Improving Fisheries Science with Advanced Sampling Technologies

Feature Article 2

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INTRODUCTION

The ability of the National Marine Fisheries Service (NMFS) to meet mandates to conserve and manage the Nation's living marine resources and promote a healthy marine environment is enhanced through implementation of advanced sampling technologies for providing accurate, precise, and timely population estimates of economically and ecologically important marine species. Conventional methods for monitoring and assessing marine populations and their habitat have relied primarily on surveys involving net sampling for physical capture of marine animals. Although net sampling operations are relatively inexpensive and necessary for species identification, even the largest nets sample only a very minute proportion of the ocean, necessitating a large number of hauls to adequately sample an area. Recent efforts have incorporated advanced sampling technologies that utilize remote sensing approaches such as acoustical and optical technologies. Net and trap sampling will continue to be a critical need for biological data requirements, particularly for age-based fisheries assessments. However, NMFS' evolving goals and mandates require development of survey operations that combine advanced sampling technologies with conventional methods to achieve multidisciplinary objectives in cost-effective ways. The integration of advanced sampling technologies with conventional sampling operations provides an optimal sampling strategy for investigating spatial and temporal variability of populations, ecosystem dynamics, and pelagic (open water), benthic (seafloor), and demersal (near seafloor) habitats.

Recognizing the need for a cohesive effort to improve the quality of assessments using advanced sampling technologies, NMFS established the Advanced Sampling Technology Working Group (ASTWG) to demonstrate leadership in the implementation of existing and new technologies. The ASTWG mission is:

> "To improve the accuracy and precision of living marine resource assessments by identifying information needs through the quantification and prioritization of components of uncertainty in stock assessments; identifying new technologies, innovative uses of existing technologies, and approaches that involve a combination of technologies to address these information needs; and facilitation and conducting research to develop these sampling technologies and their standardization implementation."

Advanced sampling technologies will play an increasing role in improving survey operations for assessing commercially important marine populations, monitoring and managing ecosystems, classifying essential fish habitat (EFH), delineating marine protected areas (MPA's), and exploring the ocean realm. Agency research vessels are presently being upgraded to integrate advanced sampling technologies into ongoing National Oceanic and

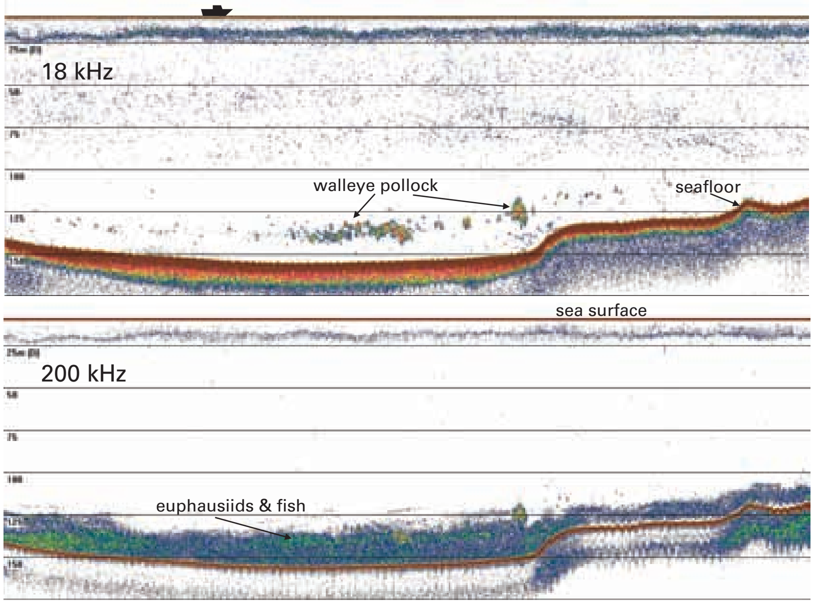


Figure 1
Acoustic echograms at frequencies of 18 kHz (upper panel) and 200 kHz (lower panel) covering about 4 n.mi. in Barnabus Trough, Alaska. Downward-facing transducers mounted on the ship's hull transmit sound pulses and receive echoes from the sea floor, fish, and zooplankton in the water column. These echograms display volume backscatter, which is representative of the number of organisms per cubic meter (i.e. density). Lower backscatter (lower organism density) is shown in blue and higher backscatter (higher organism density) in red. Echogram images are vertically exaggerated to highlight features and patterns. Differences between the two echograms highlight acoustic dependencies in fish and zooplankton scattering and potential uses for classification.

Atmospheric Administration (NOAA) surveys to achieve multidisciplinary objectives and minimize duplication of sampling efforts. For example, acoustic data can be collected concurrently with routine fisheries trawl surveys to estimate population abundances, continuously record fish and zooplankton distributions throughout the water column, map seafloor bathymetry, and characterize pelagic and benthic habitats. In this article, we describe examples of advanced technologies implemented within NMFS that provide effective approaches for achieving our strategic goals and crosscutting opportunities for intra-agency, interagency, industry, and academic partnerships.

ADVANCED SAMPLING TECHNOLOGIES

Most advanced sampling technologies operate by transmitting energy (acoustical or optical) into the water and then receiving energy scattered or reflected from objects in the water. The returning energy carries information about the objects, and the goal is to decipher this information to obtain measurements that are meaningful for biologists, ecologists, and fisheries managers. These technologies operate remotely, i.e. the instrumentation need not be located in close proximity to the species or habitat of interest. The remoteness of the instrumentation is dependent on the type of energy, where the operating frequency determines the sampling range and resolution. For example, optical and high-frequency acoustical instrumentation provide high spatial resolution, often less than 1 cm, but have limited sampling ranges of a few meters. Acoustical instrumentation operating at low frequencies can sample over scales of hundreds to thousands of meters, but provides lower-resolution data, from tens of centimeters to meters. Therefore, the selection of technologies will depend on the types of organisms or habitat to be surveyed, areal coverage, and the spatial and temporal resolution needed for target detection and classification. Recent initiatives have been devoted to integrating advanced sampling technologies into ongoing survey operations, evaluating new technologies, and developing innovative empirical and theoretical methods for quantitative data interpretation. The suite of available technologies provides a wide variety of options for surveying our living marine resources and their environment.

Acoustical technologies, such as single-beam echo sounders, SONAR (sound navigation and ranging), and multibeam systems, are efficient tools for sampling the water column and seafloor. Sound travels about 1,500 m per second (almost 5,000 feet per second) in water, and when a sound wave encounters an object, such as a fish or the bottom, an echo is generated (Figure 1). The first application of underwater acoustics was for navigation and obstacle (e.g. iceberg) avoidance. While using these SONAR and depth sounder systems, it quickly became apparent that aggregations of fish were readily detected. From the 1920's to the 1970's, echo sounders and SONAR were utilized extensively to locate fish and for qualitative investigations of fish behavior and distribution. Since the 1970's, advances in computer and electronic technologies have led to improvements in instrument performance and the development of quantitative methods that produce reliable, timely, and cost-effective population estimates. Fisheries acoustic methods are well established for quantitative population estimates, but further improvements can be made with species and habitat classification. There are other established acoustical technologies that have been routinely implemented during NOAA survey operations, such as acoustic doppler current profilers (ADCP) used for deriving current velocity profiles, or net mensuration sensors (Figure 2).

Optical technologies, such as underwater photography and video, laser-line scans, LIDAR (light detection and ranging), optical plankton counters (OPC), and video plankton recorders (VPR) are advantageous because they provide very high-resolution, in some cases photographic-quality, images. Optical methods can be used to survey fish and zooplankton in areas that cannot be surveyed using traditional net surveys, such as coral beds or rock reef habitats. Optical methods are also used to visually identify organisms, observe animal behavior in undisturbed environments and in the presence of fishing gear to understand variability in abundance estimates, and for habitat classification. Optical technologies are limited to sampling small areas—from a few meters to a few tens of meters—and in the case of photography and video, limited to the availability of natural or artificial light. As with acoustic technologies, there is a need for automated methods that can process and analyze large amounts of data.

Effective use of advanced sampling technologies in fisheries requires a multidisciplinary effort. System development and signal processing require engineering; data interpretation requires physics and biology; and applications to management require fisheries, biological, and ecological expertise. In addition, advanced sampling technologies currently require parallel biological sampling for verification of taxonomy and identification and for measures of length, weight, age, gender, and diet.

ADVANCED SAMPLING TECHNOLOGIES IN FISHERIES

Acoustics

Scientific echo sounders are the primary advanced sampling technology used by NMFS for quantitative measures of abundance and biomass and mapping spatial distributions of economically and ecologically important species. Beginning in the 1970's, the Alaska Fisheries Science Center (AFSC) pioneered the use of fisheries acoustics in the United States. Through collaboration with the academic community and industry, the first digital data collection and analysis system was developed and applied to fisheries acoustic assessments of Pacific hake and walleye pollock (Figure 1). This early echo sounder was a fairly complex collection of transmitting, receiving, and signal processing electronics, operating at a single frequency (38 kHz). In the ensuing years, echo sounders and analysis methods have improved, allowing for increased data collection and a better understanding of marine populations.

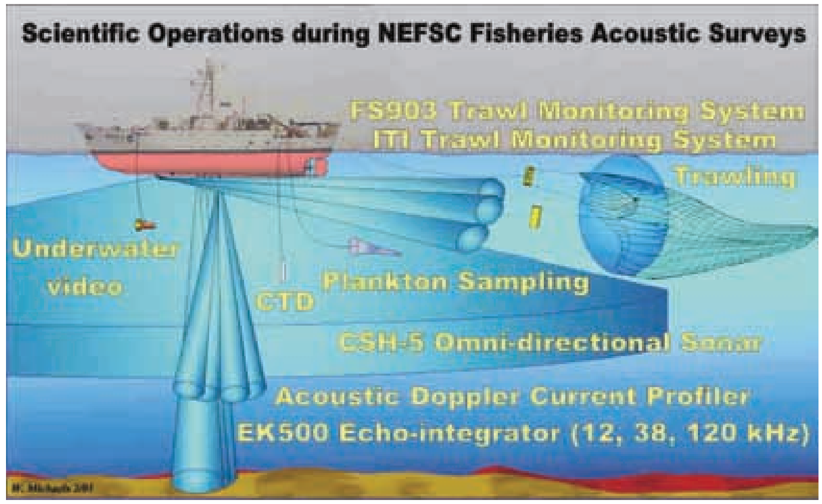


Figure 2
Acoustical systems used during routine acoustic surveys for pelagic fish. (Note: mention of trade names or commercial products does not imply endorsement by the National Marine Fisheries Service, NOAA.)

Fisheries management utilizes long-term time series of population abundance, which requires standardization of sampling methods, and in the case of advanced sampling technologies, calibration of the instruments. Scientific-grade echo sounders are calibrated to an absolute standard during each survey, providing a high level of confidence that the systems are operating properly and ensuring high-quality measurements. Calibration ensures long-term measurement consistency among surveys and ensures that changes in the acoustic population estimates are due to fluctuations in abundance, rather than changes in instrument performance.

Deriving population abundances requires surveying the entire distribution of a selected population at the appropriate spatial and temporal resolution. Since 1998, the Northeast Fisheries Science Center (NEFSC) has conducted an annual acoustic survey of Atlantic herring during the fall, when the offshore stock aggregates on Georges Bank to spawn. Combining historical commercial and scientific data with ongoing survey data has been an effective method for conducting acoustical surveys of the herring spawning stock biomass. Net hauls

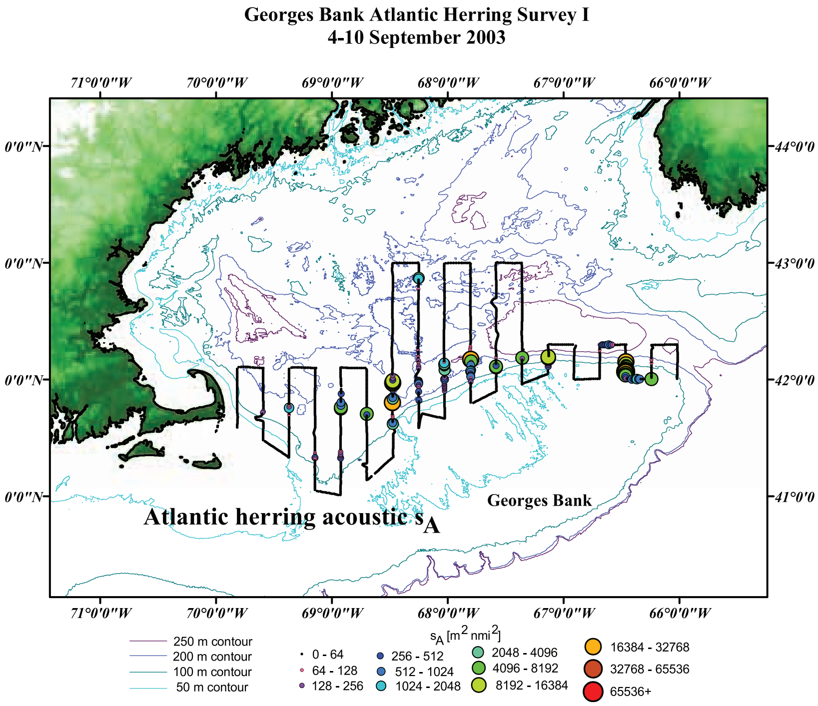
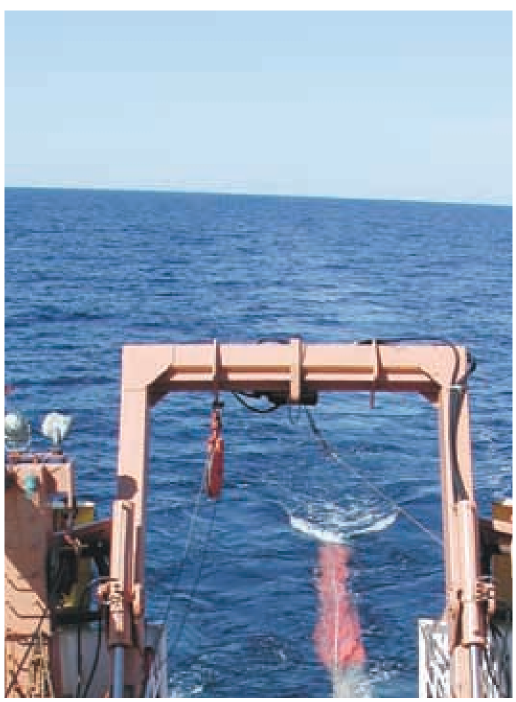


Figure 3

Spatial distribution of Atlantic herring as determined during an acoustic survey in the Georges Bank region in September 2003. Acoustic s_A is a measure of areal relative abundance, with larger numbers representing greater abundances of herring. Acoustic data are displayed in a geographic context using geographic information system (GIS) software.



NOAA Office of Marine and Aviation Operations

Figure 4

Pelagic trawl on board the NOAA ship *Miller Freeman*. Trawls are used to verify species composition of acoustic backscatter and to collect samples for obtaining biological information such as length, weight, age, gender, and diet of the targeted species.

are used in conjunction with acoustic sampling to obtain maturity, gender, age, diet, and length- and weight-frequency distributions. In addition to the biological and acoustical data, GPS (global positioning system), ship-borne sensors (e.g. sea-surface temperature), and electronic event logs are used to display and analyze the data (Figure 3). These data are used in concert to develop estimates of stock abundance in a given year.

Relating acoustic energy to taxonomic levels such as genus or species is a great challenge for fisheries acousticians. Difficulties in classification or identification are due to the anatomical and behavioral complexities of aquatic animals. For fish, echo characteristics depend on body shape (i.e. length and width), presence or absence of a swimbladder (a gas-filled organ inside the fish), shape of the swimbladder, gut fullness, gonad production, lipid content, and behavior. Additionally, the relationships between echo characteristics and these biological and behavioral characteristics are non-linear and often co-dependent. While difficulties assigning taxonomic identification to acoustic energy are not insurmountable, these complexities require collection of additional information. Classification of acoustic energy to taxonomic levels is most often verified from samples collected using nets (e.g. Figure 4), which are also used to collect biological information. Biological verification and sampling have also been improved through the use of underwater video technologies.

Acoustic technologies are effective at sampling pelagic animals, but often provide inadequate sampling at boundaries such as the sea surface or near the seafloor, especially when instrumentation is attached to a vessel's hull. The demersal habitat is especially important for a number of economically important species such as Atlantic cod in the Northeast, various grouper species in the Southeast, rockfish species in the Southwest and Northwest Regions, and walleye pollock in Alaska. Demersal fish are often associated with irregular topographic features such as sand waves and rocks or reefs (Figure 5). Positioning the acoustical transducer closer to the animals or seafloor alleviates many issues with acoustic sampling, but this process requires additional layers of technology such as pressure-tolerant housings and other specialized hardware to address data transfer issues. Nets are convenient to sample living marine resources, but are less effective in areas of irregular topography and provide limited information on behavior.

Optics

Underwater optical methods are used for directly observing and characterizing marine habitats, animal behavior, predator–prey interactions, and for enumerating various species in untrawlable regions (Figure 6). Optical methods include still photography, video, and laser-based systems. Photographic and video methods use cameras that typically have the ability to image under low-light conditions. Most photographic or video systems require some level of artificial light, although newer generation systems are able to produce quality images with very little ambient light. Artificial light has little to no effect for benthic habitat or seabed classification applications; however, the use of artificial light can be problematic when attempting to enumerate fish or quantify fish behavior, as many fish are either repelled by or attracted to light. Optical plankton counters (OPC) using laser technology and video plankton recorders (VPR) utilize laser (OPC) or photographic (VPR) technologies to enumerate and identify species and map zooplankton distributions. Utilizing optical methods for behavioral observations or species identification is an area of intense interest, and significant advances are being made in instrumentation and data interpretation and analysis (e.g. video mosaics, stereo imaging, and automated optic recognition).

ADVANCED SAMPLING TECHNOLOGIES IN FISH HABITAT STUDIES

An animal's habitat encompasses not only where it lives, but also the chemical, physical, and biological environments that surround the animal. Temperature, salinity, currents, and light are components of the physical environment commonly measured by fisheries scientists. The physical environment is important to fish as it directly influences where a fish lives, its metabolism, and its behavior. A common misconception is that habitat is associated with only the benthic environment. For pelagic animals, such as swordfish or tuna, characteristics of the seafloor play much less of a role in survival than do the properties and dynamics of the water column. Thus, it is critical that habitat studies incorporate all aspects of the environment.

The marine environment is a dynamic habitat. Temperature can dramatically change at thermal fronts and create boundaries for fish that prefer

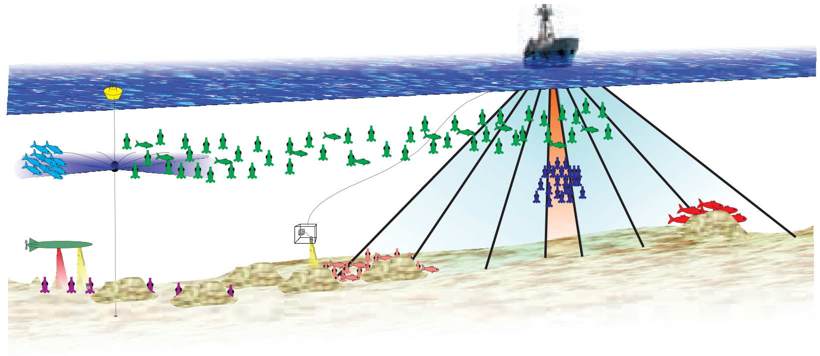


Figure 5
Ship-borne and alternative-platform-deployed acoustical and optical technologies for surveying fish in pelagic and demersal regions. Multibeam sonars (blue fan-shaped beams) significantly increase sampling volume over single-beam echo sounders (orange beam). Stationary transducers sample at one location over time, providing information on short- to long-term behavior, and are often attached to buoys for power and data storage and transmission. Autonomous underwater vehicles, towbodies, and remotely operated vehicles position acoustical and optical instrumentation near the seafloor, improving detection and quantification of fish at boundary surfaces.

NMFS

Figure 6
Image of Atlantic herring and a blue shark feeding on the herring, taken from underwater video in the Gulf of Maine.

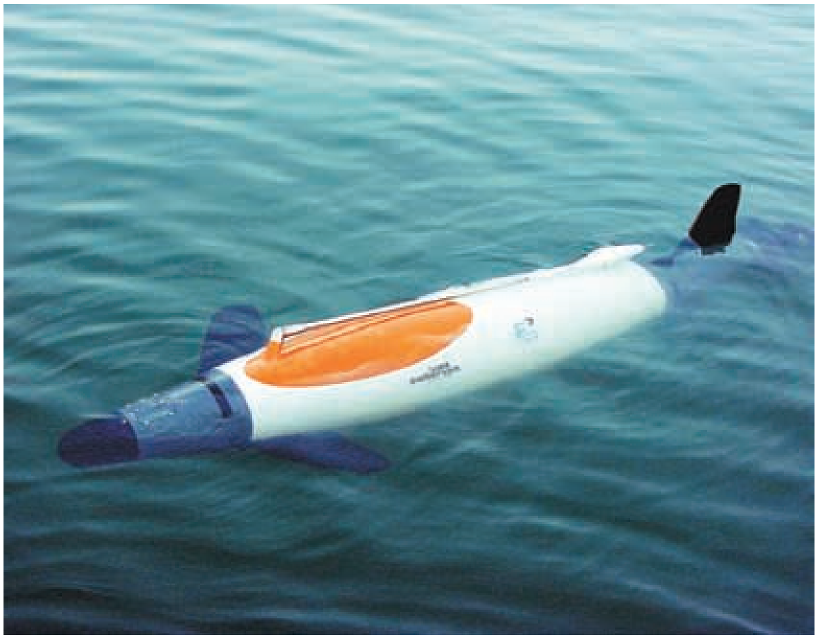


Figure 7
Fetch3X autonomous underwater vehicle (AUV) recently purchased by NMFS. The AUV is outfitted with a Falmouth Scientific CTD sensor that measures conductivity, temperature, and depth, Videre Design FireWire stereo camera system and Ocean Imaging Systems strobe, and a Simrad EK60 scientific echo sounder, for acoustical and optical investigations of pelagic and benthic habitats. (Note: mention of trade names or commercial products does not imply endorsement by the National Marine Fisheries Service, NOAA.)

certain temperatures. These fronts are affected by wind and currents and can shift vertically as well as horizontally. Predators are constantly on the move to find new food, prey fish are constantly searching for food or avoiding predators, and plankton is carried about with the currents. Light levels change from day to night, with phase of the moon, and with the seasons. The seafloor is constantly changing due to currents, biological influences such as burrowing animals, and human-induced manipulations. Because of these forces, organisms are not evenly distributed throughout the oceans; they form patches that change in response to their environment. Detecting these patches and studying how they interact with their environment requires a large field of view and concurrent physical, chemical, and biological measurements at similar resolutions and extents. Traditional sampling provides important information on marine habitats, but often the data are not at the necessary spatial and temporal resolution to improve our understanding of ecosystem dynamics. Advanced sampling technologies provide continuous high-resolution measurements that give us the ability to characterize marine habitats and detect changes in the marine environment.

Multibeam sonars use an array of narrow beams, typically in a fan shape, to significantly increase the field of view of the water column and sea floor, and are useful in multiple applications (Figure 5). Because multibeam systems are the standard tool for charting navigable waters, they are in widespread use along the U.S. coasts. Bathymetric data can be used to study the association of demersal and benthic fish with seafloor topographic features, from sand waves to seamounts. Acoustic backscatter from the seafloor can be used to classify and map the type of bottom (e.g. mud, sand, or rock), which plays an important role in where fish live and spawn. In the pelagic realm, multibeam data provide three-dimensional images of fish schools. These three-dimensional images are used to characterize schooling behavior and may improve the ability to identify acoustic echoes. Multibeam sonar can also be deployed at stationary sites to monitor behavior and predator–prey interactions.

THE FUTURE OF ADVANCED SAMPLING TECHNOLOGIES

Advancements in sampling technologies will continue to come from collaborations among the engineering, physics, and biological disciplines. As engineers develop more accurate, precise, and robust instrumentation, and physicists advance characterization and interpretation of the data, biologists are able to gain an improved understanding of living marine resources and their habitats. There is great potential for improving our ability to effectively monitor, manage, and forecast changes of our living marine resources by integrating advance technologies into existing survey operations, utilizing alternative platforms, and developing new data processing and interpretation methods.

Alternative Platforms

The fisheries research vessel is the ubiquitous platform for conducting living marine resource surveys, and it is necessary for conventional net sampling operations to obtain standardized indices of abundance and biological samples. Vessels can accommodate a diverse group of scientists who can conduct a variety of operations for durations of days to weeks or even months. While vessels will continue to be invaluable for fisheries surveys, ships can be costly to operate and are limited to areas where the vessel can safely navigate. Advanced technologies aboard alternative platforms such as remotely operated vehicles (ROV's), autonomous underwater vehicles (AUV's; Figure 7), and stationary arrays or buoys (Figure 5; Box 1) complement sampling from vessels by providing coverage in areas or times when vessel-deployed instrumentation is not practical, or for positioning the instrumentation closer to the animals or habitat being surveyed. Sampling over the entire range of a population at fine temporal and spatial resolution has the potential for significantly improving population estimates and ultimately for advancing our ability to predict the dynamic nature of fisheries populations.

Multiple Frequencies

Acoustic-based fish abundance estimates are currently derived solely from 38 kHz data. While this method has been successful for providing population estimates for several semi-demersal and pelagic species when used in conjunction with biological sampling, a single frequency is not sufficient for objective classification or identification. Increasing the bandwidth (i.e. increasing the acoustical frequency spectrum) is necessary to improve our ability to classify or identify acoustical targets. Two ways to increase the number of frequencies are to add echo sounder systems operating at different frequencies (multiple discrete frequencies) or to use broadband signals. Broadband signals transmit acoustic energy over a wide frequency spectrum and may be ideal for remote identification, but are presently not always able to sample to the depths required.

Most fisheries research vessels have multiple echo sounders operating at different frequencies (e.g. Figure 1) and these data are routinely archived and used for subjective classification of the species being surveyed. While such classification has proven successful for estimating abundances of selected species (e.g. walleye pollock, Pacific hake, and Atlantic herring), more objective methods to classify or identify target species are needed to avoid biases and to achieve consistency in data interpretation. A number of classification schemes have been proposed over the years that range in complexity from simple relationships to more involved neural networks. Complex schemes are advantageous because they are able to incorporate more information, but can be less intuitive to understand or apply. Simple schemes rely on fewer variables, but can be robust and straightforward to apply in the field (Figure 8). Regardless of the algorithms, development of robust and accurate classification methods to objectively identify species remains the ultimate goal of advanced technologies.

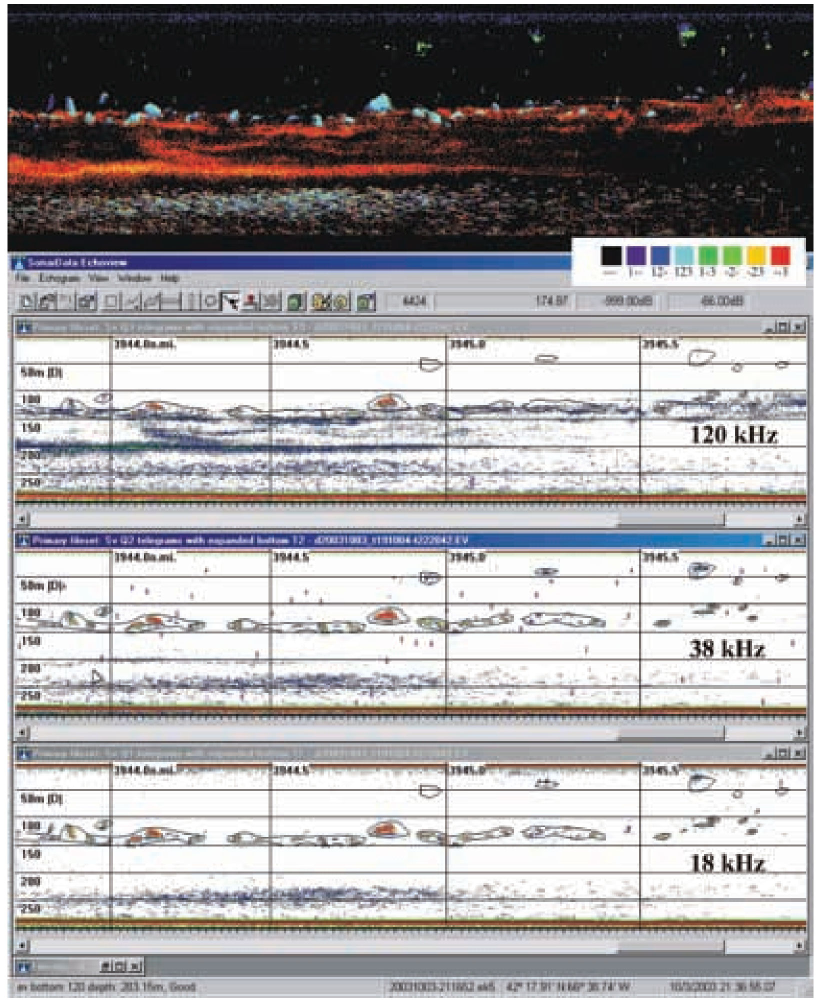
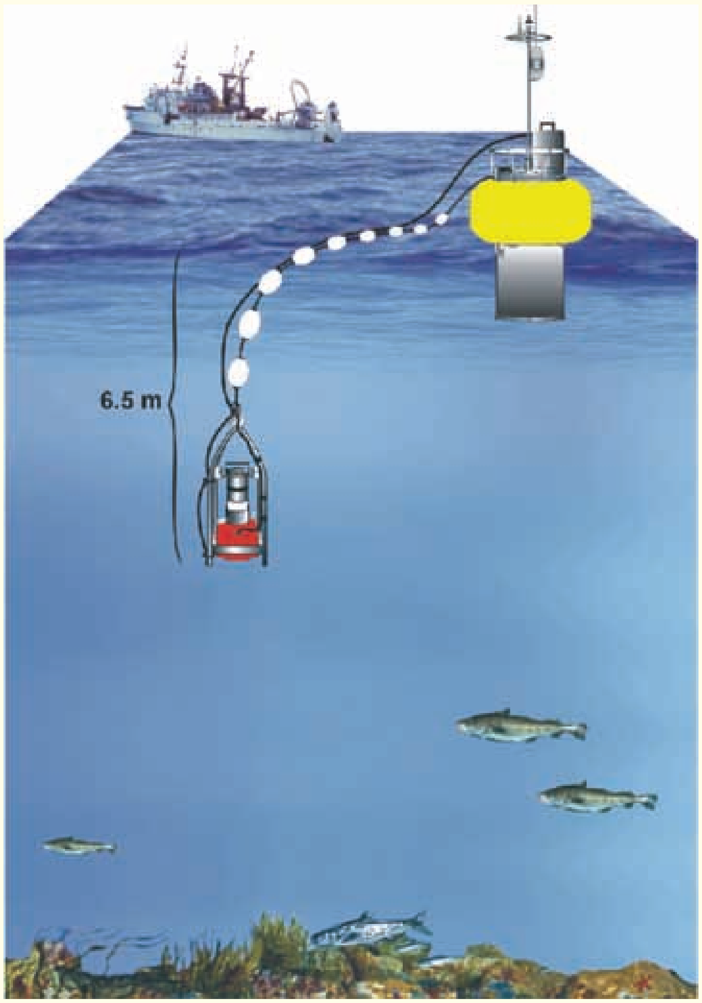


Figure 8
Classification of acoustic backscatter using three-frequency (18, 38, and 120 kHz) echo sounder data (lower panels) highlighting distributional patterns of fish and zooplankton in the Gulf of Maine. The upper panel displays the results of a simple classification algorithm where the presence or absence of backscatter from each frequency is color-coded. For example, backscatter present only in the 120-kHz echogram ("- - 3" in the color key) is represented as red, and backscatter present at all three frequencies is represented as light blue ("123" in the color bar). The light blue patches in these echograms are Atlantic herring.

Acoustic Modeling

Translating acoustical energy to meaningful biological measurements requires establishing a relationship between the reflected energy and the biological measurement. These relationships are obtained by building statistical regressions such as echo amplitude to fish length regressions from in situ (in the natural environment) or ex situ (labo-

Box 1: Fish behavior and vessel noise



Acoustical studies of fish behavior suggest that fish may exhibit a diving or fright response to noises generated by a vessel conducting surveys as well as during trawling operations. It is unknown whether this type of response is typical. If it is, however, there is a strong possibility that when survey/trawling operations are used to directly estimate population size, those estimates may be biased. For example, if the fish move away from the path of the vessel or dive to the bottom before the ship passes over them, they may not be detected by acoustic surveys. During trawl-based surveys, if fish dive into the mouth of a trawl, the effective headrope height of the trawl may be much different than the actual measured headrope height, and estimates of abundance based on area swept by the trawl may be in error. The new, acoustically quiet Fishery Survey Vessels (FSV's) currently being added to the NOAA fleet will reduce the bias caused by noise responses of target species and provide more accurate survey data for stock assessments.

A free-drifting acoustic buoy was designed and constructed by researchers from the Alaska Fisheries Science Center to evaluate the response of fish to vessel and trawl noise (see figure above). The buoy contains an echo sounder and split beam transducer operating at 38 kHz, and other instrumentation to facilitate remote operation of the buoy. An acoustic buoy is an ideal device to measure the response of fish to vessel and trawl noise because it can be rapidly deployed and recovered from the support vessel under adverse sea conditions, and it can monitor the response of fish in an undisturbed state (before the vessel/trawl passes the buoy), disturbed state (at the closest point of approach between the vessel/trawl and buoy), and during recovery to the undisturbed state (as the vessel/trawl moves away from the buoy). This allows scientists to evaluate whether avoidance reactions exist for different species of fish under many different environmental conditions.

D. Chevrier, NEFSC.

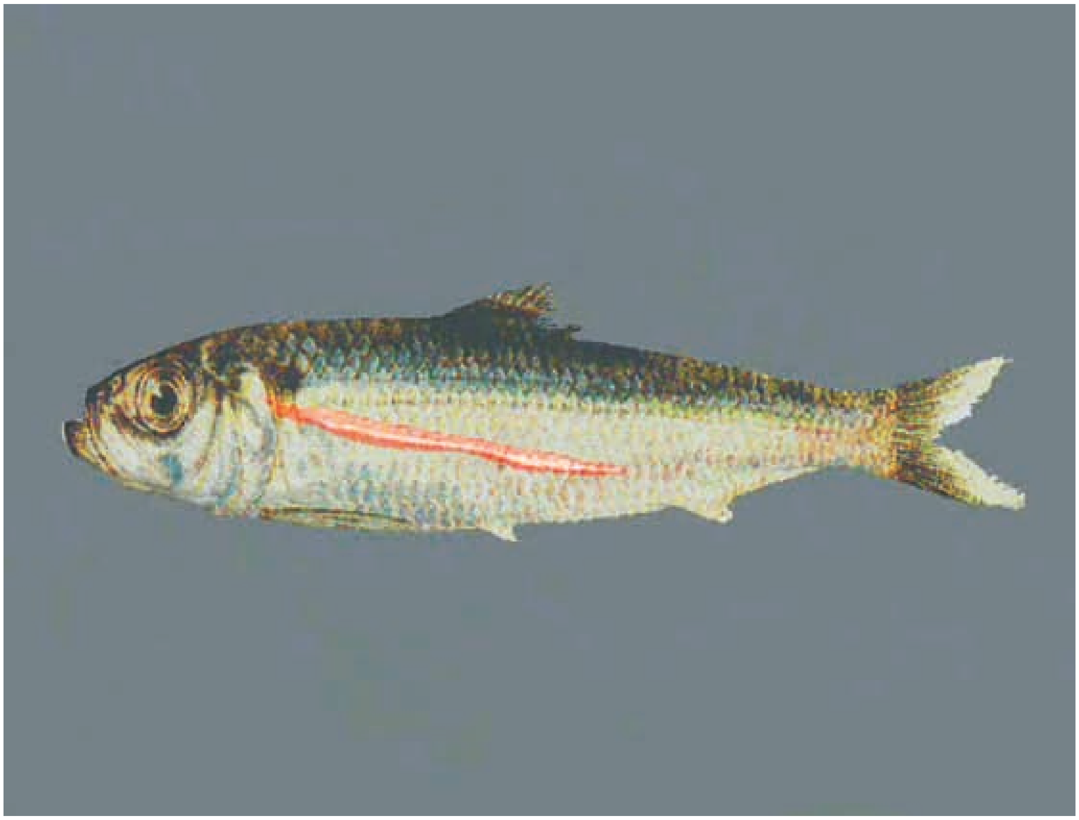


Figure 9
Three-dimensional image of an alewife and its internal swimbladder (elongated red object) derived from a computed tomography (CT) scan. A digital picture of the alewife was superimposed on the CT scan and made translucent to show the swimbladder.

ratory) measurements. Regressions derived from these measurements are advantageous because they usually incorporate the natural conditions in which the animals are surveyed. However, these measurements are difficult to obtain and often require accumulating years of data to develop a robust relationship. In addition, these statistical relationships are limited in their ability to predict outside of the conditions used to develop the relationship, such as when the fish vertically migrate, grow, feed, or develop gonads.

Mathematical models have been developed over the past few decades to predict the echo characteristics of marine animals. These models vary in their complexity and the information required for calculations. Because marine animals have complex anatomy and shapes, developing models that predict echo characteristics is difficult. In general, acoustic models are approximations that use geometric approximations of animal anatomy and shape to generate echo characteristics. Anatomical measurements of fish are obtained from dissections or x-rays, or, recently, computed tomography (CT) images (Figure 9). In spite of the complexities, models have been developed that are able to calculate echo amplitude over a wide range of frequencies and fish anatomies, thus improving our ability to predict echo characteristics over a wide range of conditions. While these models hold great promise, verification requires precise acoustic and biological measurements, as well as monitoring the behavior of the organism. Incorporating acoustic models in acoustic surveys is an area of ongoing research, and will aid in translating acoustic energy to biological measurements and in remote classification of species.