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# Acoustic approaches to remote species identification: a review

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## ABSTRACT

Noninvasive species identification remains a long-term goal of fishers, researchers, and resource managers who use sound to locate, map, and count aquatic organisms. Since the first biological applications of underwater acoustics, four approaches have been used singly or in combination to survey marine and freshwater environments: passive sonar; prior knowledge and direct sampling; echo statistics from high-frequency measures; and matching models to low-frequency measures. Echo amplitudes or targets measured using any sonar equipment are variable signals. Variability in reflected sound is influenced by physical factors associated with the transmission of sound through a compressible fluid, and by biological factors associated with the location, reflective properties, and behaviour of a target. The current trend in acoustic target identification is to increase the amount of information collected through increases in frequency bandwidth or in the number of acoustic beams. Exclusive use of acoustics to identify aquatic organisms reliably will require a set of statistical metrics that discriminate among a wide range of similar body types at any packing density, and incorporation of these algorithms in routine data processing.

**Key words:** acoustics, backscatter amplitude, species identification, target strength

## INTRODUCTION

Development of technology using sound to remotely detect aquatic organisms is less than a century old, and continues to evolve rapidly. The first biological application of acoustics was to detect the presence of fish in a tank (Kimura, 1929). Following World War II, the utility of echosounders at sea was demonstrated by researchers and fishers (Sund, 1935; Tester, 1943; Smith, 1947; Balls, 1948) who showed that sound could be used to locate and qualitatively visualize distributions, abundances, and behaviours of fish. Experienced commercial fishers were soon combining their knowledge of fishing grounds with the intensity, location, and size of marks on paper echograms to identify fish and shrimp species. The addition of correction factors (i.e. *TVG*, time-varied gain) that compensate for the range dependence of echo amplitudes enabled quantitative estimates of relative abundance. Development of standard calibration procedures (Foote *et al.*, 1983) and studies of relationships between echo amplitude and organism length (Love, 1971; Nakken and Olsen, 1977; Foote, 1987) facilitated size-based abundance estimates of fish and zooplankton. Improved resolution and digital sampling of reflected sound has further enhanced the potential for automated species identification of acoustic targets.

Automated species identification remains the ‘Holy Grail’ to acoustic researchers. The potential for objective classification of targets by species was recognized in the 1970s (Deuser *et al.*, 1979; Giryn *et al.*, 1979) but progress was constrained by a lack of computing power. Advances in digital electronics have removed many computational obstacles to ‘identifying’ targets using underwater acoustics. The term ‘identify’ has been used liberally when describing results from acoustic analyses. Under most circumstances, it is not currently possible to identify all fish and zooplankton species definitively using the amount of returned energy from a target (i.e. echo amplitude) or the time-dependent returned energy (i.e. echo shape). The amount of sound energy returned from a target is dependent on the choice and configuration of hardware, on water characteristics, and on the location, composition, and behaviour of detected targets.

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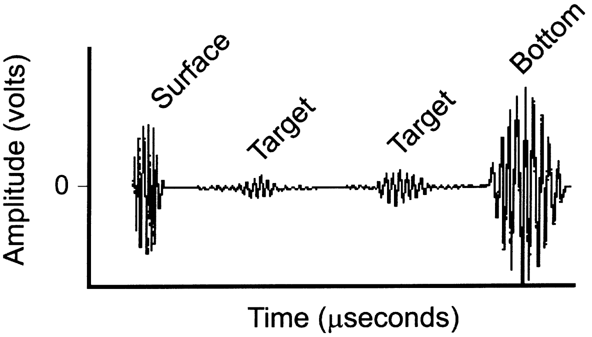
Strategic deployment of equipment in space and time is used to maximize the probability of target identification. Species identification of acoustic targets is typically inferred using supplementary information such as location in the water column, net catch data, knowledge of species' habits, or spectral signature. It is therefore important to state explicitly the basis of acoustic species identifications and to quantify factors influencing magnitudes of echo amplitudes. Understanding sources and magnitudes of variance in acoustic data provides a foundation for development of computer procedures that identify aquatic species.

This paper examines strategies using sound to discriminate and classify aquatic organisms remotely. Comprehensive texts detailing the theory and application of acoustics in aquatic environments include MacLennan and Simmonds (1992) and Medwin and Clay (1997). Choice of equipment and analytic techniques used to sonically sample marine mammals, fish, or zooplankton largely depends on the depth range, type, and size of the organisms of interest. An effort will be made to explicitly state the theory, philosophy, and assumptions associated with each technique and to detail contributions and constraints of current technology.

## HOW DOES UNDERWATER ACOUSTIC TECHNOLOGY WORK?

Sound is a mechanical disturbance that propagates through water as a pressure wave in an elastic medium. The pressure wave radiates spherically from its source with the intensity $I$ decreasing inversely with the square of the distance travelled $R$ (i.e. $I \propto 1 / R^2$). Sonar (Sound Navigation and Ranging) is a general term applied to equipment and associated software that receives and possibly transmits sound. A generic sonar samples the water column by sending short (e.g. 0.2–1.0 msec) single or repetitive pulses of sound (e.g. 5 pulses $s^{-1}$) from a point source down into the water, up from the bottom, or across a body of water such as a river. An echosounder is an instrument used by fishers and researchers to transmit and receive sound vertically through the water column. All sonars transmit sound at single or over a range of frequencies, measured as the number of acoustic wavelengths per unit time (cycles per second, Hz). Because sound travels through water at about 1500 m $s^{-1}$, the entire water column is quickly profiled. When the sound wave encounters a density difference (i.e. acoustic scatterer or target), an echo propagates radially outward from the target back to a receiver. Echoes returning to the sound source are termed backscattered sound. Receivers placed at a distance from the sound source measure forward-scattered sound. Sampling by most sonar systems is limited by near-boundary 'dead zones' where targets cannot be discriminated from the surface or the substrate (Mitson, 1983a,b; Ona and Mitson, 1996; Misund, 1997).

**Figure 1.** A representative schematic of backscattered echo amplitude plotted against time. Backscatter at the surface is high because of residual transducer noise after the transmitted pulse, and surface turbulence. Echo amplitudes from targets differ in magnitude as a function of distance from the transducer, position in the acoustic beam, and target size. Large-amplitude echoes are reflected from the bottom.



In fisheries research, classification and identification of acoustic targets traditionally combines knowledge of distribution and behaviour patterns of constituent species with collection and analysis of acoustic and catch data. The two types of data that can be directly extracted from acoustic returns are time between pulse transmission and echo return (i.e. target range, measured in seconds), and pressure detected at a receiver (i.e. echo amplitude, measured in volts) (Fig. 1). Because the speed of sound through water is known for any temperature and salinity (Colladon and Sturm, 1827; Del Grosso and Mader, 1972; Mackenzie, 1981), the elapsed time between pulse transmission and echo reception measures the distance between the sound source and the acoustic target. Sound pressures at a receiver are measured as an energy flux per unit time (i.e. intensity), often reported as a logarithmic ratio of an observed to a reference intensity (i.e. decibel, dB).

Approaches used to classify, count, and possibly identify acoustic targets depend, in part, on the distribution and packing density of organisms. If animals are dispersed throughout the water column and at low densities, it is possible to detect, measure, and count echoes from individual fish or zooplankton (Trout *et al.*, 1952). The original purpose of echo counting was to estimate the density of organisms by counting the number of targets and dividing by the sample volume.

The abundance or biomass of any area can then be estimated by multiplying the numeric or mass density by the volume of water in the area of interest (MacLennan and Simmonds, 1992). Successful echo counting relies on the ability to discriminate single echoes backscattered by isolated targets from multiple echoes that are returned from two or more targets in close proximity. Single echoes are identified by examining characteristics of the echo envelope – the time-dependent amplitude of a received pulse. Duration, amplitude, phase, and slope of the backscattered echo are criteria commonly used to separate single from multiple echoes. Conditions suitable for echo counting (i.e. random and low density distributions; see Spindel and McElroy, 1973; Stanton, 1985a) are ideal conditions for species identification of single targets.

When organisms aggregate in densities too high to discriminate among individuals (Dickie *et al*., 1983), echo counting cannot be reliably used to estimate abundance. Echo integration (Dragesund and Olsen, 1965) is a technique used to estimate the relative density of targets insonified by a sound source. This technique is based on the fact that the intensity of a received echo is proportional to the density of targets (Røttingen, 1973; Foote, 1978a, 1983). Sound pressures detected at a receiver are converted to voltages, and the squared amplitude of the voltage is integrated over arbitrary units of time. Relative densities are converted to numeric densities by dividing the integrated echo by the echo amplitude of a representative individual.

## TARGET CLASSIFICATION

There are two motivations for examining relationships between echo amplitudes and acoustic targets. The first enables the conversion of relative to numeric target densities using integrated echo data. Assuming that an aggregation consists of similar-sized organisms (Ranta and Lindström, 1990; Ranta *et al*., 1992) and that individuals swim at the same angle, the total integrated echo can be divided by the echo amplitude of a representative individual to estimate numeric density. A measure of the amount of sound reflected by a specific target at a specific frequency is the backscattering cross section. At any distance $R$ from the sound source, the backscattering cross section ($\sigma_{\mathrm{bs}}$; units: m$^2$) is defined as:

$$\sigma_{\mathrm{bs}} = R^2(I_r \div I_i), \tag{1}$$

where $I_r$ is the sound intensity reflected or backscattered from the target, and $I_i$ is the intensity of the incident pulse measured at an arbitrary distance, usually 1 m. A common convention in underwater acoustics is to express the echo amplitude as a target strength ($TS$), which is the logarithmic transformation (units: dB) of the backscattering cross section:

$$TS = 10\log_{10}(\sigma_{bs}). \tag{2}$$

Backscattering cross sections or target strengths can be measured using caged or tethered animals, measured *in situ* using dual or split-beam echosounders, or modelled using theoretical backscatter models (review: Horne and Clay, 1998). Experimental measures of individual fish lengths and acoustic backscatter can be used to derive empirical relationships between target strength and fish length (Love, 1971; Nakken and Olsen, 1977; Foote, 1987). Once target strength–length relationships are derived for any species of interest, length–frequency distributions based on net samples can be used to proportion size compositions and target strengths of animals within aggregations.

The second motivation for examining the relationship between echo amplitude and an acoustic target is to discriminate, classify, and count aquatic organisms. If each species has a characteristic range of echo amplitudes over a specified length range, then echo counting can be used to classify targets. This classification strategy works best among monospecific aggregations or when aggregations of large animals are separated from smaller animals, such as predators and their prey. Despite many years of research, characteristic echo amplitudes for many species have not been found. The echo amplitude of any object is dependent on a variety of factors including the transmitting frequency of the sonar equipment, the size of the object, the presence or absence of a swimbladder, the aspect of the object relative to the sound source, and even the stomach contents, lipid content, and reproductive stage of the animal. Variability in echo amplitude negates the ability to identify species reliably with only echo amplitudes, unless target classes differ greatly in size or in morphology (e.g. with and without swimbladders).

## VARIABILITY IN ECHO AMPLITUDES

Variability in backscattered sound is influenced by a group of physical factors associated with the transmission of sound through a compressible fluid and by a group of biological factors associated with the location and reflective properties of a target. The primary physical factor is the dependence of echo amplitude on the operating frequency or frequency range of the sound source (Hersey and Backus, 1954; McNaught, 1968, 1969). Frequencies used to sample aquatic organisms range from 200 Hz for small, mesopelagic fish (Holliday, 1972) to 10 MHz for plankton (Pieper *et al.*, 1990).

Aquatic organisms are complicated scatterers of sound by nature of their size, shape, deformation, composition, and behaviour. Among teleost fish, swimbladders provide a large acoustic contrast to flesh or skeletal elements and form the major (> 90%, Foote, 1980a) source of backscattered sound. Bubbles carried by zooplankton (Barham, 1963) or lipid globules (Sargent and Falk-Petersen, 1988; Vanderploeg *et al.*, 1992) contribute significant proportions of total backscatter among zooplankton species. A second biological factor influencing the amplitude of acoustic backscatter is an organism's length. Among fish, target strength generally increases with increasing length. Echo amplitudes from swimbladdered fish are typically an order of magnitude larger than those from similar-sized zooplankton (Horne and Clay, 1998). The general monotonic increase in backscatter with increasing length among fish does not occur across all frequencies for zooplankton (Stanton *et al.*, 1993; Martin *et al.*, 1996). The orientation of the organism relative to the incident soundwave is a third important biological factor affecting echo amplitude (review: Midttun, 1984). Olsen (1977) and Foote (1980b) have developed models based on fish aspect distributions and transducer beam shape to predict mean echo amplitudes for Atlantic cod (*Gadus morhua*). Medial axes of swimbladders typically deviate 5–10° from fish body sagittal axes (see fig. 2 in Clay and Horne, 1994). Maximum backscatter is observed when fish are orientated head down 5–10°. Among zooplankton, the curvature and roughness of the body form also influences echo amplitudes. Stanton (1989a, 1992) included shape and texture in models of decapod backscatter, and found that predictions from anatomically realistic models matched laboratory measures.

Changes in fish behaviour associated with packing density may introduce shadowing within fish aggregations (Foote, 1978a,b; Lytle and Maxwell, 1983), but shadowing is offset by higher-order scattering within aggregations of randomly distributed targets (Stanton, 1983, 1984). Alternatively, amplitudes of backscattered echoes may depend on backscatter from the ensemble, rather than contributions from individual objects (Feuillade, 1995). Further research is required to quantify effects of packing density, swimming speed, and polarized groups on backscatter from aggregations at geometric scattering frequencies.

## RAYLEIGH, RESONANT, AND GEOMETRIC BACKSCATTER

Whenever the frequency of a transmitted pulse approximates the natural oscillatory frequency of a target, the amplitude of a returned echo is maximized and the echo is described as lying within the resonance scattering region (Rayleigh, 1945). Backscatter measured at frequencies below resonance is termed Rayleigh scattering, while backscatter above resonance is called geometric backscatter. All aquatic organisms have a backscatter resonance frequency, which is a function of the size or equivalent spherical radius of the organism (Lax and Feshbach, 1948; Anderson, 1950), the body composition which includes gas in the swimbladder, insonified depth (Hersey *et al.*, 1962), and recent depth history (Sand and Hawkins, 1973). Because the presence, structure, and orientation of a swimbladder is species dependent (Jones and Marshall, 1953; Whitehead and Blaxter, 1964; Alexander, 1970), using geometric shapes to model fish backscatter inadequately represents asymmetrical swimbladders (Foote, 1985). Fish swimbladders have been shown not to resonate like ideal gas-filled spheres (Feuillade and Nero, 1998). Differences in backscatter resonance frequencies have been used to discriminate and identify species of zooplankton (Greenlaw, 1977, 1979; Holliday and Pieper, 1980; Martin *et al.*, 1996) and small fish (Zakharia and Sessarego, 1982; Sætersdal *et al.*, 1984; Cochrane *et al.*, 1991). Measures of resonance backscatter have also been used to identify and estimate abundance of commercial fish species (Holliday, 1972; Love, 1993). This is not common among fisheries management agencies, as swimbladder resonant frequencies are typically lower than the normal operating frequencies of scientific echosounders (38 kHz to 420 kHz).

The distinction between resonance and geometric backscatter forms a pseudo-division among approaches used to identify acoustic targets. This division results partly from differences in organism sizes and depth preferences.

## APPROACHES AND TECHNOLOGIES USED TO IDENTIFY TARGETS

Remote species identification benefits resource managers by reducing survey costs and increasing accuracy of abundance or biomass estimates of commercially important aquatic species. An acoustic sampling and analytic system that produces high-resolution, species-specific distribution maps benefits those examining community compositions, predator–prey interactions, and habitat use. Unfortunately, a universal procedure to identify and count organisms acoustically does not exist. The diversity of approaches used to discriminate targets and to identify constituent species suggests that unique problems are associated with acoustic identification of aquatic body types, or that the best combination of hardware and analysis has not been found. Current acoustic hardware and associated analytic methods can be grouped in four categories:

**1** Passive sonar;
**2** Prior knowledge and direct sampling;
**3** Echo statistics from geometric frequency measures;
**4** Matching models to resonance frequency measures.

### *Passive sonar*

Passive sonar is not regularly used to estimate abundance but is used to identify fish and invertebrate species. Passive sonar does not transmit a pulse but receives sound that is produced from other sources. Three groups of aquatic organisms produce sound: crustaceans (predominantly shrimp), teleost fish with swimbladders, and marine mammals (mainly whales and dolphins). One challenge associated with this technique is distinguishing biological sources from background noise. For some species, this is not an issue. Snapping shrimp are dominant sound producers in shallow waters (< 60 m depth) at latitudes less than 40° (Everest *et al.*, 1948; Knudsen *et al.*, 1948; Cato, 1993). A peak-to-peak source level from a single snap has been recorded at 185 dB (*re* 1 $\mu$Pa) over a frequency spectrum of 200 kHz (Au and Banks, 1998). Localization of concentrated snapping has been used to identify shrimp colonies in nearshore Florida waters (Olivieri and Glegg, 1998). Knowledge of sound production and communication among fish (i.e. soniferous fishes) is not new ( Myrberg *et al.*, 1965; Marshall, 1966; Fish and Mowbray, 1970). Muscles associated with the swimbladder wall are used to produce sound (Jones and Marshall, 1953; Hawkins, 1993). Several species produce sound during courtship and spawning (Guest and Lasswell, 1978; Connaughton and Taylor, 1995, 1996; Crawford *et al.*, 1997) and during aggressive encounters (Winn *et al.*, 1964; Caldwell and Caldwell, 1967). Sciaenid fish (e.g. weakfish and red drum) produce species-specific sounds at source levels up to 145 dB (*re* 1 $\mu$Pa) during the spawning season (Luczkovich *et al.*, 1999). Fish mating or spawning sounds originate over limited times and in restricted locations. This is advantageous when enumerating animals and identifying spawning habitat, but limits opportunities to assess population abundances and spatial distributions. General application of passive acoustics for species identification and abundance estimates requires receivers capable of detecting sound over large frequency ranges, deployments of fixed and mobile receiver arrays, algorithms that convert sound intensity to abundance, and a library of species-specific sounds.

Identity and movements of individual fish are also monitored using transponding acoustic tags. A miniature electronic pinger is placed subcutaneously or in the abdominal cavity of an individual animal. Hydrophones are then used to track the animal's horizontal and vertical movements (Arnold and Greer Walker, 1992; Wroblewski *et al.*, 1994, 2000). Tags transmit at specific frequencies to provide a unique marker for each individual. Constraints to current technology include cost and size of tags, labour required to tag and track each animal, duration of tag transmission (about 1 year), and range of tag detection. Tag detection range and transmission duration are proportional to tag size. Tag size determines the battery size that can be used and the size of an animal that can be tagged. If tags are modified to transmit a pulse when interrogated or to reflect a distinct signature when insonified, then hydrophone arrays could be strategically positioned to detect fish or other aquatic organisms as they pass during seasonal migrations. Miniaturization of tags is desirable through reduction or elimination of power requirements, and reductions in tag costs would enable more animals to be monitored. Recovery of tags would enable tag reuse with little additional cost. Because some aquatic species aggregate among conspecifics (Ranta and Lindström, 1990; Ranta *et al.*, 1992), detection of an individual within an aggregation potentially identifies the species and size of organisms in a group.

Other examples of passive sonar monitoring include the use of data from the US Navy IUSS hydrophone arrays to locate, identify, and track movements of whales (Watkins and Schevil, 1972; Clark *et al.*, 1986; Nishimura and Conlon, 1994). Triangulations from three hydrophones have also been used to track positions of spawning cephalopods that have acoustic tags inserted in their mantles (O'Dor and Seino, 1997; O'Dor *et al.*, 1998). Similar arrays might be used to detect tagged anadromous fish as they enter or exit spawning rivers (Lord and Acker, 1976) or species such as Atlantic cod as they follow traditional migration routes to feeding grounds (Rose, 1993).

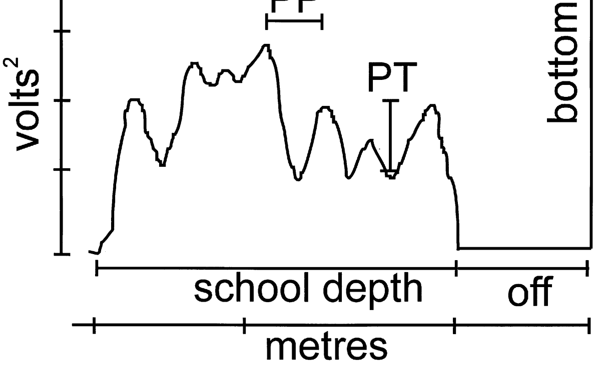
### *Prior knowledge and direct sampling*

Fish and zooplankton researchers traditionally use direct sampling and prior experience to classify and identify acoustic targets detected with active sonars and echosounders (Sund, 1935; Balls, 1948; Beamish, 1966). Familiarity with the biology of an area increases the ability to identify acoustic targets qualitatively using knowledge of organisms' residence times, depth or habitat preferences, and relative sizes (Midttun and Nakken, 1977; Azzali, 1982). This approach has been formalized using pattern recognition algorithms that discriminate among associated substrate types or identify species on digitized echograms (Nion and Castaldo, 1982; Richards *et al.*, 1991). Direct sampling technologies include still or video cameras, gill nets, seines, midwater or bottom trawls, and traps or weirs that are set in the area. If acoustic and direct samples cannot be obtained from the same platform, catches can be sampled for species composition and length frequency on commercial vessels, at the point of landing, or in processing plants. The proportion of each species caught in a net haul is used to apportion acoustic targets in a sample (Nakken and Dommasnes, 1975). This technique assumes that catchability by a net is equivalent to the detectability of the sonar system, and that the net provides a representative sample of the organisms of interest. Given the limited vertical coverage, integrative catch hauls, and selective catchability of all nets, the gear chosen to verify species and length compositions must adequately sample acoustic targets of interest, and catches must be adjusted to include net biases (Aglen *et al.*, 1999).

### *Echo statistics from geometric frequency echosounders*

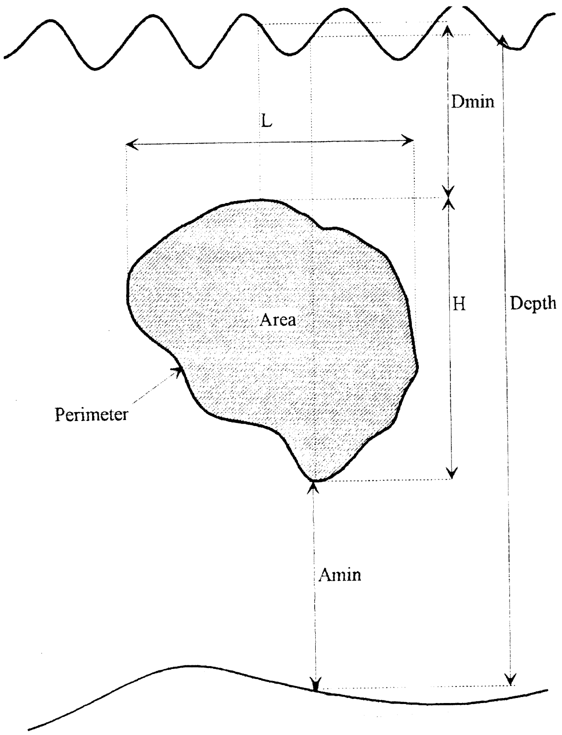
Echo statistics used to identify species are derived from data collected using narrowband, high-frequency echosounders; multiple-frequency echosounders and the inverse approach; and broadband, high-frequency echosounders. Narrowband refers to a discrete carrier frequency used to transmit a pulse. High-frequency refers to frequencies transmitted in the geometric region of the scattering curve (approximately ≥ 10 kHz for fish). If organisms form characteristic aggregation shapes or sizes, then constituent species may be identified based on a set of indices that describe the structure of the aggregation. During the 1970s, 11 kHz and 30 kHz sonars were used to map, count, and identify aggregations of pelagic fish. Location, surface observations, purse seine hauls, and variations in density and school dimensions were all used to distinguish northern anchovy (*Engraulis mordax*) from other species in the California Current (Smith, 1970; Hewitt, 1975; Hewitt *et al.*, 1976). Fish aggregations have also been characterized using parameters from theoretical frequency distributions that were fitted to echo amplitude probability distribution functions (Stanton and Clay, 1986; Stanton *et al.*, 1993; Scalabrin *et al.*, 1996). Changes in parameters over time or among species can be used to classify target types, behaviour (Clay and Heist, 1984), and acoustic carrier frequency (Jech *et al.*, 1995).

**Figure 2.** Schematic diagram of discriminating fish school measurements used by Rose and Leggett (1988). Time measures (school depth, off-bottom distance, peak to peak distance (*PP*)) are calculated in metres from initial measure ($P = \Sigma_1^n PT_i \cdot n^{-1}$). Voltage measures (maximum, mean, SD, and peak-to-trough distance (*PT*)) are calculated in V$^2$.



Other statistics are used to describe and classify aggregation size, shape, location in the water column, position relative to other aggregations, and echo amplitudes (Vray *et al.*, 1990). Discriminant functions based on measures of echo envelopes were used to categorize Atlantic cod, capelin (*Mallotus villosus*), and mackerel (*Scomber scombrus*) aggregations (Rose and Leggett, 1988, Fig. 2). Biological and physical indices from digitized echograms were also used in discriminant function analyses (DFA) and principal component analyses (PCA) to classify known anchovy (*Engraulis encrasicolus*), sardine (*Sardina pilchardus*), and horse mackerel (*Trachurus trachurus*) aggregations (Scalabrin and Massé, 1993; Scalabrin *et al.*, 1994, 1996, Fig. 3). Classification success of single-species aggregations using discriminant functions ranged from 41% to 96%. Nero and Magnuson (1989) found that 31% to 79% of water mass categories in the Atlantic Gulf Stream could be successfully discriminated based on fish 'patch' descriptors (Fig. 4). This study differed from the previous two species-identification efforts in that the objective was to classify biological patches without knowledge of constituent species. Discriminant functions and artificial neural networks (ANN) developed using metrics of patch size, shape, and relative position in the water column were used to classify anchovy, sardine, and horse mackerel aggregations (Haralabous and Georgakarakos, 1996, Fig. 5). Successful classification of schools using discriminant

**Figure 3.** Schematic diagram and explanatory table of discriminating patch measurements used by Scalabrin *et al.* (1994).



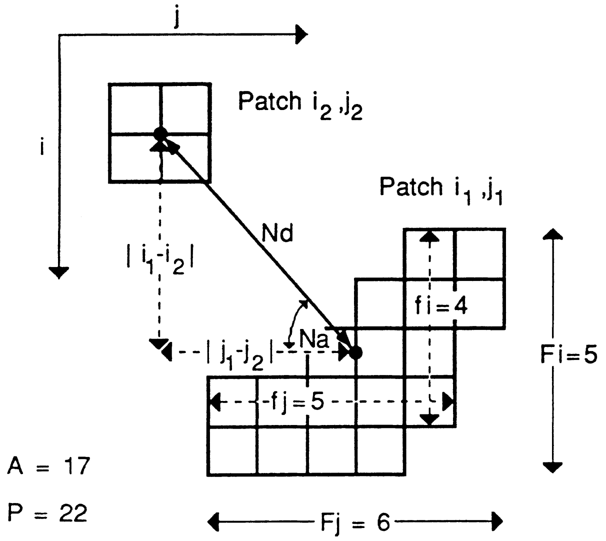
| Abbreviation | Shoal Descriptor | Unit |
|---|---|---|
| | **General** | |
| | File identificator and shoal feature number | |
| | Survey | |
| *Loch* | Relative distance covered (~ESDU) | 0.1 mile |
| *S* | Vessel speed | knot |
| | **Acoustic** | |
| *F* | Echo-sounder frequency | kHz |
| *N* | Number of pings | |
| $S_a$ | Sample number above echo-integration threshold | |
| $S_t$ | Total sample number | |
| | **Time and space position** | |
| *Year* | Year | |
| *Day* | Day of the year | |
| *Hour* | Time | decimal |
| *Quad* | Geographic quadrant | |
| *Lati* | Latitude | decimal |
| *Long* | Longitude | decimal |
| | **Morphological** | |
| *H* | Height | meter |
| *L* | Length | m |
| *P* | Perimeter | m |
| *A* | Cross-sectional area | $m^2$ |
| *DFrct* | Fractal dimension | |
| *Elon* | Elongation | |
| | **Bathymetric** | |
| *Depth* | Bottom depth | m |
| *Dmin* | Shoal depth | m |
| *Amin* | Shoal minimal altitude | m |
| *Arel* | Shoal altitude index | |
| | **Energetic** | |
| *Qd* | Deviation | |
| *Rv* | Volume reverberation index | decibel (dB) |
| *E* | Back-scattered energy | $mV^2$ |
| $A_{max}$ | Amplitude sample maximal value | mV |
| *A* | Amplitude mean value | mV |
| $A_s$ | Amplitude standard deviation | mV |
| $A_{cv}$ | Amplitude variation coefficient | |

functions was lower (75–96%) than that using the best ANN (94–100%). Despite high success in efforts to re-classify aggregations of known fish species, descriptors that discriminate and identify individual organisms or aggregations of all species have not been defined.

When densities of organisms are too high to size and discriminate individual targets (e.g. Dickie *et al.*, 1983), narrowband frequency data from multiple transducers and the inverse approach is an alternate technique used to count and possibly identify species (McNaught, 1968, 1969; Holliday, 1977a; Johnson, 1977a). The inverse approach combines theoretical estimates of echo backscatter by individual organisms with multifrequency data to estimate length-based abundances of insonified targets. If species can be separated by size, then target sizes will identify species. When this method is applied to small fish and zooplankton, resonance peaks are used to discriminate size classes. The inverse approach has been used to map length-frequency densities of small zooplankton (Holliday, 1980; Kleppel *et al.*, 1988; Holliday *et al.*, 1989; Pieper *et al.*, 1990; Smith *et al.*, 1992; Napp *et al.*, 1993), krill (Greenlaw, 1979) and small fish (Johnson, 1977b; Holliday, 1980; Kalish *et al.*, 1986); to separate fish from plankton in abundance estimates (Sætersdal *et al.*, 1984; Cochrane *et al.*, 1991); to classify fish by species (Zakharia and Sessarego, 1982); and to estimate size-based abundances of commercial fish (Horne and Jech, 1999).

Broadband, high-frequency echosounders are also used to classify targets and to identify fish species (Bjørnø and Kjærgaard, 1986; Lebourges, 1990). Broadband sonars transmit and then receive a range of frequencies using a single transducer. The purpose of a broadband signal is to maximize the information received from a target and to reduce the effects of an organism's behaviour on echo amplitude measures

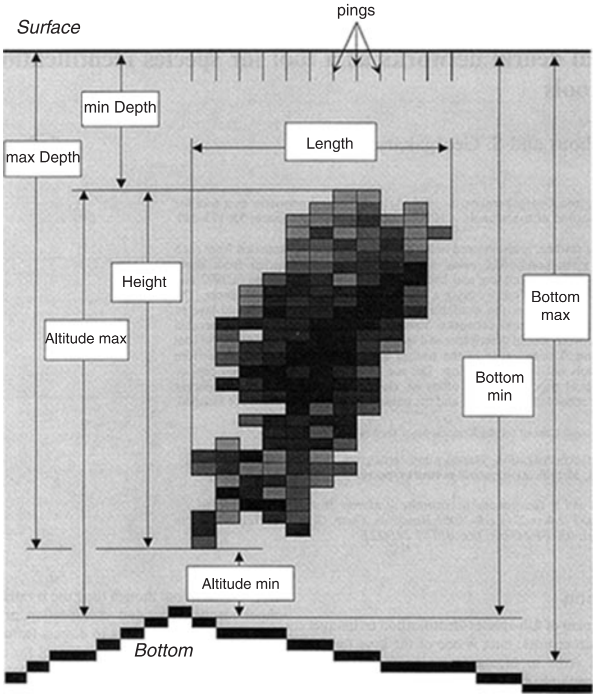
**Figure 4.** Schematic diagram and explanatory table of discriminating patch measurements used by Nero and Magnuson (1989).



| Abbrevation | Variable name | Computation |
|---|---|---|
| | *Location and oceanographic* | |
| $i$ | Row index | |
| $j$ | Column index | |
| $T_m$ | Mean temperature | |
| $T_r$ | Temperature range | |
| $W$ | Water mass | |
| | *Relational* | |
| $N_n$ | Nearest neighbor | |
| $N_d$ | Distance to $N_n$ | $[(i_1 - i_2)^2 + (j_1 - j_2)^2]^{1/2}$ |
| $N_a$ | Angle to $N_n$ | $\tan^{-1} [\lvert i_1 - i_2 \rvert / \lvert j_1 - j_2 \rvert]$ |
| $E_b$ | Mean $\langle E \rangle_b$ | $\frac{\mathrm{k}}{A} \sum \langle E \rangle_b$ |
| | *Size and shape* | |
| $F_i$ | External height | See text |
| $F_j$ | External width | See text |
| $f_i$ | Internal height | See text |
| $f_j$ | Internal width | See text |
| $A$ | Area | Value of 1 per element |
| $P$ | Perimeter length | Value of 1 per element side |
| $D$ | Fractal dimension | $\frac{\ln (P/4) \cdot 2}{\ln (A)}$ |
| | *Internal features of patches* | |
| $E_m$ | Mean $\langle E \rangle$ | $\frac{\sum \langle E \rangle}{A}$ |
| $E_{\mathrm{pk}}$ | Peak $\langle E \rangle$ | Maximum $\langle E \rangle$ value within a patch |
| $E_s^2$ | Variance $\langle E \rangle$ | $\sum \frac{(\langle E \rangle - E_m)^2}{A - 1}$ |
| $E_{\mathrm{cv}}$ | Coefficient of variance | $E_S^2 / E_m$ |
| $R_h^2$ | Horizontal roughness | $\sum \frac{(\langle E \rangle_{ij} - \langle E \rangle_{i,j+1})^2}{A - 1}$ |
| $R_v^2$ | Vertical roughness | $\sum \frac{(\langle E \rangle_{ij} - \langle E \rangle_{i+1,j})^2}{A - 1}$ |
| $R_{\mathrm{ch}}$ | Coefficient of horizontal roughness | $R_h^2 / E_m$ |
| $R_{\mathrm{cv}}$ | Coefficient of vertical roughness | $R_v^2 / E_m$ |
| $E_{\mathrm{sk}}$ | Skewness | Zar 1984, equations 7.7 and 7.8 |
| $E_{\mathrm{ku}}$ | Kurtosis | Zar 1984, equations 7.13 and 7.15 |

(Zakharia, 1990a). Filters are used to 'isolate' narrow frequency bands. If each frequency band contains a unique perspective on a target, increasing the number of bands will increase the information content of the data. Frequency-dependent echo amplitudes can then be used to discriminate and identify targets. Simmonds and colleagues (Simmonds and Copland, 1986; Simmonds and Copland, 1989; Simmonds and Armstrong,

**Figure 5.** Schematic diagram of discriminating fish school measurements used by Haralabous and Georgakarakos (1996). Grey scaling of pixels corresponds to echo amplitude.



1990; Simmonds *et al.*, 1996) measured frequency-dependent backscatter from caged cod, haddock (*Melanogrammus aeglefinus*), pollock (*Pollachius virens*), mackerel (*Scomber scombrus*), and horse mackerel over a frequency range of 27 kHz to 54 kHz. Relative mean backscatter measurements in eight frequency bands were classified using DFA and ANN. Successful species identification depended on the number of species simultaneously insonified and the number of samples used in learning sets. Successful recognition by the ANN (77–100% with the largest learning set) typically exceeded that obtained using DFA (54–99%). Zakharia and colleagues (Zakharia and Sessarego, 1982; Zakharia, 1990b; Zakharia *et al.*, 1996) measured backscatter from individual tethered anchovy, sardine, and horse mackerel over a frequency range of 20 kHz to 80 kHz. Successful classification of individual fish using the spectral signature of each species ranged from 64% to 74%. Discriminating and classifying targets for both research groups depended on the amount and quality of data used as reference sets. Ongoing challenges of this approach include increasing the frequency range, improving metrics used to discriminate targets, and amassing a reference library of backscatter measures that represent all combinations of natural conditions.

Efforts to identify zooplankton species have also used theoretical scattering models based on geometric shapes, and statistical models derived from measurements of constrained or free-ranging animals. Theoretical models use physical and geometric properties of the organisms to predict backscattered echo amplitudes (Greenlaw, 1979; Stanton, 1989b; Chu *et al.*, 1993; Stanton *et al.*, 1994, 1996). Statistical models are based on narrowband measurements from tethered (Demer and Martin, 1995), encaged (Foote *et al.*, 1990), or free-ranging animals (Holliday and Pieper, 1980; Hewitt and Demer, 1991). One approach classifies zooplankton in morphologically based categories including gas-bearing (e.g. siphonophores), fluid-like (e.g. euphausiids), and elastic-shelled (e.g. pteropods) organisms (Stanton *et al.*, 1994; Martin *et al.*, 1996). Allocation of a target to a group depends on a comparison of periodic function parameters with theoretical backscatter model predictions or spectral decomposition techniques. Classification success of known animals ranged from means of 64% to 77% and may be improved by incorporating variance characteristics of echo ensembles (Martin *et al.*, 1998).

### *Matching models to resonance frequency measures*

Broadband measures of volume reverberation at resonant frequencies (i.e. 0.5 kHz to 10 kHz) have been combined with theoretical scattering models to identify and count fish within scattering layers and aggregations. Low-frequency sound sources, such as air guns, electric sparkers, seal control bombs (2.5 g of flash powder), blasting caps, and small (0.23 kg) TNT explosive charges (Holliday, 1972; Duncan, 1985; Nero *et al.*, 1997) are combined with omnidirectional or line hydrophones to measure backscattered sound at swimbladder resonant frequencies. The resonant frequency of a swimbladder depends on a fish's size and depth in the water (Weston, 1967). Holliday (1972, 1977b) was the first to demonstrate that swimbladder size is a function of fish size. If peaks in the backscatter spectrum correspond to resonant frequencies of the swimbladder, then echo spectra may be used to determine the size of acoustic targets (Hawkins, 1977). Applying these results to target classification using low frequencies requires the assumption that if species can be separated by size, then acoustic targets may be categorized using maximum echo amplitudes at resonant frequencies and verified using net samples or acoustic models.

Acoustic models are also used to examine backscattered echo amplitudes and swimbladder resonance when samples of fish are not readily available or are difficult to obtain (Andreeva, 1964; Chapman *et al.*, 1974; Love, 1978). Studies of mesopelagic fishes in deep scattering layers used resonance backscatter models to estimate echo amplitudes from trawl catches for comparison with synoptic acoustic samples (Love, 1975; Hall and Quinn, 1983; Kalish *et al.*, 1986). Recent studies (Love, 1993; Thompson and Love, 1996; Nero *et al.*, 1997) used this approach to estimate densities and abundances, and to identify fish in the Atlantic and Pacific Oceans. Species identification is achieved by matching species-specific swimbladder resonance models to length-frequency catch data and abundance estimates. This approach may not be applicable to all species, as the ability to control the shape and rigidity of the swimbladder wall using body musculature may alter swimbladder resonance frequency (Sand and Hawkins, 1973; Feuillade and Nero, 1998). Active control of swimbladder resonance potentially influences accuracy of fish size and abundance estimates from low-frequency backscatter measures.

## MODELLING ACOUSTIC BACKSCATTER

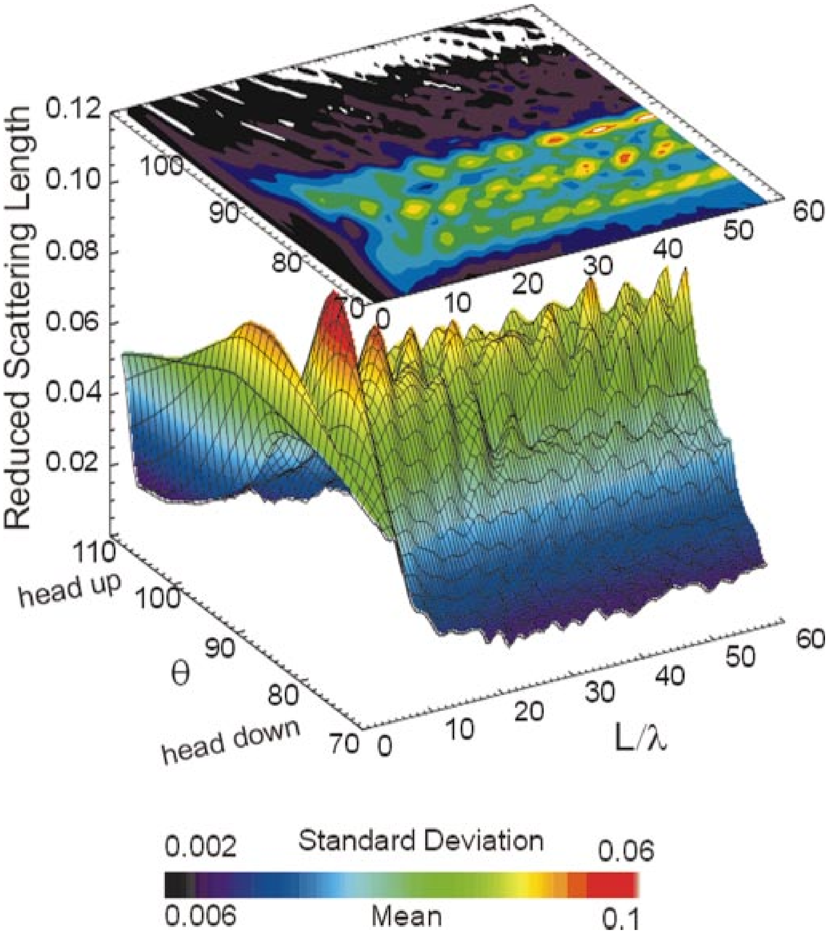
Measuring large numbers of echoes from free-ranging, individual fish is possible (Rudstam *et al.*, 1987) but difficult. Measuring sets of echoes from individual fish within aggregations is possible (Brede *et al.*, 1990; Ehrenberg and Torkelson, 1996) but more difficult. Backscatter models that predict echo amplitudes from single or aggregated animals complement laboratory and field measurements. Backscatter models quantify the relative importance of physical, anatomical, and behavioural factors influencing the magnitude of backscattered sound. Echo amplitudes can then be estimated throughout the Rayleigh and geometric scattering regions. Verifying model predictions under controlled conditions is possible for resonance (Cox and Rogers, 1987; Lewis and Rogers, 1996) and geometric (Nakken and Olsen, 1977; Rose and Porter, 1996) scattering frequencies. Models used to estimate echo amplitudes are continuously evolving (see table 1 in Horne and Clay, 1998), but can generally be grouped into geometric and empirical categories. Geometric backscatter models represent the organism of interest as a volume. Zooplankton are typically modelled as fluid-filled spheres (Anderson, 1950) or cylinders (Stanton, 1988, 1989a). Teleost fish have been modelled using gas-filled bubbles (Hersey and Backus, 1962) or cylinders (Haslett, 1965, 1966). Recent models replicate anatomical detail of the swimbladder and body (Foote, 1985; Foote and Traynor, 1988) or generalize animal morphology using combinations of regular shapes such as gas-filled (Do and Surti, 1990; Clay, 1992) and fluid-filled cylinders (Clay, 1991). Empirical backscatter models have been derived using echo amplitude measurements on caged (McCartney and Stubbs, 1971), tethered (Nakken and Olsen, 1977), or free-ranging animals (Traynor and Eherenberg, 1979).

Scattering amplitudes predicted using geometric or empirical models can be expressed for any fish species as a function of length, acoustic carrier frequency, and possibly fish aspect. To illustrate patterns and variability in backscatter amplitudes among fish, mean reduced scattering lengths were estimated for nine 200 mm Atlantic cod using Kirchhoff-ray mode backscatter models (Clay and Horne, 1994) and plotted as a function of organism length $L$, acoustic wavelength $\lambda$, and fish aspect angle $\theta$ (lower surface; Fig. 6). Peak amplitudes at any $L/\lambda$ value occur at approximately 83°. This represents a fish tilted head-down below horizontal and positions the upper surface of the swimbladder orthogonal to the transducer face. Along the fish-length-to-wavelength axis, if fish length is kept constant, then a higher $L/\lambda$ value corresponds to a higher frequency. Keeping the frequency constant illustrates effects of changing fish length on echo amplitude. Overall, there is less influence of fish aspect on target strength at lower $L/\lambda$ values. Throughout the $L/\lambda$ range, the response surface is symmetric about the peak echo amplitude. Unless a fish's swimbladder is near orthogonal (83° ± 2°) to the transducer face, echo amplitudes decrease as $L/\lambda$ values increase. Echo amplitudes decrease as $\theta$ deviates from horizontal. This drop in reduced scattering length is almost symmetric about the maximum and decreases to one-quarter of the maximum value within 15° of horizontal. In the upper contour surface (Fig. 6), standard deviation of backscatter amplitudes increased as $L/\lambda$ increased. Three, high backscatter variability ridges were formed at 77°, 83°, and 89°. The periodic peaks in the mean (lower surface) and standard deviation (upper contour plot) of scattering amplitudes correspond to areas of constructive and destructive backscatter interference. Together, the two plots provide a visual representation of the backscatter signal-to-noise ratio for fish aspect, length, and carrier frequency.

## REMAINING CHALLENGES

The current trend in fisheries acoustics is to increase the amount of information used in target classification and identification. This approach originated in plankton acoustics (McNaught, 1969; Holliday, 1972;

**Figure 6.** Estimated mean (lower surface) and standard deviation (upper contour) backscatter amplitudes (reduced scattering length $\mathscr{L}_{bs} / L$) of nine Atlantic cod (*Gadus morhua*) plotted as a function of fish aspect ($\theta$) and the ratio of fish length $L$ to acoustic wavelength $\lambda$. All fish were scaled to a length of 200 mm prior to calculations. Backscatter amplitudes were calculated using the Clay and Horne (1994) Kirchhoff-ray mode model.



Holliday and Pieper, 1995) and is being repeated in fisheries acoustics (Miyanohana *et al.*, 1990; Misund, 1993; McClatchie *et al.*, 1996). The amount of 'information' in acoustic measurements is increased by increasing frequency bandwidth or by increasing the acoustic swath. Multifrequency echosounders and broadband sonars increase the bandwidth transmitted by one or more transducers. Multibeam sonars use a single frequency and increase the number of beams transmitted and received by a single transducer. The recent availability of multibeam sonars has improved three-dimensional spatial representations of schooling fish (Misund *et al.*, 1992; Gerlotto *et al.*, 1994; Misund *et al.*, 1998) and zooplankton (Jaffe *et al.*, 1995; McGehee and Jaffe, 1996), and has provided insight into changes in shapes of fish aggregations caused by avoidance of the vessel (Olsen *et al.*, 1983; Misund and Aglen, 1992; Soria *et al.*, 1996).

The lack of a single acoustic instrument that samples all aquatic organisms suggests that the range of acoustically detectable organisms is sufficiently diverse to require several tools, or that the right combination of hardware and software has not been formulated. The diverse array of sonar equipment and analytic techniques may be a function of specialized trophic and species interests of investigators. In studies of mobile nekton, the sizes and habitats of interest rarely extend beyond a single predator species and its prey. Commercially important fish species are predominantly sampled using one or two geometric scattering frequencies, despite the early use of broad frequency ranges in investigations of deep scattering layers (Duvall and Christensen, 1946; Eyring *et al.*, 1948) and in the identification of 'biologics' for the military (*sensu* Love, 1993). This contrasts with the approach in plankton studies, where multifrequency data and the inverse approach are used to count and identify zooplankton. Backscatter from zooplankton and small fish is routinely measured at frequencies that extend from resonance to geometric scattering frequencies. Resistance to methodological changes by fisheries researchers may be influenced in part by the tradition of maintaining time series associated with commercially important fish stocks (Holliday and Pieper, 1995), the lack of trained personnel (Rose, 1992), and the limited availability and high cost of new technologies.

At least three challenges remain in the application of multichannel acoustic sensors to acoustic target identification. The first challenge is to refine data acquisition and storage when incorporating multiple data streams in integrated databases. Each data stream has at least one unique characteristic such as received frequency or angle. In addition to the challenge of indexing and integrating vast amounts of data, we do not know the number of 'perspectives' needed to adequately portray the shape and identity of aquatic organisms within an aggregation. Multifrequency echosounders provide at least one data stream for each frequency. The number of data channels from broadband data is a function of frequency range and numbers of filters used. Multibeam sonars can receive up to 128 single-frequency data channels across a 180° horizontal swath (e.g. SM2000 multibeam, Konsberg Simrad, Norway). It is now easy to collect gigabytes of data during a survey but the quality and effective use of data remains the responsibility of the user. A confounding factor that impedes collaboration and data exchange among users is the lack of a standard data format. Two international workshops examined this topic and proposed the platform-independent HAC (hydroacoustic) standard for raw and edited hydroacoustic data (Simard *et al.*, 1997).

The second remaining challenge is efficient description and visualization of multichannel acoustic data. Computer visualization provides a mechanism to integrate biological and physical data sets; to educate and translate results to other researchers; and to bridge the gap between acoustic theory and application. Restoring spatial and temporal components of acoustic data provides a visual format to qualitatively inspect distributions of organisms, and to characterize frequency- and behaviour-dependent backscatter from individual targets or aggregations. The visible colour spectrum can be used to represent backscatter amplitudes and serve as a visual 'ruler' when integrating multiple data streams. The challenge is to design a visualization that coherently portrays relationships among frequency, backscatter amplitude, body type, species, and behaviour. An important component of any initial description or visualization of acoustic data is quantifying magnitudes and relative importance of physical and biological factors that influence backscatter amplitudes. For example, when comparing data collected using echosounders with data collected using multibeam sonars, the primary source of variability in echo amplitudes shifts from target to source.

A final remaining challenge is the development of universal metrics that identify species over a range of packing densities and environmental conditions. The ability to identify species still depends on the ability to isolate, discriminate and classify acoustic targets. Target isolation is potentially improved through the incorporation of FM chirp technology, which increases spatial resolution and signal-to-noise ratios in received signals (Mayer and LeBlanc, 1983; Ehrenberg and Torkelson, 2000). Once discriminating characters are chosen, it is imperative to include quantitative measures of uncertainty for all target identifications. Discriminant function analysis and neural networks have been used to classify targets when data are not limited, but the discriminating power of any algorithm is always constrained by the reference library. Reliable species identification of acoustic targets requires an integrated hardware and software solution. Combining multifrequency (Wiebe *et al.*, 1997) or broadband (Zakharia *et al.*, 1996) technologies that span the resonance and geometric scattering regions with multibeam technology that characterizes aggregation shapes (Misund, 1997) is predicted to consolidate fisheries acoustic equipment and may be required to provide the data needed to reliably discriminate and identify aquatic species.

## CONCLUSIONS

The use of sound to count and classify organisms is a relatively new tool in aquatic science. Exclusive use of sound to definitively identify aquatic organisms is not currently possible, as echo shapes and maximum amplitudes vary among successive returns from the same animal. Investigating the influence of an organism's morphology and behaviour on echo amplitude and shape is just beginning. Effects of an organism's aspect (Foote, 1980b; Midttun, 1984; Horne and Clay, 1998) and boat avoidance (Olsen *et al.*, 1983; Misund and Aglen, 1992; Soria *et al.*, 1996) are fairly well documented, but other factors such as abdominal cavity contents (Ona, 1990), degree of aggregation (Stanton, 1985b; Misund, 1993), animal orientation (Clay and Horne, 1995; Medwin and Clay, 1997), and the material properties of scattering structures (Chu and Wiebe, 2000) require further examination.

Variability in echo amplitudes is influenced by choice of equipment, parameter settings, sampling conditions, and the morphology and behaviour of the target. Theoretical backscatter models verified using *in situ* or laboratory-based echo amplitude measures provide powerful tools to investigate aural reflective properties of aquatic organisms. The dominant trend in hardware development is to increase the amount of information collected during data acquisition by increasing frequency bandwidth or by increasing the number of transmitted beams. Even though trophic interests of the user influence choices of equipment, frequency range, and analytic techniques, the common challenge remains the development of statistical discriminators that reliably classify and identify acoustic targets and integrate these metrics in data processing.

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