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Acoustic applications in fisheries science: the ICES contribution

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Sound is the most effective medium with which to perceive the marine environment, as evidenced from the evolution of echolocation in cetaceans developed over millions of years. In the 100 years since its inception, ICES has presided over an analogous development in fisheries science: fisheries acoustics. Echosounders were invented in the 1920s, and successful attempts to detect fish in the 1930s are recorded in the ICES literature. With the proliferation of acoustic instrumentation in the post-war years, "echo surveys" were carried out to map various fisheries resources. The first meeting on echosounding as an aid to fishing was organized by ICES in 1954, and the technique flourished in the 1960s. Progress was reported to ICES committees, and a training course was organized in 1969 in conjunction with FAO. An ICES International Symposium on "Hydro-Acoustics in Fisheries Research" took place in Bergen, Norway in 1973. This was one of four more successful symposia documenting a global view of fisheries acoustics through the proceedings published by ICES. It was largely as a result of the third conference that a specific group was set up to cater for the expanding contributions within the field. The ICES Working Group on Fisheries Acoustics Science and Technology (WGFAST) met for the first time in 1984 and has been active ever since, providing authoritative documentation on important topics in the field. This paper reviews the ICES contributions in the field and describes the general principles of a technique which has evolved to provide a powerful means for investigating the abundance, distribution, behaviour, and ecology of fish, plankton, and other marine organisms.

Keywords: acoustics, echosounders, fisheries, history, ICES, sonar, WGFAST.

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Introduction

The penetration of sound in water is significantly greater than that of light. Active acoustic instruments which, by definition, transmit and receive sound waves are, therefore, capable of detecting fish or other objects far beyond the range of any visual system. The exploitation of this property has been most evident in the millions of years of evolution that have given rise to the sophisticated echolocation facilities of whales and dolphins (Au, 1993). At the beginning of the 20th century, when the International Council for the Exploration of the Sea (ICES) was formed, there were no instruments remotely capable of emulating this capability. Acoustic instruments are now essential requirements for any fishing vessel to determine the location of fish and the seabed. Similarly, acoustic applications are now widespread in fisheries science to assess the abundance, distribution, and behaviour of fish, plankton, and other marine organisms; they are also used in monitoring the performance of sampling gears (see Walsh *et al.*, 2001).

ICES has been at the forefront of the development of these applications: it has documented pioneering research, organized training courses, convened symposia, brought experts together in working groups, and coordinated multinational acoustic surveys. This paper reviews the contribution that ICES has made to what is now the scientific discipline of fisheries acoustics. After a brief description of some basic principles and current applications, an account is given of historical accomplishments. Finally, consideration is given to future developments which are likely to see acoustic applications become even more significant in the coming century.

Principles and applications

The theoretical basis of fisheries acoustics has been reviewed at regular intervals, but one of the first descriptions was an ICES publication (Craig, 1955). The more general science of underwater acoustics and its sibling discipline, acoustical oceanography, has been covered extensively by Urick (1983) and Medwin and Clay (1998). Most of the essential physical principles related to fisheries are covered in the more specific fisheries acoustics texts (Forbes and Nakken, 1972; Cushing, 1973; Burczynski, 1982; Johanneson and Mitson, 1983; Thorne, 1983; Mitson, 1984), the latest of which (MacLennan and Simmonds, 1992) provides a comprehensive treatment of the discipline.

The basic tool in fisheries acoustics is the scientific echosounder. This instrument produces an electrical signal which is converted by a transducer to an acoustic pulse or "ping". The transducer is mounted on a suitable platform, such as the hull of a ship, and the "ping" is directed vertically downwards into the water column in a beam (typically of the order of 10°) which geometrically is the acoustical analogue of a beam of light from a torch. When objects such as fish are insonified by the sound, part of the acoustic energy is reflected and received by the transducer as an echo which is then converted to electrical energy. The distance or range to the fish is obtained by timing the interval between transmission and reception (knowing the speed of sound in water, approximately 1500 m s^{-1}). The energy is then amplified to compensate for the effects of geometrical spreading and absorption.

An echosounder will typically ping at a rate of one pulse per second. When calibrated, the absolute echo levels are quantified by averaging a number of transmissions using echo integration, yielding a quantity which is proportional to fish density according to the linearity principle (Foote, 1983). The calculated fish densities, obtained from survey vessels travelling along defined transects, are then interpolated and raised to the survey area to give an estimate of fish abundance (Simmonds *et al.*, 1992). The acoustic properties of the fish must be known, and these are obtained from species-specific, target-strength (TS) relationships once the fish have been identified. Although echo characteristics may often be sufficient to identify fish to species (Reid, 2000), confirmation is obtained from trawl samples which also provide length, age, and maturity composition.

Within the ICES community, there are currently over 20 fish stocks for which acoustic assessments are carried out. Most of these are pelagic (midwater) species such as herring, sprat, sardine, and anchovy. The technique has traditionally not been suitable for the detection of demersal fish that occur very close to the bottom in the acoustic "dead zone" (Mitson, 1983). This is, however, changing with improvements in seabed recognition and the application of correction factors (Ona and Mitson, 1996). The data from acoustic surveys are used in stock assessments as indices of abundance-at-age, but mean weights-at-age, spatial distribution, and absolute biomass may also be used. Throughout the world, acoustic techniques are equally widespread and used in an even greater variety of fisheries, such as Antarctic krill (Everson, 1982; Hewitt and Demer, 1991) and the deepwater acoustic surveys of orange roughy off Tasmania (Kloser, 1996).

There is a wide variety of other acoustic instruments, collectively known as sonar, based on principles similar to the echosounder. Most of the variants encompass a wider, insonifying beam angle (up to 360° in the case of omni-directional sonar) and are distinguished from echosounders by orientating their beam(s) in any aspect (e.g., horizontally). This makes quantitative interpretation difficult because of refraction through layers of water with different temperatures and because the scattering properties of fish are generally only known for their dorsal surface and not from side aspects. Despite these limitations, sonars have the capability of detecting fish at large (horizontal) distances from the vessel, making them invaluable tools for observing fish behaviour, especially schooling (Pitcher *et al.*, 1996) and the reaction of fish to gear or a survey vessel (Gerlotto *et al.*, 1999).

The wide variety of current applications in fisheries acoustics is reflected in the diverse categories of papers submitted to ICES-sponsored acoustic symposia (Table 1). The discipline has diversified significantly from its humble beginnings concentrating on the simple detection of fish.

Echosounding – the formative years

Although rudimentary observations of underwater sound can be traced to Leonardo da Vinci, the history of active echo sounding really began with Maury's (1859) thwarted attempts to "fathom the ocean ...by sound". It wasn't until the early 1900s that echo-ranging was developed, initially for locating icebergs (post-"Titanic") and then later for detecting submarines during World War I. The invention of the piezoelectric transducer by the French physicist Langevin in 1917 spawned a number of practical echosounding devices, including Marconi's "echometer" and the American "fathometer"; it also gave impetus to the Royal Navy's ASDIC experiments (**A**nti-**S**ubmarine **D**ivision and the suffix "ic"). By 1925, the term "echosounding" was commonly used and a number of instruments were available (Anon., 1925). "Marti" and "Langevin-Florisson" echosounders were described to the ICES community for the first time by the French expert Belloc (1929a, 1929b).

Table 1. Number (and percentage) of published articles according to theme at acoustic symposia. For 1973, 1982, and 1987, the papers are grouped by subject into the themes of the 1995 symposium, with the exception of survey results which were not presented in 1987 and 1995. The first ICES acoustics meeting took place in Charlottenlund in 1954 and was attended by at least eight participants from the ICES Herring Committee.

Theme	Bergen 1973	Bergen 1982	Seattle 1987	Aberdeen 1995
Fish, plankton, and environment	1 (2)	0 (0)	1 (2)	6 (10)
Classification and identification	5 (12)	2 (6)	2 (4)	7 (11)
Fish and plankton TS	4 (11)	6 (16)	12 (26)	16 (26)
Technical methods	15 (36)	9 (25)	13 (28)	11 (18)
Data analysis methods	6 (14)	9 (25)	7 (15)	8 (13)
Fish and plankton behaviour	1 (2)	2 (6)	7 (15)	7 (11)
Validation	1 (2)	4 (11)	4 (9)	6 (10)
Survey results	9 (21)	4 (11)	–	–
Total	42	36	46	61
No. of participants	125	148	250	267

In the early 1920s, reference had already been made to the possibility of detecting echoes from sardine and herring schools (Portier, 1924). In 1926, the French navigator Rallier du Baty (1927) attributed abnormal signals on his sounder to a shoal of cod on the Grand Banks, and in 1928, he detected herring whilst on board a Bologne drifter. A report of the first successful experiment demonstrating the acoustic detection of fish was published the following year (Kimura, 1929). In 1933, Edgell (1935) detected fish from HMS "Challenger", and more significantly, William Hodgson (later Chair of the ICES Herring Committee) noticed false echoes, which he attributed to herring. It was on Hodgson's recommendation that the skipper Ronald Balls then undertook seven pioneering years of fishing with an echosounder (1933–1939) on his herring drifter "Violet and Rose" (Balls, 1946, 1948). By this time, the recording echosounder had been developed by Wood *et al.* (1935) and marketed by Hughes. It was first used on the "Glen Kidston" on a voyage from Hull to Bergen in 1933, and in July 1934, the first echogram was published (Anon., 1934), attributed to the Norwegian R. Bokn of the fishing vessel "Signal". The same type of sounder was used by the ICES Delegate Oscar Sund (1935) in his famous publication on echograms of cod in the Vestfjord. By 1937, the Norwegians were conducting acoustic surveys to plot the distribution of herring (Runnstrom, 1937, 1941; Sund, 1943). Progress, interrupted by World War II, then flourished from technological advances made during the war. ASDIC or sonar (**so**und **na**vigation and **r**anging – a term coined late in the war as a counterpart to radar) was used for the first time for successfully locating clupeoids in the English Channel in 1946 (Renou and Tchernia, 1947).

By the late 1940s, echosounders were being widely used in fish finding (Tester, 1943; Hodgson, 1950), gear monitoring (Hodgson and Richardson, 1949; Wood and Parrish, 1950), systematic acoustic surveying (Krefft and Schubert, 1950; Richardson, 1950; Devold, 1952; Craig, 1952), fish behaviour (Balls, 1951), marine biology (Dietz, 1948), and plankton studies (Johnson, 1948; Moore, 1950). As early as 1949, Cushing and Richardson (1953) were experimenting with multiple frequencies to identify fish echoes and even touched on the concept of linearity. The proliferation of these applications prompted the ICES Herring Committee to conduct an enquiry which, in 1954, resulted in the first symposium on echosounding as an aid to fishing (Hodgson and Fridriksson, 1955). This included descriptions of the techniques, a review of activities in various countries, and a pioneering proposal for an "organised echo-search in North Sea herring" (Parrish, 1953).

Towards quantification

By the early 1950s, attempts were being made to quantify echo returns. Schüler and Krefft (1951), Cushing (1952), and Tungate (1958) measured the widths of echo traces, and the latter authors published contour maps as numbers of soundings (in echo units or mm) per distance steamed. Richardson *et al.* (1959) took the next step by showing that the abundance of cod could be well estimated from the visual inspection of the sum of signals (as amplitude) per unit distance steamed; this method was soon automated by the application of electronic signal processing (Mitson and Wood, 1962). The development of the echo integrator, attributed to the

Norwegian Ingvar Hoff (Dragesund and Olsen, 1965), enabled the summation of received voltages to be made over short time periods and formed the basis of modern acoustic abundance estimation (MacLennan, 1990). However, an important adjustment of the integration principle was not immediately realized until the work of Scherbino and Truskanov (1966); their calibrations showed empirically that squared echo voltage (i.e., echo intensity) is proportional to fish density. They also reported to ICES the first series of acoustic biomass estimates of the stock of Norwegian spring-spawning herring in 1961–1964. They computed school volumes from echograms, measured the corresponding echo voltages, and calibrated the voltage readings by fish density estimates from underwater photographs. Their estimates of stock size compared well with estimates obtained by other methods at that time.

Acoustic survey programmes were soon flourishing throughout the world. Other examples included the Peruvian Eureka Program (Villanûeva, 1971), where commercial vessels were used to map the geographical distribution of anchoveta; the Icelandic Herring Search and Information Service (Jakobsson, 1971); the Japanese service of forecasting fishing conditions in the East China Sea (Ura and Mori, 1971); and the Norwegian sonar surveys of herring (Devold, 1963). In cases where single fish could be detected, producing the classic "comet" trace, it was soon realized that these could be counted to produce absolute abundance estimates (Midttun and Sætersdal, 1957). This relatively simple method of "echo counting" was used extensively thereafter where appropriate (Sætersdal and Hylen, 1959).

In parallel with the developments in abundance estimation techniques, substantial achievements were made regarding interpretations of echo records and the scattering properties of fish and other organisms. Measurements of target strength were made by a variety of workers (see Cushing, 1973). By the early 1950s, it was well known that the echo amplitude was seriously affected by the presence or absence of a swimbladder (Tucker, 1951). It was soon realized that a number of other factors were also important: instrument characteristics, such as the beam pattern of the transducer (Raitt, 1948) and acoustic frequency (Cushing and Richardson, 1953; Hashimoto and Kikuchi, 1959); depth, recognizing the need for time-varied gain (Craig, 1955); and target characteristics, such as the size, shape, and tilt angle of individuals (Midttun and Hoff, 1962).

As results from fully controlled experiments gradually became available, the complexity of the relationship between echo and fish species, size, aspect angle, and density was realized, and the demand for more controlled measurements grew. The methodology for estimating density distributions of target strength of individual targets (Craig and Forbes, 1969) was a major step in size determination of fish during surveying. It provided true estimates of numbers per unit volume (or area) for each target-size group by removing the effects of the beam pattern of the transducer.

Towards the end of the 1960s, more complex acoustic instruments were becoming available. Transducers deployed on trawl headlines (known as *netzsondes*) were used to measure trawl dimensions (Scharfe, 1968). Side-scan sonar, where the acoustic beam is directed sideways, was initially developed for geological (seabed) surveys, but was also used to survey sprat shoals (Cushing, 1963). Doppler sonar, measuring the frequency shift caused by the movement of insonified objects, was first used to detect fish shoals by Hester (1967). More successful, however, was the development of the sector scanner (Tucker and Welsby, 1960). This instrument transmitted on a wide beam and received by electronically scanning an array with many channels giving two-dimensional images for each transmission. It was used to study the behaviour of herring shoals in relation to tidal movements (Welsby *et al.*, 1963) and to study packing densities in pilchard schools (Cushing and Harden Jones, 1967).

The significant developments in abundance estimation during the late 1960s persuaded ICES (Gear and Behaviour Committee) to collaborate with the Food and Agriculture Organization of the United Nations (FAO) to organize a training course for fisheries scientists; this was held in Svolvær, Norway in 1969. It was during this course that the theoretical considerations of squaring the echo voltage were explained by Bobby Craig; this rather important concept had just been incorporated as a "squaring unit" in the new generation of echo integrators. The course produced a number of preliminary manuals, ultimately culminating in the work of Forbes and Nakken (1972). This widely distributed document established a common methodology for conducting fisheries surveys and was used as a guide by fisheries acousticians for much of the decade.

In reviewing the outcome of the 1969 training course, the Gear and Behaviour Committee made two recommendations: 1) that an acoustics group be set up within the Committee; and 2) that steps be taken to organize a symposium on "Acoustic Methods in Fisheries Research". The former was not to come about until later; the second, however, went forward as a recommendation which ultimately led to the symposium being held in Bergen in 1973 (Margetts, 1977). The symposium was well attended and covered a wide variety of subjects in the field (Table 1).

The digital age

The stability, or more accurately, the lack thereof, of analog acoustical receivers during the 1960s often required heroic efforts from the new adherents of echo integration. The 1970s witnessed a major advance in technology – the rapid introduction of relatively inexpensive digital electronics. Employing digital processing in acoustic receivers meant one could calibrate a system and thereafter avoid much of the error associated with the omnipresent "drift" in signal levels that had been previously associated with analog circuitry. The parallel introduction of shipboard digital mini-computers provided a means of archiving, rapid processing, and display of acoustical data in quantities never before possible (e.g., Nickerson and Dowd, 1977).

The TS measurements made in the 1970s laid the foundations for our current understanding of echo formation in fish and in fish schools. Love (1971), MacCartney and Stubbs (1971), and Nakken and Olsen (1977) described the functional dependence and variability of TS with the physiology and depth history of a fish. Behaviour, especially tilt angle whilst swimming, was recognized as an important factor (Olsen, 1971). Work on swimbladder resonance for sizing fish was also carried out (Hawkins, 1977; Holliday, 1977a).

A number of specialized acoustic methods evolved in the 1970s. These included low-frequency sidescan sonar (Rusby *et al.*, 1973), the sea-going version of the sector-scanning sonar (Mitson and Cook, 1971), transponding fish tags (Mitson and Storeton-West, 1971), horizontal sonar for the assessment of small epipelagic fishes (Smith, 1970), and the use of doppler to examine the swimming behaviour and internal dynamics of schools (Holliday, 1974). The use of multiple frequencies for studies of zooplankton was also a significant development (Greenlaw, 1977; Holliday, 1977b).

ICES initiated, convened, and organized two further symposia in the 1980s (Table 1), one in 1982 in Bergen, Norway (Craig, 1984), and the second in 1987 in Seattle, Washington, USA (Karp, 1990). The 1982 symposium provided the forum for the presentation of the definitive study on the linearity of the integration method. The infamous MP1 experiment (Swingler and Hampton, 1981), which had brought the linearity principle into question, was commented on by John Ehrenberg, who explained the fundamental flaw in the experiments which had used targets at fixed locations. In contrast, Ken Foote presented experimental evidence of linearity using live fish in cages as targets and later published the results (Foote, 1983) in perhaps the most important paper of the decade.

The birth of WGFAST

As a result of the organization and high quality of papers presented at the 1982 symposium, the ICES Fish Capture Committee (once again) considered the formation of a specific acoustics working group. This was finally proposed, and the Working Group on Fisheries Acoustics Science and Technology (WGFAST) met for the first time in Hirtshals, Denmark in May 1984, chaired by Kjell Olsen. Since then, WGFAST has provided the only consistent international forum for discussion and presentation of new ideas in the field of fisheries acoustics; it has also produced a variety of documents detailing good practice.

In the early 1980s, there were no common acoustic calibration standards and often no methods for comparing the results from two or more acoustic surveys. This deficiency was one of the primary problems tackled by WGFAST in its first formal publication, the practical calibration guide by Foote *et al.* (1987) which described the standard sphere calibration method still used today. To check both calibration and vessel performance, the procedures for analysing inter-ship calibration, taking account of the error on both ships, were also documented (MacLennan and Pope, 1983). The ability to control equipment performance provided the basis for developing more reliable long-term survey time-series.

Techniques and considerations in the design of acoustic surveys were first considered comprehensively by Shotton and Bazigos (1984). Aglen (1983) examined a number of surveys by comparison and resampling, and by the end of the decade had assembled an extensive set of surveys worldwide and proposed empirical predictions of survey precision according to sampling intensity (Aglen, 1989).

The 1980s witnessed a wealth of fish TS investigations. Measurements on caged aggregations were reported (Edwards and Armstrong, 1983; Ona, 1984) as well as further investigations on the influences of fish physiology and behaviour (Foote, 1980; Halldórsson, 1983; Ona, 1990). TS results reported at ICES were summarized by Foote (1987) and included values for herring, sprat, cod, capelin, walleye pollack, and Pacific whiting. Measurements of *in situ* target strength became more common. Single-beam sounders could be used if algorithms to remove the beam-pattern amplitude distribution were employed (Jacobson *et al.*, 1990). However, two technical solutions dominated further development of *in situ* measurements: dual-beam (Ehrenberg, 1974) and split-beam systems (Carlson and Jackson, 1980).

The late Jimmy Traynor, WGFAST's second Chair (1989–1992), was a driving force in the application of this technology, and ultimately the split-beam system became the preferred option (Traynor and Ehrenberg, 1990). This was due not only to its capabilities for *in situ* TS measurement, but also the facility for locating the target sphere in calibration, and for fish tracking. Associated with the development of new split-beam systems (e.g., Bodholt *et al.*, 1989) were new post-processing tools allowing for more sophisticated analyses (Foote, 1991). Soule *et al.* (1996) later identified some problems with single-target recognition criteria in split-beam TS measurements and made suggestions for improvements. Methodological aspects of TS measurements were then examined by a WGFAST study group (Ona, 1999).

A large proportion of the work in the 1990s focused on ways to evaluate and improve the precision of acoustic data. The issue of survey design was discussed extensively by WGFAST under the new Chair, John

Simmonds (1993–1996), ultimately leading to an extensive review by Simmonds *et al.* (1992). It soon became evident that the standard statistical methods were not particularly well suited to the analysis of acoustic survey data. Some attempts were made to adapt the survey design to conventional statistics (Jolly and Hampton, 1990), but this quickly demonstrated its limitations. Another method explored in the early 1990s was the adaptation of geostatistics to acoustic survey data. A study group was set up, which recommended that spatial statistical techniques be applied to acoustic survey data for estimating abundance with an associated estimate of precision, and mapping the spatial distribution of the stock (ICES, 1993). This led to the application of specific spatial statistical tools for survey analysis (e.g., Petitgas, 1993).

Significant progress was made in the measurement and evaluation of the effect of noise created by survey vessels. In order to help improve the design of modern research vessels, another WGFAST study group was set up to provide a noise specification and review (Mitson, 1995).

The fifth acoustic symposium took place in Aberdeen, Scotland, in 1995 (Simmonds, 1996). One notable feature of this meeting was the movement away from dealing with instrumentation problems and the greater emphasis on extracting information on aquatic animals and their environment (MacLennan and Holliday, 1996).

The evaluation of biases in abundance estimates was documented in several WGFAST reports towards the latter part of the decade. A questionnaire distributed amongst WGFAST members revealed that fish behaviour was a major source of undocumented bias (ICES, 1998). An ICES Symposium on "Fish Behaviour in Relation to Fishing Operations" was held in Bergen in 1992 (Wardle and Hollingworth, 1993). This illustrated how fisheries acoustics as a method could be strongly affected by fish behaviour (mainly through fish avoidance of survey vessels) whilst at the same time being unique as an ideal tool for *in situ* behavioural research. Consequently, fish behaviour became a major theme for discussions at WGFAST meetings under the new Chair, François Gerlotto (1997–2000), and also at joint sessions with the Working Group on Fishing Technology and Fish Behaviour (chaired by Jacques Massé).

Since the early 1990s, schooling behaviour has been recognized as a key factor affecting pelagic stock assessment (as reviewed by Fréon and Misund, 1999). The dynamics of schooling behaviour has been the subject of several studies (Fréon *et al.*, 1993; Petitgas and Levenez, 1996; Pitcher *et al.*, 1996). One outcome of these studies was the realization that single-beam echosounders were not capable of sampling the volumes required for adequate measurement of school parameters (Reid, 2000). This led to the adaptation of multibeam sonar to fisheries acoustics used in the horizontal (Misund *et al.*, 1995) or vertical (Gerlotto *et al.*, 1999) directions, allowing for dynamic or three-dimensional observations of fish schools, respectively.

Future directions in fisheries acoustics

The development of multi-beam sonar systems provides a key to future development. The ability to combine what has become the traditional echo-integration survey with observation of fish school shape, structure, and distribution around the vessel provides data for species recognition, detection of behavioural problems, and an increased sampling volume for a more precise statistical evaluation of the survey. Associated with this technology is the increasing capacity of computer processing and data storage and the miniaturization of multi-frequency acoustic systems integrated with environmental sensors (Wiebe *et al.*, 1999). This will facilitate more extensive *in situ* surveying, using small vessels or alternative platforms, such as autonomous underwater vehicles (Fernandes *et al.*, 2000), allowing for the exploration of new domains, such as shallow-water areas (littoral zone, sea surface) and bathypelagic areas.

Acoustic survey data are becoming ever more prevalent in fish stock assessment such that abundance estimation remains the cornerstone of fisheries acoustics. Traditional assessments that rely on commercial catch statistics can have major shortcomings, and so the need for more fishery-independent (survey) data will increase (Carl Walters, cited in Anderson, 1996). ICES already coordinates a number of multi-national acoustic surveys covering large areas, such as the North Sea herring survey, realizing the pioneering proposal first put forward 50 years ago by Parrish (1953). Demersal species such as cod are now beginning to be surveyed acoustically (Rose, 1995; Michalsen *et al.*, 1996; McQuinn *et al.*, 1999). In addition, the increasing trend towards a multispecies and ecosystems approach to fisheries management demands the sort of information that can only be obtained from surveys (spatial distribution of fish, by size and age, in relation to oceanography and prey, and stomach contents).

Automatic species identification, using single-frequency (Scalabrin *et al.*, 1996), multi-frequency (Brierley *et al.*, 1998), and broadband (Simmonds *et al.*, 1996) techniques, has great potential to increase the utility of multispecies surveys and the accuracy of abundance estimates. Survey precision can now be evaluated using geostatistics (Rivoirard *et al.*, 2000). Developments are also taking place in understanding the dependence of behaviour and the environment on TS (Demer and Martin, 1995; Ona, 1999), incorporating specific scattering models for both plankton (Stanton *et al.*, 1996) and fish (Horne and Jech, 1999).

Many of these advances are current issues of debate at WGFAST meetings as special topics or contributions, under the new Chair, Yvan Simard. Through WGFAST, ICES continues its dedication to exploring the advanced technology of fisheries acoustics, and thus to providing an accurate tool for the estimation of the abundance and distribution of fish stocks and other biota in aquatic ecosystems.

References

Aglen, A. 1983. Random errors of acoustic fish abundance estimates in relation to the survey grid density applied. FAO Fisheries Report, 300: 293–298.

Aglen, A. 1989. Empirical results on precision–effort relationships for acoustic surveys. ICES CM 1989/B:30. 28 pp.

Anderson, C. 1996. Fishing on thin ice. Western Fisheries, January 1996: 41–44.

Anonymous. 1925. Echo sounding. Nature, 115: 689–690.

Anonymous. 1934. Forsøkene med Ekkolodd ved Brislingfisket (Trials with an echo sounder during the sprat fishery). Tidsskrifter for Hermetikindustri (Bulletin of the Canning Industry), Stavanger, July 1934, 222. (In Norwegian).

Au, W. 1993. The Sonar of Dolphins. Springer-Verlag, New York. 277 pp.

Balls, R. 1946. Fish on the spotline. Marconi International Marine Communication Company Ltd., London. 37 pp.

Balls, R. 1948. Herring fishing with the echometer. Journal du Conseil International pour l'Exploration de la Mer, 15: 193–206.

Balls, R. 1951. Environmental changes in herring behaviour: a theory of light avoidance, as suggested by echo-sounding observations in the North Sea. Journal du Conseil International pour l'Exploration de la Mer, 17: 274–298.

Belloc, M. G. 1929a. La croisière de la Tanche (Août 1927). Rapports et Procès-Verbaux des Réunions du Conseil International pour l'Exploration de la Mer, 55: 139–150.

Belloc, M. G. 1929b. Croisière de la "Tanche" en Juillet–Août 1928. Rapports et Procès-Verbaux des Réunions du Conseil International pour l'Exploration de la Mer, 62: 66–78.

Bodholt, H., Ness, H., and Solli, H. 1989. A new echo-sounder system. Proceedings of the Institute of Acoustics, 11: 123–130.

Brierley, A. S., Ward, P., Watkins, J. L., and Goss, C. 1998. Acoustic discrimination of Southern Ocean zooplankton. Deep-Sea Research II, 45: 1155–1173.

Burczynski, J. 1982. Introduction to the use of sonar systems for estimating fish biomass. FAO Fisheries Technical Paper, 191 (Revision 1). 89 pp.

Carlson, T. J., and Jackson, D. R. 1980. Empirical evaluation of the feasibility of split beam methods for direct in situ target strength measurement of single fish. Report of the Applied Physics Laboratory of the University of Washington (APL-UW 8006).

Craig, R. E. 1952. Echo sounding for herring. Part I. Fishing News, 2048: 9–10.

Craig, R. E. 1955. The use of echo-sounder in fish location – A survey of present knowledge, with notes on the use of Asdic. Rapports et Procès-Verbaux des Réunions du Conseil International pour l'Exploration de la Mer, 139: 32–49.

Craig, R. E. (Ed.) 1984. Fisheries Acoustics. Rapports et Procès-Verbaux des Réunions du Conseil International pour l'Exploration de la Mer, 184: 154 pp.

Craig, R. E., and Forbes, S. T. 1969. Design of a sonar for fish counting. Report on Norwegian Fishery and Marine Investigations 15: 210–219.

Cushing, D. H. 1952. Echo-surveys of fish. Journal du Conseil International pour l'Exploration de la Mer, 18: 45–60.

Cushing, D. H. 1963. The uses of echo sounding for fishermen. Fisheries Bulletin, HMSO, London. 28 pp.

Cushing, D. H. 1973. The Detection of Fish. Pergamon Press, Oxford. 200 pp.

Cushing, D. H., and Harden Jones, F. R. 1967. Sea trials with modulation sector scanning sonar. Journal du Conseil International pour l'Exploration de la Mer, 30: 324–345.

Cushing, D. H., and Richardson, I. D. 1953. Echo sounding experiments on fish. ICES CM 1953/Pelagic Committee:7. 8 pp.

Demer, D. A., and Martin, L. V. 1995. Zooplankton target strength: volumetric or areal dependence? Journal of the Acoustical Society of America, 98: 1111–1118.

Devold, F. 1952. A contribution to the study of the migrations of Atlanto-Scandian herring. Rapports et Procès-Verbaux des Réunions du Conseil International pour l'Exploration de la Mer, 131: 103–107.

Devold, F. 1963. The life history of Atlanto-Scandian herring. Rapports et Procès-Verbaux des Réunions du Conseil International pour l'Exploration de la Mer, 154: 98–108.

Dietz, R. S. 1948. Deep scattering layer in the Pacific and Antarctic Oceans. Journal of Marine Research, 7: 430–442.

Dragesund, O., and Olsen, S. 1965. On the possibility of estimating year-class strength by measuring echo-abundance of 0-group fish. Report on Norwegian Fishery and Marine Investigations, 13: 47–75.

Edgell, J. A. 1935. False echoes in deep water. Hydrographic Review, 12: 19–20.

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

Ehrenberg, J. E. 1974. Two applications for a dual beam transducer in hydroacoustic fish assessment systems. *In* Proceedings of the Conference on Engineering in the Ocean Environment, Halifax, Nova Scotia, August 1974, pp. 152–155. Institute of Electrical and Electronic Engineering, New York. 318 pp.

Everson, I. 1982. Diurnal variations in mean volume backscattering strength of an Antarctic krill (*Euphausia superba*) patch. Journal of Plankton Research, 4: 155–162.

Fernandes, P. G., Brierley, A. S., Simmonds, E. J., Millard, N. W., McPhail, S. D., Armstrong, F., Stevenson, P., and Squires, M. 2000. Fish do not avoid survey vessels. Nature, 404: 35–36.

Foote, K. G. 1980. Effect of fish behaviour on echo energy: the need for measurements of orientation distributions. Journal du Conseil International pour l'Exploration de la Mer, 39: 193–201.

Foote, K. G. 1983. Linearity of fisheries acoustics, with additional theorems. Journal of the Acoustical Society of America, 73: 1932–1940.

Foote, K. G. 1987. Fish target strengths for use in echo integrator surveys. Journal of the Acoustical Society of America, 82: 981–987.

Foote, K. G. 1991. Postprocessing system for echo sounder data. Journal of the Acoustical Society of America, 90: 37–47.

Foote, K. G., Knudsen, H. P., Vestnes, G., MacLennan, D. N., and Simmonds, E. J. 1987. Calibration of acoustic instruments for fish density estimation: a practical guide. ICES Cooperative Research Report, 144. 57 pp.

Forbes, S. T., and Nakken, O. 1972. Manual of methods for fisheries resource and appraisal. Part 2. The use of acoustic instruments for fish detection and abundance estimation. FAO Manual in Fisheries Science, 5. 138 pp.

Fréon, P., Gerlotto, F., and Misund, O. A. 1993. Consequences of fish behaviour for stock assessment. ICES Marine Science Symposia, 196: 190–195.

Fréon, P., and Misund, O. A. 1999. Dynamics of pelagic fish distribution and behaviour: effects on fisheries and stock assessment. Fishing News Books Ltd., Oxford. 348 pp.

Gerlotto, F., Soria, M., and Fréon, P. 1999. From 2 dimensions to 3: the use of multibeam sonar for a new approach in fisheries acoustics. Canadian Journal of Fisheries and Aquatic Sciences, 56: 6–12.

Greenlaw, C. F. 1977. Backscattering spectra of preserved zooplankton. Journal of the Acoustical Society of America, 62: 44–52.

Halldórsson, O. 1983. On the behaviour of the Icelandic summer spawning herring (*C. harengus* L.) during echo surveying and depth dependence of acoustic target strength *in situ*. ICES CM 1983/H:36. 35 pp.

Hashimoto, T., and Kikuchi, Y. 1959. Studies on the behaviour of ultrasound in sea water. *In* Modern Fishing Gear of the World, pp. 478–482. Ed. by H. Kristjonsson. Fishing News (Books) Ltd., London. 607 pp.

Hawkins, A. D. 1977. Fish sizing by means of swimbladder resonance. Rapports et Procès-Verbaux des Réunions du Conseil International pour l'Exploration de la Mer, 170: 122–129.

Hester, F. J. 1967. Identification of biological sonar targets from body motion Doppler shifts. Marine Bioacoustics, 2: 59–74.

Hewitt, R. P., and Demer, D. A. 1991. Krill abundance. Nature, 353: 310.

Hodgson, W. C. 1950. Echosounding and the pelagic fisheries. Ministry of Agriculture and Fisheries Fishery Investigations Series 2, 17(4). 25 pp.

Hodgson, W. C., and Fridriksson, A. 1955. Report on echosounding and Asdic for fishing purposes. Rapports et Procès-Verbaux des Réunions du Conseil International pour l'Exploration de la Mer, 139: 1–49.

Hodgson, W. C., and Richardson, I. D. 1949. The experiments on the Cornish pilchard fishery in 1947–48. Ministry of Agriculture and Fisheries Fishery Investigations Series 2, 17(2). 21 pp.

Holliday, D. V. 1974. Doppler structure in echoes from schools of pelagic fish. Journal of the Acoustical Society of America, 55: 1313–1322.

Holliday, D. V. 1977a. The use of swimbladder resonance in the sizing of schooled pelagic fish. Rapports et Procès-Verbaux des Réunions du Conseil International pour l'Exploration de la Mer, 170: 130–135.

Holliday, D. V. 1977b. Extracting bio-physical information from the acoustic signatures of marine organisms. *In* Oceanic Sound Scattering Prediction, pp. 619–624. Ed. by N. R. Andersen and B. J. Zahuranec. Plenum Press, New York. 859 pp.

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

ICES. 1993. Report on the Workshop on the Applicability of Spatial Statistical Techniques to Acoustic Survey Data. ICES Cooperative Research Report, 195. 87 pp.

ICES. 1998. Report of the Working Group on Fisheries Acoustics Science and Technology (FAST). ICES CM 1998/B:4. 37 pp.

Jacobson, P. T., Clay, C. S., and Magnusson, J. J. 1990. Size, distribution and abundance by deconvolution of single-beam acoustic data. Rapports et Procès-Verbaux des Réunions du Conseil International pour l'Exploration de la Mer, 189: 304–311.

Jakobsson, J. 1971. The Icelandic herring search and information services. *In* Modern Fishing Gear of the World: 3, pp. 32–37. Ed. by H. Kristjonsson. Fishing News (Books) Ltd., London. 537 pp.

Johannesson, K. A., and Mitson, R. B. 1983. Fisheries acoustics. A practical manual for aquatic biomass estimation. FAO Fisheries Technical Paper, 240. 249 pp.

Johnson, M. W. 1948. Sound as a tool in marine ecology from data on biological noises and the deep scattering layer. Journal of Marine Research, 7: 443–458.

Jolly, G. M., and Hampton, I. 1990. Some problems in the statistical design and analysis of acoustic surveys to assess fish biomass. Rapports et Procès-Verbaux des Réunions du Conseil International pour l'Exploration de la Mer, 189: 415–420.

Karp, W. A. (Ed.). 1990. Developments in Fisheries Acoustics. Rapports et Procès-Verbaux des Réunions du Conseil International pour l'Exploration de la Mer, 189. 442 pp.

Kimura, K. 1929. On the detection of fish groups by an acoustic method. Journal of the Imperial Fisheries Institute, Tokyo, 24: 41–45.

Kloser, R. J. 1996. Improved precision of acoustic surveys of benthopelagic fish by means of a deep-towed transducer. ICES Journal of Marine Science, 53: 407–413.

Krefft, G., and Schubert, K. 1950. Beobachtungen über Einfluss künstlicher Beleuchtung der Meeresoberfläche auf Fische (Observations of the influence of artificial illumination of the sea surface on fish). Fischereiwelt (Fisheries World), 6: 86–88. (In German).

Love, R. H. 1971. Measurements of fish target strength: a review. Fishery Bulletin, 69: 703–715.

MacCartney, B. S., and Stubbs, A. R. 1971. Measurements of the acoustic target strengths of fish in dorsal aspect, including swimbladder resonance. Journal of Sound Vibration, 15: 397–420.

MacLennan, D. N. 1990. Acoustical measurement of fish abundance. Journal of the Acoustical Society of America, 87: 1–15.

MacLennan, D. N., and Holliday, D. V. 1996. Fisheries and plankton acoustics: past, present, and future. ICES Journal of Marine Science, 53: 513–516.

MacLennan, D. N., and Pope, J. A. 1983. Analysis procedure for the inter-ship calibration of echo integrators. ICES CM 1983/B:22. 7 pp.

MacLennan, D. N., and Simmonds, E. J. 1992. Fisheries Acoustics. Chapman & Hall, London. 325 pp.

Margetts, A. R. (Ed.). 1977. Hydro-acoustics in Fisheries Research. Rapports et Procès-Verbaux des Réunions du Conseil International pour l'Exploration de la Mer, 170. 327 pp.

Maury, M. F. 1859. The Physical Geography of the Sea. Thomas Nelson, London. 493 pp.

McQuinn, I., Simard, Y., Beaulieu, J.-L., Landry, J., Lavoie, D., and Walsh, S. 1999. An adaptive integrated acoustic-trawl survey on Atlantic cod. ICES CM 1999/J:11. 7 pp.

Medwin, H., and Clay, C. S. 1998. Fundamentals of Acoustical Oceanography. Academic Press, San Diego, California. 712 pp.

Michalsen, K., Godø, O. R., and Ferno, A. 1996. Diel variation in the catchability of gadoids and its influence on the reliability of abundance indices. ICES Journal of Marine Science, 53: 389–396.

Midttun, L., and Hoff, L. 1962. Determination of the reflection of sound by fish. Report on Norwegian Fishery and Marine Investigations, 13. 18 pp.

Midttun, L., and Sætersdal, G. 1957. On the use of echo sounder observations for estimating fish abundance. Special Publication, International Commission for the Northwest Atlantic Fisheries, 11: 260–266.

Misund, O. A., Aglen, A., and Frønæs, E. 1995. Mapping the shape, size and density of fish schools by echo integration and a high resolution sonar. ICES Journal of Marine Science, 52: 11–20.

Mitson, R. B. 1983. Acoustic detection and estimation of fish near the seabed and surface. FAO Fisheries Report, 300: 24–37.

Mitson, R. B. 1984. Fisheries Sonar. Fishing News (Books) Ltd., London. 287 pp.

Mitson, R. B. 1995. Underwater noise of research vessels. Review and recommendations. ICES Cooperative Research Report, 209. 61 pp.

Mitson, R. B., and Cook, J. C. 1971. Shipboard installation and trials of an electronic sector scanning sonar. Radio and Electronic Engineering, 41: 339–350.

Mitson, R. B., and Storeton-West, T. J. 1971. A transponding acoustic tag. Radio and Electronic Engineering, 41: 483–489.

Mitson, R. B., and Wood, R. J. 1962. An automatic method of counting fish echoes. Journal du Conseil International pour l'Exploration de la Mer, 26: 281–291.

Moore, B. H. 1950. Relation between the scattering layer and the *Euphausiacea*. Biological Bulletin, 99: 181–212.

Nakken, O., and Olsen, K. 1977. Target strength measurements of fish. Rapports et Procès-Verbaux des Réunions du Conseil International pour l'Exploration de la Mer, 170: 52–69.

Nickerson, T. B., and Dowd, R. G. 1977. Design and operation of survey patterns for demersal fishes using the computerised echo counting system. Rapports et Procès-Verbaux des Réunions du Conseil International pour l'Exploration de la Mer, 170: 232–236.

Olsen, K. 1971. Orientation measurements of the cod in Lofoten obtained from underwater photographs and their relation to target strength. ICES CM 1971/B:17. 8 pp.

Ona, E. 1984. *In situ* observation of swimbladder compression in herring. ICES CM 1984/B:18. 15 pp.

Ona, E. 1990. Physiological factors causing natural variations in acoustic target strength of fish. Journal of the Marine Biological Association of the United Kingdom, 70: 107–127.

Ona, E. 1999. Methodology for target strength measurements (With special reference to *in situ* techniques for fish and mikro-nekton). ICES Cooperative Research Report, 235. 59 pp.

Ona, E., and Mitson, R. B. 1996. Acoustic sampling and signal processing near the seabed: the deadzone revisited. ICES Journal of Marine Science, 53: 677–690.

Parrish, B. B. 1953. A proposal for the introduction of organised echo-search in North Sea herring investigations. ICES CM 1953/Pelagic Committee:30. 4 pp.

Petitgas, P. 1993. Geostatistics for fish stock assessments: a review and an acoustic application. ICES Journal of Marine Science, 50: 285–298.

Petitgas, P., and Levenez, J. J. 1996. Spatial organisation of pelagic fish: echogram structure, spatio-temporal condition, and biomass in Senegalese waters. ICES Journal of Marine Science, 53: 147–153.

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 Journal of Marine Science, 53: 449–452.

Portier 1924. Sur l'application des ondes ultra-sonores aux recherches d'océanographie biologique. C. R. Société Biologique, Paris, 91.

Raitt, R. W. 1948. Sound scatterers in the sea. Journal of Marine Research, 7: 393–409.

Rallier du Baty, R. 1927. La pêche sur le banc de Terre-Neuve et autour des îles Saint-Pierre et Miquelon. Office Scientifique et Technique des Pêches Maritimes. Mémoires (Série Spéciale), 7. 142 pp.

Reid, D. G. 2000. Echo trace classification. ICES Cooperative Research Report, 238. 115 pp.

Renou, J., and Tchernia, P. 1947. Détection des bancs de poissons par ultrasons. Comité d'Océanographie des Côtes, Ministère de la Marine, Paris, 1947: 21–29.

Richardson, I. D. 1950. The use of an echo sounder to chart sprat concentrations. Annales Biologiques du Conseil International pour l'Exploration de la Mer, 6: 136–139.

Richardson, I. D., Cushing, D. H., Harden Jones, F. R., Beverton, R. J. H., and Blacker, R. W. 1959. Echo sounding experiments in the Barents Sea. Fishery Investigations, 22. 55 pp.

Rivoirard, J., Simmonds, E. J., Foote, K. F., Fernandes, P. G., and Bez, N. 2000. Geostatistics for Estimating Fish Abundance. Blackwell Science Ltd, Oxford. 206 pp.

Rose, G. A. 1995. Cod spawning on a migration highway in the north-west Atlantic. Nature, 366: 458–461.

Runnstrom, S. 1937. A review of the Norwegian herring investigations in recent years. Journal du Conseil International pour l'Exploration de la Mer, 12: 123–143.

Runnstrom, S. 1941. Quantitative investigations on herring spawning and its yearly fluctuations at the west coast of Norway. Report on Norwegian Fishery and Marine Investigations, 6. 71 pp.

Rusby, J. S. M., Somers, M. L., Revie, J., McCartney, B. S., and Stubbs, A. R. 1973. An experimental survey of a herring fishery by long range sonar. Marine Biology, 22: 271–292.

Scalabrin, C., Diner, N., Weill, A., Hillion, A., and Mouchot, M. C. 1996. Narrowband acoustic identification of monospecific fish shoals. ICES Journal of Marine Science, 53: 181–188.

Scharfe, J. 1968. Das deutsche Einschiff-Schwimmschleppnetz (The German single-ship pelagic trawl). Informationen für Fischwirtshaft (Information for the Fishing Industry), 15: 104–167. (In German).

Scherbino, M., and Truskanov, M. D. 1966. Determination of fish concentration by means of hydroacoustic apparatus. ICES CM 1966/F:3. 6 pp.

Schüler, F., and Krefft, G. 1951. Zur Frage der Verwendung des Echographen in der Loggerfischerei (An investigation of the application of echograms in the lugger fishery). Fischereiwelt (Fisheries World), 3(4). 63 pp. (In German).

Shotton, R., and Bazigos, G. P. 1984. Techniques and considerations in the design of acoustic surveys. Rapports et Procès-Verbaux des Réunions du Conseil International pour l'Exploration de la Mer, 184: 34–57.

Simmonds, E. J. 1996. Introduction. ICES Journal of Marine Science, 53: 129.

Simmonds, E. J., Armstrong, F., and Copland, P. J. 1996. Species identification using wideband backscatter with neural network and discriminant analysis. ICES Journal of Marine Science, 53: 189–195.

Simmonds, E. J., Williamson, N. J., Gerlotto, F., and Aglen, A. 1992. Acoustic survey design and analysis procedure: a comprehensive review of current practice. ICES Cooperative Research Report, 187. 127 pp.

Smith, P. E. 1970. The horizontal dimensions and abundance of fish schools in the upper mixed layer as measured by sonar. *In* Proceedings of the International Symposium on Biological Sound Scattering in the Ocean, Maury Center for Ocean Science, Washington, DC, pp. 563–591. Ed. by G. B. Farquhar. US Government Printing Office, Washington. 629 pp.

Soule, M., Hampton, I., and Barange, M. 1996. Potential improvements to current methods of recognising single targets with a split-beam echosounder. ICES Journal of Marine Science, 52: 237–243.

Stanton, Y. K., Chu, D., and Wiebe, P. H. 1996. Acoustic scattering characteristics of several zooplankton groups. ICES Journal of Marine Science, 53: 289–295.

Sund, O. 1935. Echo sounding in fishery research. Nature, 135: 953.

Sund, O. 1943. The fat and small herring on the coast of Norway in 1940. Annales Biologiques du Conseil International pour l'Exploration de la Mer, 1: 58–79.

Swingler, N., and Hampton, I. 1981. Investigation and comparison of current theories for the echo-integration technique of investigating fish abundance and of their verification by experiment. *In* Proceedings of the Meeting on Hydroacoustical Methods for the Estimation of Marine Fish Populations, 25–29 June 1979, The Charles Stark Draper Laboratory, Massachusetts, USA, pp. 97–156.

Sætersdal, G., and Hylen, A. 1959. Skreiundersøkelsene og skreifisket i 1959 (Investigations of the Barents Sea cod population and fishery in 1959). Fisken og Havet (The Fish and the Ocean), 1: 1–18. (In Norwegian).

Tester, A. L. 1943. Use of the echo sounder to locate herring in British Columbia waters. Bulletin of the Fisheries Research Board of Canada, 63. 21 pp.

Thorne, R. E. 1983. Assessment of population abundance by hydroacoustics. Biological Oceanography, 2: 253–262.

Traynor, J. J., and Ehrenberg, J. E. 1990. Fish and standard-sphere target-strength measurements obtained with a dual-beam and split-beam echo-sounding system. Rapports et Procès-Verbaux des Réunions du Conseil International pour l'Exploration de la Mer, 189: 325–335.

Tucker, D. G., and Welsby, V. G. 1960. Electronic sector-scanning asdic; an improved fish locator and navigational instrument. Nature, 185: 277–279.

Tucker, G. H. 1951. Relation of fishes and other organisms to the scattering of underwater sound. Journal of Marine Research, 10: 215–238.

Tungate, D. S. 1958. Echo-sounder surveys in the autumn of 1956. Fishery Investigations, Series 2, 12: 3–17.

Ura, E., and Mori, I. 1971. Purse seine fishery in East China Sea. *In* Modern Fishing Gear of the World, 3: 70–80. Ed. by H. Kristjonsson. Fishing News (Books) Ltd., London. 537 pp.

Urick, R. J. 1983. Principles of Underwater Sound. McGraw Hill, New York. 423 pp.

Villanûeva, R. 1971. The Peruvian Eureka programme of rapid acoustic survey. *In* Modern Fishing Gear of the World: 3, pp. 20–24. Ed. by H. Kristjonsson. Fishing News (Books) Ltd., London. 537 pp.

Walsh, S. J., Engås, A., Ferro, R. S. T., Fontaine, R., and Van Marlen, B. 2002. To catch or conserve more fish: the evolution of fishing technology in fisheries science. ICES Marine Science Symposia, 215: 493–503. (This volume).

Wardle, C. S., and Hollingworth, C. E. (Eds.). 1993. Fish Behaviour in Relation to Fishing Operations. ICES Marine Science Symposia, 196. 216 pp.

Welsby, V. G., Blaxter, J. H. S., and Chapman, C. J. 1963. Electronically scanned sonar in the investigation of fish behaviour. Nature, 199: 980–981.

Wiebe, P. H., Stanton, T. K., Greene, C. H., Benfield, M., and Austin, T. 1999. BIOMAPER II: an integrated instrument platform for coupled biological and physical measurements in coastal and oceanic regimes. ICES CM 1999/M:07. 12 pp.

Wood, A. B., Smith, F. D., and McGeachy, J. A. 1935. A magnetostriction echo depth-recorder. Journal of the Institute of Electrical Engineers, 76: 550–567.

Wood, H., and Parrish, B. B. 1950. Echo-sounding experiments on fishing gear in action. Journal du Conseil International pour l'Exploration de la Mer, 17: 25–36.