

Experiments on the discrimination of fish and seabed echoes

D. N. MacLennan, P. J. Copland, E. Armstrong, and E. J. Simmonds

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During acoustic surveys for biomass estimation, fish aggregations near the seabed may not be correctly measured due to false detection of the bottom echo. The extent of this problem depends on the spatial and density features of the near-seabed aggregations. We conducted experiments using a tower structure deployed close to the bottom of a sea loch. The tower is 10 m high with a split-beam transducer at the top and a fish cage at the bottom. The effect of a bottom slope is simulated by tilting the transducer. In experiments with various densities and sizes of gadoids in the cage, echoes from the vicinity of the seabed were studied over hard and soft ground. In addition to the range, the split-beam echosounder gives two angular coordinates of the target direction. These may be combined into one measure of angular displacement, namely, the angle between the apparent target direction and the transducer axis. We call this the split-beam angle (SBA). We found that the SBA is not necessarily an accurate indication of the target direction. Echoes from fish aggregations and the seabed have different characteristics in this respect. When the seabed echo is detected with few interfering targets above, the SBA is an accurate indication of the seabed slope, and assuming the slope does not change over a short series of pings, the SBA is highly correlated. On the other hand, the SBA from multiple fish echoes is highly variable, as expected, and the ping-to-ping variation is essentially random. Furthermore, when the seabed echo is transmitted through a substantial density of fish, the interference can change the SBA, although the ping-to-ping correlation of the seabed SBA remains superior to that of fish aggregations. We also studied records from acoustic surveys on various research vessels to provide comparable results at full scale. When there is a low density of near-seabed fish, the correlation between the fore-aft SBA and the seabed gradient is optimal at the start of the first seabed echo; it declines at sub-bottom ranges. When there are dense aggregations of fish near the seabed, the automatic bottom-detection algorithm may be located on top of the aggregation, so that the echo integration misses a substantial quantity of fish. Examples from acoustic surveys in the North Sea are presented to illustrate this problem.

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D. N. MacLennan, P. J. Copland, E. Armstrong, and E. J. Simmonds: FRS Marine Laboratory, Victoria Road, Aberdeen AB11 9DB, Scotland, UK. Correspondence to P. J. Copland: tel: +44 (0)1224 295361; fax: +44 (0)1224 295511; e-mail: P.Copland@marlab.ac.uk

Introduction

Acoustic surveying is an established technique for estimating the abundance of pelagic fish (MacLennan and Simmonds, 1992). For the demersal or semi-demersal fish found close to the seabed, however, it is difficult to resolve fish echoes against the generally stronger reflection from the bottom. An important problem is how to determine the instant at which the seabed echo becomes dominant and the detection of fish is no longer practicable.

Because of the finite width of the acoustic beam, there is a “dead zone” where echoes from near-bottom fish are received after the start of the seabed echo. Direct detection

of these fish is usually impossible but Ona and Mitson (1996) showed how the effective sampling volume might be estimated to compensate for the dead zone, assuming, of course, that the seabed has been properly detected. Here, we consider a different problem. The algorithms currently used to detect the seabed in real-time sometimes malfunction. When there are dense schools of fish, the top of the school might be wrongly selected as the bottom. Conversely, over soft and weakly reflecting ground, the algorithm might place the bottom below the true level. In these circumstances, the fish abundance indicated by echo integration in the bottom zone could be wrong by a substantial amount. It is possible to correct such errors

in manual post-processing, see, for example, Foote *et al.* (1991), but an automatic procedure would be faster and probably more consistent.

The bottom-detection algorithms in current fishery echosounders depend on echo-amplitude measurements alone. There is limited scope for improvement without further information to aid the discrimination. One possibility is the split-beam echosounder now commonly used in acoustic surveying (Carlson and Jackson, 1980). The split-beam transducer is divided into four sectors. The instrument measures the echo-phase differences between the sectors as well as the amplitude. When a single target much smaller than the sampling volume is detected, the phase differences indicate the target direction. In the case of large targets such as the seabed or a fish school, the phase differences are still measured, although the indicated direction is not necessarily meaningful. The split-beam principle has been applied in hydrographic work where the primary objective is accurate depth measurement. Essentially, the measured phases are used to correct the echo amplitude for the transducer directivity, thus allowing a more precise bottom-detection threshold to be set (Kongsberg Simrad, 1998).

There is extensive literature on acoustic scattering by the seabed (e.g. Ogilvy, 1992; Medwin and Clay, 1998). Again, the focus has been on echo-amplitude features, in applications such as seabed classification (Chivers *et al.*, 1990; Greenstreet *et al.*, 1997). The bottom echo is often considered as the sum of a coherent (phase-consistent) component and an incoherent (random) component. Chotiros (1994) notes the potential of the echo phase, meaning the actual phase of the coherent component, as an additional seabed classifier. Unfortunately, the incoherent component dominates the bottom echo at frequencies above 30 kHz. This problem is not necessarily relevant to the phase differences measured by the split-beam method. Thus, additional criteria based on phase-difference measurements at the transducer could be useful for bottom detection.

To investigate this possibility, we conducted experiments on live fish in a cage located on or close to the seabed. In addition, records from acoustic surveys have been studied to determine the circumstances in which bottom detection fails, and to investigate the scope for improved methods applicable to survey conditions.

Materials and methods

Caged-fish experiments

Experimental studies have been conducted at the Loch Duich field station on the West Coast of Scotland, using an aluminium tower frame deployed from a moored raft (Figure 1). The tower is 10 m high, 2.2 m across the top with a 5.1-m diameter at the base. It comprises four sections, labelled S1 at the top to S4 at the bottom, which are bolted together to form the complete structure. The

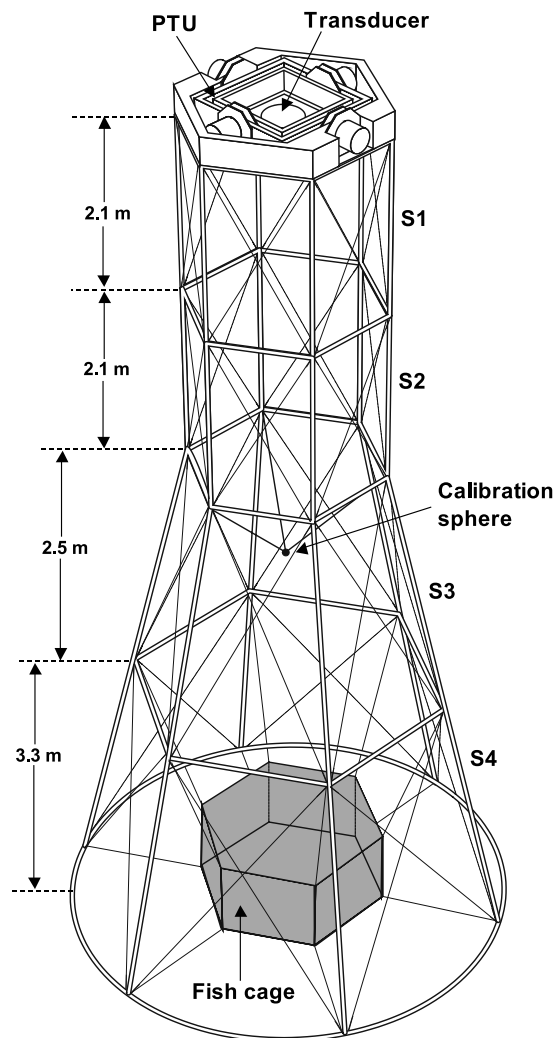


Figure 1. An oblique view of the tower frame showing the four separable sections (S1–4). The top hexagonal sections are 2.2 m wide; the bottom ring has a 5.1-m diameter; the fish cage is 2 m wide and 1 m deep.

vertical struts and the bottom ring are aluminium tubes with 5.1-mm wall thickness and 48.3-mm outside diameter. The horizontal struts are made from an angle bar 9.5 mm thick. The bar cross-sections are 63.5×63.5 mm in S1 and S2, and 76.2×76.2 mm in S3 and the top of S4. Within each section the struts are welded together. Fine stainless-steel bracing wires 1 mm in diameter are attached crossways between the top and the bottom strut junctions in each section and tensioned with screw couplings to increase the rigidity of the structure.

The split-beam transducer of a SIMRAD EK500 echosounder is located in a Pan-Tilt Unit (PTU) at the top of the tower. The PTU can rotate the transducer in two

perpendicular planes, up to $\pm 15^\circ$ off the central position, where the transducer and tower axes are aligned. Instruments attached to the PTU frame provide real-time measurements of the tower orientation (heel and pitch angles), the water depth, and the temperature and salinity near the transducer. The sound speed is obtained from temperature and salinity, using the Mackenzie (1981) equation.

A fish cage 2 m wide and 1 m high is at the bottom of the tower. It is constructed from knotless nylon netting and is attached to the tower by monofilament nylon lines. The lower lines are tensioned more than the upper lines, so that the bottom of the fish cage is close to the plane of the bottom ring. A standard target (tungsten carbide sphere, 38.1-mm diameter, target strength -42.4 dB at 38 kHz) is suspended centrally in S3, to provide continuous calibration of the echo integrator during experiments.

Interfering echoes from the bottom of the tower had to be as small as practicable. To achieve this, the bottom ring of the tower subtends an angle of 28.6° at the transducer. When the transducer axis is central, this places the bottom ring in the second null of the acoustic-beam pattern. The location of the second null was determined experimentally, using the method described by Simmonds (1984).

The echosounder frequency was 38 kHz. The transducer beam widths were 7.1° , 14.3° , and 21.4° between the half-power points, the first nulls, and the first sidelobes of the directivity pattern, respectively. The sensitivity in the first sidelobe was 26 dB below the maximum (on-axis) level. The pulse duration and bandwidth were 0.3 ms and 3 kHz, respectively. The EK500 sounder was connected to a BI500 data-logging system (Foote *et al.*, 1991), via an ethernet link operating over a fibre-optic cable between the raft and the shore cabin at the Loch Duich site. The acoustic data were archived on DAT tape cassettes. The stored records included the volume-scattering strength (S_v) and the two phase angles that determine the direction in the case of single targets, measured at 0.1-m range intervals from 4 to 40 m from the transducer.

The raft was moored in 39-m water depth, at a position where the seabed had a 9° slope. There were no convenient areas with a lesser slope at the depth required but mechanical calculations showed that the freestanding tower would be stable on slopes up to 20° .

In order to obtain measurements with the fish cage on and just above the seabed, with minimal disturbance to the fish, the tower frame was lowered to the bottom with a fixed cable length such that, at low water, there was 1–2 m of slack wire. The tidal height was around 3 m and so, during a tidal cycle, the frame slowly lifted off and later settled back on the bottom. Each fish experiment ran for at least 2 days covering four tidal cycles.

The natural seabed in Loch Duich is mainly soft sand and mud, with hard rocky areas close to the shore. Consequently, the measurements over soft ground presented no difficulty but the rocky areas were too shallow for mooring the raft. In order to study the bottom-recognition problem

over hard ground, a patch was constructed artificially by dumping 10 tonnes of aggregate below the raft. The aggregate was a mixture, mostly sandstone with some granite. The mean weight and density of the stones were 38.2 g and 2250 kg m^{-3} , respectively. This corresponds to a mean size (equivalent spherical diameter) of 3.2 cm. Inspection by television after the dumping showed that the stones were evenly distributed over an area several metres in diameter and they almost completely covered the ground. The hard patch was large enough to ensure that when the tower frame was dropped to the seabed, the fish cage always sat on a stone base.

The fish used in this work were mixed gadoids: cod, haddock, whiting, and saithe. Most came from the aquarium at the Marine Laboratory in Aberdeen, having been caught by a trawl on the East Coast some time before. They were transported to Loch Duich in aerated tanks. Additional supplies, mainly small saithe, were obtained from local creel fishermen. The fish were held in keep cages at 10-m depth for at least 2 days prior to the experiments.

Each series of experiments began with the maximum number of fish in the cage. After each experiment, some or all of the fish were removed and their sizes and weights were recorded. At the end of the series, all the fish having been measured, the details for each experiment could be calculated retrospectively.

In situ observations

Acoustic records of fish and various seabed topographies have been collected during research cruises in Norway and Scotland, using 38-kHz SIMRAD EK500 split-beam echosounders. Two sets of such data have been examined in the present study. Firstly, the Institute of Marine Research (IMR) in Bergen provided records from a cruise of RV “Michael Sars” in the Lofoten area when concentrations of large cod were present. The second set comes from Scottish surveys of herring in the North Sea. In each case, ping-by-ping data on the echo amplitude and other parameters were recorded along the vessel tracks, as depth samples at 0.1- or 0.5-m intervals.

Results

Acoustic characteristics of the tower

Initial tests were done to observe the echo interference from the tower. A typical echogram is shown in Figure 2. The fish cage is empty, the tower is in mid-water so there is no bottom echo, and the transducer is aligned centrally to minimize the interference. Weak echoes from the empty fish cage can be seen, and just below that the main echo and a “ghost” from the bottom ring (labelled R4) are seen. The ghost is due to forward scattering by other parts of the structure, giving a greater path length leading to separation of the direct and ghost echoes. The Nautical Area

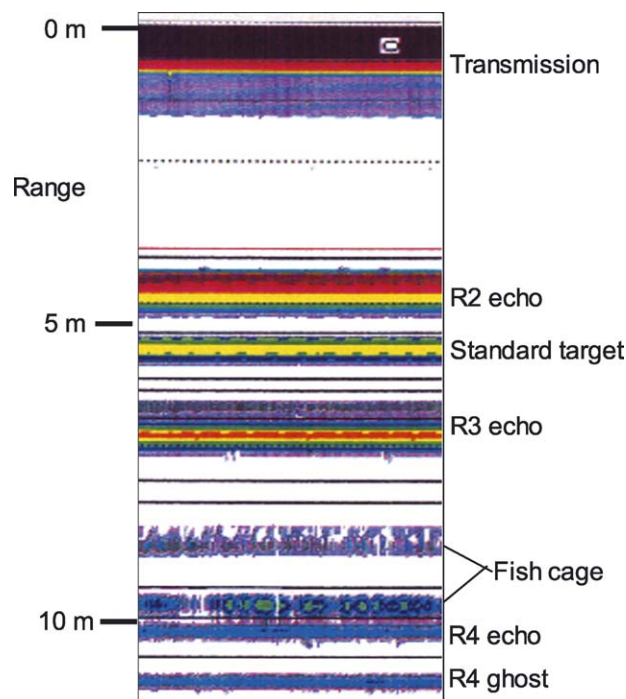


Figure 2. An echogram of the reflections from components of the tower when it is clear of the seabed. R2–R4 are the horizontal joining rings below sections S2–S4 (cf. Figure 1); R4 produces direct and ghost echoes from the bottom ring in mid-water; the standard target is a WC 38.1-mm sphere; the fish cage is empty but weak echoes are seen from the top and bottom panels.

Scattering Coefficient (NASC) of the empty cage is about three times that of R4 or the ghost. Thus, interference from the tower echoes is unimportant at least when the transducer axis is central.

As the transducer axis rotates away from the central position, the interfering echoes from R4 increase and eventually dominate the near-bottom signal. To determine the useful range of angles, a narrow layer around the R4 echo was integrated, with the tower in mid-water, while the transducer was rotated in two dimensions (called, arbitrarily, the X and Y directions). We assumed that the R4 echo could be ignored when its NASC was less than 10^4 ($\text{m}^2 \text{nmi}^{-2}$), about the same as that of 1 kg fish in the cage. This criterion was satisfied in a central region covering some 6° and 4° in the X and Y directions, respectively. The central region is not symmetrical because of the hexagonal sections in the upper parts of the tower. Thus, different areas of the bottom may be ensounded by rotating the transducer. The fish cage is large enough so that, for any direction in the stated region, the acoustic beam still intersects the cage.

Fish experiments

Twelve experiments each lasting at least 2 days were conducted with various aggregations of fish in the cage and

the details are shown in Table 1. The use of the rise and fall of the tide to slowly move the tower allowed the position of the fish cage relative to the seabed to be well defined at all times. Figure 3 shows a series of echo profiles averaged over 100 successive pings, when 38 fish (mainly cod) were in the cage over the hard ground. The profiles are at 30-min intervals as the cage dropped onto the seabed from 2 m above. The fish-echo pattern is much the same at all times, suggesting that the behaviour of the fish is not affected by the cage movement.

Figure 4 shows the NASC (s_A) of the caged fish as means for each experiment, corrected for the empty-cage integral, against the area density. The fish s_A increased consistently with the density, up to 3.10^5 ($\text{m}^2 \text{nmi}^{-2}$) at the highest density (8 kg m^{-2}). For comparison, the empty-cage integral was about 2300 ($\text{m}^2 \text{nmi}^{-2}$). The peak bottom echoes (s_A per 0.1-m sample) were approximately 1.10^6 and 3.10^7 ($\text{m}^2 \text{nmi}^{-2}$) for the soft and hard ground, respectively.

Echo-direction measurements

The apparent direction of the echoes from each 0.1-m range interval is defined by the split-beam phase differences, giving two orthogonal angular coordinates of the target. These may be combined into one measure of the angular displacement, namely, the angle between the apparent

Table 1. Experiments with various aggregations of mixed gadoids in the fish cage. Summary of fish sizes and weights. The fish density is the total weight divided by the cage cross-section (3.14 m^2).

Experiment reference	Type of ground	Number of fish	Length (cm)		Total weight (kg)	Area density (kg m^{-2})
			Mean	Standard deviation		
96/08	Soft	46	33.2	4.4	16.55	5.27
96/09	Soft	20	33.1	4.7	7.31	2.33
96/10	Soft	10	35.8	4.7	4.41	1.41
96/11	Soft	4	38.9	5.1	2.18	0.69
96/12	Soft	2	38.5	3.5	0.89	0.28
96/13	Soft	112	11.2	1.8	1.33	0.42
97/07	Soft	1	74.0		2.66	0.85
97/08	Soft	15	40.5	4.1	8.05	2.56
97/09	Soft	8	40.6	3.7	4.36	1.39
97/11	Hard	38	42.4	7.0	25.45	8.11
97/12	Hard	20	42.3	5.3	13.08	4.17
97/13	Hard	1	60.0		1.54	0.49

target direction and the transducer axis. We call this the split-beam angle (SBA). The 3-D charts in Figure 5 illustrate important features of the SBA from fish and bottom echoes. The SBA is shown over a series of 10 pings and a range interval that includes the initial bottom echo. The fish SBA is highly variable, while that of the bottom is fairly constant, at least for the initial one or two depth-bins on the rise of the bottom echo. Note that the fish density is small in this example, 0.42 kg m^{-2} .

The statistics of the SBA variation have been investigated for most of the experiments, excluding those

with very few fish in the cage. We define RSD (n) to be the standard deviation of the SBAs observed in the n th range sample over a sequence of 10 pings. From each experiment, 200 10-ping sequences were selected at various times when the tower was in bottom contact, thus ensuring contiguous fish and bottom echoes, and various directions of the transducer beam within the $6^\circ \times 4^\circ$ central region. In each sequence, the RSD of the fish cage and bottom was determined, taking “ n ” at two sample widths ($2 \times 0.1 \text{ m}$) past the start of the relevant signal. Figure 6 shows the overall mean RSD and the inter-quartile range from the 200

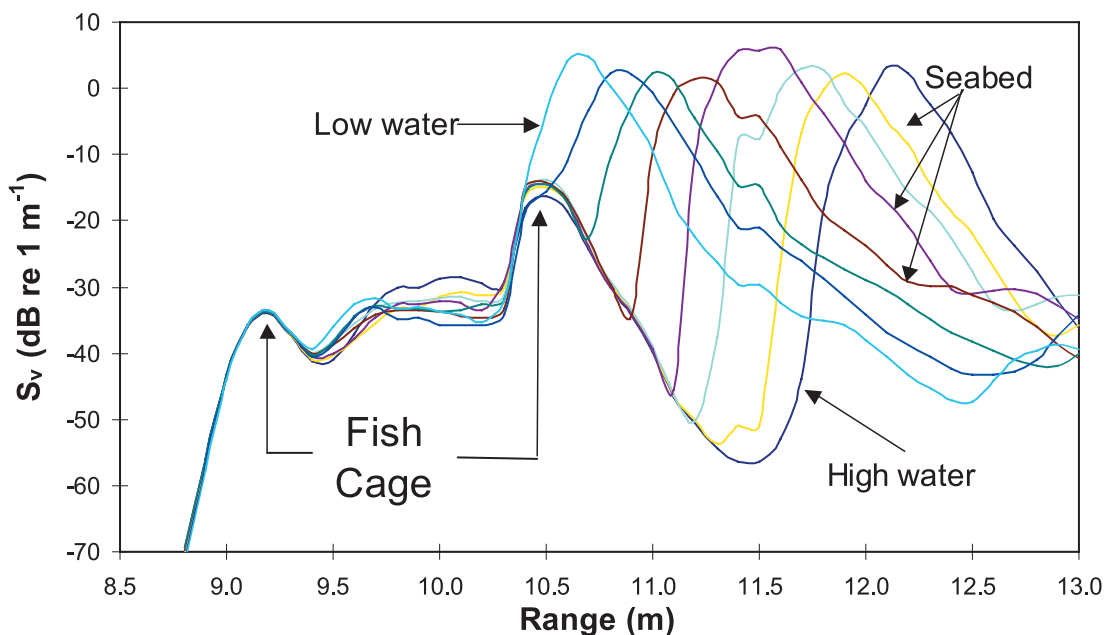


Figure 3. Echo profiles (S_v , volume-backscattering strength) against range from the transducer at approximately 30-min intervals from high to low water. Exp 97/11; 38 fish (mainly cod) in the cage; mean length 42.4 cm; area density 8.11 kg m^{-2} .

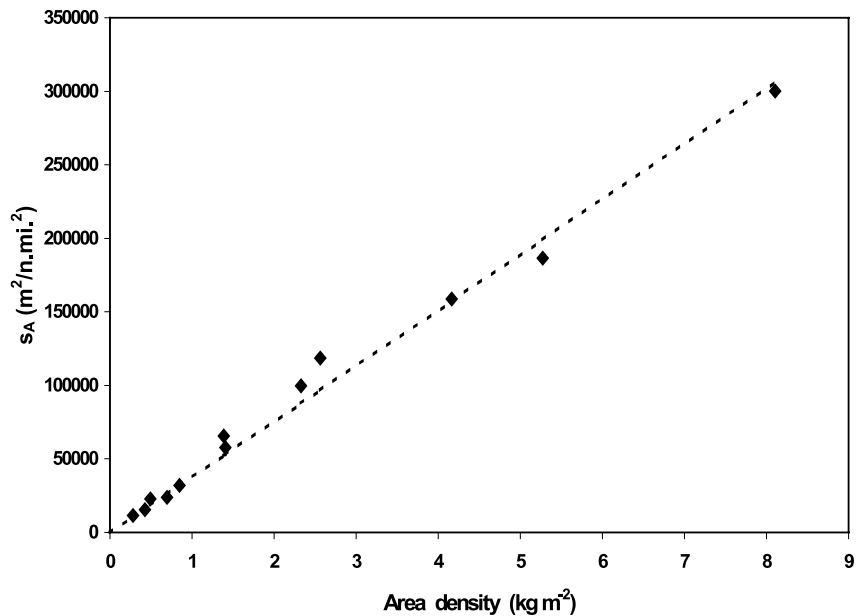


Figure 4. NASC of the cage echo integral plotted against the area density of fish. Points are the mean results for each experiment (cf. Table 1). The trend line ($y = 37800x$) is the least-squares-fit forced through the origin.

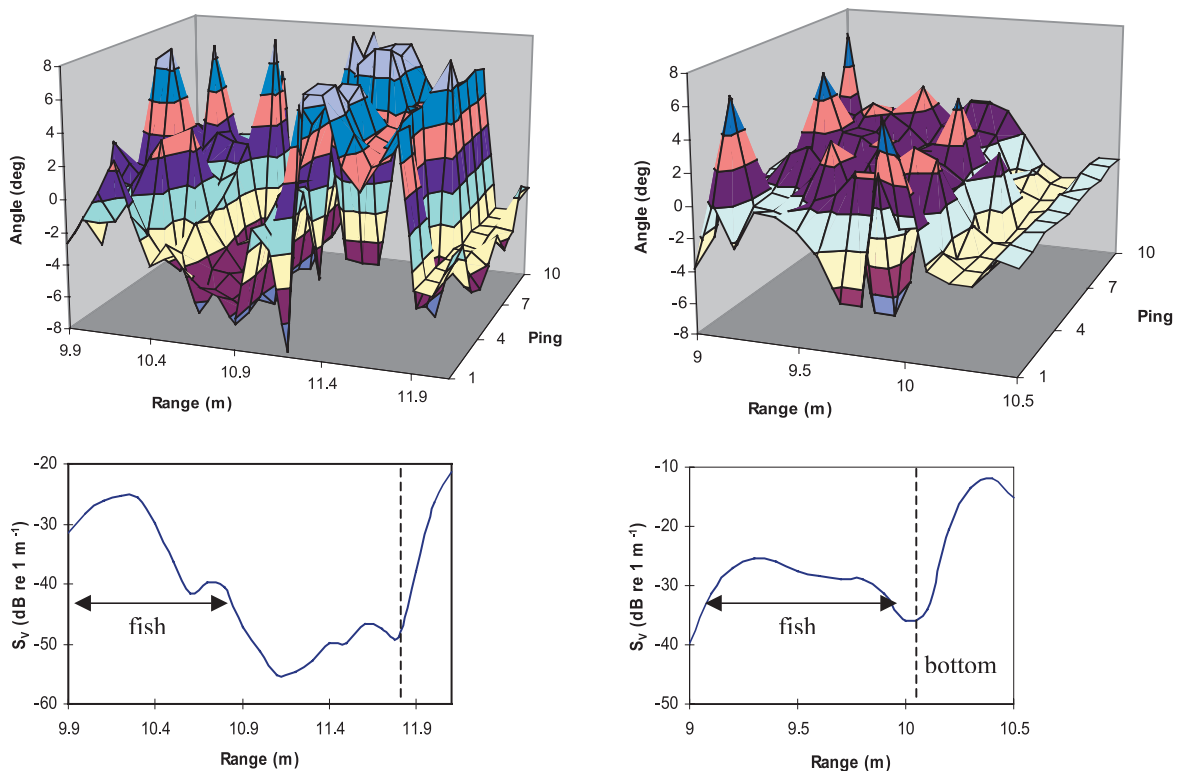


Figure 5. Echo directions according to phase measurements in successive 0.1-m-depth samples, for a series of 10 pings. Examples are shown for the tower in mid-water (left side) and on the seabed (right side). The lower figures show S_v against a range averaged over the ping series. The horizontal arrowed lines indicate the fish cage. The bottom is to the right of the vertical dashed lines. Exp 96/13; soft ground; small saithe (0.42 kg m^{-2}).

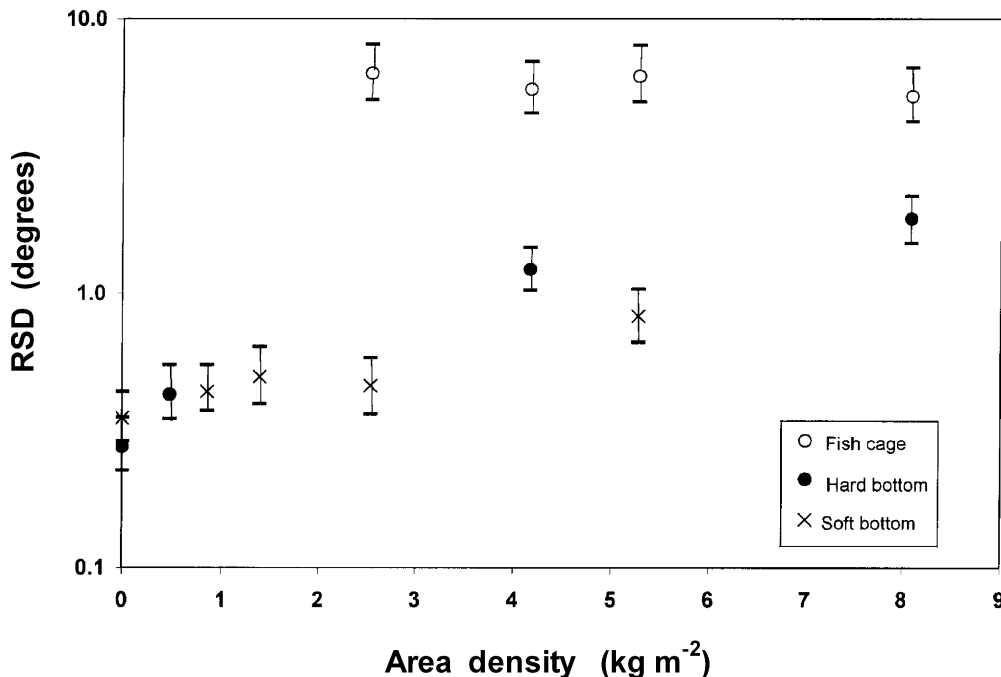


Figure 6. Standard deviation (RSD) of the split-beam angle (SBA) over 10 consecutive pings. Points are mean RSDs and bars show the inter-quartile ranges for 200 10-ping sequences at the same fish density.

sequences per experiment. Fish RSDs at densities less than 2 kg m^{-2} are not shown since the apparent direction in that case was essentially random. The bottom RSD tends to increase with the fish density, at a slightly greater rate for the hard bottom, but it is always substantially less than the fish RSD.

In situ observations

Figure 7 shows a short echogram recorded during RV “Michael Sars” cruise 1995/2003 in the Lofoten area off Norway. The ping interval is 0.61 s and the vessel speed is 10 knots (5.144 m s^{-1}) on a straight course. The bottom gradient can be estimated from the ping-to-ping depth change (G_{pp}), and also from the fore-aft, split-beam angle given by the echo phases (G_{sb}). G_{sb} depends on the range at which the phases are measured relative to the detected bottom depth. We found that the correlation between G_{sb} and G_{pp} was best at two sample widths ($2 \times 0.1 \text{ m}$) past the detected bottom. At greater depths, the correlation decreased steadily as more of the seabed contributed to the bottom echo. Figure 8 compares G_{pp} with G_{sb} at the optimum correlation range. The RSD of the scatter about the linear regression line is 1.55° . The two slope estimates are reasonably consistent, and much of the scatter is probably due to vessel motion. The presence of fish seems to have had little effect on the bottom-echo phase in this example.

Figure 9 shows an echogram of a dense herring school close to the bottom, recorded during a survey on RV “Scotia” in July 1993, with the bottom discriminator of the EK500 echosounder set at the default level (-50 dB). This is an example of failure in the bottom-detection algorithm. On many pings, the “bottom” is placed at the top of the school. The species was confirmed by trawl fishing, and repeating the track showed beyond reasonable doubt that the on-bottom echo trace was fish, not a fixed solid object. A higher bottom-discriminator threshold might have prevented this particular failure, but at the risk of softer bottom features being wrongly detected as fish.

Discussion and conclusions

The tower method has been successfully developed as a means of the acoustical observation of known fish aggregations held in a controlled position relative to the seabed. Tilting the transducer while the tower is on the seabed simulates bottom slopes of up to a few degrees. That limit is determined by the need for the bottom-ring echo to be small compared to echoes from the caged fish.

Twelve experiments have been conducted over two years with various aggregations of gadoid fish differing in area density, species, and size composition, using a split-beam echosounder. They include observations over both soft and hard ground. The results show that the SBA of the first

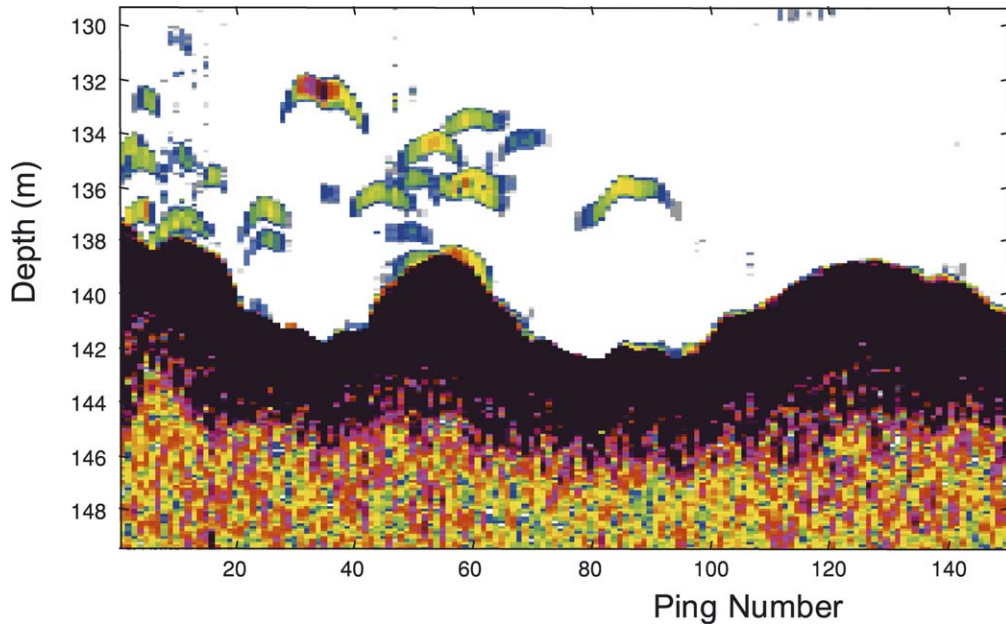


Figure 7. Fish echoes from large cod over sloping ground. RV “Michael Sars”, Lofoten Islands, Norway. Vertical resolution is 0.5 m pixel^{-1} .

samples from the bottom echo have different statistical characteristics compared to the echoes from fish schools. The SBA from a school is more variable from ping to ping, and between depth samples within the same ping, than that of the bottom.

We found that the SBA is not necessarily an accurate indication of the target direction. When the seabed echo is detected with few interfering targets above, the SBA is an

accurate indication of the seabed slope and, if the slope does not change over a short series of pings, the SBA is highly auto-correlated. On the other hand, the SBAs from fish echoes are highly variable and the ping-to-ping variation is essentially random. Furthermore, when the seabed echo is transmitted through a substantial density of fish, the interference can change the SBA, although the ping-to-ping correlation of the seabed SBA normally

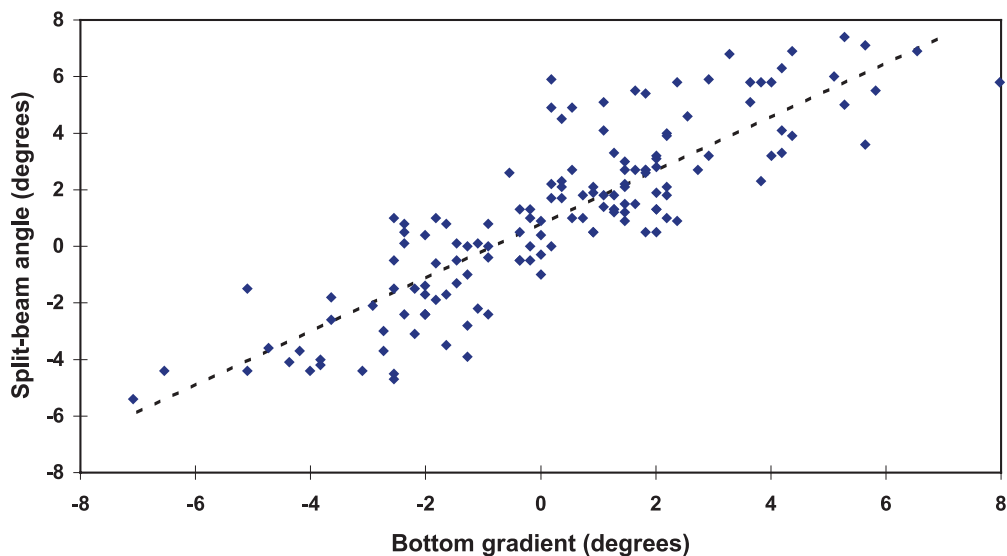


Figure 8. Split-beam, fore-aft angles plotted against the bottom gradient averaged over 5 pings. Data from RV “Michael Sars”, Lofoten Islands, Norway. The dashed line is the least-squares regression $y = 0.95x + 0.79$.

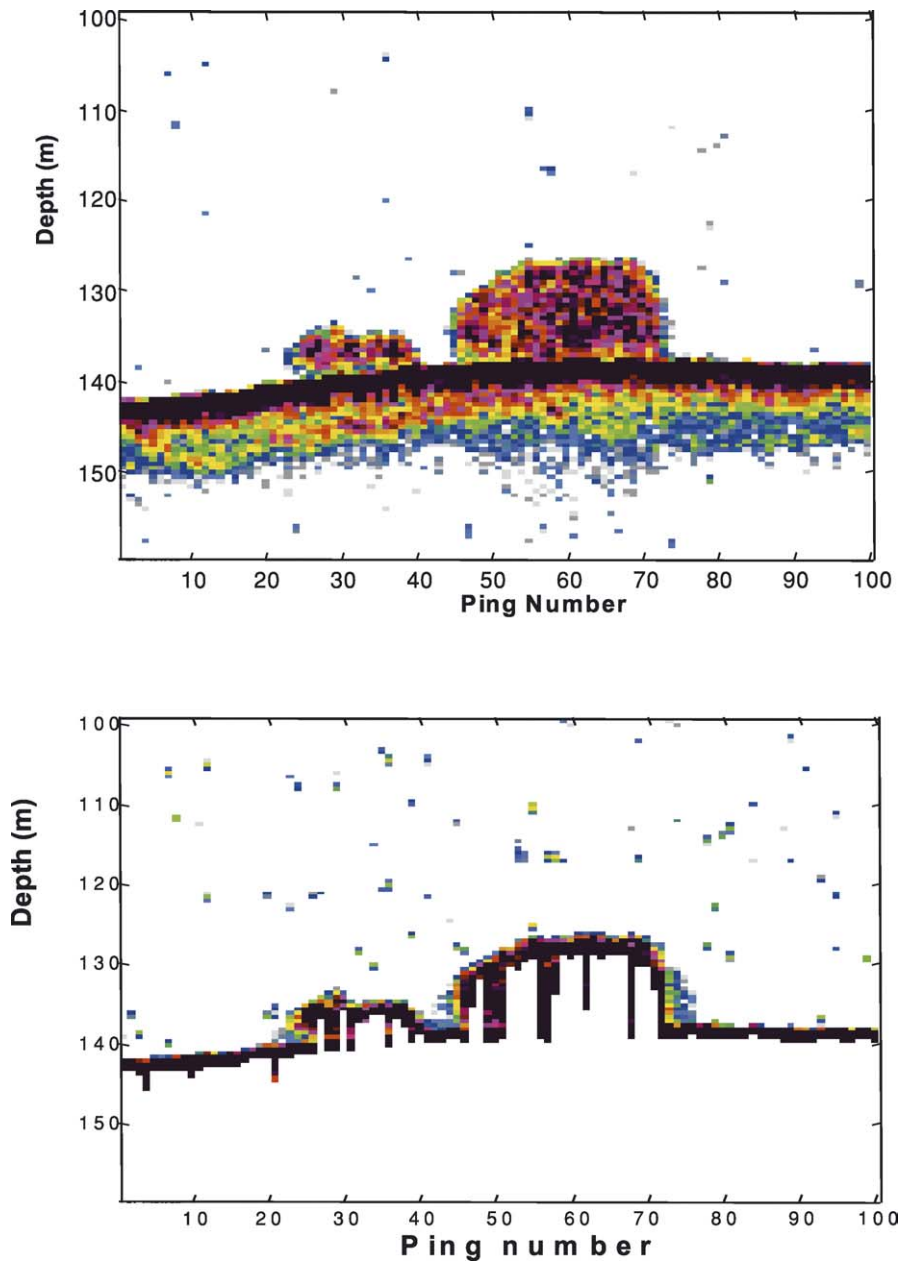


Figure 9. Upper panel: An echogram of dense herring schools on the bottom. RV “Scotia”, North Sea, July 1993. Lower panel: The same echogram with the zone below the “detected bottom” blanked to illustrate the erratic detection of the seabed. Vertical resolution is 0.5 m pixel^{-1} .

remains superior to that of fish aggregations. These effects are caused by interference between the many echoes originating within the school. The received signal is a combination of backscattered echoes and forward scattering of each direct echo by any fish closer to the transducer. The forward-scattered signals are weak but numerous, and they have various phases due to the different path lengths involved. The path lengths change as the fish move between pings. Thus, the interference between all these signals is

highly variable, resulting in the near-random phase of the combined echo as observed with fish schools.

Further analysis should be done to extend these conclusions and to quantify the statistical differences for the various conditions of fish aggregations and seabed geometry that can occur in nature. The present work has provided valuable reference data on the acoustical properties of fish schools in close proximity to the seabed. An important application is the development of improved

methods for the near-bottom discrimination of fish targets. The phase information provided by the split-beam echosounder may be incorporated in new algorithms for that purpose. Finally, we note that the phase statistics of school echoes may be influenced *inter alia* by the behaviour and physiology of the fish concerned. If these factors change consistently between different categories of fish, the additional information from phase measurements could lead to improved methods for the classification of echo traces in terms of their species and size composition.

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