CHAPTER 2: BENTHIC HABITAT MAP CREATION

Benthic habitats of the moderate-depth marine environment in and around the Virgin Islands Coral Reef National Monument were mapped using a combination of semi-automated classification and visual interpretation of acoustic imagery. Acoustic imagery has been successfully used to derive the location, extent and attributes of marine habitats (Prada et al., 2008; Kendall et al., 2005; Kostylev et al., 2001). NOAA scientists were able to accurately and reliably delineate the boundaries of features in the imagery using a combination of Geographic Information System (GIS) and remote sensing software. Field investigations were conducted on both small and large vessels in order to understand and validate the acoustic signatures created by habitat features on the seafloor (Figure 2.1). Spatially and thematically accurate habitat maps were developed using this process, providing researchers and natural resource managers with a quantitative understanding of the benthic resources in and around the VICRNM.

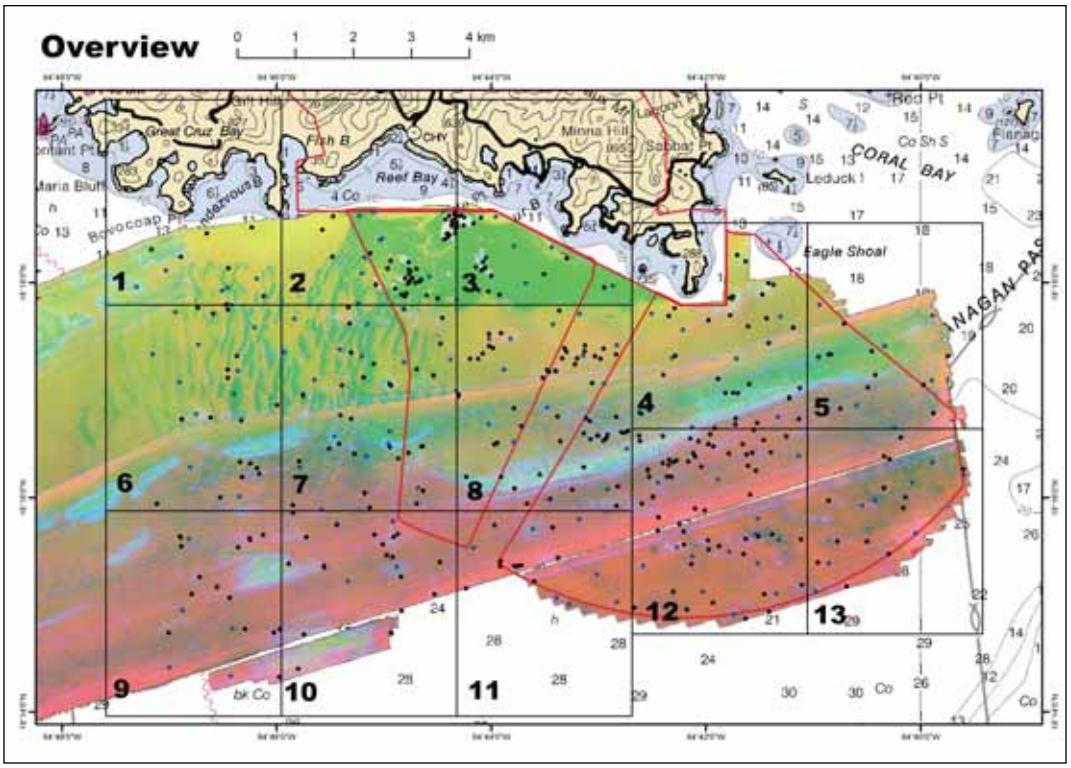


Figure 2.1. Laminated maps were used in the field to help keep track of which drop camera points had already been collected.

2.1 GENERAL MAPPING APPROACH

NOAA's approach to moderate-depth benthic habitat mapping was a six-step process:

1. Imagery Acquisition and Processing – The first step in this process was to acquire and process high-resolution acoustic imagery. Acoustic imagery was collected during two separate years, in order to map the full geographic extent of the VICRNM's southern boundaries. Several metrics were derived from the depth imagery, in order to describe the complexity of the seafloor in different ways. Principal components analysis was then used to reduce the redundancy of information contained in these metrics.

2. Habitat Boundary Delineation – A first draft benthic habitat map was generated using edge detection algorithms to delineate features on the seafloor with discrete acoustic signatures. During the creation of this first draft map, the cartographer placed discrete points on features in the map that had unknown acoustic signatures. Points were also placed on features with known acoustic signatures (evenly distributed throughout the geographic extent of the map) to confirm that the habitats associated with these signatures remained consistent through the area of interest. These two types of points were labeled as "ground validation" sites and were visited in the field.

3. Ground Validation (GV) – NOAA scientists explored these ground validation locations using two different sampling techniques and two different pieces of equipment. Specifically, underwater video was collected along 13 transects using a remotely operated vehicle (ROV), and at 117 discrete points using a manually operated drop camera. The resulting GPS and video information was processed, analyzed and used to train the classification algorithm that was used to generate the second draft map.

4. Habitat Classification – A CART-like (Classification and Regression Tree) algorithm was used to classify each habitat feature delineated by the edge-detection algorithms described in step 2. To simplify this classification process, coral reef habitat features, and soft bottom and rhodolith habitat features were classified separately. The classification algorithm separated these two habitat feature types into different major and detailed structure, biological cover and lives coral classes. The two, resulting classifications were merged together and manually edited to create a final seamless habitat map.

5. Accuracy Assessment (AA) – AA sites were generated using a stratified random sampling design (based on detailed structure type) that allowed for a statistically rigorous assessment of map accuracy. Underwater video was collected at these 299 sites using a manually operated drop camera.

6. Final Product Creation – A final benthic habitat map for the VICRNM was generated by correcting inaccuracies identified by the accuracy assessment. Additionally, all associated datasets, including GIS files, field video and metadata were packaged and provided to project partners.

2.2 REMOTELY SENSED IMAGERY

Multibeam (MBES) Sound Navigation and Ranging (SoNAR) sensors actively emit sound to measure the depth, hardness/softness and roughness/smoothness of the seafloor (Figure 2.2). Depth is measured by determining the time required for an individual ping of sound to travel from the sensor to the seafloor and back again. These individual measurements were used to create seamless images of the seafloor's depth, which will be referred to hereafter as "bathymetry" (Figure 2.3). Hardness/softness and roughness/smoothness are measured by calculating the intensity of an individual ping of sound scattered from the seafloor. These individual measurements were used to create continuous images of the seafloor's physical structure, which will be referred to hereafter as "intensity" (Figure 2.3). The resulting acoustic images (i.e., bathymetry and intensity) are valuable tools for natural resource managers and researchers because they provide baseline information on the location and extent of seafloor habitats in turbid waters and in deep waters beyond the limits of optical imagery (i.e., approximately 30 m).

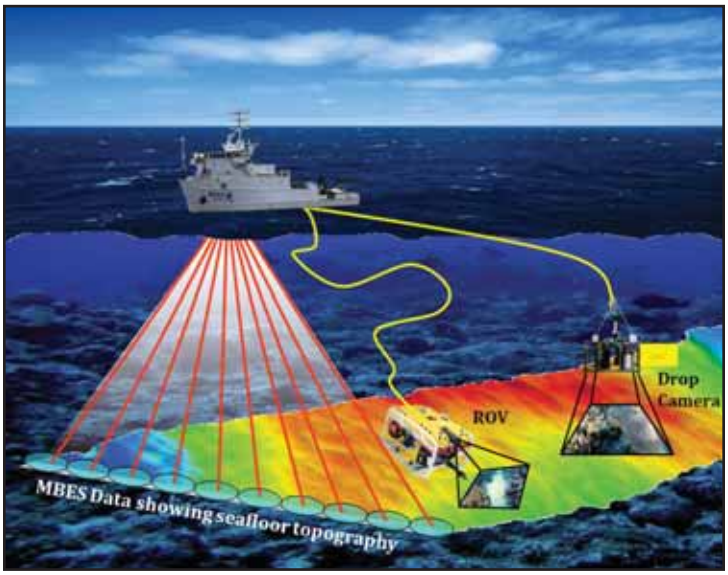


Figure 2.2. Diagram illustrating the collection of data for moderate-depth habitat mapping. The acoustic imagery and underwater video datasets are integrated to create a final map product.

Acquisition Of Remotely Sensed Imagery

Acoustic imagery was acquired for the southern VICRNM boundaries on two separate missions onboard the NOAA ship, *Nancy Foster* (Figure 2.4). The first mission took place from 2/18 to 3/5/2004, and the second mission took place from 2/1 to 2/12/2005. On both missions, seafloor depths between 14 to 55 m were mapped using a RESON SeaBat 8101 ER (240 kHz) MBES sensor (Figure 2.5). This pole-mounted system measured water depths across a 150° swath consisting of 101 individual 1.5° x 1.5° beams. The vessel survey speed was between 5 and 8 knots. In 2004, the ship's location was determined by a Trimble DSM 132 DGPS system, which provided a RTCM differential data stream from the U.S. Coast Guard Continually Operating Reference Station (CORS) at Port Isabel, Puerto Rico. Gyro, heave, pitch and roll correctors were acquired using an Ixsea Octans gyrocompass. In 2005, the ship's positioning and orientation were determined by the Applanix POS/MV 320 V4, which is a GPS aided Inertial Motion Unit (IMU) providing measurements of roll, pitch and heading. The POS/MV obtained its positions from two dual frequency Trimble Zephyr GPS antennae. An auxiliary Trimble DSM 132 DGPS system provided a RTCM differential data stream from the U.S. Coast Guard CORS at Port Isabel, Puerto Rico. For both years, CTD (conductivity, temperature and depth) measurements were taken approximately every 4 hours using a Seabird Electronics SBE-19 to correct for changing sound velocities in the water column. In 2004,

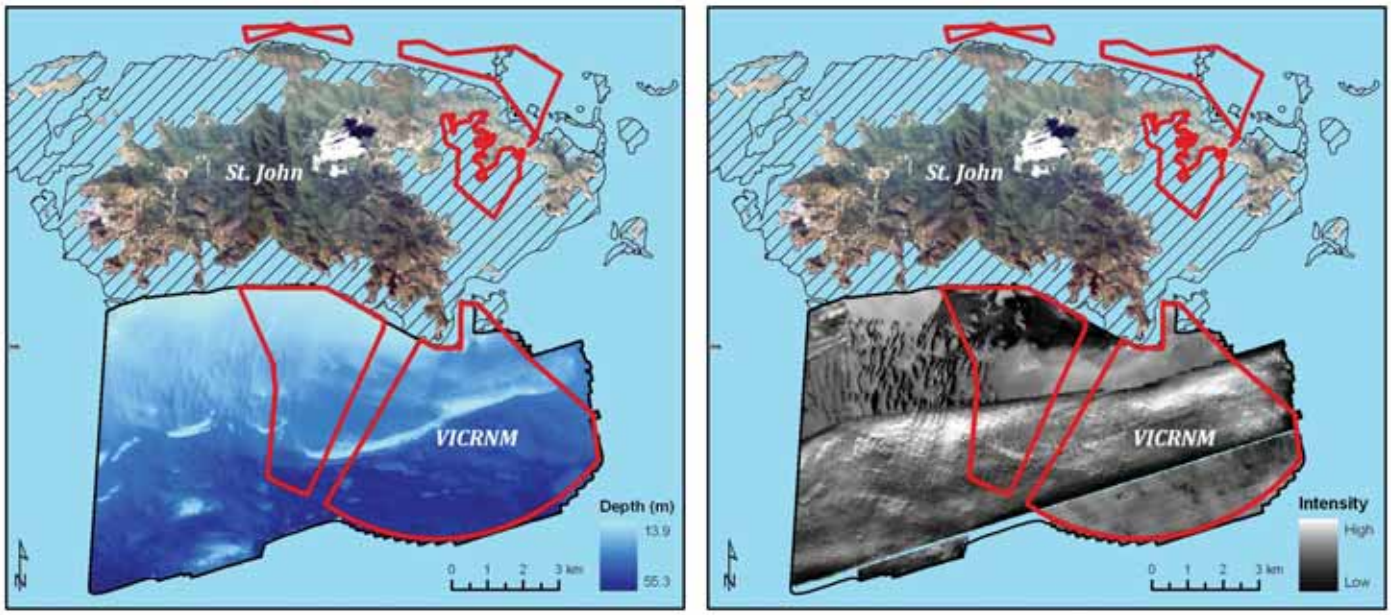


Figure 2.3. These maps depict the two types of imagery (i.e., bathymetry and intensity) collected using an MBES sensor. The bathymetry or depth surface (left) was measured by determining the time required for an individual ping of sound to travel from the sensor to the seafloor and back again. The backscatter or intensity surface (right) was determined by measuring the strength of an individual ping of sound scattered from the seafloor. The black hatched polygon denotes the area mapped using optical imagery. The red polygons show the boundaries of the VICRNM.

raw data were referenced to the WGS84 UTM 20 N horizontal coordinate system, and were logged in .xtf (extended triton format) using Triton ISIS® software 6.2. In 2005, raw data were referenced to the NAD83 UTM 20 N horizontal coordinate system, and were logged in .gsf (generic sensor format) using SAIC ISS 2000 software. Data for both years were referenced to the Mean Lower Low Water (MLLW) vertical tidal coordinate system. For a complete description of the data acquisition and processing parameters, please see the data acquisition and processing reports (DAPRs) for projects: NF-04-06-VI and NF-05--05-USVI (Monaco and Rooney, 2004; Battista and Lazar, 2005).

Figure 2.4. The NOAA ship *Nancy Foster* was used to acquire MBES imagery and ROV data during two, two week missions in 2004 and 2005.

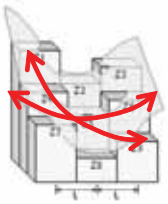
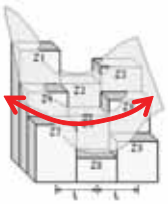
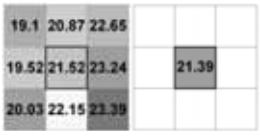
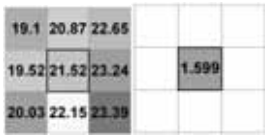
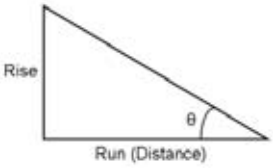
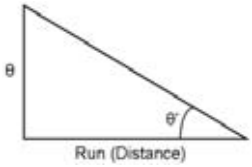
Processing Of Remotely Sensed Imagery

Creating Bathymetry and Intensity Surfaces

The 2004 and 2005 MBES bathymetric data were corrected for sensor offsets, latency, roll, pitch, yaw, static draft, the changing speed of sound in the water column and the influence of tides in CARIS Hips and Sips 5.3 and 5.4, respectively. The 2004 data was then binned to create a 1 x 1 m raster surface, and the 2005 data was binned to a create 2 x 2 m raster surface. After these final surfaces were created, the datum for the 2004 bathymetric surfaces was transformed from WGS84 to NAD83 using the "Project Raster" function in ArcGIS 9.1. The 2004 surface was transformed so that it would have the same datum as the 2005 surface. The 2004 bathymetric surface was then down sampled from 1 x 1

Figure 2.5. The RESON SeaBat 8101 ER (240 kHz) MBES sensor was pole-mounted on the NOAA ship *Nancy Foster* during two, two week missions in 2004 and 2005. It was used to collect MBES bathymetry and intensity imagery.

Table 2.1. Descriptions of the morphometrics used to characterize the complexity of the seafloor in and around VICRNM. The GIS tools used to derive these metrics from the MBES bathymetry surface are also included in the table below.

DATASET		UNIT	DESCRIPTION	TOOL
Curvature		1/100 z units – = concave + = convex	Rate of change in curvature across the surface highlighting ridges, crests and valleys (3 x 3 cell neighborhood)	Curvature function in ArcGIS 3D Analyst
Plan Curvature		1/100 z units – = concave + = convex	Curvature of the surface perpendicular to the slope direction (3 x 3 cell neighborhood)	Plan curvature function in ArcGIS 3D Analyst
Profile Curvature		1/100 z units – = convex + = concave	Curvature of the surface in the direction (3 x 3 cell neighborhood)	Profile curvature function in ArcGIS 3D Analyst
Depth (Mean)		Meters	Average water depth (3 x 3 cell neighborhood)	Focal statistic function in ArcGIS Spatial Analyst
Depth (Standard Deviation)		Meters	Dispersion of water depth values about the mean (3 x 3 cell neighborhood)	Focal statistic function in ArcGIS Spatial Analyst
Surface rugosity		Ratio value	Ratio of surface area to planar area (3 x 3 cell neighborhood)	Rugosity function in the Benthic Terrain Modeler toolbox (Jenness 2002, 2004; Wright et al., 2005)
Slope		Degrees	Maximum rate of change in slope between cell and 8 neighbors (3 x 3 cell neighborhood)	ArcGIS Spatial Analyst's slope function
Slope of the slope		Degrees of degrees	Maximum rate of maximum slope change between cell and eight neighbors (3 x 3 cell neighborhood)	ArcGIS Spatial Analyst's slope function

to 2 x 2 m using the "Resample" function in ArcGIS 9.1. The 2004 surface was resampled so it would have the same spatial resolution as the 2005 surface. Having the same coordinate systems and spatial resolutions, the final 2004 and 2005 bathymetry rasters were then merged using the Raster Calculator function "Merge" in ArcGIS's Spatial Analyst Extension to create a seamless bathymetry surface for the entire VICRNM area south of St. John.

The 2004 and 2005 MBES intensity data were received as raw.xtf and .gsf files (respectively), which recorded the uncorrected intensity value from each snippet (i.e., from each beam of sound for each ping of sound). The .xtf and .gsf files were geometrically and radiometrically corrected using Geocoder 3.0 (Fonseca and Calder, 2005). In particular, the intensity surface was geometrically corrected for navigation attitude, transducer attitude and slant range distortion using the MBES bathymetric surface. It was radiometrically corrected for changes in acquisition gains, power levels, pulse widths, incidence angles and ensonification areas. All snippets were preserved during these corrections, allowing the full resolution data to be used to create the final mosaic. Systematic noise in 2004 intensity mosaic was then filtered in frequency space using the "fast Fourier transformation" (Mather 2004; Lillesand and Kiefer, 2000) function in ENVI 4.5. The final 2004 and 2005 intensity rasters were converted to relative 8-bit (0 – 255) values, since neither intensity surface was calibrated. These 8-bit images were then color balanced and merged using ENVI's "Mosaicing (Georeferenced)" function to create a seamless intensity surface of the entire VICRNM area south of St. John.

Creating Derivative Surfaces

A suite of eight metrics were derived from the final, merged bathymetry surface, in order to characterize the complexity and structure of the seafloor. These metrics specifically included: (1) mean depth, (2) standard deviation of depth, (3) curvature, (4) plan curvature, (5) profile curvature, (6) rugosity, (7) slope, and (8) slope of slope. Each of these metrics was calculated using a square 3 x 3 cell neighborhood, where the central pixel in the neighborhood was assigned the calculated value. These metrics are described in more detail in Table 2.1.

Table 2.2. The amount (%) of variance in a principal component that is explained by a single complexity surface. For example, the bathymetry surface contributed 11.1%, 5.7% and 22.5% of the information contained in the transformed image's first, second and third principal components, respectively.

		PC NUMBER	
	1	2	3
Bathymetry	11.1	5.7	22.5
Bathymetry (Mean)	11.1	5.7	22.3
Bathymetry (Stdev)	11.1	5.4	35.7
Curvature	11.1	5.5	2.2
Curvature (Plan)	11.1	5.5	2.3
Curvature (Profile)	11.1	5.5	0.3
Rugosity	11.1	22.1	2.8
Slope	11.1	22.1	2.3
Slope of Slope	11.1	22.5	9.6

These eight complexity surfaces were subsequently stacked, and exported to create one image with several different bands (each band representing a specific metric). This image was then transformed into its first three principal components using the "Principal Components Analysis" (PCA) (Mather 2004; Lillesand and Kiefer, 2000) function in ENVI 4.6. This transformation reduced the dimensionality of the dataset by removing information that was redundant across the different bands. The resulting three band PCA image only contained information that uniquely described the complexity and structure of the seafloor (Table 2.2). It is important to note that each metric contributed equally to the information contained in the first principal component. Rugosity and slope explained the most amount of the variance contained in the second principal component. The three flavors of bathymetry (i.e., depth, mean depth, and standard deviation of depth) explained the most amount of the variance contained in the third principal component. Each of these three bands were converted from 16-bit, floating point values to 8-bit, integer values, so that they could be imported into ENVI Zoom 4.6

2.3 HABITAT BOUNDARY DELINEATION AND CLASSIFICATION

The majority of shallow-water coral reef habitats have been successfully characterized at high thematic resolutions (≤ 32 classes) by conducting heads-up digitizing and interpretation of high resolution (≤ 4 x 4 m) imagery (Kendall et al., 2001; Battista et al., 2007[a]; Battista et al., 2007[b]). These resulting maps, however, are time-intensive to produce, limited by the size of the minimum mapping unit, and ultimately subjective and irreproducible because they depend on the accuracy and interpretation of the person that is digitizing.

In order to address these difficulties and increase the repeatability and efficiency with which maps are produced, the Biogeography Branch has been experimenting with alternative techniques to automate the process of delineating and attributing features on the seafloor. This moderate-depth map represents the Biogeography Branch's first attempt to create a benthic habitat map from acoustic imagery using this new semi-automated methodology. This method specifically employs a combination of object and pixel-based classification techniques to delineate and classify benthic habitat features. This process is described in a general way in Figure 2.6, and in more detail in the following paragraphs.

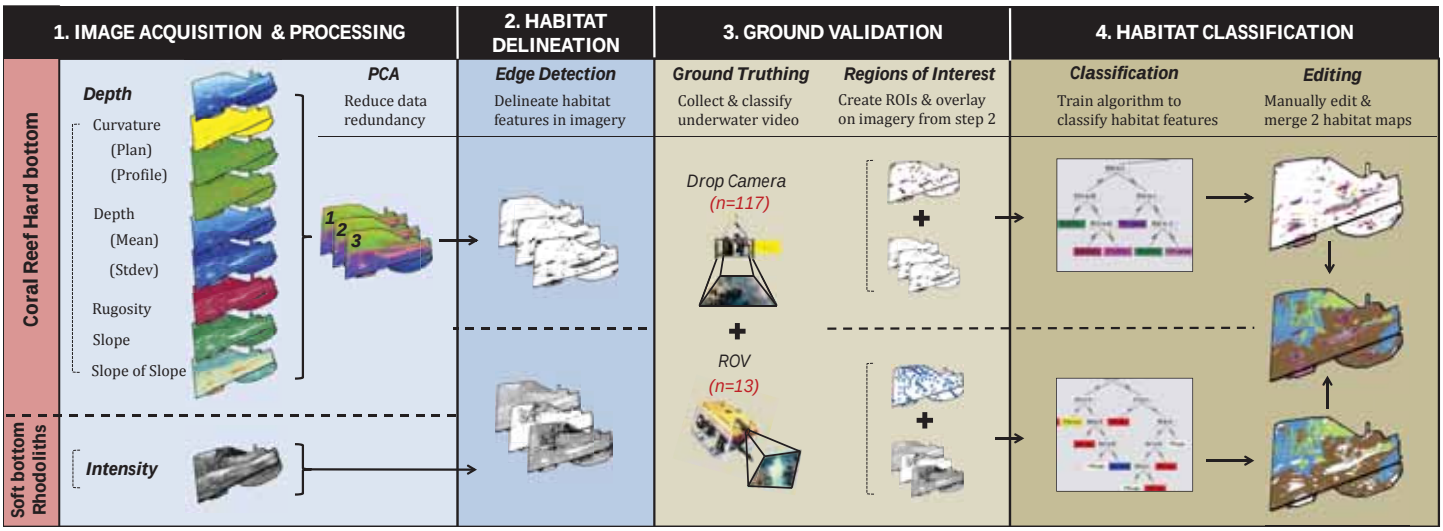


Figure 2.6. Diagram illustrating the process used to create the moderate-depth benthic habitat south of St. John.

Results from this new mapping approach suggest that it is 7x more time efficient than heads-up habitat delineation and attribution. Additionally, less than 40% of the polygons created using the semi-automated method were manually edited, indicating that the majority of the moderate-depth map produced using this method is completely reproducible. These initial results indicate that this new semi-automated approach has the potential to increase the repeatability and efficiency with which maps are produced.

Habitat Delineation

Habitat features on the seafloor were identified and extracted using ENVI Zoom 4.6 Feature Extraction (Fx) Module. This module uses edge detection algorithms to detect and delineate objects in a single image or in a suite of spatially coincident images. An object is defined as a region of interest with unique spatial, spectral (brightness and color), and/or textural characteristics that make it visually distinct from its surroundings (ITT VIS, 2008[a]). There are four steps involved in extracting discrete objects from an image (or images). These steps specifically include: (1) segmenting the image, (2) merging smaller segments into larger objects, and (3) computing spatial, spectral, textual and custom attributes for each object. The first two steps are interactive, allowing the user to adjust the input parameters to extract the features in which they are most interested. In particular, step 1 allows the user to alter the "scale level" of the edge detection algorithm to determine the size of the objects to be extracted. Choosing a higher scale level (>75) causes a smaller number of larger segments to be defined, while choosing a lower scale level (<25) causes a greater number of smaller segments to be defined (ITT VIS, 2008[b]). Step 2 allows the user to alter the "merge level" of the algorithm and to merge smaller segments into larger objects. Choosing a higher merge level (>75) causes segments with faded or faint edges to be merged, while choosing a lower merge level (<25) preserves more of these features with faded or faint edges (ITT VIS, 2008[b]; Robinson et al., 2002). In step 3, ENVI Fx computes 14 spatial metrics, 4 textual metrics, 1 band ratio metric, 3 hue, saturation and intensity (HSI) metrics and 4 spectral metrics (for each input band) for each distinct object. These different

Table 2.3. Descriptions of the spatial metrics calculated by ENVI Fx for each habitat polygon identified during the edge-detection process (ITT VIS, 2008[b]).

ATTRIBUTE	DESCRIPTION	FORMULA
AREA	Total area of the polygon, minus the area of the holes. Values are in map units.	-
LENGTH	The combined length of all boundaries of the polygon, including the boundaries of the holes. This is different than the MAXAXISLEN attribute. Values are in map units.	-
COMPACT	A shape measure that indicates the compactness of the polygon. A circle is the most compact shape with a value of 1 / pi. The compactness value of a square is 1 / 2(sqrt(pi)).	= Sqrt (4*AREA/pi) / outer contour length
CONVEXITY	Polygons are either convex or concave. This attribute measures the convexity of the polygon. The convexity value for a convex polygon with no holes is 1.0, while the value for a concave polygon is less than 1.0.	= length of convex hull / LENGTH
SOLIDITY	A shape measure that compares the area of the polygon to the area of a convex hull surrounding the polygon. The solidity value for a convex polygon with no holes is 1.0, and the value for a concave polygon is less than 1.0.	= AREA / area of convex hull
ROUNDNESS	A shape measure that compares the area of the polygon to the square of the maximum diameter of the polygon. The “maximum diameter” is the length of the major axis of an oriented bounding box enclosing the polygon. Circle = 1 and square = 4/pi.	= 4 * (AREA) / (pi * MAXAXISLEN2)
FORMFACTOR	A shape measure that compares the area of the polygon to the square of the total perimeter. The form factor value of a circle is 1, and the value of a square is pi / 4.	= 4 * pi * (AREA) / (total perimeter)^2
ELONGATION	A shape measure that indicates the ratio of the major axis of the polygon to the minor axis of the polygon. The major and minor axes are derived from an oriented bounding box containing the polygon. Square = 1 and Rectangle > 1.	= MAXAXISLEN / MINAXISLEN
RECT_FIT	A shape measure that indicates how well the shape is described by a rectangle. This attribute compares the area of the polygon to the area of the oriented bounding box enclosing the polygon. Rectangle = 1 and non-rectangle < 1.	= AREA / (MAXAXISLEN * MINAXISLEN)
MAINDIR	The angle subtended by the major axis of the polygon and the x-axis in degrees. The main direction value ranges from 0 to 180 degrees. 90 degrees is North/South, and 0 and 180 degrees is East/West.	-
MAJAXISLEN	The length of the major axis of an oriented bounding box enclosing the polygon. Values are map units of the pixel size. If the image is not georeferenced, then pixel units are reported.	-
MINAXISLEN	The length of the minor axis of an oriented bounding box enclosing the polygon. Values are map units of the pixel size. If the image is not georeferenced, then pixel units are reported.	-
NUMHOLES	The number of holes in the polygon. Integer value.	-
HOLESOLRAT	The ratio of the total area of the polygon to the area of the outer contour of the polygon. The hole solid ratio value for a polygon with no holes is 1.0.	= AREA / outer contour area

metrics will be referred to hereafter as "Fx object attributes," and are described in more detail in Tables 2.3 and 2.4 (ITT VIS, 2008[b]). After these Fx object attributes are calculated, the user may export all of the objects and their associated spatial, textual, HSI, ratio and spectral attributes as a single ESRI shapefile (Figure 2.7).

Table 2.4. Descriptions of the textual, ratio, hue saturation and intensity (HSI), and spectral metrics calculated by ENVI Fx for each habitat polygon identified during the edge-detection process (ITT VIS, 2008[b]).

	ATTRIBUTE	DESCRIPTION
TEXTUAL	TX_RANGE	Average data range of the pixels comprising the region inside the kernel. A kernel is an array of pixels used to constrain an operation to a subset of pixels.
	TX_MEAN	Average value of the pixels comprising the region inside the kernel.
	TX_VARIANCE	Average variance of the pixels comprising the region inside the kernel.
	TX_ENTROPY	Average entropy value of the pixels comprising the region inside the kernel. ENVI Zoom computes entropy, in part, from the Max Bins in Histogram preference.
RATIO	BANDRATIO	"Values range from -1.0 to 1.0.ENVI Zoom computes a normalized band ratio between two bands, using the following equation: (B2 - B1) / (B2 + B1 + eps), where eps is a small number to avoid division by zero."
H S I	HUE	Hue is often used as a color filter and is measured in degrees from 0 to 360. A value of 0 is red, 120 is green, and 240 is blue.
	SATURATION	Saturation is often used as a color filter and is measured in floating-point values that range from 0 to 1.0.
	INTENSITY	Intensity often provides a better measure of brightness than using the AVGBAND_x spectral attribute. Intensity is measured in floating-point values from 0 to 1.0.
SPECTRAL	MINBAND_X	Minimum value of the pixels comprising the region in band x.
	MAXBAND_X	Maximum value of the pixels comprising the region in band x.
	AVGBAND_X	Average value of the pixels comprising the region in band x.
	STDBAND_X	Standard deviation value of the pixels comprising the region in band x.

Using this ENVI Fx workflow, discrete habitat features were identified and delineated in the acoustic imagery. Specifically, features that appeared to be coral reef habitats (i.e., either aggregate reef, patch reefs, aggregated patch reefs, pavement or pavement with sand channels) were extracted from the PCA image using a scale level of 75 and an merge level of 99.2 (Figures 2.8 a-d). Features that appeared to be soft bottom habitats (i.e., either sand or scattered coral and rock) or a mixture of soft bottom and rhodolith habitats were extracted from the intensity surface using a scale level of 25 and a merge level of 99.1. The final coral reef habitats features, as well as soft bottom and rhodolith habitat features, were exported from ENVI Zoom as two separate shapefiles. The attribute tables of these shapefiles contained the spatial, textual, HSI, ratio and spectral metrics calculated for each habitat feature. Each shapefile was then visually inspected and polygons (or pieces of polygons) were manually removed, if they appeared to be the result of acoustic noise (Figure 2.9). Each of the Fx object attributes associated with each habitat feature were then converted to rasters using a custom script built in ArcGIS's Model Builder. In total, there were 34 attribute rasters associated with the 1,287 coral reef features and 22 attribute rasters associated with the 11,421 soft bottom and rhodolith features. The 34 coral reef rasters and 22 soft bottom and rhodoliths rasters were respectively stacked, and exported to create two separate images with several different bands (each band representing a specific metric). The next step in the mapping process sought to better understand, identify, and quantify the correlations between these object-based metrics and specific habitat classes.

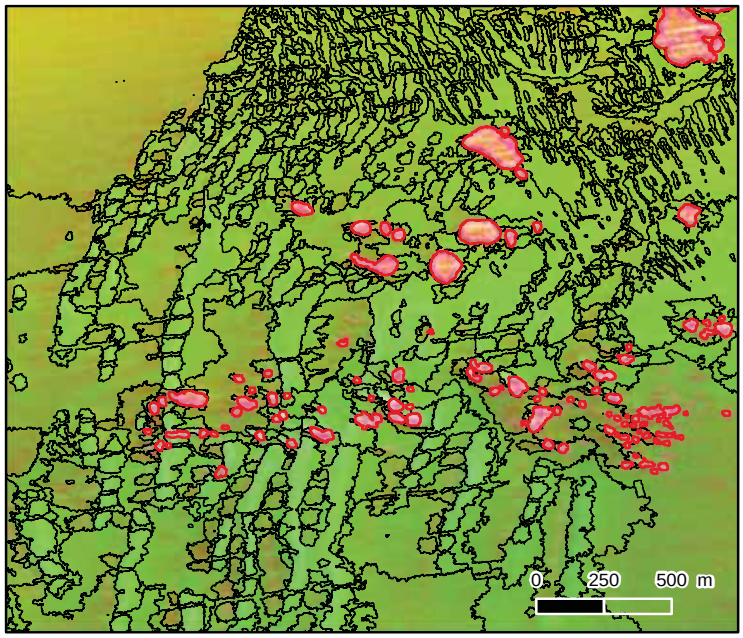


Figure 2.7. This map depicts a subset of habitat objects that were exported from ENVI Fx as a single ESRI shapefile. The pink/red objects are coral reef habitats features, while the green/brown objects are soft bottom and rhodoliths habitats features.

Figure 2.8. This series of screenshots depicts (step-by-step) the ENVI Fx 4.6 feature extraction process used to identify and delineate visually distinct habitat features. ENVI Fx is an add-on module that is nested within ENVI Zoom.

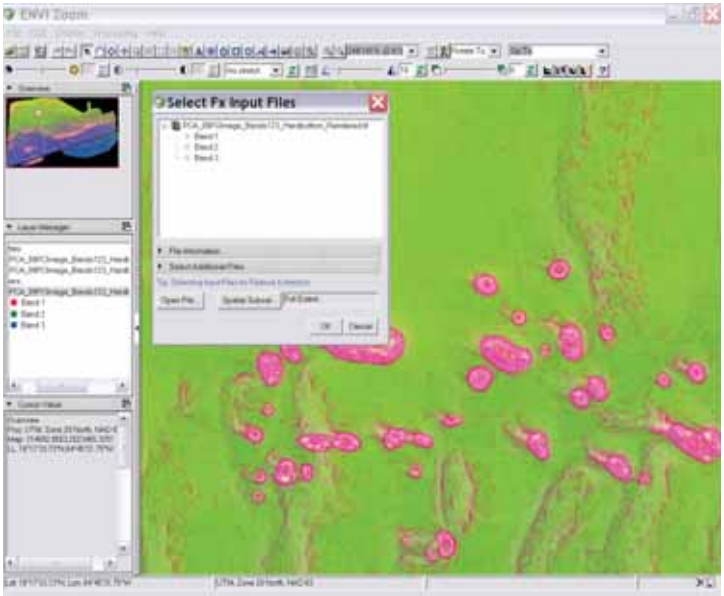


Figure 2.8a. Screenshot depicting the first step (i.e., choosing the input or source image) in the ENVI Fx feature extraction process. Specifically, this screenshot shows the source image (i.e., PCA image) from which coral reef habitat features were extracted. Bands 1, 2 and 3 in the PCA image correspond to the image's first, second and third principal components, respectively.

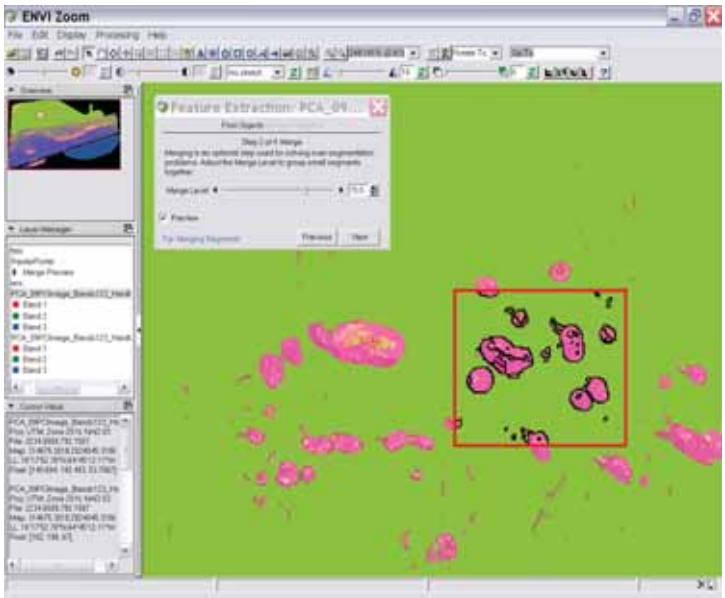


Figure 2.8b. Screenshot depicting the second step (i.e., choosing a scale level) in the ENVI Fx feature extraction process. Specifically, this screenshot shows the scale level (i.e., 0.0) used to identify coral reef habitat features. The preliminary results from choosing this scale level are seen in the red box in the lower right corner of the screenshot.

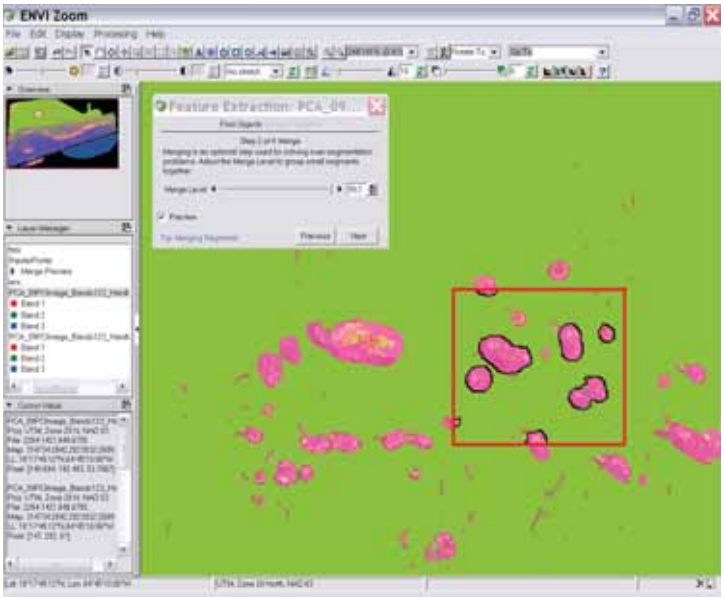


Figure 2.8c. Screenshot depicting the third step (i.e., choosing a merge level) in the ENVI Fx feature extraction process. Specifically, this screenshot shows the merge level (i.e., 99.2) used to aggregate coral reef habitat features into larger objects. The preliminary results from choosing this merge level are seen in the red box in the lower right corner of the screenshot.

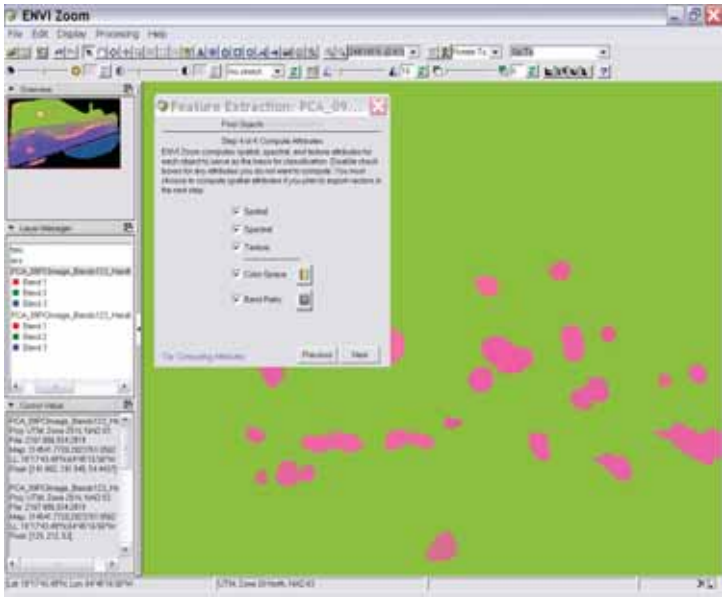


Figure 2.8d. Screenshot depicting the fourth and final step (i.e., calculating polygon attributes) in the ENVI Fx feature extraction process. Specifically, this screenshot shows that spatial, textual, HSI, ratio and spectral metrics were calculated for each of the coral reef habitat polygons identified by the feature extraction process. After these attributes were calculated, the final coral reef polygons (and their associated attributes) were exported as a single ESRI shapefile.

Ground Validation

Extensive field work is needed to create high-quality benthic habitat maps because it enhances the accuracy of habitat attribution and (to a lesser degree) habitat delineation. Given the importance of field work, a team of NOAA scientists visited predetermined locations to explore and verify existing habitat information on the seafloor. These "ground validation" (GV) locations were targeted by the cartographer to satisfy the following objectives:

1. Explore features in the imagery with unknown or confusing acoustic signatures
2. Confirm that the habitat type correlated with a particular acoustic signature remained consistent throughout the entire study area.

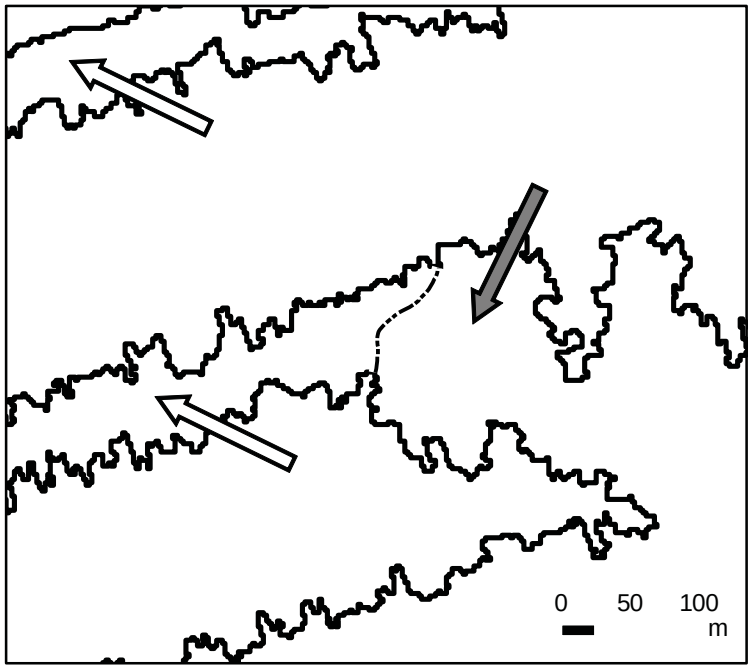


Figure 2.9. This graphic depicts how artifacts in the acoustic imagery were manually removed from the benthic habitat map. Some habitat polygons (denoted by the black lines) were manually deleted or edited because they included acoustic noise within their boundaries. The white arrows point to artifacts in the PCA image that were falsely identified as discrete habitat features. The gray arrow points to real habitat features in the PCA image. The white and black dotted line denotes where this polygon was manually split to remove the artifacts from the habitat polygon.

To achieve this first objective, the cartographer manually placed GV points in, or transects that intersected, features with unknown habitat types. These points and transects were important for understanding the habitat class associated with these distinct, but unknown acoustic signatures. To achieve the second objective, the cartographer manually placed GV points in, or transects that intersected, features with known habitat types distributed throughout the entire spatial extent of the mapped area. These points and transects were important to the GV process because the same habitat type may exhibit slightly different signatures in different parts of the study area. A single habitat type may exhibit slightly different acoustic signatures because polygons contain some structural and biological cover heterogeneity within them (e.g., polygons attributed as "rhodoliths" contain varying amounts of sand and algae).

Two different GV sampling methods (i.e., points and transects) were used because the GV data were collected during two different years (2005 and 2009) using two different pieces of equipment. In 2005, GV data were collected along 13 transects using a remotely operated vehicle or ROV (Figure 2.10) from 2/1 to 2/12 onboard the

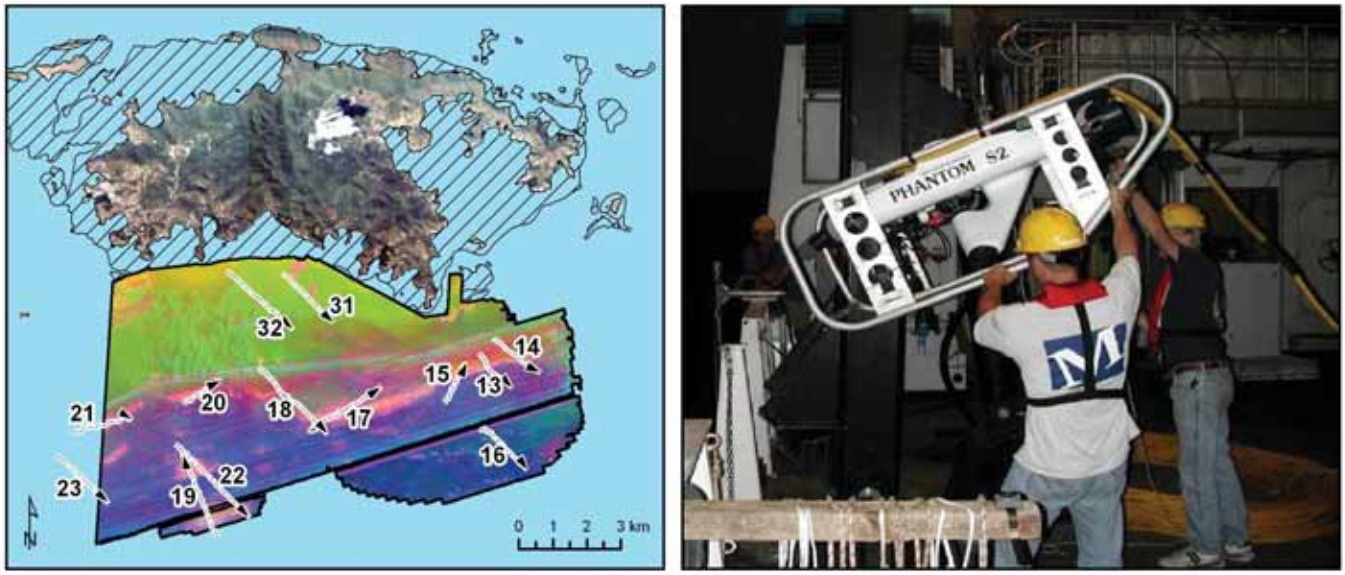


Figure 2.10. In 2005, the Spectrum Phantom S2 ROV (right) collected underwater video and high resolution photographs of the seafloor along 13 transects. These datasets were used for ground validation purposes. The map (left) depicts these 13 transects (and their orientation) overlayed on the PCA image. The thin black, hatched polygons denote the extent of the shallow-water maps developed using optical imagery. The thick black polygon denotes the spatial extent of the acoustic imagery.

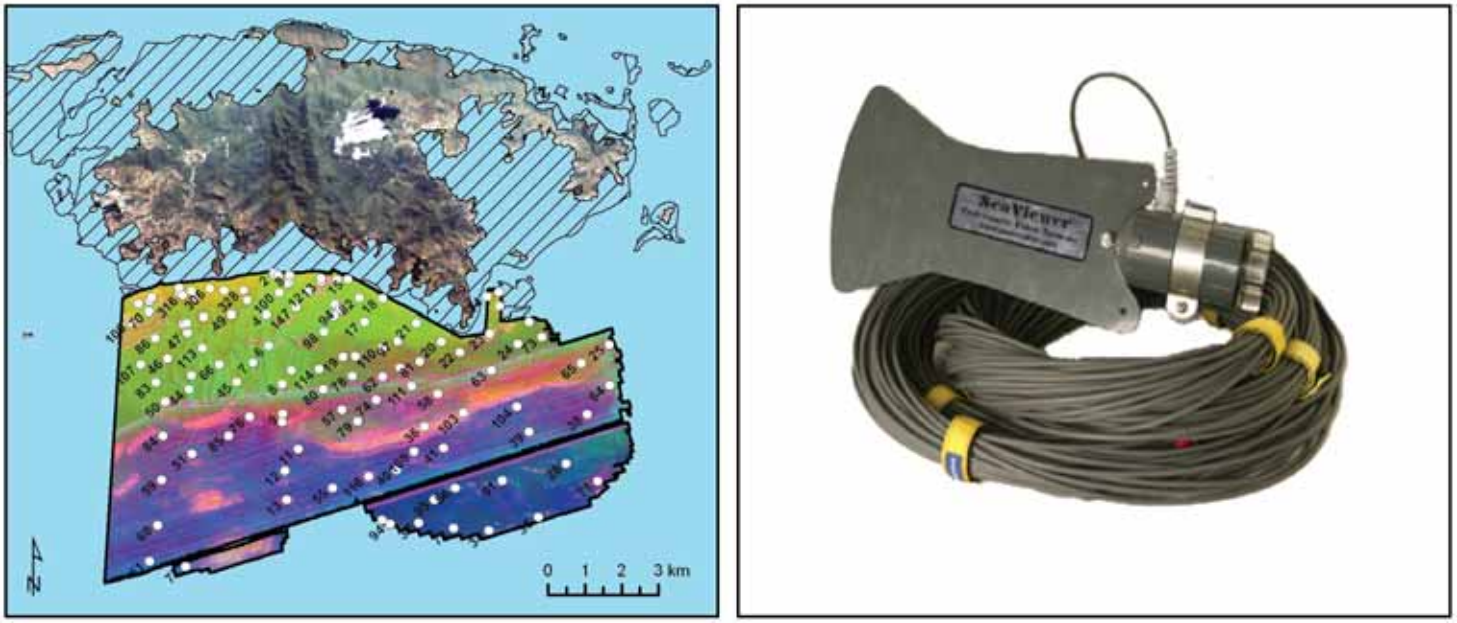


Figure 2.11. In 2009, the SeaViewer Sea-Drop 950 camera (right) collected underwater video of the seafloor at 117 discrete locations. This dataset was used for ground validation purposes. The map (left) depicts these 117 points as white dots overlayed on the PCA image. The thin black, hatched polygons denote the extent of the shallow-water maps developed using optical imagery. The thick black polygon denotes the spatial extent of the acoustic imagery.

NOAA ship, *Nancy Foster*. In 2009, GV data were collected at 117 GV sites using an underwater drop camera (Figure 2.11) from 1/5 to 1/16, 2/9 to 2/20 and 5/31 to 6/7 onboard small research vessels provided by the National Park Service (Figure 2.12).

Figure 2.12. A U.S. National Park Service vessel was used to collect underwater video in support of habitat map development.

For the 2005 mission, the GV transects were systematically placed over the study area to include as many benthic habitat features and transition zones as possible. Distinct features and transitional areas were identified by visual examination of fine-scale multibeam bathymetry data collected in 2004 and moderate-scale GEODAS bathymetry data (GEODAS, 2005). The bathymetry data were divided into distinct benthic habitats using variations in depth, roughness and spatial patterning (ridges, bumps, troughs, regular undulations, etc.). Georeferenced underwater video and photographs were acquired using a video camera and high-resolution digital still camera mounted on a Spectrum Phantom S2 ROV. High powered strobe lights mounted on the ROV were used to supplement ambient light levels during the day and served as the only source of light during night operations. Data from the cameras were transmitted and immediately recorded to a computer's hard drive. Video data were collected during an entire transect, and still photos were collected every 30 seconds. The forward-facing video camera was pointed at a 45 degree downward angle to give ROV pilots a view of upcoming obstacles and researchers a view of the benthic habitat. The ROV's height above the substrate and speed were approximately 2 m and 1 m/s, respectively. The ROV pilot attempted to keep the ROV height and speed as constant to standardize the field of view and spatial resolution of interpretations. Two downward pointing parallel lasers separated by 5 cm and the scale of habitat features and organisms were used to estimate height off the bottom. Still photo images were acquired using a downward pointed camera. A transducer attached to the ROV and an acoustic receiver (suspended off the side of the ship) were used to determine the ROV's relative position to the ship. The ROV's absolute geographic position was estimated using this relative position and the shipboard GPS. The positional accuracy was estimated to be within +/-5 m.

For the 2009 missions, GV sites were systematically placed in features with unknown acoustic signatures, and in parts of the study area that were not explored using the ROV in 2005. These GV sites were prioritized as high, medium and low in case there was not enough time to visit all of them during the field mission. Geographic coordinates for these sites were uploaded to a hand-held Garmin 76 CS WAAS-enabled GPS unit (Figure 2.13). At the beginning of every morning, a specific region was selected (depending on the weather) to work in during that day. Often, this meant working in areas with more challenging sea conditions first, and then moving inshore or to more protected areas as the day progressed. GV sites were navigated to using the hand-held Garmin 76 CS GPS unit. The vessel was maneuvered to within 5 m of the target location. Once in position, NOAA scientists would concurrently deploy a SeaViewer Sea-Drop 950 camera (attached to a down weight and 300 feet of line), as well as begin logging a waypoint on a Trimble GeoXT GPS receiver. The drop camera reached the bottom in approximately 60 - 90 seconds. While on site, the vessel's position was captured as an epic (i.e., point) approximately every 5-10 seconds depending on the number of satellites detected by the GPS antennae. The underwater video was recorded onto mini-video tapes using a Sony Walkman video recorder. The camera operator adjusted the camera lens to get a downward view of the seafloor approximately 2 m from the bottom, and a side view of the seafloor. This allowed for accurate measurements of percent biological cover and a broader scale understanding of the structure at each site. No attempt was made to standardize the amount of time the camera was on the seafloor. In fact, it was often advantageous to drift across habitat transitions, as it allowed the cartographer to understand the ecotone at many locations (Figure 2.14). While the camera was recording video of the seafloor, an observer viewed the video real-time on a Panasonic Toughbook, and classified the major/detailed geomorphological structure, major/detailed biological cover, and percent coral for each site. Water-proof field maps (depicting the draft habitat map and source imagery) were used to visually link signatures in the imagery with the *in situ* habitats at seen in the video (Figure 2.1). In many cases, suggestions on boundary delineation and habitat classifications were made directly on the field maps with permanent marker.

Figure 2.13. The equipment used in the field to collect georeferenced underwater video. The Panasonic Toughbook (left) was used to view the video in real-time. The Trimble GeoXT GPS receiver (middle) was used to record the location of the drop-camera. The Garmin 76 WAAS-enabled GPS unit (right) was used to navigate to each GV site.

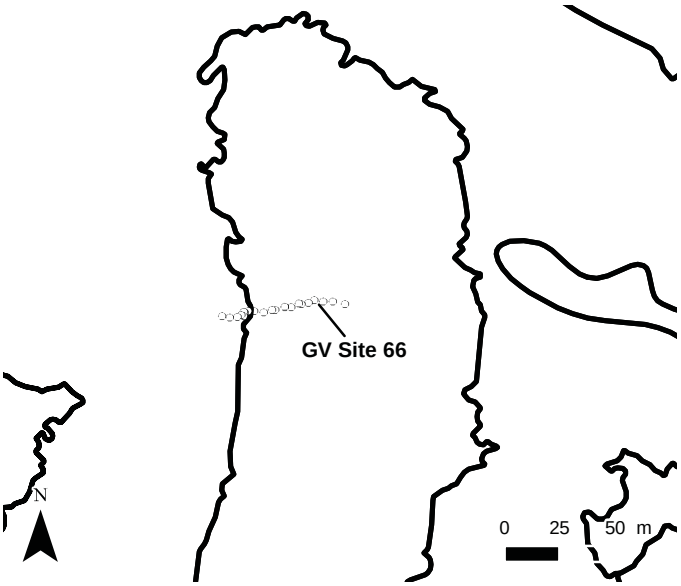


Figure 2.14. This map illustrates how the drop camera (denoted by the white points) drifted over a habitat transition (denoted by the black line) at GV site 66, allowing the cartographer to understand both habitat types.

Once back in the office, Trimble Pathfinder Office software was used to post process and differentially correct the raw GPS data to the Continually Operating Reference System (CORS) station at St. Thomas, U.S. Virgin Islands (VITH). The underwater video was converted from the mini-tapes to softcopy form using Final Cut Pro software. The classification of each GPS location (completed in the field) was then reviewed in conjunction with the acoustic imagery and the associated underwater video, to develop a final classified set of GV points (Figure 2.15). Next, the final classified GV points were separated into multiple shapefiles (i.e., one file for each unique habitat class combining structure, cover, percent cover

Figure 2.15. A final classified set of GV points was developed by concurrently viewing the acoustic imagery and underwater video for a specific location. The map (left) depicts the drop camera location (denoted by the white points) for GV site 13 overlayed on the PCA image. The screenshot (right) depicts the underwater video associated with GV site 13.

and live coral cover) using the "Split Layer by Attribute" toolbox in ArcGIS 9.3 (Patterson 2008). Each shapefile was subsequently imported into ENVI 4.6, and converted to ROIs (Regions of Interest) using the "Import Vector Files" and "Export Active Layer to ROIs" functions (Figure 2.16). These ROIs were needed to create a second draft habitat map.

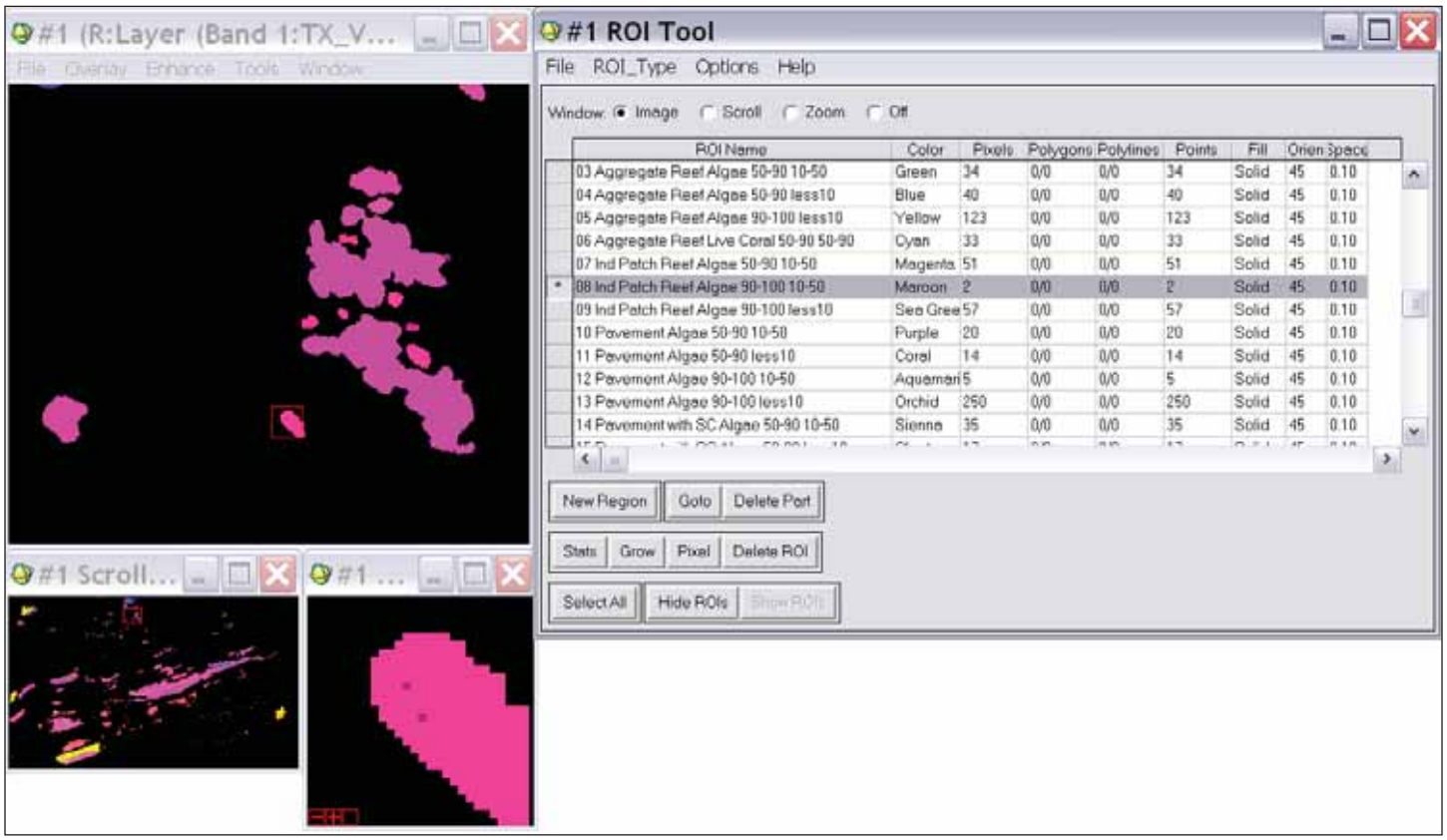


Figure 2.16. The classified GV points were converted from ESRI shapefiles to ENVI 4.6 ROIs. The table (right) shows these converted ROIs. The map (left) depicts the coral reef features extracted by ENVI Fx at three different scales. The location of the ROI highlighted in the table (i.e., 08 Ind Patch Reef Algae 90-100 10-50) is denoted by two maroon pixels overlayed on a coral reef feature in the finest scale window (bottom right).

Habitat Classification

QUEST (Quick, Unbiased, Efficient Statistical Tree)

The ROIs created from the classified GV locations and video (above) were used to train the classification algorithm and to develop a second draft habitat map. These tasks were performed using ENVI 4.6's RuleGen 1.02 add-on (Figure 2.17; Jengo 2004). This add-on contains the Quick, Unbiased, Efficient Statistical Tree (QUEST) algorithm (Loh and Shih, 1997), which is implemented via ENVI's native Decision Tree Tool. QUEST is a type of Classification and Regression Tree (CART) (Breiman et al., 1984) that: (1) is non-parametric and nonlinear, (2) has negligible variable selection bias, (3) is computationally simplistic, and (4) yields binary splits for categorical predictor variables, ordinal predictor variables, or a mix of both types of predictors. Unlike CART however, the QUEST algorithm separates objects in an image into classes using univariate (axis-orthogonal) discriminat-based splits. This type of analysis separates the classification process into two parts at each split (or node) in the decision tree (Figure 2.19). The first step in this analysis, *independent variable selection*, finds the independent variable (i.e., input band) that is significantly different from the other variables in order to create the most efficient split. The second step in this analysis, *binary split identification*, identifies the threshold at which to split the previously selected input band into two classes that are as homogenous as possible.

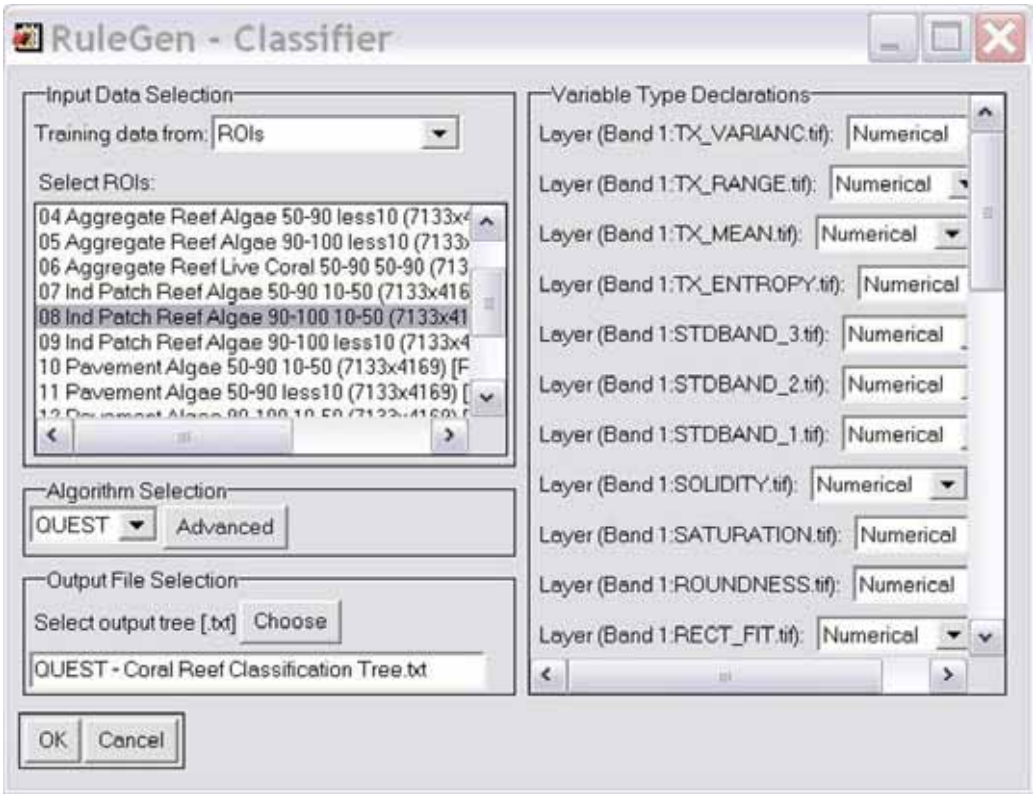


Figure 2.17. The converted ROIs were used to create a QUEST classification tree using ENVI 4.6's RuleGen 1.02 add-on. The variable type declarations included all of the spatial, textual, ratio, HSI and spectral metrics calculated for each polygon by ENVI's Fx module.

More specifically, during *independent variable selection* stage, QUEST uses the Pearson contingency table Chi-squared test of independence to approximate the statistical significance (*p*-value) of each input band. If the smallest *p*-value for these input bands is less than a predefined threshold (as determined by the Bonferroni method for multiple comparisons), then the corresponding input band is selected to be included in the classification. If not, then Levene's *F*-test for unequal variances is

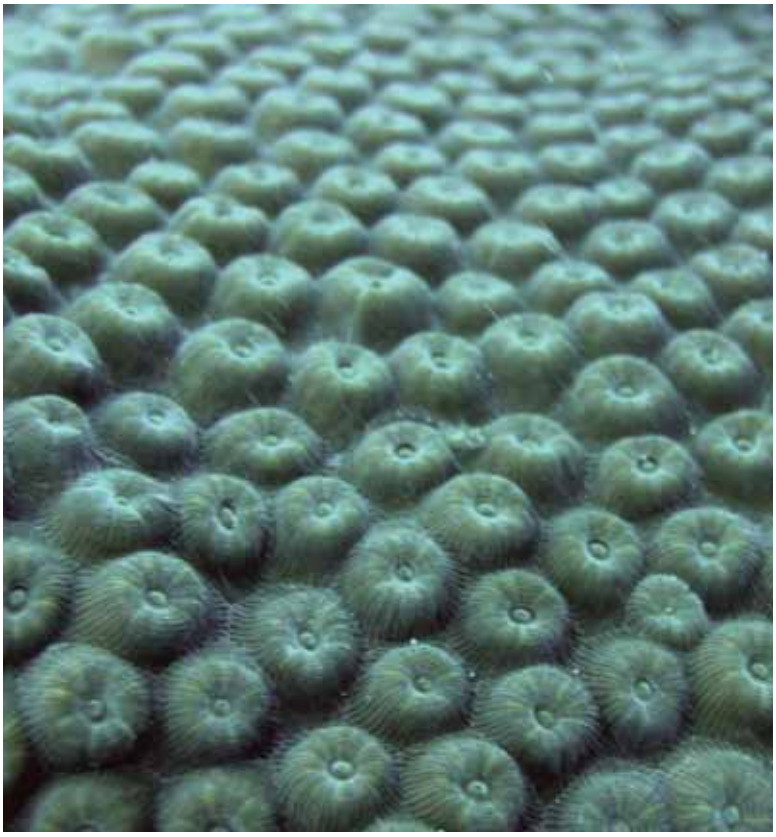


Figure 2.18. Underwater photograph of the Great Star Coral (*Montastraea cavernosa*).

calculated for each input band. If the smallest *p*-value from this *F*-test is less than another predefined threshold (again, as determined by the Bonferroni method), then the corresponding input band is selected to be included in the classification. If not, then the input band with the smallest *p*-value from the first Chi-squared test is selected to be included in the classification (Loh and Shih, 1997). Thus, if all the input bands are uninformative with respect to partitioning an image, then each band has approximately the same chance of being selected to split a node.

Once the statistically significant input band has been selected, this input band is then used during the *binary split identification* step to partition objects in the image into different classes. To determine the location of these splits, QUEST uses a 2-means clustering algorithm (Hartigan and Wong, 1979), which minimizes the within-cluster sum of squares, to preliminarily group objects in the image into two super classes clustered around the two most extreme sample means. If the two super class means are identical, then the class with the largest number of samples becomes one superclass, while the remaining classes are grouped into the second superclass. The ideal split between these two classes is then identified using a modified version of quadratic discriminant analysis. This modified analytical technique accounts for unequal variances by only using the quadratic root closest to the sample mean of each class. This quadratic root is then used to find the ideal split between the two super classes at the intersection of their density curves (Figure 2.20). Once the split is made, the entire process of variable selection and partitioning starts over, and continues iteratively until no more useful splits are found in the data, or until pruning or a predefined rule or tells the algorithm to stop (Loh and Shih, 1997).

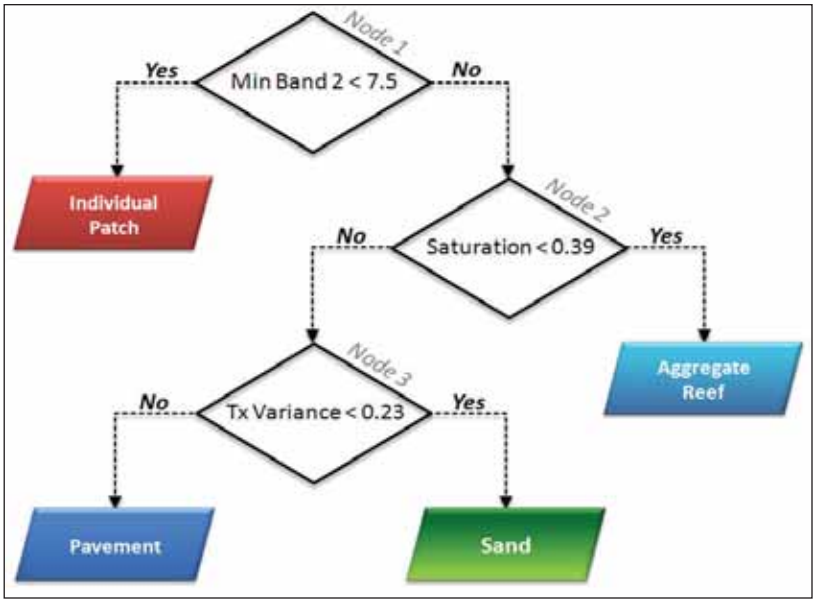


Figure 2.19. This diagram illustrates how QUEST uses binary decisions to split an image into different classes. For example at node 1, if a habitat object's Minimum Band value is < 7.5, then it is attributed with the Individual Patch Reef detailed structure type. However, if a habitat object's Minimum Band value is ≥ 7.5, then QUEST moves on to node 2 and so on down the line. While this sample decision tree only has three nodes, the final coral reef and soft bottom/rhodoliths decision trees had 91 and 71 nodes, respectively.

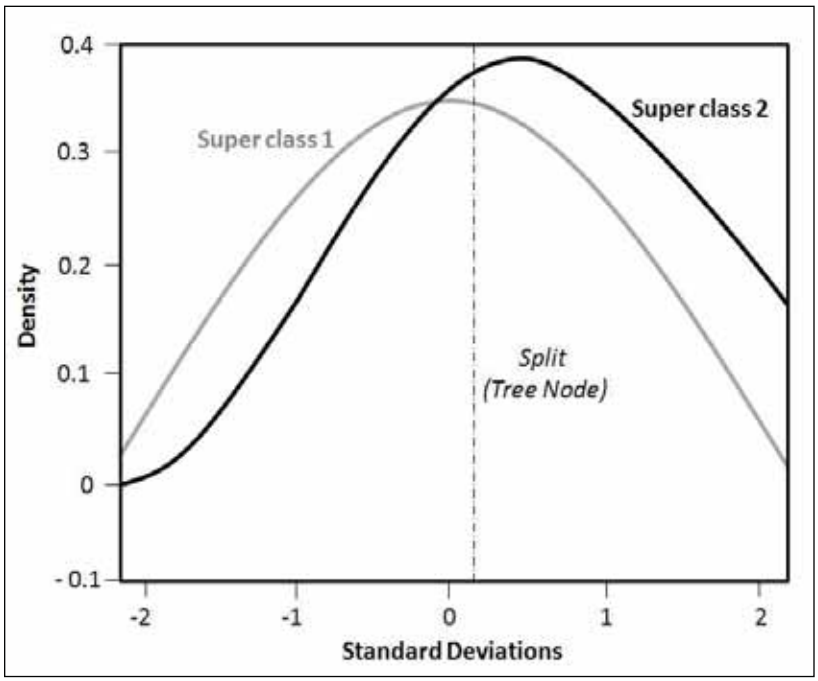


Figure 2.20. This graph describes how QUEST determines where to split super classes into two groups. The density curves of Superclass 1 and 2 are depicted in gray and black, respectively. The ideal split between the 2 super classes (denoted by the vertical dashed line) is determined by using the quadratic root closest to the sample mean of each class near the intersection of their density curves. This split becomes a binary node in the decision tree.

Classifying Objects on the Seafloor

The QUEST algorithm was used to classify each habitat object delineated by ENVI Fx. To simplify this classification process, coral reef habitats as well as soft bottom and rhodolith habitats were classified separately. This means that ROIs for coral reef features and ROIs for soft bottom and rhodoliths features were used to train the QUEST algorithm separately to develop two different classification trees. These trees were built using the same input parameters (Table 2.5), but different combinations of the spatial, spectral, textual, HSI and band ratio attributes. In total, the algorithm found 91 and

71 useful splits when grouping coral reef features and soft bottom/rhodoliths features, respectively. For coral reef habitats in particular, the algorithm found 19 (of the 34) ENVI Fx object attributes useful when splitting these objects into 20 distinct classes. For soft bottom and rhodoliths habitats, the algorithm found 14 (of the 22) ENVI Fx object attributes useful when splitting these objects into 11 distinct classes (Table 2.6). The distinct classes for both coral reef habitats as well as soft bottom and rhodoliths habitats were based on unique combinations of major structure, detailed structure, major biological cover, percent major biological cover and percent live coral cover classes. The final coral reef and soft bottom and rhodoliths classifications were exported from ENVI 4.6 as separate ESRI shapefiles.

Table 2.5. Descriptions of the input parameters used when building the QUEST classification trees.

INPUT PARAMETER	INPUT VALUES USED	IMPACT OF PARAMETER	DEFINITION
Minimum Node Size	5	When to stop the tree from growing	The smallest number of samples in a node during tree construction. The node will not be split if it contains fewer cases than this number. The smaller this value is, the larger the initial tree will be prior to pruning. The default value is max (5, n/100), where n is the total number of observations (Shih, 2004).
Split Method	Univariate	How to split input bands	The user can choose to create discriminant-based splits using a single variable (to examine the effects of predictor variables one at time) or a linear combination of variables (Shih, 2004; StatSoft, 2007).
Variable Selection Method	Unbiased	How to select important input bands	The user can choose between the unbiased variable selection method described in Loh and Shih (1997) or the biased exhaustive search method which is used in CART described in Breiman et al. (1984) (Shih, 2004). The unbiased method uses discriminant-based split methods to prevent biased in variable selection. Thus, if all the attributes are uninformative with respect to the class attribute, then each has approximately the same chance of being selected to split a node (Lim et al., 2000).
Alpha Value (α)	0.05	When to consider a variable as significant	Alpha value is a number $0 \leq \alpha \leq 1$ at which point a *p*-value is considered significant. If the unbiased variable selection method is used, then an alpha value is needed to conduct the tests (Shih, 2004).
Number of SEs for pruning	1	How much of the tree to prune	The number of SEs (standard errors) controls the size of the pruned tree. SE = 0 gives the tree with the smallest cross validation estimate of misclassification cost or error (Shih, 2004).
Number of Folds (V)	10	How to calculate SE for the tree	The user can choose the value of V in V-fold cross-validation. 10-fold is usually recommended and is the default in CART (Shih, 2004). This means that when V = 10, the dataset is randomly divided into 10 roughly equal parts. One part is left out while a regression estimate is constructed using the 9 remaining parts. The left-out part is then used to estimate the prediction mean standard error for the tree (Loh, 2002).
CV Tree Details	No	N/A	The user can choose whether the details of the cross validation tree are reported (Shih, 2004).
Output PStricks tree?	No	N/A	The user can choose whether to use the PSTricks package (to access PostScript features that are otherwise not directly accessible from LaTeX) to draw the QUEST tree. LaTeX is a document preparation system for the TeX typesetting program, offering desktop publishing features for automating aspects of typesetting and desktop publishing.

Classification Post Processing and Evaluation

These ESRI shapefiles were then brought into ArcGIS 9.3 for additional post processing and visual quality assurance and control. In particular, these steps included: (1) removing polygons smaller than the minimum mapping unit and filling gaps in the shapefiles, (2) merging the coral reef as well as soft bottom and rhodoliths maps, (3) visually evaluating and editing this merged map, and (4) smoothing the final habitat polygon boundaries. In step 1, habitat polygons, which were smaller than the 1,000 m² MMU, were merged with adjacent polygons using ET Geowizards "Eliminate" function (Tchoukanski 2008). This function removed these polygons by merging them into neighboring polygons with which they shared their longest common border (Figure 2.21). In total, this function merged 2,717 soft bottom and rhodoliths polygons into 638 soft bottom and rhodoliths polygons, and 698 coral reef polygons into 290 coral reef polygons. After these polygons with < 1,000 m² area were removed, gaps in the soft bottom and rhodoliths shapefile were filled using ET Geowizards "Clean Gaps" function (Tchoukanski 2008). This function added 360 unattributed polygons into the soft bottom and rhodoliths shapefile.

Table 2.6. The polygon metrics (calculated by ENVI Fx) that were identified by QUEST as being significant for classifying coral reef habitats and soft bottom/rhodolith habitats. In total, 19 metrics were used to classify coral reef habitats, and 14 metrics were used to classify the soft bottom and rhodolith habitats.

# of BANDS	FX ATTRIBUTE (Coral Reef)	FX ATTRIBUTE (Soft bottom & Rhodoliths)
1	AVGBAND_1	AREA
2	BANDRATIO	AVGBAND_1
3	COMPACT	CONVEXITY
4	FORMFACTOR	HOLESOLRAT
5	HUE	MAINDIR
6	INTENSITY	MAJAXISLEN
7	MAINDIR	MAX_BAND_1
8	MAXBAND	MINBAND_1
9	MAXBAND_2	NUMHOLES
10	MAXBAND_3	ROUNDNESS
11	MINAXISLEN	STDBAND_1
12	MINBAND_2	TX_ENTROPY
13	MINBAND_3	TX_MEAN
14	RECT_FIT	TX_VARIANC
15	SATURATION	
16	SOLIDITY	
17	TX_ENTROPY	
18	TX_MEAN	
19	TX_VARIANC	

In step 2, the coral reef and soft bottom and rhodoliths shapefiles were integrated (during an active Editing session) to produce one shapefile. To do so, all 290 of the coral reef polygons were selected, copied and pasted into the soft bottom and rhodoliths shapefile. These polygons were then merged and used to collectively clip the soft bottom and rhodoliths polygons, discarding the area that intersected. Clipping the soft bottom and rhodoliths polygons with the coral reef polygons ensured that there was no overlap between habitat types. After clipping, all of the coral reef polygons were then selected, copied and pasted again into the soft bottom and rhodoliths shapefile to create a continuous map. The ET Geowizards "Eliminate" function was then run again on this continuous map to remove any polygon slivers < 1,000 m² created during the merge process.

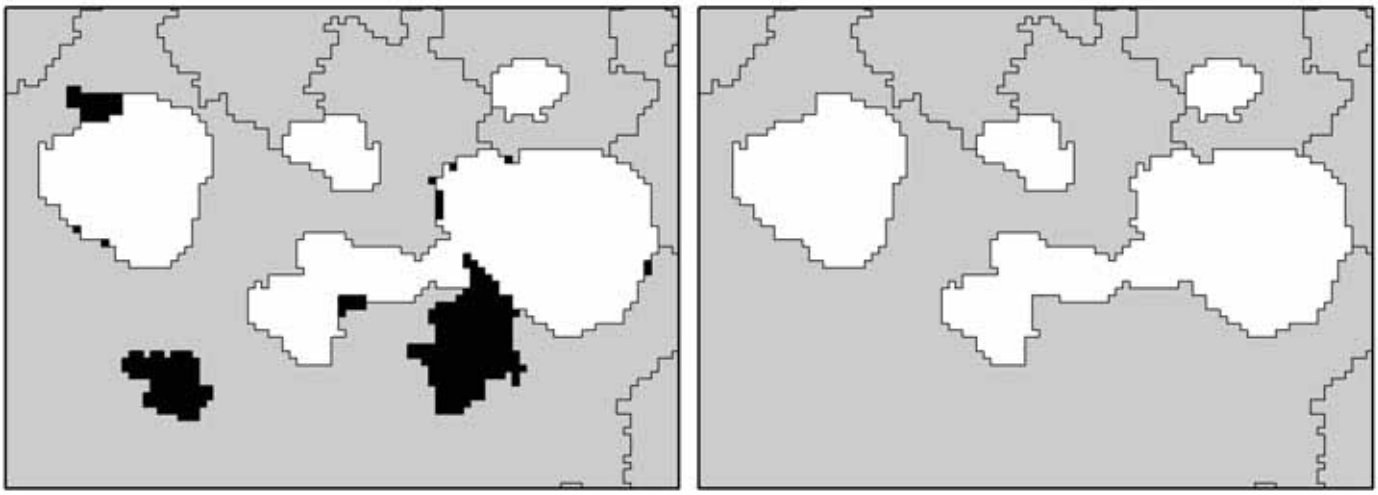


Figure 2.21. The ET Geowizard's "Eliminate" function was used to merge polygons < 1,000 m² with neighboring polygons with which they shared their longest common border. The map on the left shows the habitat map before these polygons were merged, and the map on the right shows the habitat map after these polygons were merged. Polygons smaller than the map's MMU are black. Coral reef features are white, and soft bottom and rhodoliths features are gray.

In step 3, the merged map was visually evaluated, and polygons were manually edited if necessary. These edits included reclassifying, merging or deleting polygons where the cartographer disagreed with the algorithm's interpretation. They also included manually digitizing habitat features (>1,000 m² at a scale of 1:2,000) that were overlooked during the feature extraction process (Table 2.7). During this QA/QC process, approximately 40% of the total number of polygons were manually deleted or merged and approximately 37% of the total number of polygons were manually added (Table 2.8). In the final step, (step 4), ET Geowizard's "Smooth Polygons" function was used to smooth the pixilated appearance of the polygon lines (Figure 2.22). The B-spline smoothing algorithm was used with the input parameters "smooth" and "freedom" set to 10 and 5, respectively. The end result was a seamless habitat map of the seafloor area between 14 to 55 m deep within and around the VICRNM.

Table 2.7. Estimated number of polygons that were manually deleted, added or merged.

	TOTAL # POLYGONS	% OF POLYGONS
Unedited Map	1,324*	-
Final Map	1,283	-
Deleted/Merged	514	(514/1,283)*100 = 40%
Added	473	(473/1,283)*100 = 37%

Note: * = 7,221 polygon slivers < 1,000 m² were subtracted from the total number of polygons (8,545) in the unedited map to derive this number.

Table 2.8. Estimated number of polygons that were manually reattributed because they were deleted, added and/or reclassified. These numbers are based on a randomly distributed sample of 1,000 points stratified by detailed structure type and weighted by area. Habitat classifications contained in the original map (i.e., the unedited map produced by QUEST) and the final map (i.e., the map that was manually edited and delivered to the NPS) were extracted at each of these 1,000 points, and compared to determine whether they had been changed.

POLYGON ATTRIBUTE	TOTAL # UNEDITED POLYGONS	% UNEDITED POLYGONS	TOTAL # EDITED POLYGONS	% EDITED POLYGONS
Major Structure	1,149	90%	134	10%
Detailed Structure	1,106	86%	177	14%
Major Cover	1,137	89%	146	11%
% Cover	888	69%	395	31%
Major + % Cover	844	66%	439	34%
% Live Coral Cover	1,239	97%	44	3%

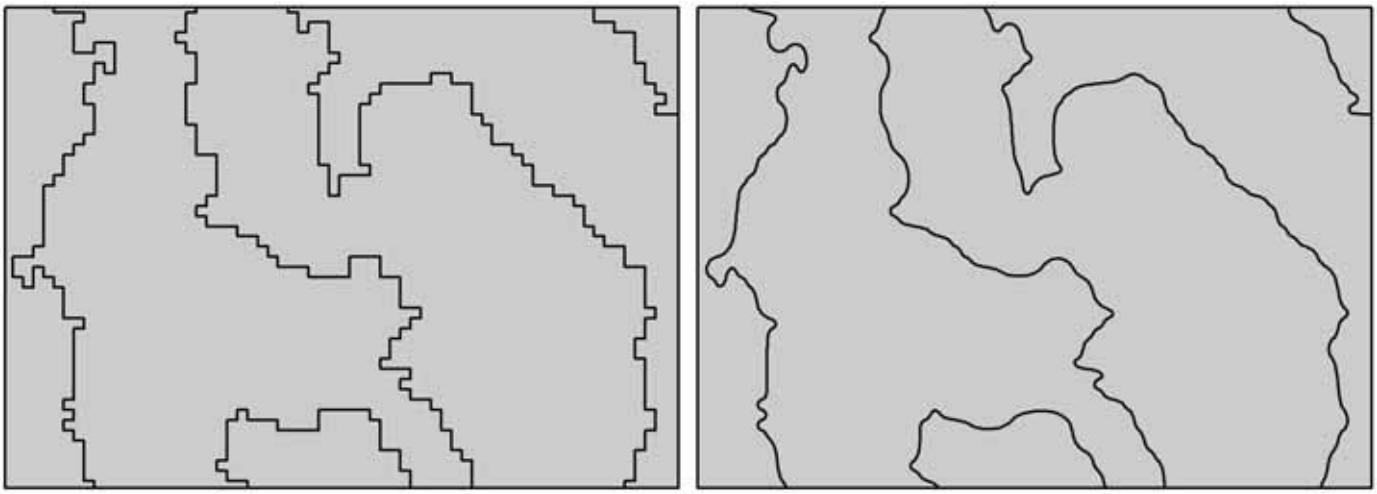


Figure 2.22. ET Geowizard's "Smooth Polygons" function was used to smooth the pixilated appearance of the polygon lines. The map on the left shows the habitat map before the polygon lines were smoothed, and the map on the right shows the habitat map after the polygon lines were smoothed.

2.4 GIS QUALITY CONTROL

All GIS deliverable products generated throughout the mapping process were examined for attribution and topological errors. Particular attention was given to polygon geometry and attribution of the benthic habitat map, as well as to the attribution of each GV point. Multipart, sliver and void polygons were all removed using standard ArcGIS Spatial Analyst tools. Two custom ArcGIS extensions were employed to identify the following conditions:

1. Adjacency – polygons that shared a common boundary and exact attribute combination that were delineated separately (Buja, 2008[a])
2. Overlap – polygons sharing the same geographic space, thus violating mutual exclusion (Buja, 2008[b])

Errors resulting from either of these GIS routines were corrected in the draft maps and eliminated from the final product. A visual inspection of attributes on a feature-by-feature basis was conducted to correct for any misspellings or illogical attribute combinations. These quality assessments and controls ensured that the GIS data from this work were topologically clean and free of attribution errors. In addition, metadata summaries were prepared in an FGDC-compliant format for all GIS products that were supplied during final delivery.

LITERATURE CITED

Battista, T. A., and J.V. Lazar. 2005. MBES data acquisition and processing report: Project NF-05-05-USVI, NOAA Data Acquisition and Processing Report, NOS NCCOS CCMA (Online).

Battista, T. A., B.M. Costa and S.M. Anderson. 2007[a]. Shallow-water benthic habitats of the main eight Hawaiian islands. NOAA Technical Memorandum NOS NCCOS 61(Online).

Battista, T.A., B.M. Costa and S.M. Anderson. (2007)[b]. Shallow-Water Benthic Habitats of the Republic of Palau. NOAA Technical Memorandum NOS NCCOS 59 (Online).

Breiman, L., J.H. Friedman, R.A. Olshend and C.J. Stone. 1984. Classification and regression trees. Belmont, California: Wadsworth International Group. p 324.

Buja, K. 2008[a]. Find adjacent features. ESRI Support Center. Online: http://arcscripts.esri.com/details.asp?dbid=15805. Accessed March 2009.

Buja, K. 2008[b]. Find overlapping polygons. ESRI Support Center. Online: http://arcscripts.esri.com/details.asp?dbid=15198. Accessed March 2009.

Fonseca, L., and B. Calder. 2005. Geocoder: an efficient backscatter map constructor. Proceedings of the U.S. Hydrographic Conference 2005, San Diego, CA.

GEODAS. 2005. NOAA's GEOphysical DAta System (GEODAS). Online: http://www.ngdc.noaa.gov/mgg/geodas/geodas.html. Accessed September, 2005.

Hartigan, J. A. and M.A. Wong. 1979. Algorithm AS 136: A k-means Clustering Algorithm. Applied Statistics. 28, 100-108.

ITT VIS (Visual Information Solutions). 2008[a]. Chapter 1: Introduction. ENVI Feature Extraction Module 4.6 User's Guide. pp. 1−78.

ITT VIS (Visual Information Solutions). 2008[b]. Chapter 3: Finding Objects. ENVI Feature Extraction Module 4.6 User's Guide. pp. 1−78.

Jengo, C. 2004. RuleGen 1.02. ITT VIS (Visual Information Solutions), Online: http://www.ittvis.com/UserCommunity/CodeLibrary.aspx. Accessed November, 2007.

Jenness, J. 2002. ArcView 3.x extension: Surface Areas and Ratios from Elevation Grid v1.2. Online: http://www.jennessent.com/arcview/surface_areas.htm. Accessed September, 2009.

Jenness, J. 2004. Calculating landscape surface area from digital elevation models. Wildlife Society Bulletin, 32, 829–839.

Kendall, M.S., M.E. Monaco, K.R. Buja, J.D. Christensen, C.R. Kruer, M. Finkbeiner and R.A. Warner. 2001. Methods used to map the benthic habitats of Puerto Rico and the U.S. Virgin Islands. NOAA Technical Report (Online).

Kendall, M.S., O.P. Jensen, C. Alexander, D. Field, G. McFall, R. Bohne and M.E. Monaco. 2005. Benthic Mapping Using Sonar, Video Transects, and an Innovative Approach to Accuracy Assessment: A Characterization of Bottom Features in the Georgia Bight. Journal of Coastal Research. 21:6, 1154-1165.

Kostylev, V.E., B.J. Todd, G.B.J. Fader, R.C. Courtney, G.D.M. Cameron and R.A. Pickrill. 2001. Benthic habitat mapping on the Scotian Shelf based on multibeam bathymetry, surficial geology and sea floor photographs. Marine Ecology Progress Series. 219, 121-137.

Lillesand, T.M. and R.W. Kiefer. 2000. Remote sensing and image interpretation, 4th ed. New York, U.S.A.: John Wiley and Sons Ltd. p 724.

Lim, T-S., W-Y. Loh and Y-S. Shih 2000. A Comparison of Prediction Accuracy, Complexity, and Training Time of Thirty-three Old and New Classification Algorithms. Machine Learning, 40, 203-229.

Loh, W-Y. 2002. Regression Trees with Unbiased Variable Selection and Interaction Detection. Statistica Sinica, 12, 361-386.

Loh, W-Y. and Y-S. Shih. 1997. Split Selection Methods for Classification Trees. Statistica Sinica, 7, 815-840.

Mather, P.M. 2004. Computer processing of remotely-sensed images, 3rd ed. West Sussex, England: John Wiley and Sons Ltd. pp. 1−324.

Monaco, M.E. and S.C. Rooney. 2004. MBES data acquisition and processing report: Project NF-04-06-VI, NOAA Data Acquisition and Processing Report, NOS NCCOS CCMA (On-line).

Patterson, D. 2008. Split Layer by Attributes. ESRI Support Center. Online: http://arcscripts.esri.com/details.asp?dbid=14127. Accessed August, 2009.

Prada, M.C., R.S. Appeldoorn and J.A. Rivera. 2008. Improving Coral Reef Habitat Mapping of the Puerto Rico Insular Shelf Using Side Scan Sonar. Marine Geodesy. 31, 49-73.

Robinson, D.J., N.J. Redding and D.J. Crisp. 2002. Implementation of a fast algorithm for segmenting SAR imagery, Scientific and Technical Report, 01 January 2002. Australia: Defense Science and Technology Organization.

Shih, Y-S. 2004. QUEST User's Manual. National Chung Cheng University, Taiwan. p 28. Online: http://www.stat.wisc.edu/~loh/treeprogs/quest/questman.pdf. Accessed September 2009.

StatSoft, Inc. 2007. Electronic Statistics Textbook (Classification Trees). Tulsa, OK. Online: http://www.statsoft.com/textbook/stclatre.html#computation2. Accessed September, 2009.

Tchoukanski, I. 2008. ET Geo Wizards 9.8 for ArcGIS 9.2. ET Spatial Techniques. Pretoria, South Africa. Online: http://www.ian-ko.com/. Accessed September, 2009.

Wright, D.J., E.R. Lundblad, E.M. Larkin, R.W. Rinehart, J. Murphy, L. Cary-Kothera and K. Draganov. 2005. ArcGIS Benthic Terrain Modeler (BTM). Corvallis, Oregon. Oregon State University, Davey Jones Locker Seafloor Mapping/Marine GIS Laboratory and NOAA Coastal Services Center. Online: http://www.csc.noaa.gov/products/btm/. Accessed September, 2009.

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