) and fishing aggregations (FA) target images and ancillary text file with position and reference information. All images are from MCDW and MCDE. A) Ancillary text file with position and reference information. B) Port and starboard transducer SSS image record separated by center black line. USO's are represented by black dots. Image is from MCDW at shelf drop off. C) USO target image from right SSS transducer only to provide more detail. D) FA signal patterns pointed out by arrows. Benthic habitat is primarily flatten coral plate (*Montastrea spp.*). E) Undulating fish signals indicate swimming movement relative to SSS transducer. F) Bell shaped FA pointed out by arrow. Target marker line is correlated with target data file for locating position.

At the end of each data collection day, fish target image files were cataloged by date and survey line number. After cataloging, each target image was visually inspected to verify that the signal saved was a possible fish signal return. The cataloged ancillary target image text files were then transferred into an Excel spreadsheet in preparation for spatial analysis. All geographic positions were converted into UTM 83 Zone 20 northing and easting grid values for plotting in the GIS using the geodetic conversion software Tralaine (version 5.17, Mentor Software, Inc., Golden, Colorado). The coordinates for each target file were then plotted as a point overlay on available habitat maps. Using the Geoprocessing tool in ArcView, information on habitat was introduced into the point attribute table. This allowed estimation of the total number of USOs and fish aggregations (FAs) by habitat type. Some points had no benthic habitat classification because their position placed them on the shelf edge; these were classified as shelf edge (Table 1). Some target files contained more than one FA; therefore number of locations may differ from the number of FAs.

Individual FAs were digitized from georeferenced target files using ArcView. These target files raster images were transformed from .jpg format to .bmp format in order to permit ArcView to process them. A pixel size of 0.15 m was specified for all target files into the final text file containing the georeference. The whole dataset of FAs was then divided into four subsets to match their respective locations: MCDW, MCDE, LB, and MS. Bathymetry and habitat maps were also parsed by location.

Digitizing of each FA signal area was performed at a scale of 1:1000 (same as that generated for habitat maps). It was not possible to estimate FA density based on fish counts within a FA image mainly because resolution was lost in raster transformation and in some cases the fish density was too high to permit discrimination of individual fish signals. Calculation of FA signal area was then obtained by running an ArcView Script (Calcacre.ave) on the delineated and digitized polygon file. The attribute tables of all the polygon files created for the four studied areas were copied into an Excel worksheet for statistical analysis. Georeferencing of the FAs may not be as precise as bathymetry or SSS data, since a target file position is referenced to the first raster line of the image; however, the FA position will be within 10 m of the target file reference position.

Results

Location of mapped areas

In total, more than 800 km (average of 30 km of line per day) of line survey were run to collect the bathymetry and side-scan sonar data. The total area covered by the bathymetric survey was approximately 18 km^2. Slightly less coverage was obtained with the SSS due to the entanglement of SSS transducer with surface buoys from fish traps, affecting collection of imagery for partial areas of LB and MS.

Bathymetry

All three mapped areas were split into a series of 1.86 km^2 sections. This resulted in the generation of 19 sections for the MCD, 6 sections for LB, and 3 sections for MS. The final processed bathymetry data consisted of depth grids at 1 m resolution which, in our opinion, represented the optimal resolution obtainable from the data. The final maps displayed the one-meter grids using a color depth coding scheme and sun-illuminated overlay. Complete details about paper map products can be obtained from a report by Geophysics GPR International, Inc[3]. The color table used is based on a histogram equalization scheme, and therefore was not linear, but the smallest color interval was 0.2 meters. Each of the color maps has a printed color scale bar for interpretation purposes. These maps were produced at a scale of 1:10,000 (Figs. 7 and 8).

Side scan sonar mosaics

The final processed SSS mosaics were produced utilizing the software SonarWeb. Each SSS mosaic represented a 1.86 km^2 section of the seabed which matched the equivalent bathymetric section. The mosaics were exported as geo-referenced geotiff files, and imported into Oasis Montaj (version 5.1.7, Geosoft, Inc., Toronto, Canada) where they could be placed on the background coordinate grid and printed as a final product. The mosaics were re-processed at 1 m resolution for printing. The mosaics were produced using the SonarWeb color scheme “Brown” with a 5% contrast setting. In this scheme, black represents low backscatter strength, and light brown represents high backscatter strength.

Habitat classification

Eleven of the 23 habitat types of the classification scheme used by Prada (2002) were found at the mapped areas. See Table 1 for details of the classification scheme and Table 2 for acreage summary by habitat type. The complementary set of 28 habitat classification digital maps covered a total of 5462.3 ha, with the MCDW accounting for 45% of that area, MCDE for 26%, LB for 17%, and MS the remaining 13%.

With the exception of MS, corals and gorgonians on consolidated habitats were significantly more abundant than submerged aquatic vegetation (SAV) on unconsolidated sediments or unconsolidated sediments alone, as shown in Table 1. Continuous coral habitat was the most abundant consolidated habitat for both MCDW and MCDE (41% and 43% respectively). The LB and MS areas had consolidated habitats predominantly consisting of gorgonian plain habitat (95% and 83% respectively). Coral limestone habitat was more abundant than coral patch habitat and was found near the shelf break in MS, MCDW, and MCDE. At LB, there was minimal coverage for either of those habitat types.

SAV habitats were the second most abundant habitat group in MCDW and MCDE, the most abundant in MS, and almost non existent in LB. Unconsolidated habitats were present in all areas but not dominant anywhere (Table 2, Fig. 9).

Position of fish signals

A total of 671 fish signal target files were saved for the entire mapped areas (Fig. 7 and 8). Within each target

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[3] Geophysics GPR, International, Inc. 2003, Marine Habitat Mapping Offshore St. Thomas & St. Croix, USVI EEZ. M-03704. Report to the Caribbean Fisheries Management Council, 30 p., maps plus appendixes, 2 volumes. Caribbean Fisheries Management Council, 268 Muñoz Rivera Ave., Suite 1108, San Juan, PR 00918-2577.

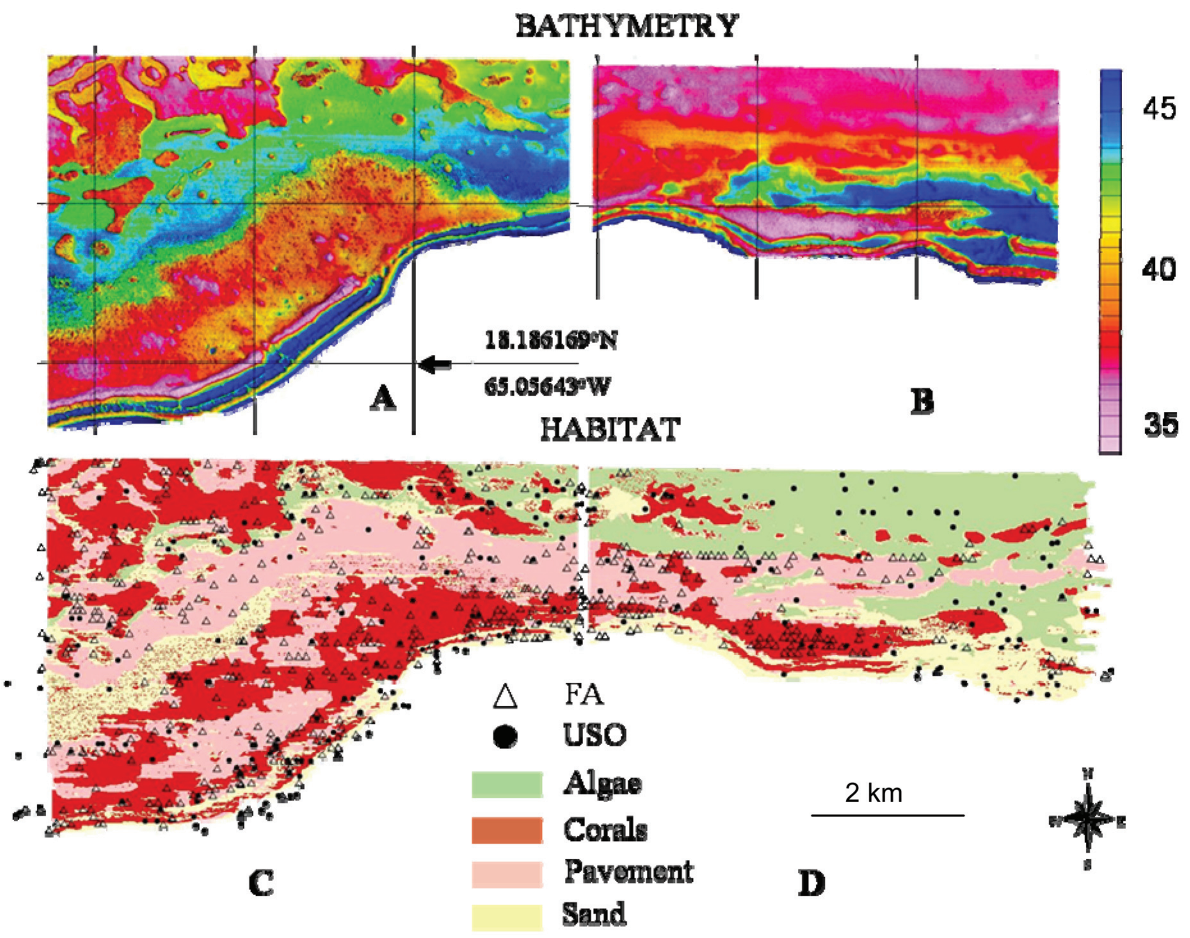

Figure 7

Bathymetry, habitat classification and fish signal positions for the MCDW and MCDE south of St. Thomas. A) MCDW, bathymetry color scale denotes depth in meters. B) MCDE. C) MCDW, habitat types; pavement denotes coral communities and gorgonians. Fish signals classified as fish aggregations (FA) are represented by triangles, black circles represent unidentified swimming objects (USO). D) MCDE. Scale is 1:40,000.

file, fish signals were classified into two categories. If the fish signal was large and isolated, it was identified as a unidentified swimming object (USO). If the fish signal was a pattern of echoes forming an aggregation or school of fish it was identified as a fish aggregation (FA). Most of the identified target files were found in the water column portion of the SSS signal return, usually within the first 20 m of the 50 m SSS channel range. Fish aggregations were either vertically or horizontally oriented. We made no distinction between these patterns of aggregation in this study.

The majority of the FA's positions were located over continuous coral, gorgonian, and sand habitat types (Fig. 9). FAs were also common over the shelf edge or drop off. The majority of USOs were located over sand and shelf edge habitat types, although they were also common over continuous coral and gorgonian habitat types. The highest density of FAs were found in the MCDW and MCDE locations; LB and MS densities were about five times smaller (Fig. 10). USO's densities were similar at all the locations (Fig. 10). The mean FA signal areas were similar between MCDW, MCDE, and LB. However, the mean FA signal area for MS was significantly smaller than the other three locations (Fig. 11).

Discussion

Most single vertical beam sounders used to interpret fish signals have beamwidths of 6–30° and at times undersample the ensonified sea bottom compared to an SSS (Misund et al., 1996). The SSS has a narrow fore-

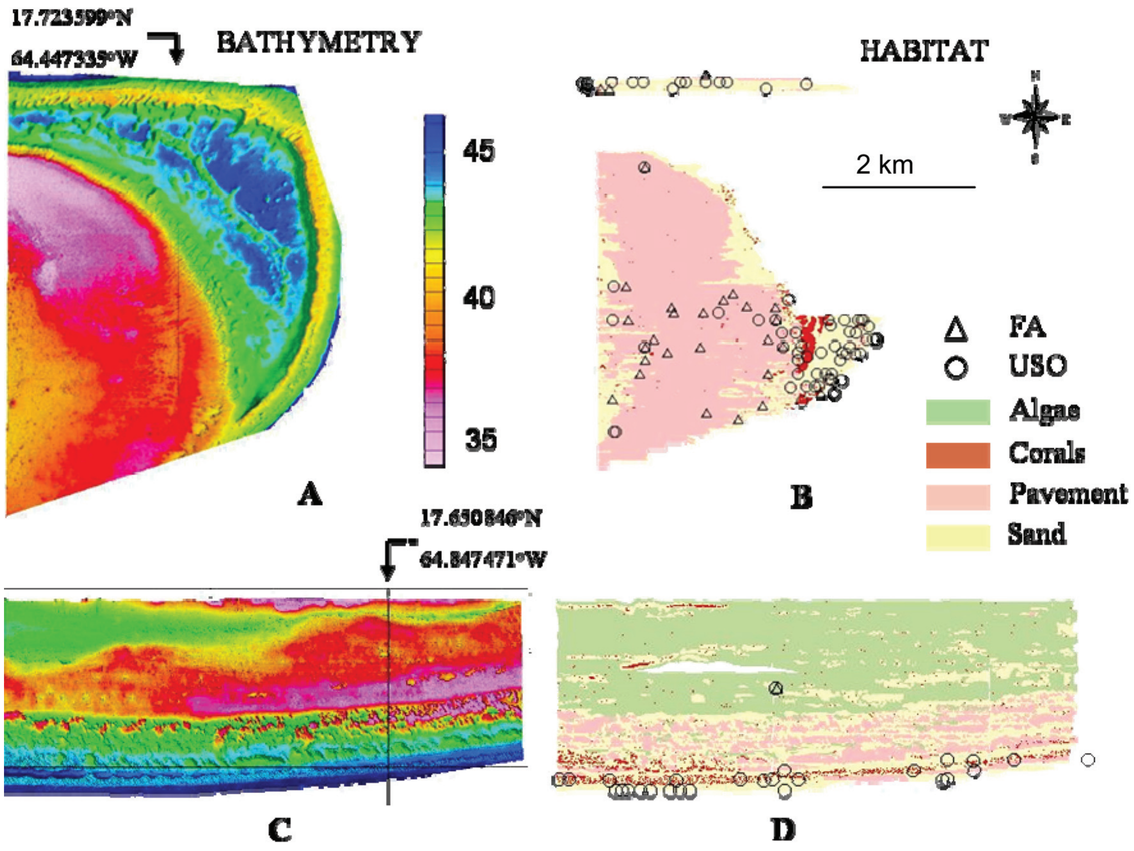

Figure 8

Bathymetry, habitat classification, and fish signal positions for the LB and MS southwest and east of St. Croix respectively. A) LB, bathymetry color scale denotes depth in meters. B) LB, habitat types; pavement denotes coral communities and gorgonians. Fish signals classified as fish aggregations (FA) are represented by triangles, circles represent unidentified swimming objects (USO). C) MS, bathymetry. D) MS, habitat types. White backgrounds within habitat map boundary denote lack of SSS imagery. Scale is 1:40,000.

aft beamwidth of 2° and a wide vertical beam of 20–30° extending to each side of the transducer. These characteristics enable it to resolve short horizontal wavelengths even at long ranges. The backscatter obtained from an SSS facilitates seabed characterization. To effectively use SSS systems, slower sampling vessel speeds (in the order of 3.5 to 5 knots) usually are required to ensure adequate resolution and sampling. Newer models are able to maintain resolution at higher speeds (ca. 5 to 8 knots). The larger sweep area of the SSS also enhances its efficiency in locating water column fish aggregations compared to single vertical beam systems.

A disadvantage of the SSS is that one usually cannot obtain fish species identification from the return acoustic signal, although sometimes one can identify the characteristic shapes of species if the range and resolution of the imagery are appropriate. This is due primarily to the lack of transducer calibrated backscattering strength data (Hammerstad[4]). Also, one normally needs either a vessel platform or an AUV on which to stage a SSS system. Sonar imagery cannot be collected independent of these platforms very easily. Processing SSS imagery requires a minimal amount of expertise and specialized software. Unlike low frequency single beam sounders, high frequency SSS signals cannot penetrate to great ranges in the water column. However, in deep water, one can usually lower the SSS transducer to the required depth by paying out wire from the cable winch aboard the vessel or by programming an AUV for the desired depths. Future research needs to address a more automated quantitative method of correctly classifying SSS acoustic signals to infer habitat designations.

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[4] Hammerstad, E. 2000. EM technical note: backscattering and seabed image reflectivity. Kongsberg maritime products, hydroacoustics, underwater vehicles and systems, echosounders, multibeam related links at http://www.km.kongsberg.com.

Table 2

Total area (ha) of benthic habitats for MCD, LB and MS. Habitat codes as presented in Table 1.

SITE	COCO	COPA	COLI	GOPA	GOPL	ALIN	DEAL	SPAL	SAIN	SANR	SARI	Total
MCD1W	47.7	3.9	3.1		49.4	60.3	1.1	48.9	28.0	2.3		244.9
MCD2W	37.1	13.0	2.3		125.5	15.4		15.2	39.4	5.9		253.8
MCD3W	37.1	13.0	2.3		125.5	15.4		15.2	39.4	5.9		253.8
MCD4W	47.3	6.1	5.8		95.6	25.0	0.1	44.1	30.1	7.3		261.3
MCD5W	34.4	3.1	6.4		67.9	0.4		6.9	62.2	4.5		185.8
MCD6W	106.3	2.9	8.4		141.2	0.7		2.4	85.2	1.6		348.7
MCD7W	169.4	6.6	0.8		107.7	0.1			26.0	4.7		315.3
MCD8W	82.7	26.7	4.5		36.9	0.0		0.5	18.8	13.8		183.8
MCD9W	60.3	2.4	2.0		41.3	0.0		0.0	21.7	3.8		131.5
MCD10W	84.0	2.6	0.0		103.9	0.1		0.6	25.1	6.4		222.7
MCD11W	21.1	2.6	0.0		18.7	0.0		0.0	14.6	6.8		63.9
Total MCDW	727.5	83.0	35.6		913.4	117.3	1.2	134.0	390.4	63.0		2465.5
MCD1E	47.7	3.9	3.1		49.4	60.3	1.1	48.9	28.0	2.3		244.9
MCD2E	5.2	3.2			45.6	76.0	1.0	103.8	10.8	0.2		245.8
MCD3E	15.9	2.3			29.2	73.9	2.3	112.1	8.8	0.5		245.2
MCD4E	3.2	0.8			8.7	12.5		17.3	2.8	0.1		45.4
MCD5E	35.4	2.0	0.1		58.4	0.2		2.1	20.1	19.6		137.9
MCD6E	84.6	2.1	0.1		52.5	7.0	0.2	11.7	28.4	24.5		211.0
MCD7E	20.6	8.2			7.4	45.5	0.2	28.8	46.7	69.3		226.8
MCD8E	2.2	3.5				4.5		10.5	10.8	13.9		45.5
Total MCDE	214.8	26.1	3.3		251.2	279.9	4.9	335.2	156.4	130.4		1402.4
LB1		0.3	0.6		105.2	0.7			32.7	11.9		151.4
LB2					3.4	0.4			11.9	3.1		18.8
LB3		0.5	0.1	0.6	285.2				49.2	1.3		336.9
LB4	9.5	0.9	10.1		49.4				36.2	24.9		131.0
LB5	0.0	0.3		0.3	163.2				29.0	5.7		198.6
LB6	3.2	0.6	0.3	0.5	22.0				28.7	9.9		65.1
Total LB	12.7	2.7	11.1	1.4	628.4	1.1			187.8	56.8		901.9
MS1		3.3	10.0		35.5	149.8	2.0	3.8	74.3	17.6	0.0	296.3
MS2		1.1	3.8		46.1	144.8	0.7	7.9	66.3	18.8	0.1	289.5
MS3		0.3	1.9		21.2	46.7	0.1	2.0	22.3	11.8	0.3	106.6
Total MS		4.7	15.6		102.9	341.3	2.8	13.6	162.9	48.2	0.4	692.4

This would expedite data processing time, providing an economic incentive to collect SSS data by resource managers that need this type of information.

Development of methods for the identification of fish species needs to be encouraged. Species target strength determinations need be made for as many reef inhabiting species as possible, to provide the acoustic signal strength criteria for unambiguous identification. The use of multiple or broadband frequency sonars have the potential to aid in resolving species identification problems (Fleisher[5]). The integration of video imagery or sonar imagery of near video quality collection synoptically with either SSS or calibrated fish finders when performing surveys can provide dynamic visual information essential to fish species identification not available with static acoustic means alone. More research on fish species daily water column movement patterns can help sort out species identification conflicts by incorporating information about species preferred depth strata behaviors. Tagging known species with acoustic tags could also be used as method of identifying the tracked location of the known species in reference to the fish that surround it. This can help identify similar acoustic or echo signal shapes as same species. Incorporating hydrophone techniques to collocate fish emitted sounds with acoustic tag tracking can also help improve species identification for more cryptic inhabiting species (Berk, 1998; Evans and Norris, 1993) by helping to correlate emitted sound position with tagged fish position.

Future research will focus on elucidating the species identification of USOs and FAs through acoustic target strength characterization with in situ verification by

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[5] Fleischer, G. W., 2005. Personal commun. NOAA, NMFS, 2725 Montlake Blvd. East, Seattle, WA 98112

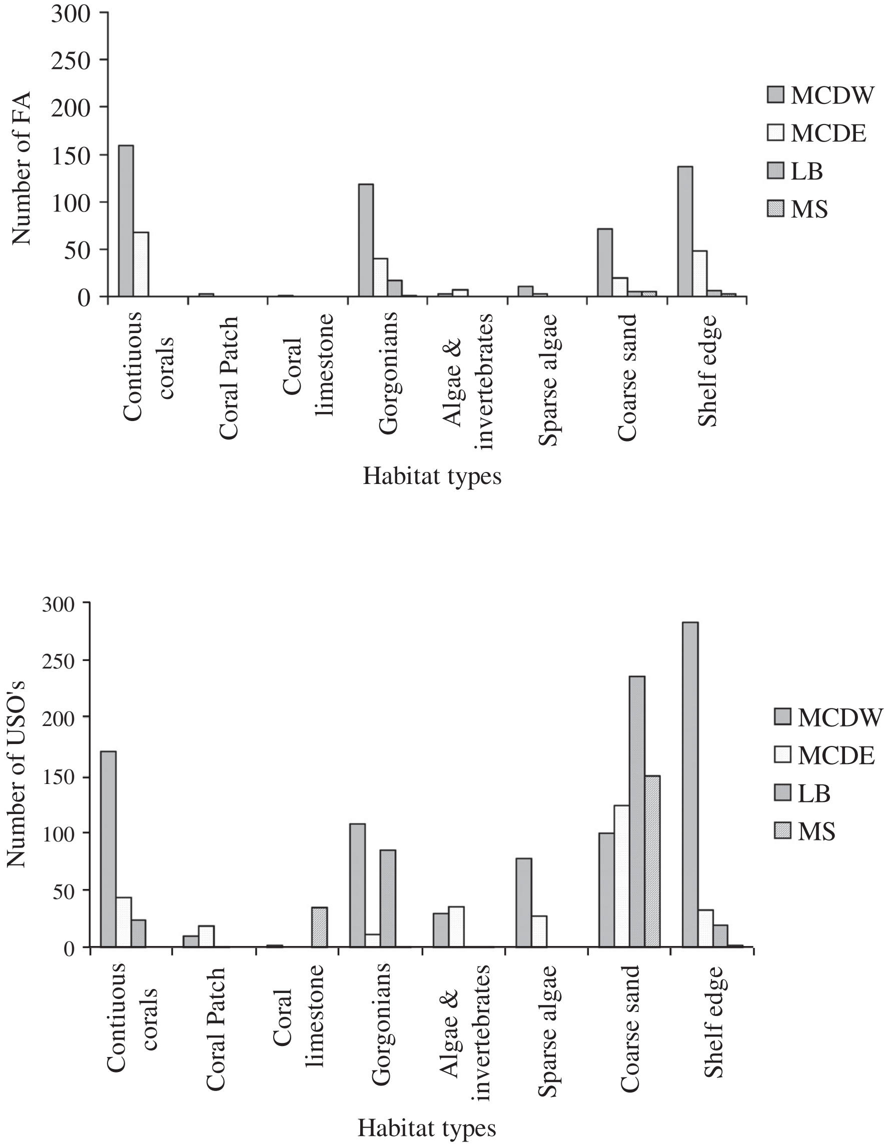

Figure 9

Top: fish aggregations frequency distribution by habitat type for all study areas. Bottom: unidentified swimming object (USO) frequency distribution by habitat type for all study area sites. Only 60% of LB was mapped with SSS.

video observations. We currently suspect that USOs may be echoes from turtles since the sampling period coincides with their nesting season and the intensity of the acoustic signal appears roughly consistent with a turtle body size (Rivera and Arsenault[6]). However, the echoes could also be from Cubera snappers (*Lutjanus cyanopterus*) which have been reported for the MCDW and MCDE locations of the study area by Beets and Friedlander[7]. This same species has been also reported to aggregate for reproduction at the Grammanic Bank just east of the MCDE sampling area at the same sam-

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[6] Rivera, J. A., and J. Arsenault, 2003. Unpublished data. See author address for data access.

[7] Beets, J., and A. Friedlander, 1997. Evaluation of the Spawning Aggregation for Red Hind (*Epinephelus Guttatus*), St. Thomas, US Virgin Islands. Report to the Caribbean Fisheries Management Council, 268 Munoz Rivera Avenue, Suite 1108, San Juan, Puerto Rico, 00918-2577, 26 p.

[8] Whitman, E., 2004. Personal commun. Center for Marine and Environmental Studies, University of the Virgin Islands, St. Thomas, USVI 00802-9990.

pling period as this study (Whitman[8]). Cubera snapper size (1–1.5 m) also fit the derived length from the echo signal shape.

While producing a benthic habitat map of three federal jurisdiction fishery management areas with SSS technology, we were able to obtain relative fish density indices by habitat. At little incremental cost, these indices provide fishery managers with resource insights not previously available. Specifically, for our survey, the largest FA densities were located at MCDW and MCDE over coral communities that occupied up to 70% of the benthic habitat. USO's densities were similar for the differing locations with highest densities primarily over sand and shelf edge areas. FA's school size was significantly smaller at MS than the other three locations (MCDW, MCDE, and LB).

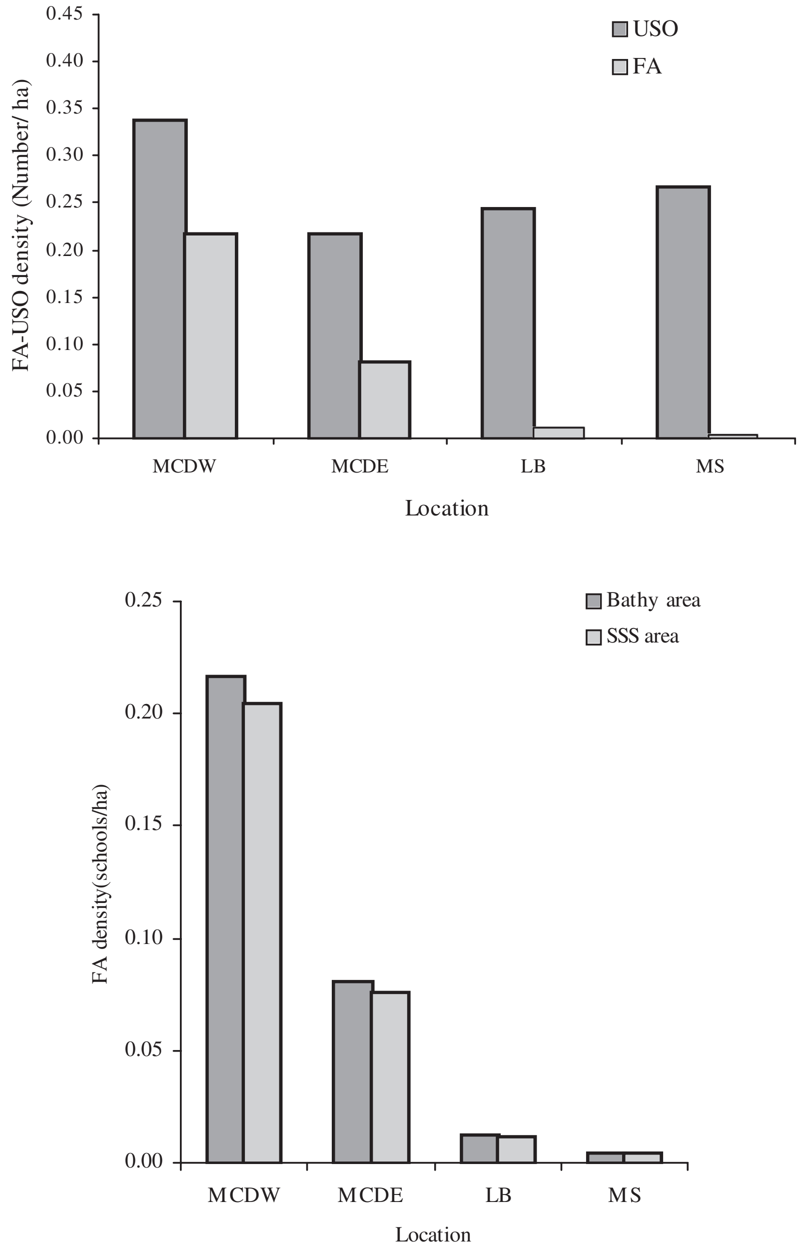

Figure 10

Top: FA's density by location total mapped area. Bottom: unidentified swimming object (USO) density estimates by location. Only 60% of LB was mapped with SSS. Area in hectares (ha).

Acknowledgements

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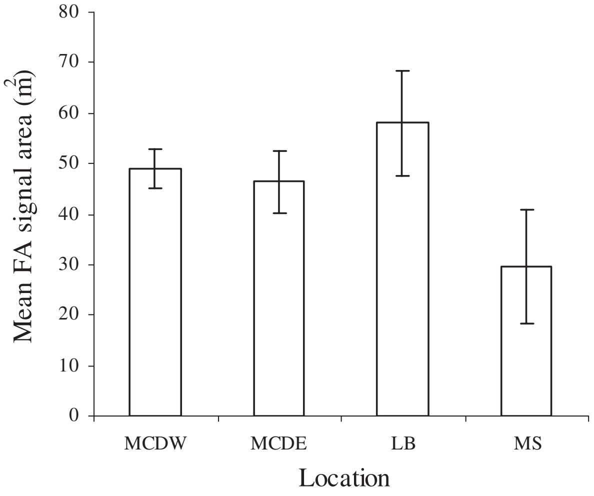

Figure 11

Mean Fish Aggregation (FA) signal area (m^2) for each location. Error bars indicate standard error.

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Appendix A

Parameter Report

System	Parameter	Value
Geoswath system	Roll offset (positive starboard horizon)	0.98°
	Pitch offset (positive aft horizon)	–0.05°
	Yaw (heading) offset relative to gyrocompass	2.93°
	Time latency (s)	< 0.01
	Transducer draft from static waterline	1.14 m
	System frequency	250 kHz
	Swath width (average)	60 m
	Pings per second (average)	9
RTK GPS system	Main antenna offset (starboard positive))	0.91 m
	Main antenna offset (forward positive)	0.98 m
	Main antenna offset (height above SWL)	5.51 m
	Time latency (s)	0.02
	Position update rate	5 Hz
RTK Radio Modem	Effective baud rate	4800
Side-scan sonar system	Frequency	100/500 kHz
	Horizontal beam width	1°/0.2°
	Slant range	50 m
	Gains: Auto CPU return & offset, Att. STBD & PORT	7,9,A,A
Sonarwiz DAQ	Digitizing rate	66 kHz
	Resolution	16 bit

Survey Equipment List

No.	Item	Manufacturer	Model
1	Swath echo-sounder system	Geoacoustics Ltd. (UK)	Geoswath
2	Side-scan sonar system, 500kHz	Klein Sonar Inc. (USA)	595
3	Sonarwiz data acquisition system	Chesapeake Technology (USA)	N/A
4	Sound velocity probe	Valeport Ltd. (UK)	Soundbar
5	Motion reference unit	TSS Ltd. (UK)	DMS-05
6	Gyrocompass	TSS Ltd. (UK)	Meridian surveyor
7	Electric winch for sonar	Sea Mac Inc. (USA)	EM-302
8	RTK GPS system	Trimble Inc. (USA)	5700
9	Radio modem system for RTK GPS	Pacific Crest Corp. (USA)	RFM96W
10	Navigation software	Coastal Oceanographics (USA)	Hypack Max (v02.12)

Processing Software List

No.	Item	Manufacturer	Name & Version
1	Side-scan sonar data processing	Chesapeake Technology (USA)	SonarWeb Pro (v3.15G)
2	Bathymetry data processing	Geoacoustics Ltd. (UK)	Swath32 (v2.17s)
3	Data presentation software	Geosoft Inc.(Canada)	Oasis Montaj (v5.1.7)