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Acoustic Resonance Classification of Swimbladder-Bearing Fish at Multiple Scales

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LONG-TERM GOALS

Accurately describe the spatial and temporal distributions of fish and quantify the mid-frequency clutter characteristics of fish.

OBJECTIVES

To conduct a new class of quantitative acoustic studies of scattering by swimbladder-bearing fish utilizing new broadband-acoustic technology that is optimized for use in the resonance scattering region of fish. The studies, which include use of a long-range horizontal-looking system and a short-range downward-looking system, exploit the resonance scattering of the fish to significantly reduce ambiguities in the interpretation of the data.

APPROACH

Building on the success of three previous major experiments, which includes the NRL pilot measurements in 2008, we are now making a fully-integrated set of measurements through two two-

ship experiments (Sept. 2010 and Sept 2011) involving a NOAA fisheries vessel and a UNOLS vessel. We are exploiting the broadband capabilities of each of the mid-frequency acoustic systems (WHOI-Edgetech and NRL systems), along with their complementary deployment geometries (short-range downward-looking vs. long-range horizontal-looking, respectively) for both resonance classification of swimbladder-bearing fish and characterization of their patchiness at different spatial and temporal scales. Province-wide variability of the fish distribution, resonance signature, and clutter features are studied with the long-range system while the strong depth dependence of the resonance, multiple resonances associated with mixed assemblages, and short-range patch structure (in the vertical plane) are studied with the short-range system. Complementing these mid-frequency measurements are the use of nets to sample the fish and traditional high frequency acoustics for intercomparison with standard techniques.

The end result of the measurements would be first-of-a-kind maps of distributions of swimbladder-bearing fish in two planes (vertical and horizontal) as derived from two broadband mid-frequency sonars at multiple scales. *What makes these results unique and powerful is that, not only are the data to be collected at high spatial resolution in these two orthogonal planes, but the data are also broadband and contain resonance information eliminating significant ambiguities in interpretation.* In addition, key parameters (relevant to Navy signal processors) of the echo statistics of the long-range sonar due to the patchiness would be determined, allowing the development of physics-based bioclutter models and clutter-reduction methods.

Tim Stanton (WHOI) oversees the entire program and is involved in every aspect, with an emphasis on the WHOI short-range downward-looking system. Cindy Sellers (WHOI) participates in preparation and participation in the cruises, data processing and analysis. Mike Jech (NOAA/NMFS) conducts the biological sampling, performs high frequency acoustic surveys, and is involved in the design and execution of the cruises. Roger Gauss (NRL) leads the NRL team (including Richard Menis, Ed Kunz, and Joe Fialkowski) involving use of their prototype mid-frequency broadband system for long-range detection and classification of fish.

WORK COMPLETED

This year focused on processing data and conducting an initial analysis from the September 2010 cruise, and preparing for and conducting the September 2011 cruise. In addition, a paper submitted in the previous year based on the September 2008 cruise was revised based on reviewer recommendations and resubmitted to the refereed journal.

Continued analysis of data from previous cruises

1. Research manuscript

The paper describing the resonance classification of mixed assemblages of fish from the 2008 cruise was revised this year after review by the refereed journal and resubmitted (Stanton et al., submitted).

2. Data processing, analysis, and synthesis: 2010 cruise
The net samples and acoustic data from all acoustic systems from the 2010 cruise were processed and calibrated for analysis. The data were then integrated for one particular area of interest (Figs. 1, 2). This is an area in which there were long shoals of fish near the bottom at the northern edge of Georges Bank. The nets indicate that these shoals consisted primarily of Atlantic herring in the 20-25 cm length range. The depth-dependence of the resonances, as measured with the WHOI downward-looking system and illustrated in the upper left panel of Fig. 1, is consistent with herring. The resonances measured from the long-range sonar are consistent with herring at the deeper depths (upper right panel of Fig. 1).

The data from a smaller study over Franklin Swell and conducted solely by the NRL horizontal-looking system were also processed. These data showed the fish to be grouped in dense compact aggregations (left polar plot in Fig. 1) as compared with the long dispersed shoals over Georges Bank (right polar plot in Fig. 1). The echo statistics from the patches of fish over Franklin Swell were strongly non-Rayleigh (elevated "tail" of the echo amplitude histogram) due to the patchiness.

3. Echo statistics of mixed assemblages (from 2008 and 2010 cruises)
This year, a new analytical formulation was developed to describe echo statistics from mixed assemblages of scatterers and applied to data from previous cruises (2008 and 2010). This formulation is an extension of a formula developed in another ONR project (ONR Undersea Signal Processing N00014-09-1-0428; Keith Davidson) in which the echo statistics was described for an arbitrary number of scatterers or patches of scatterers randomly distributed in the sonar beam. In this current project, we extended it to describe the case in which the scatterers were from two different size classes, such as in the mixed assemblages observed in our ocean data. The results show that the shape of the statistical distribution of the echoes and, particularly the tail of the distribution, depends upon the relative sizes of the scatterers and relative numerical densities.

The newly developed model has been demonstrated to fit the shape of the echo histograms from previous cruises (Fig. 3). In some cases where there is noise, a mixed distribution is required in which noise (Rayleigh distribution) is incorporated. Through the process of fitting the theoretical curve to the data, the relative sizes of the two size groups of fish, as well as their relative numerical density, are inferred.

Preparation for 2011 cruise

Modifications to NRL equipment and testing of both WHOI and NRL systems. Calibration of NRL source was conducted at Seneca Lake after the September-2010 cruise. The receive line array of NRL that had been constructed for the previous cruise underwent a major upgrade with new hydrophones and cabling, resulting in significantly improved noise levels and dynamic range. The WHOI system was tested off and on at the test well in the WHOI pier throughout the spring and summer as a means of checking that the system would be ready for the 2011 cruise and to refine methods.

Additionally, hull-mounted on the WHOI/NRL ship was a 4-frequency narrowband, split-beam WHOI echosounder that provided complementary echogram coverage throughout the 2011 cruise.

Conducting 2011 cruise

Overview. The 2011 ocean experiment, which involved two ships through a collaboration between WHOI, NRL, and NMFS/NOAA, was conducted during the period September 8-16, 2011. The experiment was a success. We completed our objective of measuring the spatial distribution of various fish species using several advanced methods that involve different scales, and with the emphasis on the NRL broadband long-range sonar. A series of coordinated measurements were conducted, mostly near Franklin Swell, which had been the subject of a preliminary study at the end of the 2010 cruise. A small study was also conducted over Jeffreys Basin and Ledge. The coordinated measurements were as follows- WHOI-NMFS intercomparison of measurements, WHOI-NRL intercomparison of measurements, NRL-NMFS intercomparison of measurements, and WHOI-NRL-NMFS intercomparison of measurements. In each intercomparison, the spatial distribution of fish was studied through the different sensing tools each institution brought. In the end, the spatial distribution was characterized over a range of scales, from fine scale with the downward-looking echo sounders through large scale with the long-range sonar. Through a combination of resonance classification of the fish, short- and long-range sonar, and net samples, the spatial variability of different size classes and species of fish was studied. These studies are unique and are fertile material for studying the fish behavior. We look forward to processing these data in order to extract new understanding of fish behavior.

Some details. 1) All scientific equipment worked. In spite of the vast complexity of the NRL broadband, multi-beam, long-range sonar, the NRL team had the system configured for use immediately at sea. 2) All of the equipment was recovered safely, undamaged. 3) The fish cooperated. They were in abundant numbers throughout the two regions. The spatial and temporal distributions of the fish were observed to be characteristically variable. 4) The weather cooperated. The first 8 days involved excellent sea conditions for our work at the two sites (because of a local storm affecting the Franklin Swell area, we initially worked at Jeffreys Basin/Ledge which had excellent sea conditions). Because of a storm at the end of the cruise period, we returned one day early, losing one science day. 5) In addition to the scientific measurements and engineering tests, WHOI conducted a full calibration of the Edgetech system at sea in deep water as a function of depth of towbody. 6) Because of a failure of the ship's engine, we lost one science day at the beginning of the cruise, thus giving a total of two science days lost due to weather and ship failure. However, because of the fact that the science equipment worked, the weather was good, and the fish were found immediately at each site, the science objectives were completed.

Preliminary results. NMFS characterization of the fish. During the joint WHOI/NRL/NOAA cruise, the NOAA FRV Delaware II collected multi-frequency (18, 38, and 120 kHz) acoustic data using a hull-mounted Simrad EK60 scientific echo sounder, CTD profiles, Dual-frequency Identification Sonar (DIDSON) and stereo video data from a towed vehicle, and mid-water trawl hauls. The Delaware II collected over 1100 nautical miles of echo sounder data, 65 CTD profiles, 6 towed-vehicle deployments, and 32 mid-water trawl hauls. Trawls were conducted on an *ad hoc* basis, when aggregations of fish were observed in the echo-sounder data. Atlantic herring (Clupea harengus), Acadian redfish (*Sebastes fasciatus*), and silver hake (*Merluccius bilinearis*) comprised the majority of the trawl catches. Other finfish and squid species were caught in low numbers, and euphausiid, shrimp, and myctophid species were patchily found in trawl hauls as well as observed in the acoustic data.

Atlantic herring, Acadian redfish, and larger silver hake (>15 cm) were caught at depths greater than 150 m. Smaller silver hake (<10 cm) were caught shallower than 100 m, and often numerically dominated the catch. The herring had unimodal length distributions that were fairly narrow (19-22 cm) and a mode centered at about 20 cm fork length. The redfish length distributions were also unimodal but the distribution was much wider (17-40 cm) and centered about 24-28 cm. Between herring and redfish, herring tended to dominate the catches (Fig. 4).

Spatial characteristics of fish. All downward-looking echosounders observed a variety of distributions of demersal fish, ranging from miles-long diffuse shoals near the seafloor to sparsely distributed small dense patches of fish. The WHOI downward-looking system was towed deep just above the shoals and obtained high quality broadband data in the 1-6 kHz band from thousands of individual fish in the Franklin Swell area (Fig. 5). Both the broadband and narrowband downward-looking echosounders observed small (~100-m-long) dense patches of fish on the seafloor in the Franklin Swell area (Fig. 6). The patches were so dense, that second-order scattering appears to be present in the patches in which streaks in the echo appear below the patches (see bottom panel of Fig. 6). The NRL long-range sonar system revealed dense patches of fish that were relatively sparsely distributed in the Franklin Swell area (Fig. 7). These patches were detected after applying a split-window normalizer to the data that removed background diffuse reverberation.

Resonance classification of fish. The NRL system also revealed that the spectral content of the echoes from the patches was generally non-uniform and had a resonance peak occurring at approximately 2.8 kHz (Fig. 7). This peak corresponded to 20 cm Atlantic Herring at the deeper part of the water column. Analysis of one of the seafloor patches in Fig. 6 from the WHOI downward-looking system showed the spectral content to be relatively uniform, suggesting a much larger fish with a resonance well below the frequency band.

Non-Rayleigh nature of echo statistics from NRL mid-frequency system. The echo amplitude probability density functions (PDFs) of the echoes were generally strongly non-Rayleigh when the beam swept across the sparse compact patches over Franklin Swell.

RESULTS

This cruise concludes the two-cruise series (2010 and 2011). Between the two cruises, three distinct regions have been studied—Georges Bank, Franklin Swell, and Jeffreys Basin/Ledge—in which there are correspondingly three distinct forms of fish behavior present. Georges Bank was characterized principally by miles-long diffuse shoals of fish, Franklin Swell was characterized principally by dense compact patches of fish interspersed with dispersed fish, and Jeffreys Basin/Ledge was characterized principally by diffuse distributions of demersal fish.

1. *Inferring properties of mixed assemblages of fish through echo statistics (short-range, downward-looking broadband system) (2008 and 2010 cruise data).* Through development and application of a new echo statistics formulation to our cruise data, properties of mixed assemblages of fish can be inferred. Specifically, the relative size of fish and relative numerical density of the fish can be inferred.

2. *Spatial and temporal variability of fish aggregations (long-range, horizontal-looking broadband system) (2010 and 2011 cruises).* Much high quality data were collected that will be used to quantify the spatial and temporal characteristics. The data from both cruises show that the spatial characteristics of the fish are specific to geographical region. (At least for this time of year---since all these cruises are September cruises.) Also, the echo statistics from the long-range sonar were region-specific demonstrating the variability of clutter characteristics of the fish with respect to region. These long-range data provided rapid regional fish-distribution assessments. Through spectral analysis, the presence of different size classes was observed.

IMPACT/APPLICATIONS

This substantial set of broadband long-range data is a first of a kind and is revealing important information on the behavior of fish. Through the instantaneous long-range ensonification, the patches of fish were rapidly globally observed for the different regions. Through spectral analysis, the presence of different size classes was observed. This approach sets a new high standard by which acoustic measurements should be made: using broadband sound in two planes (vertical and horizontal). In addition to the scientific benefit, valuable information quantifying the clutter characteristics of the fish was obtained that can be used for sonar performance predictions in ASW applications.

TRANSITION

In September, 2011, the results of our work on our pilot cruise that preceded this project were transitioned to the ACB13 SAST (PEO IWS 5A) via a sequence of the ONR Undersea Signal Processing D&I program (Keith Davidson) and the HiFAST FNC program (Mike Vaccaro) and in collaboration with Dr. Brian La Cour of ARL:UT and LCDR Ben Jones of NPS.

1. The statistical properties of mid-frequency echoes from fish were measured in our pilot cruise in 2005. In that cruise, the patchiness of the fish was observed at high resolution through towing our system (funded by ONR DURIP) deep and just over the patches of fish. The data spanned several important geometries—sonar beam within a patch, sonar beam sweeping across one patch edge, and sonar beam sweeping across multiple patches.

2. The data described in #1 above served as the basis for developed analytical descriptions of the sonar echo statistics in the ONR Undersea Signal Processing program. Models were developed for each scattering geometry. Furthermore, a general echo statistics model was developed, inspired by this first analysis.

3. In the HiFAST program, we modeled the clutter due to patches of fish. Part of the analysis involved use of the scattering models that we applied in analyzing the data in this current (ONR Biology) program, hence the models were grounded in scientific data (which included net samples provided by NMFS). Furthermore, in order to reduce computation time, many simplifying assumptions were made in the modeling. The fidelity of the simplified models was tested, in part, through use of the new statistics models that we developed in #2 above.

RELATED PROJECTS

1. Stanton has been funded through the Undersea Signal Processing Division of ONR to study the statistics of the fish echoes (sequence of D&I grants N00014-07-1-0232 and N00014-09-0428). The data from this (Biology) program have been used as a basis for studying echo statistics of mid-frequency echoes due to the presence as fish (Stanton and Chu, 2010) as well as to inspire development of new advanced theoretical formulations for echo statistics.

2. Under the HiFAST FNC program of ONR (grant N00014-11-1-0241; Mike Vaccaro), Stanton has collaborated with Drs. Brian LaCour of ARL:UT and LCDR Ben Jones of NPS to *transition* the new knowledge that originated in this project to the ACB13 SAST (see above in "Transition"). Other Navy systems are targeted for future transitions.

3. Commencing in FY10, Gauss has participated on a PEO C4I & Space (PMW 120; Marcus Speckhahn) panel to help develop a phenomenological approach that can nowcast/forecast spatial distributions of biologics for mid-frequency ASW applications based on oceanographic, biologic, and acoustic data and models. Gauss is also on the ONR 322 (Robert Headrick) Applied Reverberation Modeling Board (ARM-B) whose charter it is to understand the limitations/major challenges presented by today's and tomorrow's active sonars relative to reverberation and clutter predictive capabilities, and recommend solutions (the way ahead). Its initial focus is on mid-frequency active monostatic sonars. Both of these high-profile positions allow Gauss to identify and act on technology insertion points. Additionally, Gauss has in transition to CNMOC's Oceanographic and Atmospheric Master Library (OAML) the first Navy-standard Fish Scattering Strength (FSS) algorithm. The planned Stanton enhancements to his scattering formulations could serve as a basis of FSS upgrades. Gauss has been developing moment-based clutter-rejection techniques for improving automated active Navy classifiers that will be under evaluation for transition to the ACB AN/SQQ-89 A(V) 15 system in FY12-14 under the ONR Active Sonar Automation Enabling Capability Project (Keith Davidson). Gauss is also working with NUWC (Wendy Petersen—2010 cruise participant) regarding providing bioclutter data as a potential upgrade to the Characterization and Reduction of Active False Tracks (CRAFT) database.

PUBLICATION

Stanton, T.K., C. Sellers, and J.M. Jech, "Resonance classification of mixed assemblages of fish with swimbladders using a broadband echosounder at 1-6 kHz. Revised based on reviewer recommendations and re-submitted to *Can. J. Fish Aq. Sci.*

2010 Experiment: Results overview

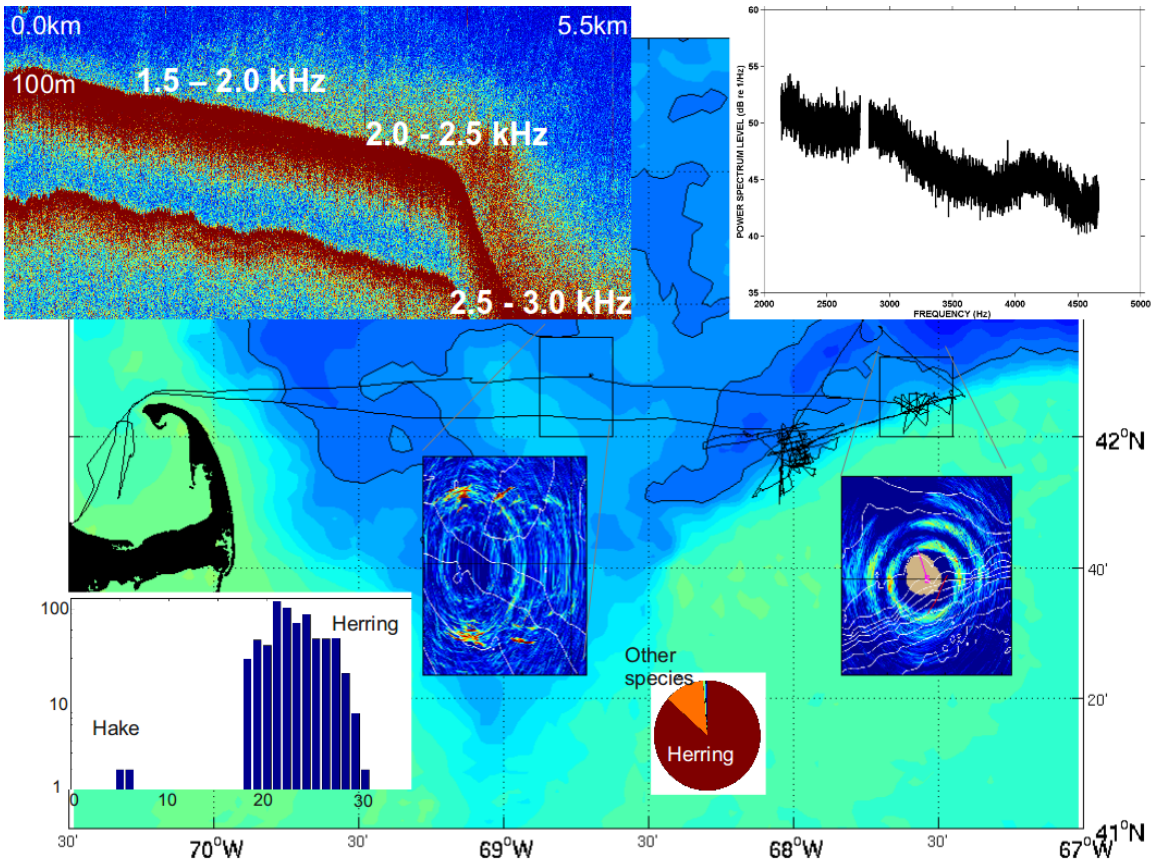

Figure 1. Synthesis of data collected in two regions, Franklin Swell (left black box) and Georges Bank (right black box). Polar plots of data from NRL long-range sonar in those areas are given directly below the corresponding boxes. Upper left panel: 1-6 kHz echogram from WHOI downward-looking system, with range of resonances given in white numbers. Upper right panel: Spectrum of data from NRL system from Georges Bank. Lower left panel and pie chart: net samples from Georges Bank.

Georges Bank 2010: shoals of fish at bank edge (1-6 kHz)

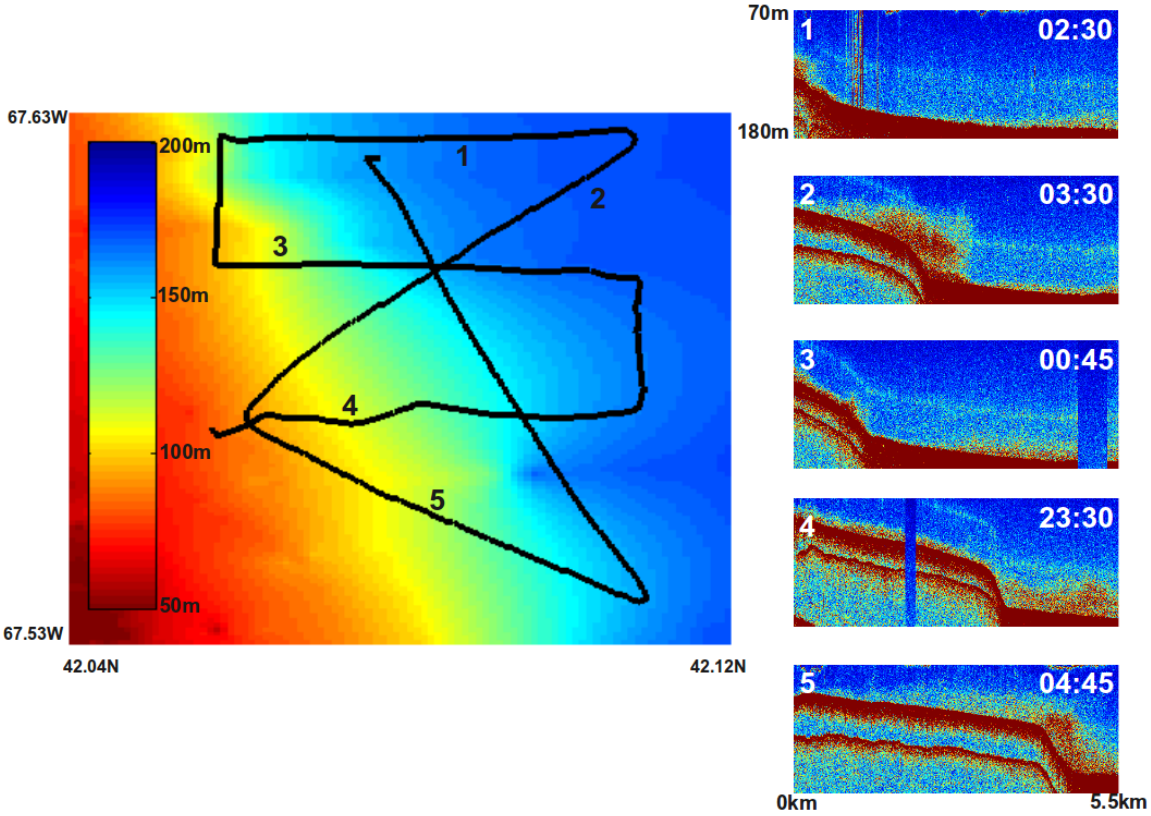

Figure 2. Left: transects of WHOI downward-looking system studying one area of Georges Bank. Right: echograms from WHOI system for each of the track lines, illustrating the spatial variability—along-bank and cross-bank—of the herring. A resonance analysis of one of the track lines is given in the upper left panel of Fig. 1.

Georges Bank 2008: 30-70 kHz channel

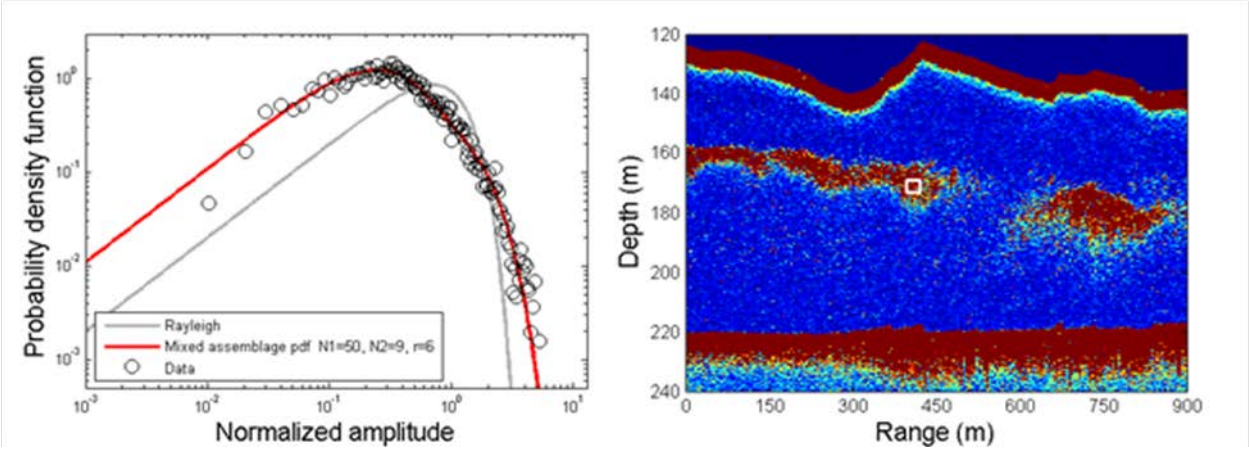

Figure 3. Statistics of echoes from mixed assemblages of fish. Left: our newly developed analytical model for echo probability density function (PDF) is compared with data. Right: echogram of fish patch. The white box is the sample window analyzed.

Franklin Swell 2011: trawl samples

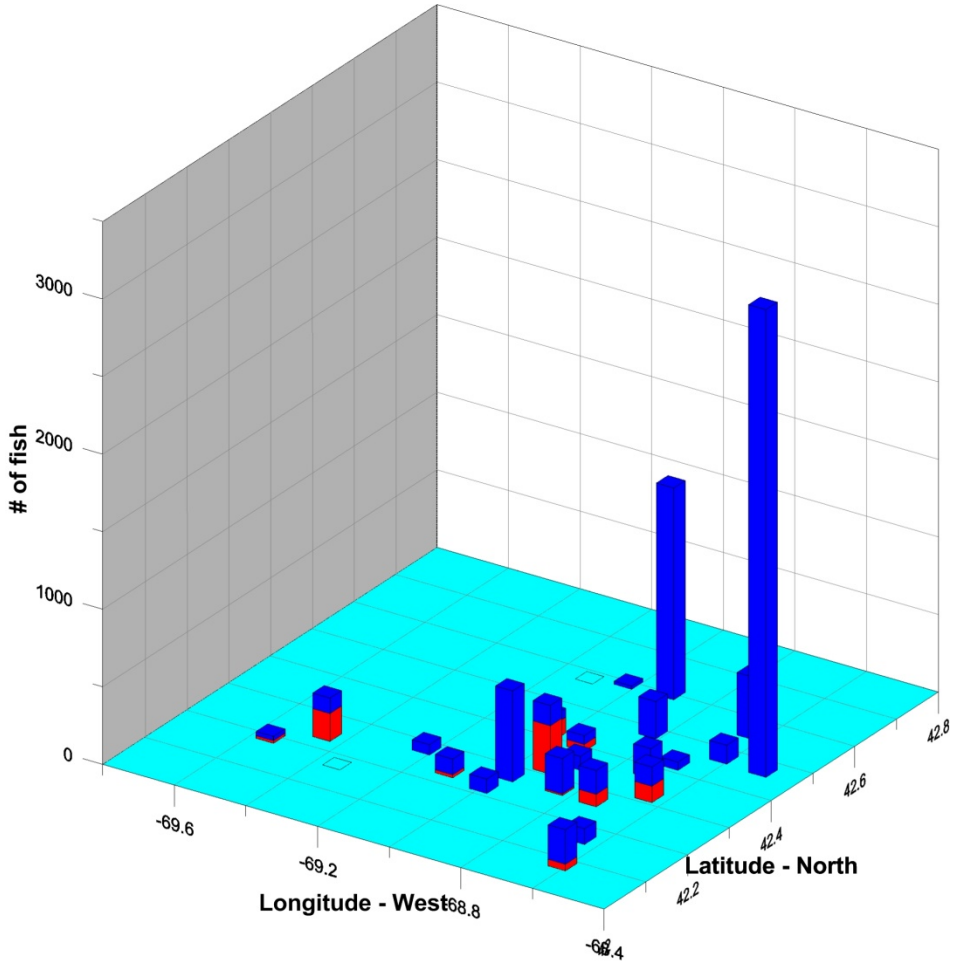

Figure 4. Each column represents one mid-water trawl location in the Franklin Swell area. Blue: Atlantic herring (Clupea harengus). Red: Acadian redfish (Sebastes fasciatus).

Franklin Swell 2011: Individual fish at 1-6 kHz

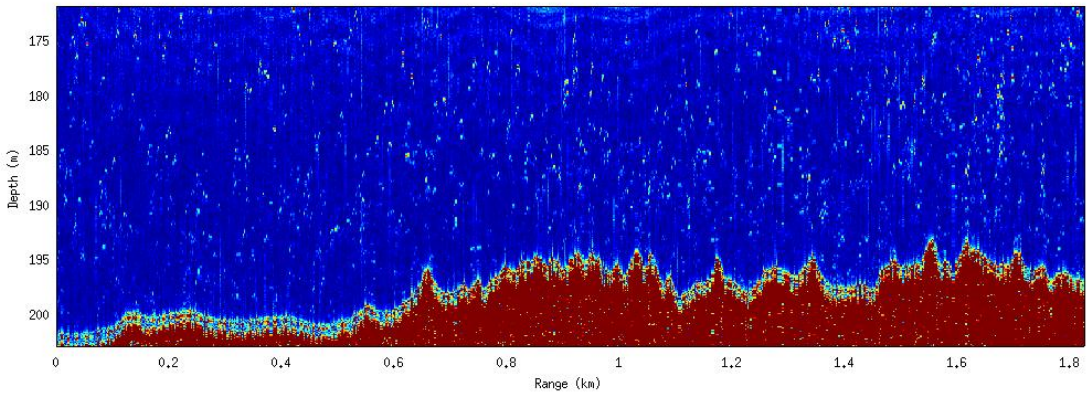

Figure 5. Echoes from individual fish in a miles-long shoal as measured with the WHOI downward-looking system. The system was towed deep and just above the shoal so as to resolve the individuals and increase the signal-to-noise ratio.

Franklin Swell 2011: Dense fish aggregations on seafloor

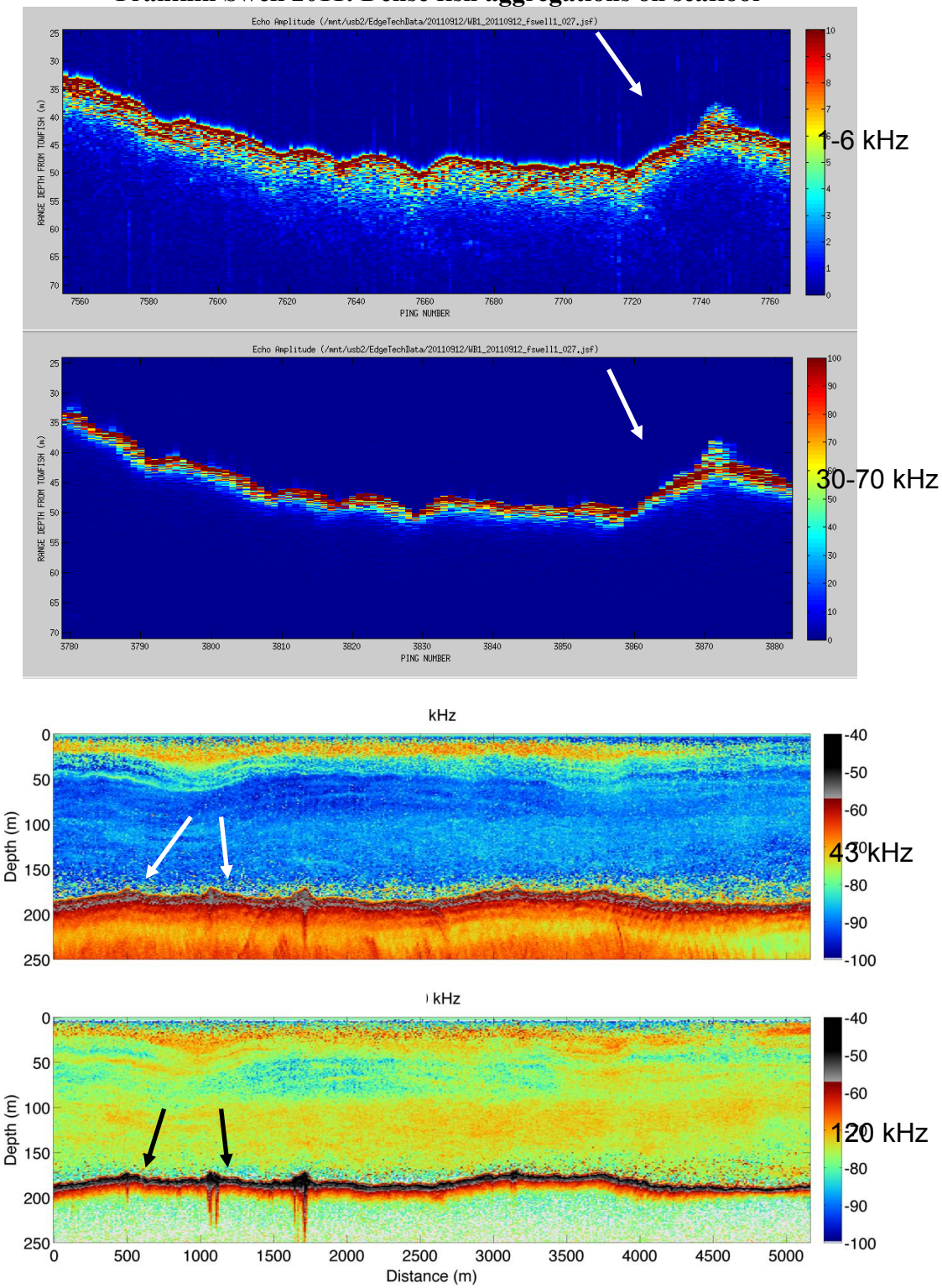

Figure 6. Observations of 100-m-long dense patches of fish on the seafloor. The streaks below the 120 kHz data (bottom panel) suggest second-order scattering.

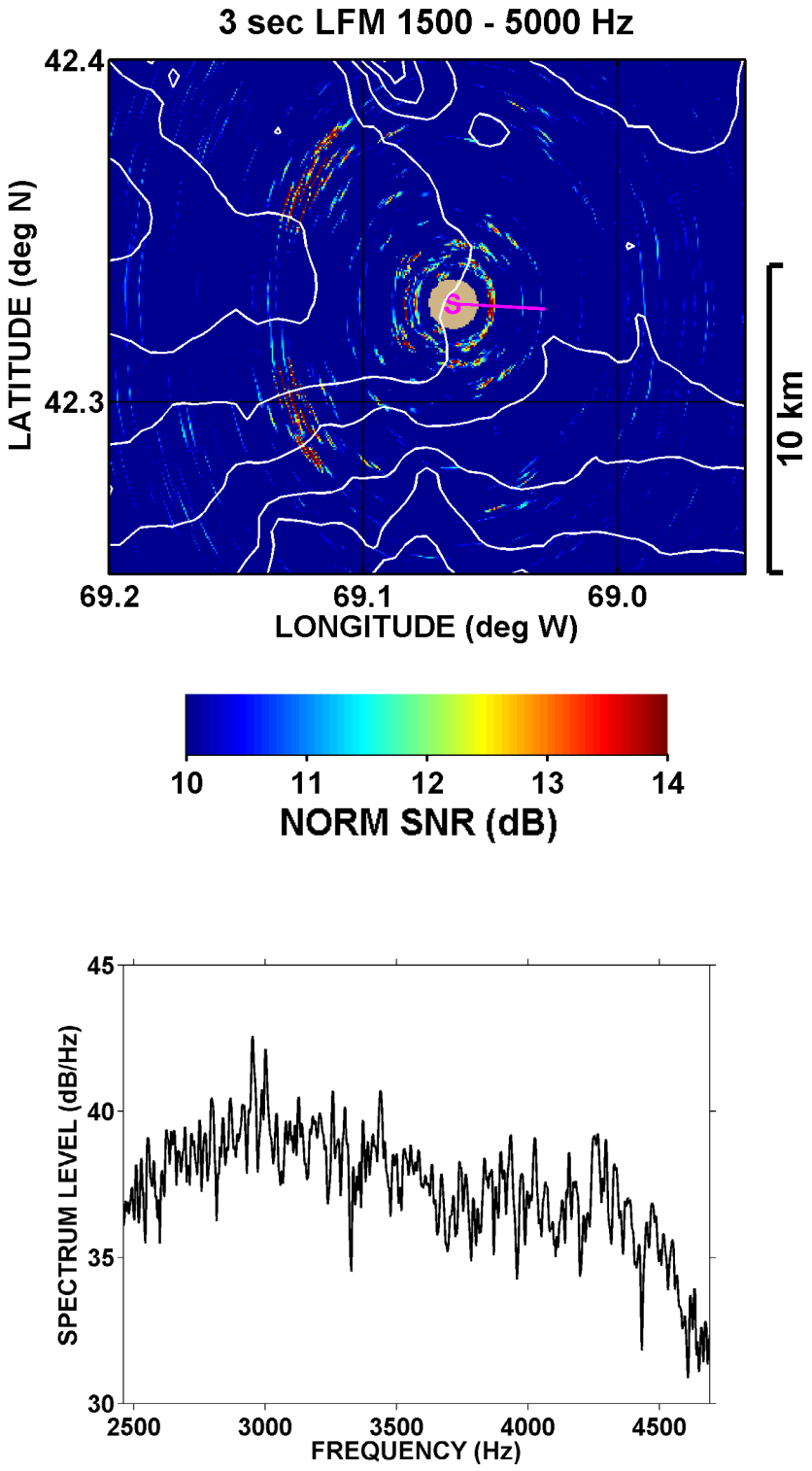

Figure 7. Data from NRL long-range sonar.