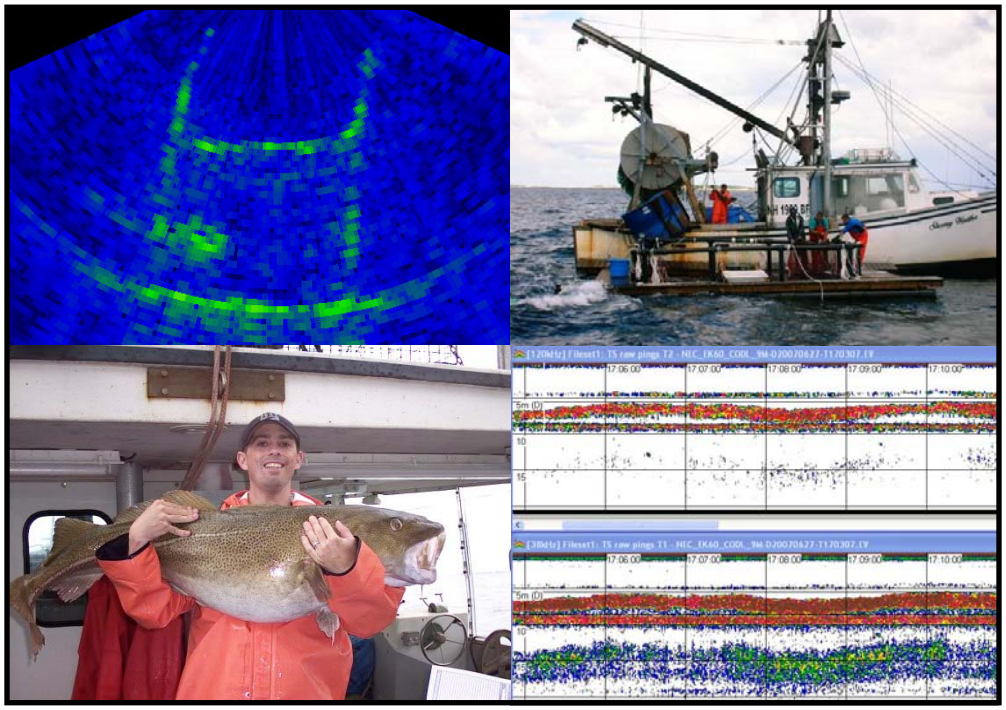
Development of multi-beam sonar as a fisheries tool for stock assessment and essential fish habitat identification of groundfish in the Western Gulf of Maine

2006 Project Development Award



FINAL REPORT

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Abstract

Stock assessments based on accurate abundance and distribution data are essential to developing effective management strategies for the Gulf of Maine stock of Atlantic cod, *Gadus morhua.* The purpose of this study was to prove the concept of using multi-beam sonar as a fisheries tool for studying the behavior and quantifying the abundance of groundfish. The focus of this research was was to develop multi-beam sonar (MBS) as a fisheries survey tool. MBS can complement traditional narrow-beam echosounder and trawl surveys because MBS has a large sampling volume, three-dimensional spatial description, and potentially fewer behavior-related sampling biases than traditional trawl surveys. Relationships between acoustic backscatter and fish biology need to be understood before reliable acoustic surveys using MBS can provide science-based information for stock assessments. A series of acoustic and optical measurements were made using 38- and 120-kHz EK60 split-beam echosounders and a 300 kHz EM3002 MBS. These were fixed to a surface platform over a 98 cubic meter submersible cage of 5-cm stretched mesh twine. After standard sphere calibration, the cage was stocked with 195 live Atlantic cod with a mean total length of 80.7 ± 0.8 cm (± standard error; range 51.5-105.0 cm) from nearby spawning grounds 10-15 km off the New Hampshire coast, USA. The sonars were synchronized to collect acoustic data on a captive population of mature cod of known size and number under video surveillance by two underwater cameras. Cod were incrementally removed from the cage to provide a time-series of acoustic backscatter at four densities (n=195, 116, 66, and 23). Preliminary results demonstrate the feasibility of the EM3002 MBS to detect cod and show that quantification of the acoustic backscatter is possible.

Introduction

Fisheries acoustic techniques can overcome some of the limitations and sampling biases of traditional trawl surveys, and provide important biological information on fish density and biomass, spatial distribution, and behavior. The most advanced of these acoustic techniques, multi-beam sonar, is currently used almost exclusively for seafloor mapping, but it has great potential in fisheries science, including identifying essential fish habitats (EFH), characterizing marine protected areas, studying the spatial distribution of fish, and in stock assessment (Mayer et al. 1999). The importance of developing multi-beam sonar as a fisheries survey tool is warranted because multi-beam sonar has (1) a larger sample area or volume than single- or split-beam echosounders and trawls, (2) better spatial description, and (3) potentially fewer behavior-related sampling biases (e.g. diel vertical migrations, vessel avoidance; Gerlotto et al. 2000) than traditional surveys.

In addition to the use of multi-beam sonar for seafloor mapping and habitat characterizations (Mayer et al. 1999), multi-beam sonar has recently been recognized for acoustic applications in fisheries research with advancements in hardware technology, digital acquisition of acoustic backscatter in the water column, and 3D visualization of acoustic data (Fernandes et al. 2002, Mayer et al. 2002). Early contributions using multi-beam sonar have been made for a variety of schooling species such as Atlantic herring and Atlantic mackerel (Misund 1993), capelin (Hafsteinsson & Misund 1995), sardine and anchovy (Gerlotto et al. 1999, Soria et al. 2003) and clupeids (Gerlotto & Paramo 2003, Paramo et al. 2007). These studies provided enhanced descriptions of spatial distribution (Gerllotto et al. 1999), school morphology and classification (Gerlotto & Paramo 2003, Paramo et al. 2007), migration and swimming behavior (Hafsteinsson and Misund 1995) and abundance (Misund 1993, Gerlotto et al. 2000), but also provided some fisheries-relevant behavioral findings on diel migrations, vessel avoidance, and gear performance

(Gerlotto et al. 1999, 2000; Hafsteinsson & Misund 1995). However, biomass and numerical abundance estimates derived from multi-beam sonar data with acceptable precision will not be reached until adequate calibration is done, effects from significant background noise are reduced, and the meaning of target strength (TS, echo strength compensated for beam pattern) at multiple angles are defined.

Several studies have addressed some of the challenges of using multi-beam sonar data to estimate abundance of fish. Gerlotto et al. (2000) demonstrated that density and biomass could be estimated from multi-sonar data by making VCR recordings of the video output from a RESON SEABAT 6012 sonar and then digitizing the video images for processing in an image analysis software. Misund and Coetzee (2000) showed that multi-beam sonar could be used to validate fish school recordings obtained by conventional echosounder and provide more precise abundance estimates in a comparative study using a 38 kHz Simrad EK500 split-beam echosounder and a 95 kHz SIMRAD SA950 sonar. Melvin et al. (2003) showed promising results in a comparison of acoustic backscatter from calibrated multi- and single-beam sonar using weir-confined Atlantic herring. With advancements in electronics, data acquisition, signal-processing, and 3D visualization, multi-beam sonar has become a viable fisheries tool for biomass and density estimation in the future.

Before multi-beam sonar can be used in a fisheries acoustic survey of groundfish, the feasibility needs to be investigated, and the relationship between acoustic backscatter and fish biology needs to be understood. The purpose of this study was to prove the concept of using multi-beam sonar as a fisheries tool for studying the behavior and quantifying the abundance of groundfish. Specifically, a series of cage experiments with captive Atlantic cod (*Gadus morhua*) was conducted to achieve the following objectives.

Study Objectives

1. *Can Atlantic cod be experimentally detected in cages by multi-beam sonar?*
   - Determine effective sonar configurations for acoustic measurements of encaged fish.
   - Evaluate acoustic properties and effects of a surface pen and submerged cage.
   - Calibrate sonar systems for acoustic detection and measurement of encaged fish.
   - Determine optimal equipment settings for cod detection and acoustic measurements.
2. *How does acoustic information from multi-beam compare to reality?*
   - Relate acoustic backscatter to known densities of cod.
   - Determine error or measures of uncertainty for acoustic measures
   - Test the influence of behavior and presence of other species on acoustic results and develop adjustments or identify limitations.
3. *How do results from multi-beam sonar compare to a more accepted technique of split-beam scientific echosounders?*
   - Compare acoustic results between multi- and a split-beam sonar.

Participants

- **Dr. Hunt Howell*** is a fisheries biologist and UNH professor who has done extensive cod tagging in the study area and open ocean aquaculture of cod. He will be responsible for fish handling, coordinating with the open ocean aquaculture project, and overseeing all stages of the project.
- **Capt. Carl Bouchard** is captain of a commercial bottom trawler. He will serve as the industry partner for collection of fish used in experiments.

- **Mr. Christopher W.D. Gurshin*,** M.S. in fisheries, is currently a doctoral student in Zoology at UNH under Dr. Hunt Howell. Mr. Gurshin will be responsible for coordinating all other participants and daily operations in addition to analyzing data for publication and further graduate studies.
- **Dr. J. Michael Jech*** is a Research Fisheries Biologist at the NOAA Fisheries Service Northeast Fisheries Science Center (NEFSC) in Woods Hole, MA. Dr. Jech will be assisting with data collection, processing and analysis on this project. He works closely with other academic and agency partners within Massachusetts, including MDMF, USGS, MIT and WHOI.
- **Dr. Larry Mayer** is the CCOM director and specializes in acoustics, ocean mapping 3D visualization, and coordinating multi-disciplinary studies using acoustics. He will provide oversight of the installation, calibration, and operation of the sonar systems in addition to other aspects of the project.
- **Dr. Tom Weber*** is a CCOM research professor specializing in signal processing of mid-water targets from multibeam sonar and benthic habitat mapping. He will provide his expertise in programming and signal processing of the acoustic data.

* key role in project design and implementation

Methods

Study Area

Field collections were made on spawning grounds 10-15 km off the New Hampshire coast, USA and experiments were conducted at the Open Ocean Aquaculture site located approximately 1 mile south of the Isles of Shoals, off the coast of New Hampshire (Figure 1). Dockside preparation were made at the UNH Coastal Marine Laboratory at Fort Constitution, Portsmouth, NH and the Jackson Estuarine Laboratory at Adams Point, Durham, NH.

Fish Sampling

Live Atlantic cod were collected with a 6.5-inch mesh otter trawl over a total of thirteen 30-minute tows made by F/V Stormy Weather on 21, 22 and 25 June 2007. Live Atlantic cod and haddock were individually measured (total length) and placed into 1 m^3 insulated polyethylene containers for transport to the site. A continuously running deck hose was used to circulate and exchange water in live wells during transit from the nearby fishing area to the cage. Fish were stocked in the cage and mortalities were removed each day. After experiments were completed, fish were removed from the experimental cage at the surface with large dip nets, measured, and counted. In accordance with NMFS permits and IACUC, all fish were caught using approved gear, transported live, held in captivity for a short term, and then released after experiments were completed.

Experimental Cage

A cage (4 m wide x 5 m long x 4.9 m deep; approximately 100 m^3) with 5-cm (2-inch) stretch nylon mesh, which has served as a harvest/transfer cage for the OOA project, was used for a series of acoustic measurement experiments (Figure 2). The cage consisted of a high-density polyethylene pipe of 10.2 to 25.4-cm (4 to 10-inch) diameter for the top frame, rail and flotation. A 0.9 m (3-foot) wide wood boardwalk surrounded the cage and supported multiple people and docking vessels. The net was covered with a top net and lowered by rope to any depth. The bottom of the net was weighted by a metal rectangular frame. The floating net cage was towed from Portsmouth harbor and moored offshore at the

OOA site with four mooring lines. Photographs during various stages of the project are shown in Figure 3.

Video Surveillance

Two LED underwater cameras were mounted through the mesh net of the cage to provide an upward-looking and side-looking video record of the spatial distribution and behavior of the insonified fish during the experiments. Each camera recorded to a four-channel digital video recorder (IDView).

Acoustic Sampling

A 300-kHz EM3002 multi-beam sonar system (Kongsberg Maritime) and 38- and 120-kHz Simrad EK60 split-beam echosounders were used to collect acoustic backscatter of the fish in the cage. The EM3002 single head has 160 beams each with 1.5° circular beamwidth that can collectively cover a 130° sector. The circular beamwidth of the 38 kHz and 120 kHz transducers are 12° and 7°, respectively. The multi- and split-beam transducers were mounted on a rigid pole with the EM3002 single head in the center and the 38 kHz and 120 kHz transducers mounted on either side. The transducers were center aligned according to outside physical dimensions. The transducer mount was lowered approximately 1-2 m from a bridge across the center of a fish cage (Figure 2 and 3). A profiling sound velocimeter (Odom Digibar-Pro) was used to periodically measure sound velocity profiles and upload the sound velocity profiles to the EM3002 software (Figure 4). The sound velocity probe was attached near the single EM3002 head to collect real-time sound velocity measurement at the same depth of the head for proper beam forming. Instruments transmitted data via cable to vessels tied up alongside the cage. The 10-m vessel R/V Cocheco, both operated by the Center of Coastal Ocean Mapping and Joint Hydrographic Center, provided ship support for sonar operations (Figure 5).

Calibration

Sonar systems were calibrated by standard sphere calibration as described by Foote et al. (1987, 2005). A 38-mm tungsten carbide sphere, 23-mm copper sphere, and 60-mm sphere were used to collect single TS for calibration of the 300 kHz EM3002 sonar, 38 kHz E60 and 120 kHz EK60 echosounder, respectively. For each transducer, a sphere attached to monofilament line was lowered by a fishing rod from the sonar mount platform to a depth of 8-10 m and above the lowered cage. For the EM3002, the sphere was also lowered in other beams. The difference between the mean TS and the known TS for the sphere was adjusted by setting a gain offset.

Experiments

Before stocking the cage with live fish, acoustic measurements were obtained on the empty cage to determine whether there was acoustic transparency of the net or whether the cage would be well-defined to permit experiments to be conducted with the cage submerged or at the surface with the net cover open. After determining that the net formed discrete top and bottom echoes in the split-beam echosounders' echograms and all four sides were distinct in the water column image in the EM3002 (Figure 5), all experiments were performed at depth with the cage completely sealed. Live adult cod (n=195) were stocked in the empty experimental cage at the surface at four stocking densities (approximately 0.25, 1, and 2 fish per m^3) starting with the highest density. Fish were insonified in the cage from the surface by the three synchronized echosounders at 1 ping per second. Acoustic measurements on the largest cage population continued on the first day through 2 hours past sunset to provide a preliminary assessment of diel effects on the acoustic estimates of density. Depth of the bottom of the cage was also manipulated between depths of 6 and 17 m.

Data Analysis

Acoustic data from the EM3002 and EK60 sonars were acquired using Seafloor Information System (SIS) Version 3.4.1 software and Simrad ER60 scientific echo sounder application, respectively. The latest version of SIS includes additional features for water column data collection and operational parameterization features more relevant for fisheries applications. Post-processing of datagrams and echograms were done mainly using Matlab (Math Works) and Echoview (Sonardata). Additional statistical analyses were performed using SAS software.

Only preliminary analysis has been completed, but abundance and biomass will be estimated from acoustic backscatter by several methods using target strength and backscatter amplitude. Echo counting and echo integration methods are commonly used and were previously described for Atlantic cod using split-beam data by Rose (2003) and McQuinn et al. (2005). For multi-beam sonar, echo strength will need to be compensated for beam pattern which has been studied for Atlantic herring by Melvin et al. (2003). Density and biomass will be estimated by several methods such as echo counting, echo integration (Simmonds & MacLennan 2005) and other statistical techniques such as scatter statistics (Denbigh et al. 1991), assuming relative abundance is proportional to echo intensity.

Data

Catch, length measurements and sample information collected during trawl operations were recorded on datasheets, keypunched into Microsoft Excel files, and data files were created as Excel and SAS files using SAS software. Between 19 and 29 June 2007, 17.5 hours (1.3 GB) of acoustic data were collected by the 38-kHz and 120-kHz EK60 echosounders. Data acquired from the 38-kHz and 120-kHz transducers were stored together in files (*.raw, *.bot, *.idx) with filenames automatically time stamped at the start of recording. During the same period, 15.8 hours (8.5 GB) of acoustic data were collected by the 300 kHz EM3002 sonar which triggered synchronization with the EK60 echosounders during most of the data collection. EM3002 data were stored in files with *.all, *ix1, and *ix2 file extensions and time stamped filenames. A summary of the data collected are presented in Table 1.

Results

Catch

The total catch of Atlantic cod from all 13 tows was 282 fish. Of the tows that catch was enumerated, the relative species composition of the catch from trawling in Area Closure 133 was dominated by flatfishes (38%), Atlantic cod (27%), and spiny dogfish (18%; Table 2). However, species composition of Atlantic cod are even effectively higher acoustically because acoustic backscatter from flatfishes are masked by the bottom backscatter and the acoustic backscatter from spiny dogfish is lower due to lack of swim bladder. Mean (±S.E.) total length of the 264 measured cod of the total catch was 79.7 ±0.9 cm (range 42.5 to 128.0 cm; Figure 6). Haddock accounted for about 5% of the catch. Mean total length of haddock were 56.9 ± 1.0 cm (n=7, range=52.0 to 60.5 cm). Live haddock were transported to the cage but most individuals were morbid and stocking the cage for a mixed species set of measurements was not possible due to severe morbidity or mortality encountered using the trawl.

Cod Used in Experiments

Cod which were either too large (>110 cm TL) or too small (<50 cm TL) were released alive after capture. Cod which were upside down, morbid, severely injured, or dead after transport were not used in stocking the cage for acoustic measurements. The cage was initially stocked with 195 cod over the course

of three days (21, 22 and 25 June). Stock size in the cage was subsequently reduced to 116, 66, 23, and 6 by releasing individuals back to the wild. The length distribution of cod used during acoustic measurements are shown in Figure 7. Length statistics are shown in Table 3. Mean total length of cod was not significantly different among the five stocking densities (ANOVA, F=0.41, df= 4, 401, p= 0.802). Delayed trawl-induced mortality was observed during experiments. After 24 to 96 hours of initial stocking of the cage, cumulative mortality was 34% (n=67), but 24-hour mortalities decreased to 6.9%, 3.0%, and 4.4% on subsequent days (Table 4). The condition and observed mortality may have been partially resulted from recovery of capture stress in suboptimal water temperature in the upper 5-10 m where most of experiments were conducted (Figure 8). Gross examination of gonads from a sample (n=70) of the cod mortalities removed from the cage showed 37% were female and 63% were male. Several males were observed to be milting during handling.

Acoustic Backscatter of the Cage

Before experiments were started, the echo from the empty cage was quickly determined to have distinct geometry with sufficient acoustic backscatter strength for target and cage discrimination (Figure 9). The cage sides produced a hollow rectangular echo in the water column image from the EM3002. The top and bottom sides of the cage produced echoes in the echograms of the 38-kHz and 120-kHz EK60 echosounders. The bottom of the cage produced a thicker echo with high amplitude (dB) shown as darker red colors in the echograms. The metal rectangular frame could be partially responsible for higher acoustic backscatter strength. The echoes from the cage were used to discriminate from fish and identify appropriate regions for acoustic measurements of cod.

Calibration

A time series of TS measurements of the 60-mm and 23-mm copper sphere was obtained for calibration of the EK60 echosounders with 38-kHz and 120-kHz split-beam transducers, respectively. Based on the TS distribution of the 60-mm copper sphere (Figure 10), deviation from the known TS of -33.6 dB was corrected with a 20.25 dB gain offset from the results of the beam model in the calibration program v1.0.0.9 of the ER60 data acquisition software. However, the distribution was skewed to the left tail with an apparent large mode around -30 dB and smaller mode around -33 dB (Figure 10). A more distinct bimodal distribution was seen in later measurements. Further investigation of the transmitted pulse revealed abrupt changes in the distribution of the raw power output recorded near the 38-kHz transducer over time (Figure 11). The variation over time in the raw power output from the 38-kHz EK60 echosounder was more than 1 dB which was substantially more than the variation of approximately 0.05 dB in the raw power output from the 120-kHz EK60 echosounder. The TS distribution of the 23-mm copper sphere used for calibration of the 120-kHz EK60 echosounder appears to be a Gaussian (normal) distribution (Figure 12). The mean TS for the 23-mm copper sphere was -39.9 dB as calculated from the 10Log_{10} transformed value of the average backscattering cross section $\langle\sigma_{bs}\rangle$. To correct the deviation from the known TS of -40.4 dB, a gain offset of 25.54 dB was applied to the 120-kHz data.

A time series of the acoustic backscatter amplitude of the 38.1-mm tungsten carbide sphere was obtained for calibration of the EM3002 sonar. Figure 13 shows raw amplitude and the "40Log_{10}R" amplitude or echo strength (ES, uncompensated for angle within each beam) for the sphere between 8-10 m from the transducer. Adjacent beams each with 1.5° transmit and receive beamwidths often overlapped enough to receive multiple echoes of the sphere (Figure 14). The relative frequency distribution of echo strength of the entire acoustic backscatter in the depth layer including the sphere had an arithmetic average around -73 dB, but a higher mean echo strength around -69 to -67 depending on the beam (Figure 15). The distribution of the background acoustic backscatter helped develop a threshold of -50 dB to exclude for examining the echo strength of the 38.1-mm tungsten carbide sphere. Figure 16 show the peak echo strength (ES) distribution from the four central beams (±0.4° and ±1.2° beam pointing angles), but seemed to be best described in the 0.4° beam with a mean ES of -45.13 ±0.41 dB (±SE). However, this

estimate can be greatly improved with better target detection algorithms to exclude contribution of the peak echo strength of samples without the sphere. When a known target strength is determined for this sphere at 300 kHz, additional statistical approaches can be applied to describe the empirical TS distribution of the sphere using the EM3002. Once an empirical TS distribution is obtained, a calibration offset can be applied to correct for any difference between the measured and theoretical TS.

Video Observations

The two cameras provided video footage showing the distribution and behavior of the cod during acoustic measurements. The up-looking camera located at the bottom center of the cage revealed periods when the cod appeared to be randomly distributed horizontally in the cage or clustered in loose to dense schools depending on stocking density (Figure 17). During the first day of acoustic measurements with 195 cod, individuals appeared to be randomly distributed. When the density of cod was reduced to 66 individuals in the cage on 27 June, cod formed a tight group. The side camera at 1-m of the bottom of the cage provided some observation of their vertical orientation in the cage (Figure 17) which appeared to be mostly horizontally-oriented. Some individuals strayed from the group particularly when cod density was reduced to 23 fish.

Density Estimates

At this time, preliminary results can show detection of cod at four densities using the EM3002 multi-beam sonar is possible (Figures 18-24). However, at depth of 13-17 m the cage is often completely or partially outside the beam due to strong currents (Figure 19). Individuals and groups of cod were visually discriminated from the cage in the images of the water column backscatter. Figure 25 shows the volume backscattering strength (s_v) of the cage and cod at four densities from a single ping by the EM3002. The data are sufficient for future quantification of the relative densities. Once acoustic estimates of cod abundance in the cage are determined from the EM3002 data, they can easily be compared to densities derived from EK60 data (Figure 26).

Conclusions

The preliminary results presented in this report support the following conclusions.

- The current analysis shows that echoes from cod were detected and discriminated from the acoustic backscatter of the cage.
- Echo strength distributions of standard targets like the 38.1-mm tungsten carbide sphere can be used calibrate the EM3002 for acoustic abundance estimation once a known target strength is modeled.
- Qualitative analysis shows differences in the echo strength and volume backscattering strength of cod at different densities and behaviors (spatial distribution).
- Preliminary results demonstrate these data can be used for continued post-processing and modeling.
- Results provided experience and knowledge of sonar and experiment configurations that will work or not work for future research. A problem of temperature-induced mortality, currents at depth, stress-induced mortality of haddock were the biggest limitations and provide information for improving future research. Cage experiments in the future should be attempted when the water temperatures are cooler and a thermocline is absent or small. Use of the cage at depth offshore may be limited to slack tides and dependent on strength of tidal currents.

Partnerships

The success of this project was a product of partnership among a commercial trawler, NOAA Fisheries scientist, hydrographers, and fisheries biologists. The experience and flexibility of fish sampling by commercial fishermen allowed for the experiments to occur. A project with many technical, technological components and expensive equipment required such partnership among the Center for Coastal Ocean Mapping/Joint Hydrographic Center, Northeast Fisheries Science Center's Advanced Sampling Technologies Research Group, Open Ocean Aquaculture Project, UNH Zoology Department and Kongsberg Maritime.

Impacts and Applications

Preliminary results showed reasons for continued research and development of multi-beam applications in stock assessment of Atlantic cod. Data collected can serve for additional research and development in scattering theory and fisheries acoustics.

Related Projects

This project was done in association with objectives and resources from other research such as the Open Ocean Aquaculture Project, CCOM's research with non-traditional mapping products, and NOAA objectives within the Advanced Sampling Technologies Research Group.

Scheduled Presentations

Gurshin, Christopher W.D., J. Michael Jech, W. Huntting Howell, Thomas C. Weber, and Larry A. Mayer. 2008. Target strength and density measurements of captive Atlantic cod using a 300 kHz multi-beam sonar synchronized with 38- and 120-kHz split-beam echosounders. Ecosystem Approach with Fisheries Acoustics and Complementary Technologies (SEAFACTS). Bergin, Norway. 16-20 June 2008.

Student Participation

<u>Graduate Students</u>
Travis Ford, University of New Hampshire
Christopher W.D. Gurshin, University of New Hampshire
Mashkoor Malik, University of New Hampshire
Laughlin Sicelof, University of New Hampshire
Michelle Walsh, University of New Hampshire

<u>Undergraduate Students</u>
Chelsea Humbyrd, Texas A&M University
Takiwi Milton, Paine College

Published Reports and Papers

None.

Images

See figures

Future Research

The results and experience from this project led to a 2008-2009 New Hampshire Sea Grant award for more extensive experimentation (1) to estimate abundance of Atlantic cod from acoustic backscatter using multi-beam sonar; (2) to determine diel and depth effects on acoustic indices of abundance from multi-beam sonar; (3) to characterize relationships between fish size and acoustic indices of abundance from multi-beam sonar; (4) to determine effect of the presence of other species on acoustic detection and abundance estimates of cod; (5) to characterize error and uncertainty of acoustic indices of abundance from multi-beam sonar; (6) to compare results from multi-beam sonar with multi-frequency split-beam sonar. Plans to conduct a dual-purpose hydrographic survey to collect water column data and bathymetry are currently being discussed.

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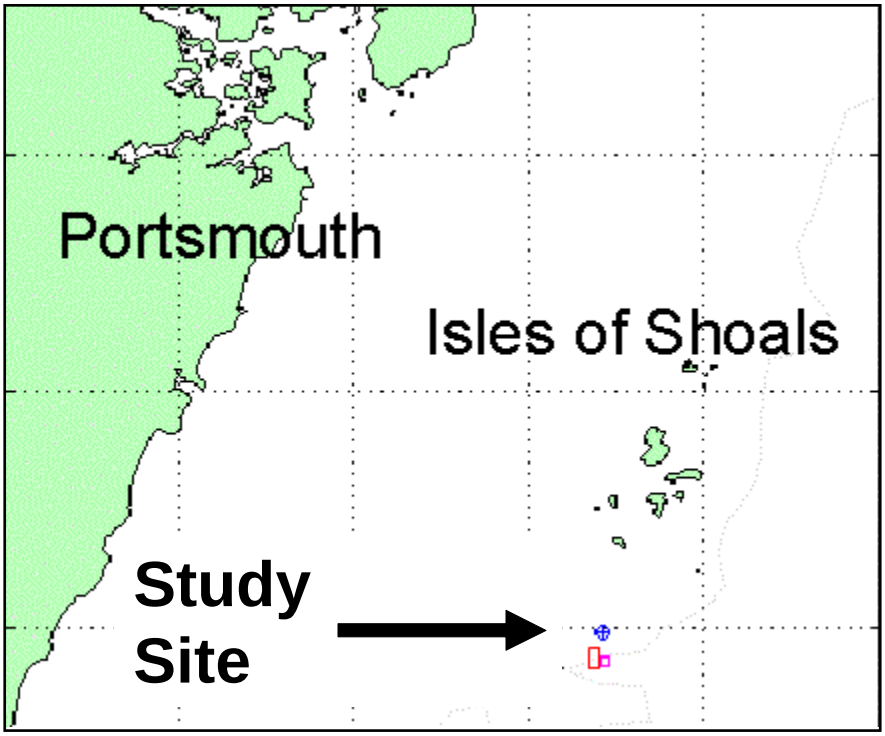

Figure 1. Study area for cage experiments located off Portsmouth, New Hampshire and south of Isles of Shoals at the Open Ocean Aquaculture project site.

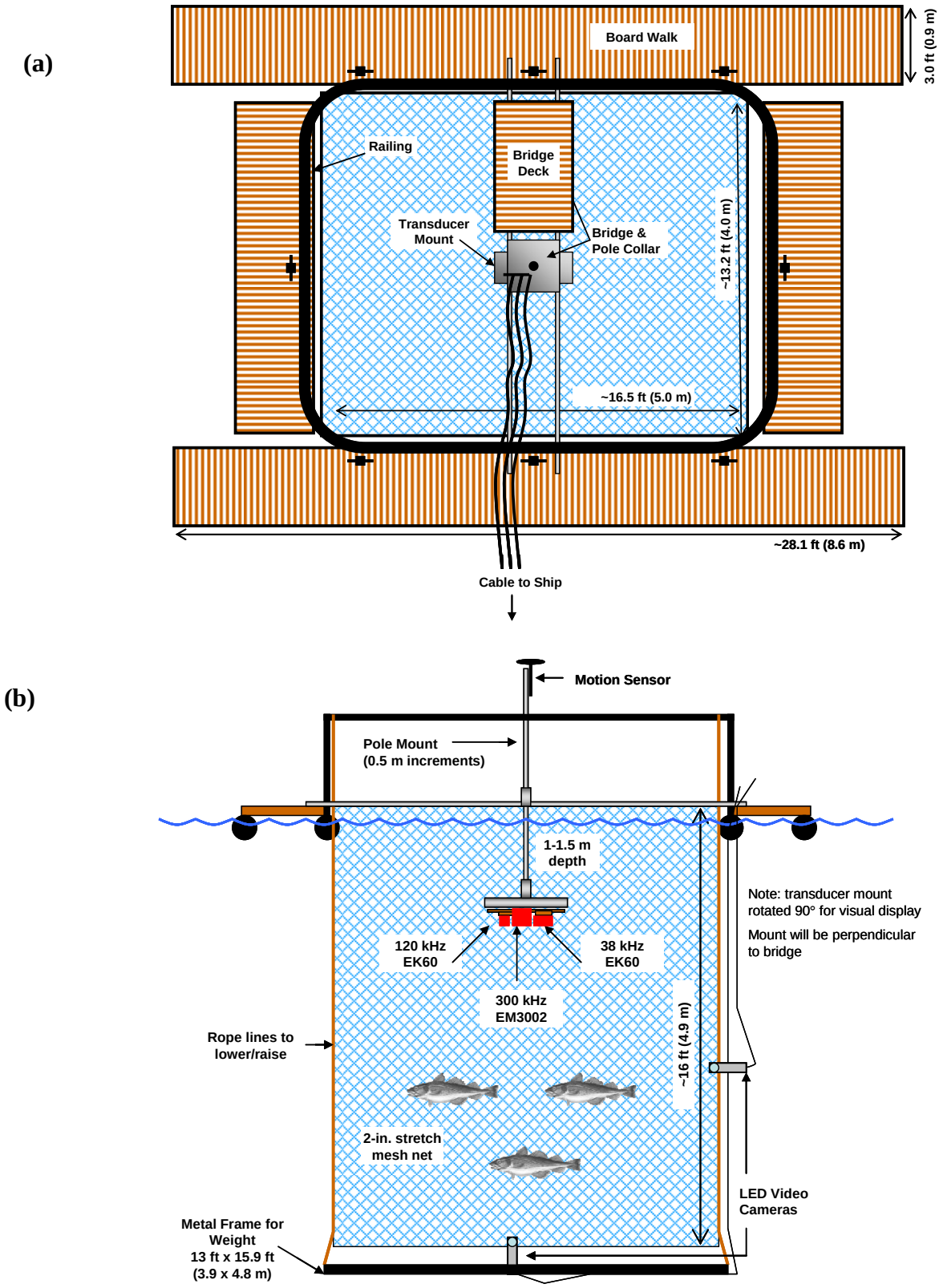

Figure 2. Diagram of the (a) top view and (b) side view of the cage setup for *ex situ* acoustic measurements of Atlantic cod.

Figure 3. The floating cage being towed out of the harbor by small vessel (A) and out to sea by the R/V Rock N Roll (B). The floating cage on site for sonar operations and being stocked with cod from the F/V Stormy Weather (D). The net top was closed after stocking (E) or reopened for removal (F).

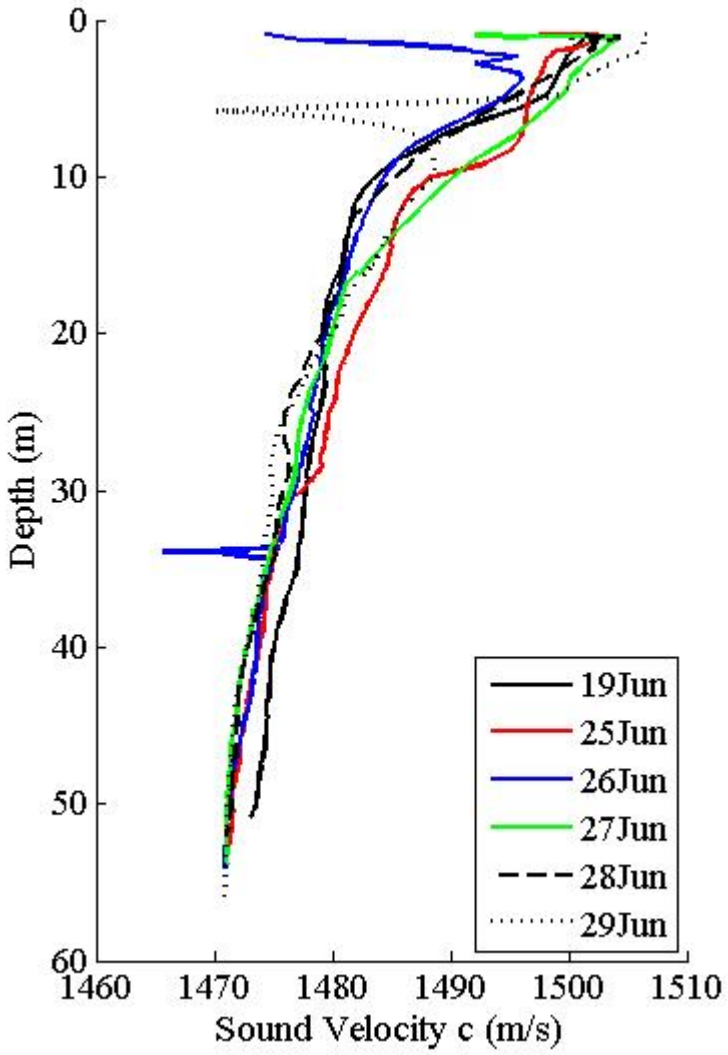

Figure 4. Sound velocity profile during acoustic measurements on 19 and 25-29 June 2007.

Figure 5. (A) The NOAA vessel R/V Cocheco at dock and (B) at the offshore cage during sonar installation . (C) All electronics were housed in the fore cabin of the R/V Cocheco. (D) The R/V Cocheco tied up to the cage during removal of experimental fish.

Table 1. Summary of acoustic data of encaged Atlantic cod collected by a dual 38 kHz/120kHz split-beam EK60 echosounder and 300 Hz EM3002 sonar during 19-29 June 2007.

Date	Sonar	Time	Duration (minutes)	Pings	Cage Population	Manipulations
19 June	EK60 (38 kHz)	16:52:59 to 17:33:14	39.85	2386	empty	60-mm copper sphere calibration
	EK60 (120 kHz)	18:33:32 to 18:42:58	9.43	565	empty	23-mm copper sphere calibration
	EK60	19:40:29 to 20:04:09	23.67	1421	empty	38-mm tungsten carbide sphere calibration of EM3002
	EK60	20:04:10 to 20:26:31	20.77	1240	empty	
	EM3002	19:41:46 to 20:04:01	22.25	1335	empty	38-mm tungsten carbide sphere calibration
	EM3002	20:05:46 to 20:26:21	20.58	1234	empty	
25 June	EK60	18:49:12 to 01:43:48	376.88	22620	196	near surface (2-6 m), descent, at depth (13-17 m), ascent, sunset, night
	EM3002	19:57:04 to 01:43:36	343.72	19237	196	
26 June	EK60	17:33:49 to 19:33:17	119.40	7165	116	Cage (4-8 m)
	EM3002	17:25:42 to 19:33:22	127.52	7653	116	Cage (4-8 m)
27 June	EK60	17:02:43 to 17:53:56	51.20	3054	66	Cage (5.5-9.0 m); Descent (17:40-17:47)
	EK60	17:53:56 to 18:32:07	37.97	6047	66	Cage (7.5-11 m; 17:47 to 18:29:30)
	EK60	18:32:07 to 18:37:10	5.05	1988	66	Cage (6-9 m; 18:31:00 to 18:37:10)
	EM3002	16:50:39 to 18:37:02	94.53	10177	66	Cage (6.0-9.0 m)
28 June	EK60	17:55:33 to 19:44:13	105.55	6423	23	Cage (5.5-9.0 m)
	EM3002	17:55:32 to 19:43:53	105.22	6413	23	Cage (5.5-9.0 m)
29 June	EK60	14:59:35 to 15:24:09	24.57	1475	23	pulse length = 0.512 ms, 1 ping s^{-1}
	EK60	15:25:10 to 15:40:24; 18:18:28 to 19:09:07	91.27	19275	23	pulse length = 0.512 ms, 5 ping s^{-1}
	EK60	16:34:20 to 17:17:08	42.78	12745	23	with tungsten carbide calibration sphere 1 (pulse length=0.256 ms, 5 Hz)
	EK60	17:37:02 to 18:17:54	40.63	10838	23	with tungsten carbide calibration sphere 2 (pulse length=0.256 ms, 5 Hz)
	EK60	15:41:41 to 16:343:08	58.35	17004	23	without sphere (pulse length=0.256 ms, 5 Hz)
	EK60	20:18:56 to 20:23:49	4.88	1198		few fish
	EM3002	14:55:54 to 15:26:13	28.05	1685	23	1 ping per second
	EM3002	15:26:15 to 19:09:11	201.27	57035	23	5 ping per second
	EM3002	20:18:44 to 20:23:22	4.63	1203	6	few fish

Table 2. Mean and standard error (S.E.) for numerical abundance, catch-per-unit-effort (CPUE, fish per 30-minute tow), and percent composition (%) of fish enumerated in 10 tows of a 6.5-inch mesh otter trawl by F/V Stormy Weather in Area Closure 133 on 21, 22, and 25 June 2008.

Taxon	Total Catch	Catch		CPUE		Percent Composition	
		Mean	S.E.	Mean	S.E.	Mean	S.E.
American plaice (*Hippoglossoides platessoides*)	135	13.50	3.28	15.13	3.35	17.28	4.47
Atlantic cod (*Gadus morhua*)	215	21.50	10.20	36.52	18.81	27.03	9.11
Butterfish (*Peprilus triacanthus*)	6	0.60	0.27	0.60	0.27	0.75	0.33
Haddock (*Melanogrammus aeglefinus*)	27	2.70	0.75	3.97	1.33	4.79	2.07
Goosefish (*Lophius americanus*)	5	0.50	0.17	0.78	0.27	0.78	0.32
Red hake (*Urohycis chuss*)	9	0.90	0.38	1.16	0.58	1.00	0.39
Sculpin spp. (*Myoxocephalus* spp.)	5	0.50	0.27	0.50	0.27	0.73	0.41
Sea raven (*Hemitripterus americanus*)	1	0.10	0.10	0.10	0.10	0.12	0.12
Silver hake (*Merluccius bilinearis*)	36	3.60	1.43	4.62	1.82	5.20	1.85
Skate spp. (Rajidae)	18	1.80	0.55	2.29	0.83	2.24	0.70
Spiny dogfish (*Squalus acanthias*)	112	11.20	2.15	13.16	1.89	18.31	3.43
Witch flounder (*Glyptocephalus cynoglossus*)	104	10.40	2.94	11.57	2.68	14.97	3.42
Wolffish (*Anarhichas lupus*)	3	0.30	0.21	0.30	0.21	0.38	0.27
Yellowtail flounder (*Limanda ferruginea*)	36	3.60	0.88	4.61	1.27	6.42	2.29
Total	712	71.20	10.93	95.29	21.02	100.00	0.00

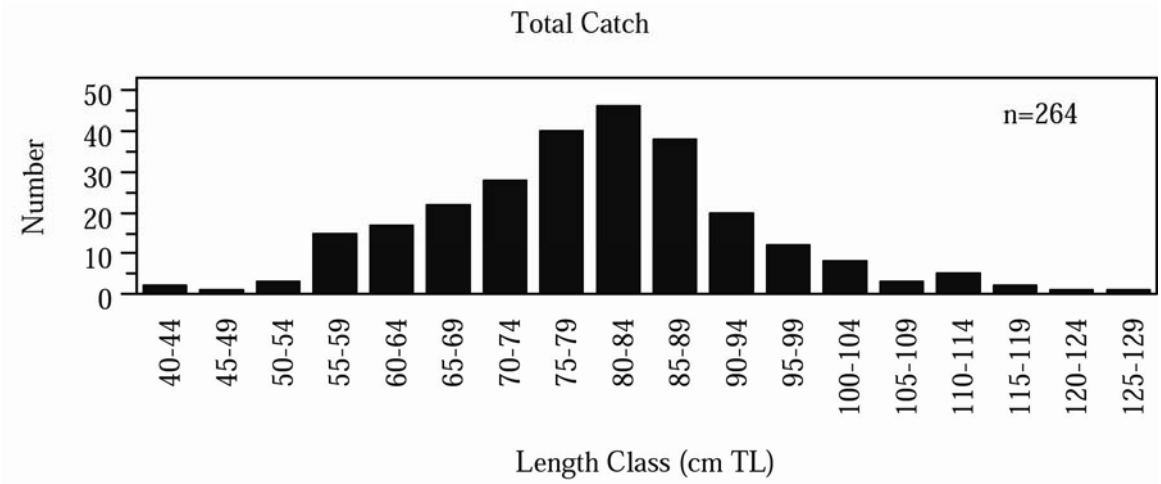

Figure 6. Length frequency distribution of all measured Atlantic cod caught by 13 otter trawl tows off New Hampshire coast in Area Closure 133 on 21, 22, and 25 June 2008.

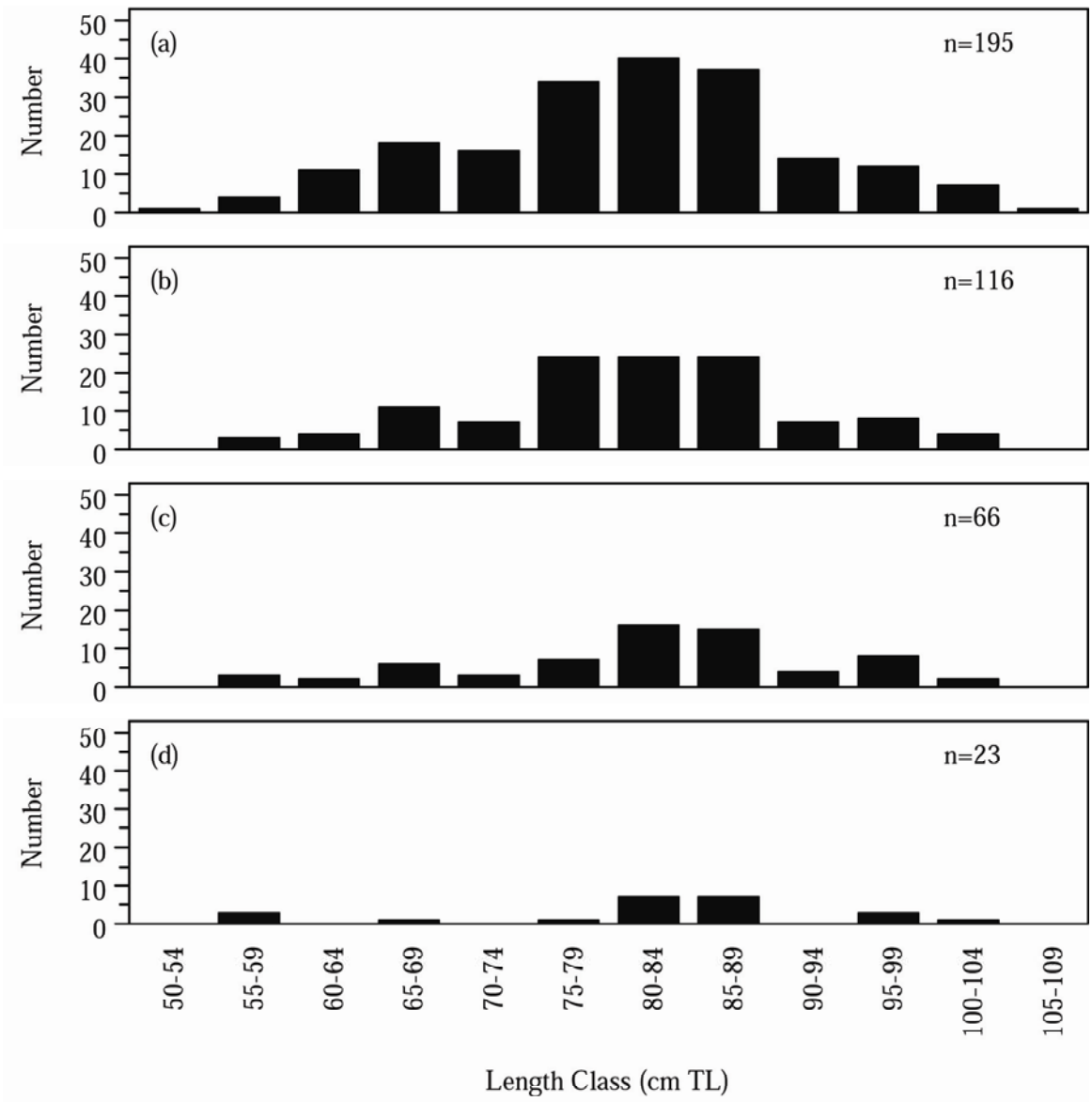

Figure 7. Length frequency distribution of encaged Atlantic cod used to obtained acoustic measurements by three echosounders over four densities (a-d).

Table 3. Statistics of total length (cm) of Atlantic cod (*Gadus morhua*) used in *ex situ* experiments of target strength and density measurements by a 38-kHz and 120-kHz EK60 split-beam echosounder and a 300-kHz EM3002 multi-beam echosounder during 25-29 June 2007.

Experiment	N	Min.	Mean	Median	Max.	S.E.	S.D.	Lower 95% confidence limit	Upper 95% confidence limit
1	195	51.5	80.7	81.0	105.0	0.8	10.9	79.1	82.2
2	116	55.0	81.1	81.8	103.0	1.0	10.5	79.2	83.1
3	66	55.0	82.1	83.8	102.5	1.4	11.7	79.2	85.0
4	23	55.0	82.9	84.5	102.0	2.8	13.6	77.0	88.8
5	6	55.0	83.5	94.5	102.0	9.1	22.3	60.1	106.9

S.E. = standard error
S.D. = standard deviation

Table 4. Statistics of total length (cm) of Atlantic cod (*Gadus morhua*) used in *ex situ* experiments of target strength and density measurements by a 38-kHz and 120-kHz EK60 split-beam echosounder and a 300-kHz EM3002 multi-beam echosounder during 25-29 June 2007.

Experiment	Date	Stock Size	Released Alive	Released Dead	24-hour Mortality (%)	Cumulative Mortality (%)
1	25 June	195	--	--	--	--
2	26 June	166	12	67	--[A]	34.4
3	27 June	66	42	8	8.9	38.5
4	28 June	23	41	2	3.0	39.5
5	29 June	6	17	1	4.3	40.0

[A] See cumulative mortality after 24 to 96 hours after stocking the cage.

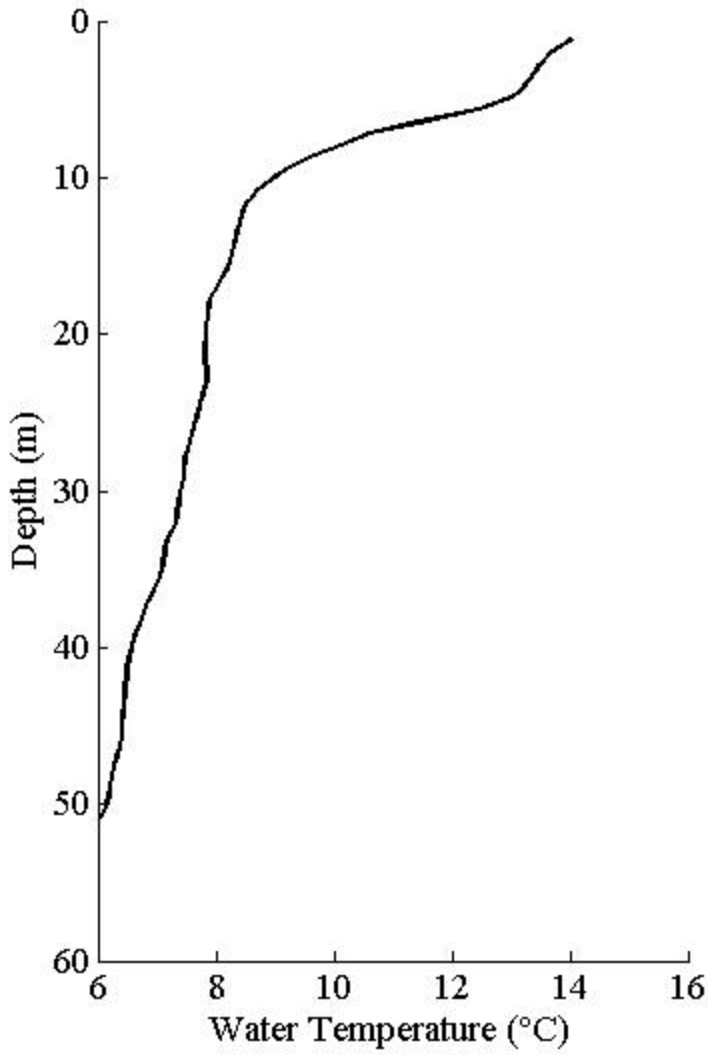

Figure 8. Temperature-depth profile at the cage during calibration on 19 June 2007.

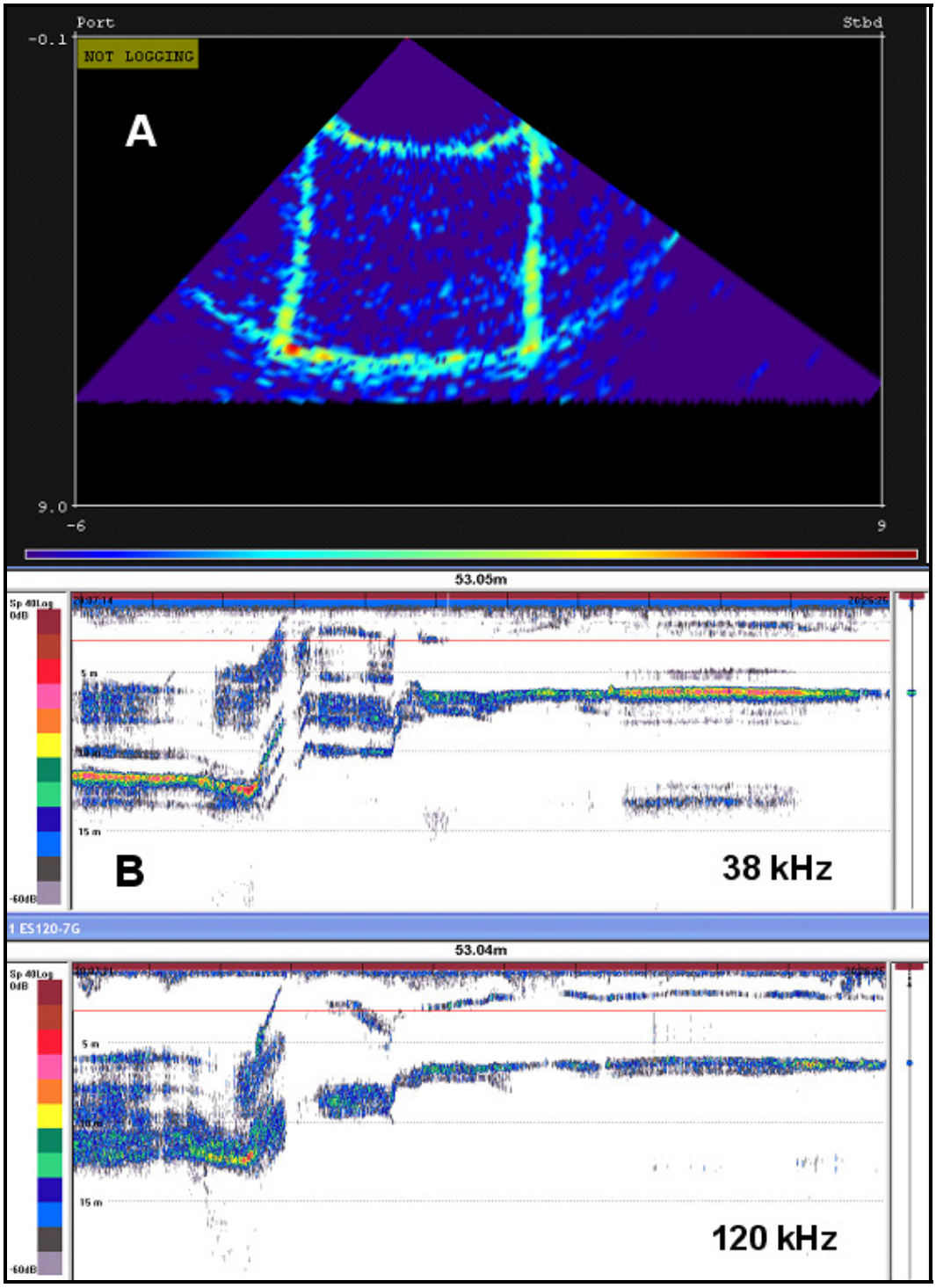

Figure 9. (A) The echo of the empty net cage used in acoustic measurements of cod shown in the water column by the EM3002 sonar as acquired by the SIS software. (B) Echograms of the empty cage (4-5 m high) being raised to the surface from the 38-kHz and 120 kHz EK60 echosounder as acquired using the Simrad ER60 software during 16 June 2007.

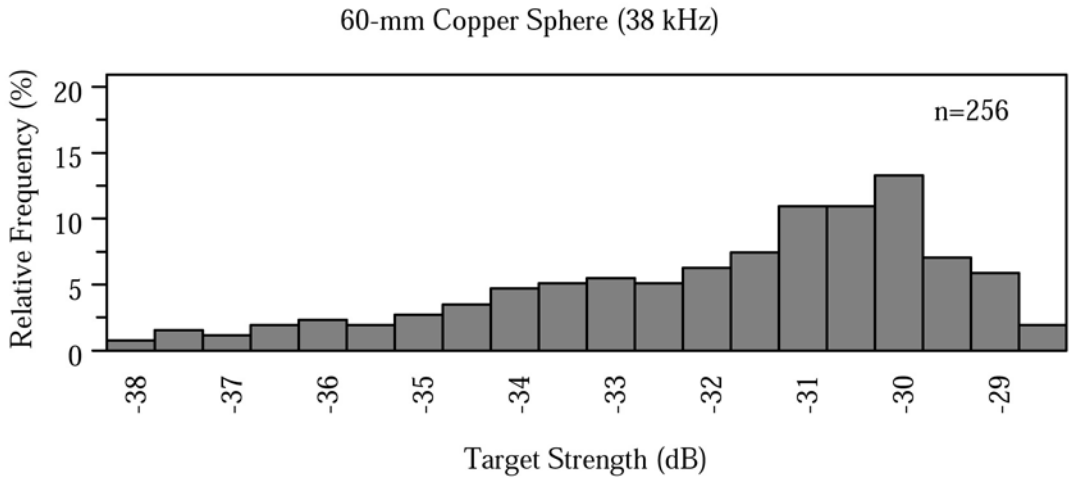

Figure 10. Target strength distribution of a 60-mm copper sphere with a known TS of -33.6 dB obtained during calibration of a 38-kHz split-beam EK60 echosounder at a range of 8-10 m on 19 June 2007.

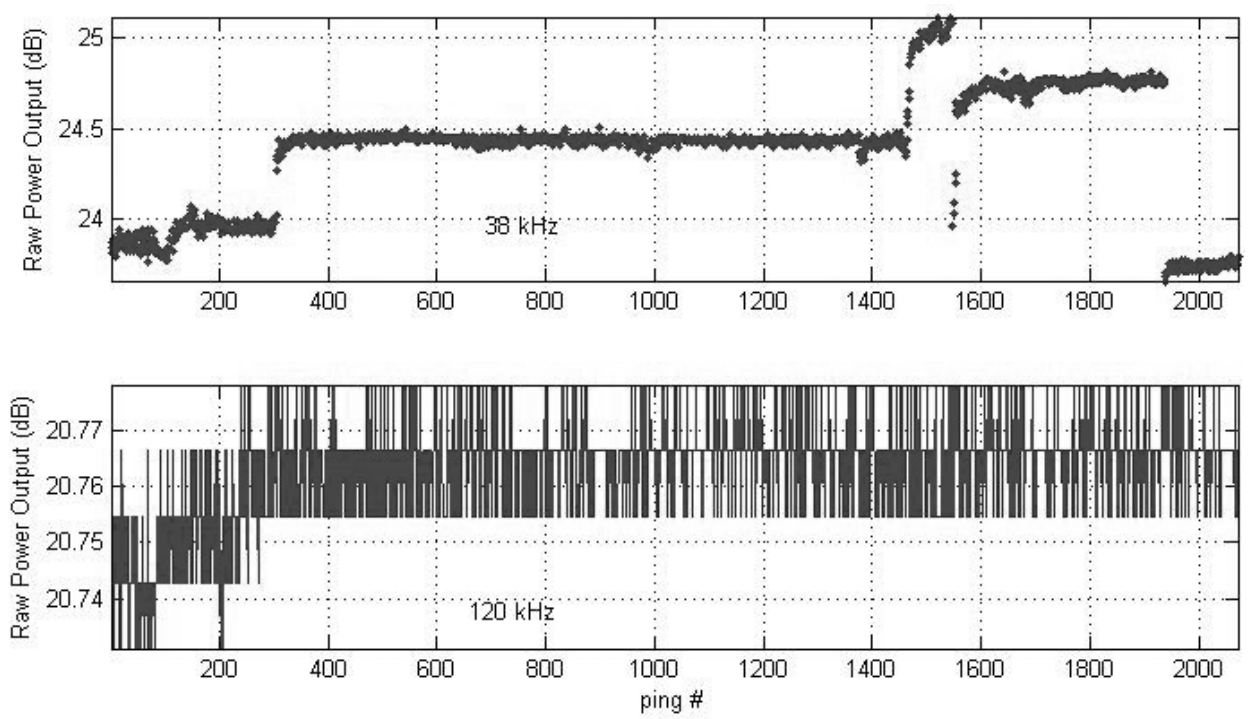

Figure 11. Raw power output (dB) recieved from sample 3 (0.382 m range) over 2073 pings by the 38-kHz (top) and 120-kHz (bottom) EK60 echosounder each with 1000 W of transmitted power during calibration on 19 June 2007. Note: different scales on y-axis.

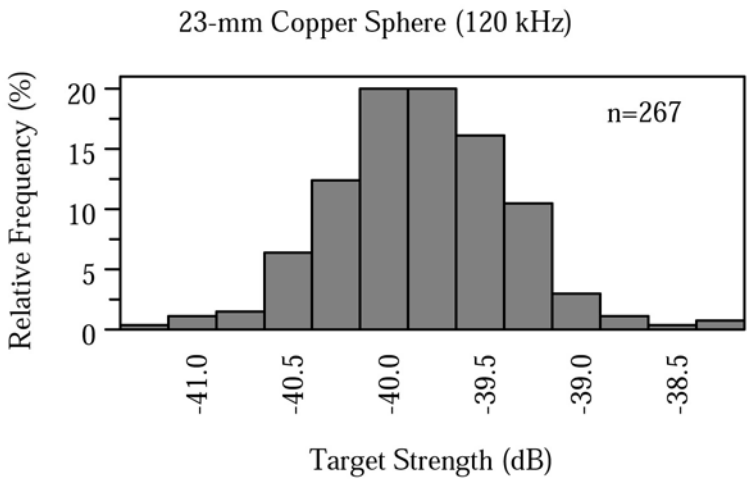

Figure 12. Target strength distribution of a 23-mm copper sphere with a known TS of -40.4 dB obtained during calibration of a 120-kHz split-beam EK60 echosounder at a range of 8-10 m on 19 June 2007.

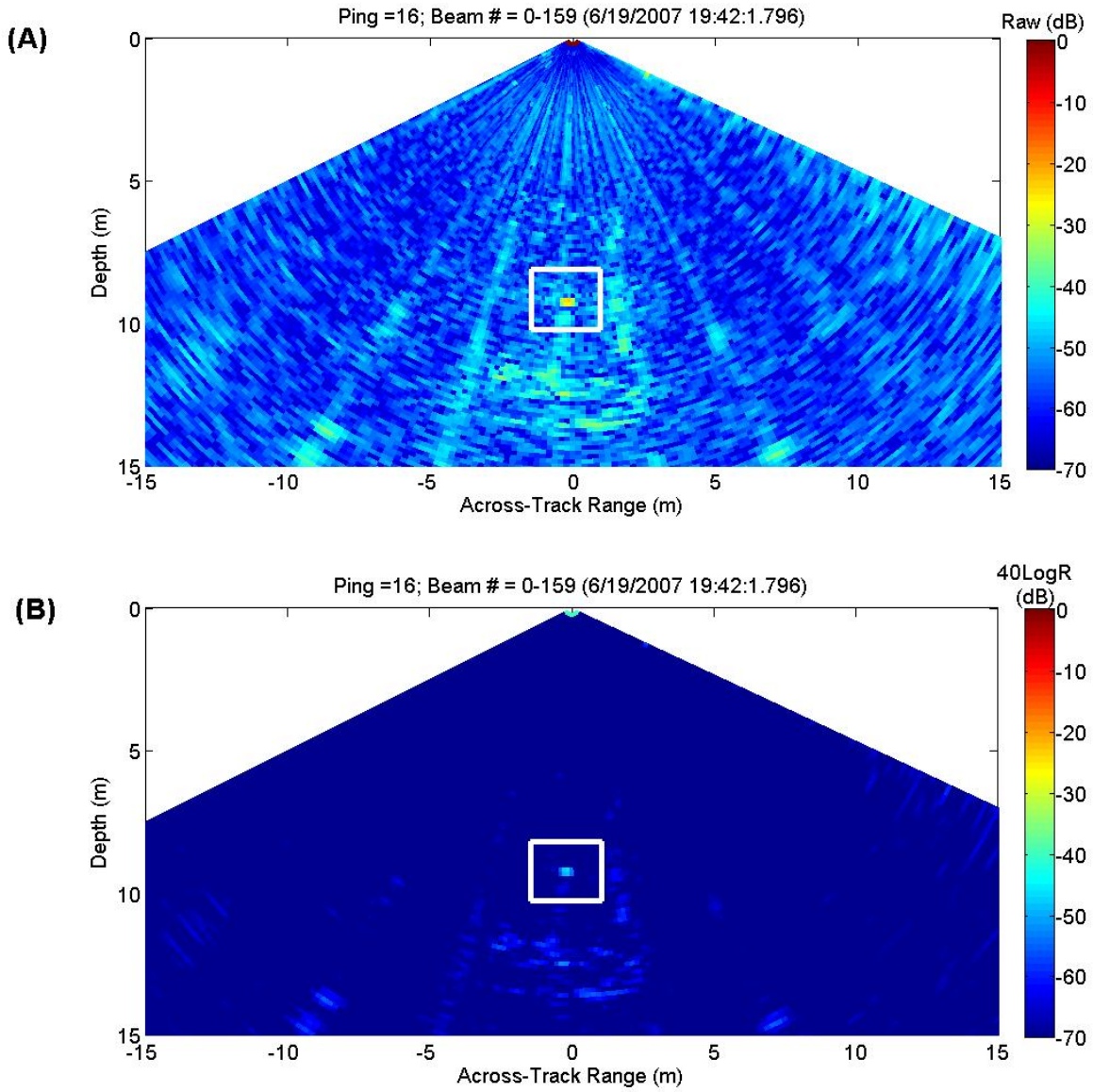

Figure 13. (A) Raw amplitude and (B) echo strength of a 38.1-mm tungsten carbide sphere (bright-colored echo in white box) shown in the top 15 m of the water column during calibration of the EM3002 sonar during 19 June 2007. Note: depth-dependent TVG applied to echo strength was $40Log_{10}R$.

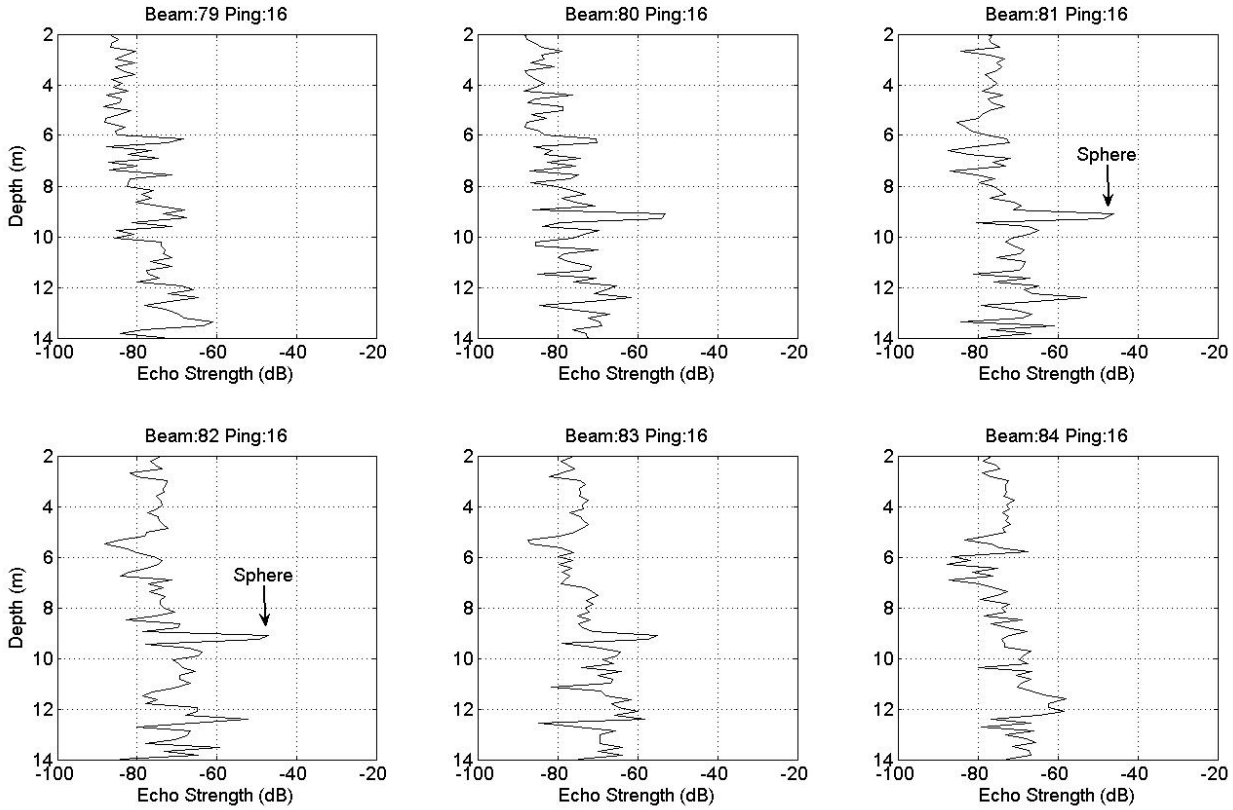

Figure 14. Depth profile of the echo strength (dB) measurements in ping 16 for beams 79-84 during calibration of the EM3002 sonar using a 38.1-mm tungsten carbide on 19 June 2007. Note: depth-dependent TVG applied to echo strength was $40Log_{10}R$.

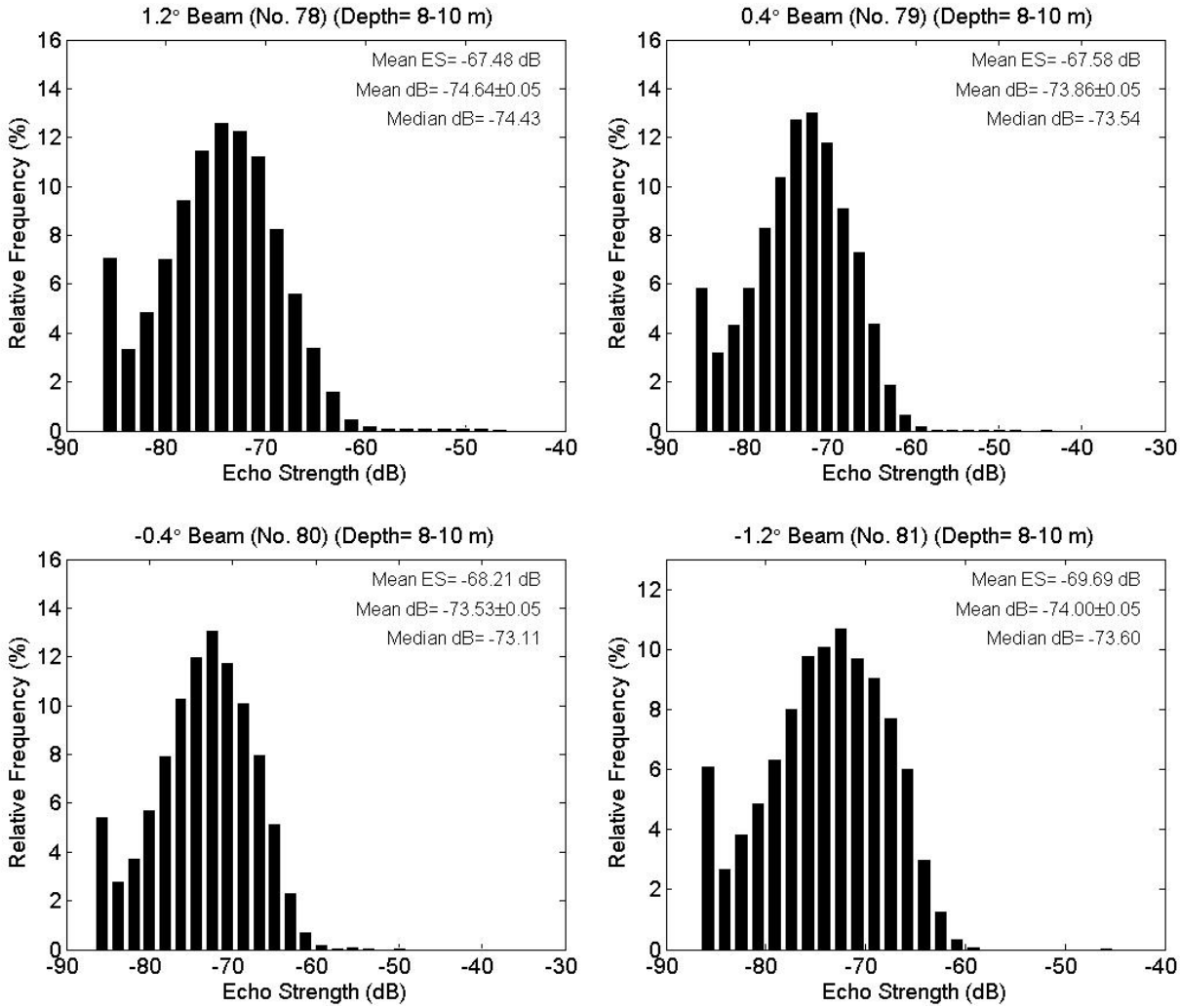

Figure 15. Relative frequency distribution of the echo strength (dB) of all acoustic backscatter between 8 and 10 m from 1335 pings for four central beams in the EM3002 sonar obtained during sphere calibration on 19 June 2007.

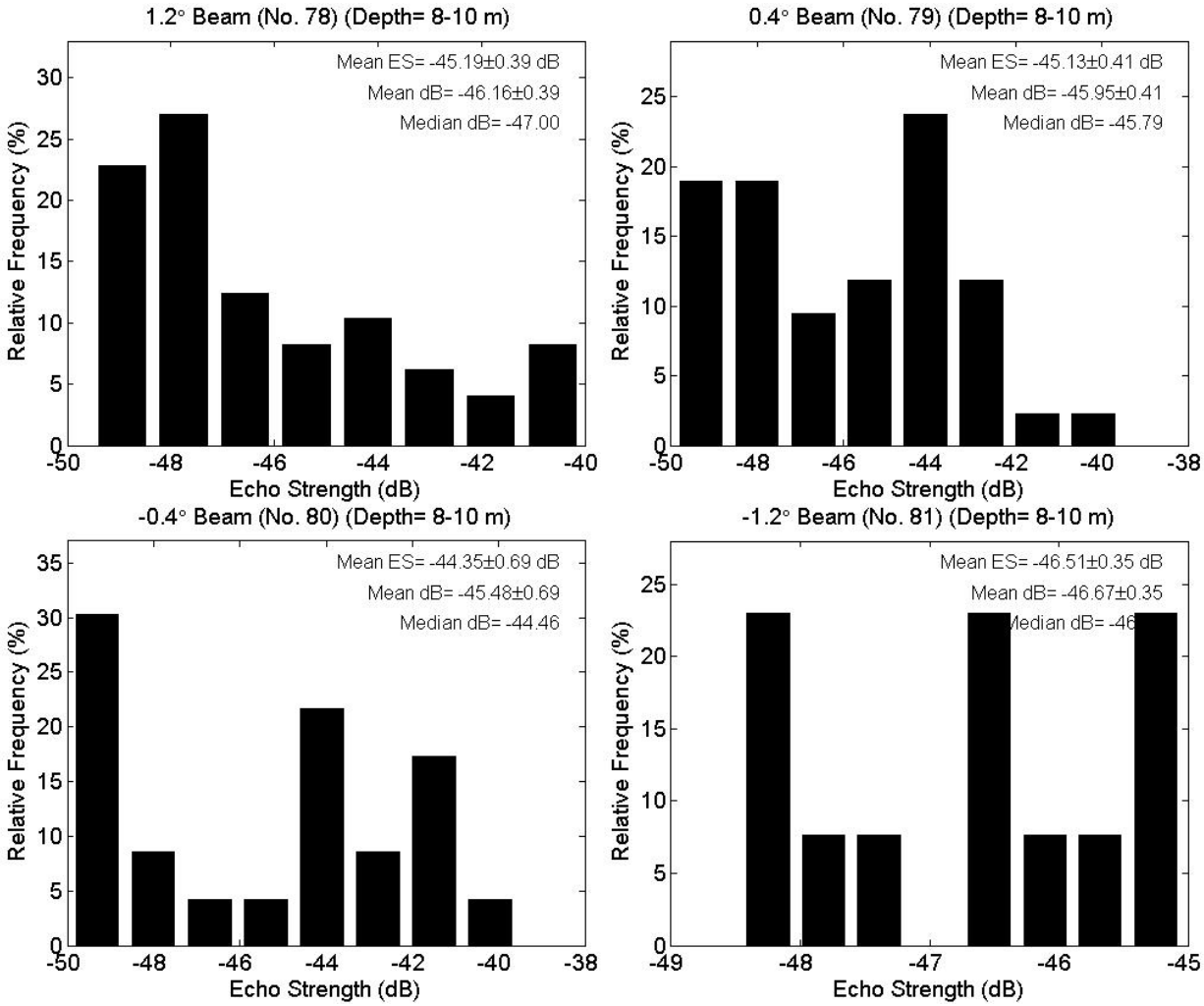

Figure 16. Relative frequency distribution of the peak echo strength (dB) within each of the four central beam between 8 and 10 m from 1335 pings during calibration of the EM3002 sonar using 38.1-mm tungsten carbide sphere a on 19 June 2007. Note: different scales on axes.

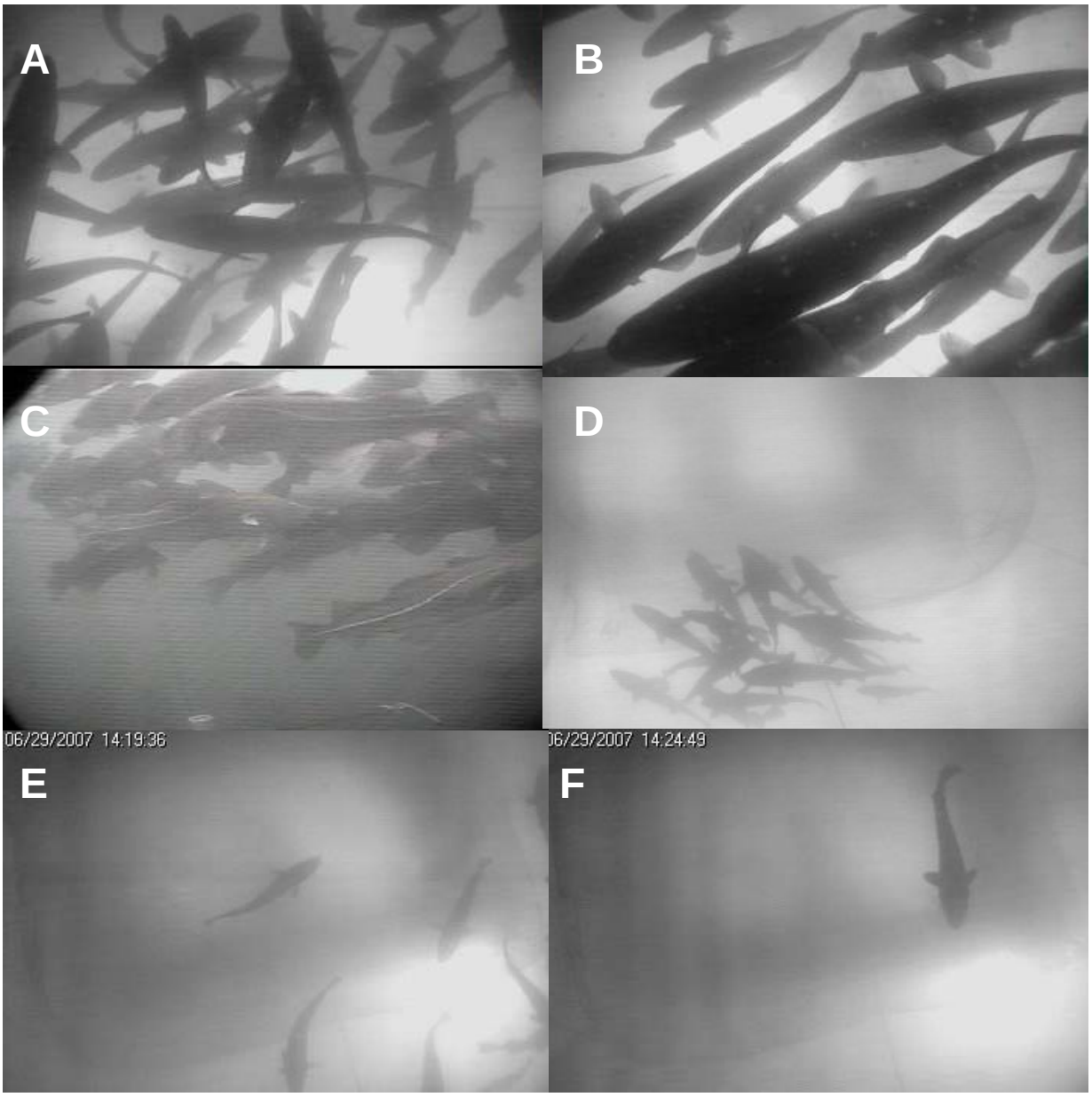

Figure 17. Underwater video footage of (A) random distribution of 66 cod and (B) directional swimming from bottom camera on 27 June 2007; (C) vertical distribution of cod in cage from side camera about 1 m from bottom on 27 June 2007; (D) small school of 23 cod in cage from bottom camera, (E) individual movements of cod in center of cage, and (F) single individual cod swimming in center of cage on 29 June 2007.

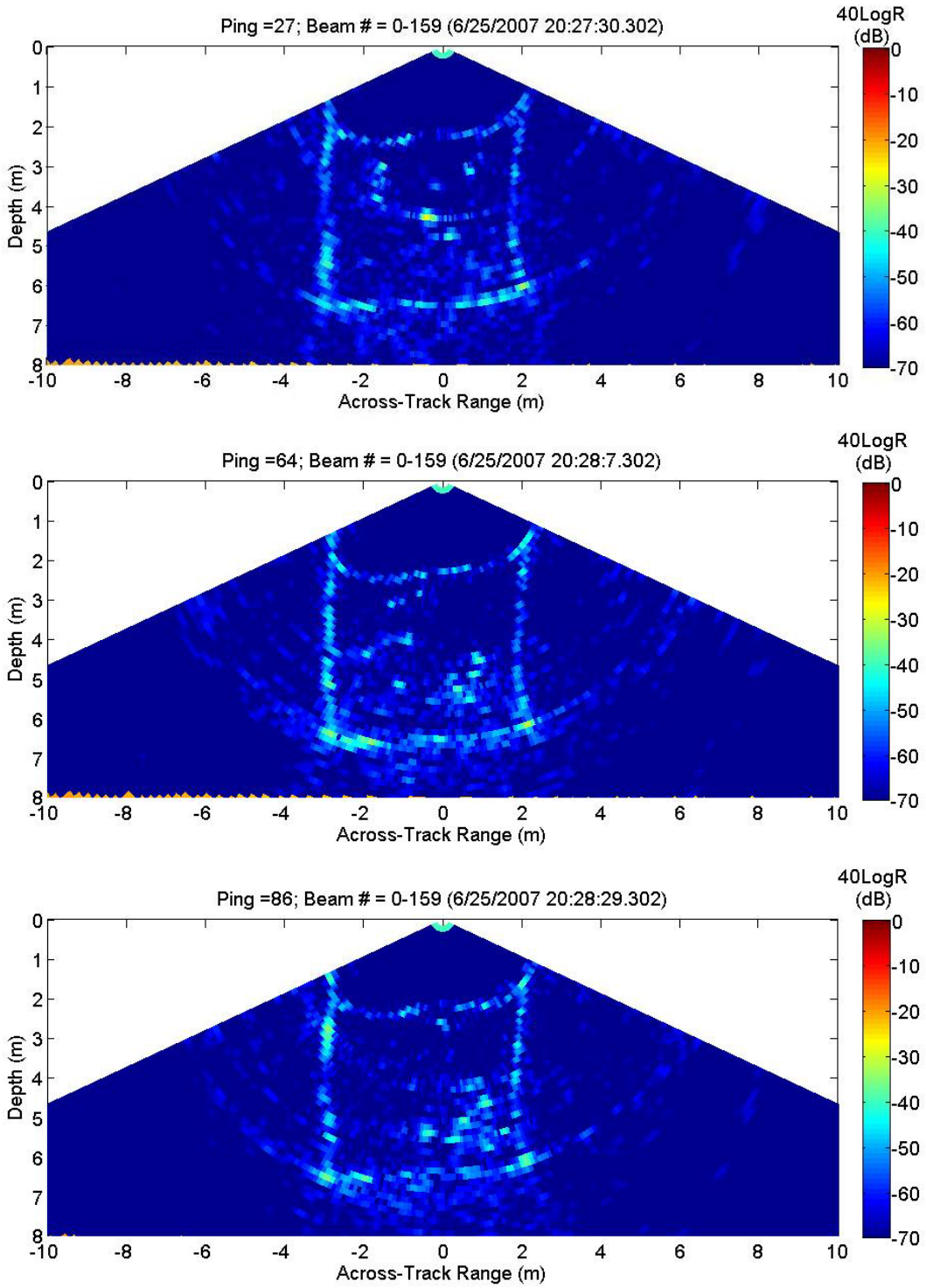

Figure 18. Water column image of single pings from the EM3002 illustrating the echo strength (TVG=40LogR) of the acoustic backscatter from the cage stocked with 195 Atlantic cod (*Gadus morhua*) during the day on 25 June 2007.

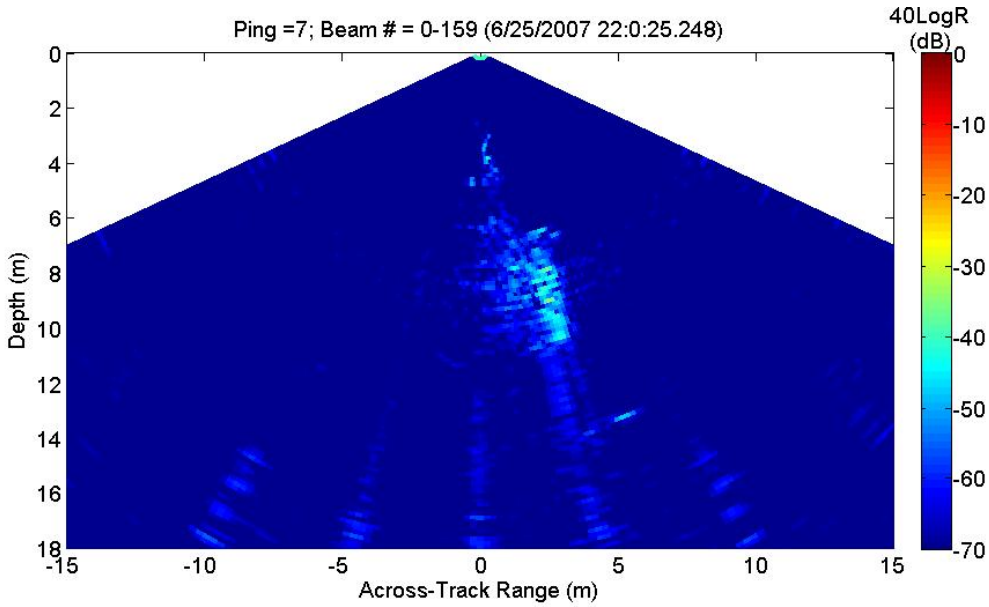

Figure 19. Water column image of a single ping from the EM3002 illustrating the echo strength (TVG=40LogR) of the acoustic backscatter from the cage stocked with 195 Atlantic cod (*Gadus morhua*) lowered 9 m during the day on 25 June 2007.

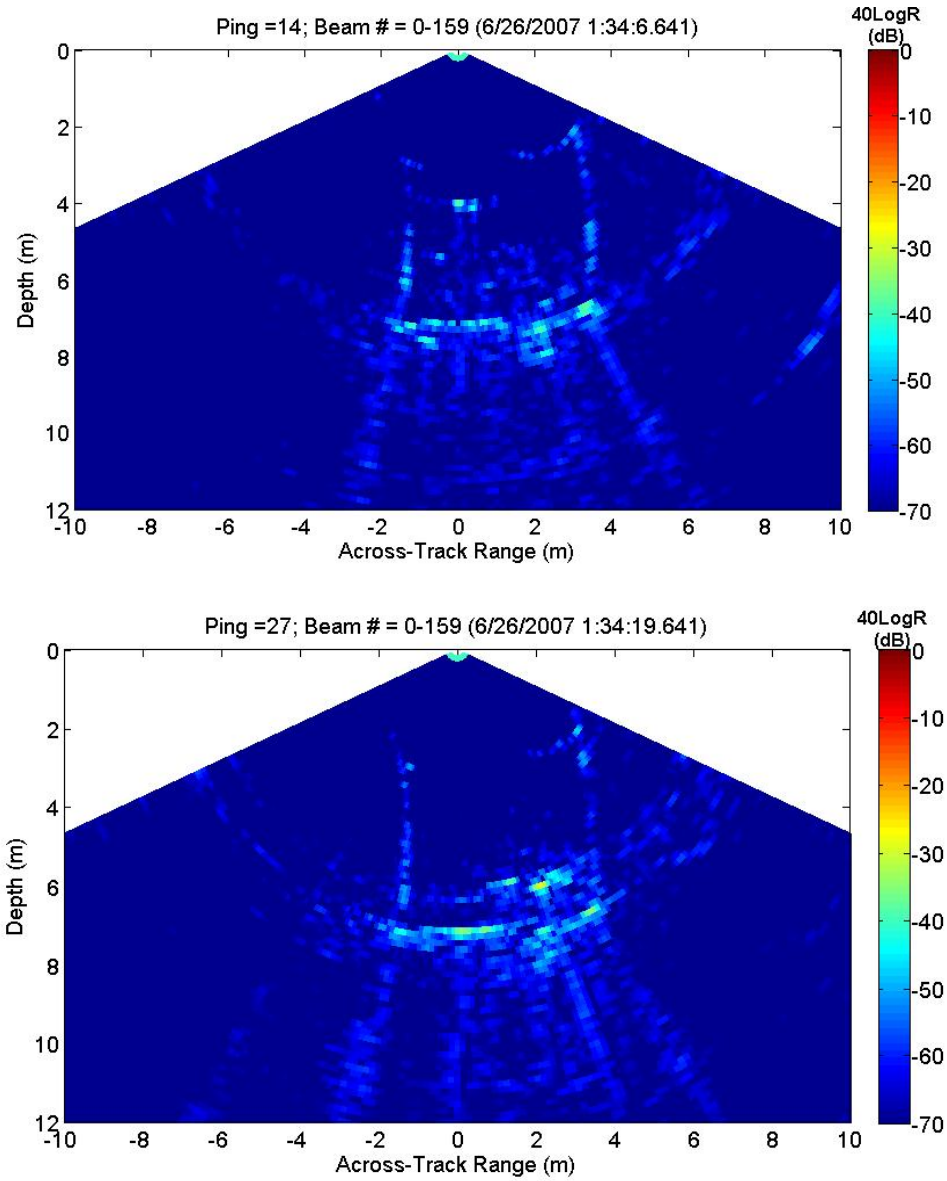

Figure 20. Water column image of two single pings from the EM3002 illustrating the echo strength (TVG=40LogR) of the acoustic backscatter from the cage stocked with 195 Atlantic cod (*Gadus morhua*) during the night on 25 June 2007.

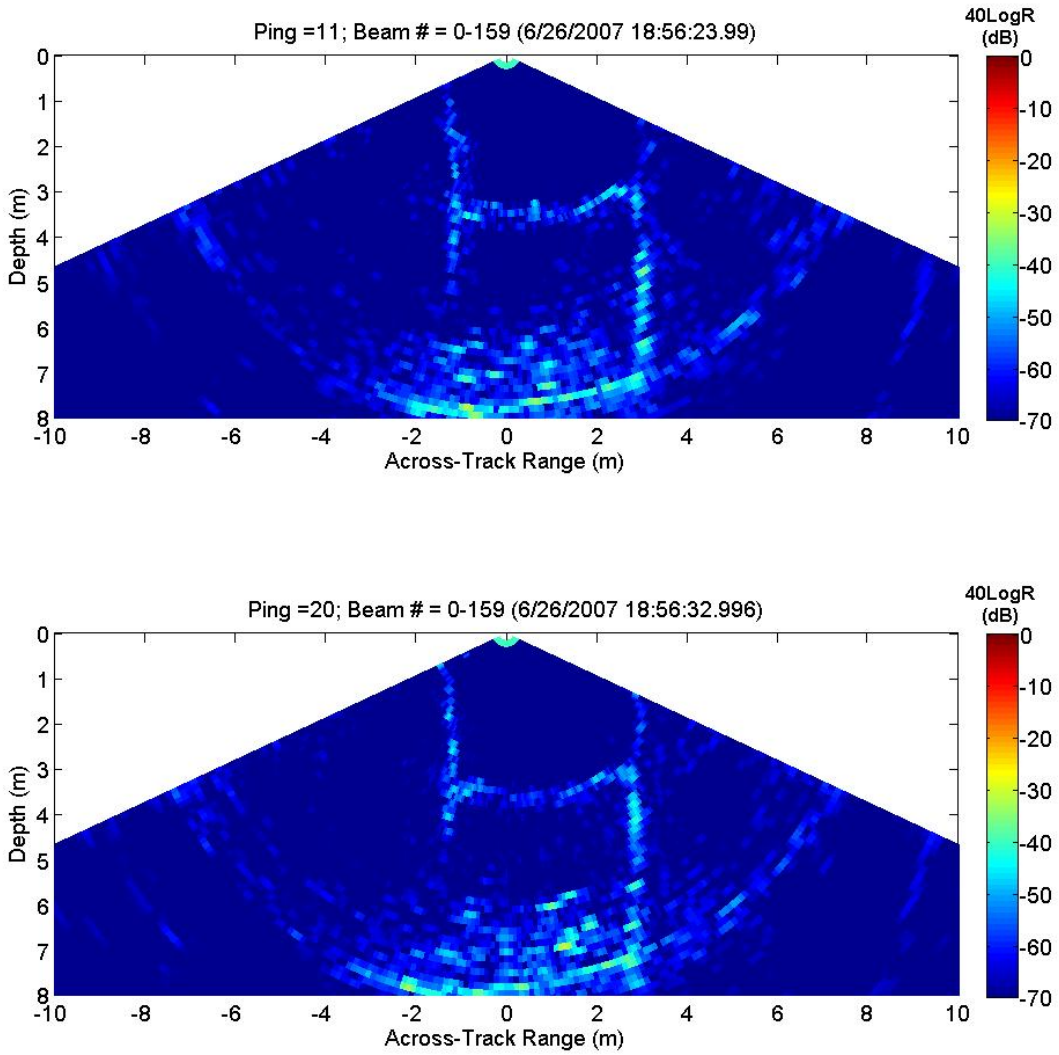

Figure 21. Water column image of two single pings from the EM3002 illustrating the echo strength (TVG=40LogR) of the acoustic backscatter from the cage stocked with 116 Atlantic cod (*Gadus morhua*) on 26 June 2007.

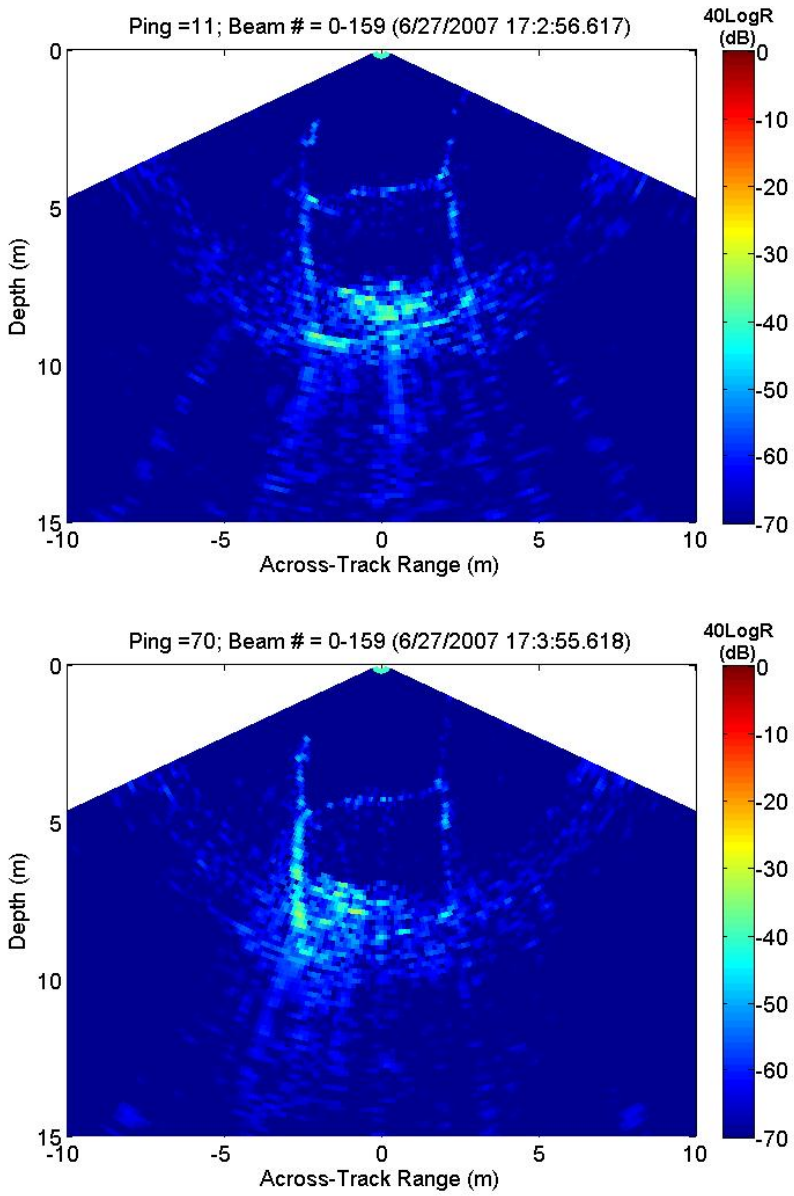

Figure 22. Water column image of two single pings from the EM3002 illustrating the echo strength (TVG=40LogR) of the acoustic backscatter from the cage stocked with 66 Atlantic cod (*Gadus morhua*) schooling close together on 27 June 2007.

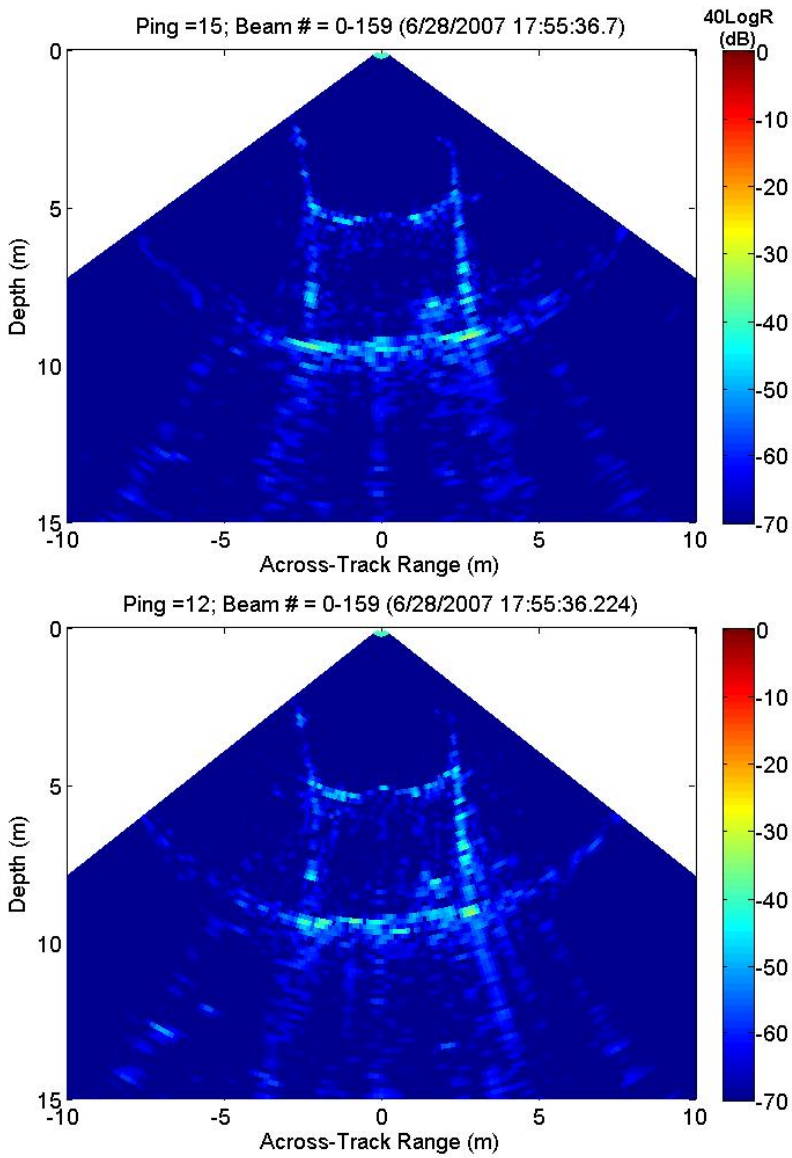

Figure 23. Water column image of two single pings from the EM3002 illustrating the echo strength (TVG=40LogR) of the acoustic backscatter from the cage stocked with 23 Atlantic cod (*Gadus morhua*) in more scattered distribution of individuals on 28 June 2007.

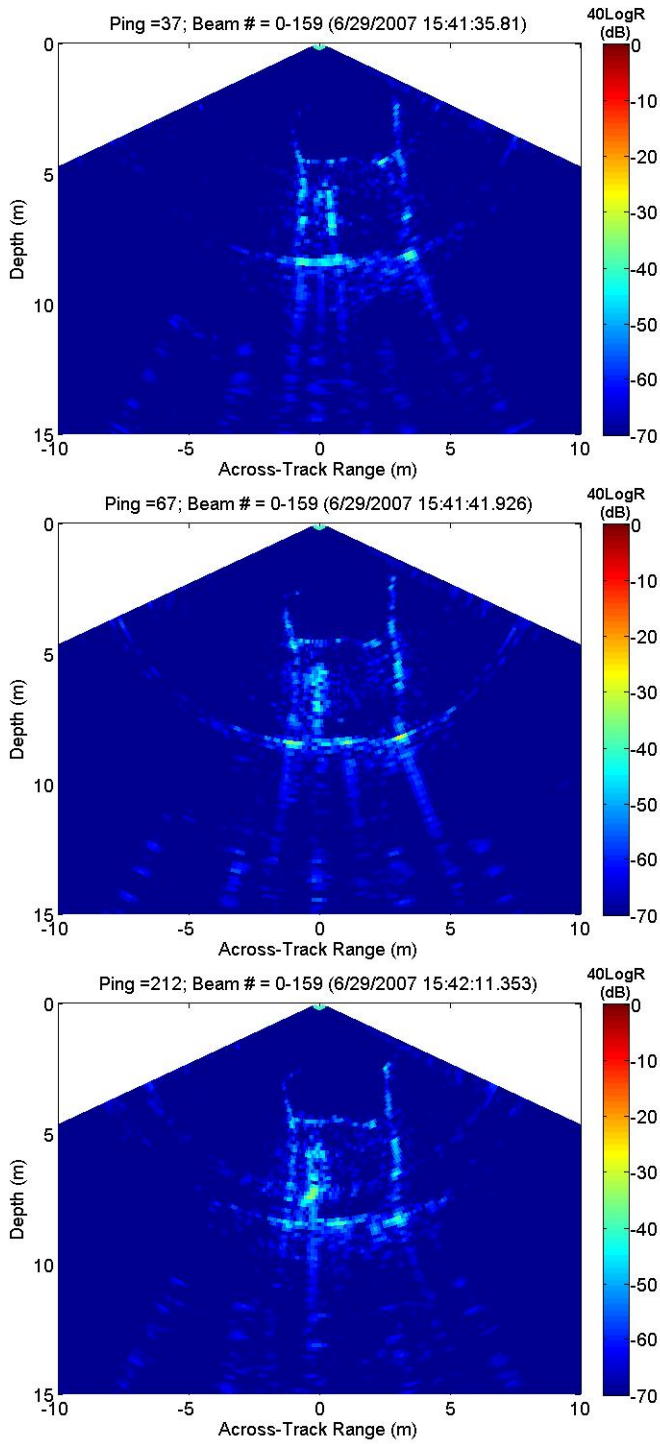

Figure 24. Water column image of single pings from the EM3002 illustrating the echo strength (TVG=40LogR) of the acoustic backscatter from the cage stocked with 23 Atlantic cod (*Gadus morhua*) at a higher ping rate of 5 pings per second on 28 June 2007.

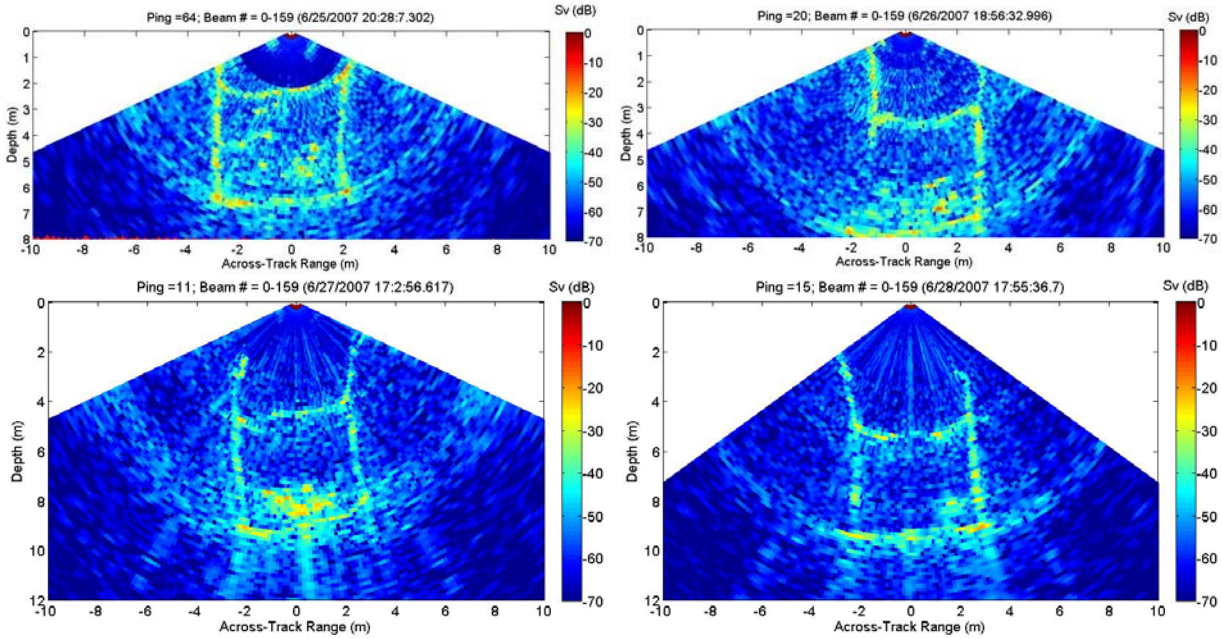

Figure 25. Water column image of single pings from the EM3002 illustrating the volume backscattering strength (S_v) in decibels of the cage stocked with 195, 116, 66, and 23 Atlantic cod (*Gadus morhua*) on separate days on 25-28 June 2007.

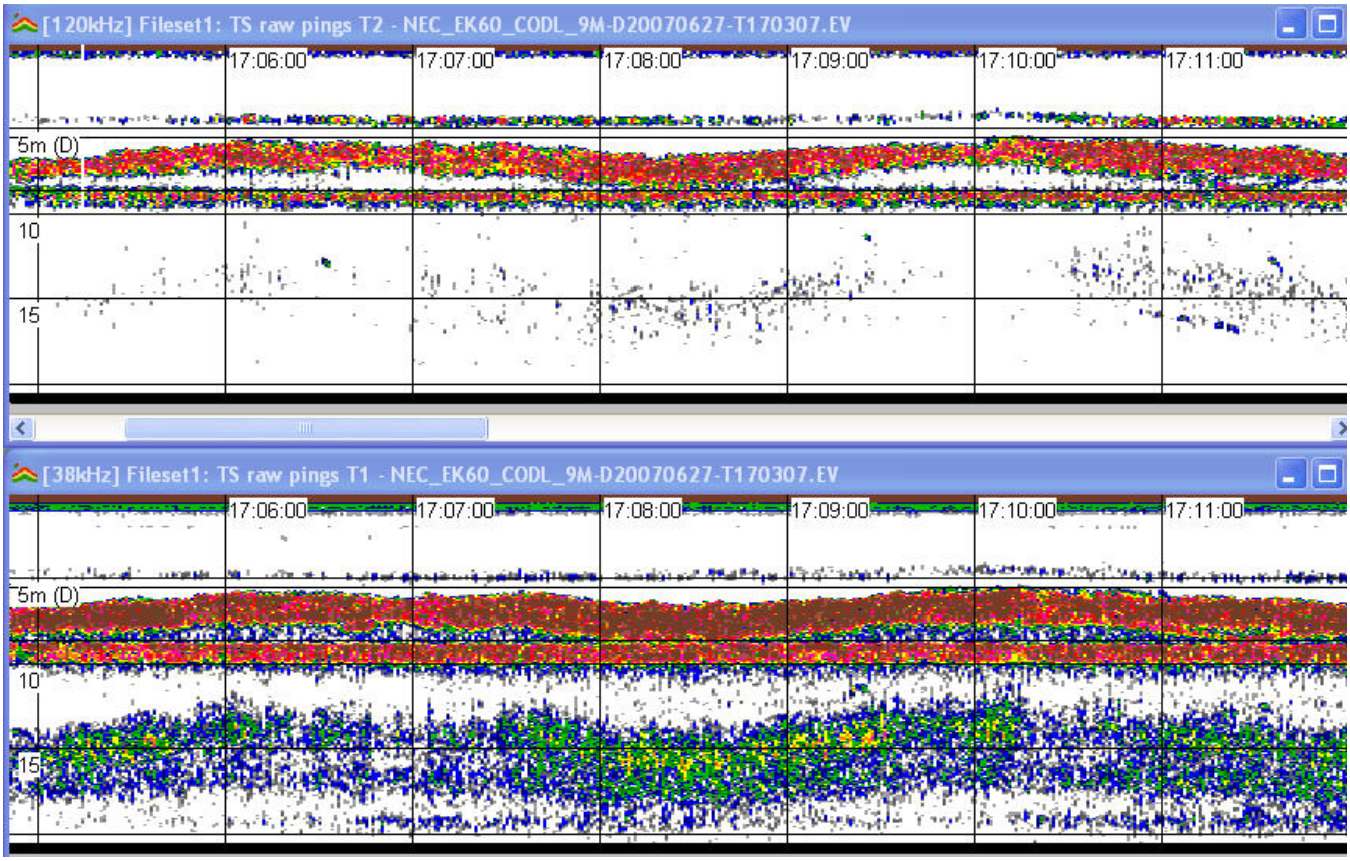

Figure 26. Time-series echogram from a dual 38- and 120-kHz frequency EK60 echosounder of a captive school of 66 Atlantic cod (*Gadus morhua*) in a cage (cage top is 5 m from transducer, cage bottom is 9.5 m from transducer) on 27 June 2007.