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Visualizing fish movement, behavior, and acoustic backscatter

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Abstract

Acoustic surveys of aquatic organisms are notorious for large data sets. Density distribution results from these surveys are traditionally graphed as two-dimensional plots. Increasing information content through wider acoustic frequency ranges or multiple angular perspectives has increased the amount and complexity of acoustic data. As humans are visually oriented, our ability to assimilate and understand information is limited until it is displayed. Computer visualization has extended acoustic data presentation beyond two dimensions but an ongoing challenge is to coherently summarize complex data. Our goal is to develop visualizations that portray frequency- and behavior-dependent backscatter of individual fish within aggregations. Incorporating individual fish behavior illustrates group dynamics and provides insight on the resulting acoustic backscatter. Object-oriented applications are used to visualize fish bodies and swimbladders, predicted Kirchhoff-ray mode (KRM) backscatter amplitudes, and fish swimming trajectories in three spatial dimensions over time. Through the visualization of empirical and simulated data, our goal is to understand how fish anatomy and behavior influence acoustic backscatter and to incorporate this information in acoustic data analyses.

Keywords: Acoustics; Backscatter; Kirchhoff-ray mode; Target strength; Visualization

1. Introduction

Fisheries acoustic surveys collect large data sets. A common challenge when presenting any large data set is to parsimoniously represent data characteristics (e.g. amplitudes, ranges, variances), while maximizing the amount of information portrayed. Acoustic data contain quantitative information on density and size distributions of backscattering organisms. An important analytic task is to partition the backscattered energy into categories representing size classes, species, or species groups. Classification of acoustic backscatter utilizes echo amplitude or echo envelope metrics when targets can be resolved, or patterns of backscatter from aggregations when targets are not resolvable. Fluctuations in backscatter amplitudes from an individual impede consistent and accurate classification of single targets. Variability in the amount of sound reflected by an aquatic organism is caused by the transmission of sound through water and by a suite of biological factors including anatomy, physiology, and behavior.

Simultaneously measuring the influence of all biological factors on backscatter amplitudes is not yet possible. As an alternative, numeric and analytic models estimate backscatter as a function of biological or physical factors of interest. Backscatter models augment experimental measures by predicting echo amplitudes from individuals under known conditions. To illustrate by example, Kirchhoff-ray mode (KRM) backscatter models (Clay and Horne, 1994) have been used to characterize frequency- and behavior-dependent backscatter of individual and aggregations of fish (Horne and Jech, 1999; Jech and Horne, 2001). Visualization of results include backscatter response surfaces over a designated range of aspect angles, lengths, and carrier frequencies (Fig. 6, Horne and Jech 1999; Fig. 5, Horne et al., 2000) and in interactive representations of fish bodies, swimbladders, and the corresponding acoustic backscatter ambits (Jech and Horne, 2001, Fish3d www.acoustics.washington.edu).

One approach used to examine how biological factors influence echo amplitudes integrates modeling of organism behavior with acoustic measurements of fish distributions in computer visualizations. These visualizations should present large data sets in a coherent and comprehensive manner; reveal several levels of detail within data sets; avoid distor-

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tion of measurements; prompt the viewer to think about mechanisms that cause observed patterns; and encourage comparisons among data sets (Tufte, 1983). This paper was motivated by an interest in visualizing three-dimensional swimming behavior and the resulting effects on acoustic backscatter. Simulations of adult walleye pollock (*Theragra chalcogramma*) and capelin (*Mallotus villosus*) dynamics are integrated with backscatter models to visualize the influence of fish anatomy, orientation, and kinematics on acoustic measurements. We believe that visualization enhances the understanding of backscatter variability and can be used to improve conversions of acoustic data to biological meaningful numbers such as fish length, density, and abundance.

2. Materials and methods

Our goal is to integrate echosounder properties with fish anatomy, backscatter model predictions, and fish trajectories to visualize factors that influence patterns in backscatter data. Three autonomous visualizations are integrated into a single computer application. First, digitized walleye pollock and capelin anatomy are visualized with the corresponding frequency-dependent acoustic backscatter. Second, the movements of fish within schools are visualized from the perspective of a transducer or a member of the school. Third, these two components are integrated to visualize the effect of fish orientation and movement on echo amplitude. Interaction among the three components is facilitated using object-oriented programming.

Object-oriented programming is a ubiquitous feature of computer applications from games to scientific simulations. An object-oriented approach improves efficiency and flexibility of computer programming by coupling data and a set of actions within an object class. An object class defines the data that are stored in an object and the actions that can be performed on the object. Objects are derived from classes. Each object is an instance of a class with its' own unique set of data that can be queried, manipulated, and visualized. The three classes used in this application correspond to the echosounder, fish anatomy and associated backscatter, and fish behavior. The echosounder class includes transducer properties; the echofish class includes acoustical, anatomical, and behavioral characteristics of individual fish; the trajectory class defines fish movements in a shoaling and schooling simulator (Fig. 1).

The echosounder class contains all properties of the echosounder and transducers used in the application: location, orientation, beam width, and frequency. The echosounder tabulates backscatter by determining which targets are in the beam, calculating the incident angle relative to the target's local axes, and then querying each target for a backscatter value. Backscatter amplitudes incorporate target orientations (i.e. tilt and roll) within the beam but are not corrected for transducer beam patterns. Echo amplitudes are equivalent to on axis targets at a variety of tilt and roll angles.

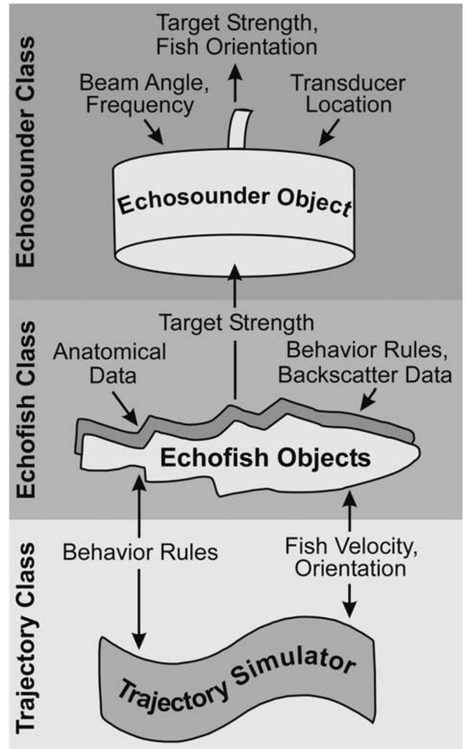

Fig. 1. Schematic diagram showing the relationship between the visualization classes, objects, and data.

The echofish class combines individual fish anatomical and acoustic data with behavioral and physical properties. The echofish class defines the location in space, velocity, and the orientation as physical properties of echofish objects. The anatomical data stored in an echofish object are used to create a three-dimensional model of the fish used in the display. Acoustic backscatter data, either modeled or empirical, can be queried at specified tilt and roll orientations of an echofish object. Because the echofish was designed to interact with any number of behavior simulators, specific behavioral parameters are not defined in this class. The echofish class can read and write behavioral parameters so that behavior simulators can define and modify parameters at any time. This permits simulators with varying parameter requirements to interact with echofish through a common interface and permits each echofish to be parameterized independently if needed.

Fish behavior is simulated by the trajectory class. Fish velocities are calculated using a three-dimensional shoaling and schooling model. The formation and maintenance of fish aggregations is based on opposing forces of attraction and repulsion among individuals (Parr, 1927; Breder, 1954; Horne, 1995). Magnitudes of attraction and repulsion forces are a function of the distance between individuals, canceling at the mean distance between individuals. Parameter values of the behavioral model are based on experimental or empirical observations adapted to approximate walleye pollock and capelin kinematics. In our simulations, all fish are acoustically resolved at any frequency. One walleye pollock is chosen as the “lead” fish among the 20 echofish objects in the simulation. This pollock follows a specified trajectory through the acoustic beam six times at a depth of approximately 100 m. The force of attraction between the lead and follow fish is 10 times greater than that among follow fish. Trajectories of the 19 “follow” fish generally followed the lead fish and included a random force to add individual behavior. Locations and orientations of the “follow” fish were recorded at 0.1 s intervals for approximately 5 min. Attraction and repulsion forces among group members are calculated at each time interval and a random force is added as an additional behavioral component. All forces are summed and new location, orientation, and velocity values are updated for each fish.

Acoustic backscatter data for walleye pollock and capelin are generated using a KRM model (Clay and Horne, 1994). Anatomical data used in model calculations are generated by digitizing dorsal and lateral radiographs of walleye pollock and capelin bodies and swimbladders. Three-dimensional grids used to display fish bodies and swimbladders are generated from anatomical measurements (Jech and Horne, 2002). Grid points between the dorsal and lateral planes are elliptically interpolated at 2° intervals. In the KRM model, the fish body is represented by a set of contiguous fluid-filled cylinders that surround a set of contiguous gas-filled cylinders representing the swimbladder. Backscatter from each cylinder in the body and the swimbladder is computed and then added coherently to estimate total backscatter as a function of fish length, orientation (i.e. tilt and roll), and acoustic wavelength. Values for the speed of sound through water, fish body, and swimbladder are set at 1470, 1575 and 345 m s^{-1}. Densities of the fish and surrounding medium are set at 1070 kg m^{-3} for the fish body, 1.24 kg m^{-3} for the fish swimbladder, and 1030 kg m^{-3} for seawater. Full details of the model can be found in Clay and Horne (1994), Jech et al. (1995), or the appendix in Horne and Jech (1999). KRM models are used to predict backscatter within 30° of normal incidence. For the visualizations, we calculated backscatter at 38 and 120 kHz at a resolution of 2° in both tilt and roll planes. These backscatter values are assumed to incorporate all echosounder gains.

The simulation data enabled real-time comparisons of target strength variability within or among individual walleye pollock and capelin. Each fish in the aggregation traveled in the same general direction, while being influenced by surrounding fish and its own behavior. Location, orientation, and backscatter data are recorded for each fish at 38 and 120 kHz as they passed through the beam. Simulation transducers with beam widths of 10° are placed at the surface in the center of the domain.

3. Results

A three-dimensional surface (i.e. backscatter ambit, cf. Jech and Horne, 2002) visualizes the effects of fish anatomy and orientation on echoamplitude (Fig. 2). The amplitude of each point in the backscatter matrix is represented in the ambit by color (purple = low, red = high) and by the distance from the surface to intersection of the *x*, *y*, and *z* axes. The dominant feature of all ambits is the high amplitude band of backscatter near the vertical axis. Maximum backscatter occurs at an angle corresponding to the angle of the swimbladder relative to the sagittal axis of the fish body. Among gadoids, the swimbladder is generally tilted 5–10° toward the posterior. The backscatter ambits indicate that the walleye pollock swimbladder (Fig. 2a,b) deviates more from horizontal (9°) than the swimbladder (2°) of the capelin (Fig. 2c,d). For this walleye pollock, peak dorsal backscatter amplitude occurs when the fish swims head down at an angle of 81°. Typical of all teleosts, backscatter amplitudes decrease as incident angles approach the head or tail of the fish in dorsal/ventral and lateral planes. Echo amplitudes are more sensitive to tilt and roll at higher fish length (L) to acoustic wavelength (λ) ratios. As L/λ increases, the directionality of the backscatter increases and the number of “ridges” and “folds” in backscattering ambits increases. As an example, compare the ‘roughness’ of the ambits at 120 kHz (Fig. 2b,d) to that at 38 kHz (Fig. 2a,c).

A view of a fish aggregation from a 120 kHz transducer’s perspective (Fig. 3a) shows the orientation and target strength of individual fish as they pass through the beam at approximately 100 m depth. Fish in the walleye pollock aggregation are shallower than the capelin on the right side of the panel. The backscatter amplitude of each fish is color-coded using the same 256 color scheme used in the backscatter ambit displays (Fig. 2). Target strengths range from near minimum to near maximum for fish of the same species within the school. We can also view the same school by using the perspective of a fish within the aggregation (Fig. 3b). Tilt and roll angles differ among individuals, but the coordinated motion of the aggregation is evident. When the application is running, orientations and corresponding backscatter amplitudes of any fish can be queried in the display.

To illustrate the effect of behavior on frequency-dependent target strengths, orientations and apparent lengths of a walleye pollock and a capelin are plotted as they pass through the transducer beams. Target strengths of the walleye pollock are consistently greater than that of the capelin at both frequencies (Fig. 4a). In the time segment shown, target strengths of walleye pollock at 120 kHz fluctuate by as much as 15 dB between successive measurements. Similar fluctuations, although not as large, occur at 38 kHz. Fluctuations in target strength for both species correspond to large changes in tilt angles (Fig. 4b). Negative changes in tilt angles represent head down tilts relative to horizontal. Positive changes in roll angle correspond to roll angles on the right half of the fish relative to dorsal incidence. Large changes in target strength do not always correspond to large changes in roll angle. Higher roll values can also correspond to higher off-axis angles relative to the transducer.

The apparent length of the walleye pollock and capelin are tracked at each time step. We used published target strength-

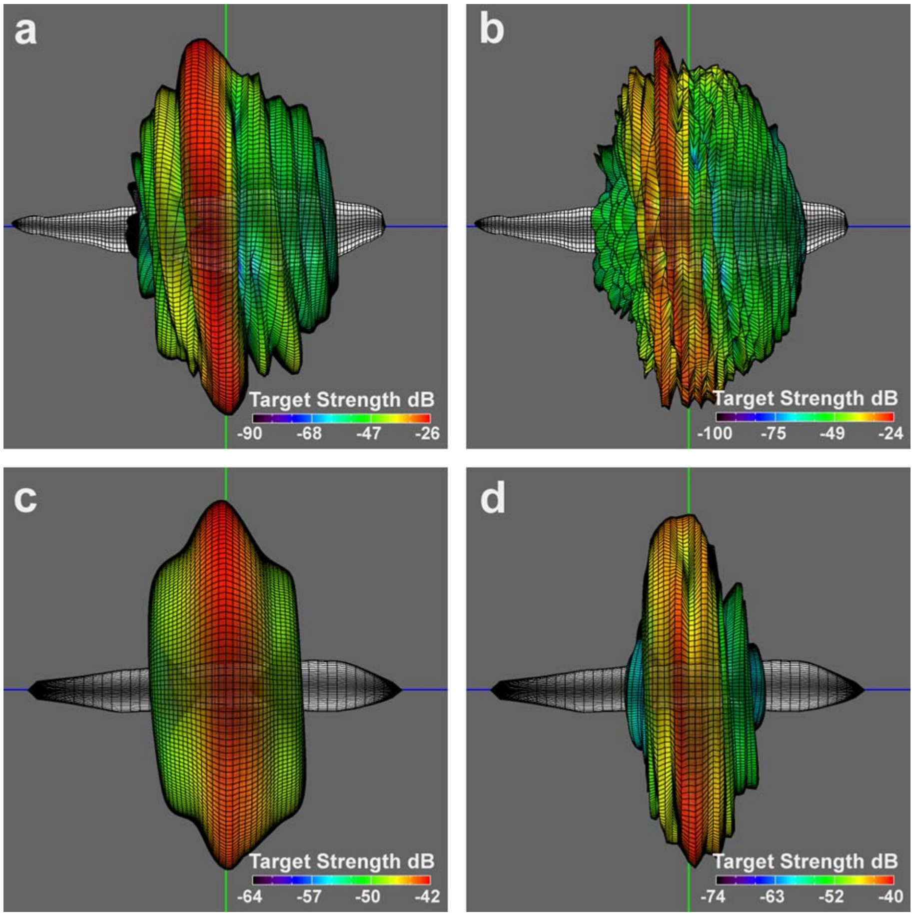

Fig. 2. Acoustic backscatter ambits of a 425 mm walleye pollock (*Theragra chalcogramma*) at (a) 38 kHz and (b) 120 kHz and a 134 mm capelin (*Mallotus villosus*) at (c) 38 kHz and (d) 120 kHz. Backscatter amplitude is represented as distance from the center of the axes and color-coded using red for high amplitude and blue for low amplitude. Target strengths are resolved at 2° in the tilt plane and 2° in the roll plane. Maximum amplitude occurs when the swimbladder is orthogonal to the incident wave front. Note that the color scale minimum and maximum values differ among panels.

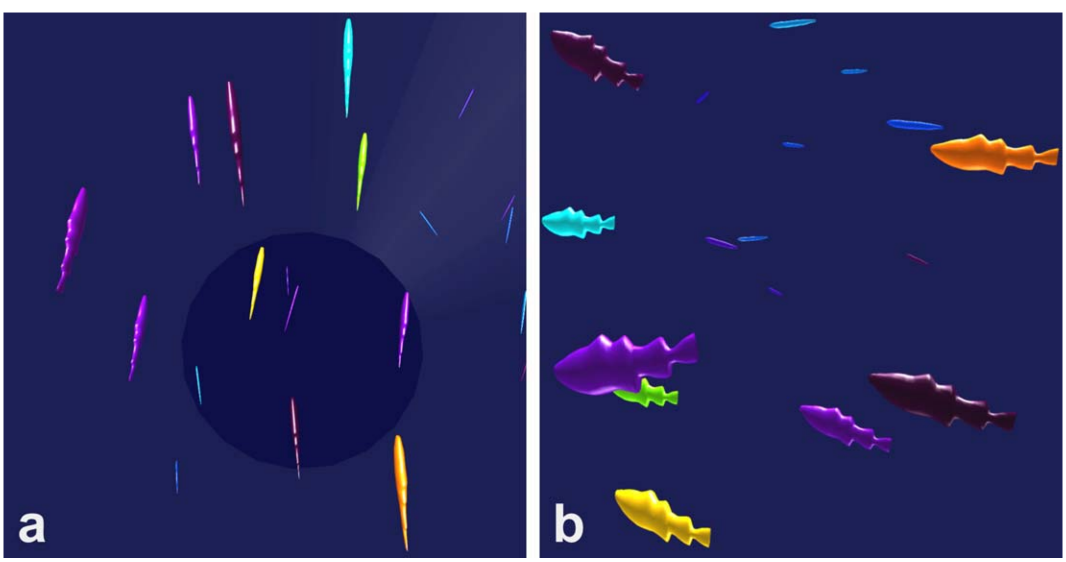

Fig. 3. Snapshots of the Walleye pollock (*Theragra chalcogramma*) and capelin (*Mallotus villosus*) visualization from (a) a 120 kHz transducer's and (b) a fish's perspective of the aggregation. The dark circle in the echosounder perspective delineates the 10° beamwidth of the transducer. Each fish is color-coded depending on the KRM backscatter model prediction of target strength (dB). Color codes range from dark purple (low) to red (high) depending on tilt and roll.

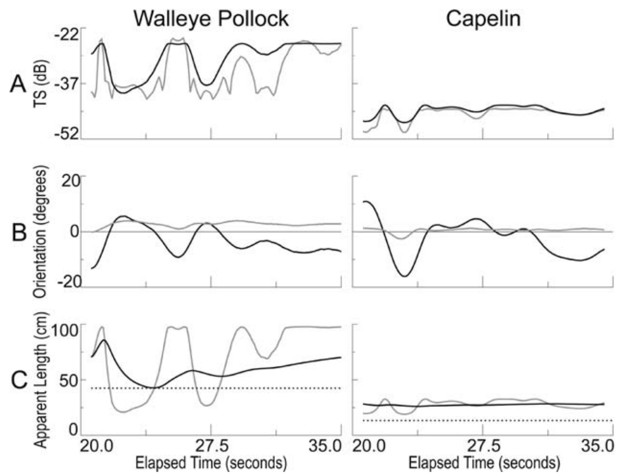

Fig. 4. Tracking of a Walleye pollock (*Theragra chalcogramma*) and capelin (*Mallotus villosus*) (a) predicted target strengths (dB) at 38 kHz (black) and 120 kHz (gray), and (b) orientation: tilt (degrees, positive head up, black), roll (degrees, positive right side, gray) relative to the sagittal and vertical axes of the fish. (c) Apparent length (cm, gray) of each fish is tracked over time using TS = 20 log(L_{cm})-66 (Traynor and Williamson, 1983) for pollock and TS = 20 log(L_{cm})-73.1 (Rose, 1998) for capelin. Dashed lines are the true length of each fish. Black lines are the running mean of each fish's apparent length.

length regression equations for pollock (Traynor and Williamson, 1983) and capelin (Rose, 1998) to translate KRM-predicted target strength to fish lengths (Fig. 4c). Variability in the apparent length of walleye pollock is much greater than that observed in capelin. This is expected, as the range of target strengths predicted for the walleye pollock is larger than that for the capelin. The actual length of each fish is plotted as a dashed line for reference. Apparent length as a running average is plotted for each fish. As the number of echoes increased, accuracy of the length estimation does not always increase.

4. Discussion

Scientific visualization continues to expand its role in fishery research and management. This expansion is due in part to concomitant increases in data volume and in access to computer-based visualization tools. Fisheries acoustic research and management applications are no exception. Visualization facilitates the display and initial analysis of spatially or temporally indexed data and is used to convey technical information to scientists, managers, and other decision makers. Following the lead of other scientific visualization efforts (e.g. Kemp and Meaden, 2002), our goal is to facilitate the discovery and extraction of spatial and temporal patterns from complex data. Our design objectives for this project were:

- to provide dynamic visualizations (Andrienko et al., 2001) that incorporate data exploration;
- to view pattern in data and to view process in simulation;
- to incorporate change or evolution of variables (DiBiase et al., 1992);
- to manage data independent of visualization;
- to interactively manipulate visualization attributes.

Our simulations use a known population of animals with specified behaviors. Simulating fish trajectories provides the advantage of knowing the position and orientation of each individual at every time step. KRM backscatter models are used to predict target strengths for any individual within the acoustic beam based on the orientation (pitch, yaw, roll) at each time step (i.e. echosounder received pulse). This analytic visualization integrates three-dimensional movement with numeric backscatter modeling over time, fulfills the need to integrate data from several sources (Kemp and Meaden, 2002; Stanley et al., 2002), and enables the analysis of derived data sets (Musick and Critchlow, 1999; Lucas, 2000). Two unique features of this application distinguish it from other analytic methods: visual comparison of individual target strengths over time instead of areal or volumetric backscatter summaries and the potential to generate and visualize data for target discrimination among fish sizes or species.

The object-oriented design of the simulation provides a flexible environment to create additional objects or applications. Object classes created for this visualization can be assigned additional attributes and be used in ways not originally conceived during initial development. The use of object classes also eases collaboration and group participation in application development. Objects contain both routines and data that represent an identifiable item with a well-defined role in the application (Smith and Tockey, 1988). Objects appeal to human cognition, are more resilient to change than non-object-oriented programs and allow for faster application development (Booch, 1994).

In our simulation, individual behavior influenced group dynamics and backscatter amplitudes of any fish within an aggregation. The field study by MacLennan et al. (1990) is one of the first investigations to quantify individual and group behaviors while measuring fish target strengths. Tilt-dependent target strengths have been reported for caged (e.g. Edwards and Armstrong, 1983) and tethered (e.g. Nakken and Olsen, 1977; Foote and Nakken, 1978) fish. Fluctuations in target strengths influence accuracy of acoustic size to organism size conversions. Simulating fish trajectories provides the advantage of knowing the position and orientation of each individual within our virtual school. Foote (1980a, b) advocates including fish orientation distributions when establishing relationships between acoustic size and fish length. Combining the ability to track the influence of individual or group behavior on target strength and simultaneously tabulating echo amplitude frequency distributions provides an additional tool when analyzing the causes of backscatter variability. A logical next step would use Boolean operators to combine backscatter amplitudes into target discriminatory metrics.

The visual dominance of human perception poses interesting challenges when analyzing multidimensional data. Graphing one or two variables is easily done in black and white. Graphing multiple variables in multiple dimensions requires creative thinking. The use of color expands our capability to present echo amplitude predictions from both individual and aggregations of fish. Our challenge was to design a visualization that coherently portrayed relationships among frequency, backscatter amplitude, fish species, orientation, and behavior. The use of multiple images with different characteristics (i.e. fish size and orientation) allows and encourages comparison among images in real time (Tufte, 1990). We hope that the results of this work will directly increase the understanding of fish ensemble structure and dynamics, improve accuracy of acoustic target recognition, and enhance the collection and visualization of acoustic data.

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References

Andrienko, N., Andrienko, G., Gatalsky, P., 2001. Exploring changes in census time series with interactive dynamic maps and graphics. Computational Stat. 49, 141–152.

Booch, G., 1994. Object-oriented Analysis and Design with Applications. Benjamin/Cummings Publishing Co., CA, pp. 589.

Breder Jr, C.M., 1954. Equations descriptive of fish schools and other aggregations. Ecology 35, 361–370.

Clay, C.S., Horne, J.K., 1994. Acoustic models of fish: the Atlantic cod (*Gadus morhua*). J. Acoust. Soc. Am. 96, 1661–1668.

DiBiase, D., MacEachren, A.M., Krygier, J.B., Reeves, C., 1992. Animation and the role of map design in scientific visualization. Cartography GIS 19, 201–214.

Edwards, J.I., Armstrong, F., 1983. Measurement of the target strength of live herring and mackerel. FAO Fish. Rep. 300, 69–77.

Foote, K.G., 1980a. Effect of fish behavior on echo energy: the need for measurements of orientation distributions. J. Cons. Int. Explor. Mer 39, 193–201.

Foote, K.G., 1980b. Averaging of fish target strength functions. J. Acoust. Soc.Am. 67, 504–515.

Foote, K.G., Nakken, O., 1978. Dorsal-aspect target strength functions of six fishes at two ultrasonic frequencies. Fisken of Havet Ser. B 1978, 1–96.

Horne, J.K., 1995. Spatial variance of mobile aquatic organisms: capelin and cod in coastal Newfoundland waters. Ph. D. Thesis, Memorial University of Newfoundland. pp. 185.

Horne, J.K., Jech, J.M., 1999. Multi-frequency estimates of fish abundance: constraints of rather high frequencies. ICES J. Mar. Sci. 56, 184–199.

Horne, J.K., Walline, P.D., Jech, J.M., 2000. Comparing acoustic model predictions to in situ backscatter measurements of fish with dual-chambered swimbladders. J. Fish Biol. 57, 1105–1121.

Jech, J.M., Horne, J.K., 2001. Effects of in situ target spatial distributions on acoustic density estimates. ICES J. Mar. Sci. 58, 123–136.

Jech, J.M., Horne, J.K., 2002. Three-dimensional visualization of fish morphometry and acoustic backscatter. Acoust. Res. Lett. Online 3, 35–40.

Jech, J.M., Schael, D.M., Clay, C.S., 1995. Application of three sound scattering models to threadfin shad (*Dorosoma petenense*). J. Acoust. Soc. Am. 98, 2262–2269.

Kemp, Z., Meaden, G., 2002. Visualization for fisheries management from a spatiotemporal perspective. ICES J. Mar. Sci. 59, 190–202.

Lucas, A., 2000. Representation of variability in marine environmental data. In: Wright, D., Bartlett, D. (Eds.), Marine and Coastal Geographical Information Systems. Taylor and Francis, London, pp. 53–70.

MacLennan, D.N., Magurran, A.E., Pitcher, T.J., Hollingworth, C.E., 1990. Behavioral determinants of fish target strength. Rapp. P.-v. Réun. Cons. Int. Explor. Mer. 189, 245–253.

Musick, R., Critchlow, T., 1999. Practical lessons in supporting large-scale computational science. SIGMOD Record 28, 49–57.

Nakken, O., Olsen, K., 1977. Target-strength measurements of fish. Rapp. P.-v. Réun. Cons. Int. Explor. Mer. 170, 52–69.

Parr, A.E., 1927. A contribution to the theoretical analysis of the schooling behavior of fishes. Occasional Papers of the Bingham Oceanography College 1, 1–32.

Rose, G.A., 1998. Acoustic target strengths of capelin in Newfoundland waters. ICES J. Mar. Sci. 55, 918–923.

Smith, M.K., Tockey, S.R., 1988. An integrated approach to software requirements definition using objects. Proceedings of Ada Expo 1988. Galaxy Productions, Frederick, MD, pp. 21.

Stanley, R.D., Kieser, R., Hajirakar, M., 2002. Three-dimensional visualization of a widow rockfish (*Sebastes entomelas*) shoal over interpolated bathymetry. ICES J. Mar. Sci. 59, 151–155.

Traynor, J.J., Williamson, N.J., 1983. Target strength measurements of walleye pollock (*Theragra chalcogramma*) and a simulation study of the dual beam method. In: Nakken, O., Venema, S.C. (Eds.), Symposium on fisheries acoustics. Selected papers of the ICES/FAO Symposium on Fisheries Acoustics. Bergen Norway, 21–24 June, 1982. FAO Fisheries Report 300. pp. 112–124.

Tufte, E.R., 1983. The Visual Display of Quantitative Information. Graphics Press. Cheshire, CT, pp. 197.

Tufte, E.R., 1990. Envisioning Information. Graphics Press. Cheshire, CT, pp. 126.