Fisheries Acoustics

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Fisheries Acoustics

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Fisheries Acoustics

Theory and Practice

Second Edition

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Series Foreword

'. . . The sound must seem an echo to the sense'
(*Sound and Sense* by Alexander Pope, 1688–1744)

Fish researchers (a.k.a. fish freaks) like to explain, to the bemused bystander, how fish have evolved an astonishing array of adaptations, so much so that it can be difficult for them to comprehend why anyone would study anything else. Yet, at the same time, fish are among the last wild creatures on our planet that are hunted by humans for sport or food. As a consequence, today we recognize that the reconciliation of exploitation with the conservation of biodiversity provides a major challenge to our current scientific knowledge and expertise. Even evaluating the trade-offs that are needed is a difficult task. Moreover, solving this pivotal issue calls for a multidisciplinary convergence of fish physiology, biology and ecology with social sciences such as economics and anthropology in order to probe the frontiers of applied science. In addition to food, recreation (and inspiration for us fish freaks), it has, moreover, recently been realized that fish are essential components of aquatic ecosystems that provide vital services to human communities. Sadly, virtually all sectors of the stunning biodiversity of fishes are at risk from human activities. In fresh water, for example, the largest mass extinction event since the end of the dinosaurs occurred as a result of the introduction of Nile perch to Lake Victoria, which eliminated over 100 species of endemic haplochromine fish. But, at the same time, precious food and income from the Nile perch fishery was created in a miserably poor region. In the oceans, we have barely begun to understand the profound changes that have accompanied a vast expansion of human fishing over the past 100 years. The Blackwell Publishing *Fish and Aquatic Resources Series* is an initiative aimed at providing key, peer-reviewed texts in this fast-moving field.

How many fish are in the sea? This question has always been important, but today has added relevance as we realize how fishing has devastated ocean resources. Most standard methods of counting fish end up killing them with nets, traps or hooks. Photography or visual counts can be used, but the clear waters necessary are rare. Examining the characteristics of reflected sound waves in an analogous way to radar is a smart alternative because it is non-lethal, works in turbid waters, covers vast areas and can be very cost-effective compared to catching the fish. To use the words of Douglas Adams (1979), analysing echoes is 'mostly harmless', and so ways of encouraging its use should be supported.

This book on *Fisheries Acoustics*, written by two of the world's leading practitioners, reviews the fundamental principles and practical techniques by which acoustic echoes are transformed into measurements of fish schools and stock biomass, with descriptions of the various types of hardware and software employed.

A brief review of the use of underwater sound, going back to Leonardo da Vinci listening down a tube for the sound of distant ships, is followed by a history of how acoustics came to be used to estimate the biomass of fish. Echograms were used for locating fish schools in the 1930s, but rapid improvements in sonar technology during the Second World War led to the first quantitative estimates of fish abundance in the 1950s. Echo integration methods, split-, dual- and multi-beam devices soon followed. The book goes on to provide an explanation of the theory of sound underwater, presenting rigorous and standardized descriptors of its characteristics. It contains a valuable synoptic review of how fish species, size and behaviour can affect target strengths and outlines calibration procedures for fisheries acoustic gear. Two chapters thoroughly review the fundamentals of geostatistical analysis for the design and interpretation of fisheries acoustic surveys.

It is not only fish that may be studied with underwater acoustics. At one end of the size spectrum, small plankton, which have a wide range of acoustic properties due to whiskers, elastic or gelatinous bodies and gas-filled buoyancy bladders, are measured using variations in sound speed rather than target strengths. Multi-beam sonar can provide three-dimensional images for recording behaviour. At the very large end of the size spectrum, marine mammals, which are extremely mobile and produce their own complex acoustic signals, have also been studied using acoustics.

Underwater acoustic devices are not only valuable for quantifying the amount of fish present; acoustic records that are almost as detailed as optical film have been employed to support behavioural and evolutionary studies. For example, high resolution multi-beam, side-scan sonar enabled the documentation of the anti-predator tactics of Norwegian herring schools under attack by cod and saithe (Pitcher *et al.* 1996), by orcas (Nøttestad and Axelsen 1999) and even by fin whales (Nøttestad *et al.* 2002). In the future, this book suggests that developments in sonar will make the seas even more transparent.

The first version of this book, published in 1992, rapidly became the standard resource text for anyone considering the use and application of acoustics in fisheries. Thirteen years later, this revised, expanded, reorganized and updated text will surely soon be regarded as the definitive reference work on fisheries acoustics.

Professor Tony J. Pitcher
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Pitcher, T.J., Misund, O.A., Fernö, A., Totland, B. and Melle, V. (1996) Adaptive behaviour of herring schools in the Norwegian Sea as revealed by high-resolution sonar. *ICES J. Mar. Sci.* **53**, 449–52.

Preface

This book has been written primarily for postgraduate students, professional scientists active in fishery research and administrators concerned with fishery management. It provides a broad description of the underlying theory and practical considerations in the use of underwater sound for the study of fish (and other lifeforms) in water. We present it hopefully as a comprehensive introduction particularly for those starting in the field of fisheries acoustics who might want a broad basis from which to move their careers forward.

It is now more than 12 years since the publication of our first textbook on fisheries acoustics (MacLennan and Simmonds 1992). That seemed at the time to say everything that should be said on the subject. However, as in most areas of technology, much has changed since then. It has taken much more work and time than we would have imagined to provide this volume. Modern sonars are now highly sophisticated compared to the earlier generation, computer processing has provided great opportunities, new applications have emerged for the study of plankton and mammals as well as fish, and there is now much better understanding of how to interpret acoustic observations of aquatic life in a rigorously scientific manner.

These developments are reflected in the large bibliography (around 770 references) which will be found at the end of the present volume. Some of the citations are in what is commonly known as the 'grey' literature. These can be rather variable in quality, but in some cases important findings have emerged from scientific working groups and meetings which were only documented informally. We felt the bibliography should be a comprehensive record, for the benefit of readers who wish to explore the subject in more detail than has been possible here, within the constraints of producing a volume of reasonable size. Therefore, we have cited various informal documents (which should nevertheless be accessible through institutional libraries or other sources), in cases where important findings have been reported but not in the peer-reviewed literature. While providing the necessary links to the literature, we have tried to restrict references to the key texts, giving readers a good place to start rather than a long string of references to choose from. Modern bibliographic systems allow simpler and faster means of information retrieval, but the drive to publish has greatly increased the volume of text that the reader must sift through. Our references are therefore provided as an introduction to the literature rather than a fully comprehensive review.

Notwithstanding the many developments and innovations that have arisen in recent years, some aspects of fisheries have not changed that much. Many fish stocks continue to be over-exploited and the goal of sustainable fishery management remains elusive (though in some cases, particularly the herring which are surveyed with acoustics, the stocks are doing better than many e.g. the gadoids which are not accessible to acoustics). There is much concern about the environmental impact of fishing and other human activities in the sea. Proper attention to these problems calls for scientific knowledge that must come from well designed and competently executed research programmes. To the extent that acoustic methods can and do make an important contribution, we hope this book will help to promote better understanding between the scientists and others concerned with fisheries, recognizing that they have many objectives in common.

John Simmonds
David MacLennan

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Chapter 1
Introduction

The living resources of the sea and fresh waters have long been an important source of food and, more generally, of economic activity in both industrial and artisanal societies. Their exploitation in a rational manner is rather problematical, to say the least. Too often, fisheries have suffered from boom-and-bust cycles, or even worse, catastrophic failures when fish stocks collapse (Beverton 1990). The environmental impact of fishing is another area of increasing concern, raising issues of species diversity, habitat destruction and damage to non-target populations (notably the marine mammals). Further discussion of these problems is not appropriate here, except for one important factor: long-term success in fishery management depends on knowledge of the exploited population, the size and distribution of which may change unpredictably from year to year. Much of this knowledge comes from the investigation of fish in their natural environment. This book is primarily about acoustic techniques which have been developed for the remote observation and monitoring of aquatic lifeforms.

At the wavelengths of human vision, light does not penetrate more than a few metres below the water surface, and much less when the medium is loaded with suspended solids or biota such as plankton. However, sound waves travel much longer distances through water. Thus acoustic instruments which transmit and receive sound waves can be used to detect fish or other objects far beyond the range of vision. Consequently, acoustic technology has had a major impact on fishing. The information provided by sonars and echosounders is an important factor in the efficiency of modern fishing operations. Purse seining and pelagic trawling are two methods which depend on the skilful interpretation of acoustic images to ensure success.

In fisheries research too, acoustic techniques have become increasingly sophisticated and useful over the years. With sonar it is possible to search a large volume of water in a short time; other sampling methods such as trawl fishing are very slow by comparison. Acoustic echoes may be observed from fish anywhere in the water column, except in the near-surface region and just above the seabed. Sonar has contributed greatly to our understanding of life in the sea and fresh waters, especially how wild populations are distributed in space and how they change with time. There is a large and expanding literature in fisheries acoustics. Practical applications are many and varied. For general background on particular topics, see Gunderson (1993) on survey methods, Fréon and Misund (1999) on fish behaviour, Mitson (1983) on fishing technology, Medwin and Clay (1998) on acoustical oceanography (which includes *inter alia* much on plankton acoustics) and Richardson *et al.* (1995) on marine mammals.

The measurement of fish abundance is an especially important application of acoustics in fisheries research (Gunderson 1993). Fishery management, as currently practised by most authorities, depends on controlling the quantity caught in relation to the size of the exploited population (Gulland 1983). To do this, it is necessary to estimate the current size (abundance) of the population, or that in the recent past. One approach to this problem is to conduct an acoustic survey. This involves running transects of some area while recording the echoes from fish detected by echosounder or sonar, and the abundance is estimated as the quantity of fish which would be expected to produce such echoes. However, the technique of acoustic survey is useful only when the fish of interest are conveniently located. They must not be too close to the surface or the bottom, where the fish echoes are obscured by much stronger reflections from these boundaries. Thus acoustic methods of observation are unsuited to the flatfish and other species which live in close association with the seabed, but many important species are found in midwater, far enough away from interfering boundaries. These include the herring family (Clupeidae), the mackerels (Scombridae), the anchovies (Engraulidae) and the salmonids (Salmonidae). In appropriate circumstances, an acoustic survey provides a synoptic estimate of the abundance which is independent of the fishery.

Sound also has a natural importance for the fish and mammals that live in water. They use it as a means of communication, navigation, the detection of prey and the avoidance of predators. It is therefore pertinent to consider the extent to which anthropogenic noise disturbs the natural behaviour of aquatic animals. These aspects of underwater acoustics have also been the subject of much research (Hawkins 1993; Richardson *et al.* 1995; Heathershaw *et al.* 2001).

1.1 A brief history

References to underwater sound can be traced back as far as mediaeval times. Urick (1983) mentions a notebook, dated 1490, in which Leonardo da Vinci observed that by listening to one end of a long tube, with the other end in the sea, 'you will hear ships at a great distance'. The speed of underwater sound, about 1450 $\mathrm{m\,s^{-1}}$ in fresh water, was first measured by Colladon and Sturm in 1827. They simultaneously transmitted a flash of light and the sound of an immersed bell across Lake Geneva in Switzerland, and deduced the sound speed from the time delay between the received signals. However, practical applications had to await more advanced technology, notably the piezo-electric transducer which was invented by the French physicist Langevin in 1917. As a result of research motivated by the First World War, it was discovered that submarines could be detected by listening for the echo of a sound transmission. The term 'echosounding' first appeared in the 1920s, referring to the technique of

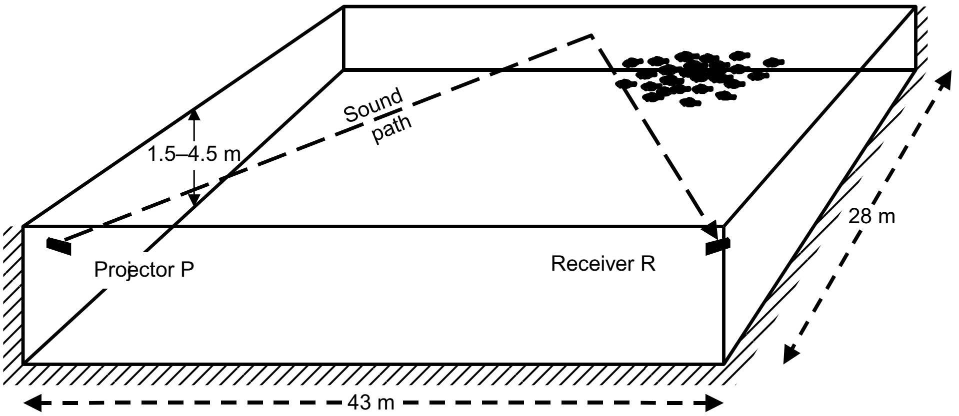

Fig. 1.1 Apparatus used by Kimura (1929) in the first acoustic detection of fish. Sound from the projector P is reflected by the far side of the pond (1.5–4.5 m deep) and detected by the receiver R. Fish passing through the beam cause the amplitude of the received signal to fluctuate.

measuring water depth from the time delay of a two-way transmission between the surface and the bottom (Anon 1925).

The French navigator Rallier du Baty (1927) described unexpected sounder signals originating in midwater, which he attributed to echoes from fish schools, a possibility first mentioned by Portier (1924). The first successful experiment on the acoustic detection of fish was reported by Kimura (1929). He installed a transmitter and a separate receiver in a fish-cultivation pond. The sound was transmitted in a 20° beam and detected after reflection from the opposite side of the pond as illustrated in Fig. 1.1. The transmission was continuous at 200 kHz frequency, with the amplitude modulated at 1 kHz so that the rectified signal was audible. The pond contained a school of *Pagrosomus major*, about 25 fish of length 40–50 cm. Kimura recorded the received sound by photographing the waveforms displayed on an oscilloscope (Fig. 1.2). He found that the amplitude was noticeably disturbed when fish were in the beam, although reliable detection depended on the surface of the pond being flat calm. In this experiment, the fish were detected by the fluctuation of the forward transmission caused by their movement. However, it soon became obvious that the alternative 'monostatic' arrangement, with the same transducer used for transmission and reception, is a more practical way to observe fish in the wild.

Further advances came with the development of the recording echosounder which produced echograms on paper (Wood *et al.* 1935). Once this device became commercially available at a reasonable cost, it had obvious potential as a fishing aid. From 1933 onwards, the British skipper Ronnie Balls experimented with an echosounder on his herring drifter 'Violet and Rose', though he only reported the work later (Balls 1946; 1948). The Norwegian Reinert Bokn, skipper of the seiner 'Signal', was conducting similar investigations at much the same time. Bokn is credited with the first example of a fish echogram to be published (Fig. 1.3). He fished on the near-surface

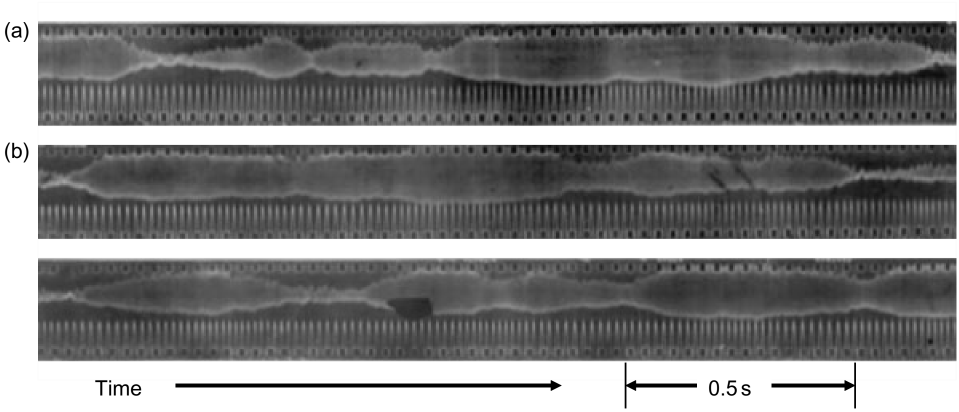

Fig. 1.2 Three sections of photographed oscillograms, from Kimura (1929). Each section shows two traces; the upper one (a) is the received acoustic signal, perturbed by the passage of fish through the beam; the lower one (b) is a constant 60 Hz signal giving a time reference.

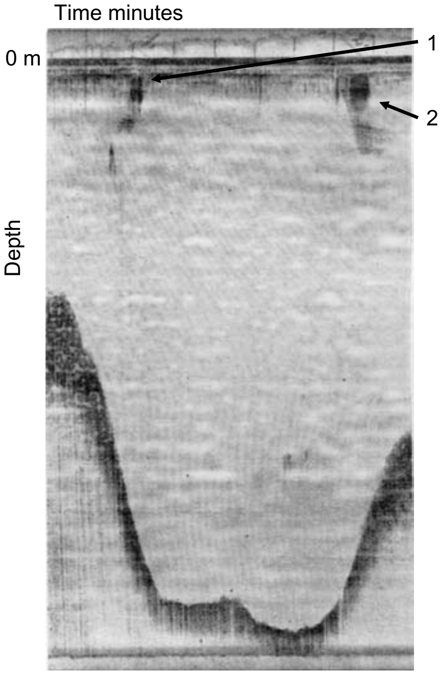

Fig. 1.3 Early example of fish detection by an echosounder, from Anon (1934), recorded by Reinert Bokn in Frafjord, Norway. The horizontal line at the top is the sea surface. A near-surface fish school is first detected at position (1). Then the boat turns and re-locates the same school at position (2). A seine cast at this location gave a catch of 400 bushels (15 tonnes) of sprat.

marks and showed they were schools of sprat *Sprattus sprattus* (Anon 1934). Other Norwegian investigators made notable contributions, especially Sund (1935) who published echograms of the cod, *Gadus morhua*, using a 16 kHz echosounder with a magneto-strictive transducer on the research vessel 'Johan Hjort'. This equipment revealed many unsuspected features of the fish distribution, notably that the cod were confined to a narrow layer 10 m thick at a constant depth below the surface. Two years later, the Norwegians were even conducting acoustic surveys to chart the geographic distribution of herring schools (see Runnstrom 1937).

There was another period of rapid development during the Second World War, after which fishers soon discovered the civilian potential of the acoustic techniques developed by the military (Hodgson 1950; Hodgson and Fridriksson 1955). The power and resolution of sonars continued to improve as new instruments were designed specifically for fish detection. Many different kinds of sonar are now employed in fishing, from the simple echosounder to scanning sonars which provide radar-like images of detected targets, and transducers on trawls which locate the net relative to the seabed and fish schools. The multi-coloured echogram gives a clearer perception of the signal strength, compared to the original monochrome display, while the concurrent use of two or more frequencies gives the user more information about the detected targets. Fishers have exploited these developments with great skill, especially in pelagic fishing where efficient searching for schools and accurate deployment of the gear are essential to success.

Acoustic methods of fish abundance estimation were first investigated in the 1950s. Initially these were based on simple ideas of counting individual echoes (Tungate 1958; Mitson and Wood 1962), or summing the echo amplitudes (Richardson *et al.* 1959). The latter is essentially the technique of echo integration, attributed to the Norwegian Ingvar Hoff, as described by Dragesund and Olsen (1965). However, Scherbino and Truskanov (1966) showed that the correct approach is to integrate the echo intensity, not the amplitude, and that remains a fundamental principle of fish abundance estimation. In the early days, the results that could be obtained were subject to large errors. The calibration methods of the time were imprecise, and the target strength of fish was uncertain. Intensive theoretical and experimental investigations in the 1970s and 1980s led to a better understanding of what acoustic techniques could and could not do. High-performance scientific echosounders were introduced with digital signal processing, giving larger dynamic range, more stable gain characteristics and better compensation of the propagation losses. Calibration is no longer a limiting factor, provided it is done in the recommended way (Foote *et al.* 1987). New techniques evolved for measuring the target strength of fish *in situ* (i.e. in their natural environment), notably the dual-beam and split-beam echosounders, although it has to be said that the uncertainty of target strength is still a significant error factor (among others) in acoustic abundance estimation. Nevertheless, the progressive development of scientific instrumentation, scattering theory and data analysis techniques brings us to the present state of the art: acoustic methods have greatly advanced our understanding of fish and fisheries. In particular, surveys using echo integrators or echo counters are in many cases an essential part of fish stock assessment.

Much of the fisheries-related work on acoustics, over the past 50 years or more, has been promoted by the International Council for the Exploration of the Sea (ICES) through various working groups and conferences that brought together experts from the many disciplines involved. Historical reviews that highlight the ICES contribution will be found in Fernandes *et al.* (2002) and Rozwadowski (2002).

1.2 Synopsis

This book is an update of our previous text on fisheries acoustics (MacLennan and Simmonds 1992) and it follows a similar structure. A major addition is the new Chapter 7 which recognizes the importance of recent developments in plankton acoustics. Chapters 2 and 5 cover the basic principles of fish detection which are largely unchanged. Chapter 3 describes modern acoustic instruments whose capabilities have advanced by leaps and bounds over the past decade. Chapter 4 on biological acoustics contains new material on the environmental impact of anthropogenic noise. The changes to Chapter 6 reflect the considerable work done on modelling the target strength of fish, and the many experimental investigations conducted over the past 15 years. Chapters 8 and 9 are concerned with, respectively, the design of acoustic surveys and the subsequent analysis of the results. Again, there have been substantial advances to report, especially in the evaluation of errors in acoustic estimates of fish density and abundance.

We have described the physics of underwater sound to the extent necessary to show the advantages and disadvantages of acoustic methods in fishery investigations. Bearing in mind that many readers will have a background in the biological sciences, and may be less familiar with mathematics, we have tried to explain the subject in words and illustrative graphics, to reduce the reliance on mathematical shorthand which is rather too common in acoustic publications. However, some theory is essential for the proper understanding of underwater sound, the nature of fish as acoustic targets and the statistical problems which are common to any kind of survey. A collected list of symbols is provided in Section 1.3. Throughout this book, the emphasis is on acoustics as an applied science. Practical advice is given on the use of acoustic instruments in the field and the solution of problems which are often ignored by those who prefer the purely theoretical approach.

Chapter 2 is an introduction to the concept of energy transmission by sound waves and the remote detection of targets. We discuss the generation of sound by transducers, the propagation of waves, the scattering properties of targets and the formation of echoes. The competing requirements of resolving close targets and detection at long range are considered in relation to the frequency of the sound waves and the limits imposed by ambient noise in the ocean.

The operating principles of modern acoustic instruments are described in Chapter 3. The basic echosounder or sonar transmits sound in a single beam. This permits the range but not the direction of targets to be determined, although two-dimensional mapping is achieved when the sonar is on a moving vessel. More sophisticated devices are capable of angular resolution. They include the dual-beam, split-beam, multi-beam and sector-scanning sonars that are now used extensively.

The full three-dimensional imaging of targets is possible using new types of sonar that are currently progressing from the experimental stage to full commercial implementation. The multi-frequency sonar is another important development. This offers the possibility of identifying targets from the spectrum of echoes, however, truly wideband systems are still at an early stage of development. The calibration of acoustic instruments is discussed with reference to scanning sonars as well as echo-sounders. Practical advice is given on how to perform the calibration in accordance with internationally accepted standards.

In Chapter 4, we review various topics to do with the physiology and the behavioural importance of sound for life in the sea and fresh waters. We discuss the sensitivity of hearing, the production of sound by animals and the remarkable sonar capability of the aquatic mammals. These natural phenomena must be understood to assess the environmental impact of anthropogenic sounds which range from low-amplitude noise pollution to the shock waves produced by explosive devices. The biological consequences of noisy human activities are discussed, and we show how the impacts in terms of behavioural changes and physiological damage can be assessed. Theoretical models for predicting the strength of shock waves and the mortality of exposed fish are reviewed. Another biological topic (of a less sensitive nature) is the phenomenon of swimbladder resonance. This has potential as a means of determining fish size from the echo spectra observed at low frequencies.

Chapter 5 is concerned with the observation and measurement of fish, or in other words how to interpret the information provided by acoustic instruments. We begin with the simple echogram and the technique of school-counting. The measurement of fish density calls for more advanced techniques, notably echo-counting and echo-integration. The density is supposed to be proportional to the integral of the echo energy returned from the depth channel of interest. This assumption depends on the linearity principle which is central to the theory of fisheries acoustics. The evidence in support of linearity is discussed, and the particular conditions (e.g. very dense aggregations of fish) in which it might not apply. We describe various other acoustic techniques which can provide useful information on the behaviour, distribution and abundance of fish.

The target strength of fish is reviewed in Chapter 6. Experimental techniques for measuring the target strength are described. In addition, theoretical models of acoustic scattering have given useful insights through better interpretation of experiments and understanding the physical principles that determine the target strength. The swimbladder is the dominant sound reflector in those species which have one. Accordingly, fish targets may be classified in groups of species having similar acoustic properties, according to the type of swimbladder possessed. Within each category, fish of the same size have similar target strengths on average, but there is much residual variation which emphasizes the stochastic nature of target strength. The dependence of the target strength on the fish size is an important consideration. This is normally expressed in terms of the fish length, through the so-called target-strength function. The importance of fish behaviour and physiology in explaining the variability of target strength is discussed. Published experimental results are presented in tables arranged to provide easy means of reference.

Chapter 7 begins with the classification of plankton as acoustic targets. Three broad classes are identified – FL (fluid-like), ES (elastic shell) and GB (gas bearing). Theoretical scattering models are especially important here; without these it is difficult to relate the target strength to the size of very small animals. Various models and approximate solutions are described. For the FL plankton, model calculations depend on the density and sound speed contrasts in the body. Measurement techniques and current knowledge of these parameters are reviewed. The target strength is still a useful descriptor of large plankton like the Antarctic krill, and the results of theoretical and experimental studies are presented. The traditional method of abundance estimation (based on the size dependence of target strength) has been applied to krill, but more sophisticated methods are generally required for plankton. The concurrent use of several frequencies gives information on the size distribution as well as the abundance, provided the model assumptions are reliable. Some progress has been made on the identification of species from their echo characteristics, but in many cases this still depends on the collection of samples by fishing. Various acoustic methods for observing the behaviour of plankton are discussed, particularly the use of multi-beam sonar to provide three-dimensional images.

The last two chapters (8 and 9) deal with the practice of acoustic surveying to measure the abundance and distribution of fish. The emphasis is on the practical problems that arise in applying the theoretical principles discussed earlier. In Chapter 8, we consider the design of the cruise track and the sampling strategy to make the best use of the available time. We discuss the balance of time between running transects to record acoustic data and other activities such as fishing to identify the echo traces. We give examples of inter-ship comparisons which test the overall performance of the survey equipment in the field, although they are not a substitute for the recommended calibration procedure. In Chapter 9, we discuss the analysis of the data collected during the survey. The aim is to calculate abundance estimates within defined confidence limits. First, the echo-integrals must be partitioned between species, and the surveyed area may be stratified depending on the stationarity of the fish density. An echo-integrator conversion factor is calculated for each species and stratum from which the density samples are obtained. The total abundance is estimated from the observed densities. There are a number of approaches to this problem, which is complicated by the statistics of spatial correlation. We describe contour mapping, geostatistics and numerical methods based on rectangular grid strata. The various factors which contribute error are discussed and we show how the overall accuracy of the abundance estimate can be assessed. The results obtained from acoustic surveys are compared with those of alternative methods, again to indicate the accuracy that can be expected in typical circumstances.

In compiling the references, we have concentrated on the many publications which have appeared in the past 35 years or so, avoiding obsolete material but including key references to earlier work that laid the foundations of modern fisheries acoustics.

A useful source of earlier reference material can be found in Venema (1985) which is a selected bibliography of publications relating to fisheries acoustics.

1.3 Acoustic terminology and symbols

There has been much confusion over the years about the precise meaning of terms such as the 'acoustic cross-section' of a target. In this book, we use the standard terminology and symbols for fishery applications recommended by MacLennan *et al.* (2002). In particular, readers should note that the acoustic reflectivity of a target is normally described by the backscattering cross-section, σ_{bs}. This is an important change from the treatment in MacLennan and Simmonds (1992) which was based on the spherical scattering cross-section, σ_{sp}. Thus some of the equations in this book have a different formulation, but they accord with what is now regarded as standard practice in fisheries acoustics. If formulas or data from older publications are being used, it is important to be clear about the units relevant to acoustic scattering parameters. Mistakes in this area can result in very large errors.

This following list defines the mathematical symbols used in this book. They mostly follow current practice and should have a similar interpretation elsewhere in the acoustics literature (MacLennan *et al.* 2002). Some are uniquely defined and may occur in several chapters (the common symbols). Others are specific to one chapter and are listed as such. Occasionally, the same symbol has alternative definitions, but the meaning in each case is always defined in nearby text.

Common symbols

c	Sound speed in water
CV	Coefficient of variation (the standard error divided by the mean)
EBA	Equivalent beam angle of a transducer, in dB relative to 1 steradian
f	Frequency (cycles per second)
$\overline{g}$	Time-varied-gain (TVG) correction factor
I	Intensity of a sound wave (power transmitted per unit area)
J	Flux of a sound or shock wave (energy transmitted per unit area)
k	The wavenumber, equal to $2\pi/\lambda$
L	Body length of a scatterer (normally the total length in the case of fish)
L_{bs}	Backscattering length of a target (a complex variable, $\sigma_{bs} = \|L_{bs}\|^2$)
p	Instantaneous pressure amplitude of a sound wave
s_a	Area scattering coefficient (units m^2/m^2)
s_A	Nautical area scattering coefficient, equal to $4\pi(1852)^2 s_a$
s_v	Volume backscattering coefficient (linear measure)
S_v	Volume backscattering strength (log measure, in dB re $1\,m^{-1}$)
S	Salinity of water

SE	Standard error (the standard deviation of the sample mean)
SNR	Signal-to-noise ratio (expressed in dB)
SL	Source level, dB measure usually re 1 μPa at 1 m from the source
t	Time (exception in Chapter 9)
T	Water temperature
TS	Target strength of one scatterer, a logarithmic measure of σ_{bs}
$\mathrm{TS}_{\mathrm{kg}}$	Target strength normalized to 1 kg weight of scatterers
v	Particle velocity associated with a sound wave
Z	Acoustic impedance of a medium, equal to the density times the sound speed
α	Acoustic absorption coefficient in dB per unit distance
β	Acoustic absorption coefficient in nepers ($1\,\mathrm{Np} = 8.686\,\mathrm{dB}$) per unit distance
Φ	The impulse (integral of pressure w.r.t. time) transmitted by shock waves
η	Phase difference between two signals
λ	Wavelength, distance between successive peaks of a sound wave
ρ	Density of water
$\sigma(\theta,\phi)$	Differential scattering cross-section, defines scattering in direction (θ,ϕ)
σ_{bs}	Backscattering cross-section, same as $\sigma(\theta,\phi)$ for $\theta = -\pi$ and $\phi = 0$
σ_{sp}	Spherical scattering cross-section, equal to $4\pi\sigma_{\mathrm{bs}}$
$\sigma(\omega)$	Backscattering cross-section at frequency ω
τ	Duration of a sonar transmission pulse, time from start to finish
ψ	Equivalent beam angle of a transducer in steradians
ω	Angular frequency (radians per second)

Chapter 2

a	Radius of a sphere, or the side of a square
b	The beam pattern; function of direction describing the amplitude sensitivity
B	Bandwidth of the sonar receiver
c_1	Speed of longitudinal sound waves in a solid
c_2	Speed of transverse sound waves in a solid
d	Characteristic linear size of a target
E	Energy
f_0	Frequency of the sine waves within a pulse
f_1	Frequency of the lowest resonance in a solid target
F	Form function (ratio of spherical scattering and geometric cross-sections)
I_0	Intensity normalized to 1 m range
I_{bs}	Intensity of the backscattered wave
I_i	Intensity of the incident wave
I_m	Mean intensity
L_p	Pulse length in water

N	Number of targets, cycles etc.
$\lvert p\rvert$	Amplitude of the sound pressure variation
$\lvert p_0\rvert$	Sound pressure amplitude normalized to 1 m range
P_0	Ambient pressure in the water
p_{rad}	Radiation pressure in the water (at a target)
p_{rms}	Root-mean-square (average) of the instantaneous sound pressure
$P(\omega)$	Power response of the sonar at frequency ω
r_{b}	Reflection coefficient; proportion of incident energy reflected at a boundary
r_{dB}	Ratio of two intensities expressed in decibels
R	Range or distance
R_{b}	Range at the boundary between the near and far fields
t_{e}	Time between the transmitter pulse and the echo being received
$\lvert v\rvert$	Amplitude of the particle velocity variation
V_0	Sampled volume
x	Distance along the propagation path, or a general variable
z	Depth below the water surface
Z_{r}	Acoustic impedance of a reflector
Z_{w}	Acoustic impedance of water
θ	Angle from the acoustic axis
ϕ	Azimuthal angle in the transducer plane
ρ_1	Density of a solid target
θ, ϕ	Angular coordinates of the scattering direction relative to the incident wave

Chapter 3

a(t)	Ideal TVG function for exact range compensation
A(t)	Actual TVG function of an echosounder
b_{n}	One-way amplitude sensitivity of the narrow beam
b_{w}	One-way amplitude sensitivity of the wide beam
B	Two-way energy sensitivity of the transducer
C_{a}	Calibration factor for the on-axis sensitivity
c_1	Longitudinal sound speed in a standard target
c_2	Transverse sound speed in a standard target
c_{f}	Sound speed at the fish depth
c_{o}	Assumed sound speed (as entered in the sounder settings)
c_{s}	Sound speed at the transducer
c_{z}	Mean sound speed along the path between the transducer and the fish
d	Linear size of the transducer face
E	Echo-integral
E_{t}	Echo-integral of a standard target
E_0	Echo-integral of a target on the acoustic axis