REVIEW

Electronics in the fishing industry

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Abstract: Standard electronic equipment such as radar and ship's logs are used in the fishing industry as in any seagoing trade. The more specialised equipment is the acoustic instrument used for finding fish. The development of commercial echo sounders owes much to their intelligent use by fishermen, and as a consequence they have diverged into specialist uses. It is likely that in the future the use of higher frequencies will become more widespread. Because acoustic instruments are used by navies to find submarines there is considerable fall out to the fishing industry, particularly in the use of research equipment. Some of this is used by fisheries scientists in the study of fish behaviour and in the assessment of fish stocks, but experience with advanced machines also leads to developments used directly by the fishermen. In the past large fishing vessels of the distant-water fleets have carried expensive equipment for locating fish. Since the establishing of national economic zones out to 200 miles, distant-water fleets have declined. They have been, or will be, replaced with more numerous smaller vessels, with smaller capacity to buy expensive equipment. The need to locate fish effectively remains, however, with cheaper machines scattered among more vessels.

1 Introduction

Not very long ago the only electronic device on a fishing vessel was the radio, and yet today the wheelhouse of a relatively small boat is filled with instruments and control equipment of one sort or another. For the purposes of this paper, the fishing industry comprises solely the catchers at sea, not because the processors do not use electronic equipment but because it is common to other food processing industries and not, in general, peculiar to the fishing industry. The catchers use instruments to find where they are at sea and to find fish, and we are concerned primarily with these two functions.

A short description of the fisheries is given for two reasons. The first is to give an account of the scale of fisheries throughout the world. The total annual catch from the sea amounts to between 65 000 000 and 70 000 000 t, and a large number of fishermen are employed. But because there are many varieties of fish living in all depths of water down to about 600–700 m there are many forms of fisheries. The second reason for describing the fisheries is to introduce their diversity in a little detail so that the differences in requirement are displayed against an appropriate industrial background.

In former times fishermen used three devices to find where they were at sea, log, compass and deep-sea lead. Today they use electronic logs, echo sounders, and radio aids such as the Decca navigator. All are common to other users of the sea, but fishermen make specialised use of them. Of course they use echo sounders to find fish as well as to establish the depth for navigational purposes. Finding fish is obviously the most important requirement, and this is reflected in the diversity of echo sounders and the multivariate uses to which they are put by fishermen. For our present purposes a Section is added on the use of acoustics in fisheries research partly because it represents a small but very active market, and partly because advances can be made in research vessels that fishermen could not afford. Also, large equipments have been used in fisheries research for particular purposes as will be described in the last Section of this paper, but all three of them originated from naval requirements more compelling than those of the fishing industry. Indeed the recording echo sounder, so familiar to fishermen throughout the world was invented in the UK at the Admiralty Research Laboratory in Teddington. Some of the information gained from such complex machines is passed to the fishermen, but necessarily it is only a small part.

2 Nature of fisheries

Stocks of commercial fish are very abundant, and any one might comprise as many as 10^{10} individuals and yield tens or hundreds of thousands of tons to the fishermen. Those caught on the sea bed by otter trawl or by long line (which is set with a hook every fathom or so in two miles of line) are called *demersal*; such fish include the cod, haddock, whiting, saithe, plaice and sole caught in the North Sea, and, of these, cod and haddock are caught in large quantities in the Barents Sea, off the Grand Banks and off Iceland. In the Bering Sea there are large stocks of Alaska pollack and in the major upwelling areas off the western coasts of the African and American continents live large stocks of hake. In the Gulf of Thailand there are more than 40 demersal species which together yield more than 1 000 000 t.

Pelagic or midwater species such as herring, sprat, mackerel, sardine or sardinella are caught with purse seines which are large encircling nets shot from the surface or with midwater trawls. Until the 1950s pelagic fish were often caught with drift nets – long curtains of netting hung from the surface and driven with the tide – but today there are few such fisheries, excepting that salmon are still caught by drift net in the Strait of Juan de Fuca between Vancouver Island and the State of Washington and in the open western Pacific south of the Aleutians. Tuna are caught by pelagic long lines with unbaited hooks right across the deep subtropical ocean; these nets are up to 80 km in length, as long as the salmon drift nets used by the Japanese in the NW Pacific gyre, but most pelagic fish are caught with purse seines: anchoveta off Peru, sardines off Namibia and South Africa, capelin in the Barents Sea, menhaden off the eastern seaboard of the United States, mackerel in the Minches (between the outer Hebrides and the Scottish mainland) or off Cornwall. Herring in the North Sea have been caught with midwater trawls, as are mackerel off Cornwall.

Much demersal fish is today frozen when caught and sold filletted or as fish fingers, but much is still preserved on ice. However, the Norwegians still export dried salted cod to West Africa as they have done for a very long time, and the Portuguese 'white fleet' still maintain a few boats that catch cod for drying into 'bacalão' on the Grand Banks off Newfoundland. (The white fleet comprised sailing vessels, with white sails from which the fishermen put out in dories to

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catch cod with hook and line.) In the past, catches of pelagic fish such as herring supported many ancillary processing trades which made kippers, bloaters, red herring, roll mops among many others. Today the largest proportion of catches of pelagic fish such as sardine, anchovy, menhaden and capelin are converted to fishmeal for animal foodstuffs.

There are many forms of fishing fleet that work the world ocean. Inshore vessels of less than 12 m in length work in shallow water close to port and catch fish in small quantities day by day for a local fresh market. Such are found in all seas wherever there are such ports and markets, not off the west coast of South Africa where there are no little ports, nor off most of the coast of northern Australia, where there are few local markets. Larger vessels, of 21–37 m in length, make trips in the North Sea of 10–14 d and land fish on ice or in chilled sea water. Their analogues work in shelf seas like the North sea, the Baltic, much of the Mediterranean, the coasts of subtropical oceans, the Yellow Sea and parts of the Caribbean. Before coastal states declared fishing zones of 200 miles in the late 1970s, large freezer stern trawlers or factory vessels were used to fish worldwide. Traditionally such distant water vessels sailed from western European ports but, since the Second World War, Russian and Japanese vessels have predominated in distant water fishing and between them have caught up to 15 000 000 t each year off the coasts of other nations. Such vessels survive particularly where fish must be caught in quantity in heavy weather, as in the waters off Iceland. But many of them have been, or will be, replaced by smaller boats more suitable to the waters of a coastal state than to those of a whole ocean.

There are many specialised fleets that work in different parts of the world. Norwegian purse seiners with power blocks to haul the nets worked on herring in the Norwegian Sea (and even in the east Icelandic current in late autumn), on mackerel in the North Sea and in recent years on capelin in the Barents Sea. Purse seiners from San Diego in southern California catch tuna in the eastern tropical Pacific, but in the last decade or so they have operated off Angola and New Zealand. Danish 'near-bottom' trawlers catch sand eels in summer with lengthened trawls on the tops of sand banks in many parts of the North Sea. In the autumn they catch Norway pout in the deeper water of the northern North Sea and in winter and early spring they catch sprats in the central North Sea. Their total catches each year amount to nearly 2 000 000 t, all of which is converted to fishmeal. In the northern North Sea and West of Scotland, Scotsmen work multipurpose vessels of 21–28 m in length with trawls or Danish seines for demersal fish and with ring nets for pelagic fish such as sprats and herring. Dutch beam trawlers fish for sole and plaice in the North Sea, Irish Sea and English Channel. All are somewhat specialised fleets which have developed particular niches in the economic ecosystem in which they work.

In the Gulf of Mexico small trawlers work for shrimps on muddy grounds, as did Spanish trawlers off the mouth of the Zambezi, as French trawlers did off Brazil and Guyana and French, Irish and British trawlers still do in the Irish Sea. In the Strait of Georgia between Vancouver Island and the Canadian mainland, salmon trollers work for sockeye salmon as they return to the Fraser river where they spawn and die. A troller trails hooks near the surface from a steaming vessel. Similar trollers used to work for albacore from Brittany in the Bay of Biscay and south of Ireland. On the continental shelf off Washington State, Russian trawlers fish for hake in high summer as they have done off South Africa and, on occasion, off Argentina.

Fisheries are very diverse but large vessels search for, and catch, large quantities of fish usually, but not always, in water up to 200–400 m deep. Such large quantities can be easily detected and perhaps estimated acoustically. Such vessels are expensive, and it is for them that the most sophisticated machines have been developed, whether they are stern trawlers or purse seiners. The numbers of such vessels must inevitably decline throughout the world, but they will decline to a low level of numbers rather than vanish. They will be replaced by vessels of intermediate size catching somewhat smaller quantities with rather less advanced equipment. However, the numbers of vessels, and hence machines, will remain large even if international management will restrain their expansion. Hence echo sounders and sonars will no longer be produced in specialised low numbers, but better machines could well be produced in long runs. The smallest boats catch small quantities of fish that sometimes live too far apart to make detection worthwhile. The last generalisation that we can make is that pelagic fish are always detected in quantity more readily than demersal ones. But, because so much of the herring-like fishes are destined for fish meal, the vessels that catch them are less profitable and tend to use echo sounders merely as presence or absence indicators.

3.1 Position finding

In the distant centuries fishermen found their way across the sea with few navigational aids. In the North Sea, fishermen used a weighted line with tallow on the lead which sampled the sediments. With long practice skippers proceeded from point to point largely on the sediment charts each carried in his head. Further, they always knew that to the westward lay England which they could find even without a compass. They used dead reckoning with log and compass, and by this means arctic trawlermen found their way from Bear Island direct to the Spurn light off the Humber.

There are various forms of log available today based on propellers, pitot tubes, electromagnetic induction or the acoustic doppler shift principle, all of which use electronics to process and display, usually on the bridge, the speed of the ship through the water. Fishermen are particularly interested in the speed of their vessels over the ground with respect to tide or current, particularly when currents at the surface and bottom flow at an angle to each other, or even against each other. From the set of the trawl warps with respect to the stern and the record of the log as the vessel proceeds, the skipper can find the best way in which the trawl on the sea bed can be manoeuvred.

A number of radio navigation aids are used by fishermen. The first was probably the radio direction finder based on a beam transmitted on a fixed vector; deviations from it are recorded on the fishing vessel as variations in signal, and so with another beam transmitted on a different vector the skipper can determine his position. Later developments such as the Decca navigator and Loran C depend on the wide beams from three transmitters and lines of equal differences in phase or time of arrival arranged on a hyperbolic grid. Such grids are printed on the navigational charts used by fishermen, and the receivers carried by the fishing vessels display the numbered 'lanes' which can be located on the charts. The Decca navigator can indicate position quite accurately to within 30 m or so under the best conditions, although this may vary considerably. Fishermen often use the Decca charts directly, referring to grounds by the hyperbolic co-ordinates rather than the more traditional names, such as Tea Kettle Hole or the Hospital Ground. Because they can navigate quite precisely with such devices, skippers can find and return to small closely defined grounds which perhaps would not have been exploited before without loss of gear. Of the two methods in use, the Decca navigator is a relatively short range one, suitable for the continental shelf adjoining a coastal state, whereas Loran C uses long-range transmitters which may be used by distant water vessels, such as British trawlers in the Barents Sea. One of the advantages available to users of the Decca navigator system is the track plotter which records the vessel's track over the ground. A course by dead reckoning (with log and compass) can be compared with the recorded track, and the difference indicates the drift of the vessel due to tide or current. Although this method has been used frequently by fisheries scientists, its use in the fishing fleets is probably limited because the fishermen are well used to doing the computations needed almost automatically.

There are more sophisticated forms of navigational instrument which find their way into research vessels which sometimes need to establish their positions with the greatest precision possible. Such systems depend upon navigational satellites with receivers on the vessels; computers update the information continuously. However, such instruments are not used in fishing vessels, perhaps because they are too complex and expensive.

Fishermen use radio directly for communication between fishing vessels and with the shore. Medium wave sets of various power outputs are used for transmitting to shore through shore stations, or sometimes to local company stations, for the transmission of market information, fishing intelligence, crews' personal messages and the daily position for safety reasons. Perhaps the most interesting use of radio is in the collection of fisheries intelligence by skippers from others. On the way towards a fishing ground a skipper will spend much time listening to the continuous radio conversations. Such a system would not work at all unless a significant proportion of the information was verified, although perhaps some of it may be concealed to some degree. Indeed British trawler skippers in the Barents Sea used to use the seamen's medical book as a source of codes. Simple enough to be obvious to a compatriot, but very hard for a foreigner to break.

All fishing vessels, except the smallest inshore ones, use radar, perhaps two equipments, for safety in navigation. The main use of radar is to detect other vessels, the shore or other navigational hazards at night or in poor weather. The characters of ships can be recognised on radar, as a tanker for example yields a strong signal on a constant course at a characteristic speed. A fishing vessel steams at 2–4 knots when trawling on an idiosyncratic course. Indeed a skilful skipper can make good educated guesses about what another vessel is doing if he watches its behaviour on radar for long enough. Another use of radar is the search for aggregations of fishing vessels. Where fishing is good, boats will gather, and radar is the quickest way of finding them. Once located fully on the screen, the distribution of ships, their courses, where they haul and where they shoot, are displayed kinematically, and a good skipper can watch the display with insight and then go straight into the right position and make good catches or even the best catches. True motion radar is available to the fishermen and they make use of it. Fishermen use radar reflectors on their dhan buoys which mark the positions of their gear, which may be lobster pots, fixed gill nets on the sea bed or merely to mark the point where to shoot or haul on a particular ground. From time to time fisheries scientists have examined such displays and have photographed them, but none have made a full study of the changes in aggregation and dispersal which must take place.

The instruments used in the fishing industry for position finding are standard equipment in the merchant fleet. But fishermen make use of appropriate items in very particular ways concerned with navigation and communication. Their use varies from sea to sea, for example, Decca predominates in the North Sea, a region of close grounds with vessels somewhat dispersed. In the Barents Sea radar is used to a greater extent because the catch rates are high and the boats crowd on to the patches of fish. I should imagine that the nature of radio chatter changes sharply from one part of the sea to another, from one season to another and from one nationality to another.

3.2 Use of echo sounders and sonar by fishermen

Echo sounders were developed in the period between the wars and the first records of fish were made in the 1920s. In the early 1930s a very remarkable fisherman, skipper Ronnie Balls, used an early echo sounder with a neon-tube display to detect herring from his drifter. But much more than that, from 5 years of observation he was able to show that he caught more herring when he used an echo sounder than when he did not; in the near half century since then, the same observation has been repeated by countless fishermen throughout the world. Despite the skill and determination of skipper Balls with his neon-tube indicator, it was the development of the recording echo sounder by Wood, Smith and McGeachy [1] that led eventually to the use of echo sounders by fishermen. This machine displayed on starch-iodide paper, a quasi-continuous record of the sea bed and the surface was indicated at a little distance about the transmission. Fig. 1 shows a famous record of cod in the Vestfjord [2]. The fish spawn in 140 m on the northern side of the fjord between January and early April, and this record shows the fish within the 'fish-carrying layer' in 140 m. The equipment was simplified by Kelvin & Hughes Ltd. and used by naval vessels during the Second World War; similar machines were available to fishermen throughout the world after 1945.

The early recording echo sounder was developed as a navigational instrument for the depth is the shortest path from ship to sea bed and back again. Given the speed of sound in sea water (1500 m/s), half the time interval between transmission and reception divided by the speed of sound is an estimate of depth, to which the distance from transmitter to the sea surface must be added. Fishermen were first interested in the recording echo sounder because not only did they navigate partly by the depth of water, as indicated in the preceding Section, but they knew that particular fish lived in certain depths at certain times of the year, which was as true of herring fishermen as of demersal fishermen. When the fishermen found traces of fish in midwater or on the bottom they regarded them as a bonus. The first British echo sounders, such

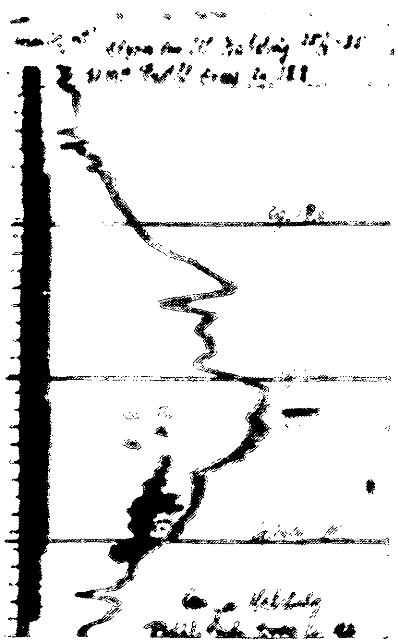

Fig. 1 *Echo chart of cod observed in 'fish-carrying layer' in the Vestfjord [2]*

as the Kelvin & Hughes MS 12, were operated at a frequency of 15 kHz with nickel transducers and the transmitter was a contacter box which generated a few hundred watts of electrical power.

During the 1950s echo-sounder manufacturers developed the standard echo sounder which is virtually that used by fishermen today. The operating frequency lies between 30 kHz and 50 kHz and about 1 kW of electrical power is passed into the transducer which is usually of lead zirconate titanate (although nickel is still used by some manufacturers). The paper may be wet or dry, and the presentation is usually rectangular. The wet starch-iodide paper has a somewhat greater dynamic range than the dry forms such as teledeltos. However, the latter is permanent if dirty, whereas the record on starch iodide paper tends to fade after a long period of time. Today fishermen are tending to return to wet paper because, being more sensitive, it yields more information. Such machines are very reliable and, in particular, are adapted to the varying voltages and frequencies found on fishing vessels. Since the early 1960s echo sounders have been transistorised and converted to solid state which means that standard power outputs are possible on boats and that amplifiers with better characteristics could be used. However, they remain instruments that display qualitative differences from transmission to transmission, yet little would be needed to convert them into equipments of a more quantitative character, such as the present generation of scientific echo sounders used in fisheries research. The standard model used by fishermen is really a development of the navigational echo sounder and, however useful it is to resourceful man, it is very little more than that.

However, fishermen were responsible for specific developments. They desired particular ranges, scales or repetition rates and indeed particular quantities and types of recording paper. Hence different arrangements of such simple characteristics evolved for different depths of water, different sea beds and different densities of fish, but in the first place they were usually limited to variation on a single simple design. Perhaps the most important development made by fishermen was their use of the A-scan presentation in the early 1950s. This display was introduced to save money on recording paper; with depth as the time base, the bottom was represented as a strong amplitude and fish as weaker amplitudes near the sea bed or in midwater. Fishermen soon realised that fish could be recognised close to the sea bed; the spot which indicates the relatively weak signal from fish is brighter than that from the strong bottom signal because it travels a much shorter distance on the cathode ray tube face. The bright signal of weak amplitude just above the thin one of strong amplitude allowed fishermen to detect demersal fish close to the bottom (Fig. 2). For a period, an A-scan presentation on an oscilloscope was a necessity for all demersal fishermen; the first models were of German manufacture and were often called 'fish loops' (fischlupen).

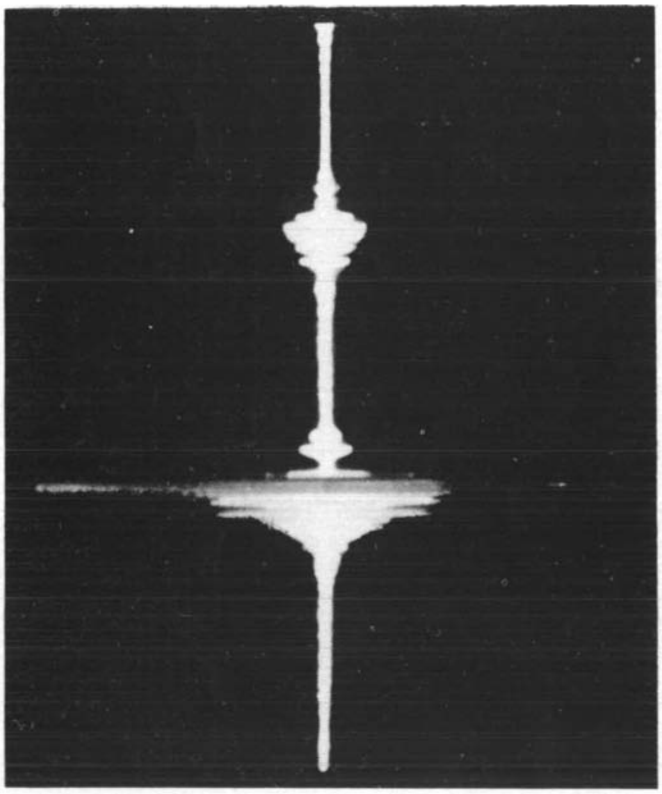

Fig. 2 *Bright spot due to fish close to sea bed, weak signal from fish just above strong signal from bottom*

Later the same objective was obtained on the paper record with the so-called white-line device. When a very strong signal (such as that from the sea bed) is received, the output of the amplifiers is switched reducing the recorded signal leaving the paper white. The device can be arranged so that the switched signal is slightly delayed, and so the recorded bottom signal is very short indeed. As the record is a quasicontinuous one the signal received from the sea bed appears as a thin line. The amplitudes of bottom signals vary from transmission to transmission, and a predetermined fraction is estimated by a comparison circuit. Because the signal lasts for only about 1 ms, records from fish close to the sea bed are shown very clearly (Fig. 3). Sometimes when the signals from the fish are very strong, the shoals may 'white line' also; however, the fish shoals remain outlined above the bottom record – in any case such events are infrequent. Like so many records made by echo sounders and by sonar, the technique depends upon trace-to-trace correlation, by which the eye creates continuity from one trace to the next and many of the applications used by fishermen depend on it. Since the white line was first devised many variants have been used, grey lines on dry paper, and, more recently, forms of colour presentation.

Perhaps the most remarkable development in the display of echo signals for fishermen has been made by Koden Electronics in Japan. The paper record is replaced by one on a screen; the signals are stored on tape and are played back continuously for a restricted period defined by the width of the screen. The picture is composed of successive time bases and amplitude is expressed in colour, of which there are eight grades and there are also two tones. The dynamic range of a factor of 16 is much greater than that of any dry paper and perhaps greater than that of wet paper. The great advantage of the colour presentation is that with trace-to-trace correlation the eye can construct matrices of difference in time and space. With the forms of scale expansion in time used by Koden, demersal fish can be distinguished against the sea bed much as fishermen did when they first used the A-scan, as described above. This machine is the most considerable development of that started by the fishermen nearly 30 years ago.

Fishermen often work in deep water, up to 500 m on the edge of the continental shelf, for cod or Alaska pollack in high latitudes and for hake in low or middle latitudes. The need to detect a single fish of 70–120 cm in length in such deep water imposes a number of severe restrictions. The first and most important is to measure the target strength of fish (i.e. the ratio of received to transmitted intensity as at 1 m from the target) before the acoustic nature of the equipment can be specified. Twenty years ago experiments were made on dead fish with artificial air bladders (most fish have swim bladders or air bladders by which they maintain neutral buoyancy – it comprises about 5% of the volume and contributes about half or more of the signal [3]). However, today the results of such experiments have only historical value. In recent years two sets of experiments have been made on live fish; Goddard and Welsby [4] made many thousands of measurements on live cod-like fish within an acoustically transparent cage of plastic; Nakken and Olsen [5] observed target fish at all angles between the side and the back of fish which had been stunned after they had been kept for three days at the depth of observation in order to stabilise the swim bladder. Fig. 4A shows the dependence of target strength of cod on log length; one conclusion is that $T \propto W^{0.72}$, where T is target strength in dB with reference to a 1 m sphere, and where W is weight in grammes. Fig. 4B shows the distribution of target strength in angle for a cod of 70 cm [5]. Although incomplete, such material provides enough information to calculate the acoustic power required to detect a large cod in 500 m. Such estimates are the best so far available, but are subject to some fairly obvious biases in how the live fish arrange themselves with respect to the transducer and whether the swim bladder of stunned fish is representative in a physiological sense. Before we leave the subject of target strength it is worth noting that methods are being developed to estimate the target strength of fish at sea; the method developed by my colleague, B.J. Robinson, depends first on the automatic discrimination of single targets (i.e. of one pulse length in successive transmission and other criteria) and secondly on the proper estimate of the average strength within the beam; in other words the variability due to directivity is taken into account. Provided that the fish are adequately identified such methods will be developed in the future to stratify estimates of target strength in different regions of the acoustic surveys used by fisheries biologists.

Any echo sounder reports signals above noise and the gain is set just below the level at which noise is recorded on the

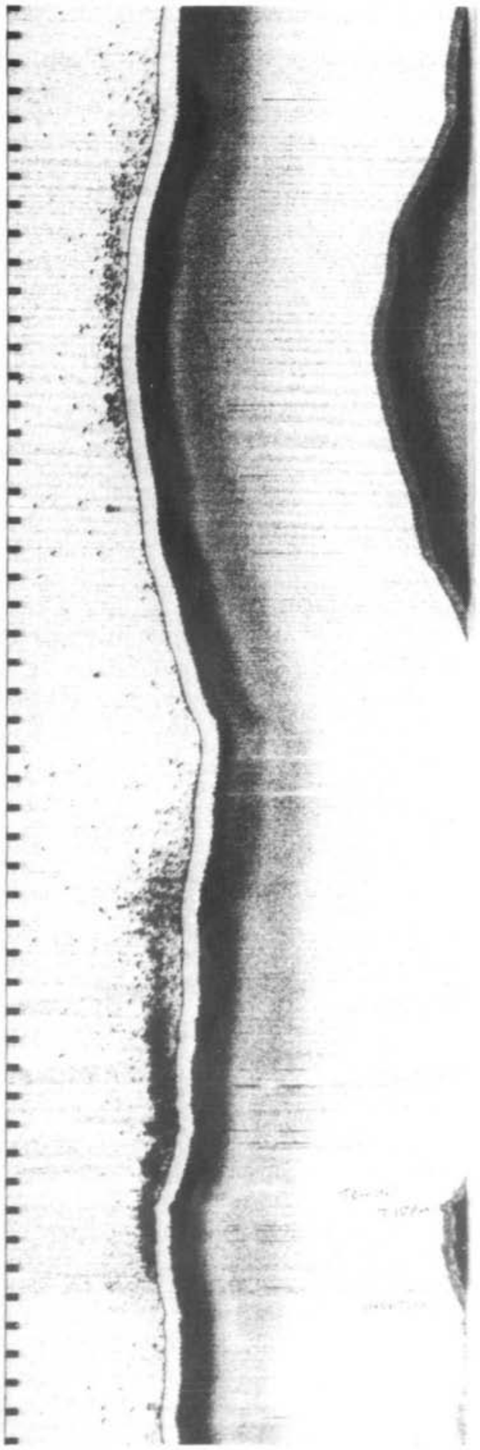

Fig. 3 *'White line' record of fish close to sea bed*

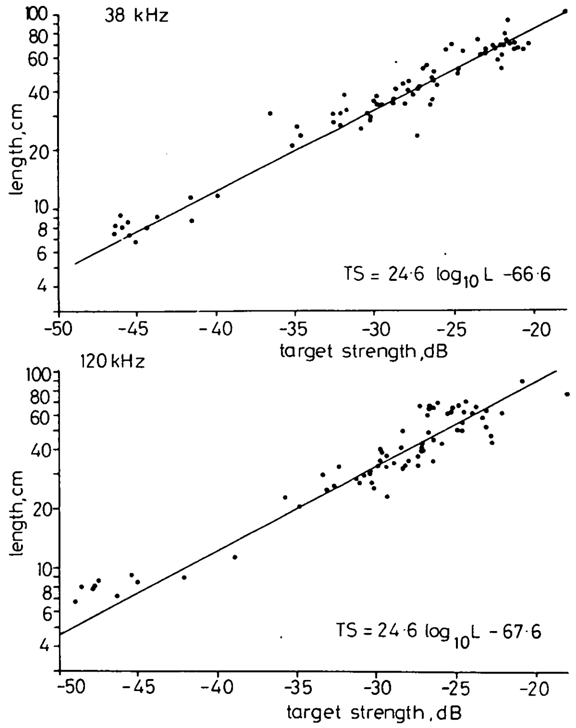

Fig. 4A *Dependence of target strength of cod on logarithm of length [5]*

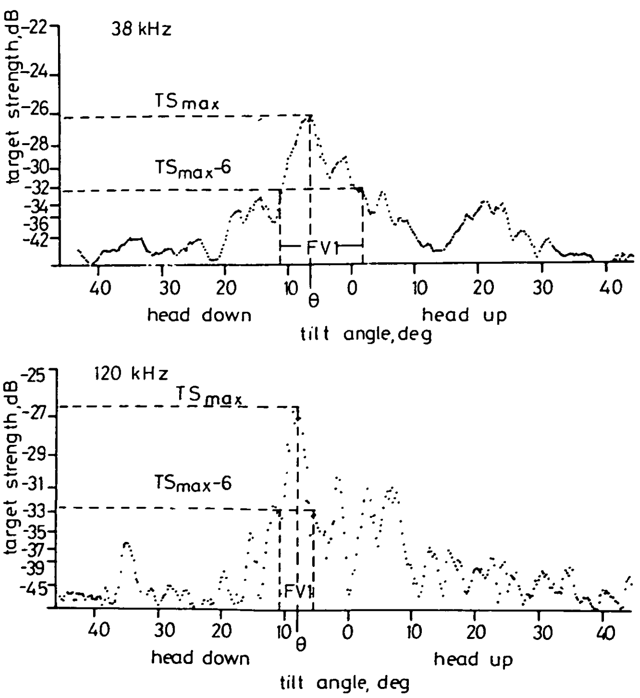

Fig. 4B *Distribution of target strength by angle of aspect for 70 cm cod [5]* paper. In the sea there are three components of noise, instrumental, that in the water itself (ambient) and that due to the propeller of the ship which makes the water cavitate at the blades as it turns. Although bad weather generates the most noise, the most important source is the propeller. Naval vessels have specially quiet propellers but fishing vessels use those provided by the builder with no reference to any acoustic requirement, which, clearly, would be expensive. The noise of the cavitating air bubbles from the propeller is reflected partly back into the transducer by the sea bed, from which it follows that all acoustic systems are less noisy in deep water than they are in shallow. Acoustic engineers use sonar equations to calculate, for example, the expected echo level from a given target at a given range, taking into account losses due to spreading due to the inverse square law and to attenuation, the loss of signal due to absorption partly due at higher frequencies to magnesium sulphate in sea water. A similar sonar equation is used to calculate the power and beam angle needed with a given signal/noise ratio to detect a large single fish in 500 m. There is however an important point – the signal/noise ratio for mere detection is much less (say 3:1) than that required for quantitative estimation (say 20:1); strictly a quantitative estimate needs a continuous noise recorder such as can be provided by an integrator. The fisherman is usually concerned only with the presence or absence of fish, whereas the quantities available are usually the concern of the fisheries biologist. It is possible that, in the future, fishermen will need more quantitative estimates than they use at present. Two devices are in use today which ease presentation. The first is a time-varied gain, TVG, which compensates for losses due to spreading and attenuation with range. As a consequence a signal from a single fish or a fish shoal has the same recorded value at any depth or range and it is the first step towards quantitative echosounders used by fishermen. There are two varieties of TVG, '20 log R' and '40 log R'; the first corrects for scattering across the whole beam with range R and the second for single targets with range. The second device is used to reduce noise in a SIMRAD sonar, which might well be used in echo sounders; signals are added for three transmissions and then presented, a procedure which reduces noise by about 3 dB.

The first step in making an echo sounder to detect fish in deep water is to reduce the beam width. The beam of an echo sounder is described either as the angle between 3 dB points or as that between the first minima before the side lobes. An ordinary machine may have a beam of 20°–30° between 3 dB points and if such a beam is reduced to 20° between the first minima the acoustic power output has been increased by a factor of eight. However, the transducer has to be increased in area by about that factor, but then a greater acoustic power can be transmitted into the water; however such larger transducers cost a lot of money. Two machines have been made to operate at about 30–40 kHz with relatively narrow beam angles (for example 9° × 14° half angles between the first minima) and with an electrical power output into the transducer of about 10 kW; they achieve a source level of about 229 dB with reference to 1 μPa at 1 m. The cavitation level for the transducer at 30 kHz is 226 dB. Any increase in acoustic power at these frequencies would cause the water to cavitate and hence the acoustic energy would be dissipated. Thus for the frequency used and the beam angle, such echo sounders have reached the limit in power, but they can do what is required, that is detect a single cod at a range of 500 m if the sea is not too rough. Because such echo sounders operate at a relatively low frequency, the range resolution is rather coarse, the pulse length being usually between 0.5 and 1 ms, or 0.75–1.50 m in transmission, 0.375–0.75 m in echo. At extreme range the single large fish is detected on the acoustic axis only, which means that in deep water the angular resolution of the equipment is much greater than that specified.

An echo sounder resolves targets in range and in angle. Transducers usually resonate at their working frequency; a quality factor Q describes the narrowness of that resonance and with high Q, damping is low and more cycles of electrical energy are needed to reach peak energy and vice versa. For the same Q, a higher frequency transducer can respond to shorter electrical pulses more effectively. For transducers of the same size, narrower beam angles can be produced at higher frequency, and so greater angular resolution is obtained. But with increased frequency the attenuation of transmitted energy rises sharply, and for fish finders there is an upper useful limit in frequency of about 400 kHz. For deep-water machines, such frequencies waste too much of the energy transmitted in attenuation, and so they employ frequencies of between 30 kHz and 50 kHz, with some loss of range resolution. A rough classification of potential fish-finding echo sounders is shown in Table 1. In practice angular resolution is governed by the sampling volume needed for adequate detection, as more than one signal received from a single target is needed to establish an adequate trace-to-trace correlation, which consequently means that the narrowest beam, which also concentrates the power, is used in deeper water. Most machines in use today are operated at 30–50 kHz. The difference between the deep-water and moderate-depth machines is often only in the high power and narrow beam in deep water and the broader beam and less power in moderate depths of water. Some machines are available at frequencies of about 100 kHz for use in moderate depths of water, but not as many as one might expect from first principles. None are available at 400 kHz for shallow-water use which is a pity because of the great capacity for angular and range resolution.

A theoretical case can be made out for making all three forms of machine at a frequency of 100 kHz with a transducer from which narrow-, medium- and wide-angle beams can be generated. The reason is that the threshold of cavitation increases with frequency and more power can be emitted at 100 kHz than at 30 kHz. Hence the quantity of acoustic power could also be varied with the depth desired, with rather higher resolution in range and variable angular resolution. The same argument could be advanced for the 400 kHz machine, but probably only a simple version is needed. A machine such as a universal 100 kHz one would be expensive to develop, and might not be proposed until fishing becomes more profitable and the stocks become less heavily exploited.

The development of deep-water echo sounders led to an advance in presentation. Trawlermen were interested in the fish in the path of the trawl, i.e. within about a fathom of the sea bed. One fathom in a hundred is a small part of the potential scale, and so the problem was to expand part of that potential scale to display a fathom or so. The first machine to examine the fish in the path of the trawl in this way was a stabilised unrectified A-scan with an expanded time base which showed only 4 fathoms above the sea bed on the oscilloscope. The bottom signal was stabilised to the range of the sea bed on the previous transmission, because that range was stored on tape, and the difference between it and its successor was added or subtracted to stabilise the position of the bottom signal on the time base. Other methods were developed to present the same material on a paper record, either separately

Table 1: Potential fish-finding echo sounders

	Deep (up to 500 m)	Moderate depths (50–200 m)	Shallow (0–50 m)
Frequency	30–50 kHz	100 kHz	400 kHz
Range resolution (in echo)	1 ms (0.75 m)	0.5 ms (0.375 m)	0.1 ms (0.075 m)

or as adjunct to the main record from surface to sea bed. Indeed it is now possible to arrange the expanded record to follow the normal sea bed record. However this presentation is less simple than it appears. An echo sounder records the depth of the sea bed accurately, but any target above it is most probably recorded at an angle to the acoustic axis and hence its depth is overestimated. This is particularly true of signals from fish in midwater and the bias is greater at middle ranges. The bias, however, is not defined in the characteristics of the transducer, but in the echo level with respect to the noise level in the system. In deep water the angle is small and the overestimate of depth is quite low, but if a small shoal is recorded as being within a fathom of the sea bed it might not be caught by the trawl because the shoal which yielded a strong signal swam above the headline.

It would be desirable, if expensive, to stabilise the beam of a deep-water echo sounder. Two or three such machines have been made; one has large narrow-beam transducers arranged to transmit when the beam is vertical in roll [6] and receives on a wide-angle transducer. Miyajama [7] described a gimbal-mounted transducer stabilised mechanically with reference to a pendulum. Fig. 5 shows exactly contemporaneous charts of cod traces within 4 fathoms of the sea bed (*a*) with an unstabilised beam at 45 kHz and (*b*) with a stabilised beam of

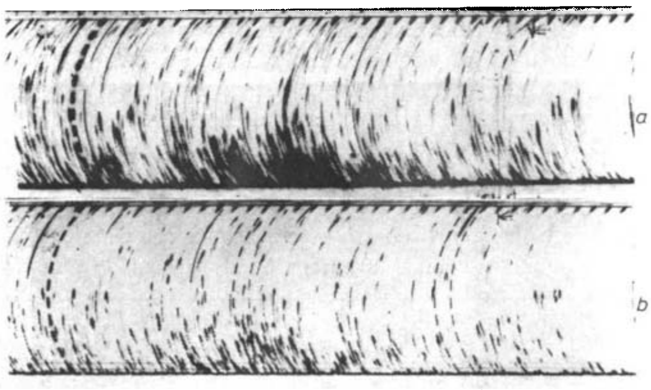

Fig. 5 *Simultaneously recorded charts of cod traces from very high speed recorder within 4 fathoms of sea bed [6]*

a Unstabilised beam
b Stabilised beam

the same dimensions at 30 kHz. It will be seen that fewer signals were received on the stabilised equipment (the difference in frequency can be ignored) which illustrates the fact that the unstabilised transducer can record fish from a much broader angle, and hence a greater proportion will be received from above the headline. The recording was made with a special very high speed recorder which expands the time base on the paper record. Fig. 6 shows another solution to the problem of expanding the time base. Tanaka [8] used a multistylus recorder which displays the ordinary time base and the expanded one on the same paper record. There are as many as 2.5 styli/mm, and so it is relatively easy to separate the two time bases and yet display them in temporal sequence on the same paper chart. Tanaka's system can of course be used for other purposes, with sonars or netzsondes (trawl echo sounders to be described below) or any display that requires signals of multiple origins.

Echo sounders that work at 120 kHz made by SIMRAD have been in use for a number of years for scientific purposes, but for fishermen machines of this character are made only in Japan and in the USA. Such machines as made by Furono among others are used extensively for fishermen working in relatively shallow water. Fig. 7 shows two echograms recorded with a Ross Fineline machine working at 105 kHz. Figure 7*a* is an echo trace of hake in Port Susan (in Puget Sound, Washington State) and Fig. 7*b* shows a trace of herring at night in Carr Inlet (also in Puget Sound) [9]. The interesting point is that in both charts signals from single fish predominate. Fishermen believe that fish can be identified by the characteristic nature of the trace, but what is observed is a catch of those fish expected at the expected place at the expected season; the differences in trace pattern are differences in shoal size within the beam [10], and reflect differences in behaviour common to many different types of fish. The echo charts in Fig. 7 show single fish and the average interfish distance which might in the future be useful to help identify fish traces. The Ross Fineline echo sounder has a narrow beam and short pulse length with high angular and range resolution.

To a fisheries biologist such records yield much more information than those of the standard machines used at lower frequencies, and the time will come when fishermen are allowed by the manufacturers to use them. The bottom

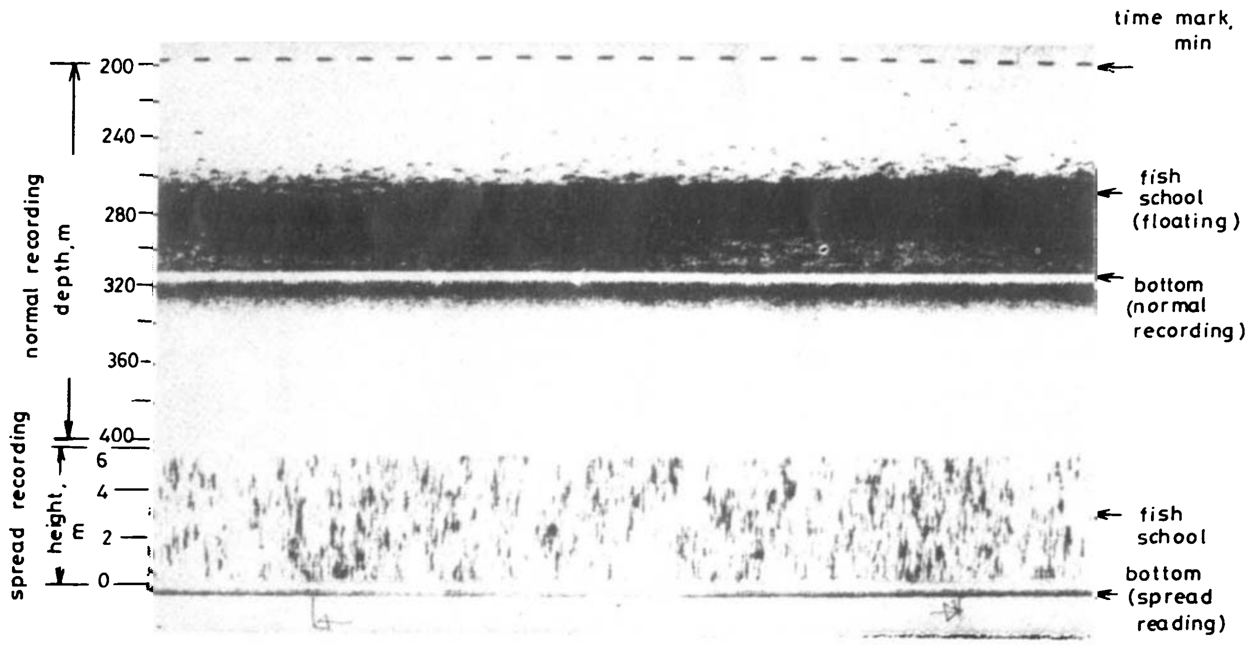

Fig. 6 *Traces of fish on ordinary chart and on 'scale, expanded' chart, which follows undulations of sea bed, both displayed on same record with multistylus recorder [8]*

signals in the echo charts in Fig. 6 are short in duration which indicate a narrow beam because the first signal in the bottom trace is received directly from the sea bed on the shortest path, the depth, but the last signal in the trace is received at the extreme effective beam angle. Thus the extent of the bottom trace in time (i.e. in range on the record) indicates the effective beam angle of the transducer for the same type of sea bed. Then with a wide beam, in somewhat shallow water, differences in sediment type are revealed as differences in the extent of the bottom trace. Fig. 8 shows examples of different sediments, mud, sand and rock as detected with a ground-discrimination echo sounder. Fishermen use such instruments to find the mud on which live shrimps and *Nephrops*, the Dublin bay prawn, and the gravel sand on which scallops live. It is difficult to distinguish sediments acoustically, save by this method, but it is not extensively used by fishermen. Fishermen are interested in differences in sediment types because they sometimes indicate the presence of different species of fish. In general the particles of the sediments are too small to be resolved acoustically (although interesting differences appear on sidescan sonar records – see below) yet the ground-discrimination machine sums the overall scattering from the selfsame particles. Fishermen have made some use of this machine, but fisheries biologists have not exploited the potential technique to the degree that they might have done; a variable beam width might yield considerable information for them.

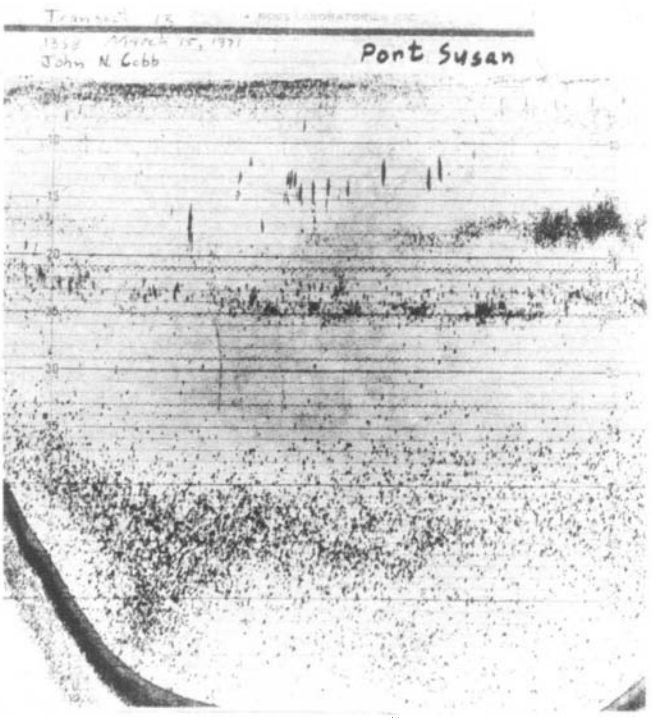

Fig. 7A *Echo trace of hake in Port Susan, Puget Sound, USA*
Trace made with narrow-beam echo sounder at 105 kHz

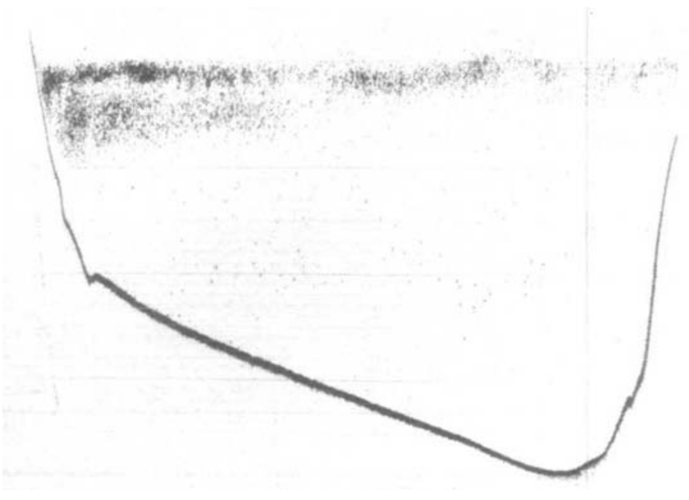

Fig. 7B *Echo trace of herring in Carr Inlet, Puget Sound*
Trace made with narrow-beam echo sounder at 105 kHz

A particular form of echo sounder is the netzsonde or trawl sounder mounted on the headline of a trawl, usually, but not necessarily in midwater. The simplest netzsonde consists of a transducer mounted on the headline of a midwater trawl in such a way that it fires downward and records the height of the headline above the sea bed and the fish that are about to enter the trawl. The transducer is linked to the trawler by cable which is usually managed by an automatic torque-controlled winch in such a way that the cable is reeved on shooting the trawl, hauled with the trawl. Necessarily the cable is long, perhaps 2000 m, and hence preamplifiers are sometimes used to overcome the losses in the cable. The record is today presented on the same recorder that displays the depth which means that the two time bases are operated independently of each other. Fig. 9 shows a shipborne record of herring, together with a netzsonde record [11] of herring entering the trawl; in this case separate recorders were used. The same equipment was used for catching quite close to the bottom and one of its great virtues is that the trawl can be manoevred very close to the sea bed without damage. Tanaka [8] has adapted his multistylus equipment to present both a netzsonde record and a conventional depth record on the same chart. There are many potential developments of the netzsonde, those firing upwards to the sea surface and others firing sideways and ahead [12], but it is unlikely that many of these developments have found widespread use in the fishing industry. However, displays are available which show speed, course, direction, latitude and longitude and sea temperature at the depth of the trawl – the latter device is of particular value when fishing for cod in the Barents Sea or on the Grand Banks off Newfoundland. Towed bodies have been used by oceanographers for deepwater echo sounding for at least two decades, and fisheries biologists have used them to carry transducers firing upwards or sideways. The remote transducers used by fishermen are limited to midwater trawling, although they could be used for other purposes if needed, such as searching nearer the sea bed in deep water.

There are other methods of finding the depth at which the trawl flies. A number of trawl-depth telemeters have been developed, of which two are pre-eminent. The first is a

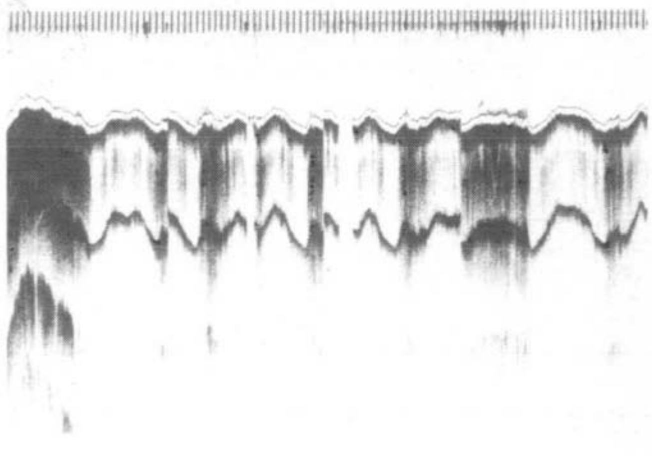

Fig. 8 *Charts of different sediments recorded with ground-discrimination echo sounder*

frequency-modulated instrument which transmits information on depth by differences in frequency and the second is a pulsed instrument which transmits information, coded in the form of pulses in time [13]. Such instruments can send information acoustically through the water, but they have not been used in the fishing fleets of the world in much more than an experimental manner. Each machine suffers from difficulties in transmission, e.g. if there is a temperature discontinuity or thermocline, or if the weather is a bit rough, the signals cannot reach the receiver through the bubble layer. The reason why the netzsonde finds a more general market is, not only that it is more reliable, but it presents a record which can be interpreted immediately by the fishing skipper. Some of the telemeters now incorporate echo sounders.

Signals from fish were recorded with sonar by naval ships during the Second World War and in the late forties the herring spawning grounds in the eastern English Channel were described from signals from spawning fish recorded by Tchernia [14]. The traditional searchlight sonars were used by Norwegian and Icelandic purse seine fishermen to great effect. However, this development really depended upon the puretic power block, a hydraulically driven block by which the purse seine could be hauled mechanically. Before this block was invented in California, the Norwegian purse seiners worked near the fjords because the nets were hauled by hand. Subsequently, however, such purse seiners were able to work in the open sea far from land. Then the sonars were able to work in deep water away from the skerries and skippers were able to detect shoals of herring, describe their position in the water and shoot the purse seine around them. Fishing for herring in the Norwegian Sea and off Iceland in very profitable quantities taught the fishermen how to use sonar in the most efficient way. The search techniques developed by submarine hunters during the Second World War were applied almost immediately and automatically because they were simpler and obvious; indeed such procedures can be and are incorporated in programmed search methods. A standard fisherman's searchlight sonar can be tilted and has a wide and narrow beam. With the search procedure, the sonar is swung from 60° on the port beam to ahead and then from 60° on the starboard beam back to ahead until a target is detected at extreme range. Then the search angle is narrowed to maintain contact with the target, and, as the range shortens, the beam angle of the sonar is spread wider so that, with the reduced search procedure in angle, there is less chance of losing the target. If necessary the beam is tilted downwards as the range between ship and fish shoal closes. Then, as the position of the shoal is held, the purse seine skipper shoots his net around it, draws the purse lines to close it and then the fish are brailed abroad. Today, searchlight sonars may be linked to log and compass and courses displayed on a PPI in relative or true motion.

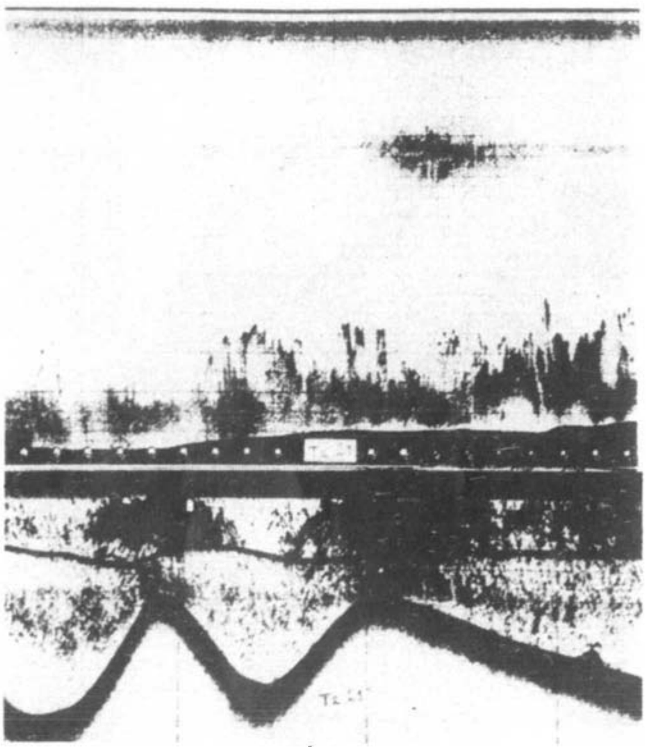

Fig. 9 *Netzonde record of herring entering midwater trawl together with usual record of same shoal among others [11]*

Sonars are also used by midwater trawlers. They are tiltable searchlight sonars which detect fish shoals ahead with the same procedures as used by purse seiners. But, after detection, the midwater trawl must be shot and aimed at the shoal using a netzsonde. As distinct from purse seining, a midwater trawler can work steadily from shoal to shoal if necessary at slightly different depths. Sonars have been used by bottom trawlers, but perhaps improperly because they detect fish above the headline of the trawl and the trawl catches those which are not detected. There is one specialised machine, the so-called sector scanning sonar designed for use in purse seine or midwater fisheries; it transmits on a wide beam and receives signals on a number of channels and resolves the phase differences between channels. The signals with such machines are presented on a B-scan, bearing on range or on a PPI. In this machine the beam is scanned both in the horizontal and vertical dimensions, with six channels in each, displaying information on two B-scans. A program in the system indicates the estimated course of the shoal, and a computer updates the information on each transmission, so long as it is needed (in other words it behaves as a most efficient long persistence screen [15]). The advantage of such a system is that very much more information is received in each transmission than with the simple searchlight sonar. Such sonars may have water inflated domes and special reverberation filters. Another development for the same type of vessel is one which transmits continuously with a cylindrical transducer as the beam is swung through 360° (or a narrower sector if needed). The signals are presented on a PPI with a long-persistence screen, and obviously an attack on a fish shoal would involve modifications of angle and range, all of which can be created and computed within the quantity of information received.

Sonar is vulnerable to poor weather, and, because of refraction, reception is unreliable across a thermocline or a density discontinuity. Hence, the best performance is attained in seasons or latitudes where no discontinuity develops and the weather is not too bad, e.g. in high latitudes in summer. Norwegian purse seiners caught herring in the East Icelandic current in autumn and capelin in the Barents Sea in early spring, but in neither region was there any thermal discontinuity. It might be a little difficult to use sonars in low latitudes, where thermoclines may be present all the year round. For such reasons the sonar is not a quantitative machine in the sense that an echo sounder might be in the future.

Fishermen would very much like to know how much they are about to catch or how much they have caught before the gear is hauled. Fisheries biologists estimate the quantity of fish in the sea under favourable conditions. As will be described in the following Section, echo sounders used for quantitative survey can estimate the stocks of fish in the sea; they are standardised machines which record signals on the chart of an integrator. However, under good and steady weather conditions in the same depth of water, a fisherman can use an echo sounder in a quantitative manner, as was shown by Ronnie Balls in the early 1930s. There are two machines available [16, 17] which estimate the quantities of fish caught or about to be caught; both sum the voltages received from fish (resolved from the echo of the sea bed) within a fixed range of the bottom. The equipment has not been used very much in the fishing industry. Within the region of abundance where the fishermen work, the haul-to-haul variance is high and it takes many hauls to establish any differences. However Drever and Ellis [18] have shown how an ordinary deep-water echo sounder can be used to discover and survey such a localised area and then how the patches revealed can be most efficiently exploited.

Probably more important than the attempt to estimate the amount of fish beneath the trawler is the need to know how much is caught, and hence when to haul the trawl. Warp load meters are used in large trawlers; strain gauges in the warps measure the strain as the trawl is dragged over the sea bed or hauled through the midwater and report their signals on meters (one for each warp) on the bridge. This simple device is used extensively on large British trawlers and it has other uses:

(*a*) to describe the nature of a fastener (a wreck or a rock) by comparing the strains on the two warps

(*b*) to assess the efficiency of fishing against or with the wind [19].

Because submarines have to be detected underwater, large amounts of money are invested in underwater acoustics and, as a consequence, some commercial equipments have been devised beyond the skills and needs of fishermen. Furthermore, the most expensive equipment was developed for the large stern trawlers and big purse seiners, both of which are really vessels of an earlier age when the waters beyond 3 miles were free to any fisherman. As fishermen will, in general, be restricted to the waters of their own coastal states some of these vessels will become redundant. A use will remain for stern trawlers in deep water in heavy weather and the future purse seiners might be rather smaller vessels. The trend towards smaller vessels will probably be more general, and they may depend on somewhat lighter catches. But if the present rate of overexploitation were reduced the average catches would be greater and fishing would become more profitable. The effects of these trends on the use of echo sounders and sonars to find fish is really that less money will be available for development and that a different distribution of machines will become available. There will remain three groups of echo sounder as arranged by depth but fewer in the deep-water range; in general deep-water stocks have been exploited much too heavily, and, as noted above, in many seas the excess number of vessels from countries other than the coastal stage have been withdrawn. It seems probable that there is a need for a relatively simple but well developed echo sounder which could be devised to meet practically all the requirements of the fishing industry. It is difficult to see how the use of sonar will develop, save that smaller equipments are more likely to survive than larger ones, but again it would be desirable that they were well developed.

4 Use of acoustic equipment in fisheries research

Fisheries biologists use acoustic equipment for a variety of purposes, to examine fishing gear, to study fish behaviour and to estimate quantities of fish stocks independently of the catches from fishing vessels. The latter development is widespread; surveys of relative abundance were made as long ago as the late 1930s [20] with ordinary echo sounders and such continue all over the world. However, with the development of an integrator [21], a quantitative estimate becomes possible; within a given range gate, signals from single fish and shoals are summed in time and the integrator records the total signal summed above a threshold (or noise level). The use of a TVG makes it possible to integrate across a wide-range gate. It is likely that a 40 log *R* TVG (or time-varied gain) is the most reasonable because most fish arrange themselves with respect to the transducer in small shoals and single targets with an occasional large shoal; from time to time in local areas a predominance of large shoals is found, but it is a mistake to concentrate surveys on a few large shoals. Before such estimates become fully quantitative good measures of target strength are needed (only few of which are available, as indicated above) and the whole system should remain in calibration.

Ideally there are two ways of estimating the numbers of fish in the sea, with an integrator or with a fish counter. A counter estimates the numbers of single fish within a range gate and the important point about such a system is that all fishes larger than a given size are counted. This procedure is very like that used by fisheries biologists who measure fish in length on the market, each larger than a minimum landing size. Fig. 10 shows a distribution of hake off Namibia and South Africa based on the counts of single fish 4 fathoms above the sea bed. In principle, although it has rarely been shown, it is possible to size the single fish recorded just as they can be recorded as fish larger than a threshold size. Such a system requires rather a higher frequency than usually used so that shoals can be separated as far as possible into single fish. However, it is unlikely that a complete resolution of all fish into single targets is always possible, and so there will always be a mixture of single targets and of shoals. Such a system which sized targets as single fishes would be that most desired by fisheries biologists, even if it does not yet exist.

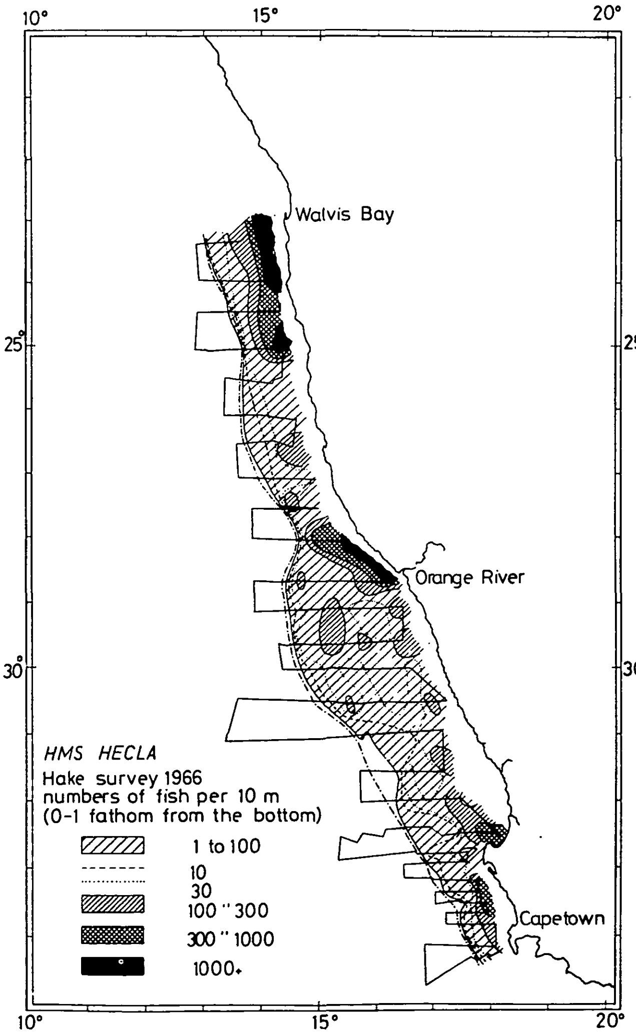

Fig. 10 *Echo survey of hake off Namibia and South Africa based on counts of single fish in 4 fathoms just above sea bed [22]*

Where there is a predominance of fish shoals sampled by an integrator, bias is possible. Whereas a fish counter records signals from targets above a conventional size, an integrator records any signal above threshold (or noise level), for example a few large fishes or many small fishes, or even very many animals smaller than expected. Hence it is possible that the integrator may receive unwanted signals. The best solution is to find a frequency at which shoals form a small minority of received signals and from which it is likely that each shoal comprises fish which are the same as those recorded as single targets.

One of the major difficulties of this form of quantitative survey is to establish the target strength of a fish of a given size. As indicated above, our knowledge of target strength is limited to two sets of observations on live fish within an acoustically transparent cage, or on stunned live fish; neither method yields entirely reliable results, and it would be desirable to develop present methods of measuring *in situ* target strengths of fishes at sea. In the future, such methods could well be extended to collect large quantities of information on fish of different species and sizes, and surveys could well be stratified by target strength in different parts of the survey. Such forms of survey might in the future yield information on fish stocks of sufficient precision to make surveys independent of information from catches as desired by fisheries biologists.

Echo sounders have been used to examine the behaviour of fish, the density of fish shoals and the responses of fish to fishing gear. An example of the latter is shown in Fig. 9 which illustrates the use of a netzsonde. The vertical migration of fish shoals at different levels of light intensity has been examined on a number of occasions. But most such attempts are unsuccessful because it is difficult to establish what the fish are really doing in the picture so beautifully displayed. However, fisheries biologists do make great use of the pictorial nature of the echo sounder. Fish shoals usually (but not always) disperse at night to variable masses of single targets. The information displayed is the distance apart of single fishes or of shoals at different depths by night or day. The information is rarely used explicitly in any analytical manner, but the patterns are used to recognise the known distributions. It is the source of the fishermen's form of identification but they then add information on position and season. The information remains to be exploited fully.

A more exact way of tackling the same type of problem is to use a sector scanning sonar. The ARL scanner at 300 kHz has a scanned sector of 25°, at an angular resolution of 0.33° and a range resolution of 7.5 cm and is mounted on a package which stabilises the transducer in roll and pitch with hydraulic rams. The display is a B-scan of bearing on range, and, because the transducer can be rapidly switched from one plane to another, it can present a horizontal picture of sea bed, including wrecks, or a picture of a vertical transect of the water column with fish shoals in the midwater. The range of this equipment is about 300 m, but the significant advance is its facility for use with a small acoustically transponding tag pinned to a fish.

Plaice tagged with such transponders were released in the path of a trawl, and by following their path towards capture or escape the efficiency of the trawl was estimated. Further the fish were observed to respond in detail to different parts of the trawl, and indeed the herding effect of trawl doors and trawl warps was shown in detail. But the most dramatic result has emerged from the study of migration. Plaice with transponding tags (about 5 cm in length, 1 cm diameter) were tracked for up to 80 h in the Southern Bight of the North Sea, and it was found that they remained on the sea bed during one phase of the tide and in midwater on the next. Before spawning, the fish migrate south by staying on the bottom on the north-bound tide and drift south in midwater on the south-bound tide. After spawning, the fish reverse their behaviour and migrate in a northerly direction. A further development is a compass transponder which reports the heading of the fish in midwater (or on the sea bed) to the scanner. A remarkable discovery showed that the fish maintain their heading in midwater in full darkness which implies a form of inertial navigation (this is not impossible as, with their semicircular canals, the fish can measure angular accelerations).

A very long range sonar (transmitting at about 1 kHz), with a range of more than 18 nautical miles has been used to examine pilchard shoals off the north coast of Cornwall over periods of days. The shoals drive with the tide and move back and forth with respect to the transducer which was fixed on the shore. The trace-to-trace correlation shows the fish shoals quite clearly for whole tidal cycles and represents most clearly the demonstration that fish drift with the tide, both night and day, even if the diffuse echoes at night are less clear (Fig. 11). The same equipment was used to estimate the densities of fish, and Weston and Revie [23] concluded that the swim bladders of pilchards resonated, and that they lived in shoals in a density of 2 shoals/km; the estimate was made from variations in sound propagation. One of the important factors in presentation was the use of correlation techniques to free the signals from noise. The method depended entirely on the resonance of swim bladders to the transmitted frequency. For fish of between 10 and 100 cm in length and at between 10 and 100 m in depth, the resonant frequency lies between 0.08 and 2.48 kHz; resonant frequency increases with depth and decreases with increasing size of swim bladder or size of fish. In general the swim bladders of commercial fish resonate at 80–2000 Hz, those of the small fish of the deep scattering layer (which lies between 800 m and the surface in the deep ocean of middle and low latitudes) and of fish larvae resonate at 10–40 kHz.

The resonance of ideal gas bubbles in water is well described, and the damping due to fish tissue can be estimated, hence the question arises whether fish can be identified by the resonance of their swim bladders, if they have them. A number of attempts were made, but only fairly recently have they become successful. Holliday [24] and Løvik and Hovem [25] both used a spark source (commonly used in seismic work) which transmits a range of frequencies, and hence the received

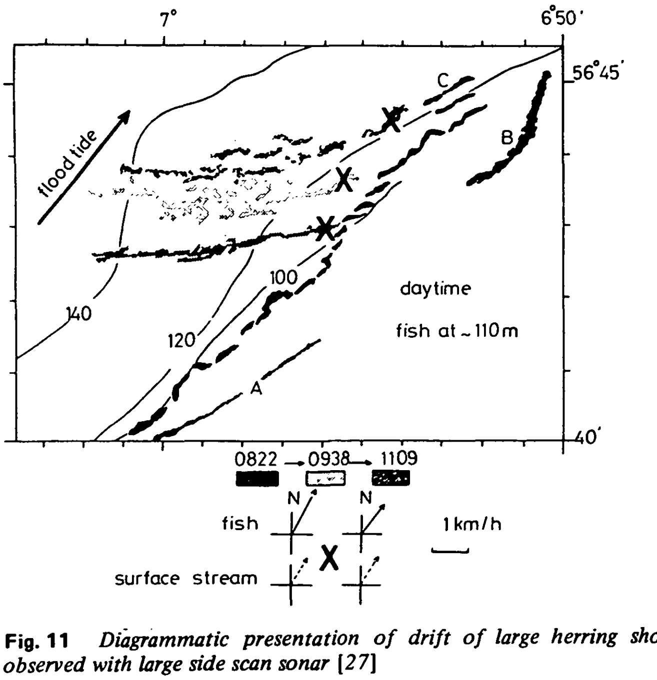

Fig. 11 *Diagrammatic presentation of drift of large herring shoal observed with large side scan sonar* [27]

signals must be displayed in frequency as a function of size. Because the spark source is necessarily highly variable in amplitude and frequency, both have to be monitored continuously so that the ratio of received to transmitted signal can be established at each frequency. Fig. 12 shows results for two groups of fish, off California and in the Norwegian Sea. It is clear that the sizes of fish were discriminated in these examples. With many more samples under more diverse conditions, the method might be established as a means of fish identification. Whatever fishermen may say, neither echo sounder nor sonar can be used to identify fish reliably. Analogous techniques have been used to examine the animals in the deep scattering layer with frequency analysis by depth, and it was found that there were two forms of resonator, one which allowed their swim bladders to expand and contract during the nightly vertical migration and the other which maintained them at constant volume [26].

Fisheries biologists also make use of side-scan sonar, a vertical fan fixed abeam to examine the sea bed for irregularities as revealed by shadow casting. Under certain circumstances fish can be detected as a continuously charted plan abeam of the ship and differences in sea bed texture can be detected which may well be related to the food that lives in the sea bed. However, the most remarkable use of a side-scan sonar was that by Rusby *et al.* [27]. Gloria is a very large machine working at 4 kHz, designed for large-scale survey of the sea bed in the deep ocean and over the continental shelf. It was used to examine herring shoals in a broad area off the west coast of Scotland. *RRS Discovery* made a preliminary survey of the sea bed to construct a chart against which the movement of large herring shoals could be detected. Fig. 13 shows a diagram of the movement of a large shoal throughout a tidal cycle as *RRS Discovery* surveyed from the base of its sonar range. It was the largest fish shoal recorded continuously for a long period as it drifted with the tide.

It is no accident that dramatic discoveries have been made with remarkable and sophisticated equipment developed for other purposes, partly military and partly civil. The prime result on a large scale has been to show that fish drift with the tide in such a way that it is incontrovertible; the biological importance of this result is considerable because until it was published [23, 27–29] it was thought that fish swam against tide or current. The reversal of this idea has changed our ideas of fish migration quite radically. It is perhaps unlikely that such advance will be sustained at the same rate because these machines were the result of technical advances which have perhaps reached a limit.

Quantitative estimates of fish stocks were made laboriously by counting echoes from fish, but the invention of the integrator allowed automatic estimates to be made. At the present time such automated surveys suffer from a bias inherent in the use of an integrator (the acceptance of signals from large numbers of small unwanted targets, if present), and

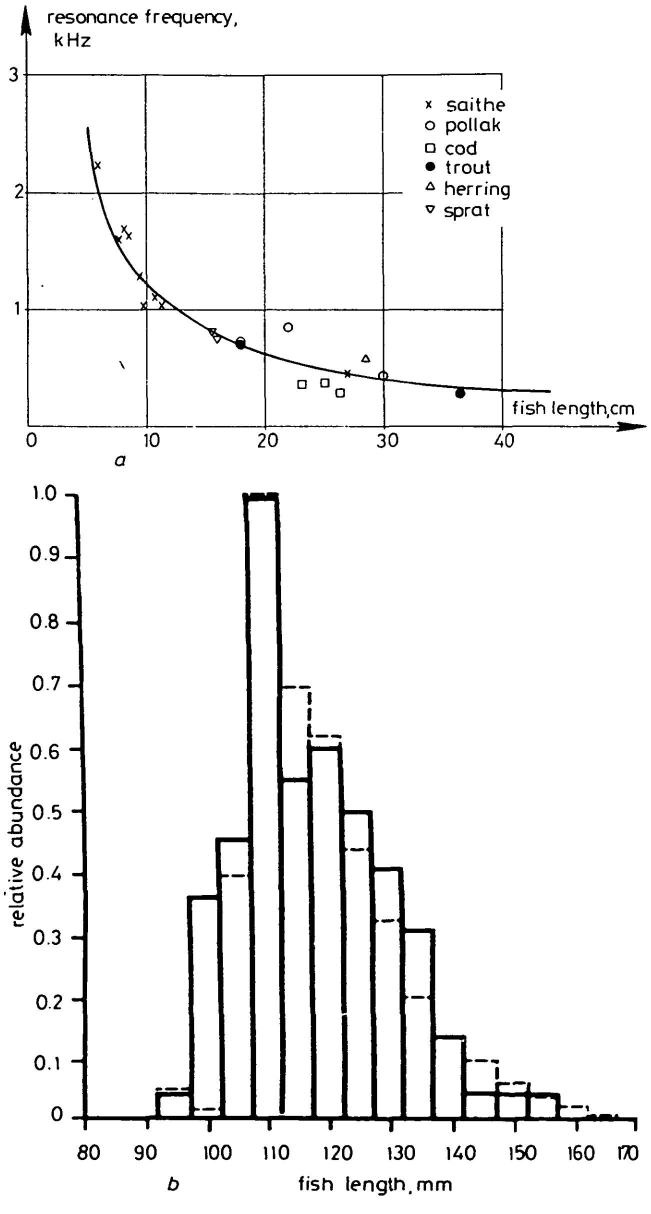

Fig. 12 *Discrimination of fish size by resonance of their swim bladders*

a Dependence of resonant frequency on fish length from survey off Norway
b Comparison of trawl and acoustic estimates off California [24]
——— trawl data — — — acoustic estimate
Correlation coefficient = 0.92

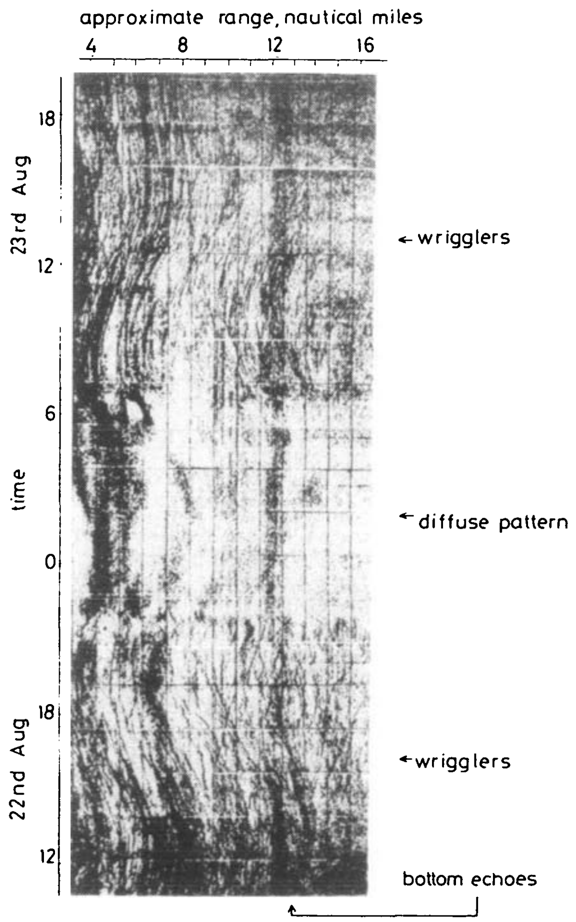

Fig. 13 *Records of pilchards made with very long range sonar during two or three tidal cycles* [23]

so lack proper estimates of the target strength of fishes as single targets or as multiple targets. Although such echo surveys arose in the past from exploratory needs, we have always hoped that acoustic estimates will provide stock assessments independent of the catches of fishermen. Today 43 fish stocks in the north east Atlantic are assessed in quantity each year by the International Council for the Exploration of the Sea and, of these, 18 are overexploited. From time to time the stock estimates require independent support; in the future we may bring them towards the precision needed for the usual fish stock assessment. However, considerable technical advances are needed, in target strength estimation, in fish shoal studies and in machine specifications in frequency, beam and power.

5 Conclusion

In recent years there have been two countervailing trends in the use of electronics in the fishing industry. The first was the developmental phase, until the early 1970s, when the worldwide industry expanded considerably, often with disastrous effects on the stock of fish which they exploited. During this period all the advances of solid-state electronics were incorporated in the instruments found in the wheelhouses of fishing vessels. At the same time the acoustic advances made in naval laboratories thoughout the world reached a point at which the best use can be made of a simple machine like the recording echo sounder. Further, the same advances allowed certain more complex instruments to be developed.

The second trend is the restraint of fishing since 1970. Until the early 1960s it was believed that fish stocks could be controlled by use of fairly simple measures such as mesh regulation, but once the best meshes for a trawl have been agreed it was always possible to increase the number of ships, and such was the effect during the 1960s. As a consequence quotas were introduced in the north west Atlantic in 1970 and in the north east Atlantic in 1974. As a further consequence of the same processes coastal states in 1977 declared exclusive fisheries zones out to 200 miles from their shores. The long-term effect was to reduce, but not extinguish, the distant-water fleets. Such vessels are still needed to work in deep water in poor weather, but as the foreign fleets leave coastal-state waters, and as quotas restrain the total amount of fishing on the stocks, the total numbers have been reduced. Hence the distribution of vessels has shifted, and will continue to shift towards the moderately sized vessels.

The combination of the trends suggests that the capacity of the fishing industry to absorb expensive developments will be reduced to some degree. Hence the present need must be for the best and most reliable machines that have so far been developed. However, if we become successful in managing fish stocks, the stocks will increase considerably. The average catch of a fishing vessel is a rough index of stock, and hence if stock increases, so does average catch and hence profit. Hence if the good management of fisheries becomes successful, the fishermen will have more money to spend. If fishermen made more money than expected in the past they spent it on a new boat, but in a successful management regime with quotas such ventures might be restricted.

If new machines were developed what form would they take?

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