Acoustic signatures of the seafloor: tools for predicting grouper habitat

Arthur C. R. Gleason
Division of Marine Geology and Geophysics
Rosenstiel School of Marine and
Atmospheric Science
University of Miami
4600 Rickenbacker Cswy.
Miami, FL 33149
E-mail address: art.gleason@miami.edu

Anne-Marie Eklund
Southeast Fisheries Science Center
National Marine Fisheries Service, NOAA
75 Virginia Beach Dr.
Miami, FL 33149

R. Pamela Reid
Division of Marine Geology and Geophysics
Rosenstiel School of Marine and
Atmospheric Science
University of Miami
4600 Rickenbacker Cswy.
Miami, FL 33149

Veronique Koch
Southeast Fisheries Science Center
National Marine Fisheries Service, NOAA
75 Virginia Beach Dr.
Miami, FL 33149

Abstract—Groupers are important components of commercial and recreational fisheries. Current methods of diver-based grouper census surveys could potentially benefit from development of remotely sensed methods of seabed classification. The goal of the present study was to determine if areas of high grouper abundance have characteristic acoustic signatures.

A commercial acoustic seabed mapping system, QTC View Series V, was used to survey an area near Carysfort Reef, Florida Keys. Acoustic data were clustered using QTC IMPACT software, resulting in three main acoustic classes covering 94% of the area surveyed. Diver-based data indicate that one of the acoustic classes corresponded to hard substrate and the other two represented sediment. A new measurement of seabed heterogeneity, designated acoustic variability, was also computed from the acoustic survey data in order to more fully characterize the acoustic response (i.e., the signature) of the seafloor.

When compared with diver-based grouper census data, both acoustic classification and acoustic variability were significantly different at sites with and without groupers. Sites with groupers were characterized by hard bottom substrate and high acoustic variability. Thus, the acoustic signature of a site, as measured by acoustic classification or acoustic variability, is a potentially useful tool for stratifying diver sampling effort for grouper census.

Introduction

Several species of groupers (family: Serranidae) are important components of recreational and commercial fisheries. These fish also contribute to healthy coral reef ecosystems and are often a focus of recreational diving and photography. As such, preserving healthy populations of groupers is desirable for economic, ecological, and aesthetic reasons.

The life history and behavior of groupers make them especially susceptible to overexploitation (Coleman et al., 1999). Groupers are top predators in the coral reef ecosystem, with long life spans and a low natural mortality rate. When predation by man decreases their abundance, however, groupers are slow to recover because they do not begin to reproduce until late ages (Polovina and Ralston, 1987; Sadovy, 1994). Many species of grouper, such as goliath grouper (*Epinephelus itajara*), Nassau grouper (*E. striatus*), and red grouper (*E. morio*), are unwary of divers and are easily caught in traps or by angling. Furthermore, many groupers form predictable, seasonal, and site specific aggregations, which are easy to eradicate once located by fishermen (Polovina and Ralston, 1987; Sadovy, 1994; Coleman et al., 1999; Sadovy and Eklund, 1999). For these reasons, groupers are a family of fishes that are likely to benefit from marine protected areas (MPAs; areas of no take).

For MPAs to be useful in grouper conservation, they must incorporate appropriate habitat. Currently, however, essential grouper habitat is poorly defined. Like most reef fishes, groupers prefer hard bottom (e.g., coral reef) to unconsolidated substrate (e.g., seagrass or bare sediment). Beyond this, knowledge of grouper habitat is largely anecdotal. The National Oceanic and Atmospheric Administration (NOAA) National Marine Fisheries Service (NMFS) Southeast Fisheries Science Center (SEFSC) has been monitoring grouper density near Carysfort Reef since 1994 (Eklund et al., 2000) and more recently at other reefs of the Florida Keys. Through experience, the NOAA divers have developed a qualitative “feel” for good grouper habitat, which often includes features such as high relief and the presence of caves or crevices, especially on steeply sloping surfaces.

Maps showing the distribution of potential grouper habitat are limited. In the Florida Keys, for example, an aggregation of 70–100 black groupers (*Mycteroperca bonaci*) was observed just 100 m outside the protected area at Carysfort Reef less than a year after the preserve opened (Eklund et al., 2000). Discovery of the first known aggregation of any grouper species in the Florida Keys (Eklund et al., 2000) just outside the largest MPA in the Keys is ironic. Information on the distribution of fish habitat is highly relevant to MPA design, yet often such critical information is unavailable. The experience at Carysfort underscores the need for efficient methods of 1) seabed mapping and 2) prioritizing limited dive time for fish census.

Diver-based grouper census surveys could potentially benefit from improved methods of remotely sensed seabed classification. Optical mapping products, such as the Benthic Habitats of the Florida Keys (FMRI, 1998), are useful in some applications; however, much important grouper habitat, including the area of the large aggregation observed by Eklund et al. (2000) outside the Carysfort MPA, is located in deeper water where optical mapping techniques are not useful. Acoustic mapping systems are a promising technology for mapping areas where the bottom cannot be detected by optical methods.

Acoustic methods have been successfully used to discriminate substrate classes in many areas around the world (e.g., Hamilton et al., 1999; Morrison et al., 2001; Anderson et al., 2002; Ellingsen et al., 2002; Freitas et al., 2003a). To date, however, applications of this methodology in carbonate reefal environments are limited. The overall goal of the present study was to evaluate the potential of a commercial acoustic mapping system, QTC View Series V (QTC-V; Quester Tangent Corporation, Sidney, BC, Canada, 2001), to identify potential grouper habitat and prioritize sites for diver surveys.

Specifically, this project addressed the question: Do areas of high grouper abundance have characteristic acoustic signatures? Results demonstrate two effective predictors of grouper presence or absence: 1) simple acoustic seabed classification, which distinguishes hard bottom from sediment substrate, and 2) a newly developed index of acoustic variability.

Methods

The study focused on Carysfort Reef, Florida Keys (Fig. 1). An acoustic survey was performed and the resulting data processed in two ways. First, clusters of acoustically distinct echoes were segmented using commercially available software. Second, a new index of acoustic variability was developed. This index was designed to measure seabed heterogeneity by quantifying the degree to which the echo at a particular location is similar to other nearby echoes.

The acoustic survey was complemented with diver surveys, which collected "ground truth" data on bottom type and grouper abundance. Correlations between acoustic and diver surveys were conducted to test the value of using acoustic signatures for identifying potential sites for grouper habitat and prioritizing sites for diver surveys. Details of the methods are presented below.

Acoustic survey

Data collection and seabed classification The acoustic survey at Carysfort Reef (Fig. 1) was conducted using a QTC-V acoustic mapping system. Acoustic data were recorded using a Suzuki 50 kHz echo sounder (model 2025). A wide area augmentation system (WAAS) enabled global positioning system (GPS), mounted with its antenna directly over the acoustic transducer, provided vessel positioning. The survey, conducted on 14 March, 28 March, and 4 April 2002, consisted of transects spaced 100 m apart running perpendicular to the reef crest from an inshore depth of 3 m to a maximum offshore depth of 42 m.

Data processing for seabed classification involved four steps (Fig. 2). Processing was done using IMPACT (version 3.4, QTC, Sidney, BC, 2004), the processing software provided with QTC-V. During the first step, the data acquisition phase, the signal generated by an echo sounder is passed to a head amplifier that applies both time-varying gain, to compensate for beam spreading and water depth, and auto gain control, to compensate for variable bottom reflectance. Individual echoes are then digitized using a 5 MHz analog to digital card and recorded by a computer.

In the second step, the data reduction phase, the raw bi-polar waveforms are converted to echo "envelopes" (essentially echo amplitude only). The echo envelopes are stacked (averaged) in groups of five to reduce ping-to-ping variability. The stacked echoes are characterized by a number of algorithms that respond to features of the echo shape. The ensemble of features is reduced using principal components analysis (PCA) to the first three principal components. The end result is that each stacked echo is represented by a single point in three-dimensions ("Q-space"; QTC, 2004). The shape of the stacked echo determines the coordinates of this point.

In the third step, the clustering phase, the "cloud" of points in Q-space is partitioned into clusters using a simulated annealing clustering procedure. The statistical descriptions (mean, covariance) of these clusters comprise a "catalog" (QTC, 2004).

Finally, in the classification stage, a catalog is used to assign a class to all points in a dataset. The catalog can be applied to the original data used to create the catalog (via clustering) or it can be applied to another data set acquired with the same hardware configuration.

The four steps of acquisition, reduction, clustering, and classification are fundamental to the IMPACT

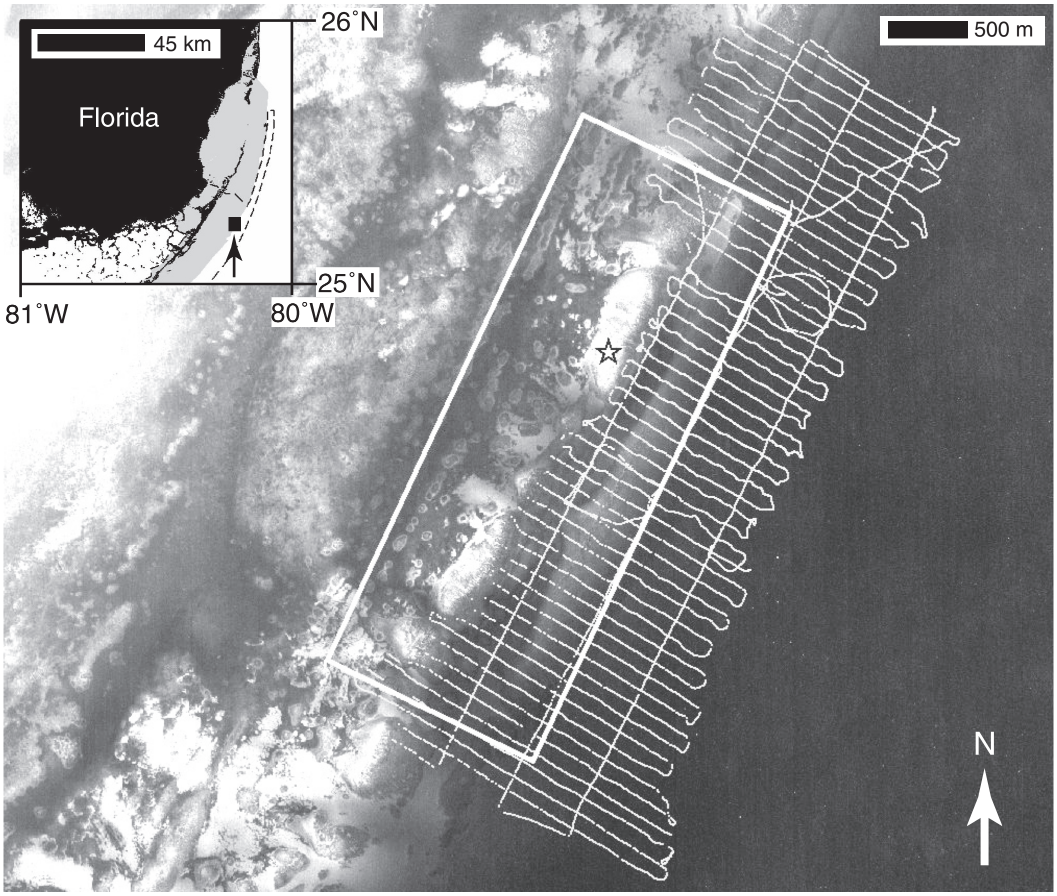

Figure 1

Track lines from the acoustic survey superimposed on an IKONOS satellite image of Carysfort Reef and surroundings. The Carysfort lighthouse (star) and protected area (bold rectangular box) are also shown. The arrow in the inset shows the location of the IKONOS image in the wider context of South Florida (solid black), the Florida Keys National Marine Sanctuary (dashed line), and the area that has been mapped by FMRI (1998) from aerial photography (grey). The track lines extend from near the reef crest to deeper water where the bottom is no longer visible.

processing procedure. The overview above is similar to previous descriptions of data processing using QTC View Series IV and older versions of the IMPACT software (e.g. Hamilton et al., 1999; Morrison et al., 2001; Anderson et al., 2002; Ellingsen et al., 2002; Freitas et al., 2003a). A series of conference papers (e.g. Preston[1]) provide more detailed descriptions of each of the four steps.

Acoustic variability index Standard QTC analysis, as described above, characterizes the acoustic response of a position on the seafloor relative to all others in the survey area based solely on echo shape. The geographic location of the echo is irrelevant in the clustering process; location is used only to plot the classification results. An additional way to characterize acoustic response at a point is to quantify the degree to which a particular echo is similar in shape to its geographic neighbors (as opposed to its neighbors in Q-space). Such a measure, designated acoustic variability, was developed as part of this study (Fig. 3). The computation of acoustic variability, described below, complements the standard QTC classification to more fully characterize the acoustic signature of any given location on the seafloor.

---

[1] Preston, J. M., A. C. Christney, L. S. Beran, and W. T. Collins. 2004. Statistical Seabed Segmentation - From Images and Echoes to Objective Clustering. 7th European Conference on Underwater Acoustics, Delft, Netherlands, 5–8 July 2004. 6 p. is available, along with other papers describing the details of processing QTC View data, from the QTC Web site: http://www.questertangent.com [Accessed on 21 Dec 2004]

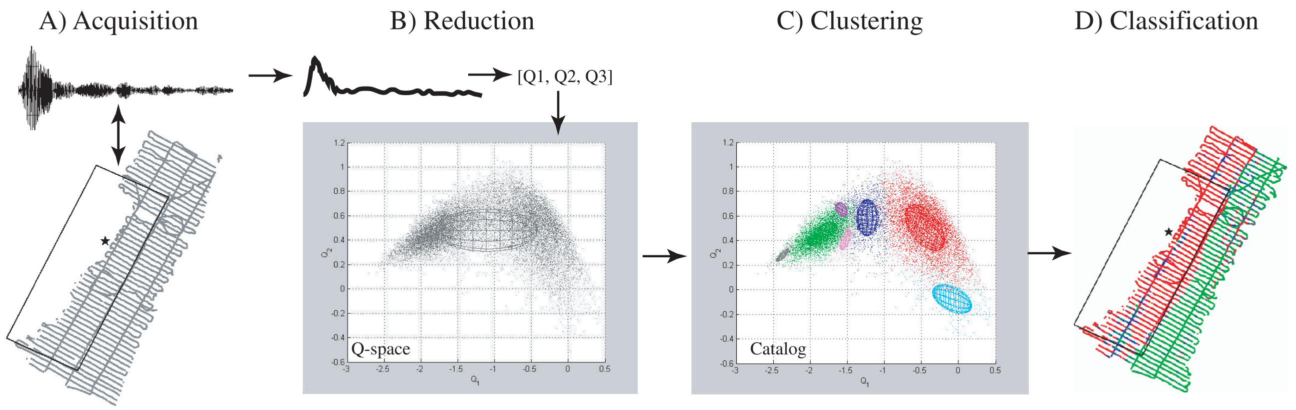

Figure 2

Overview of acoustic processing. A) The full waveform for each point is acquired, georeferenced, and recorded. B) Each echo is converted to three coordinates in "Q-space" based on the shape of the echo "envelope" (echo amplitude). C) Q-space is partitioned into distinct groups defined by their means and covariances. D) Each point is assigned a class based on its location in Q-space.

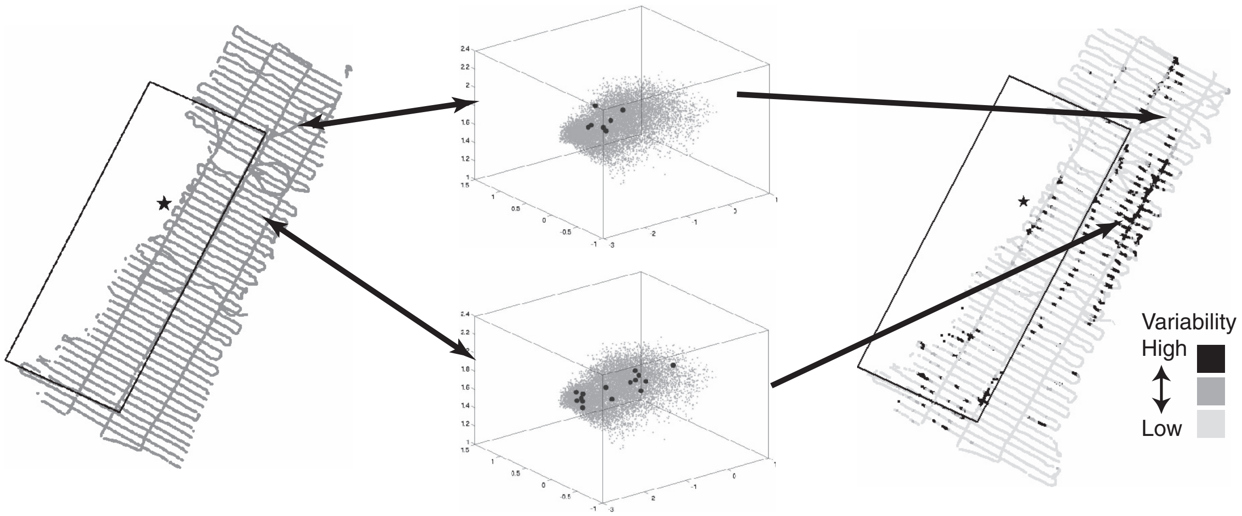

Figure 3

Computation of acoustic variability. A moving window sliding over the geographic dataset (left plot) selects neighboring points. Variability is the sum of the lengths of the principal axes of the cloud formed by the selected points in Q-space. If these points have low acoustic variability, they will cluster close together in Q-space (upper center plot). If they have high acoustic variability, they will form a scattered cloud in Q-space (lower center plot). The spatial pattern of variability is apparent when displayed using the geographic location of each echo (right plot).

Acoustic variability was computed point-by-point across the data set by considering a small moving window applied around each echo in the survey (Fig. 3). For each point, all the echoes within 40 m of that point were identified. In Q-space this subset of the data produces a small cloud of points (typically between 10–20 points, depending on vessel speed). Variability was defined as the sum of the standard deviations along the three principal axes of this cloud of points and was computed by taking the square root of the trace of the covariance matrix computed for each subset of data (Davis, 1986). A window of data that includes echoes that are all very similar will have points very close to one another in Q-space and will therefore have low acoustic variability.

Conversely, a window of data containing echoes that are all very dissimilar will have points spread across Q-space and will have high acoustic variability.

Diver survey

Twenty-two dives were conducted near Carysfort during August of 2002 and October of 2003 to acquire “ground truth” for the acoustic measurements. The locations of the dives were chosen based on the maps of seafloor classification and acoustic variability. Since only a limited number of dives were possible, the sites were chosen to ensure that multiple dives were placed in 1) homogenous areas of each acoustic class, and 2) areas of high and low acoustic variability.

Diver surveys followed NOAA/SEFSC procedures for conducting fish census (Bohnsack and Bannerot, 1986) and benthic habitat assessment (Franklin et al., 2003), as described by McClellan and Miller (2003). At every site, two divers each surveyed non-overlapping, 7.5 m radius cylinders; results from the two divers were averaged to produce a single set of values for each dive site. Diver collected data that were compared with the acoustics were: 1) the number of groupers (*Epinephelus* and *Mycteroperca* spp.) observed in a five minute interval, and 2) estimated percent cover of three substrate classes (sediment, hard bottom, and rubble).

Comparison of acoustic and diver surveys

Results from acoustic and diver surveys were compared to 1) assess the accuracy of the acoustic classification, and 2) correlate grouper abundance with acoustic classification and variability. The general strategy in both cases was to compare a diver-estimated parameter with the closest acoustically derived values.

Acoustic classification accuracy assessment Assessing the accuracy of acoustic classification involved two steps. First, diver-estimated bottom cover was overlain on the acoustic classification map to visually determine which acoustic classes corresponded with which bottom types. Second, the accuracy of the classification was assessed using an error matrix.

The error matrix is a common method of quantifying the accuracy of a thematic map by comparing “ground truth” for a sample of points on the map with the predictions made by the map (Congalton and Green, 1999). Ground truth is often acquired by visiting sites and visually determining what is there (e.g., by divers). A matrix can then be constructed with one column per ground truth class, one row per map class, and entries in the appropriate row and column for each ground truth point visited. The sum of all the elements in the matrix equals the total number of ground truth points, and the sum of the elements in the matrix for which the ground truth class is the same as the map class is the total number of “correct” points visited on the map. The overall accuracy is the latter divided by the former. This technique was used here with one modification. Usually each point visited is assigned one ground truth class and one map class. In this study, however, each ground truth site (a single dive) was assigned a mixture of three classes (sediment, hard bottom, and rubble), but an echo had only one acoustic class. To accommodate mixed bottom types, the entry in the error matrix for the closest echo to a particular dive site was divided among the columns of the matrix in proportion to the diver-estimated bottom cover for that site.

Grouper abundance vs. acoustic classification and variability Acoustic classes and variability were compared with grouper abundance using analysis of variance (ANOVA) and multiple comparison tests to determine the significance of any correlation. Dive sites were grouped into treatments by the number of groupers at the site, and two ANOVA procedures were run. The first tested the null hypothesis that the mean percent of a given acoustic class was the same for sites with different number of groupers. The second tested the null hypothesis that mean variability was the same for sites with different numbers of groupers.

The MATLAB statistics toolbox (Version 4.0:R13; The MathWorks, Inc., Natick, MA 2002) was used to perform the tests. First, the null hypothesis that the variables being compared followed a normal distribution was evaluated using a Lilliefors test (“lillietest” command; see also Conover, 1980). Based on the output of the Lilliefors test, the parametric (“anova1”) or non-parametric (“kruskalwallis”) MATLAB implementations of ANOVA were used to test the significance of differences between the group means. Finally, if the null hypothesis that all group means were equal was rejected by the ANOVA, the “multcompare” function (based on procedures from Hochberg and Tamhane, 1987) was used to determine which pairs of means were significantly different from one another. A 95% confidence interval ($P < 0.05$) was used for all statistical tests.

Results

Acoustic survey

Clustering the acoustic survey data discriminated seven acoustic classes. The three major classes, which comprised 94% of the echoes in the survey area, are plotted in Figure 4. The four minor classes were dispersed widely across the study area. Due to limited dive time,

Figure 4

The three main acoustic classes, which comprise 94% of echoes in the survey, and diver-estimated substrate at 22 sites. Visual observation of this figure suggests that Acoustic Class 1 corresponds to hard bottom and Acoustic Classes 2 and 3 both correspond to sediment.

the sites chosen for ground truth focused on the three largest classes.

Diver survey

Diver estimates of substrate at the twenty-two sites selected to ground truth the three major acoustic classes are shown in Figure 4. All sites were dominated by sand or hard bottom substrate. Seven sites had small amounts of rubble substrate, with only one site having >10% rubble (Fig. 4).

Grouper abundance at each of the dive sites is shown in Figure 5. At ten sites, no groupers were observed. Groupers were observed at 12 sites, with higher numbers corresponding to decreasing frequency of sites. The maximum number of groupers observed at any site was six (n=1).

Acoustic classification accuracy assessment

Bottom types were assigned to acoustic classes based on visual observation of diver survey results overlain on the acoustic classification map (Fig. 4). Visually, Acoustic Class 1 corresponds with the dive sites dominated by hard bottom and Acoustic Classes 2 and 3 both correspond with the dive sites dominated by sediment (Fig. 4).

The overall accuracy of the acoustic classification considering only hard bottom and sand classes was 86% (Table 1), which is comparable to the accuracy of optical

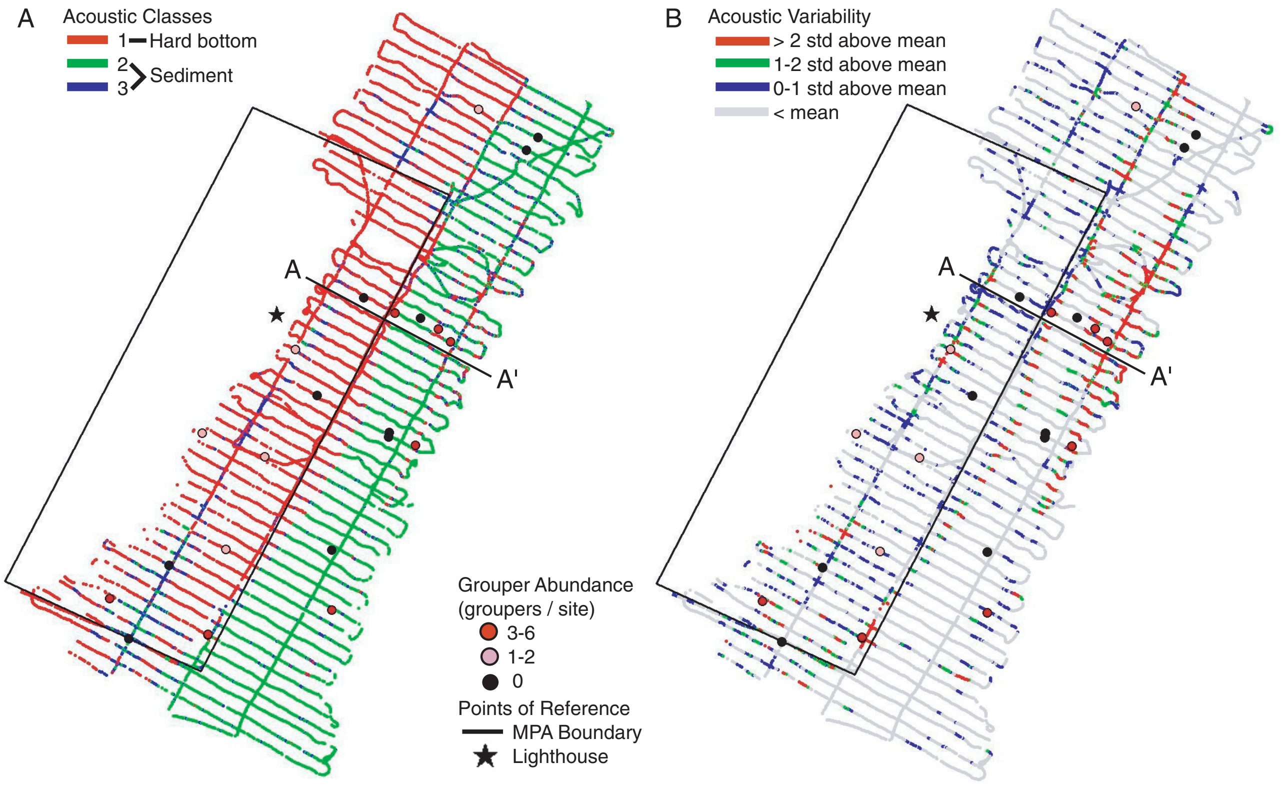

Figure 5

Grouper (*Epinephelus* and *Mycteroperca* spp.) abundance at each of the dive sites relative to (A) acoustic classification and (B) acoustic variability. Groupers were found primarily in areas with hard bottom substrate and high acoustic variability. Note that the area of high variability is much smaller than the area of hard bottom. Transect A-A′ is plotted in Figure 7.

sensors for mapping coarse bottom types (Mumby and Edwards, 2002).

Grouper abundance vs. acoustic classification and variability

Visual inspection of the grouper abundance data in Figure 5 suggests that sites with high grouper abundance were associated with hard bottom and had higher acoustic variability than sites with fewer groupers. The differences between group means were not, however, statistically significant when the data were tested with ANOVA using seven categories (one each for sites with number of groupers from zero to six); this negative result may be due to the small number of sites in most categories. The ANOVA analysis was repeated with sites grouped into only two categories based on the presence (n=12) or absence (n=10) of groupers. Sites with groupers had both a significantly higher percentage of hard bottom relative to sand ($P = 0.006$) and significantly higher acoustic variability ($P < 0.001$) than sites without groupers (Fig. 6).

Discussion

Results from this study demonstrate that acoustic signatures consisting of a simple substrate classification and an index of local heterogeneity were different for dive sites with and without groupers at Carysfort Reef. In general, sites where groupers were present had hard substrate with high local heterogeneity, and sites without groupers had sediment substrate with low local heterogeneity.

QTC systems have previously distinguished outcropping rock from sediment (e.g. Anderson et al., 2002); most of these studies, however, have focused on siliciclastic environments. Moreover, previous work with an older QTC-IV system suggested that rough terrain could adversely affect system accuracy (Hamilton et al., 1999). It is therefore noteworthy that results from this study show that acoustics can be used to distinguish hard bottom and sediment with high accuracy in a high relief, carbonate reef environment.

The reason that sediment in the Carysfort Reef area maps as two distinct acoustic classes (Fig 4) is uncertain,

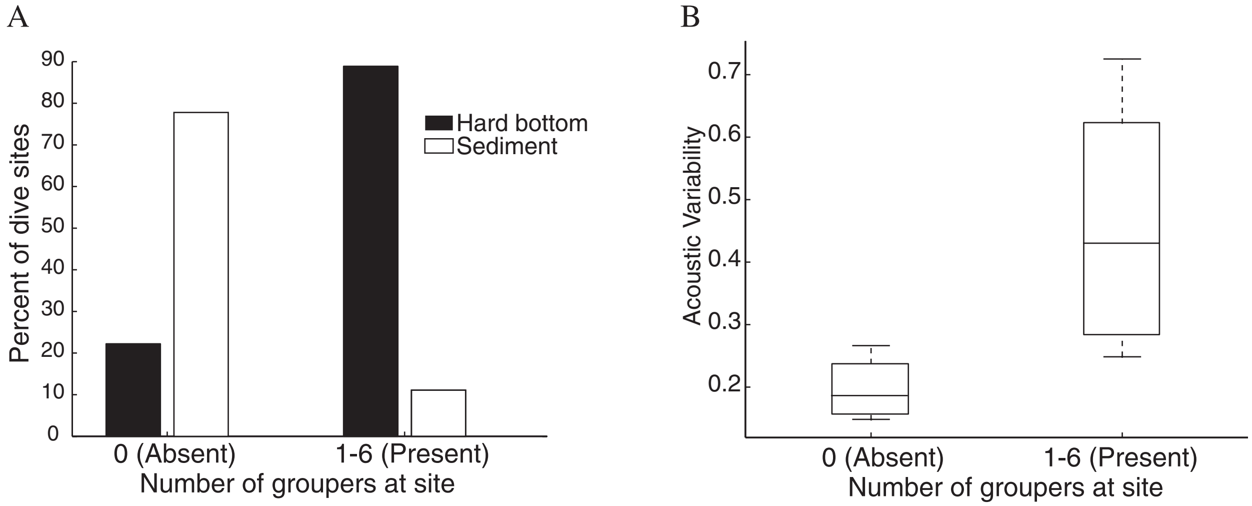

Figure 6

Acoustic classification and acoustic variability computed from the echoes closest to each dive site and grouped by the presence/absence of groupers (*Epinephelus* and *Mycteroperca* spp.). A) Bars indicate the percent of dive sites for which the closest echo classified as hard bottom (Acoustic Class 1) or sediment (Acoustic Classes 2 or 3). B) Box plots of acoustic variability near dive sites. Horizontal lines mark the lower quartile, median, and upper quartile values. The lines extending from each end of the box show the range of all data. Note that grouper presence correlates with hard bottom and high acoustic variability.

but is likely related to differences in physical properties, such as sediment grain size. Clustering of sediment with different grain sizes as distinct acoustic classes would be consistent with previous QTC-derived classification schemes (Anderson et al., 2002; Ellingsen et al., 2002; Freitas et al., 2003a; Freitas et al., 2003b).

The acoustic classification results at Carysfort Reef demonstrate that the location of a point in Q-space is related to physical characteristics of the bottom. A set of points that are spread out in Q-space are therefore more likely to represent different bottom types than a set of points that are tightly clustered in Q-space. Areas where different bottom types are located close together, such as patchy environments or along edges, have high acoustic variability, and areas where the bottom does not change rapidly have low acoustic variability (Fig. 7). Like the Berger-Parker index (Morrison et al., 2001), acoustic variability highlights transitions between classes (edges) and heterogeneous areas with mixed classes. Acoustic variability, however, is computed directly from the reduced acoustic echo features (Q-space) as opposed to operating on classified data. Operating directly on the Q-values may be advantageous because differences between echoes are measured continuously, rather than in discrete classes, and because the results are not dependent on the classification scheme used.

Table 1

Error matrix comparing acoustic classification with diver-based "ground truth." Acoustic Class 1 was interpreted as a hard bottom class, and Acoustic Classes 2 and 3 were combined to form a single sediment substrate class. Fractional values are possible because the entry for each point was divided proportionally by the diver-estimated substrate at that site. The sum of all entries is 18, indicating that the closest echoes to 18 of the 22 dive sites were classified as Acoustic Classes 1, 2, or 3.

	Diver-estimated substrate			
Acoustic classes	Hard bottom	Sediment	Rubble	Overall accuracy
Class 1 (hard bottom)	8.2	1.1	0.7	0.86
Class 2+3 (sediment)	0.7	7.3	0.0	

Observations by NMFS divers that groupers are often found over "complex" bottoms (caves, crevices, ledges) led to the idea of testing acoustic variability. It should be noted, however, that topographic complexity as observed by divers is not the same as acoustic variability as defined in this study. Topographic complexity occurs on

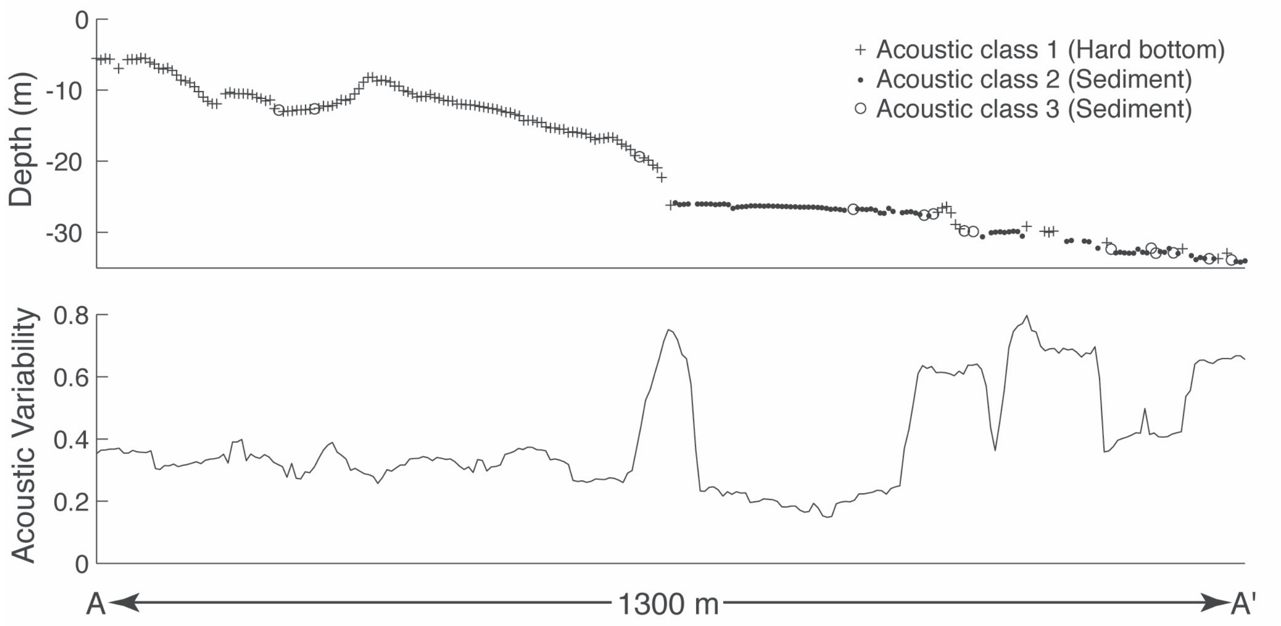

Figure 7

Depth, acoustic class, and acoustic variability along transect A-A′, shown in Figure 5. Acoustic variability within large areas of a single class ranges from high to low, but the highest variability is found at the transitions between classes. Patchy areas, such as the deep outcropping hard bottom, can form extended regions of high acoustic variability.

the scale of meters and might be thought of as a rough or steep bottom. Acoustic variability, on the other hand, is measured on the scale of tens of meters and reflects the proximity of acoustically distinct bottom types.

The observation that sites with groupers had higher acoustic variability than sites without groupers does not mean that acoustic variability is a measure of essential grouper habitat. Acoustic variability does not measure what a diver might perceive as important variables for grouper habitat. Acoustic variability could, however, help prioritize diving effort for grouper population surveys. Acoustic variability might also contribute to a better understanding of grouper habitat. For example, it is not clear why aggregations are so site-specific. From a diver's point of view, the bottom at the site of an aggregation can appear very similar to the bottom just a few hundred meters away. Measurements of acoustic variability may help to interpret diver observations by providing context on a larger spatial scale.

The distinct differences in acoustic signatures of sites with and without groupers (Fig. 6) suggest that acoustic classification and acoustic variability are potentially useful tools for stratifying diver sampling effort for grouper census. A simple map distinguishing hard bottom from sediment, which can be easily produced with acoustics, is a substantial improvement over a lack of any bottom type information in optically deep water. A map of acoustic variability may further refine the location of potential grouper habitat, thereby increasing the efficiency of divers to conduct fish census surveys.

Conclusions

The results of this study showed:

1. A commercial acoustic seafloor classification system (QTC View V) was successfully used to discriminate hard bottom from sediment in a carbonate reef environment.
2. A simple map of hard bottom versus sediment was a useful first step in discriminating potential grouper habitat.
3. An index of acoustic variability, which measures heterogeneity of bottom types, complemented the simple bottom classification map to further target areas of potential grouper habitat.

Therefore, the acoustic signature of the seafloor, as measured with acoustic classification and acoustic diversity, is a useful tool for stratifying sampling effort for diver-based grouper census surveys. Both acoustic classification and acoustic variability can be rapidly and inexpensively acquired when needed by fisheries and park managers around the world because they are easily measured with a single beam echo sounder.

Acknowledgments

Funding for this project was provided by a grant from the NOAA-NMFS Coral Reef Initiative (A.M.E.) and ONR grant N000140110671 (R.P.R.). Small boat and SCUBA diving operations were conducted with the invaluable help of D. McClellan, D. Harper, G.M. Miller, J. Contillo, H. Balchowsky, J. Schull, S. Cimilluca, J. Javech, and N. Baertlein. The authors appreciate insight provided by W. Collins and J. Preston, Quester Tangent Corporation, during the analysis of the acoustic data. Two anonymous reviewers provided detailed and helpful comments on the manuscript.

Literature cited

Anderson, J. T., R. S. Gregory, and W. T. Collins.
2002. Acoustic classification of marine habitats in coastal Newfoundland. ICES J. Mar. Sci. 59:156–167.
Bohnsack, J. A., and S. P. Bannerot.
1986. A stationary visual census technique for quantitatively assessing community structure of coral reef fishes. NOAA Tech. Rep. NMFS 41, 15 p.
Coleman, F. C., C. C. Koenig, A.-M. Eklund, and C. B. Grimes.
1999. Management and conservation of temperate reef fish in the southeastern United States. *In* Life in the slow lane— ecology and conservation of long-lived marine animals (J. A. Musick, ed.), p. 233–242. American Fisheries Society Bethesda, Maryland.
Congalton, R. G., and K. Green.
1999. Assessing the accuracy of remotely sensed data: Principles and practices. Lewis Publishers, Boca Raton, 137 p.
Conover, W. J.
1980. Practical nonparametric statistics. Wiley, New York, 493 p.
Davis, J. C.
1986. Statistics and data analysis in geology. John Wiley & Sons, New York, 646 p.
Eklund, A.-M., D. B. McClellan, and D. E. Harper.
2000. Black grouper aggregations in relation to protected areas within the Florida Keys National Marine Sanctuary. Bull. Mar. Sci. 66(3):721–728.
Ellingsen, K. E., J. S. Gray, and E. Bjornbom.
2002. Acoustic classification of seabed habitats using the QTC VIEW system. ICES J. Mar. Sci.(59):825–835.
Florida Marine Research Institute (FMRI).
1998. Benthic habitats of the Florida Keys. FMRI Technical Report TR-4, 53 p.
Franklin, E. C., J. S. Ault, S. G. Smith, J. Luo, G. A. Meester, G. A. Diaz, M. Chiappone, D. W. Swanson, S. L. Miller, and J. A. Bohnsack.
2003. Benthic habitat mapping in the Tortugas Region, Florida. Mar. Geod. 26:19–34.
Freitas, R., A. M. Rodrigues, and V. Quintino.
2003a. Benthic biotopes remote sensing using acoustics. J. Exp. Mar. Biol. Ecol. 285–286:339–353.
Freitas, R., S. Silva, V. Quintino, A. M. Rodrigues, K. Rhynas, and W. T. Collins.
2003b. Acoustic seabed classification of marine habitats: studies in the western coastal-shelf area of Portugal. ICES J. Mar. Sci. 60:599–608.
Hamilton, L. J., P. J. Mulhearn, and R. Poeckert.
1999. Comparison of RoxAnn and QTC-View acoustic bottom classification system performance for the Cairns area, Great Barrier Reef, Australia. Cont. Shelf. Res. 19:1577–1597.
Hochberg, Y., and A. C. Tamhane.
1987. Multiple comparison procedures, Wiley, 450 p.
McClellan, D. B., and G. M. Miller.
2003. Reef fish abundance, biomass, species composition, and habitat characterization of Navassa Island. *In* Status of reef resources of Navassa Island: Nov. 2002 (M. W. Miller, ed.), p. 24–42. NOAA Tech. Memo. NMFS-SEFSC-501.
Morrison, M. A., S. F. Thrush, and R. Budd.
2001. Detection of acoustic class boundaries in soft sediment systems using the seafloor acoustic discrimination system QTC VIEW. J. Sea Res. 46:233–243.
Mumby, P. J., and A. J. Edwards.
2002. Mapping marine environments with IKONOS imagery: enhanced spatial resolution can deliver greater thematic accuracy. Remote Sens. Environ. 82:248–257.
Polovina, J. J., and S. Ralston.
1987. Tropical snappers and groupers: biology and fisheries management. Westview Press, Boulder, CO, 659 p.
Quester Tangent Corporation (QTC).
2004. QTC IMPACT User Guide Version 3.40, Sidney, BC, Canada, 126 p.
Sadovy, Y.
1994. Grouper stocks of the western central Atlantic: the need for management and management needs. Proc. Gulf Carib. Fish. Inst. 43:43–64.
Sadovy, Y., and A.-M. Eklund.
1999. Synopsis of biological data on the Nassau grouper, *Epinephelus striatus* (Bloch, 1792), and the jewfish *E. itajara* (Lichtenstein, 1822). NOAA Tech. Rep. NMFS 146, 65 p.