

PERSPECTIVE

Sonar systems and aquatic organisms: matching equipment and model parameters¹

John K. Horne and Clarence S. Clay

Abstract: Acoustic technology is an accepted and important component of aquatic research and resource management. Despite the widespread use of echosounders, few guidelines aid in the choice of appropriate sonar system parameters for acoustic surveys. Choice of acoustic carrier frequency is analogous to the choice of spotlight colour used to illuminate a painting. Three primary biological factors influence the scattering of sound by aquatic organisms: swimbladder presence, organism length, and organism behaviour. We illustrate the influence of these factors on the amplitude of backscattered echoes using a Kirchhoff-ray mode scattering model to quantify fish and zooplankton backscatter as a function of carrier frequency, fish length, and swimbladder aspect. Model results illustrate that echo amplitudes from aquatic organisms are largely dependent on the presence or absence of a swimbladder. Target strengths generally increase with increasing carrier frequency and organism length. Swimbladder angle relative to the incident sound wave affects scattering amplitudes at all frequencies. Measurements of backscatter from swimbladdered fish are relatively robust when the ratio of fish length to acoustic frequency wavelength ranges between 2 and 10. As fish length to frequency wavelength ratios increase, echo amplitudes become more dependent on aspect and peak when the swimbladder is perpendicular to the acoustic wavefront.

Résumé : La technologie acoustique est un élément accepté et important de la recherche et de la gestion des ressources aquatiques. Malgré l'utilisation répandue des échosondeurs, il existe peu de lignes directrices qui aident à choisir les paramètres du système sonar convenant aux relevés acoustiques. Le choix de la fréquence porteuse est analogue au choix de la couleur d'un projecteur utilisé pour éclairer une peinture. Trois facteurs biologiques majeurs influent sur la diffusion du son par les organismes aquatiques : la présence d'une vessie natatoire, la longueur de l'organisme visé et son comportement. Nous illustrons l'effet de ces facteurs sur l'amplitude des échos rétrodiffusés à l'aide d'un modèle de diffusion des modes de rayonnement de Kirchhoff pour quantifier la rétrodiffusion due aux poissons et au zooplancton en tant que fonction de la fréquence porteuse, de la longueur des poissons et de l'aspect de la vessie natatoire. Les résultats du modèle indiquent que l'amplitude de l'écho provenant d'organismes aquatiques dépend largement de la présence ou de l'absence d'une vessie natatoire. L'intensité de cible augmente généralement en fonction de l'augmentation de la fréquence porteuse et de la longueur de l'organisme. L'angle de la vessie natatoire relativement à l'onde sonore incidente affecte l'amplitude de diffusion à toutes les fréquences. Les mesures de la rétrodiffusion provenant des poissons avec vessie natatoire sont relativement robustes lorsque le rapport entre la longueur des poissons et la longueur d'onde de la fréquence acoustique se situe entre les valeurs 2 et 10. À mesure que ce rapport augmente, l'amplitude des échos dépend de plus en plus de l'aspect de la vessie et atteint un maximum lorsque celle-ci est perpendiculaire au front d'onde acoustique.

[Traduit par la Rédaction]

Introduction

Recent advances in sonar technology have increased the use of acoustic data in aquatic ecosystem research and in the

management of harvestable resources. Federal governments, including Canada (cf. McFarlane and Kieser 1993), are increasing resources for use in acoustic research and surveys. These surveys quantify distributions, densities, and sizes of

Received March 24, 1997. Accepted December 5, 1997.
J13926

J.K. Horne.² Great Lakes Center, State University of New York at Buffalo State College, 1300 Elmwood Avenue, Buffalo, NY 14222-1095, U.S.A.

C.S. Clay. Department of Geology and Geophysics, University of Wisconsin–Madison, 1215 West Dayton Street, Madison, WI 53706, U.S.A.

¹ Contribution No. 581 of the Geophysical and Polar Research Center, University of Wisconsin, Madison, WI.

² Author to whom all correspondence should be addressed. Present address: Cooperative Institute for Limnology and Ecosystems Research, 2205 Commonwealth Boulevard, Ann Arbor, MI 48105, U.S.A. e-mail: horne@glrl.noaa.gov

Table 1. Summary of acoustic scattering models and measures of aquatic organisms or anatomical structures.

Organism or structure	Geometric form or measurement	Reference(s)
Zooplankton	Fluid-filled spheres	Anderson 1950; Johnson 1977a; Greenlaw 1977; Holliday and Pieper 1980
	Fluid-filled cylinders Bent, fluid-filled cylinders	Stanton 1988, 1989, 1990 Stanton 1988; Foote et al. 1990; Chu et al. 1993
Fish body	Gas-filled sphere	Hersey and Backus 1962; Andreeva and Chindinova 1964; Chapman and Marshall 1966
	Array of point scatterers	Huang and Clay 1980; Clay and Heist 1984
Fish swimbladder	Gas-filled spherical bubbles	Minnaert 1933; Andreeva 1964; Haslett 1965; Batzler and Pickwell 1970
	Gas-filled spheroid bubbles	Strasberg 1953; Devin 1959; Weston 1967; McCartney and Stubbs 1971; Love 1977, 1978; Furusawa 1988
Whole fish	Gas-filled cylinders	Haslett 1965, 1966
	Gas-filled swimbladder	Foote 1985; Ye and Farmer 1994
	Gas- and fluid-filled cylinders	Clay 1991, 1992
Empirical models	Literature review	Love 1971
	Caged	McCartney and Stubs 1971; Johannesson and Losse 1977; Foote 1983, 1986; Foote et al. 1990
	Tethered	Smith 1954; Hasimoto and Maniwa 1956; Harden Jones and Pearce 1958; Nakken and Olsen 1977; Foote 1983
	In situ	Traynor and Ehrenberg 1979; Foote 1987; Foote and Traynor 1988; Rose and Leggett 1988
	Statistical	Craig and Forbes 1969; Ehrenberg 1972; Peterson et al. 1976; Robinson 1978; Clay 1983

organisms through the entire water column over large geographic areas. Accurate conversions of acoustic data to population estimates require an understanding of the acoustic scattering properties of fish and invertebrates. Population estimates are based on theoretical, empirical, and statistical models of backscattering cross section or target strengths of aquatic organisms. We propose that the integration of theoretical acoustic models with empirical measures of backscatter forms a logical approach to understanding the biological scattering of sound.

Models and measures of acoustic scattering by zooplankton, fish and their swimbladders are continuously evolving (Table 1). Zooplankton have been modeled as fluid-filled spheres and bent, fluid-filled cylinders. Early swimbladder models were based on gas-filled spherical or spheroid bubbles and gas-filled cylinders. The fish body was first modeled as a gas-filled sphere, which ignored the shape of the animal.

Arrays of point scatterers have also been used to model the fish body form. More anatomically correct models use fluid-filled cylinders for zooplankton or a combination of gas- and fluid-filled cylinders for fish. Empirical scattering models of fish and zooplankton are derived using backscattered echo measurements and scattering lengths of caged, tethered, or free-ranging organisms. Statistical models of fish backscatter assume a theoretical, or tabulate an empirical, probability density function (PDF) of scattering amplitudes within an insonified beam.

The diversity of acoustic backscatter models and the range of commercially available sonar frequencies emphasizes the need for a general acoustic model of aquatic organisms. Simple geometric shapes regularly used in theoretical acoustic models inadequately represent asymmetrically shaped swimbladders (Foote 1985). Moreover the presence, structure, and orientation of swimbladders in fish is species dependent

(cf. Jones and Marshall 1953; Whitehead and Blaxter 1964; Alexander 1970). An ideal, general model must accurately represent anatomical structures of a large number of fish and zooplankton species, be applicable over wide ranges of organism lengths and acoustic frequencies, and include low-frequency resonance for species containing a swimbladder or other gas filled organ.

Despite the long awareness of frequency-dependent scattering by aquatic organisms (e.g., Hersey and Backus 1954; McNaught 1968, 1969), few general guidelines aid in the selection of sonar frequencies and other system parameters for bioacoustical research. One rule of thumb commonly used by fisheries scientists is "the smaller the organism, the higher the frequency." This strategy is based on observations that echo amplitudes from zooplankton decrease rapidly when the wavelength of sound, λ , is greater than the circumference of the organism (Anderson 1950; McNaught 1968, 1969; Greenlaw 1979). This results in larger echo amplitudes at high frequency (i.e., short λ) compared with echo amplitudes from the same organism observed at low frequency (i.e., long λ).

Aquatic organisms scatter sound in a complicated matter, and this general guideline is not without caveats. Simply increasing the carrier frequency will not avoid additional complications caused by frequency-dependent scattering. Martin et al. (1996) showed that target strengths of decapod shrimp decreased 10 dB when the carrier frequency was increased from 400 to 500 kHz. To address this problem, Greenlaw (1977) and Holliday and Pieper (1980) used simple theoretical models and measures of zooplankton backscatter to demonstrate that multiple frequency sonar data can be used to measure sizes of individuals and identify constituent species within zooplankton aggregations. A second limitation is the ability of an echosounder to resolve individual targets within the sonar beam. Increasing the carrier frequency of an echosounder reduces the wavelength and potentially increases target resolution. Unfortunately, an increase in frequency without an increase in transmission power reduces the effective range of the echosounder. Assuming negligible transducer motion, the ability to separate echoes from a pair of targets is dependent on the effective ping duration of the sonar system and the speed of sound in water. The minimum resolvable distance between two targets is equal to one-half the effective ping duration multiplied by the sound speed. Minimum ping duration of a sonar system is determined by the resonant frequency of the transducer and a quality factor of the transducer, Q . Most transducers are like bells, they transmit 10–20 cycles of sound at their resonant frequency with decreasing amplitude after being excited. High-frequency transducers typically have shorter minimum ping durations than low-frequency transducers. However, if two echosounders have different frequencies but the same effective ping duration then the resolution of the two systems is the same.

Sound-scattering characteristics of swimbladdered fish differ from those of similar sized zooplankton. Gas-filled swimbladders resonate sound at wavelengths, λ , that are many times larger than the length of the fish, L . The backscattering cross section, σ_{bs} , from any fish is dependent on acoustic carrier frequency over a large range of L/λ . Furusawa (1991) recommends that a value of $L/\lambda \geq 2$ provides relatively robust measures of sound scatter by aquatic organisms.

Logistic constraints, such as the size of a transducer or the required depth of observations, may influence the choice of acoustic carrier frequency, but we believe that organism morphology and behaviour should be included in the criteria used to select carrier frequency. Sonar carrier frequencies commercially available for fisheries research range from 12 to 420 kHz. Low carrier frequencies are primarily limited by transducer dimensions, while sound absorption in sea water often limits the maximum carrier frequency. In this paper, we use a Kirchhoff-ray mode model (Clay and Horne 1994) as a representative scattering model to demonstrate the dependence of echo amplitude on acoustic carrier frequency, organism length, body morphology, and angle of swimbladder relative to the incident sound wave. This model is used to calculate species-, angle-, and frequency-dependent acoustic backscatter from aquatic organisms and to guide the choice of carrier frequencies and system parameters for acoustic measurements.

Quantifying acoustic scattering

Returned echoes received at a sonar transducer are measured as pressures. Transducers used in fisheries research typically use the same elements to transmit and receive sound. Echoes returning to the transducer are said to be backscattered sound. The pressure of backscattered sound p_{scat} (units μPa) is calculated as

$$(1) \quad p_{scat} = D_t D_r \frac{[p_0 R_0]}{R^2} l_{bs}$$

where D_t is the transmitting beam pattern or directivity of the transducer, D_r is the receiving beam pattern of the transducer, p_0 is the on-axis source sound pressure at a reference range, R_0 , of 1 m; R is the range (units m) to the scattering object, and l_{bs} is the scattering length (units m) of the scattering object. The combination of terms ($p_0 R_0$) is the source calibration of the sonar. Equation 1 is a form of the sonar equation and can be rearranged to provide a solution for scattering length l_{bs} :

$$(2) \quad l_{bs} = \frac{p_{scat} R^2}{D_t D_r [p_0 R_0]}$$

A variety of derived terms have been used to quantify the scattering of sound by aquatic organisms. Backscattering length, l_{bs} , is dependent on the acoustic frequency, f , or wave number, $k = 2\pi/\lambda$ (where λ is the wavelength, units m), the equivalent spherical radius of the organism, a (units m), L (units m), and the angle of the organism relative to the sonar beam χ (units degrees). The square of the absolute scattering length is σ_{bs} (Clay and Medwin 1977):

$$(3) \quad \sigma_{bs} = |l_{bs}|^2$$

The logarithmic transformation of back scattering cross section is the target strength, TS (units dB):

$$(4) \quad \text{TS} = 10 \log_{10}(\sigma_{bs}/L_0^2) = 20 \log_{10}(|l_{bs}|/L_0)$$

where L_0 is the reference length, typically 1 m.

Fig. 1. Schematic diagram illustrating the geometric construction of Kirchhoff-ray mode acoustic models of an Atlantic cod (*Gadus morhua*) in (a) lateral and (b) dorsal view. The fish body and swimbladder are represented by a series ($j = 1, 2, \dots, n$) of short, fluid- (body) and gas- (swimbladder) filled cylinders. χ is the aspect angle of the swimbladder measured relative to the longitudinal axis of the fish. (c) Coordinate systems used in model calculations. The ray path from the transducer and its normals form directions of the x, y, z coordinate system (solid lines). The u, v, w coordinate system is relative to the fish (broken lines).

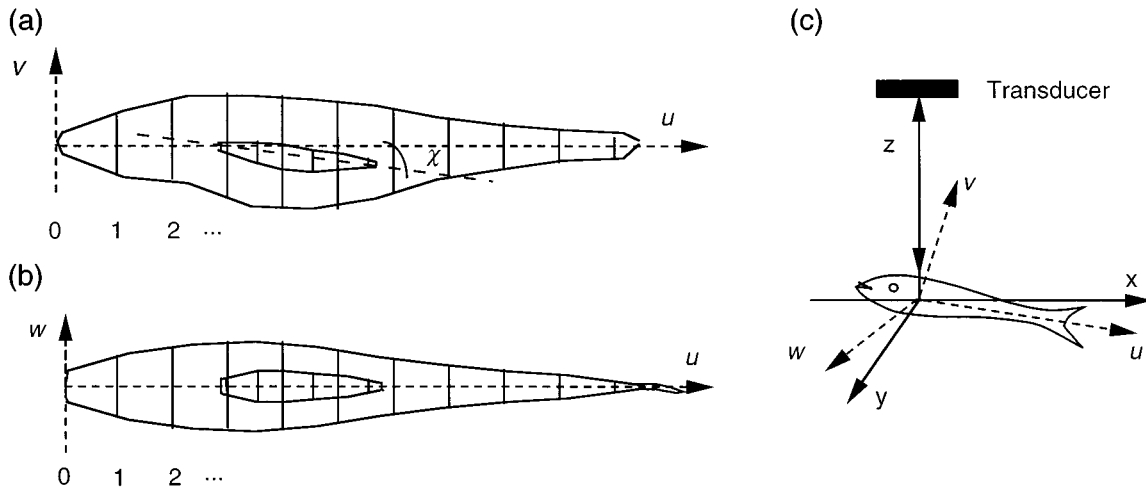
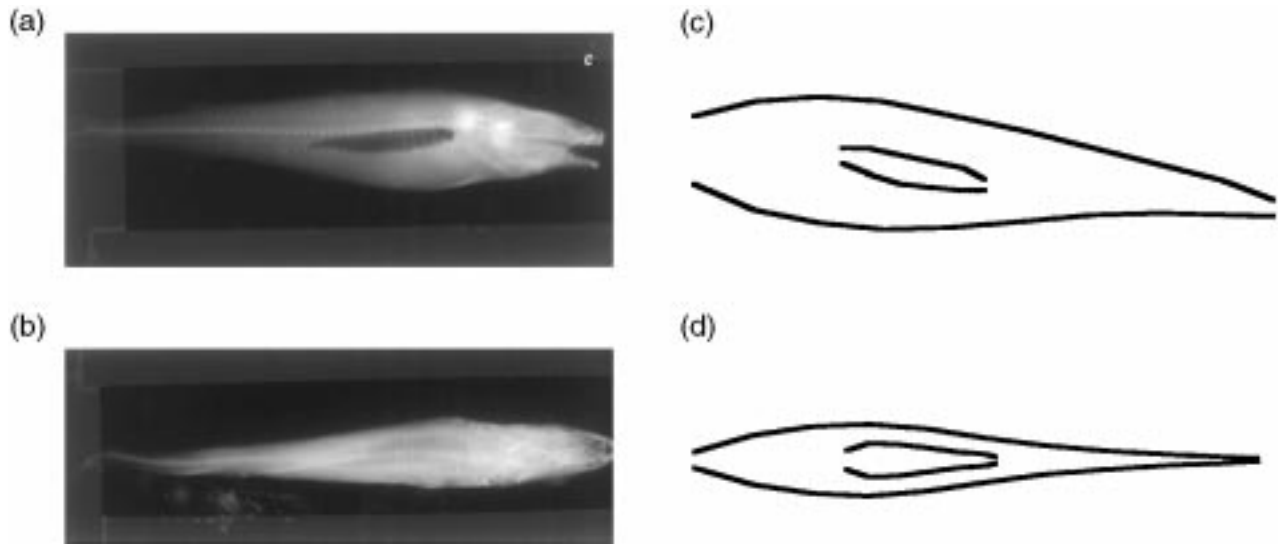


Fig. 2. (a) Lateral and (b) dorsal X-ray images of a 323-mm, 286-g Atlantic cod (*Gadus morhua*). The swimbladder is silhouetted in the body. Corresponding (c) lateral and (d) dorsal digitized images of the same cod used in the Kirchhoff-ray mode acoustic model.



The following “reduced” quantities are convenient as scattering length is often proportional to L :

- (5) Reduced scattering length = l_{bs}/L
- (6) Reduced backscattering cross section = σ_{bs}/L^2

Reduced scattering lengths and reduced backscattering cross sections are dimensionless quantities. The reduced TS is calculated as

$$(7) \quad TS_{\text{reduced}} = 10 \log_{10}(\sigma_{bs}/L^2) = 20 \log_{10}(|l_{bs}|/L)$$

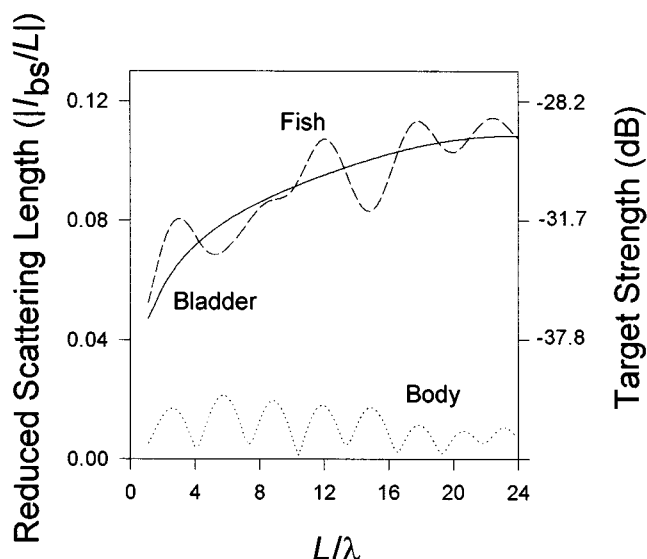
We compute echo amplitudes as reduced scattering lengths

to standardize the effect of organism length and then convert to TS (units dB) to provide familiar units to fisheries readers.

Model structure

Foote (1985) and Foote and Traynor (1988) developed an accurate and elaborate method to calculate the scattering of sound by swimbladdered fish. Clay and Horne (1994) simplified this technique by modeling a fish’s body and swimbladder as a set of fluid- and gas-filled cylinders (Fig. 1). In the original model, fish bodies and swimbladders were digitized from dorsal and lateral X-ray images (Fig. 2) of Atlantic cod (*Gadus morhua*). Either a gas-filled prolate spheroid or a low-mode cylinder solution can be used to compute the scattering

Fig. 3. Reduced scattering lengths of a Kirchhoff-ray mode modeled swimbladder, fish body, and whole fish plotted as a function of fish length to wavelength ratio L/λ . Calculations were based on a 323-mm Atlantic cod (*Gadus morhua*).

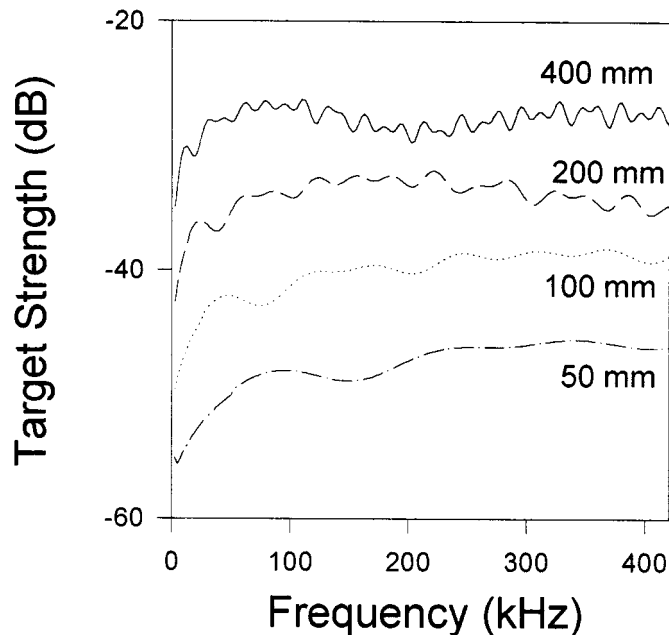


length of the swimbladder at the low-frequency, breathing-mode resonance (Love 1978; Clay 1992). Low-frequency, breathing-mode resonance has been used to identify species in ensembles of organisms (e.g., Greenlaw 1979; Holliday 1980; Zakharia and Sessarego 1982), but breath-mode resonance is very dependent on organism behaviour (Feuillade and Nero 1998) and recent depth history (Sand and Hawkins 1973). A low-mode solution for a gas-filled cylinder is used to compute the low-frequency, breathing-mode resonance. At high frequencies, $L/\lambda > 1$, sound is scattered by the top surface of the swimbladder and is independent of depth. The acoustic contrast between the top surface and the rest of swimbladder is so large that all anatomical structure below the top surface contributes little to the sound scattered by the swimbladder. We use Kirchhoff-ray approximations to compute high-frequency acoustic scattering (Foote 1985; Clay 1991) by the swimbladder and by the fish body. Backscatter from the swimbladder and fish body are then summed to estimate backscatter from the whole fish. Backscatter from non-swimbladdered aquatic organisms such as zooplankton can be estimated by omitting the backscatter from the swimbladder.

Biological influences on scattered sound

Aquatic organisms are complicated scatterers by nature of their shape (cylindrical or spheroid), deformation (curvature of the body and swimbladder), and composition (exoskeleton, muscle, bone, fat, presence and shape of swimbladder). The presence of a swimbladder is the most important factor affecting the amplitude of a returned echo. Swimbladders provide a large acoustic contrast to flesh or skeletal elements and form the major ($\geq 90\%$; Foote 1980a) source of backscattered sound in teleost fish. For typical fish lengths (1–100 cm), swimbladders scatter sound over a range of three orders of frequency magnitude (hundreds of Hz to hundreds of kHz). Acoustic scattering by a swimbladder is four or more times

Fig. 4. Target strengths (dB) of a 323-mm Atlantic cod (*Gadus morhua*) scaled to 50, 100, 200, and 400 mm plotted as a function of frequency (kHz).

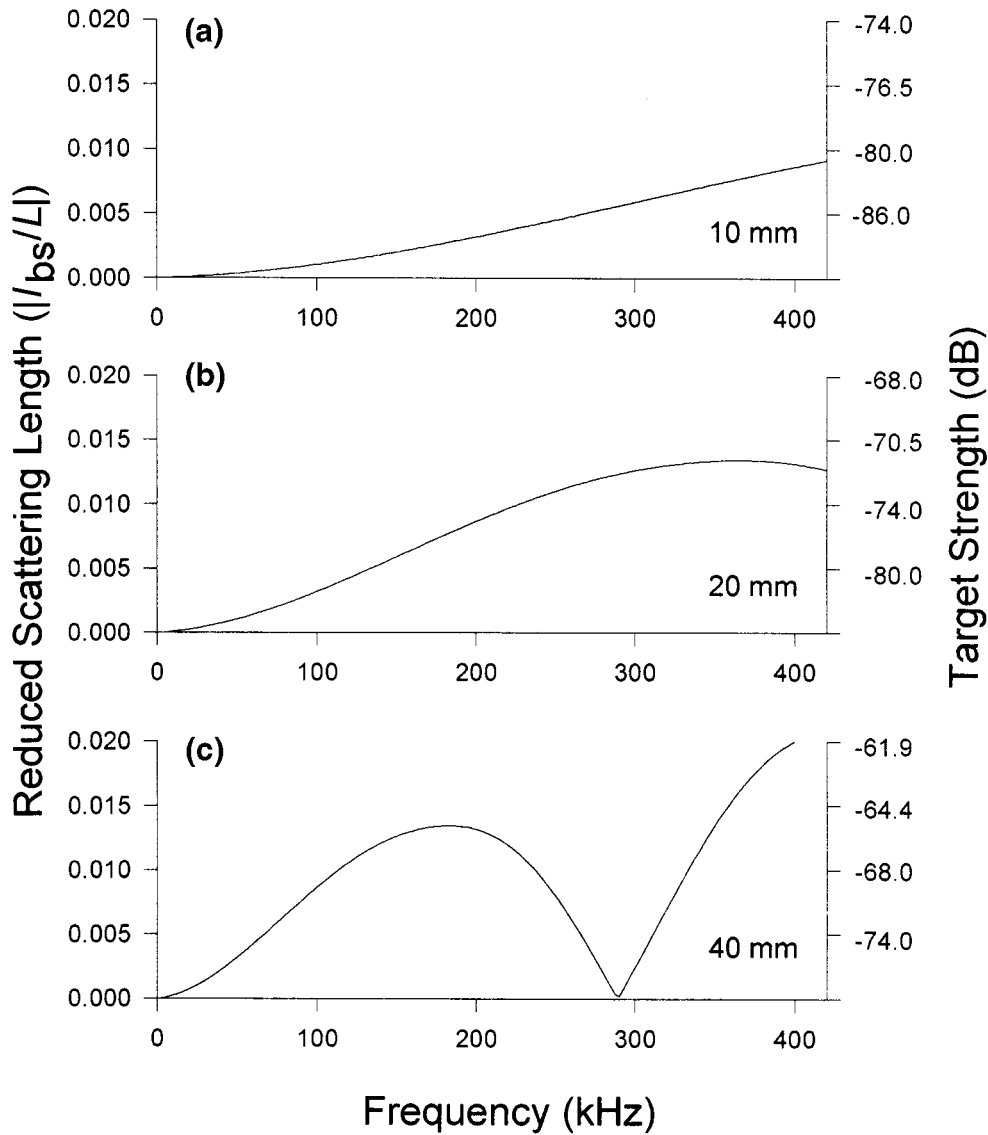


greater than the scattering by fish bodies at any given frequency (Fig. 3). Frequency-dependent changes in the magnitude of backscatter for the entire fish are primarily due to the morphology of the swimbladder; oscillations in scattering magnitudes are primarily due to the fish body. As examined below, these frequency-dependent oscillations also depend on the aspect of the swimbladder relative to the incident sonar beam.

At low frequencies (ca. 100–1000 Hz), backscattered sound is largely due to resonance within the swimbladder (Clay 1991, 1992). Variability in swimbladder resonance due to differences in swimbladder size and morphology can potentially be used to help identify fish species in acoustic data. Empirical measures of resonance scattering by swimbladdered fish have been used to identify and estimate numbers of commercial fish species (e.g., Holliday 1972; Love 1993). This is not a common practice in fisheries research, as the resonance frequency region is lower than normal operating frequencies of fisheries echosounders. At high frequencies (>1000 Hz), sound is reflected from the upper surface of the swimbladder and is not significantly influenced by fish depth, stomach fullness, or gonad development.

A second factor influencing the amplitude of acoustic backscatter is organism length. Backscatter from a 323-mm X-rayed cod (Fig. 2), scaled from 50 to 400 mm, was calculated using the Kirchhoff-ray mode model, converted to target strengths, and plotted as a function of frequency. Clay and Horne (1994) found that for comparative purposes, cod could be linearly scaled to a common length. Target strength generally increases with increasing frequency and length of an animal (Fig. 4). The overall “shape” of the scattering curve is due to backscatter by the swimbladder. Transition from resonant to geometric scattering by the swimbladder occurs below 1 kHz. Comparison of the 50–400 mm scattering curves illus-

Fig. 5. Reduced scattering lengths of a 60-mm calanoid zooplankter scaled to (a) 10, (b) 20, and (c) 40 mm plotted as a function of frequency.



trates how the influence of the fish body on the scattering curve increases as fish length increases.

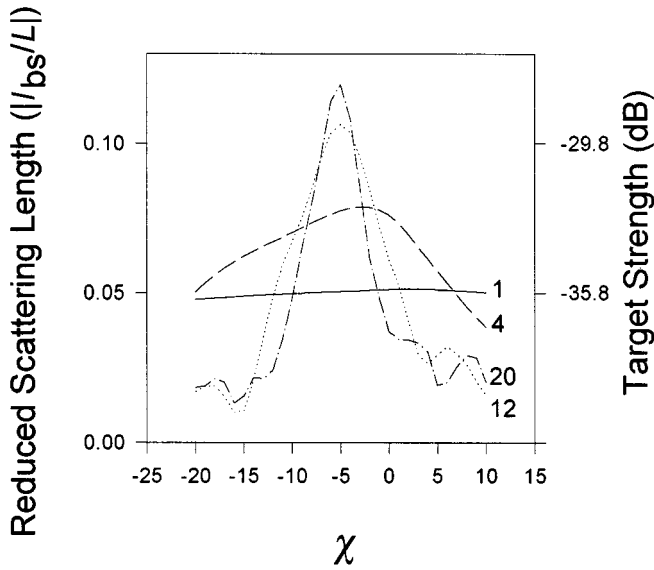
The frequency dependence of scattering amplitude on organism length is also observed among non-swimbladdered animals. The Kirchhoff-ray mode model can be used to estimate backscatter from non-swimbladdered fish or zooplankton. As an example, acoustic backscatter of a 60-mm decapod zooplankter was estimated at three lengths and plotted as a function of frequency (Fig. 5). Reduced scattering lengths of zooplankton are an order of magnitude lower than those of swimbladdered fish (Fig. 4) and do not contain frequency-dependent, small-amplitude oscillations present in the scattering curves of fish. The general monotonic increase in backscatter with increasing fish length does not occur across all frequencies for zooplankton.

The angle of an organism's swimbladder relative to the incident sound wave affects scattering amplitudes at all frequencies. Midttun (1984) reviews studies that cite the dependence of target strength on fish aspect angle. Olsen (1977) and Foote (1980b) have developed models to predict mean

target strength of Atlantic cod based on fish aspect distributions and transducer beam patterns. Swimbladder angles typically differ from fish body aspects by 5–10° (see Fig. 1). For example, the swimbladder in the 323-mm cod deviates 5° from horizontal with the posterior end of the swimbladder pointed downward (Fig. 2). Reduced scattering lengths of the 323-mm cod scaled to 150 mm were computed for L/λ values of 1, 4, 12, and 20 and plotted as a function of aspect angles ranging from -25° to 15° (Fig. 6). The swimbladder is perpendicular to the incident sound wave at -5° from horizontal. At low L/λ values, scattering amplitudes are almost independent of aspect angle. As L/λ values increase, scattering lengths become more dependent on aspect and peak when the swimbladder is perpendicular to the acoustic wavefront. At $L/\lambda = 20$, scattering lengths range from 0.01 to 0.12, which is equivalent to a target strength change of 20 dB. Insonifying a single animal that varies its aspect or insonifying an aggregation of animals oriented at a variety of angles will result in a distribution of echo amplitudes.

In mobile surveys, it should be noted that the combination

Fig. 6. Reduced scattering lengths of a 323-mm Atlantic cod (*Gadus morhua*) scaled to 150 mm and plotted as a function of swimbladder deviation from horizontal for fish length to wavelength ratios: $L/\lambda = 1$ (solid line), 4 (broken line), 12 (dotted line), and 20 (dash-dot line).



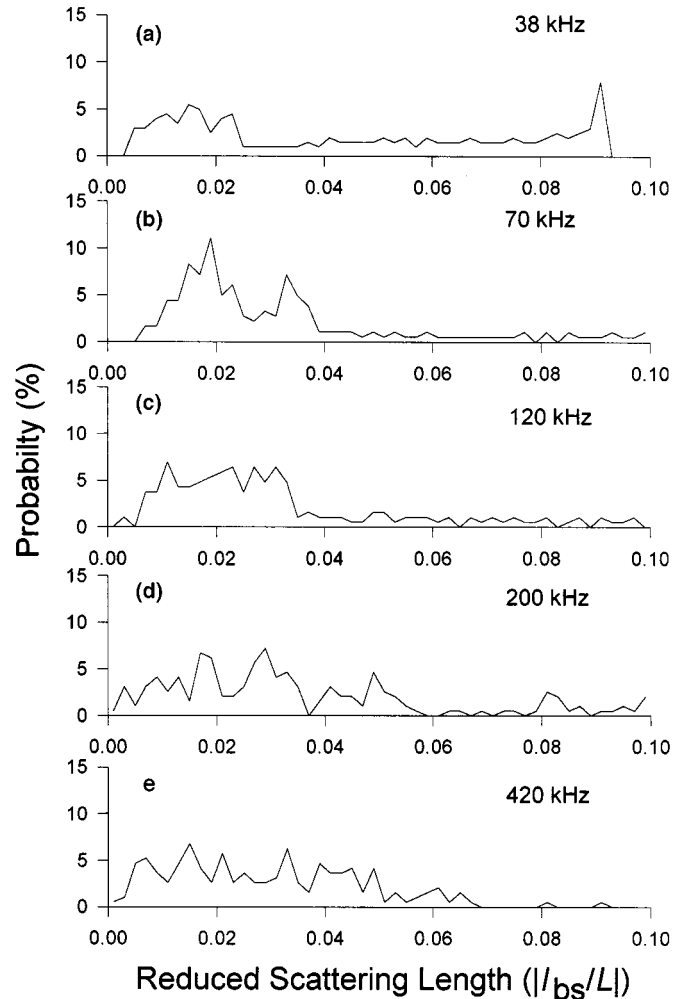
of narrow-beam transducers ($<10^\circ$; Furusawa 1991), transducer motion, and aspect angle potentially bias acoustic data to smaller target strengths because of a reduction in apparent equivalent beam angle. With as little as 4° of transducer motion, Stanton (1982) found that echo amplitudes of a fish at 400 m deviated by as much as 64% for a 5° beamwidth transducer but only 1.4% for a 40° beamwidth transducer. For any individual fish, this bias diminishes at lower frequencies as L/λ decreases. It may be possible to use data from multiple or broadband sonars to determine aspect deviation of insonified targets by comparing target strengths to L/λ ratios (cf. Furusawa and Miyano-hana 1990).

Repeated measures of a single fish at different aspects produces a PDF of scattering lengths. We tabulated the probability of reduced scattering lengths for a 323-mm cod over a uniformly distributed range of angles from -25° to 15° for the five common fisheries acoustic frequencies (Fig. 7). In general, the range of scattering lengths with a probability of occurring greater than 4% (arbitrary level) increases with an increase in acoustic carrier frequency. This is attributed to larger differences in scattering amplitudes as the swimbladder aspect deviates (positive or negative) from horizontal at higher frequencies (see Fig. 6). These empirical probability distributions could also be modeled using a theoretical Rician PDF. Clay and Heist (1984) use the mean backscattering cross section $\overline{\sigma}_{bs}$ and γ to parameterize Rician PDFs of fish backscatter. γ is the ratio of the concentrated or mean backscattering cross section σ_{bs} to the distributed or random component of the backscattering cross section σ_d :

$$(8) \quad \gamma = \frac{\overline{\sigma}_{bs}}{\sigma_d}$$

The value of γ has been shown to depend on fish morphology, behaviour, and L/λ . Values of small fish are larger than those

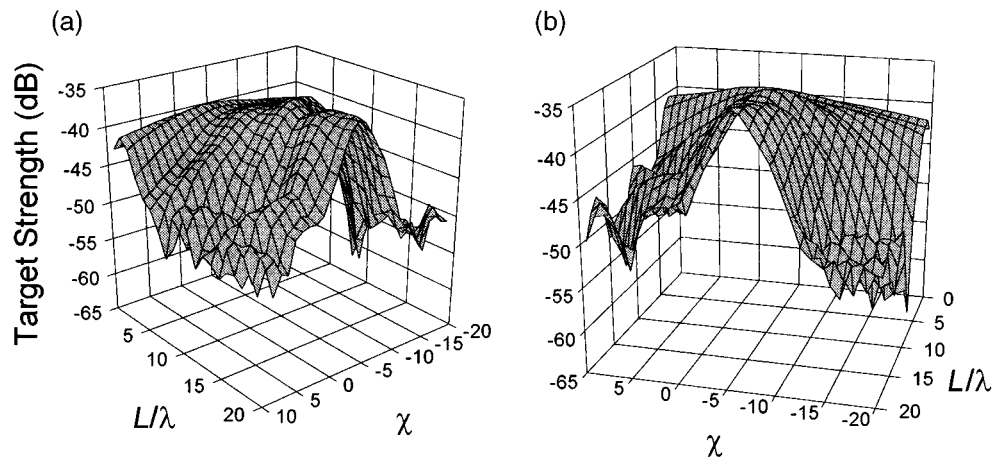
Fig. 7. Probability of backscatter (%) from a 323-mm Atlantic cod (*Gadus morhua*) at (a) 38, (b) 70, (c) 120, (d) 200, and (e) 420 kHz plotted as a function of reduced scattering length.



of large fish. As L/λ increases, γ decreases and tends to zero for $L/\lambda > 12$. Rician PDFs have been used to model the distribution of echo amplitudes in decapod shrimp (Wiebe et al. 1990) and to compare γ values from zooplankton (Stanton et al. 1993) and fish (Trevorrov 1996) aggregations. A reason for using theoretical PDFs for descriptions of echo amplitudes is that, if target species and behaviour are known, comparison of echo statistics such as γ from multiple frequencies may provide a way to differentiate among targets in acoustic survey data (Jech et al. 1995).

To summarize factors influencing acoustic backscatter of swimbladdered fish, target strengths of the scaled 150-mm Atlantic cod were plotted as a function of the ratio of organism length to acoustic wavelength and aspect angle (Fig. 8). Unless a fish's swimbladder is near orthogonal ($90 \pm 2^\circ$) to the face of the transducer, target strengths decrease as L/λ increases (Fig. 8a). The drop in target strengths is non-monotonic and decreases three and one-third times the maximum (i.e., 20 dB) over a L/λ range of 1–20. The dependence of target strength on swimbladder aspect is emphasized by rotating the three-dimensional mesh diagram (Fig. 8b). As χ deviates from horizontal, target strengths decrease. Decreases

Fig. 8. (a) Modeled target strengths from a 323-mm Atlantic cod (scaled to 150 mm) plotted as a function of length to wavelength ratio, L/λ , and aspect angle, χ . (b) Plot was rotated to emphasize changes in target strength as fish aspect deviates from horizontal. Maximum target strength is at -5° , which corresponds to the aspect of the swimbladder relative to the longitudinal axis of the fish (see Figs. 2a and 2c).



in target strengths are greater at higher values of L/λ . At high L/λ values, the curve is almost symmetric about the maximum scattering amplitude. Target strengths range 20 dB within 15° of horizontal. Fish length, carrier frequency, and fish aspect all interact to influence the magnitude of returned echoes.

Acoustic constraints

Organism behaviour combined with variation in morphology complicates the calculation of organism lengths from target strengths (Nakken and Olsen 1977; Huang and Clay 1980; Ehrenberg et al. 1981) and potentially influences precision in estimates of organism number or biomass (Hawkins 1981). Exclusive reliance on empirical backscatter measurements in a regression equation does not ensure accurate conversion of acoustic sizes to organism lengths. An implicit assumption in this approach is that animals insonified by the echosounder are within the same length range used to determine the statistical relationship between fish length and amplitude of returned echo. The range of target strengths that can be converted to fish lengths should not be extrapolated beyond the limits of data used to establish the relationship. A second common assumption is that statistical relationships between echo amplitudes and fish lengths are independent of acoustic frequency. We have shown that backscatter amplitudes are dependent on fish species, fish aspect, fish length, and acoustic carrier frequency. Theoretical acoustic models of swimbladdered and non-swimbladdered organisms are needed to explain variability in backscatter measurements, to improve estimation of animal length from acoustic target size, and to improve target recognition and discrimination among types of acoustic backscatterers (e.g., swimbladdered from non-swimbladdered organisms).

The conversion of single-frequency acoustic sizes to organism lengths is also constrained by the ability of sonars to resolve single targets. Resolution of single targets depends on effective pulse duration, sonar beam width, the speed of sound in water, and organism density. Many species of aquatic organisms shoal or school at densities too high to acoustically discriminate among individuals (Dickie et al.

1983). In this situation, individuals on the periphery of an aggregation are often used to tabulate a length-frequency distribution of the group. This frequency distribution is used in a regression equation to estimate lengths and densities of organisms within an aggregation (e.g., Haslett 1969; Holliday and Pieper 1980; Ehrenberg et al. 1981). This approach assumes that the type and length-frequency distribution of organisms at the periphery matches that of individuals within the aggregation. This may not always be the case. Rose (1993) found that aggregations of migrating Atlantic cod were structured by fish length.

One way to resolve and size organisms within aggregations is to use multifrequency or broadband sonars and high-resolution signal processing (Holliday et al. 1989). Multifrequency sonars measure scattering amplitudes over a range of discrete frequencies, while broadband systems measure backscatter over a continuous frequency range and decompose echoes into spectral components. Resolution of a target is based on the frequency-dependent relationship between target size and magnitude of returned echo (Holliday 1972, 1980). Acoustic scatter models can be combined with multifrequency or broadband data in the inverse approach to estimate length distributions of acoustic targets (e.g., Horne and Jech 1998). The inverse approach uses backscatter amplitudes from a known population to model types and length distributions of acoustic scatterers. This reference set is then used to estimate the abundance of animals in the water column. Integrated multifrequency sounder data have been used with the inverse approach to determine length-frequency distributions of zooplankton (Greenlaw 1979; Holliday 1980; Holliday et al. 1989; Pieper et al. 1990) and small fish (Johnson 1977b; Holliday 1980), to separate fish length distributions from those of plankton (Sætersdal et al. 1984; Cochrane et al. 1991), and in an attempt to classify fish by species (Zakharia and Sessarego 1982).

The number and type of sonar frequencies chosen for fisheries research is often constrained by hardware that is currently available, or by funds available to purchase new equipment. The complexity of choosing the right equipment is compounded when the geographic area of interest contains

more than one fish species in single or multispecies aggregations. We suggest three primary factors be assessed when choosing carrier frequencies for bioacoustic research:

- (1) Presence of a swimbladder. If the species of interest does not have a swimbladder then the frequency that robustly maximizes backscattering amplitudes should be used to survey distributions. The presence of a swimbladder shifts the focus of frequency choice to the expected length and aspect distributions of the species of interest.
- (2) Organism length. To avoid bias in acoustic backscatter measures and to aid in species identification of acoustic targets, frequencies should be chosen to restrict values of L/λ from 2 to 10.
- (3) Organism behaviour. Shoaling and aspect angle are two behaviours that have large effects on backscatter amplitudes. If organisms shoal or school in single or multispecies aggregations, then multifrequency or broadband sonar systems combined with the inverse approach can be used to resolve and identify individual acoustic targets. When using single-frequency systems, sampling should be conducted when organisms are dispersed in the water column. If the species of interest has a wide distribution of aspect angles, the organism length to wavelength ratio should approximate 2 to minimize the dependence of scattering amplitude on aspect angle.

Acknowledgments

This work was supported in part by the National Science Foundation (OCE-9415740), the Office of Naval Research (N00014-89J-1515), the New York Sea Grant Institute (NA46RG0090), and the Geophysical and Polar research Center, University of Wisconsin (C.S.C.). We thank Dr. R. Kieser for a thorough review that improved the manuscript.

References

- Alexander, R.M. 1970. Functional design in fishes. 2nd ed. Hutchinson, London.
- Anderson, V.C. 1950. Sound scattering from a fluid sphere. *J. Acoust. Soc. Am.* **22**: 426–431.
- Andreeva, I.B. 1964. Scattering of sound by air bladders of fish in deep sound-scattering layers. *Sov. Phys. Acoust.* **10**: 17–20.
- Andreeva, I.B., and Chindinova, Y.G. 1964. On the nature of deep-scattering layers. *Okeanologiya* No. 4.
- Batzler, W.E., and Pickwell, G.V. 1970. Resonant acoustic scattering from gas bladder fish. *In Proceedings of an International Symposium on Biological Sound Scattering in the Ocean*, March 31 – April 2, Wamenton, Virginia. Edited by G.B. Farquhar. U.S. Government Printing Office, Washington, D.C. pp. 168–179.
- Chapman, R.P., and Marshall, J.R. 1966. Reverberation from deep scattering layers in the western North Atlantic. *J. Acoust. Soc. Am.* **40**: 405–411.
- Chu, D., Foote, K.G., and Stanton, T.K. 1993. Further analysis of target strength measurements of Antarctic krill at 38 and 120 kHz: comparison with deformed cylinder model and inference of orientation distribution. *J. Acoust. Soc. Am.* **93**: 2985–2988.
- Clay, C.S. 1983. Deconvolution of the fish scattering PDF from the echo PDF for a single transducer sonar. *J. Acoust. Soc. Am.* **73**: 1989–1994.
- Clay, C.S. 1991. Low-resolution acoustic scattering models: fluid-filled cylinders and fish with swimbladders. *J. Acoust. Soc. Am.* **89**: 2168–2179.
- Clay, C.S. 1992. Composite ray-mode approximations for backscattered sound from gas-filled cylinders and swimbladders. *J. Acoust. Soc. Am.* **92**: 2173–2180.
- Clay, C.S., and Heist, B.G. 1984. Acoustic scattering by fish—acoustic models and a two-parameter fit. *J. Acoust. Soc. Am.* **75**: 1077–1083.
- Clay, C.S., and Horne, J.K. 1994. Acoustic models of fish: the Atlantic cod (*Gadus morhua*). *J. Acoust. Soc. Am.* **96**: 1661–1668.
- Clay, C.S., and Medwin, H. 1977. *Acoustical oceanography*. Wiley, New York.
- Cochrane, N.A., Sameoto, D., Herman, A.W., and Neilson, J. 1991. Multiple-frequency acoustic backscattering and zooplankton aggregations in the inner Scotian Shelf basins. *Can. J. Fish. Aquat. Sci.* **48**: 340–355.
- Craig, R.E., and Forbes, S.T. 1969. Design of a sonar for fish counting. *Fiskeridir. Skr. Ser. Havunders.* No. 15. pp. 210–219.
- Devin, C., Jr. 1959. Survey of thermal, radiation and viscous damping of pulsating air bubbles in water. *J. Acoust. Soc. Am.* **31**: 1654–1667.
- Dickie, L.M., Kerr, S.R., and Boudreau, P.R. 1983. An echo counting and logging system (ECOLOG) for demersal fish size distributions and densities. *Can. J. Fish. Aquat. Sci.* **40**: 487–498.
- Ehrenberg, J.E. 1972. A method for extracting the fish target-strength distribution from acoustic echoes. *In Proceedings of the 1972 IEEE Conference on Engineering and the Ocean Environment*, September 13–15, Newport, R.I., U.S.A. Vol. 1. pp. 61–64.
- Ehrenberg, J.E., Carlson, T.J., Traynor, J.J., and Williamson, J.J. 1981. Indirect measurement of the mean backscattering cross section of fish. *J. Acoust. Soc. Am.* **69**: 955–962.
- Feuillade, C., and Nero, R.W. 1998. A viscous-elastic swimbladder model for describing enhanced-frequency resonance scattering from fish. *J. Acoust. Soc. Am.* **103**: 3245–3255.
- Foote, K.G. 1980a. Importance of the swimbladder in acoustic scattering by fish: a comparison of gadoid and mackerel target strengths. *J. Acoust. Soc. Am.* **67**: 2084–2089.
- Foote, K.G. 1980b. Averaging of fish target strength functions. *J. Acoust. Soc. Am.* **67**: 504–515.
- Foote, K.G. 1983. Linearity of fisheries acoustics, with addition theorems. *J. Acoust. Soc. Am.* **73**: 1932–1940.
- Foote, K.G. 1985. Rather-high-frequency sound scattered by swimbladdered fish. *J. Acoust. Soc. Am.* **78**: 688–700.
- Foote, K.G. 1986. A critique of Goddard and Welsby's paper: "The acoustic target strength of live fish." *J. Cons. Cons. Int. Explor. Mer.* **42**: 212–220.
- Foote, K.G. 1987. Fish target strengths for use in echo integrator surveys. *J. Acoust. Soc. Am.* **82**: 981–987.
- Foote, K.G., and Traynor, J.J. 1988. Comparison of walleye pollock target strength estimates determined from in situ measurements and calculations based on swimbladder form. *J. Acoust. Soc. Am.* **73**: 1932–1940.
- Foote, K.G., Everson, I., Watkins, J.L., and Bone, D.G. 1990. Target strengths of Antarctic krill (*Euphausia superba*) at 38 and 120 kHz. *J. Acoust. Soc. Am.* **87**: 16–24.
- Furusawa, M. 1988. Prolate spheroidal models for predicting general trends of fish target strength. *J. Acoust. Soc. Jpn. Ser. E*, **9**: 13–24.
- Furusawa, M. 1991. Designing quantitative echo sounders. *J. Acoust. Soc. Am.* **90**: 26–36.
- Furusawa, M., and Miyanohana, Y. 1990. Behaviour and target-strength observation through echo traces of individual fish. *Rapp. P.-v. Réun. Cons. Int. Explor. Mer.* **189**: 283–294.
- Greenlaw, C.F. 1977. Backscattering spectra of preserved zooplankton. *J. Acoust. Soc. Am.* **87**: 16–24.
- Greenlaw, C.F. 1979. Acoustical estimation of zooplankton populations. *Limnol. Oceanogr.* **24**: 226–242.
- Harden Jones, F.R., and Pearce, G. 1958. Acoustic reflection experiments with perch (*Perca fluviatilis* L.) to determine the proportion

- of the echo returned by the swimbladder. *J. Exp. Biol.* **35**: 437–450.
- Hasimoto, T., and Maniwa, Y. 1956. Study of reflection loss of ultrasonic millimeter wave on fish body. Tech. Rep. Fishing Boats No. 8.
- Haslett, R.W.G. 1965. Acoustic backscattering cross sections of fish at three frequencies and their representation on a universal graph. *Br. J. Appl. Phys.* **16**: 1143–1150.
- Haslett, R.W.G. 1966. Acoustic backscattering from an air-filled cylindrical hole embedded in a sound-translucent cylinder. *Br. J. Appl. Phys.* **17**: 549–561.
- Haslett, R.W.G. 1969. The target strengths of fish. *J. Sound Vib.* **9**: 181–191.
- Hawkins, A.D. 1981. Some biological sources of error in the acoustic assessment of fish abundance. *In Proceedings of the Meeting on Hydroacoustical Methods for the Estimation of Marine Fish Populations*, June 25–29, 1979. Vol. 2. *Edited by* J.B. Suomala. Draper Laboratories, Cambridge, Mass. pp. 1983–2000.
- Hersey, J.G., and Backus, R.H. 1954. New evidence that migrating gas bubbles, probably the swimbladders of fish, are largely responsible for scattering layers on the continental rise south of New England. *Deep-Sea Res.* **1**: 190–191.
- Hersey, J.G., and Backus, R.H. 1962. Sound scattering by marine organisms. Ch. 13. *In The sea*. Vol. 1. *Edited by* M.N. Hill. John Wiley & Sons, New York. pp. 499–507.
- Holliday, D.V. 1972. Resonance structure in echoes from schooled pelagic fish. *J. Acoust. Soc. Am.* **51**: 1322–1332.
- Holliday, D.V. 1980. Use of acoustic frequency diversity for marine biological measurements. *In Advanced concepts in ocean measurements for marine biology*. *Edited by* F.P. Diemer. Belle W. Baruch Libr. Mar. Sci. No. 10. pp. 423–460.
- Holliday, D.V., and Pieper, R.E. 1980. Volume-scattering strengths and zooplankton distributions at acoustic frequencies between 0.5 and 3 MHz. *J. Acoust. Soc. Am.* **67**: 135–146.
- Holliday, D.V., Pieper, R.E., and Kleppel, G.S. 1989. Determination of zooplankton size and distribution with multifrequency acoustic technique. *J. Cons. Cons. Int. Explor. Mer.* **46**: 52–61.
- Horne, J.K., and Jech, J.M. 1998. Multi-frequency estimates of fish abundance: constraints of rather high frequencies. *ICES J. Mar. Sci.* In press.
- Huang, K., and Clay, C.S. 1980. Backscattering cross sections of live fish: PDF and aspect. *J. Acoust. Soc. Am.* **67**: 795–802.
- Jech, J.M., Schael, D.M., and Clay, C.S. 1995. Application of three sound scattering models to threadfin shad (*Dorosoma petenense*). *J. Acoust. Soc. Am.* **98**: 2262–2269.
- Johannesson, K.A., and Losse, G.F. 1977. Methodology of acoustic estimating of fish abundance in some UNDP/FAO resource survey projects. *Rapp. P.-v. Réun. Cons. Int. Explor. Mer.* **170**: 296–318.
- Johnson, R.K. 1977a. Sound scattering from a fluid sphere revisited. *J. Acoust. Soc. Am.* **62**: 375–377.
- Johnson, R.K. 1977b. Acoustic estimation of scattering-layer composition. *J. Acoust. Soc. Am.* **61**: 1636–1639.
- Jones, F.R.H., and Marshall, N.B. 1953. The structure and function of the teleostean swimbladder. *Biol. Rev.* **28**: 16–83.
- Love, R.H. 1971. Measurements of fish target strength: a review. *Fish. Bull. U.S.* **69**: 703–715.
- Love, R.H. 1977. Target strength of an individual fish at any aspect. *J. Acoust. Soc. Am.* **62**: 1397–1403.
- Love, R.H. 1978. Resonant acoustic scattering by swimbladder-bearing fish. *J. Acoust. Soc. Am.* **64**: 571–580.
- Love, R.H. 1993. A comparison of volume scattering strength data with model calculations based on quasisynoptically collected fishery data. *J. Acoust. Soc. Am.* **94**: 2255–2268.
- Martin, L.V., Stanton, T.K., Wiebe, P.H., and Lynch, J.F. 1996. Acoustic classification of zooplankton. *ICES J. Mar. Sci.* **53**: 217–224.
- McCartney, B.S., and Stubbs, A.R. 1971. Measurement of the acoustic target strengths of fish in dorsal aspect, including swimbladder resonance. *J. Sound Vib.* **15**: 397–420.
- McFarlane, G., and Kieser, R. 1993. Canada–Japan fisheries acoustic technology workshop. Department of Fisheries and Oceans Canada, Ottawa, Ont.
- McNaught, D.C. 1968. Acoustical determination of zooplankton distributions. *Proc. Conf. Great Lakes Res.* **11**: 76–84.
- McNaught, D.C. 1969. Developments in acoustic plankton sampling. *Proc. Conf. Great Lakes Res.* **12**: 61–68.
- Midttun, L. 1984. Fish and other organisms as acoustic targets. *Rapp. P.-v. Réun. Cons. Int. Explor. Mer.* **184**: 25–33.
- Minnaert, M. 1933. On musical air bubbles and the sounds of running water. *Philos. Mag.* **16**: 235–248.
- Nakken, O., and Olsen, K. 1977. Target strength measurements of fish. *Rapp. P.-v. Réun. Cons. Int. Explor. Mer.* **170**: 52–69.
- Olsen, K. 1977. Orientation measurements of the cod in Lofoten obtained from underwater photographs and their relation to target strength. *ICES CM/B*: 25.
- Peterson, M.L., Clay, C.S., and Brandt, S.B. 1976. Acoustic estimates of fish density and scattering function. *J. Acoust. Soc. Am.* **60**: 618–622.
- Pieper, R.E., Holliday, D.V., and Kleppel, G.S. 1990. Quantitative zooplankton distributions from multifrequency acoustics. *J. Plankton Res.* **12**: 433–441.
- Robinson, B.J. 1978. In situ measurement of fish target strength. *In Proceedings of 1978 Institute of Acoustics Specialists Meeting on Acoustics in Fisheries*, September 26–27, 1978. Hull College of Higher Education, Hull, England.
- Rose, G.A. 1993. Cod spawning on a migration highway in the north-west Atlantic. *Nature (London)*, **366**: 458–461.
- Rose, G.A., and Leggett, W.C. 1988. Hydroacoustic signal classification of fish schools by species. *Can. J. Fish. Aquat. Sci.* **45**: 597–604.
- Sand, O., and Hawkins, A.D. 1973. Acoustic properties of the cod swimbladder. *J. Exp. Biol.* **58**: 797–820.
- Sætersdal, G., Stromme, T., Bakken, B., and Piekutowski, L. 1984. Some observations on frequency-dependent backscattering strength. *FAO Fish. Rep. No.* 300. pp. 150–156.
- Smith, P.F. 1954. Further measurements of the sound scattering properties of several marine organisms. *Deep-Sea Res.* **2**: 71–79.
- Stanton, T.K. 1982. Effects of transducer motion on echo-integration techniques. *J. Acoust. Soc. Am.* **72**: 510–514.
- Stanton, T.K. 1988. Sound scattering by cylinders of finite length. I. Fluid cylinders. *J. Acoust. Soc. Am.* **83**: 55–63.
- Stanton, T.K. 1989. Sound scattering by cylinders of finite length. III. Deformed cylinders. *J. Acoust. Soc. Am.* **86**: 691–705.
- Stanton, T.K. 1990. Sound scattering by zooplankton. *Rapp. P.-v. Réun. Cons. Perm. Int. Explor. Mer.* **189**: 353–362.
- Stanton, T.K., Chu, K., Wiebe, P.H., and Clay, C.S. 1993. Average echoes from randomly oriented random-length finite cylinders: zooplankton models. *J. Acoust. Soc. Am.* **94**: 3463–3472.
- Strasberg, M. 1953. The pulsation frequency of nonspherical gas bubbles in liquids. *J. Acoust. Soc. Am.* **25**: 536–537.
- Traynor, J.J., and Ehrenberg, J.E. 1979. Evaluation of the dual beam acoustic fish target strength measurement method. *J. Fish. Res. Board Can.* **36**: 1065–1075.
- Trevorov, M.V. 1996. Multifrequency acoustic investigations of juvenile and adult fish in Lake Biwa, Japan. *J. Acoust. Soc. Am.* **100**: 3042–3052.
- Weston, D.E. 1967. Sound propagation in the presence of bladder fish. *In Underwater acoustics*. *Edited by* V.M. Albers. Plenum, New York. pp. 55–88.
- Whitehead, P.J.P., and Blaxter, J.H.S. 1964. Swimbladder form in clupeoid fishes. *Zool. J. Linn. Soc.* **97**: 299–372.
- Wiebe, P.H., Greene, C.H., Stanton, T.K., and Burczynski, J. 1990. Sound scattering by live zooplankton and micronekton: empirical

- studies with a dual-beam acoustical system. *J. Acoust. Soc. Am.* **88**: 2346–2360.
- Ye, Z., and Farmer, D.M. 1994. Acoustic scattering from swim-bladder fish at low frequencies. *J. Acoust. Soc. Am.* **96**: 951–956.
- Zakharia, M., and Sessarego, J.P. 1982. Sonar target classification using a coherent echo processing. *In* Proceedings of the IEEE International Conference on Acoustics, Speech, and Signal Processing, Paris, France. May 3–5, 1982. Published by the IEEE ASSP Society, New York. pp. 331–334.