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ACOUSTIC SCATTERING BY MARINE ORGANISMS

K. G. Foote, Woods Hole Oceanographic Institution, Woods Hole, Massachusetts, USA

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Historical Overview

Development of underwater sonar as a tool for navigation and military operations, following sinking of the *Titanic* in 1912, led inevitably to applications to marine organisms. By the 1930s, echoes from fish schools had been detected. In the 1940s, the deep sound-scattering layer was observed. Its biological origin in mesopelagic fish was identified in the 1950s. At the same time, applications to commercial fish were pursued with vigor, and both scientific echo sounders and fishery echo sounders began to be manufactured.

Steady improvements in transduction enabled individual fish of certain species and sizes to be detected at ranges of hundreds of meters. The ultrasonic frequency of 38 kHz was becoming a standard at this time; it was subsequently shown to be near the optimum for achieving detection of commercially important fish in the presence of attenuation due to spherical spreading and absorption. Parallel to studies of single-fish scattering at ultrasonic frequencies were studies of scattering at sonic frequencies, especially to determine the resonance frequency in swimbladder-bearing fish, which is a measure of size.

Echo integration was introduced in 1965 as a tool for quantifying fish aggregations at essentially arbitrary conditions of numerical density. This was rapidly developed, and it has been used routinely in surveys of fish stock abundance since about 1975. Introduction of standard-target calibration in the early 1980s served the cause of quantification by providing a rapid, high-accuracy method of enabling the results of echo integration to be expressed in absolute physical units. With few exceptions, standard-target calibration has become the method of choice.

Sonar, with one or more obliquely oriented or steerable beams, began to find common application in the 1970s for counting fish schools that might be missed by a vertical echo sounder beam. This was a significant development for acknowledging the narrowness of the sampling volume of vertically oriented directional echo sounder beams and the possibility of fish avoidance reactions to the transducer platform, typically a research vessel.

In another parallel development, the Doppler principle was exploited to measure the rate of approach or recession of fish targets. Both horizontally oriented echo sounder beams and sonar beams were used. Early applications determined the swimming speeds of schools of small pelagic fish and individual salmon in rivers.

Applications of acoustics to fish in the 1970s were accompanied by notable applications to zooplankton, if pursued less intensively owing to differences in commercial importance. Because of the enormous diversity of zooplankton species in size, shape, and composition, it was recognized early that insonification over a band of frequencies is required, even for routine observation. This has usually been achieved by the use of multiple resonant transducers, but genuinely broadband sonars are also proving successful in yielding spectra of individual euphausiids and copepods.

Recognition of the importance of bandwidth in scattering by zooplankton was accompanied by appreciation of the role of interpretive models. Acoustic scattering models have been developed and applied to fish since the 1950s and to zooplankton since the 1970s.

The transition from analog to digital technologies in the 1970s facilitated processing of echo data. This has become steadily more automated and sophisticated, but always with operator control of important decisions through the man–machine interface.

Other developments in technology since the 1970s have extended the range of applications of acoustic scattering by marine organisms. Multiple-element transducers have been used to determine the three-dimensional locations and movement, as well as the target strength, of individual animals. Compact, high-frequency sonars have been mounted on fish capture gear to observe the behavior of fish during catching operations. Steerable high-frequency sonars have been used to track fish schools during capture and to map their three-dimensional shapes.

Physical Basis for Scattering

Acoustic scattering by a marine organism is, in principle, no different from that of any other kind of scattering. Differences in the physical properties of the causative bodies with respect to the surrounding medium are accompanied by reflection and refraction, or more generally diffraction, of incident waves. Organisms, with contrasts in mass density or elasticity relative to sea water, are thus sources of scattering.

The processes of reflection, refraction, and diffraction occur at surfaces, both external and internal, marking discrete changes in physical properties and throughout the volume or inside embedded inhomogeneities, as characterized by continuous changes in properties. The net result of the individual processes is a redistribution in space of the incident energy field. Changes in direction and amplitude characterize the scattering.

Classification of Marine Organisms as Scatterers

Marine organisms are conveniently divided into groups based on considerations of taxonomy and anatomy. Two major groups are those of fish and zooplankton, but others are also treated.

Fish may be distinguished as cartilaginous or bony. Bony fish may be acoustically distinguished because the fish possesses or lacks a gas-filled swimbladder. Swimbladders may be closed, with gas exchange effected by the *rete mirabile*, or open, with gas exchange effected by gulping air at the surface or by releasing a sphincter muscle on a duct leading to the exterior. The respective swimbladder types are called physoclists and physostomes. They are illustrated by cod (*Gadus morhua*) and herring (*Clupea harengus*), respectively. Some mesopelagic fish possess gas-filled swimbladders, including a number of myctophid species. Some other myctophids, as well as the deepwater fish orange roughy (*Hoplostethus atlanticus*), possess swimbladders that are invested with wax esters. The whiptail (*Coryphaenoides subserrulatus)*, a macrurid, possesses a swimbladder that contains gas in a spongy matrix of tissue. Swimbladderless fish are illustrated by mackerel (*Scomber scombrus*). Cartilaginous fish lack a swimbladder, but their liver is large and presents a marked density contrast with the surrounding fish flesh.

Zooplankton come in many shapes and sizes, but acoustically their variable physical composition admits of a severe reduction. Three prominent classes have been identified: the liquidlike, the hard-shelled, and the gas-bearing. These are illustrated by, respectively, euphausiids, pteropods, and siphonophores.

Other marine organisms have also been detected by scattering. These include squid, gelatinous zooplankton, algae, benthos, marine mammals, and even diving birds. The first five groups are considered in a separate section in the following.

Dependences of Scattering

In general, scattering by marine organisms is affected by a number of factors. Some are listed here.

Intrinsic factors. Intrinsic to the scatterers are size, shape, internal composition, and condition. Condition may be affected by the stage of development, presence of reproductive products, and degree of stomach filling. Behavior is another intrinsic factor, if often directly affected or determined by the external environment. It is typically quantified through the attitude, or orientation, of the organism and its velocity of movement.

Extrinsic factors. Scattering is affected by the insonification signal, hence by its spectral composition.

For impulsive signals, the spectrum may be broadly continuous. For a typical pulsed sinusoid containing many wavelengths, the spectrum will be narrow, and the signal can be characterized by the center frequency, pulse duration, and amplitude. Depth and history of depth excursion may also influence the scattering, as in the case of rapid depth changes for physoclists. For swimbladdered fish lacking *rete mirabile*, depth excursions will necessarily affect the swimbladder form, with the volume changing in accordance with Boyle's law, thus inversely with the ambient pressure.

Quantification of Scattering

Nomenclature

Scattering properties of organisms are distinguished as belonging to individual organisms or to aggregations of organisms. The fundamental scattering property of a single organism is the scattering amplitude. This is described through the idealization of a plane harmonic wave incident on a finite scattering body. At a great distance r from the body, the scattered pressure field or amplitude p_{sc} is related to the incident pressure amplitude p_{inc} by eqn [1].

$$p_{sc} = p_{inc} f \exp(ikr)/r \qquad [1]$$

In eqn [1] f is the far-field scattering amplitude, r is the distance from the scatterer, k is the wavenumber $2\pi/\lambda$, and λ is the acoustic wavelength. The scattering amplitude f describes the angular characteristics of the scattered field. The differential or bistatic scattering cross-section is $|f|^2$. In the backscattered direction $f = f_b$, and the backscattering cross-section is given by eqn [2], where the dual convention of using both σ_{bs} and σ is shown.

$$\sigma_{bs} = |f_b|^2 = \frac{\sigma}{4\pi} \qquad [2]$$

The target strength TS is a logarithmic measure (eqn [3]; where r_0 is the reference distance, typically 1 m).

$$TS = 10 \log \frac{\sigma_{bs}}{r_0^2} \qquad [3]$$

When many scatterers are concentrated in a volume in which individual scatterers cannot be distinguished by their echoes, a collective standard measure of scattering is used. This is the volume scattering coefficient. In the backscattered direction, the volume backscattering coefficient s_v is given by eqn [4], where $f_{b,i}$ is the backscattering amplitude for the ith scatterer of N, and V is the volume.

$$s_v = V^{-1} \sum_{i=1}^{N} |f_{b,i}|^2 \qquad [4]$$

The volume backscattering strength is given by eqn [5].

$$S_v = 10 \log(r_0 s_v) \qquad [5]$$

A quantity useful in echo integration is the area or column backscattering coefficient s_a, (eqn [6]), where the integration is performed over the range interval $[r_1, r_2]$.

$$s_a = \int_{r_1}^{r_2} s_v \, dr \qquad [6]$$

In scattering by fish, a numerically more convenient measure of s_a is eqn [7], which refers the backscattering to the reference area of one square nautical mile.

$$s_A = 4\pi 1852^2 s_a \qquad [7]$$

This form is particularly useful, for the fundamental equation of echo integration is simply eqn [8], where ρ_A is the numerical density of fish referred to the same area of one square nautical mile, and σ is the characteristic or mean backscattering cross section.

$$s_A = \rho_A \sigma \qquad [8]$$

Another measure of scattering is the extinction cross-section. This measures the relative loss of energy due to scattering and internal absorption. It may be defined for an individual scatterer, but is generally applied to aggregations of organisms if they are sufficiently numerous.

With few exceptions, the issue of calibration must be addressed when making measurements. Standard methods are available for this, the aim being to define the system characteristics so that the result of a measurement, a voltage signal for instance, can be expressed as a pressure-wave amplitude in the water medium.

Measurement

There are dozens of techniques for measuring the scattering properties of individual organisms and aggregations of organisms. These are commonly distinguished as being *in situ*, without constraint in the natural environment of the organisms, or *ex situ*, hence constrained in some way, wherever this might be.

Target strength is a key quantity in many investigations. It may be determined with a single-beam echo sounder; for example, by repeated measurement of similar organisms that are acoustically resolved and by appropriate statistical reduction of these measurements. Alternatively, it may be measured directly with a dual- or split-beam echo sounder, in which the beam pattern can be determined in the direction of the organism, enabling the backscattering cross-section to be extracted from each individual echo.

Similar measurements can be performed on single organisms *ex situ* with greater control and hence knowledge of their state during measurement. Measurements on tethered organisms, constrained to maintain a given orientation during insonification, are popular.

Aggregations of organisms are frequently quantified acoustically through the volume backscattering coefficient. If the number and occupied volume of the organisms are known, then the characteristic target strength can be inferred through eqn [9].

$$S_v = 10 \log n + TS \qquad [9]$$

Here n is the numerical density of organisms, and TS is the so-called mean target strength corresponding to a single organism, but derived as the logarithmic measure of the mean backscattering cross-section.

Cages are often employed to confine a known or knowable number of organisms to a fixed volume. Measurement of S_v can then yield a value for TS.

Modeling

The importance of target strength in many studies involving scattering by marine organisms is so great that recourse is frequently made to theoretical models. On the basis of assumptions about the shape and internal composition of subject organisms, mathematical expressions may be derived that can be evaluated for particular conditions of concentration or frequency that might not be realistically explored through measurement. Ultimately, measurements may be used to refine models, and models to interpret measurements.

Fish as Scatterers

Swimbladder-bearing Fish

The swimbladder shape varies with species and with condition of the individual specimen. An example of a swimbladder *in corpus* is shown in **Figure 1**. Here the swimbladder of an Atlantic herring (*Clupea harengus*) has been exposed by careful dissection.

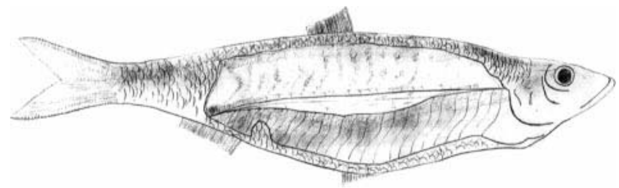

Figure 1 Drawing of a specimen of Atlantic herring (*Clupea harengus*), female, 36.0 cm long, 453 g, with exposed swimbladder. (Drawing by H. T. Kinacigil, used with permission.)

Low frequencies At low frequencies, with acoustic wavelengths much greater than characteristic swimbladder dimensions, the effect of a pressure wave on the swimbladder is essentially that of uniform compression and rarefaction. Consequently, a spherical model can be used. In fact, some swimbladder-bearing fishes have been modelled successfully as a spherical gas bubble surrounded by a finite layer of fish flesh that acts as a viscous fluid medium supporting surface tension on the interface between the shell and fish flesh. The volume of a bubble of radius a is equivalent to that of the swimbladder. Equation [10] gives the resonance frequency ν_0 of an immersed spherical gas bubble,

$$\nu_0 = \frac{1}{2\pi}\left(\frac{3\gamma P}{\rho a^2}\right)^{1/2} \qquad [10]$$

where γ is the ratio of specific heats at constant pressure and volume, P is the ambient pressure at depth, ρ is the mass density of fish flesh, and a is the equivalent spherical radius. For elongated bubbles or swimbladder shapes, the resonance frequency is modified.

The backscattering cross-section σ at frequency ν is given by eqn [11].

$$\sigma = \frac{4\pi a^2}{[\nu_0/(\nu H)]^2 + [(\nu_0/\nu)^2 - 1]^2} \qquad [11]$$

H is the damping factor given by eqn [12], where c is the speed of sound in water, and ξ is the viscosity of fish flesh.

$$H^{-1} = \frac{2\pi a \nu}{\nu_0 c} + \frac{\xi}{\pi a^2 \nu_0 \rho}, \qquad [12]$$

Some numerical values for the various parameters are $\rho = 1050\,\mathrm{kg\,m^{-3}}$ and $\xi = 50\,\mathrm{Pa\,s}$. The speed of sound in sea water varies over the range

1450–1550 m s^{-1}, depending on temperature, salinity, and pressure.

For gadoids and clupeoids in the size range 8–30 cm, ν_0 varies over 2.2–0.3 kHz. Given the inverse relationship of resonance frequency and size in eqn [10], smaller fish will have higher resonance frequencies. Thus, mesopelagic fish with partially wax-invested swimbladders may have resonance frequencies in the low ultrasonic range. Very large swimbladdered fish, say with a total fish length exceeding 1 m, will have resonance frequencies of the order of hundreds of hertz. The corresponding backscattering cross-section, hence target strength, can be computed from eqs [10]–[12]. It is important to note that the quality factor of the resonance condition, eqn [13], where $\Delta\nu$ describes the range in frequency over which σ decreases to one-half its maximum value, may be of the order of 1.5–3.

$$Q = \nu_0/\Delta\nu \qquad [13]$$

Implicit in the low-frequency condition of the model is that σ is independent of orientation. Averages of σ with respect to arbitrary orientation distributions will be identical to σ itself.

When computing average values of σ for aggregations of swimbladdered fish of varying size, σ must be averaged with respect to the size distribution. The characteristic target strength is determined from the definition in eqn [3].

Intermediate frequencies As the acoustic wavelength decreases toward characteristic swimbladder dimensions, the scattering becomes markedly directional, and the backscattering begins to depend sensitively on the orientation of the fish. From measurements made both *in situ* and *ex situ*, the empirical relationship of eqn [14] between mean target strength TS at 38 kHz and total fish length l in centimeters has been derived for a number of gadoids.

$$TS = 20\log l - 67.5 \qquad [14]$$

Equation [15] applies for clupeoids

$$TS = 20\log l - 71.9 \qquad [15]$$

The average backscattering cross-section σ may be determined immediately from eqn [3]. For a cod of length $l = 50$ cm, $TS = -33.5$ dB and $\sigma = 56\,\text{cm}^2$. For a herring of length $l = 30$ cm, $TS = -42.4$ dB and $\sigma = 7.2\,\text{cm}^2$.

Blue whiting is an important commercial stock in both hemispheres, and it is routinely surveyed by acoustics. To convert measurements of acoustic density at 38 kHz to numerical density in accordance with the echo integration equation [8], eqn [16], where l is the fork length in centimeters is used for the northern-hemisphere blue whiting (*Micromesistius poutassou*):

$$TS = 21.7\log l - 72.8 \qquad [16]$$

Equation [17] applies for the southern-hemisphere southern blue whiting (*Micromesistius australis*), where l is again the fork length in centimeters.

$$TS = 25.0\log l - 81.4 \qquad [17]$$

Coincidentally, perhaps, the target strength of yellowfin tuna (*Thunnus albacares*) at 38 kHz is nearly identical to that of *Micromesistius australis* and is given by eqn [18].

$$TS = 25.3\log l - 80.6 \qquad [18]$$

The target strength of bigeye tuna (*Thunnus obesus*) under similar conditions is given by eqn [19].

$$TS = 24.3\log l - 73.3 \qquad [19]$$

These relations were established from specimens in the approximate size range 50–130 cm and 3–50 kg.

The whiptail (*Coryphaenoides subserrulatus*), with a swimbladder containing gas-filled spongy tissue, seems to have a mean *in situ* target strength at 38 kHz that is consistent with the equation developed for another macrurid, the blue grenadier or hoki (*Macruronus novaezelandie*) (eqn [20], where l is the total fish length in centimeters).

$$TS = 20\log l - 72.7 \qquad [20]$$

Some stocks of orange roughy (*Hoplostethus atlanticus*) are being surveyed about their seamount habitats. Determination of the target strength of this deepwater fish with fat-invested swimbladder is admittedly problematical. Some work suggests convergence of the mean target strength of a 35 cm long orange roughy at 38 kHz to about -48 dB. If the standard equation for mean target strength–length were used, namely eqn [21],

$$TS = 20\log l + b \qquad [21]$$

the coefficient b would be -79 dB.

For modeling scattering by swimbladdered fish at these frequencies, the Kirchhoff approximation model can be used. This assumes that the fish is

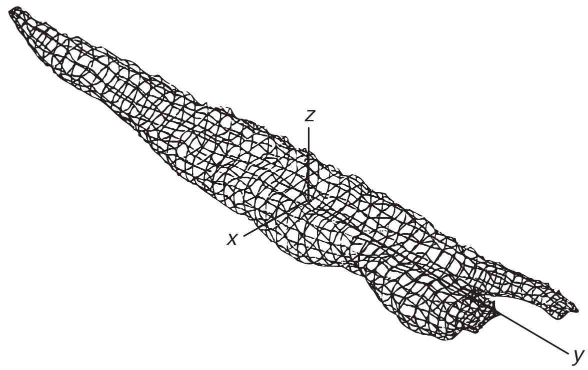

Figure 2 Boundary element model of the swimbladder of a specimen of pollack (*Pollachius pollachius*), 34.5 cm in length, with anterior end to the lower right (*y* direction). (Model by D. T. I. Francis, used with permission.)

represented by the swimbladder, which acts as a pressure-release surface where it is directly insonified, and as a surface without response otherwise.

A more general scattering model is that of the boundary-element method. The swimbladder is represented by a mesh of points, called nodes, spanning the surface, illustrated in **Figure 2**. The harmonic wave equation is solved numerically, assuming continuity of pressure and normal component of velocity at each node. It is thus possible to model the effects of internal gas density and pressure.

To convert modeled values for σ as a function of orientation to an average value, an orientation distribution is required. Ideally, this is done on the basis of *in situ* observations, but often such data are lacking and an orientation distribution must be assumed. Some orientation distributions are described in the literature. In some special circumstances it has been possible to infer the orientation distribution by a combination of acoustic measurement and modeling.

The relationship of maximum and average measures of σ is given approximately by eqn [22].

$$\sigma_{\max} \approx 7\sigma_{\text{ave}} \qquad [22]$$

Alternatively, eqn [23] can be used.

$$TS_{\max} \approx TS_{\text{ave}} + 5\,\text{dB} \qquad [23]$$

Measures of the extinction cross-section are relatively rare, there being few occasions when it is necessary to compensate for scattering losses. However, measurement or inference suggest that the extinction cross-section is very roughly 1–3 times the backscattering cross-section at intermediate frequencies. Ultimately, the cross-sections and their ratio must depend on the behavior of the organism, as quantified through the orientation distribution.

High frequencies When the acoustic wavelength becomes very small compared to the swimbladder size, scattering by other tissues may become important. The contributions of head structure, vertebrae, and even scales at very high frequencies have been established through *ex situ* measurement. Modeling of scattering by such structures can be computationally excessive, suggesting the advantages of stochastic modeling if direct measurement is not possible or convenient.

Swimbladderless Fish

The mackerel is a prominent example of a swimbladderless fish. Its target strength must be attributed to the non-swimbladder structures and hence is intrinsically complicated at nearly all frequencies. At intermediate frequencies, the mean target strength is roughly 10 dB less than that of a gadoid of comparable size (eqn [24]).

$$TS_{\text{mackerel}} \approx TS_{\text{gadoid}} - 10\,\text{dB} \qquad [24]$$

For cartilaginous fish, such as sharks, the liver may be very large. In pelagic sharks, this may be of the order of 7–23% by weight; in demersal sharks, 3–6%. The specific gravity of lipids is of the order of 0.87–0.92 in pelagic sharks and 0.93–0.94 in demersal sharks, further suggesting the role of the liver in buoyancy and its significance in acoustic scattering. At least for the pelagic sharks, the size and difference in mass density may explain much of the target strength. Were a model to be constructed, a pelagic shark might be represented by a body with the size, shape, and physical properties of the liver.

Zooplankton as Scatterers

Liquid-like Bodies

A number of prominent and abundant zooplankton can be classified as liquidlike in their acoustic properties. Extensive modeling and measurement have demonstrated that internal shear waves have negligible influence in scattering by such organisms. The animals are thus generally fluidlike in their properties. If the same animals lack sizable organs or other tissue presenting large contrasts in mass density or compressibility relative to the sea water immersion medium, then the acoustic properties of the organisms are more particularly liquidlike, and their acoustic scattering is consequently relatively weak. Two examples of zooplankton with liquidlike properties are euphausiids and copepods. These are also representative of homogeneous and inhomogeneous scatterers, respectively.

Homogeneous liquidlike bodies The expectation of relatively weak scattering by euphausiids has been confirmed by measurement. For example, the target strength of Antarctic krill (*Euphausia superba*) of mean lengths 30–39 mm is in the range from − 88 to − 83 dB at 38 kHz and from − 81 to − 74 dB at 120 kHz. The respective acoustic wavelengths are 39 and 12.5 mm.

For a scattering body that is relatively long compared to the wavelength, the scattering will be inherently directional. Laboratory measurement has demonstrated strong effects of orientation on scattering by euphausiids in the size range 30–42 mm at frequencies of 120 kHz and higher.

In modeling scattering by homogeneous liquidlike zooplankton, there are just two significant material properties, the mass density and compressibility, or longitudinal-wave sound speed. A variety of models can be used to represent shape. At low frequencies, a single euphausiid can be represented by a finite circular cylinder or even a sphere, with volume equal to that of the animal. At higher frequencies, the same animal might be represented as a finite, bent, tapered cylinder or, better, by the actual shape of the exoskeleton.

Scattering models for euphausiids have demonstrated the sensitive dependence of target strength on both the material properties and orientation of the organism. Given the rarity of measurements of material properties, their seasonal and individual variability, and the generally unknown orientation, there has been little systematization of measured values of target strength.

Theoretical understanding of scattering by euphausiids has succeeded in associating large lobes with the echo spectrum at rather short acoustic wavelengths. When these are combined with knowledge of the target strength to within about an order of magnitude, it is possible to classify euphausiids by their acoustic signature.

Inhomogeneous liquidlike bodies Copepods, like euphausiids, also display relatively weak acoustic scattering. Unlike euphausiids, however, their internal structure is acoustically distinct, being composed of two dominant scatterers, a prosome and an embedded oil sac. Because of the low density of lipids in the oil sac, of the order of 900 kg m^{-3}, the prosome must be correspondingly more massive. Because the copepod body as a whole is close to neutral buoyancy in sea water, the target strength is

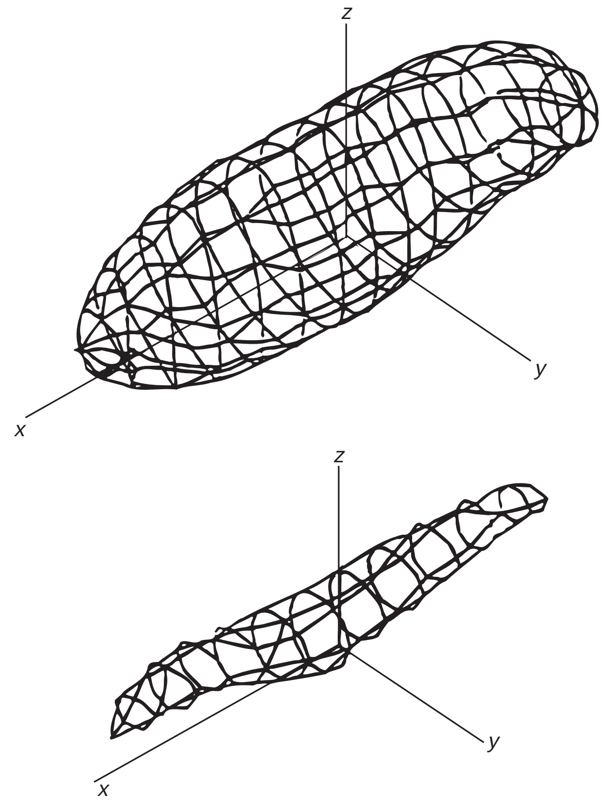

Figure 3 Boundary element models of the prosome and oil sac of a specimen of *Calanus finmarchicus*, stage 6 female, 2.74 mm in length, with anterior end to the lower left (*x* direction). (Models by D. T. I. Francis, used with permission.)

due to the internal contrast in mass density and compressibility, or longitudinal-wave sound speed, between the prosome and oil sac.

Measurement has shown that the target strength of a 2 mm long copepod, *Calanus finmarchicus*, is in the approximate range from − 95 to − 90 dB over the frequency range 1600–2400 kHz.

Copepods have been modeled as composite two-liquid-body structures. Numerical values for the mass density and longitudinal-wave sound speed have been derived from measurements or have been assumed. The shapes of embedded oil sac and encompassing prosome, illustrated in **Figure 3**, have been determined from videomicroscopic cross-sections in dorsal and lateral views. Results of modeling of copepods have shown the expected weak dependence on orientation at low or moderate frequencies, and an overall mean target strength that is in line with measured values.

Hard-shelled Bodies

An example of a hard-shelled zooplankton is the pteropod *Limacina retroversa,* a marine snail with a spiral shell, opercular opening, and wings that propel it through the mid-water column. The target strength of specimens of shell length 2 mm has been measured over the approximate frequency range from 350 to 750 kHz. The target strength varies between −80 and −60 dB, depending on both frequency and orientation.

The pteropod has been modeled as a rough spherical shell with a circular opening. Predictions of scattering have been in reasonable agreement with measurements at wavelengths roughly comparable to the maximum shell dimension.

Gas-bearing Bodies

Siphonophores are representatives of gas-bearing zooplankton, with gas inclusions in the pneumatophores. These are generally small compared to overall dimensions of specimens, and the target strength varies widely over the frequency range 350–750 kHz. In particular, the target strength varies over the range from −90 to −60 dB, but with no apparent systematic dependence on frequency. This wide range is suggestive of interference between echoes from the gas inclusions and the nongaseous tissue, the basis of an acoustic model.

Other Organisms as Scatterers

Squid

A number of specimens of squid have been observed by acoustics. These include *Todarodes pacifica*, *Loligo opalescens*, and *Loligo vulgaris reynaudii*. In a survey of the second species, performed at 120 kHz, the target strength of specimens of mean dorsal mantle length 11.6 cm and mean mass 23.7 g was about −59 dB. Thus in the standard target strength–length equation [21], but with l representing the mean dorsal mantle length, b is about −80 dB. For *Todarodes pacifica* of mean dorsal mantle length 16 cm and mean mass 95 g, the target strength is about −51 dB at 28.5 kHz and −55 dB at 96.2 kHz, corresponding to values of b of −75 and −79 dB, respectively. For *Todarodes pacifica* of mean dorsal mantle length 23.7 cm and mean mass 340 g, the respective mean target strengths at 28.5, 50, 96.2, and 200 kHz are about −45.7, −46.5, −48.0, and −47.6 dB, with respective values of b of −75, −74, −76, and −76 dB. For *Loligo vulgaris reynaudii*, the target strength was measured at 38 kHz for sufficiently dispersed animals of mean mass 300 g. The target strength when referred to 1 kg was −42.5 dB. This compares favorably with the measurements on *Loligo opalescens* at 120 kHz and *Todarodes pacifica* at 28.5 kHz. When expressed relative to 1 kg, the respective target strengths are −42.3 and −41.1 dB.

Common Jellyfish

In anticipation of acoustic surveying of the ctenophore *Mnemiopsis leidyi* and other gelatinous zooplankton, namely *Aurelia aurita* and *Pleurobrachia pileus*, in the Black Sea, measurements have been made of the target strength of the common jellyfish *Aurelia aurita*. Functional regression equations have related the mean target strength in decibels to the disk diameter d in centimeters. At 120 kHz, the relation is eqn [25].

$$TS = 14.7 \log d - 74.6 \qquad [25]$$

At 200 kHz it is eqn [26].

$$TS = 39.6 \log d - 104.4 \qquad [26]$$

Thus for a specimen with mean diameter 10 cm, $TS = -59.9$ and −64.8 dB at the respective frequencies.

Algae

Algae, such as kelp, are being surveyed by acoustics. For purposes of quantification, the acoustic properties of the plants themselves are being studied, both by experiment and by theoretical modeling. Measurements have been performed on leaves of *Laminaria saccarina* and *L. digitata* at three ultrasonic frequencies. The lengths of these span the range 0.7–2 m; the widths 0.4–0.9 m; the thicknesses 1–5 mm; and the masses 0.33–0.8 kg. Target strengths expressed relative to 1 kg of biomass vary from −35 to −28 dB at 50 kHz, from −33 to −24 dB at 70 kHz, and from −29 to −22 dB at 200 kHz.

Smaller algae, the phytoplankton *Prorocentrum micans*, *Peridinium triquetrum*, *Olistodiscus luteus*, *Dunaliella salina*, *Platimous viridis*, and *Phaeodactilum tricornutum*, are also being studied by acoustics. Measurements of reverberation, in particular, are being used in attempts to quantify the volume of gas vacuoles.

Clams

Both the razor clam (*Tagelus dombeii*) and the surf clam (*Mesodesma donacium*) have been surveyed by acoustics. Beds of the razor clam have been surveyed in shallow water over a flat bottom. Echograms that show the bottom–surface–bottom reflection in addition to the first bottom reflection show an enhanced registration above the so-called second bottom echo. Counting of its characteristic serrations provides a quantitative measure of clam density.

Marine Mammals

A few measurements have been reported on the target strength of the sperm whale (*Physeter catodon*) and the humpback whale (*Megaptera novaeangliae*) *in situ*. Measurements have been made of the Atlantic bottlenose dolphin (*Tursiops truncatus*) in captivity. Measurements made on a 2.2 m long 126 kg female dolphin in broadside aspect at the surface revealed a mean target strength that decreased from about −10 dB at the lowest measurement frequency of 23 kHz to about −24 dB at 45 kHz, rising to about −20 dB at 65 kHz, then falling to −25 dB at 80 kHz. The observed degree of variability about these nominal values due to repeated insonification was 4–11 dB to within the first standard deviation to either side.

Challenges

For all of the instances and applications of acoustic scattering by marine organisms, there is an enormous demand for enhanced imaging capability and more quantitative understanding, including both improved measurement methods and models. In addition to refinement of current measurement methods, including those for quantifying concentrations of marine organisms, instruments are being developed or adapted for application. These include high-frequency sonars, multibeam sonars, and continuously broadband echo sounders, operating at both low and high frequencies.

In general, the addition of bandwidth to acoustic devices, whether achieved by multiple frequencies or a continuous spectrum, is a firm objective of many development efforts. Its usefulness in classification is appreciated from certain studies in zooplankton scattering, but it would aid studies of nekton scattering if successful.

Recognition of the importance of understanding the acoustic properties of individual organisms is similarly influential in promoting developments and applications. Determining the properties of single organisms when found *en masse* remains a challenge, as does quantifying avoidance reactions or avoiding inducing them. While there are many techniques for determining target strength, their application requires ingenuity to elucidate some of the principal dependences. The general lack of information on the depth dependence of target strength for gas-bearing organisms is a particular, prominent example.

Modeling of scattering by marine organisms offers much potential for resolving physically intractable problems, such as those involving separation of echoes from individual organisms in the midst of their social aggregations or inferring the acoustic properties of organisms that are very fragile or that occur in extreme environments. Both analytical and numerical models, however, require knowledge of the physical properties, shape, and behavioral characteristics, such as the orientation distribution, of the subject organisms. Acoustic inference of the *in situ* properties of organisms, by special measurement techniques and aided by models, appears very attractive if generally difficult.

An enhanced imaging capability based on acoustic scattering is also valuable. If realized in a compact device, this could aid fishing practice, as in providing fishers with information on the species and size of organisms present in the water column or on the bottom without actually having to capture the organism to make the determination. For the researcher, being able to distinguish different organisms with overlapping distributions would be invaluable in aiding the study of relationships, ultimately to advance the goals of ecosystem analysis and understanding.

Acknowledgments

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See also

Acoustics, Deep Ocean. Bioacoustics. Fish Locomotion. Mesopelagic Fishes. Pelagic Fishes. Plankton. Sonar Systems.

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ACOUSTICS, ARCTIC

P. N. Mikhalevsky, Science Applications International Corporation, McLean, VA, USA

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Introduction

The Arctic Ocean is an isolated mediterranean basin with only limited communication with the world's oceans, principally the Atlantic Ocean via the Fram Strait and the Barents Sea, and the Pacific Ocean via the Bering Strait. The ubiquitous feature of the Arctic Ocean is the sea ice that covers the entire Arctic basin during the winter months and only retreats off the shallow water shelf areas in the summer months, creating a permanent cap over most of the central Arctic basin (**Figure 1**) (*see* **Sea Ice: Overview**). The presence of the year-round sea ice cover determines the unique character of acoustic propagation and ambient noise in the Arctic Ocean. The sea ice insulates the Arctic Ocean from solar heating in the summer months, creating a year-round upward refracting sound speed profile with the sound speed minimum at the water–ice interface (*see* **Acoustics, Deep Ocean**). Sound, therefore, is refracted upward and is continuously reflected from the ice as it propagates, causing attenuation by scattering, mode conversion, and absorption that increases rapidly with frequency. The lack of solar forcing and the Arctic Ocean's restricted communication with the other oceans of the world creates a very stable acoustic channel with significantly reduced fluctuations of acoustic signals in comparison with the temperate oceans. In contrast to the central basin, acoustic propagation on the Arctic shelves and in the marginal ice zones (MIZs, those areas between the average ice minimum and maximum) (**Figure 1**), is quite complex and variable owing to the seasonal retreat of the sea ice, river run-off, and bottom interaction (*see* **Acoustics, Shallow Water; Acoustics in Marine Sediments**).

Over the last half-century Arctic acoustics research and development has largely supported submarine operations. The importance of the Northern Sea Route to the Soviet Union, and the prospect of Soviet nuclear ballistic missile submarines exploiting the unique Arctic acoustic environment to remain undetected provided the need for this research. Since the end of the Cold War and the beginning of concern about 'global warming' there has been a new focus for Arctic acoustics on acoustic thermometry and acoustic remote sensing (*see* **Tomography**). The Arctic Ocean is the world's 'air-conditioner', maintaining the surface heat balance, and it provides fresh water to the world's oceans, principally in the form of sea ice discharged from the Fram Strait. The latter regulates convective overturning in the Greenland and Norwegian Seas that in turn drives the global thermohaline circulation with significant impact on climate. Monitoring changes in the temperature and stratification of the Arctic Ocean and sea ice thickness using acoustics is an important capability that will improve our understanding of the Arctic Ocean and its role in global climate change.