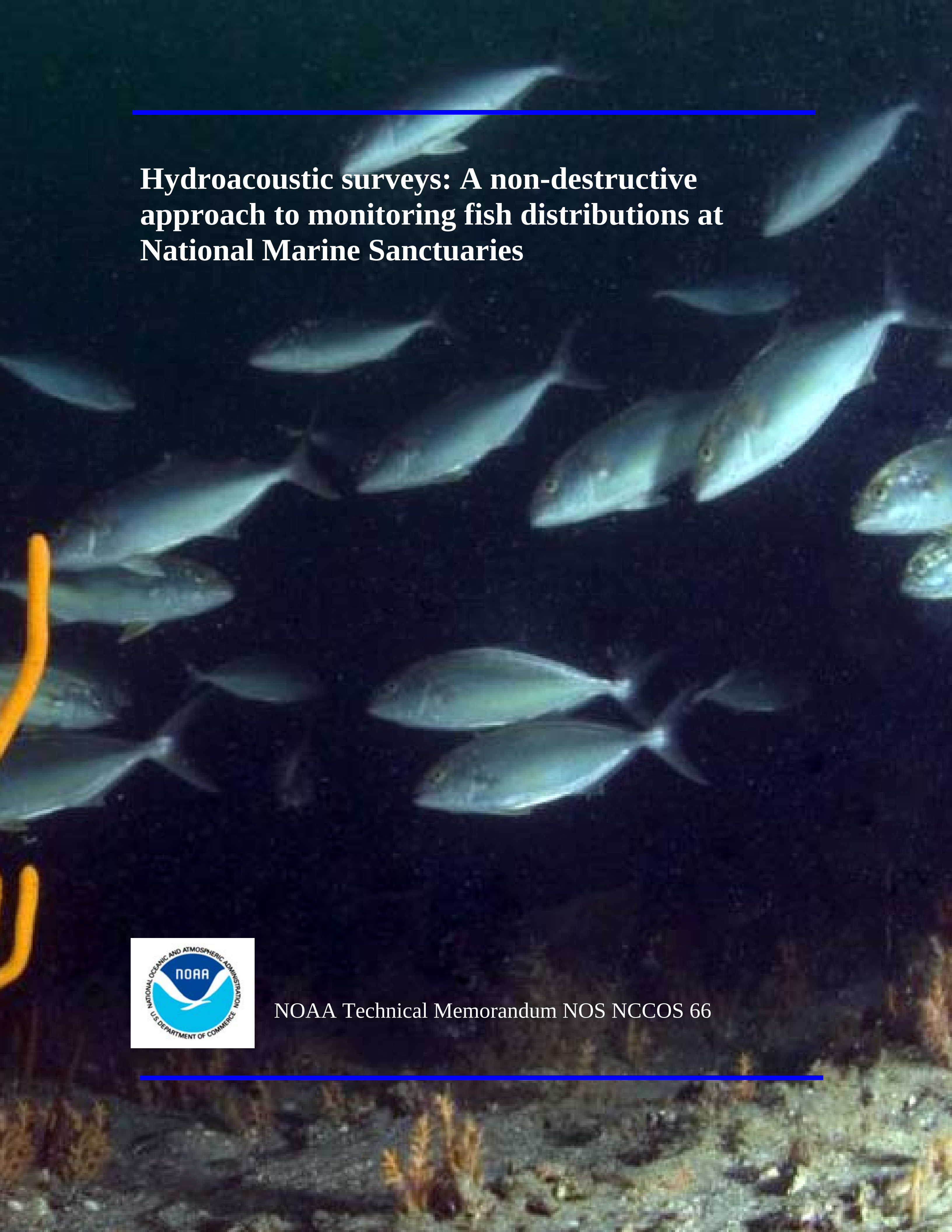


Hydroacoustic surveys: A non-destructive approach to monitoring fish distributions at National Marine Sanctuaries

NOAA Technical Memorandum NOS NCCOS 66

This report has been reviewed by the National Ocean Service of the National Oceanic and Atmospheric Administration (NOAA) and approved for publication. Mention of trade names or commercial products does not constitute endorsement or recommendation for their use by the United States government.

Citation for this Report

Kracker, L.M. 2007. Hydroacoustic surveys: A non-destructive approach to monitoring fish distributions at National Marine Sanctuaries. NOAA Technical Memorandum NOS NCCOS 66. 24 pp. Cover photo credit: Greg McFall.

Hydroacoustic surveys: A non-destructive approach to monitoring fish distributions at National Marine Sanctuaries

Laura Kracker

NOAA, National Ocean Service
National Centers for Coastal Ocean Science
Center for Coastal Environmental Health and Biomolecular Research
219 Fort Johnson Road
Charleston, South Carolina 29412-9110

NOAA Technical Memorandum NOS NCCOS 66

August, 2007

United States Department of Commerce	National Oceanic and Atmospheric Administration	National Ocean Service
Carlos M. Gutierrez Secretary	Conrad C. Lautenbacher, Jr. Administrator	John (Jack) H. Dunnigan Assistant Administrator

Laura Kracker
Center for Coastal Environmental Health and Biomolecular Research (CCEHBR)
National Centers for Coastal Ocean Science (NCCOS)

In partnership with Gray's Reef National Marine Sanctuary

Prepared for

Greg McFall
Research Coordinator
Gray's Reef National Marine Sanctuary (GRNMS)
National Marine Sanctuary Program (NMSP)

Table of Contents

Introduction

The science of fisheries acoustics and its applicability to resource management have evolved over the past several decades. This document provides a basic description of fisheries acoustics and recommendations on using this technology for research and monitoring of fish distributions and habitats within sanctuaries. It also describes recent efforts aimed at applying fisheries acoustics to Gray's Reef National Marine Sanctuary (GRNMS) (Figure 1).

Figure 1. Location of Gray's Reef National Marine Sanctuary

Historically, methods to assess the underwater environment have included net trawls, diver censuses, hook and line, video, sonar and other techniques deployed in a variety of ways. Fisheries acoustics, using active sonar, relies on the physics of sound traveling through water to quantify the distribution of biota in the water column. By sending a signal of a given frequency through the water column and recording the time of travel and the strength of the reflected signal, it is possible to determine the size and location of fish and estimate biomass from the acoustic backscatter. As a fisheries assessment tool, active hydroacoustics technology is an efficient, non-intrusive method of mapping the water column at a very fine spatial and temporal resolution. It provides a practical alternative to bottom and mid-water trawls, which are not allowed at GRNMS. Passive acoustics, which uses underwater hydrophones to record man-made and natural sounds such as fish spawning calls and sounds produced by marine mammals for communication and echolocation, can provide a useful, complementary survey tool. This report primarily deals with active acoustics, although the integration of active and passive acoustics is addressed as well.

Acoustic surveys for integrated assessments

The purpose of this document is to provide a guide for sanctuary managers interested in developing fisheries acoustic surveys in support of National Marine Sanctuary Program (NMSP) goals and objectives, using GRNMS as an example. Recently, a partnership between the Office of National Marine Sanctuaries (ONMS) and the National Centers for Coastal Ocean Science (NCCOS) was defined with the goal of effectively managing sanctuaries using the best available science, with a focus on characterizing and monitoring sanctuary resources. The applicability of acoustic fisheries techniques to specific management strategies identified in the GRNMS Final Management Plan (NOAA 2006) is summarized in Table 1.

The NOAA 2005-2010 Strategic Plan emphasizes the importance of an ecosystem management approach, and in particular, integrated ecosystem assessments (IEAs) to assimilate a wide range of information on potential factors influencing marine resources. The techniques described here can be used as a critical tool in IEAs because they provide quantitative measures of baseline conditions and an assessment of the state of fish populations over time. They may point to stressors in the system and can be used to evaluate the success of management actions. GRNMS is an ideal setting to develop and test methods applicable to integrated assessments given its manageable size, accessible location and thorough historic fisheries surveys. As part of the larger South Atlantic Bight, GRNMS is an important habitat for the North Atlantic right whale, pelagic fishes and many reef-related fishes, including the snapper-grouper complex. Expanding acoustic surveys beyond the Sanctuary boundary would be an efficient way to investigate and monitor a broad range of regional physical and biological factors that may affect resources at GRNMS (NOAA 2006).

Table 1. Applicability of fisheries acoustic techniques in addressing the Gray's Reef National Marine Sanctuary Final Management Plan (NOAA 2006)

Action Plan	Strategy (Activities)	Application
Marine Resource Protection	MRP-4: Increase protection for fish and invertebrate species	As regulatory changes are implemented (such as fishing gear restrictions), acoustic surveys can be used to monitor changes in fish size and distribution and suggest whether or not new regulations are having the desired effect.
Research and Monitoring	RM-1: Investigate ecosystem processes. (Characterize trophic dynamics).	Hydroacoustic techniques aid in quantifying daily, seasonal and annual variation in the distribution of fish to better understand ecosystem processes. Associating fish distribution with benthic habitats will address questions of trophic interaction between benthic invertebrates and fishes, as well as the movement of fish within the Sanctuary. Passive acoustics, which can detect species presence based on spawning calls, can help identify when and where this critical life stage occurs.
	RM-2: Investigate designation of a marine research area.	Fisheries acoustic surveys are non-intrusive and can be conducted in support of ongoing research within a designated marine research area. Conversely, a designated research area would advance the development of acoustics techniques within the Sanctuary through studies aimed at understanding fish length-target strength relationships necessary for a meaningful interpretation of acoustic backscatter of fishes in GRNMS.
	RM-3: Assess and characterize sanctuary resources. (Develop and update the GIS database, characterize benthic habitat, develop the Sanctuary characterization)	Active underwater acoustics can make an important contribution to characterizing sanctuary resources by estimating fish biomass both temporally and spatially at fine resolution (minutes and meters, respectively). Information from fisheries acoustics surveys is easily integrated into GIS and can be used to examine the association between benthic types and fish abundance. Predictive maps can be generated that estimate fish abundance in the entire Sanctuary. Passive acoustics, which can detect species present at a given location based on fish calls, can help identify benthic types given the known relationship between fish species and preferred bottom type.
	RM-4: Maintain and enhance monitoring programs. (Monitor the status and health of fish).	Relative biomass estimates and fish abundance are relevant measures for assessing changing fish populations and are easily obtained from active acoustic surveys. Assessing these metrics seasonally and annually provides information about fish abundance, size distribution, and top predator populations.
Education and Outreach	EO-1,2,3: Public awareness, scholastic programs, sanctuary exhibits	Public awareness and student-scientist opportunities can be enhanced by demonstrating and implementing near-real time techniques that produce quantitative assessments and visual products that convey the status of sanctuary resources.
Exploration	EX-1: Develop and implement Latitude 31^{30} Program.	Hydroacoustic surveys can be efficiently expanded beyond the Sanctuary boundaries to characterize physical and biological resources within the Latitude 31^{30} region.
Performance Evaluation	EV-1: Develop and implement a performance evaluation program for GRNMS	Active acoustic surveys provide quantitative measures to track changes within the Sanctuary. This provides managers with a performance measure against which they can evaluate expected outcomes. Relative biomass and fish abundance are relevant measures for assessing changing conditions at GRNMS.

Basics of fisheries acoustics

The characteristics of sound traveling through water can be used to aid our understanding of the marine environment and the behavior of animals that occupy it. Oceanographic properties, such as salinity gradients and thermal fronts, can be detected using active acoustics as these properties modify the waveform and affect the speed of sound in water. Plankton scattering layers also can be detected as they reflect sound generated and transmitted from echosounders. Fish targets reflect sound, primarily via the swimbladder, which provides a good indicator of fish size. Information about schooling behavior and fish migration can also be gathered from hydroacoustic surveys.

Passive acoustics uses hydrophones to record underwater sounds such as man-made noise and sounds used by animals for communication and echolocation. Using active acoustics to estimate fish abundance in conjunction with passive acoustics to record spawning events can be useful in identifying important locations and times of year for this critical life stage.

Active fisheries acoustic surveys are typically conducted using a towed or hull-mounted transducer that sends a signal down into the water column as the ship travels along a transect (Figure 2). These surveys rely on the transmission of a sound wave produced by the echosounder and the measurement of the returning echo reflected off objects in the water column. The process begins with a transducer that generates an electrical signal and converts it into pressure in the form of a sound wave. As the sound wave passes through the water column, transmission loss due to absorption and spreading occurs, the sound wave is reflected off objects in the water column and the bottom, and the return echo is detected by the transducer (Figure 3).

The amount of energy returned to the transducer is called the backscatter energy. Target strength (TS) refers to the backscatter attributed to an individual target; whereas, mean volume backscatter (S_{v_mean}) refers to the amount of backscattering energy integrated over a volume. The transducer converts the backscatter energy, or pressure, back into decibels. The time it takes for the signal to travel through the water column, reflect off an object and return back to the transducer, is equivalent to the twice the distance between the object and the echosounder. The amount of backscatter energy of the returned signal is equivalent to the size of individual fish or total biomass.

The concept of acoustic backscatter as a function of fish size has been the mainstay of fisheries acoustics and can be used to derive a relative index of biomass (Love 1971, Nakken and Olsen 1977, Foote 1980). However, the backscatter measurement only relays basic information about the reflecting target, largely determined by the swimbladder (Foote 1980, Ona 1990). The signal does not inherently contain information about species or even the type of organism or object reflecting the signal. Therefore, it is necessary to rely on secondary information to confirm which species are present and the size distribution of fish in the water column. This is typically done by conducting trawl surveys to determine species composition and size distribution at the time of the acoustic survey.

Along with trawl data, empirical models that relate TS to fish length are applied. Empirical models have been developed for a limited number of species and are variable from species to species (Nakken and Olsen 1977). Additionally, length-weight relationships contribute to estimates of biomass per unit area or volume. An important issue related to conducting acoustic surveys in protected areas is the fact that trawling often is not permitted. Therefore, information on fish size distribution and species composition may have to be derived from trawls conducted outside the Sanctuary, historic information, or other methods.

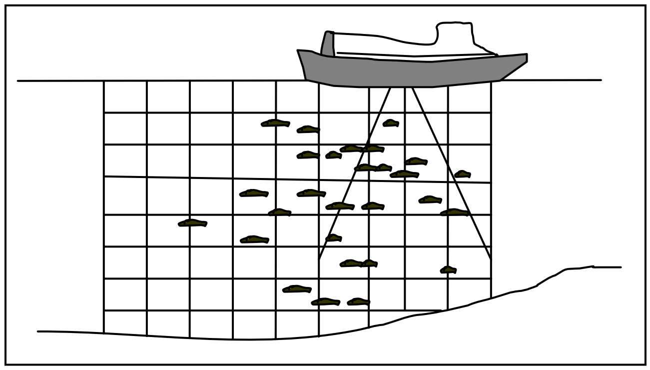


Figure 2. Underwater acoustics data collection provides fine resolution mapping of the water column. As the ship travels along a transect, a signal is sent into the water column. The strength of the returned signal and the time of travel are recorded to estimate the size and depth of the target.

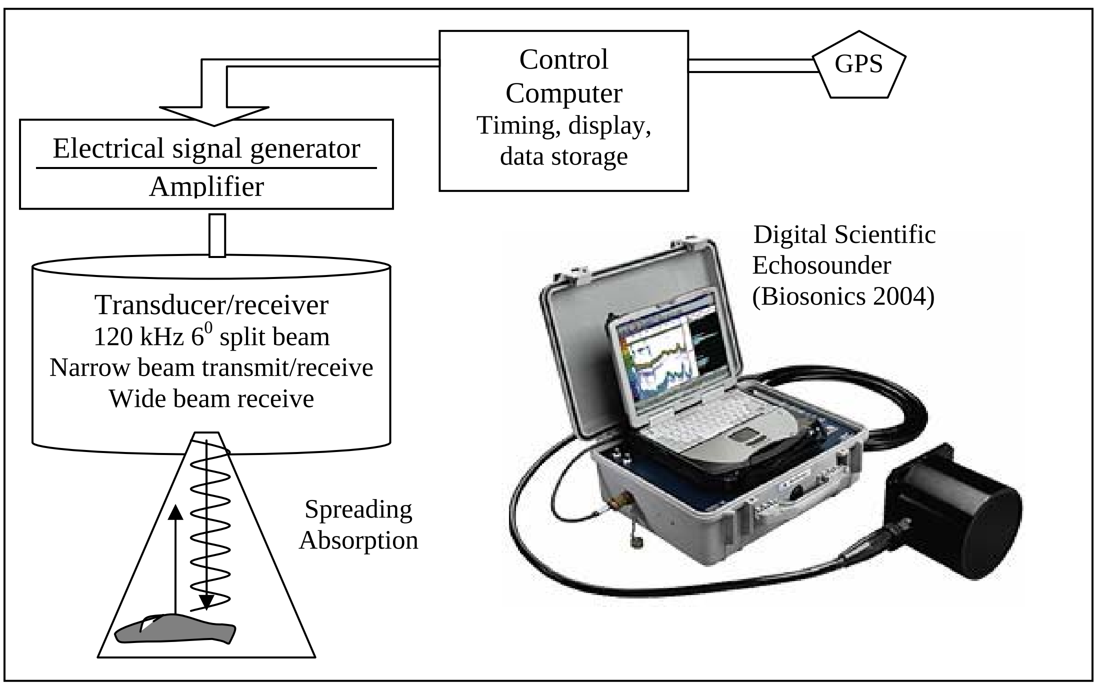


Figure 3. Basic architecture and components of a scientific fisheries acoustics system. A typical split-beam fisheries acoustics system includes a signal generator that creates the electrical signal or ping. A transducer transmits a sound pressure wave through the water column. The transducer also captures the backscatter signal in the form of sound pressure and converts it back to an electrical signal reported as volume backscattering strength in decibels. A deck side computer controls the timing of the electrical signal, data acquisition, data display, and GPS input. In a split-beam system, the beam is divided into quadrants, allowing for the location of the target within the beam to be determined and a target strength correction applied to compensate for off-axis loss of the reflected sound.

There are several factors that determine the choice of components and configuration of an acoustics system related to frequency of the transducer, pulse length and sampling rate, for example. Since shorter wavelengths of sound attenuate more quickly in the water column, lower frequency, longer wavelength transducers (in the range of 38kHz) are required for greater depths (1000+ meters). Conversely, a higher frequency, shorter wavelength sound wave is required to detect smaller objects. For instance, a 420kHz transducer or greater is typically used to quantify plankton. Backscatter measurements are most robust when the ratio of fish length to acoustic frequency wavelength ranges between 2 and 10 (Horne and Clay 1998).

Fisheries applications generally use frequencies of 38, 120, 200 or 420kHz. In addition, multi-frequency and broadband systems are now being implemented. [It should be noted that recent concerns regarding the use of sonar (particularly for naval exercises) pertains to very low (<1kHz) and mid (1kHz - 10kHz) frequency sounds (NRC 2003)].

Typically, fisheries acoustics has been applied to pelagic species. However, where fish are strongly associated with reef structures, it is necessary to differentiate fish targets from the bottom. A shorter pulse length results in finer vertical resolution and helps to distinguish fish targets from the bottom (Mason and Shaner 2001). The pulse rate and speed of the ship impact the actual number of samples within the volume of water. Pulse rate is the number of pulses or pings per time period. Depending on the pulse rate, ship speed, and the strata of interest, these factors can be tuned to reach a balance between overlapping beams, which results in duplicate target detection, and sufficient coverage of the region of interest within the water column. Adjustment of system parameters, as described here, illustrates how acoustic surveys can be fine tuned to match the purpose of the study.

Data derived from acoustic surveys

The primary variables acquired during an acoustic survey are volume backscattering coefficient (S_v) [dBre1m^{-1}] and target strength (TS) [dBre1m^{2}]. These are the basic parameters used to estimate size of individual targets and biomass within the beam volume. (S_v) is backscattering from discrete targets summed over a volume (MacLennan et al 2002). Mean volume backscatter (S_{v_mean}) is a measure of the total reflected backscatter energy within the beam derived through echo-integration (Figure 4, left panel). It is considered a surrogate for total biomass - the total weight of living organisms per unit area. Target strength refers to the strength or intensity of the returned echo reflected from a single target (Figure 4, right panel). It is defined as the ratio of the acoustic intensity reflected (I_R) from a fish (measured 1m away) to the incident acoustic intensity (I_i) and is described by the equation:

$$TS=10 \log I_R/I_i$$ (Biosonics 2004)

Backscatter results can also be reported as nautical area scattering coefficient (NASC) which scales S_v to a unit area ($m^2 nmi^{-2}$) and can be used to compare volume backscattering from region to region.

While it is not possible to differentiate between a signal returned from a biotic target versus an abiotic target, particulate matter is treated as noise and eliminated by imposing a minimum threshold level above which targets are considered a fish or other aquatic organism. Typically, a TS threshold of -60dB is applied for detection of pelagic schooling fish (ICES 2000).

Factors that influence the returned signal include spreading and absorption of the signal, as well as the aspect and morphometry of the target. Much work has been done to model the effect of fish aspect on target strength, as well as the shape of the body and swimbladder (Jech and Horne 2002; Lilja et al. 2004).

An in-depth description of the physics employed in fisheries acoustics, as well as the parameters, equations and models used can be obtained from various texts, manufacturers of scientific echosounders, and international organizations working to develop and standardize this technology (Clay and Medwin 1966, MacLennan and Simmonds 1992, ICES 2000, MacLennan et al 2002).

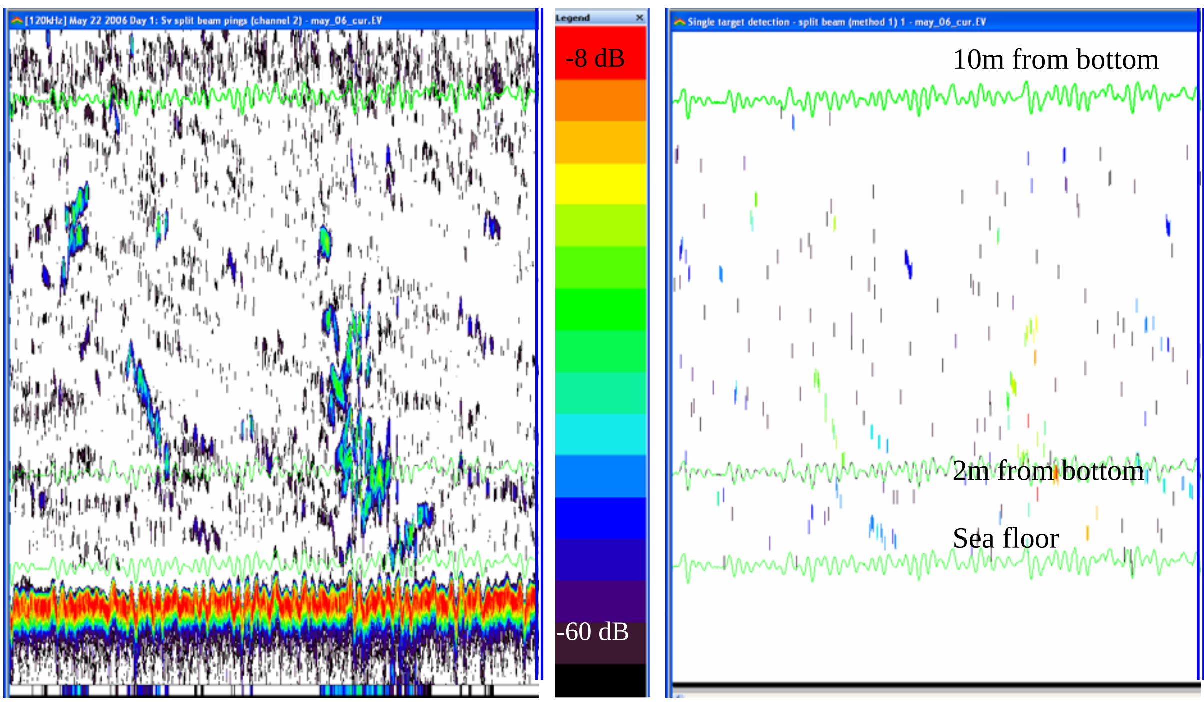


Figure 4. Echogram showing backscattering of the acoustic signal. The green lines indicate the sea floor, 2m from the bottom and 10m from the bottom. The color scale shows backscatter strength in decibels. Left panel: S_v is measured in dBre1m^{-1} with greater backscatter strength (small schools) shown in blue and green. Right panel: Individual targets extracted from an echogram. Target strength is measured in dBre1m^{-2} with larger targets shown in yellow and orange.

Considerations

Recent emphasis within the field of hydroacoustics has been on discerning the sources of variability in acoustic measurements and testing methods for species identification. Fisheries assessments using acoustics have been successfully applied primarily to pelagic species in relatively simple systems, including investigations of coastal northern cod (Rose 2003), Great Lakes fisheries (Mason et al 2001, Kracker et al 2003) and Pacific hake off the Canadian west coast (Holmes 2006). In situations where multi-species fish assemblages dominate the water column, algorithms are needed to allocate the returned acoustic signal to species.

Validation of fish targets is an essential part of interpreting the acoustic signal for any given location. If the TS to fish length relationship is known empirically for a given species, it is possible to determine fish size. If not known for the target species, an empirical relationship from the literature is often applied (eg. Love 1971, Foote 1980). Where empirical relationships are not known, TS frequency distribution and an index of biomass, S_{v_mean} can be attained from the returned acoustic signal and provide relative estimates of fish size and biomass in the water column over time. Output from acoustic surveys can be mapped in relation to bottom habitat type and bathymetry. Integrating historic and current fish surveys with acoustic surveys can provide a more complete picture of changes in fish populations at GRNMS.

In its most direct form, underwater acoustic technology produces relative information on size distribution of targets, numbers of organisms in the water column, and estimates of biomass, based on the physical properties of sound traveling through water. However, there are many factors that limit the confidence with which this information can be interpreted into accurate measures of absolute numbers of fish, fish lengths and total biomass. More significantly, the ability to determine which species are present using this technology is in its earliest stages. Some of the limitations of underwater acoustic technology in its current state are:

- It is not possible to definitively identify fish species. Secondary information is needed to confirm the species and size distribution of fish present in the water column. However, echo patterns and schooling behavior are attributes that an experienced operator can interpret given expert knowledge of a particular marine ecosystem.
- Empirical models that are designed to define the TS to fish length relationship have been developed for a limited number of species. A model developed for one species may not be applicable to another.
- Presence or absence of a swimbladder, aspect angle, swimming behavior, and morphometry affect the TS to fish length relationship.
- Mixed fish communities require algorithms to properly assign the appropriate returned signal to the community structure present.
- Overlapping beam patterns, multiple pings on the same target, compact schools, avoidance behavior and missed targets add uncertainty to estimates of fish numbers and biomass.
- Specialized knowledge is needed to apply appropriate system parameters to the monitoring or research problem. Parameters should be chosen to match the requirements and conditions of individual studies. However, this makes comparisons among studies with different settings problematic.

Preliminary surveys at GRNMS

While the science of fisheries acoustics has been applied in many underwater environments, little work has been done to test the applicability of these methods in the South Atlantic Bight. This section describes preliminary acoustic surveys that have been conducted at GRNMS to date.

In May 2004, a multi-investigator study was conducted aboard the NOAA research ship Nancy Foster coordinated by Greg McFall (Research Coordinator, GRNMS). This study was conceived in recognition of the limitations of the two techniques for monitoring fish populations allowed at GRNMS at the time: traps and visual census (Hare 2004). The goal of the May 2004 survey was to compare as many alternative methods as possible for monitoring fish populations. Several methods and technologies were deployed simultaneously, with the aim of integrating and assessing various monitoring tools. Remotely operated vehicles with video cameras, underwater photography, fish traps, passive acoustic hydrophones, diver fish censuses, and active fisheries acoustics were all used to provide a basis for examining the biota and physical features within GRNMS and compare results among the various methods.

A brief description of that initial multi-investigator study at GRNMS is reported here because it demonstrates the concept of integrated fisheries assessments using multiple detection methods, including underwater acoustics. Additional information can be found at: http://oceanica.cofc.edu/Gray's%20Reef%202004/home.htm

During the May 2004 multi-investigator study, stratified random sites from highly fished regions and non-highly fished regions of the Sanctuary were surveyed using various techniques. In addition, survey transects were conducted with towed devices. The sampling locations and transects visited during this study are mapped in GIS, using a map of benthic habitats (Kendall et al. 2005) as a basemap (Figure 5).

A significant aspect of non-stationary methods is that large areas can be sampled continuously in a short amount of time. Typically, these methods have an advantage over traditional methods such as trawling because of improved spatial coverage and resolution, as well as being non-intrusive. Technologies deployed during this study, such as underwater cameras and remotely operated vehicles, could be useful for validating fish targets from hydroacoustics.

As fisheries acoustics systems become fully integrated into research and survey vessels, the ease and efficiency of operation will improve. Ships designed specifically for this purpose are engineered to minimize interference of ship noise with acoustic signal data collection. The NOAA ship used in the multi-investigator study of 2004 was not designed for acoustic surveys and the large size of this platform may not be necessary for this type of work. As a follow-up to this work, subsequent surveys were conducted on the GRNMS Sanctuary vessel, Joe Ferguson, to assess the efficiency of a smaller platform for acoustic surveys (Figure 6).

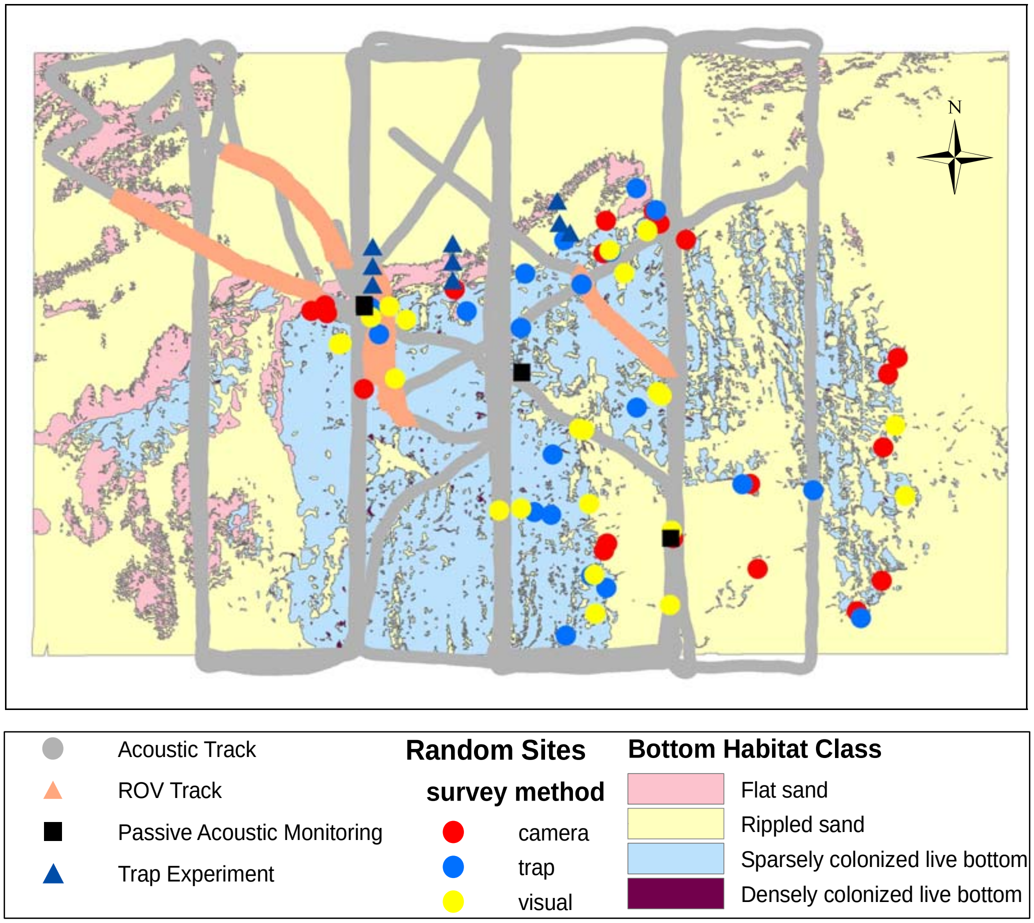


Figure 5. Survey locations and equipment deployed during Gray's Reef NMS multi-investigator survey May 2004. The extent of the bottom habitat class map follows the boundaries of the Sanctuary (4.75 x 3.5nmi). Base map from Kendall et al 2005.

Applications

This section provides several examples based on data from June 2005 and May 2006 to illustrate how acoustic surveys can be used to quantify fishes and biomass (Table 2).

Table 2. Quantitative measures extracted from acoustic survey data

Focus	Parameter	Measures	Example
Fish abundance	Single target detection	Abundance (# fish)	Quantify fish abundance and map high relief region in 3-D
Target size distribution	Target Strength (TS)	Frequency distribution of TS (dB)	Frequency distribution of TS in two portions of the water column
Biomass estimation	Volume backscatter (S_v)	Mean S_v (dB) Biomass (kg/nmi^2) NASC (m^{2}nmi^{-2})	Comparison of S_v, TS, and biomass from segments of acoustic transect over two benthic habitats
Spatial and temporal distribution	Association between fish biomass and habitat	Kriging to predict biomass (S_{v_mean})	Map S_{v_mean} with habitat type Predict S_{v_mean} for survey extent

Active and passive acoustic surveys were conducted at GRNMS in June 2005 and May 2006 by Kracker and Gilmore, in collaboration with Greg McFall, to continue to evaluate acoustic methods for fisheries assessments.

The June 2005 survey track and an echogram of the integrated acoustic backscatter are overlaid on a bottom habitat classification map (Figure 6a). A detailed section of the echogram shows acoustic backscatter, indicative of total biomass in the water column (Figure 6b). In addition, individual targets along the survey track that are above a particular size (TS>-65dB) are extracted from the echogram and mapped (Figure 6c). The results of these surveys are presented here to demonstrate the potential for quantifying and mapping the distribution of biota throughout GRNMS.

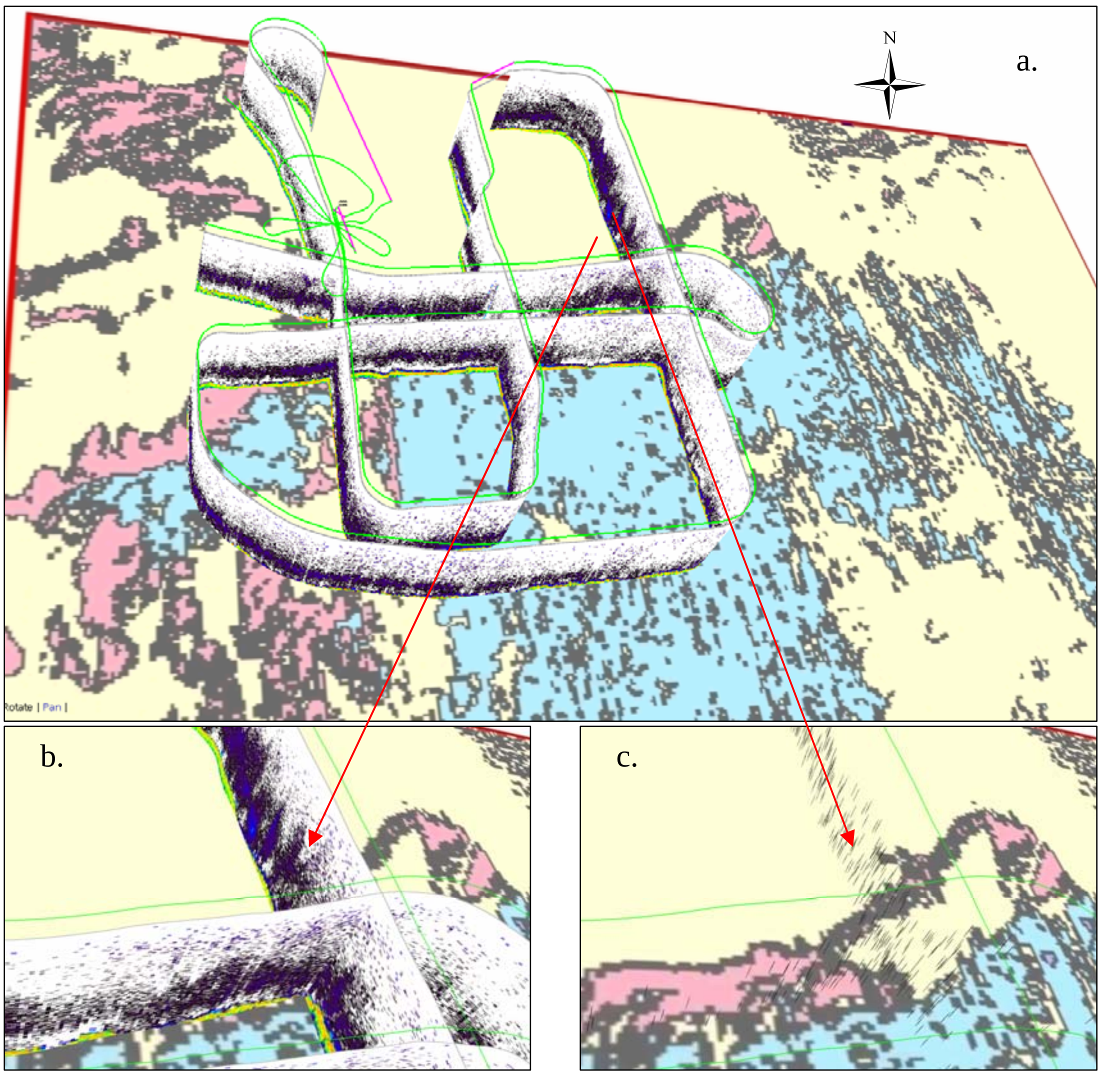


Figure 6. June 2005 daytime acoustic survey at GRNMS. a) Bottom habitat map (Kendall et al 2005), along with the ship track (green line) and an echogram (exaggerated 40 times vertically) of the acoustic data. Darker areas indicate higher biomass. b) A detailed section of the echogram shows relative biomass in the water column. c) Fish targets above a particular size (returned acoustic signal > -65dB) are extracted from the echogram and mapped.

Fish abundance

Single target detection (SonarData 2006) was used to quantify fish abundance from acoustic surveys conducted in the late afternoon on 8 June 2005 and during the evening on 22 May 2006. Survey transects are mapped on a bathymetric layer and an area of high relief (ledges up to 10 feet) is outlined (Figure 7). A threshold of -60 dB was used to differentiate fish from smaller targets. The number of targets detected along each survey track is presented in Table 3. The survey conducted in May 2006 detected more total fish targets than the survey conducted in June 2005. In both surveys the 0-2m portion of the water column contained approximately half the number of fish as the 2-10m portion. The location of fish within the water column along a segment of the May 2006 transect is mapped in Figure 8.

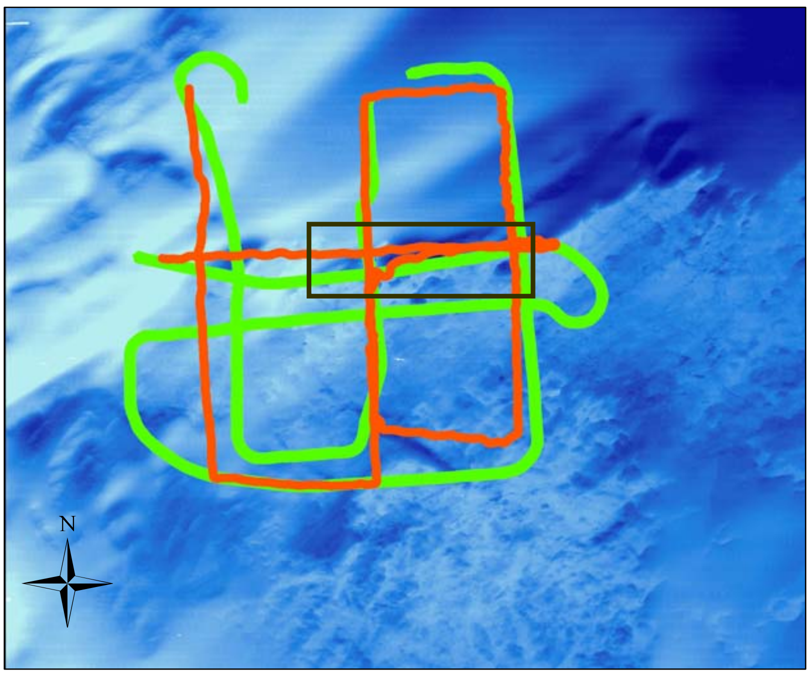


Figure 7. Relief map of GRNMS overlaid with acoustic survey tracks conducted in the late afternoon on 8 June 2005 (green) and during the evening on 22 May 2006 (red). The black rectangle indicates a region of high relief.

Table 3. Number of individual targets (> -60dB) detected during two surveys at GRNMS

Cruise date (track)	0-2m from bottom	2m-10m from bottom	Total targets	Start time	End time	Total time (hr:min)
8 June ‘05 (green)	425	927	1352	14:52	17:29	02:37
22 May ‘06 (red)	1355	2717	4067	19:33	22:39	03:06

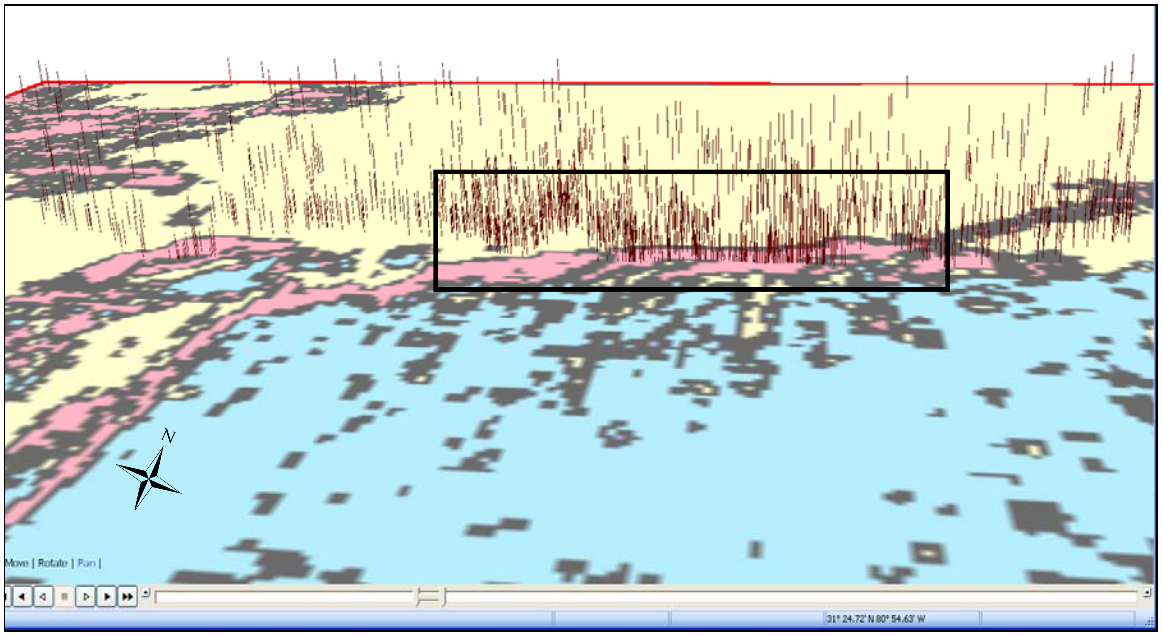


Figure 8. Location of individual fish targets at depth along the 22 May 2006 transect (22:20 to 22:28 hrs). The rectangle indicates an area of high relief and mixed benthic habitat type.

Because acoustic surveys are an efficient method of surveying, it is possible to detect changing conditions at very short temporal and spatial scales. For instance, in Figure 8, the abundance of fish targets appears to be more concentrated in the region containing high relief features than to the west along the same transect. This portion of the transect was covered in less than ten minutes, at a rate of 5 pings per second. A trap study conducted during the May 2004 multi-investigator survey indicated that the spatial scale of black sea bass presence in this area was small and closely associated with the reef structure. Questions of fish distribution can be addressed non-invasively using fisheries acoustics. In addition, display of the acoustic output is instantaneous. Mapping the output in relation to bottom habitat can be done as each transect is completed, allowing the survey design to be refined in the field.

Target size distribution

There are several questions that can be addressed by examining the size distribution of targets, using TS as a surrogate for fish size. For instance, which regions are most often occupied by large predators? What is the size distribution of fish at various times of year? What are the spatial and temporal patterns of smaller juveniles versus adults? The answers to these questions may be indicative of fish behavior or spawning aggregations. This section examines fish targets larger than -60dB and divides the water column into two regions: 0-2m off the bottom and 2-10m off the bottom. These regions of the water column are intended to be reflective of reef-related and pelagic organisms. This demarcation also eliminates noise and turbulence in the upper 8-10m of the water column caused by wave action and the movement of the ship. The frequency distribution of single targets for the entire 2005 and 2006 surveys is shown in Figure 9. There is a greater frequency of small targets in June 2005 compared to May 2006. In both surveys, the distribution of larger targets (> -50dB) occurs predominantly in the 0-2m portion of the water column. For species where the TS-fish length relationship is known, values can be converted to fish length.

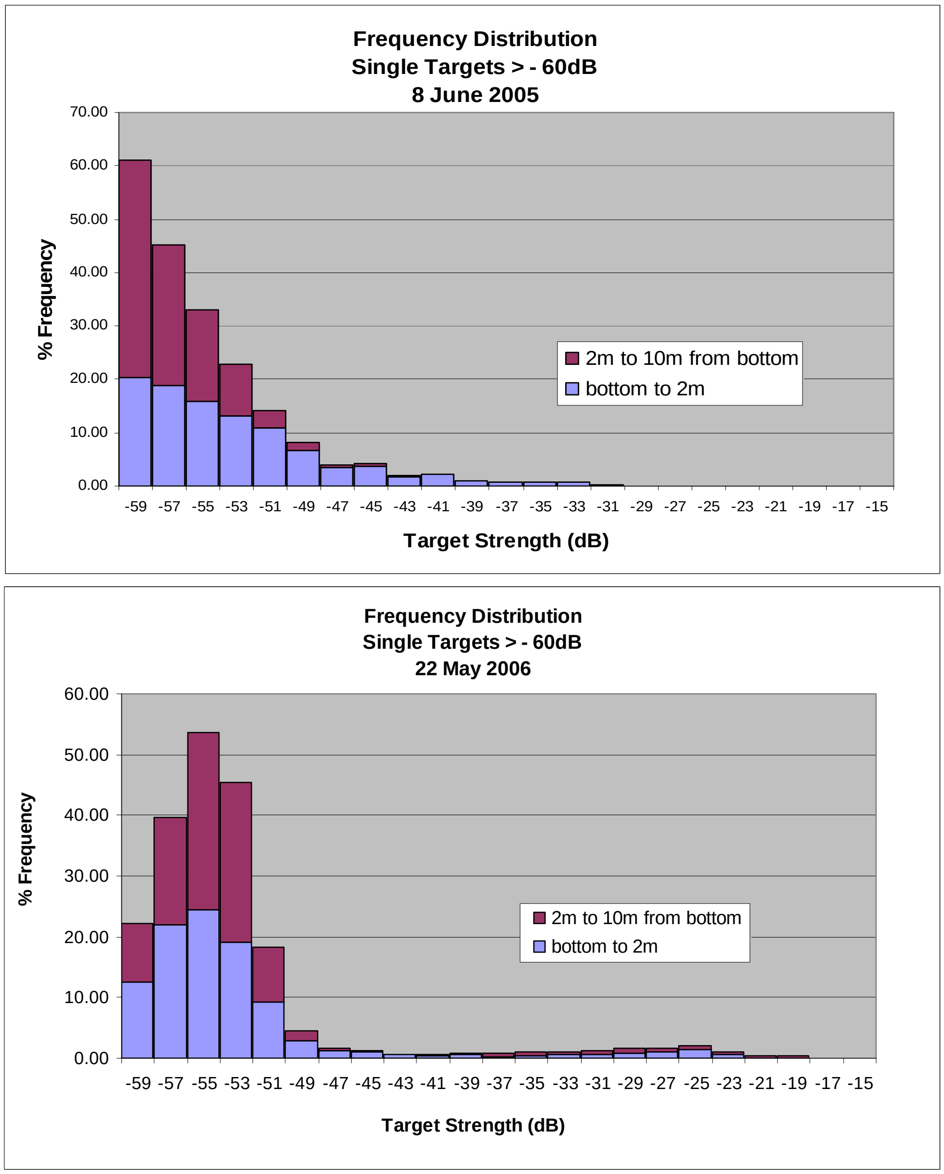


Figure 9. Frequency distribution of single targets > -60dB. The water column is divided into two regions: 0-2m from the bottom and 2-10m from the bottom.

Biomass estimation

While TS (dB) is a good relative indicator of fish size, it is typically converted to fish length. The TS-length relationship is known for some fish such as Atlantic cod, walleye pollock, anchovy, mackerel, sardines, rockfish and others through empirical testing (Love 1971, Foote 1980, Holliday 1980, Foote 1987, Foote and Traynor 1988, Clay and Horne 1994, Kang et al 2004). In the case where the TS-fish length relationship is not known for the species of interest, models from the literature are applied. During the surveys described here, the TS-length relationship was not determined for species present, nor was species composition validated in the field. Therefore, a commonly applied TS-length equation (Love 1971) was used to convert TS to fish length:

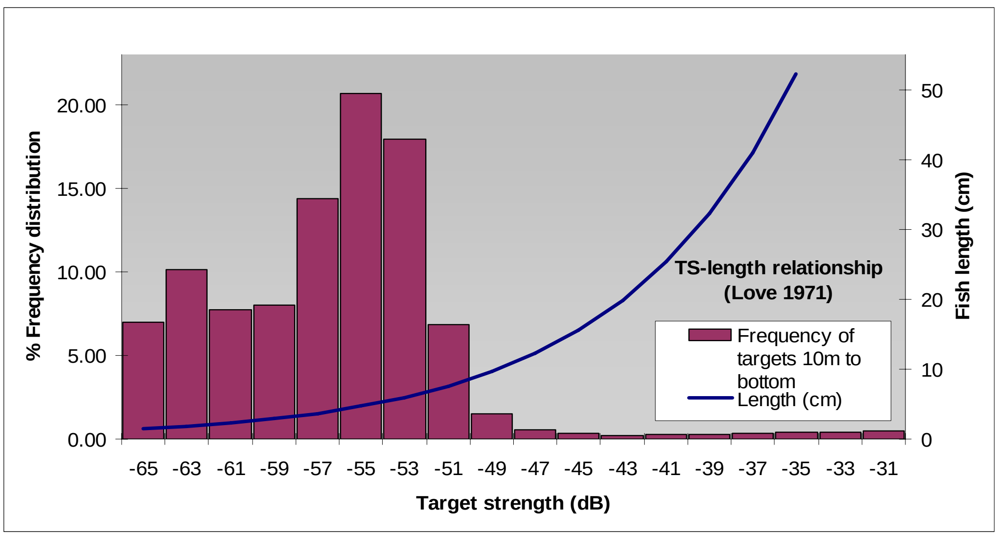
$TS = 19.1 \log L + 0.9 \log\lambda - 23.9$

where TS = target strength detected (dB), L = length of the target (cm), and λ = the frequency used (Figure 10).

Also, length-weight regressions specific to black sea bass *Centropristis striata* and sand perch *Diplectrum formosum* (two species prevalent at GRNMS in mixed/reef and sand habitats, respectively) were used to calculate weight at length for biomass estimates:

$W = a L^b$

where W = weight (g), L= length (cm), a = 0.0649, b = 2.468 for black seabass (Bohnsack and Harper 1988); a= 0.0114, b = 3.078 for sand perch (fishbase.org).



Target strength-length relationship Length-weight relationship										
TS (dB)	-57	-55	-53	-51	-49	-47	-45	-43	-41	-39
Length (cm)	2.27	2.89	3.68	4.68	5.95	7.58	9.64	12.27	15.62	19.88
Weight (g) Black seabass	0.49	0.89	1.61	2.93	5.30	9.62	17.44	31.62	57.32	03.94
Weight (g) Sand perch	0.14	0.30	0.63	1.32	2.77	5.81	12.21	25.64	53.85	13.10

Figure 10. Target strength frequency distribution (May 2006) with TS-fish length model [$TS = 19.1 \log L + 0.9 \log\lambda - 23.9$ where L=length (cm) and λ is frequency (Love 1971)]. Length-weight relationship $W = a L^b$ for black seabass (*Centropristis striata*) where a=0.0649 and b = 2.468 (Bohnsack and Harper 1988) and sand perch (*Diplectrum formosum*) where a= 0.0114 and b = 3.078 (fishbase.org).

The biomass of a given species is a function of the mean backscattering in the region, the proportion of fish in each species, their TS, the weight of individual fish in each species, and the area within the analysis domain (Kloser et al 1996).

Here S_v, TS and expected weight at length are combined to estimate biomass within 10m of the bottom at two different locations from an acoustic transect on May 22, 2006 (Figure 11).

The more northerly transect (green) is located over rippled sand habitat. A second segment (red) extends across all benthic habitat types, covering both flat and rippled sand, as well as sparsely and densely colonized live bottom. Species composition is simplified to 100% sand perch in the northerly segment (sand habitat) and 100% black seabass in the centrally-located segment (mixed/ledge habitat). The estimate of biomass in the mixed habitat is based on black sea bass with an expected length of 20 cm, weight of 103.9g, and target strength of -39dB. The estimate of biomass in the sand habitat is based on sand perch with an expected length of 7.5cm, weight of 5.8g, and target strength of -47dB. In this analysis, a threshold envelope of -60 to -25dB was applied to differentiate targets likely to be fish from background noise and plankton. The results indicate that the mixed habitat had higher biomass density than the sand habitat (3471.99 kg/nmi^2 versus 43.54 kg/nmi^2 in Table 4).

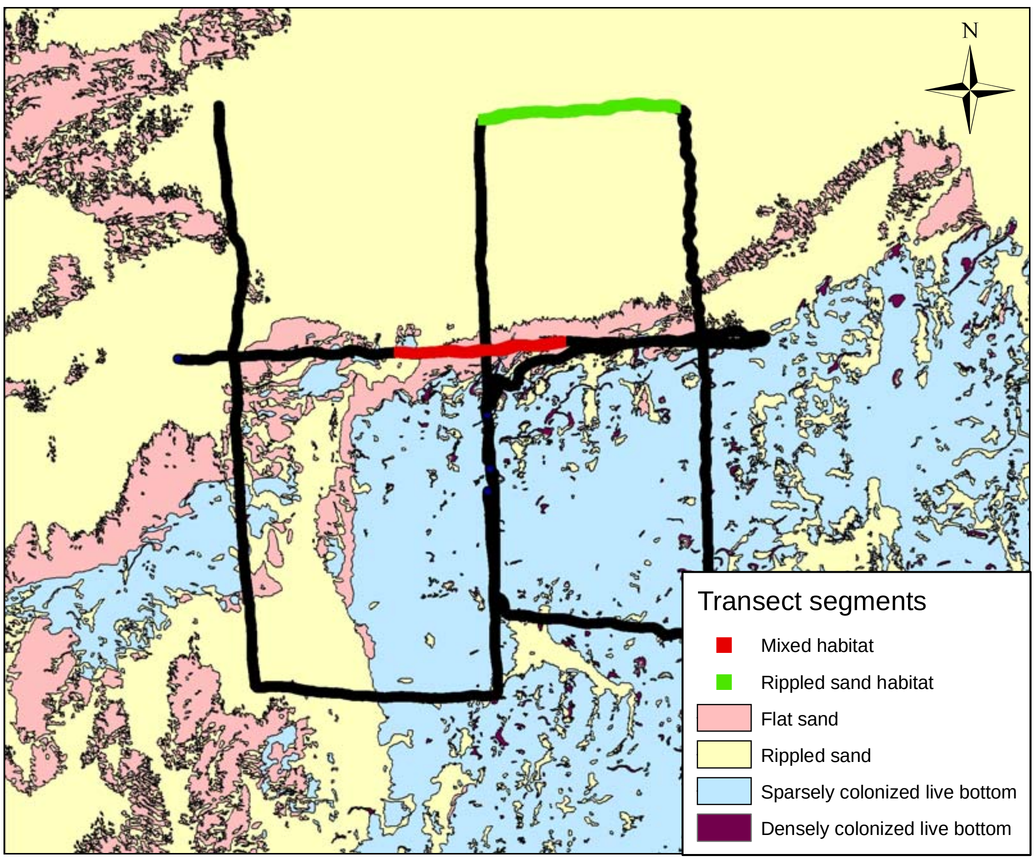


Figure 11. Location of two segments of the May 22, 2006 acoustic transect with different benthic habitat types.

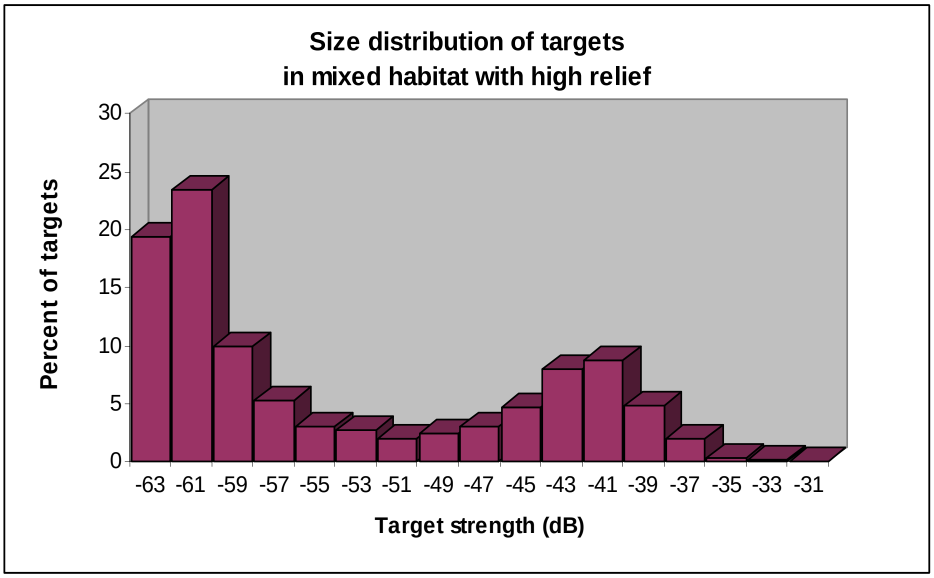
Examining several characteristics in the waters overlying different benthic types helps to define the differences in these seascape habitats. A comparison of water column characteristics over the high relief, mixed habitat versus rippled sand habitat (Table 4) indicates that the mixed habitat region has higher overall volume backscatter (S_{v_mean}). Results from single target detection indicate that the mixed habitat has a higher mean TS and higher standard deviation of TS, as well as a greater number of single targets. The frequency distribution of TS in the mixed habitat segment is bimodal, containing both small and large organisms, whereas, the rippled sand habitat is largely made up of small organisms (Figure 12).

Comparing density and biomass estimates, the mixed habitat has a higher density of targets than the sand habitat, as well as a higher biomass density (Table 4). The nautical area scattering coefficient [NASC (m^2 nmi^{-2})] is an area backscattering coefficient scaled over a square nautical mile (MacLennan et al 2002). By one description, this indicates highly dispersed aggregations in the sand habitat and dispersed aggregations in the mixed habitats (Torero and Almiron 2001).

Table 4. Measures derived from backscatter volume (S_v) and single target detection (TS) for two segments of an acoustic survey (May 22, 2006). Each segment is approximately 1km in length and 8 minutes long. Calculations include targets > -60dB

Transect segment	Mixed habitat, high relief	Rippled sand, low relief
Start/end time (hr:min)	22:20 to 22:28	20:36 to 20:44
	Integration results (S_v)	
S_v mean ($dBre1m^{-1}$)[a]	-69.11	-83.59
S_v maximum ($dBre1m^{-1}$)	-37.63	-45.41
	Single target detection (TS)	
TS mean ($dBre1m^2$)	-44.10	-54.06
TS maximum ($dBre1m^2$)	-27.88	-34.25
TS standard deviation	0.000072	0.000017
No. of single targets	1273	994
	Density and biomass estimates	
Density (# targets/nmi^2)	33407.03	7508.43
NASC[b] ($m^2 nmi^{-2}$)	52.85	1.88
Biomass density (kg/nmi^2)[c]	3471.99 [+]	43.54 [++]

[a] The calculation of S_{v_mean} includes zeroes where fish are not found, resulting in a smaller S_{v_mean} than the threshold level.
[b] Nautical Area Scattering Coefficient is an estimate of total backscattering ($dBre1m^2nmi^{-2}$).
[c] TS to fish length relationship based on Love (1971) for both regions. Biomass density is computed for each region based on fish length for two species:
[+] Mixed habitat is assigned 100% black sea bass (expected L=20cm, W=103.9g, TS=-39dB).
[++] Sand habitat is assigned 100% sand perch (expected L=7.5cm, W=5.8g, TS=-47dB).
[c] The backscatter coefficient could be further partitioned to include a variety of species. The water column also can be proportioned vertically to assign different formulas to different depths



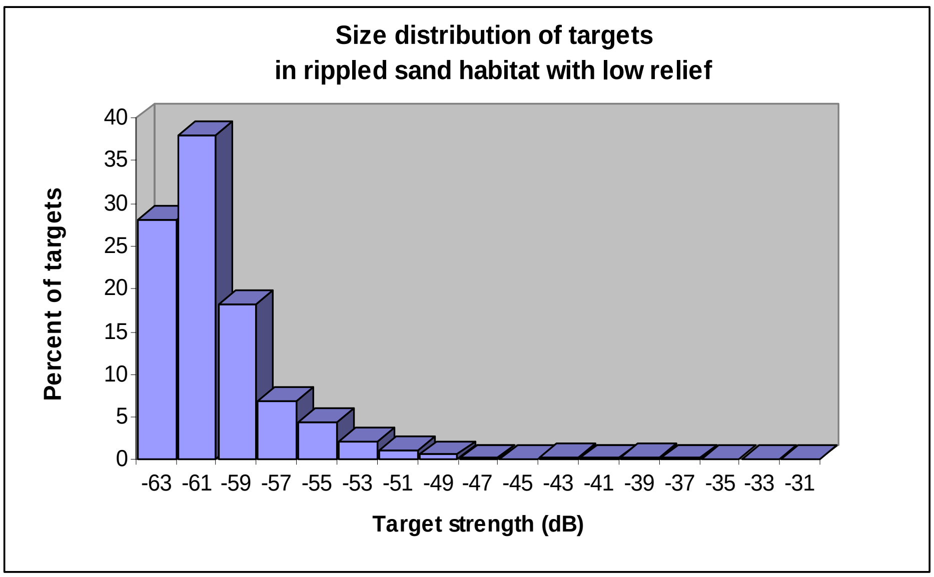


Figure 12. Distribution of target strength (as an indicator of fish size) in water regions above mixed habitat with high relief (upper graph) and rippled sand habitat with low relief (lower graph). Targets in the mixed relief habitat show a bimodal distribution compared to the sand habitat. The sand habitat has a higher percentage of smaller organisms.

Spatial and temporal distribution

Geographic Information Systems (GIS) and spatial analysis are important tools in visualizing and estimating the spatial distribution of resources. These tools can be used to examine the association between habitat type and fish distribution. This section illustrates how these factors can be mapped and modeled to facilitate the understanding of spatial and temporal patterns in the distribution of biota and potential trophic dynamics. Mapping the volume backscatter results for each minute of the May 2006 acoustic survey reveals an association of high fish biomass with mixed, complex reef habitat (Figure 13). S_{v_mean} is highest over mixed habitat types and especially near the region of ledge outcrops in the center of the Sanctuary. S_{v_mean} is lowest over rippled sand benthic habitats.

By using geostatistical methods, such as semivariance analysis and kriging, it is possible to interpolate S_{v_mean} to predict this value over the entire survey extent (Figure 14). Interpolation using kriging takes into account local variation as well as global trends to model the ‘behavior’ of a characteristic over space. The semivariance between points at a range of separation distances is modeled and then interpolated across the surface. Here, S_{v_mean} is interpolated to predict biomass density at unsampled locations. This predictive surface indicates that the spatial distribution of fish within the sanctuary at the time of this survey is sparse over sand habitats, with higher biomass fairly well distributed over much of the sparsely colonized live bottom.

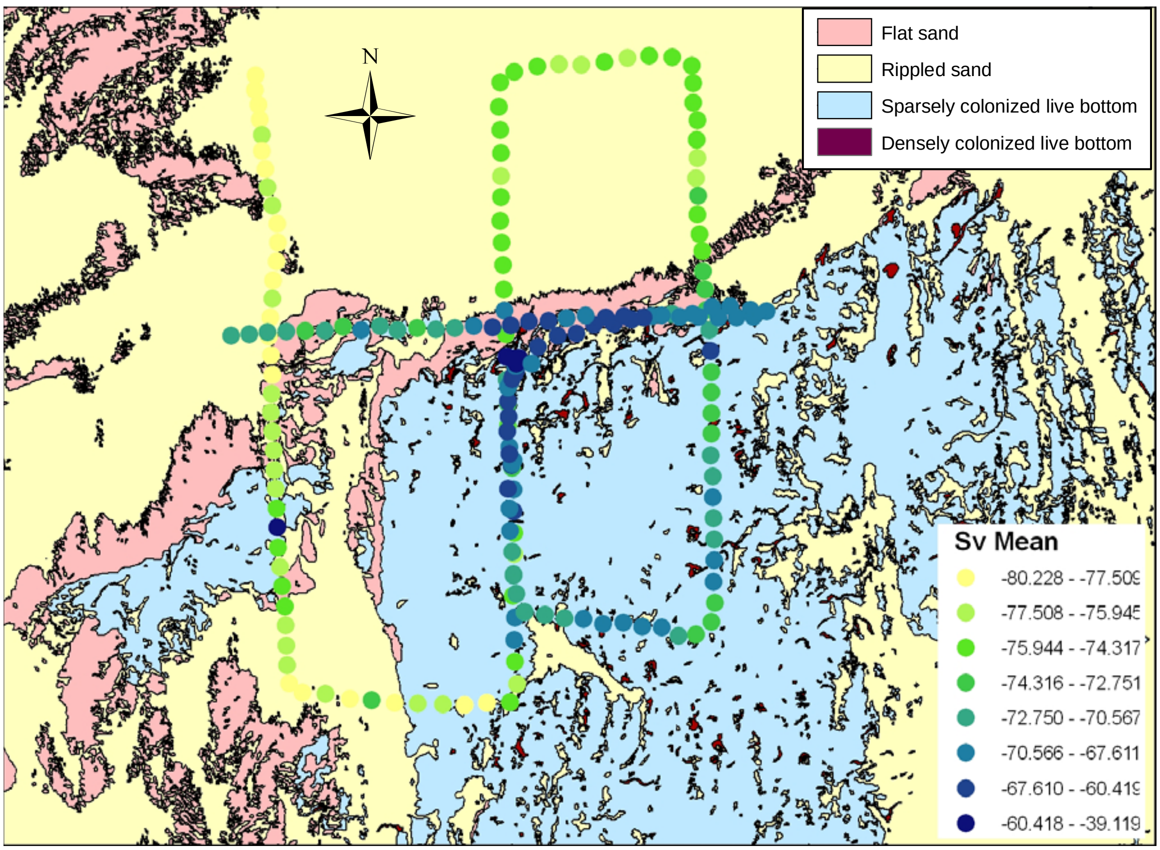


Figure 13. Map of S_{v_mean} (indicator of fish biomass) from May 2006 acoustic survey in relation to benthic habitats.

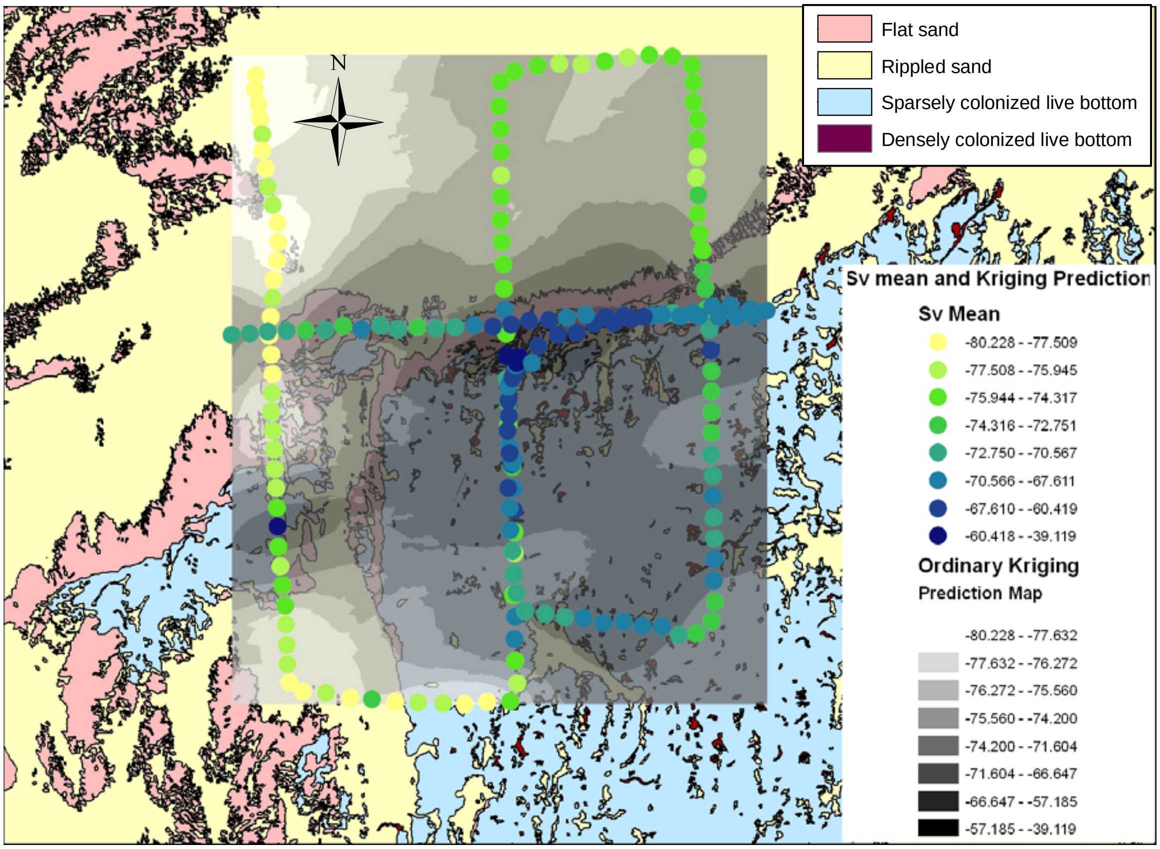


Figure 14. Interpolation of S_{v_mean} to predict distribution of fish biomass in unsampled locations (Mean prediction error = -0.0076; RSME standardized = 1.048).

Integration with other underwater technologies

Integrating active acoustic surveys with other underwater methods can optimize the interpretation and utility of results. High resolution imaging (ex. DIDSON – Dual Frequency Identification Sonar) is one method that may be helpful in documenting which species are present (Figure 15). This method of sonar imaging can be conducted during any time of night or day.

Recording fish sounds with hydrophones is another technology that can be integrated into active acoustic surveys. Of the 160 known species of fish at GRNMS, 30 are known to spawn there (NOAA 2006) and a list of soniferous fish has been developed (Gilmore pers. comm.). Sheepshead, *Archosargus probatocephalus*, and scup, *Stenotomus chrysops*, form spring aggregations at specific locations within GRNMS. Passive acoustic recordings made by Gilmore during the May 2004 multi-investigator study resemble those reported for sheepshead. Further studies to document the sounds and species present would complement the active acoustic surveys that provide information on abundance of potential sound producers and spawning activity (Gilmore pers. comm.). As more species are identified by the spawning calls that they produce and as algorithms for the classification of these sounds from spectrograms (Figure 16) are developed, the ability to link fish abundance with species presence and to identify location and timing of spawning activity will improve.

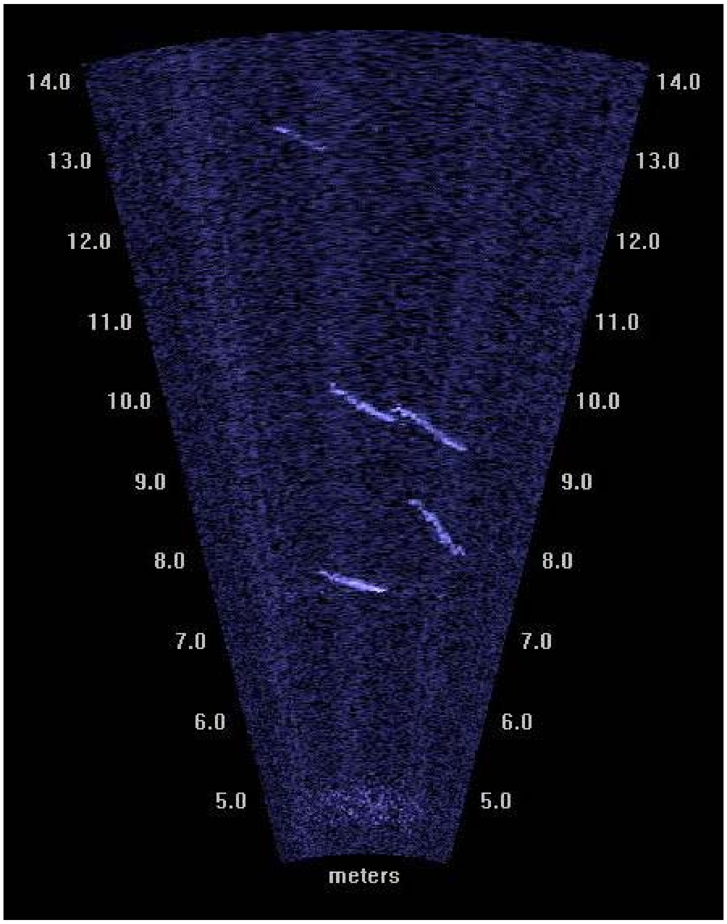


Figure 15. High resolution image (1.8mHz) taken with a DIDSON unit along the May 2006 survey track. Scale indicates distance from lens extending out horizontally.

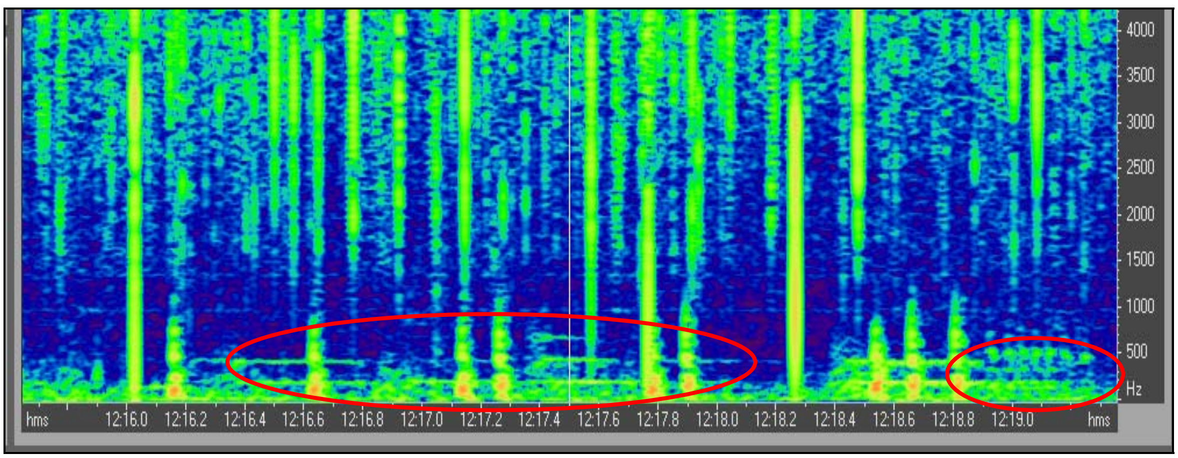


Figure 16. Spectral frequency of sounds collected using underwater passive acoustic recording devices at GRNMS during the May 2006 survey. Fish sounds recorded here include toadfish (large circle) mixed with a purring sound (small circle). These sounds range in frequency from 10 to 1200Hz.

Summary

Conducting hydroacoustic surveys in marine sanctuaries is an efficient, non-intrusive method for quantifying the abundance and distribution of fish. Advances in acoustic technology, and especially analysis software, have made this survey method even more powerful in recent years. While there are limitations in terms of species identification, acoustic surveys used in conjunction with other methods or as a relative measure, provide a quantifiable metric over the years. As part of a monitoring and assessment strategy, inclusive of other multiple indicators of ecological condition, these surveys can contribute to integrated assessments of coastal ecosystem health.

Acoustic surveys can be used to address questions of fish movement, trophic dynamics, timing and location of fish aggregations, pelagic versus demersal habitat use, and the temporal and spatial distribution of fish in relation to benthic habitats. Acoustic surveys conducted at the appropriate temporal resolution can be used to address questions related to habitat utilization by time of day and seasons. Implementing acoustic surveys on a seasonal basis (eg. early May, late August, November) that are timed to capture information on important pelagic species can support integrated assessments by providing information on mid-water biology. For the purpose of monitoring changes over time, system parameters and configuration can and should be standardized from survey to survey. These monitoring and assessment surveys could also accommodate studies designed to answer specific questions regarding trophic interactions, fish distribution, and movement of fish over a 24-hr period.

Validation of targets should occur simultaneously through the use of high resolution sonar imaging, underwater cameras, and other methods. The historic fisheries information collected at GRNMS through point counts, diver transects and video transects (Parker et al 1994), as well as trap information from the Marine Resources Monitoring, Assessment, and Prediction Program (MARMAP) surveys can enhance the interpretation of acoustic surveys. Length-weight relationships can be borrowed from previous studies at GRNMS and other locations. Future work on defining the TS to fish length relationship, as well as algorithms to align targets to species composition particular to GRNMS would also enhance assessment of fisheries and trophic processes. Likewise, information on seasonal species composition, spawning activity, and soniferous species present at GRNMS can be integrated with active acoustics to produce a more complete assessment.

Deploying passive acoustics on a regular basis, in conjunction with active acoustic surveys, would allow for monitoring of the intensity, duration, and periodicity of soniferous spawning fishes. Sampling and interpreting the passive acoustic data should involve automated analysis, to the extent possible, to recognize and classify spectral signatures. For both high resolution imaging and passive listening, a library of reference images and spectral signatures would allow for identification of species of interest and spawning activity.

In addition, acoustic or multi-beam surveys that focus on bathymetry or benthic habitats often treat the acoustic signal within the water column as noise. Likewise, fisheries surveys focused on the water column often ignore the bottom signature, except to delineate depth. Future bottom mapping efforts should examine the possibility of working with fisheries assessments, and vice versa, to retain and share acoustic data from the water column and the bottom echo.

Acknowledgements

This work was sponsored by NOAA NCCOS NOS CCEHBR with field support from GRNMS. I would like to acknowledge the collaborative spirit of all participants in this work, including, Greg McFall, Keith Golden, Scott Fowler, and Sara Fangman of GRNMS. R. Grant Gilmore of Estuarine, Coastal and Ocean Science, Inc. has provided a wealth of information on passive acoustics and sound production by fishes. In addition, constructive review of this document was provided by Len Balthis, Scott Cross, Jeff Hyland, Greg McFall, Tom Siewicki, and Emily Cooper.

References

Biosonics. User Guide Visual Analyzer 4. Biosonics, Inc. Seattle, WA. 2004.

Bohnsack, J.A. and D.E. Harper. 1988. Length-weight relationships of selected marine reef fishes from the southeastern United States and the Caribbean. NOAA Technical Memorandum NMFS-SEFC-215:31.

Clay, C.S. and J.K. Horne. 1994. Acoustic models of fish: the Atlantic cod (*Gadus morhua*). Journal of the Acoustical Society of America 96: 1661-1668.

Clay, C. S. and H. Medwin. *Acoustical Oceanography: Principles and Applications.* Wiley, New York, 1977.

Fishbase.org. Length-weight parameters for *Diplectrum formosum*. Last accessed 24 August 2007. http://fishbase.org/

Foote, K.G. 1980. Importance of the swimbladder in acoustic scattering by fish: a comparison of gadoid and mackerel target strengths. Journal of the Acoustical Society of America 67: 2084-2089.

Foote, K.G. 1987. Fish target strengths for use in echo integrator surveys. Journal of the Acoustical Society of America 82:981-987.

Foote, K.G. and J.J. Traynor. 1988. Comparison of walleye pollock target strength estimates determined from in-situ measurements and calculations based on swimbladder form. Journal of the Acoustical Society of America 73:1932-1940.

Hare, J. 2004. Annual Liaison Report on Existing and Potential ONMS/NCCOS Collaborative Studies at the Gray's Reef National Marine Sanctuary (GRNMS). http://coastalscience.noaa.gov/ecosystems/sanctuaries/pdfs/2004_GRNMS_liaison_report.pdf

Holliday, D.V. Use of acoustic frequency diversity for marine biological measurements. In *Advanced concepts in ocean measurements for marine biology.* Ed. by F.P. Diemer. Belle W. Baruch Libr. Mar, Sci. No. 10. pp. 423-460. 1980.

Holmes, J. 2006. Echo-sounding to count Pacific fish. Last accessed March 15, 2007. http://www.dfo-mpo.gc.ca/science/Story/acoustic_e.htm

Horne, J.K. and C.S. Clay. 1998. Sonar systems and aquatic organisms: matching equipment and model parameters. Canadian Journal of Aquatic Science 55:1296-1306.

ICES Cooperative Research Report No. 238. March 2000. Report on Echo Trace Classification. edited by David G. Reid. Copenhagen, Denmark.

Jech, J.M. and J.K. Horne. 2002. Three-dimensional visualization of fish morphometry and acoustic backscatter. Acoustics Research Letters Online 3(1): 35-40.

Kang, D., K. Sadayasu, T. Mukai, K. Iida, D. Hwang, K. Sawada, and K. Miyashita. 2004. Target strength estimation of black porgy *Acanthopagrus schlegeli* using acoustic measurements and a scattering model. Fisheries Science 70 (5), 819-828.

Kendall, M.S., O.P. Jensen, G. McFall, R. Bohne, R., D. Field, C. Alexander, and M.E. Monaco. 2003. Benthic Habitats of Gray's Reef National Marine Sanctuary. NOAA/NOS/NCCOS/CCMA Biogeography Team Technical Report pp 1-16.

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 21:1154–1165.

Kloser, R.J., J. A. Koslow and A. Williams. 1996. Acoustic Assessment of the Biomass of a Spawning Aggregation of Orange Roughy (*Hoplostethus atlanticus, Collett*) off South-eastern Australia, 1990-93. Marine and Freshwater Research 47:1015-24.

Kracker, L. M., L. Zhou, J.M. Jech, J.K. Horne, J.A. Tyler, and S.B. Brandt. Spatial and temporal variance in fish distributions: A Lake Ontario case study. In *State of Lake Ontario (SOLO) - Past, Present, and Future.* M. Munawar. (Ed.). Aquatic Ecosystem Health and Management Society, 385-40. 2003.

Lilja, J., T.J. Marjomäki, J. Jurvelius, T. Rossi, and E. Heikkola, E. 2004. Simulation and experimental measurement of side-aspect target strength of Atlantic salmon (*Salmo salar*) at high frequency. Canadian Journal of Aquatic Science 61: 2227–2236.

Love, R. H. 1971. Measurements of fish target strength: a review. Fishery Bulletin US. 69:703-715.

MacLennan, D. N. and E. J. Simmonds. 1992. Fisheries Acoustics. Chapman & Hall, London, England.

MacLennan, D.N., P.G. Fernandes, and J. Dalen. 2002. A consistent approach to definitions and symbols in fisheries acoustics. ICES Journal of Marine Science, 59:365–369.

Mason, D.M., A. Goyke, S.B. Brandt, J.M. Jech. Acoustic fish stock assessment in the Laurentian Great Lakes. In: M. Munawar, R.E. Hecky (Eds.), The Great Lakes of the World (GLOW): Food-web, Health and Integrity, pp. 317-339. Ecovision World Monograph Series. Backhuys Publishers, Leiden, The Netherlands. 2001.

Mason, D.M. and Shaner 2001. Report to the Great Lakes Fishery Commission: Intercalibration of Scientific Echosounders in the Great Lakes.

Nakken, O., and K. Olsen. 1977. “Target strength measurements of fish,” Rapports et Proces-Verbaux des Reunions. International Council for the Exploration of the Sea. 170:53-69.

National Research Council 2003. Ocean Noise and Marine Mammals. Committee on potential impacts of ambient noise in the ocean on Marine Mammals. The National Academies Press. Washington, DC.

NOAA. 2006. Gray’s Reef National Marine Sanctuary Final Management Plan / Final Environmental Impact Statement. NOAA NOS NMSP. Savannah, GA.

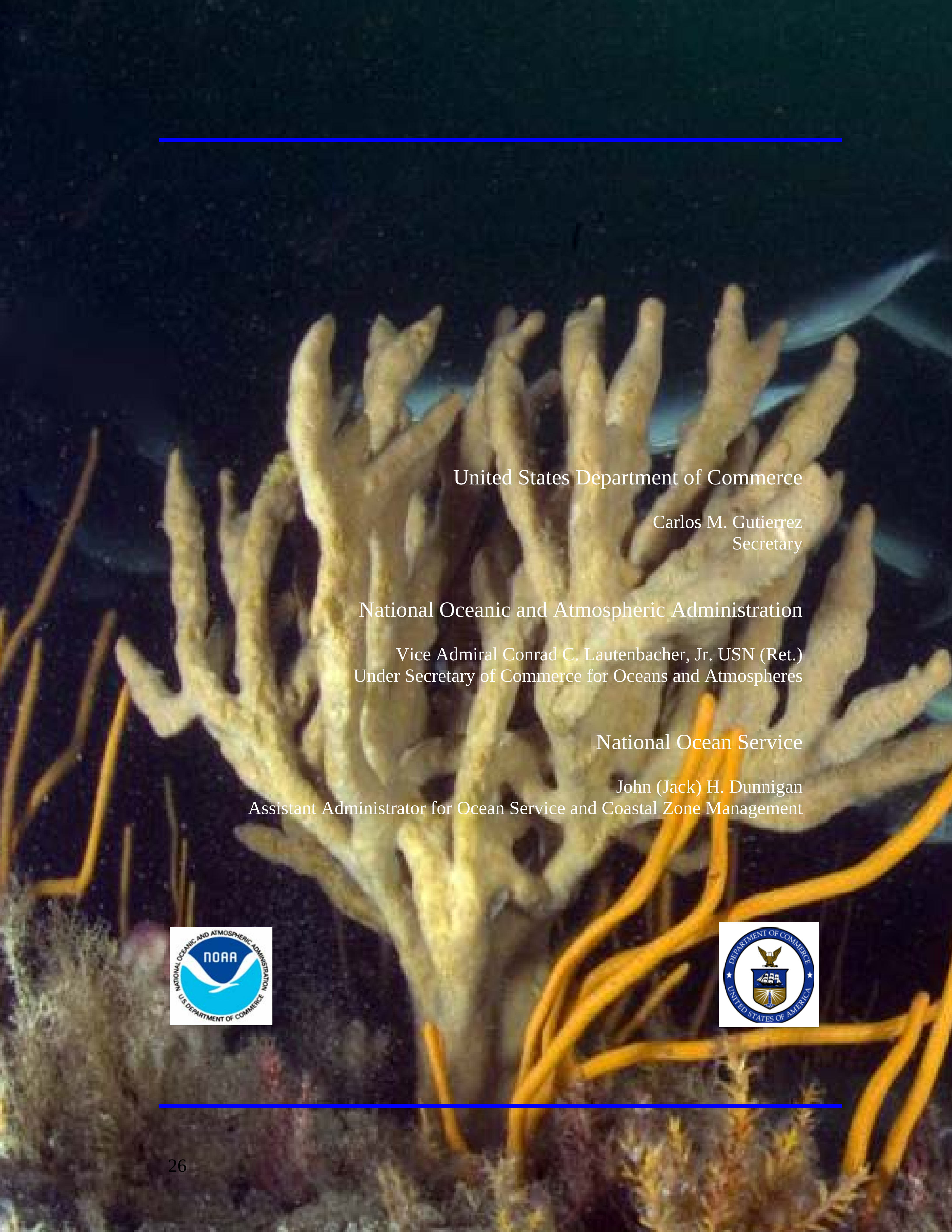
Ona, E. 1990. “Physiological factors causing natural variations in acoustic target strength of fish,” Journal of the Marine Biological Association of the United Kingdom. 70:107-127.

Parker, R.O. Jr., A.J. Chester, and R.S. Nelson. 1994. A video transect method for estimating reef fish abundance, composition, and habitat utilization at Gray's Reef National Marine Sanctuary, Georgia. Fishery Bulletin. Vol. 92, no. 4, pp. 787-799.

Rose, G. A. 2003. Monitoring coastal northern cod: towards an optimal survey of Smith Sound, Newfoundland. ICES Journal of Marine Science, 60: 453–462.

SonarData 2006. Echoview 4.0. http://www.sonardata.com/WebHelp/Echoview.htm SonarData Pty, Ltd. Hobart, Tasmania, Australia.

Torero, M.G. and N.H. Almirón. 2001. An Approach based on acoustic data to study the variability in distribution and abundance of small pelagics in the Humboldt ecosystem. Small Pelagic Fishes and Climate Change Programme GLOBEC Report No.16. Workshop on spatial approaches to the dynamics of coastal pelagic resources and their environment in upwelling areas. 6-8 September 2001. Cape Town, South Africa. ISSN 1066-7881.



United States Department of Commerce

Carlos M. Gutierrez
Secretary

National Oceanic and Atmospheric Administration

Vice Admiral Conrad C. Lautenbacher, Jr. USN (Ret.)
Under Secretary of Commerce for Oceans and Atmospheres

National Ocean Service

John (Jack) H. Dunnigan
Assistant Administrator for Ocean Service and Coastal Zone Management