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Acoustic sampling and signal processing near the seabed: the deadzone revisited

E. Ona and R. B. Mitson

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There are particular difficulties in making acoustic estimates of the abundance of demersal and semi-demersal fish. One possibility which exists in any survey situation is that the fish may move from the direct path of the vessel because of the noise it is radiating. However, the problems addressed here are primarily due to the physical characteristics of the transmitted acoustic pulse from the echo-sounder and its interaction with fish close to the seabed. This paper looks at the factors controlling the detection of these fish in terms of the acoustic sampling volumes near the bottom, the discrimination theoretically possible between fish and seabed echoes and the "depth anomaly". The acoustic deadzone is defined and its volume is determined. Practical aspects of signal processing in this near seabed situation are then described, including seabed recognition and safeguarding fish signals from contamination by the bottom echo and from noise. Next, an echo-integrator deadzone comprising the acoustic deadzone, the backstep zone, and the partial integration zone (related to pulse length) is described and defined. Equations for calculating the effective volume or effective height of this deadzone are developed. Estimation errors due to the echo-integrator deadzone are investigated and equations derived for the necessary corrections. An example is shown of partial failure of the bottom recognition system and how the echo integrator result can be corrected to compensate.

Key words: fish abundance estimation, near-seabed, acoustic deadzone, echo-integrator deadzone.

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Introduction

Important demersal, or semi-demersal fish stocks are monitored today through combined acoustic and bottom trawl surveys (Hylen *et al.*, 1986; Godø, 1990; Karp and Walters, 1994). Dependent on the fish vertical migration pattern relative to the bottom, a varying availability to the two sampling systems has been identified as a possible major source of bias in the survey estimates (Godø and Wespestad, 1993). Detailed knowledge of the methodological limitations may be useful when trying to quantify the bias and in seeking means to reduce it. In this paper we address the estimation errors occurring in the acoustic method, when trying to measure fish abundance close to the bottom.

With the subject of near-seabed estimation there are two associated matters that should be recognized, fish avoidance and the depth anomaly. Where fish avoidance of a vessel occurs, this can lead to a discrepancy between the apparent absence of fish, as indicated by the echogram, and the actual distribution of fish in the region of the surveying vessel. In the second instance, the depth anomaly, there may be a discrepancy between the observed and true height distribution of fish in relation to the seabed.

As a boundary, and in the context of one acoustic pulse, the seabed is of variable depth with small-scale contour changes and varying degrees of roughness. Fish echoes are normally of a smaller amplitude than echoes from the bottom and, when very close to the latter, the two may effectively merge, i.e. there is no separation in time between them. We need to know the limitations of fish detection and discrimination close to the seabed, in order to make estimates of total abundance from fish aggregations near this boundary. This requires a study of the factors that uniquely affect the acoustic pulse and echoes when fish and the bottom are in close proximity to one another. First, the echo from a single fish is used

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to illustrate detection when there is no nearby boundary, then the manner in which the situation changes when the echo emanates from a fish close to the seabed is described. Next, the concept of an acoustic deadzone is introduced: this is the region in which no fish detection is possible and the dimensions of this zone are evaluated.

For the practical survey situation it is essential to introduce other factors that have an important bearing on sampling in this region near the bottom. The basis of such surveys must be signal processing to provide a bottom recognition system and means of establishing a safe distance from the seabed for echo-integration to begin. The estimation process requires knowledge of correction factors to be applied to compensate for the safe distance and the acoustic deadzone by manual intervention.

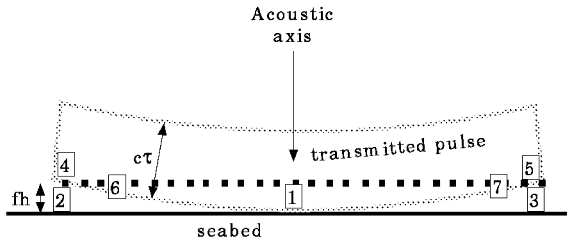

Figure 1. Fish, represented as rectangles 1 to 7, are seen in relation to the transmission pulse and the seabed. Water depth is 50 m; the transducer full beam angle is 7.5°; and the dorsi-ventral "height" of the fish (fh) is taken to be 0.1 m. 1—this fish is detected before the beam axis strikes bottom; 2, 3—these fish are in the acoustic deadzone (ADZ) so they are not detected; 4, 5—these fish are off-bottom and therefore detected but they appear at the bottom depth; 6, 7—these fish are only partially detected.

Fish distribution near the seabed

A decision has to be made between the use of wide beam angles, to sample the maximum volume of water below the ship, or to use narrow beams for maximum resolution. The overall advantages of narrow beams mean that for surveys of fish abundance they are now almost universally used. This makes it important that the natural distribution of fish is not disturbed, particularly by movement out of the immediate path of the vessel to an area where they may be missed by the echo-sounder. The use of narrow beams has the advantage of reducing the so-called "depth anomaly" (described in a following section) but we still need to be aware of the extent to which this phenomenon can distort the apparent near seabed depth distribution of fish. Before looking at the physical details of detection and discrimination of fish in relation to the seabed we consider one of the factors that might affect their distribution in this region.

Fish avoidance behaviour

Although it is an important matter, fish avoidance of vessels is not a deadzone problem. It is mentioned briefly here because it may be confused with the effect of the deadzone. There are specific limitations in the estimation of fish close to the seabed by acoustic means but these should be clearly isolated from the effect of fish avoiding the observing vessel. Avoidance is normally due to scaring of fish because of a high level of underwater radiated noise (ICES, 1995). Large bottom trawl catches, when obtained after "clean bottom recordings" from the echo-sounder, particularly in shallow water, may convince observers that the acoustic deadzone is sufficient for large quantities of fish to remain undetected by their echo-sounder.

However, with careful setting of the instruments, individual large fish are theoretically detectable by their actual body height on the acoustic axis, even when they are in physical contact with the bottom. With short pulses and high pulse repetition rates the presence of fish should at least be apparent along the path of the vessel. Nevertheless, when disturbed, fish may avoid an approaching vessel by swimming horizontally and vertically relative to the vessel path (Olsen, 1979, 1990; Olsen *et al.*, 1983; Ona, 1988; Ona and Toresen, 1988a, b; Ona and Godø, 1990; Nunnallee, 1991). Pre-vessel avoidance during a trawling operation is often greater during fishing because higher noise levels are generated than when the vessel is steaming. For groundfish, avoidance is greater in shallow water than in deep (Ona and Godø, 1990) because ship noise intensity decreases with range. Fish may hear an approaching trawler at more than 2 km (Buerkle, 1977) and may react by swimming away from the noise source at a distance of 100–200 m in front of the vessel (Ona, 1988; Engås *et al.*, 1991). In shallow water, the fish density available to a narrow vertical acoustic beam may therefore be considerably diminished. A significant gradient in fish density is then expected transversely to the vessels' path but is still available for herding by the trawl boards, which typically cover 5–40 times the area of the acoustic beam at depths less than 100 m. So, while those observations of "clean bottom recording" are correct, their interpretation may be wrong. When the depth exceeds 200 m avoidance of noisy vessels by fish close to the bottom is less likely. At such depths a fair correspondence between acoustically determined density and bottom trawl density is reported from comparative studies (Ona *et al.*, 1991; Sigurdsson, 1993).

The formation of fish and seabed echoes

Figure 1 shows a section through a transmitted pulse at a time when the leading edge of the pulse on the acoustic axis has struck the seabed. Rectangular blocks,

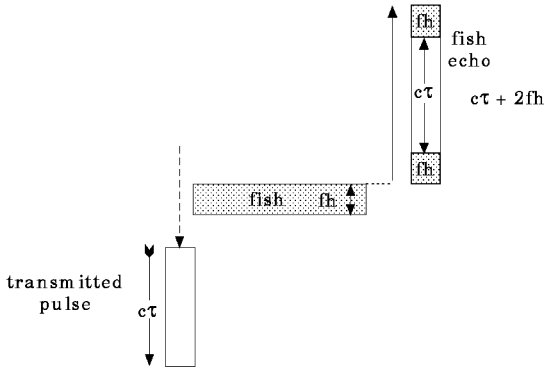

Figure 2. This shows an instant in the progression of a transmitted pulse which has passed and insonified a fish of dorsi-ventral dimension (fh) when it is in the pelagic region. The development of the echo is seen to be complete at the same instant. The full length of the echo is seen to equal the length of the transmitted pulse (cτ) plus twice the dorsi-ventral dimension of the fish.

numbered from 1 to 7, represent cross-sections of fish with a dorsi-ventral height of fh. These are placed in strategic positions to illustrate some of the factors peculiar to near-seabed detection and subsequent echo-integration. Fish 1, 2, and 3, are touching the bottom and clearly only fish 1 will be detected, although its echo will not be resolved separately from the seabed echo. For fish 6 and 7 the wavefront has partly traversed them at the instant that the axis of the beam touches the seabed; from such positions fish will return only partial echoes. Fish numbered 4 and 5 will appear to be on the bottom because they are at the same range as the seabed. Once the wavefront on the acoustic axis strikes the seabed no more fish detection is possible so fish 2 and 3 will be completely missed; they are in the acoustic deadzone (ADZ).

Mitson (1983) took a simplistic approach and concluded that there was a “definite deadzone”, defined as extending to a height of $c\tau/2$ above the seabed, where c is the speed of wave propagation in metres and τ is the duration of the transmitted pulse in seconds. This was based on the difficulty of actually *discriminating* between fish and bottom echoes for estimation purposes, as opposed to their *detection*. Advances in signal processing and post-processing techniques call for an appraisal of a deadzone definition which is effective for echo-integration purposes. This appraisal and a description of developments in acoustic near-seabed sampling form the main subjects of this paper.

Single fish echoes

We first determine the length of an echo from a fish of dorsi-ventral height fh, in midwater, clear of any boundaries. In Figure 2 a fish of this dimension (represented by a rectangle) has been insonified in passing by a transmitted pulse of length $c\tau$. The sequence of events leading to the formation of the echo can be visualized from the instant that the leading edge of the pulse wavefront struck the dorsal surface of the fish. An echo immediately starts to return to the transducer and this is illustrated on the right of Figure 2. By the time that the pulse leading edge reaches the ventral surface of the fish the echo will have a length of fh. This is shown as the block marked fh at the top of the complete echo. The full length of the pulse $c\tau$ continues on its path until the lagging end passes the ventral surface. At this point the length of the echo is equal to $fh+c\tau$. This last surface of the fish to be insonified returns energy to the echo which must travel the distance fh towards the dorsal surface. Therefore, the full length of the echo is $c\tau+2\,fh$, regardless of the distance that a fish is located away from the acoustic axis of the beam. The farther away from the axis, the greater is the reduction of energy in the transmitted pulse and the lower is the sensitivity of the receiver beam. This matter is dealt with later. In practical terms, the echo from a fish of $fh=0.1$ m, when insonified by a pulse of 0.3 ms, will be $0.45+0.2=0.65$ m in length, assuming a perfect pulse shape.

Single fish detection and resolution in relation to the seabed

The detection of an infinitely thin fish above the seabed is possible at height

$$h=d[1-\cos\theta] \quad (1)$$

where h = the distance (m) from the seabed to the dorsal surface of the fish; d = the depth of water from the transducer to the seabed; θ = angle of the fish from the beam axis.

This implies that a fish on the acoustic axis is at a minimum detection height from the bottom, but, to be exact, the height of a “real” fish of dimension (fh) is added to the above. Consider a fish of dorsi-ventral height fh on the acoustic axis, positioned with its belly (ventral surface) touching the bottom. The echo from this fish starts to propagate back towards the transducer as soon as the transmission pulse strikes the dorsal surface and will continue until it merges with the bottom echo. With no physical separation between the two, the echo-sounder detects a small signal joined to a following larger one, the difference in range being the height of the fish. In this situation, the length of the fish echo fh is prevented from exceeding the height of the fish so *discrimination* between it and the bottom echo is impossible.

Figure 3 again shows a fish with a body height of fh, which has been insonified in passing by a pulse of length equal to $c\tau$. On the left the pulse is seen divided into four sections, each representing a length of $c\tau/4$. Its lagging end is already separated from the ventral surface of the

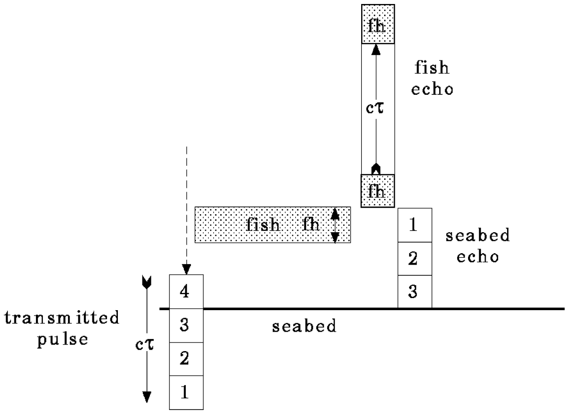

Figure 3. This situation is similar to Figure 2 except that the fish is now in the demersal region, close to the seabed. The transmitted pulse is divided into four sections to illustrate its progression and that of the subsequent seabed echo. Echoes resulting from the fish and the seabed are seen in the correct relationship at one instant of time. This shows that the fish echo cannot be resolved separately from the seabed echo when the fish is positioned at a distance of about cτ/2 above the seabed.

fish by a distance of cτ/4 as in Figure 2. A similar sequence of pulse progression and echo formation takes place as that described in the section on single fish echoes for the fish alone, until the leading edge of the pulse strikes the seabed. At that point the seabed starts to return an echo.

Figure 3 also includes the sequence of pulse progression and the echo return for the seabed, shown in relation to the fish echo. In this example, the ventral surface of the fish is cτ/2 above the seabed. As section 1 of the pulse strikes the seabed a bottom echo starts to return. This is seen as block 1 of the seabed echo at the right side of the diagram. However, in Figure 3, the pulse has already reached the point where its section 4 has arrived at the seabed. At that point two more sections of echo have formed and section 1 is seen to follow immediately behind the fish echo (no separation). Because of the different amplitudes, the fish echo may be distinguishable from the bottom echo. For the fish echo and the bottom echo to be formed separately, the distance between the two must be $>c\tau/2+fh$.

As the pulse continues to interact with the bottom, the echo from the latter will increase in length. This is because the leading edge of the pulse reaches the seabed at increasing angles until the outer edge of the beam is reached. As the distance from the axis to the outer edges of the beam increases, the depth anomaly becomes significant and this effect is discussed below.

Depth anomaly

We define the depth anomaly as the difference in height, relative to the seabed, of targets at the same range from the transducer but off the beam axis. Whatever the dimensions of the beam, the wavefront is spherical and targets on this wavefront are all insonified at the same instant. Thus, those targets on the acoustic axis of the beam coincide in *time* (same distance from the transducer) with those on the outer edges of the beam, although the latter are actually at a shallower depth, i.e. at a greater height above the seabed. The difference in height above the seabed for fish at the same range depends on the transducer beam angle and the depth of water. The wider the beam and the greater the depth, the bigger is the potential discrepancy between those on the axis and others nearer the edges of the beam. Observers often have the impression from their echo-sounder displays that the echoes they see are from "fish hard down on the bottom". This may be correct, but it can also be due to fish located off-axis at a height well above the bottom. Because of the depth anomaly they are at the same range from the transducer as those fish on the beam axis. In Figure 1 an example of this effect is seen where fish 4 and 5 are at the same range as fish 1 but are above the bottom.

Sampling volume of a conical beam

This type of beam is produced by a circular transducer, or array, and the pulse volume (Vp) can be calculated from:

$$Vp=\frac{4\pi}{3}\left[d^3-(d-c\tau)^3\right]\left[\frac{1}{2}(1-\cos\theta_3)\right] \quad (2)$$

where d=depth of water (from transducer face to seabed); c=speed of sound in ms^{-1}; τ=pulse duration in seconds; θ_3=half beam angle to the −3 dB points.

In addition to the pulse sampling volume formulated above, the final detection volume immediately before the wavefront strikes the seabed can be found. If a single fish, fish 1 in Figure 1, is on the axis of the beam and the dotted line joining the outer edges of the wavefront represents the base of a cap of a sphere, the "final" detection volume immediately above the seabed is in the form of such a cap whose volume is

$$v=\frac{\pi}{3}(fh)^2\,[3d-fh] \quad (3)$$

where v=volume of cap in m^3; fh=the dorsi-ventral height of the fish; d=depth of water from transducer face to seabed.

This "final" sampling volume is normally of little practical consequence but it illustrates the theoretical limit of detection. However, at the instant the wavefront contacts the bottom there is an important volume of water which the transducer beam cannot sample: the acoustic deadzone.

Acoustic deadzone (ADZ)

The term "acoustic deadzone" is used because this effect is due to the acoustic pulse alone whereas, later, there is a need to define three additional zones for signal processing purposes. When the spherical wavefront of the pulse strikes the seabed it leaves a zone which is unsampled, from the point of contact, out to the edges of the beam. This is because, when any part of the wavefront strikes the bottom, fish can no longer be detected by the echo-sounder. Due to the spherical surface of the pulse this zone can be significant, especially for wider beam angles and as the water depth increases.

For a conical beam the volume of the ADZ is

$$ADZ = \frac{4\pi}{3} d^3 \left\{ \frac{1}{2}[1 - \cos\theta_3] \left(\frac{\cos\frac{\theta_3}{2}}{\cos\theta_3} \right)^2 - 1 \right\} \quad (4)$$

where d=depth in m; θ_3=half beam angle to −3 dB points.
This is the volume of the acoustic deadzone, applicable to each single ping. It is also equal to the volume defined in Equation (3) at the instant the beam strikes the seabed.

Surveys are normally conducted so as to acquire maximum information. To achieve this purpose the highest feasible ping rate is used for the depth of water being sounded. This usually leads to a partial overlap of successive pulse sampling volumes along the survey track, the extent of which increases with depth. However, in the near-seabed situation, each ping produces a signal integral from the bottom gate which has an associated ADZ, as defined in Equation (4). Thus, the echo-integration process deals with the sampled and unsampled volumes on a ping-by-ping basis, so the beam overlap is of no consequence. A high ping rate with significant overlap will, however, significantly improve sampling statistics when fish density is low.

The ADZ is taken into account along with other dead zones, or where integration is partial, when signal processing is described in the following sections.

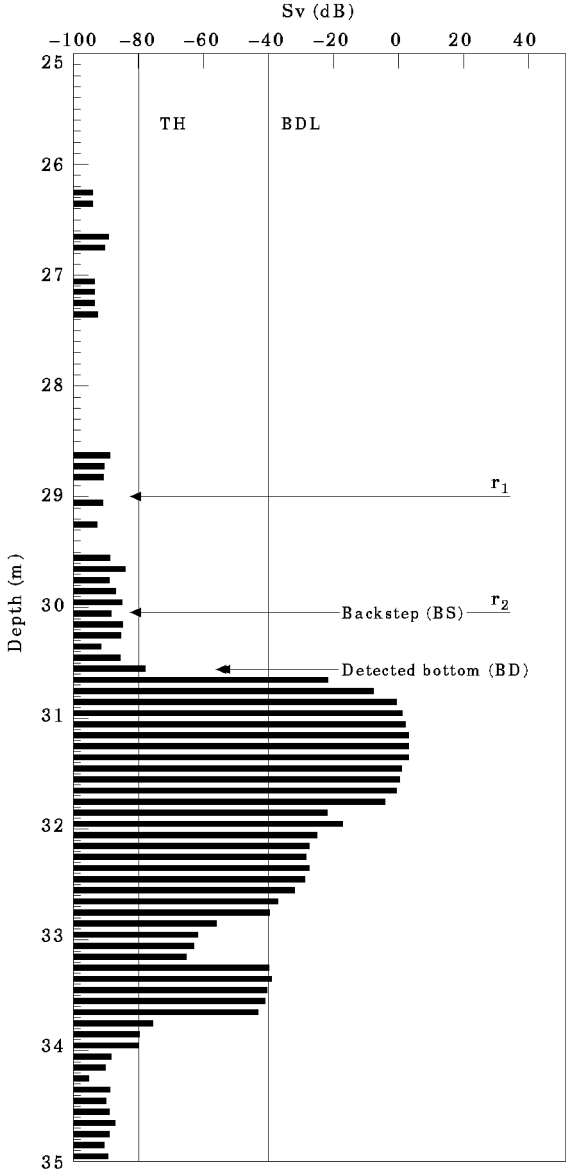

Figure 4. This echo-sounder depth interval of 10 m displays the echo signal from a 20 log R time-varied gain amplifier with the bottom echo at about 30 m depth. In this example the bottom discrimination level (BDL) is set at −40 dB, the backstep (BS) is 0.5 m and the echo-integrator signal threshold (TH) is −80 dB. The distance $r_2 - r_1$ represents a 1 m depth layer reference for calculating the effective sampling volume.

Seabed recognition

Software for bottom recognition in modern split-beam echo-sounders can receive raw calibrated signals with unsaturated digital amplitude and phase angles from paired quadrants of the transducer (Bodholt *et al.*, 1989). In addition, information from previous pings can be used to predict bottom depth. In this section we assume there is only one candidate for the bottom echo, the case in most areas where demersal fish are found. Figure 4 shows real amplitude data (S_V) from a 20 log R TVG amplifier, as recorded by a Simrad EK500 over a 10 m depth interval which covers the bottom echo at about 30 m depth. The frequency is 38 kHz, pulse duration 1 ms, and the detected, digitized output corresponds to depth increments of about 0.1 m. Three parameter settings of the instrument determine the near bottom data for echo-integration and partly decide the volume of the echo-integrator deadzone (IDZ).

Bottom discrimination level (BDL)

This sets the amplitude at which the system recognizes the bottom and is also used as a reference to set depth layers. For example, if BDL is set at $S_V = -40$ dB, the seabed discrimination algorithm will search backwards from the peak level towards the surface until the first depth sample shallower than BDL is found. This point is defined as bottom depth, BD as seen in Figure 4.

Although it works properly in normal situations, this bottom detection algorithm can produce errors under some conditions. This may occur when using standard settings on a sloping bottom and when fish schools occur close to the bottom. Corrections for such errors are made by an experienced operator during the post-processing (see further on). The algorithm used in the seabed recognition system and the applied pulse length are used to estimate the total deadzone applying to echo-integration.

Backstep from the seabed (BS)

To ensure that the entire seabed echo is excluded from the integrated fish signals, a backstep, BS, is set by the operator. Alternatively it is defined by a combination of the echo-integrator bottom channel upper limit and the total range measured from the upper limit. If working with surface-referenced depth layers towards the bottom, a margin equal to BS is specified as the stop condition where integration ceases. In Figure 4, BS=0.5 m.

Threshold for signals (TH)

A signal threshold (TH) is set to eliminate noise contributions to echo-integrator data. To be integrated, the fish echo amplitude must exceed this value. In Figure 4, the TH line $= -80$ dB.

Total deadzone calculation for echo-integration

The total deadzone comprises the zones illustrated in Figure 5a. In addition to the ADZ there is a backstep zone (BSZ) which extends from the depth detected as bottom (BD in Fig. 4), to a manually set distance above it. Then, from the top boundary of the BSZ is a further zone, at the lower end of the bottom echo-integration channel (Bch), where echoes may be only partially integrated and this is called the partial integration zone (PIZ).

Integrator deadzone (IDZ)

The echo-integrator deadzone (IDZ) is the sum of the three terms, ADZ+BSZ+PIZ. Earlier deadzone computations in this paper have considered the lost volume within the half-power points of the beam, without considering the effect of beam directivity on the targets. The contribution from off-axis targets to echo-integrator data gradually decreases as the off-axis angle increases, so "effective" height, or volume, interprets the situation more precisely than actual height or volume. We look at the lost volume in terms of the equivalent beam angle (Ψ), as when computing the effective sampling volume in the pelagic region. Figure 5b shows the nomenclature used. A 1 m depth layer ($r_2 - r_1$) for echo-integration is

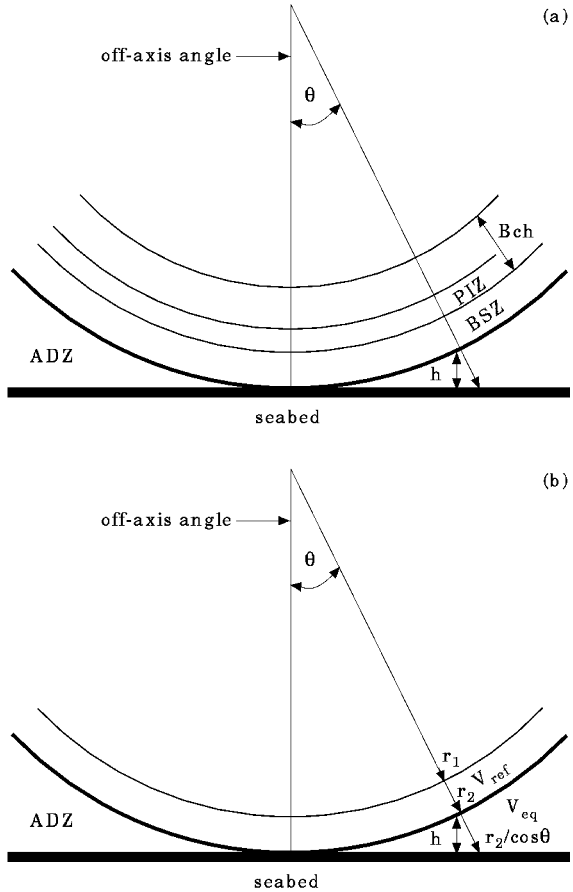

Figure 5. (a) A diagrammatic representation of the zones that go to make up the echo-integrator deadzone (IDZ) shown against a flat seabed and an off-axis transducer beam angle θ. The acoustic deadzone (ADZ) represents the volume left unsampled at the instant when the pulse wavefront strikes the bottom. A backstep zone BSZ is set immediately above the seabed. At the lower end of the bottom-locked echo-integrator channel (Bch) is the partial integration zone (PIZ) where only a portion of the echo is detected. (b) This diagram illustrates a similar near-seabed situation to Figure 5 with the leading edge of the pulse wavefront striking the sea bed. The distance $r_2 - r_1$ represents the same 1 m depth layer reference shown in Figure 4, i.e. it is used in calculating the effective sampling volume nominal for echo-integration. The nomenclature shown is that used in the text for calculation of the "lost volume" or "lost height" due to the IDZ.

assumed to be immediately behind the pulse wavefront as it hits the bottom. The effective sampling volume for this layer is:

$$V_{ref} = \frac{r_2^3 - r_1^3}{3}\Psi \tag{5}$$

where $$\Psi = 2\pi \int_0^{\frac{\pi}{2}} b^2(\theta)\sin\theta \; d\theta \tag{6}$$

b being a function describing the acoustic beam pattern.

The reference volume (V_{ref}) should now be compared with the "equivalent lost volume"

$$V_{eq} = \int_{r_2}^{r/\cos\theta} r^2 b^2(\theta)\sin\theta \; d\theta \; d\Phi \; dr \tag{7}$$

which is equal to

$$V_{ref} = \frac{2\pi}{3}\int_0^{\frac{\pi}{4}} \left(\frac{r_2^3}{\cos\theta} - r_2^3\right) b^2(\theta)\sin\theta \; d\theta \tag{8}$$

For a 1 m thick depth reference layer, the equivalent lost height is the direct ratio between the volumes

$$h_{eq} = \frac{V_{eq}}{V_{ref}} \tag{9}$$

The equation for calculating the equivalent lost volume becomes unstable at very large angles because this volume then increases towards infinity. It is arguable how far out from the acoustic axis contributions from fish will be significant, a related problem to that of computing an effective sampling volume for fish in the pelagic depth layers. In the pelagic region, the integrated density is also represented in specific depth layers, although the energy is contained within the entire half-spherical shell defined by the range gates.

Under practical conditions, the threshold set for echo-integration effectively stops signals from the edges of the beam being included in the integral. In the computation of the equivalent volume, stopping the numerical integration at π/4 may be regarded as a suitable limit. Figures 6a and b show the ratio V_{eq}/V_{ref} investigated as a function of the total integration angle. This ratio is a direct measure of equivalent lost height and reaches 98–99% of its value when the first sidelobes are included in the integral. Using a stop condition of 45° the equivalent lost height from the deadzone is shown in Figures 7a and b. From the numerical integration, the approximate equivalent lost height (h_{eq}) can be found from:

$$h_{eq} = 2404\left[\frac{d\tan^4\theta_3}{\theta_3^2}\right] \tag{10}$$

where d is the bottom depth in metres; θ_3 is the half-beam angle to the − 3 dB point.

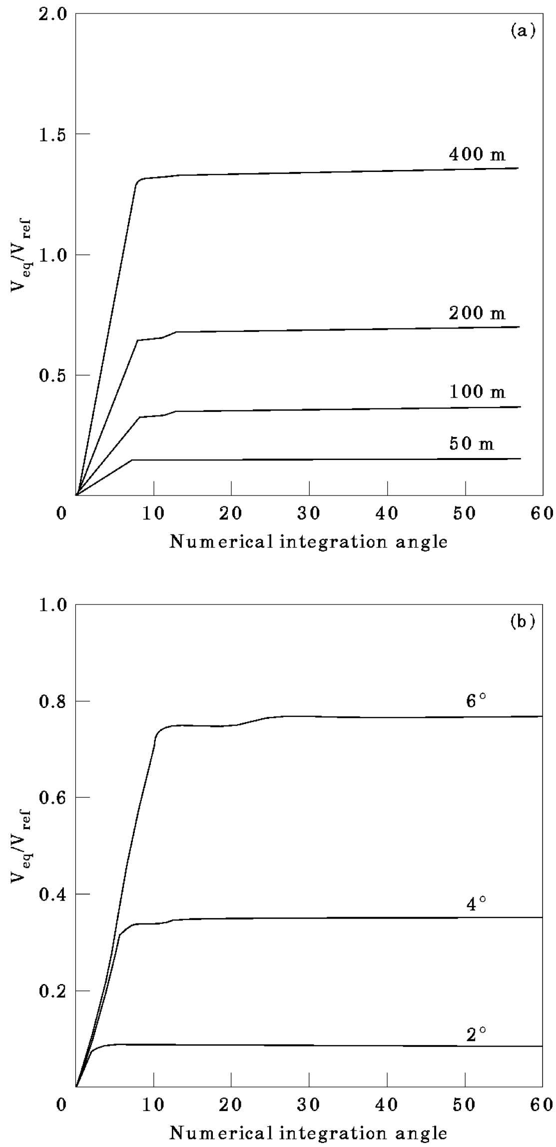

Figure 6. (a) The ratio V_{eq}/V_{ref} is plotted as a function of the numerical integration angle for depths of 400, 200, 100, and 50 m for a transducer with half-beam angle of 4°. (b) The ratio V_{eq}/V_{ref} plotted as a function of the numerical integration angle for transducer half-beam angles of 2, 4, and 6° and a depth of 100 m.

When a standard 38 kHz split-beam transducer is used $2\theta_3 = 7.1°$ so:

$$h_{eq} = 2.83 \times 10^{-3} \, d \tag{11}$$

Partial integration zone (PIZ)

Looking back at Figure 1 we see that fish 6 and 7 are only partly detected because the axis of the beam has touched the seabed, thereby stopping further detection

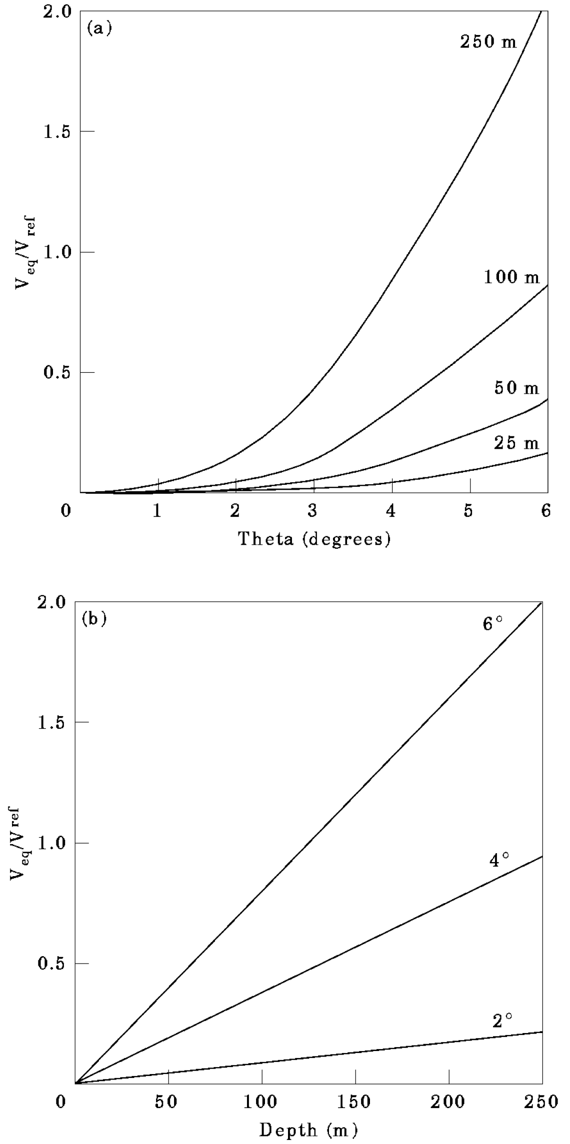

Figure 7. (a) Showing the equivalent lost height due to the IDZ plotted against the half-beam angle, θ_3, when a stop condition of 45° is applied to the numerical integration angle. Depths are 250, 100, 50, and 25 m. (b) Showing the equivalent lost height due to the IDZ plotted against depth when a stop condition of 45° is applied to the integration angle. Half-beam angles, θ_3, are 6, 4, and 2°.

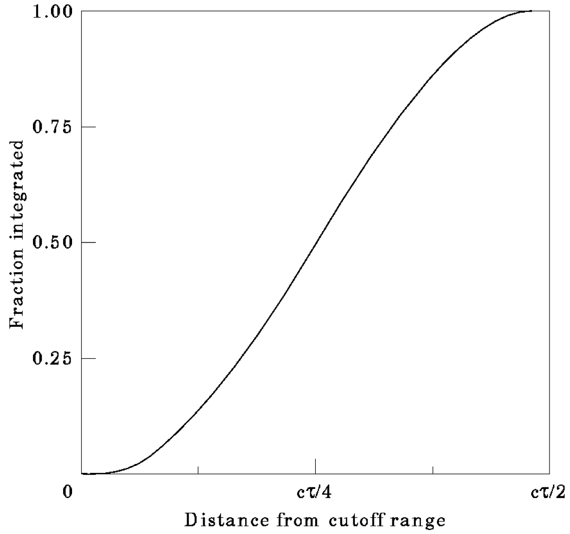

Figure 8. This shows the fraction of the echo integrated (partial integration) as a function of distance from the bottom (or the distance from the cut-off range when a backstep is used).

and preventing these fish from returning complete echoes. This effect is of concern when echo-integration is conducted.

Energy lost at the deepest part of a pelagic depth layer is compensated by echoes from the upper portion of the layer. This is not the case in the near seabed depth layer, where energy from fish not included in the echo-integration process cannot be compensated in the same way, because all fish detection ceases at the seabed.

A backstep zone has already been defined and the upper limit of this zone becomes the effective cut-off depth for echoes. This means that, for a distance above the BSZ, there is a zone where echoes are only partially integrated: the partial integration zone (PIZ). To determine the extent of the PIZ we assume a fish at range (r) whose echo will appear between (r) and ($r+c\tau/2$). The entire echo energy from the fish is received within this range increment.

Echo energy losses from targets within the ADZ are accounted for when computing the equivalent lost height. But those targets at a distance of $c\tau/2$, or less, above the upper limit of the BSZ will be partially integrated and this must also be taken into account. At the upper boundary of the PIZ, targets will contribute 100% of their energy to echo-integration but, the closer they are to the top of the BSZ, the smaller this contribution will become. Assuming targets are randomly distributed across the cut-off range, and that the echo amplitudes are symmetrical with respect to their maxima, the average echo energy for integration will be 50% of the maximum. As shown in Figure 8 this represents a lost range of $c\tau/4$ within the bottom depth layer.

Partial echo-integration is illustrated in Figure 9. This shows the echoes from three 50 mm diameter targets (separated from one another by 1.9 m) insonified by a 1 ms pulse and detected as they are pulled up and down relative to the flat seabed. At its maximum depth, the lower target is 0.42 m above the seabed so, because the pulse duration is 1 ms, the echo from this target is only partly integrated, even when the minimum backstep is used.

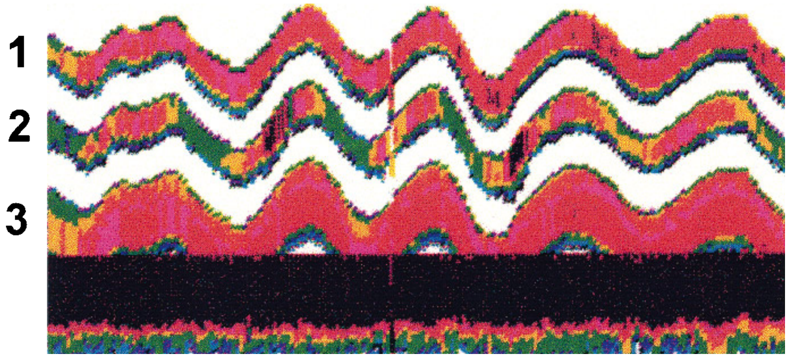

Figure 9. Three air-filled 50 mm diameter targets are detected close to a flat seabed as they are moved up and down relative to the bottom. The distance from the bottom to the targets at their closest point of detection is 0.42, 2.32, and 4.22 m, regulated by a weight at the bottom. A frequency of 38 kHz was used with a pulse duration of 1 ms and the echogram is a 10 m depth scale expansion.

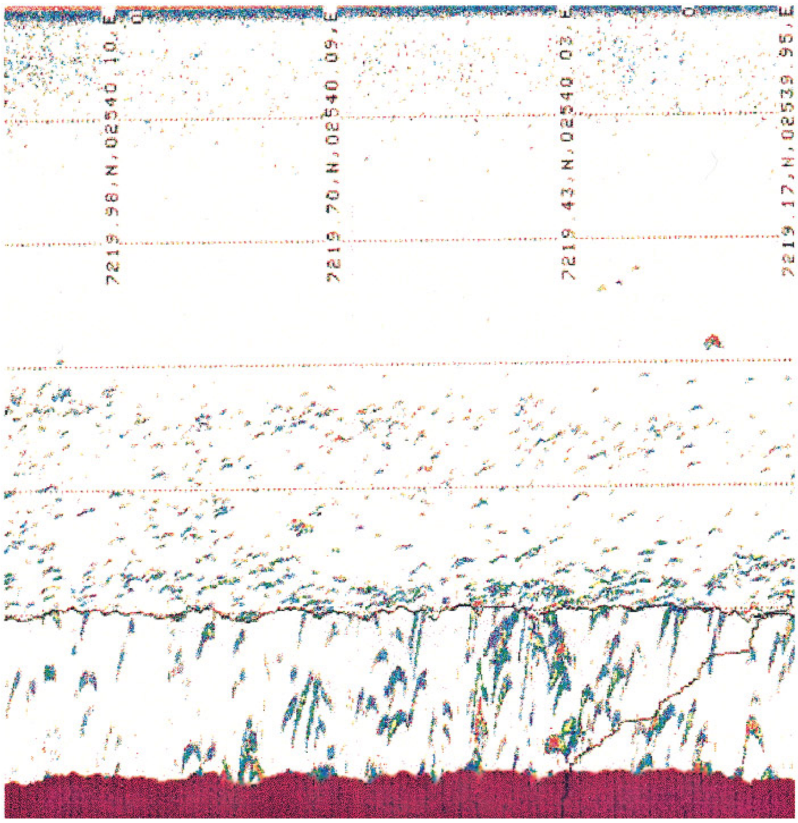

Figure 10. An echogram of cod and haddock in deep water (250 m) showing a distribution extending to about 100 m above the bottom. An analysis of these signals is given in Table 1.

The foregoing describes the overall effect of pulse length. However, other factors which include the exact pulse shape, the bandwidth, the resolution of the digitizing system, and marginally, the TVG at short ranges, have not been considered. A detailed simulation would be required for a full description of these effects, but in practice they are not expected to have serious consequences.

Corrections to the bottom depth layer

Having defined the equivalent lost height, the backstep height and the average pulse length effect, a total lost integration height, or volume, can now be defined. This can be used to correct echo-integrator data. Examples are shown in Figures 10 and 11 where corrections are

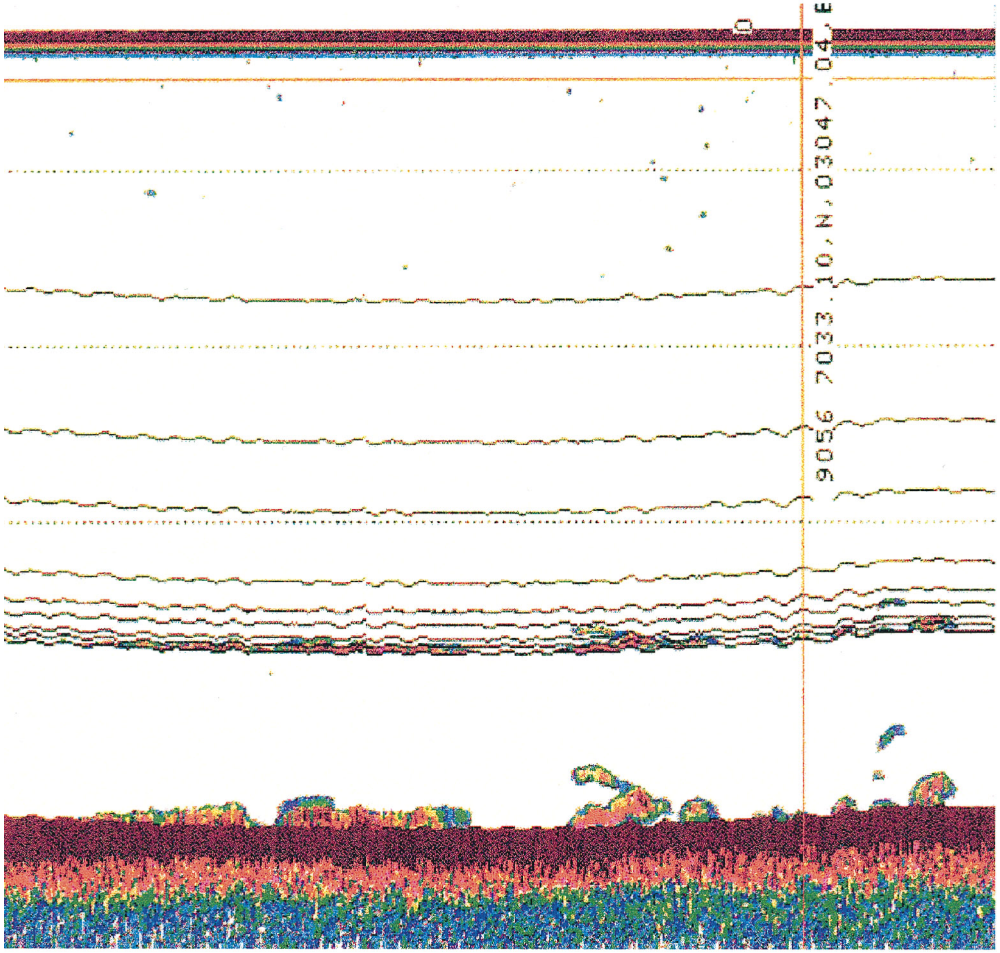

Figure 11. An echogram of haddock very close to the bottom at Persfjorden, North Norway, using an EK500 at 38 kHz with a 1 ms pulse duration and bottom-locked integrator channels. Depth is about 90 m. Corrections made because of the IDZ are shown in Table 2.

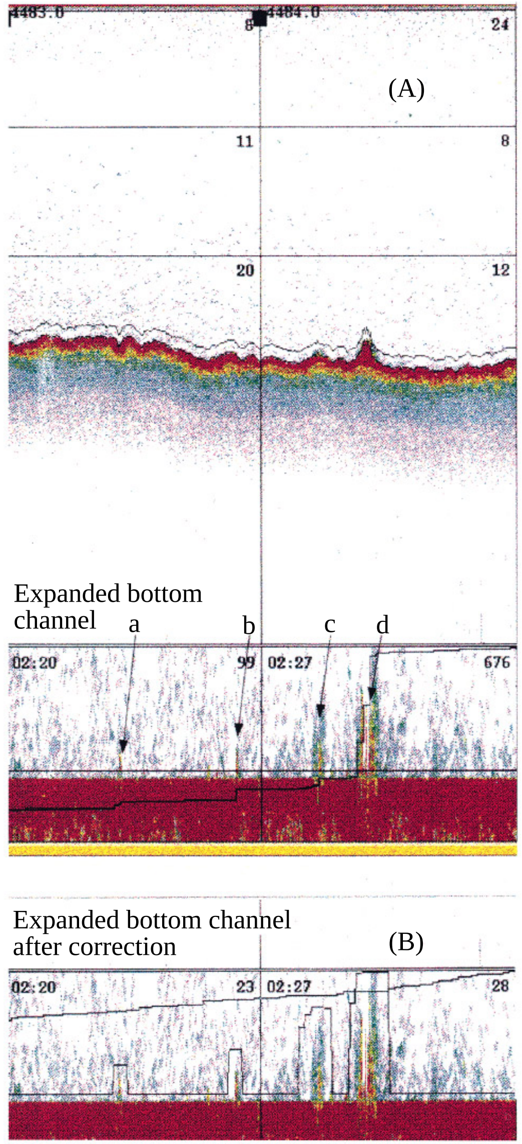

Figure 12. (A) Printout of part of a BEI-500 computer display showing bottom detection errors as "spikes" of high energy echoes extending through the backstep line in the expanded display of the bottom channel. (B) The bottom echo "spikes" have been effectively removed by the operator who has redrawn the backstep line to exclude them. As a result of this correction there is a significant reduction in the integral.

determined and applied to the echo-integrator bottom channel. The total area density (ρ_{A_T}) is the sum of the depth layer area densities, including the non-measured layer representing the IDZ

$$\rho_{A_T}=\rho_{A_1}+\rho_{A_2}+\ \ldots\ \rho_{A_N} \tag{12}$$

then, since the area density is simply the integrated volume density over a specific height,

$$\rho_{A_T}=\rho_{V_1}h_1+\rho_{V_2}h_2+\ \ldots\ \rho_{V_N}h_N \tag{13}$$

First, assume that the volume density of fish close to the seabed is equal across the bottom depth layers $\rho_1=\rho_2=\rho_N=\rho_o$, i.e. volume density observed in the measured layers, then:

$$\rho_{A_T}=\rho_o\Sigma h \tag{14}$$

which in echo-integration terms is equal to

$$\frac{s_{A_T}}{\sigma}=\frac{s_{A_o}\Sigma h}{h_o\sigma} \tag{15}$$

where s_A is the area back-scattering coefficient and σ is the average acoustic cross-section of the fish. The correction to the observed, or measured, area back-scattering coefficient is the direct ratio between the full height and the observed height.

$$s_{A_T}=s_{A_o}\frac{h_o+h_{eq}+h_{bs}+h_\tau}{h_o} \tag{16}$$

or, more correctly, as an addition

$$s_{A_T}=s_{A_o}+s_{A_o}\left(\frac{h_{eq}+h_{bs}+h_\tau}{h_o}\right) \tag{17}$$

As the observed height (h_o) can be varied, the assumption of equal density towards the bottom may be omitted, because h_o may only represent a thin depth layer next to the non-measured volume. In a more sophisticated approach, the density observed in a number of depth layers next to the non-measured layer may be used to extrapolate, or predict, a density in the non-measured volume.

From the foregoing it is clear that the IDZ can be made smaller by the use of a narrower acoustic beam, a shorter pulse duration and a small backstep. However, in areas where fish are distributed extremely close to the seabed, the most significant part of the echo is lost and corrections are impossible. In practice, the oceanic stocks of demersal fish such as cod and haddock are very seldom found in this position and the majority of the fish can be measured easily.

Compensating for the IDZ

Two examples are given in Figures 10 and 11. The first uses acoustic data collected in May 1992 from the Barents Sea at about 250 m depth, showing a typical mixture of demersal cod and haddock (Fig. 10). As is typical for a deep water situation at this time of year, the fish are well distributed vertically with only minor day to night changes. The weather conditions were good, and the recordings were made with a Simrad 38 kHz EK500 echo-sounder, using a circular 7.1° full beam angle, split-beam transducer, and 1 ms pulse duration. The area density of fish within this one nautical mile recording is shown and summarized in Table 1. These are raw scrutinized data within 50 m depth layers in the pelagic region. There is one 10 m bottom-locked echo-integrator channel where data are collected in five 2 m depth layers. Here the lower 0–2 m layer is measured from the backstep and up into the water column. Total observed area backscattering coefficient is 125 [m^2 nmi^{-2}], from which 50 are recorded in the 10 m bottom-locked echo-integrator channel. By using the IDZ correction, and assuming equal density in the non-measured volume and in the neighbouring 2 m depth layer, a correction of $s_A=9$ [m^2 nmi^{-2}], or 7% to the total density is added to the result.

A more difficult example from the coast of Finnmark, North Norway, is seen in Figure 11. This is in shallower water of 85–90 m, where most of the haddock are recorded closer than 4 m to the seabed. A hard and flat seabed enabled the use of 0.0 m backstep, and the echo-integrator depth layers are bottom-locked (Table 2). As much as 38% of the total area back-scattering coefficient was recorded in the 0–1 m off-bottom layer. Using a 1 ms pulse at this depth with no backstep makes the PIZ larger than the ADZ. Basing the correction density on the lower depth layer adds $s_A=87$ [m^2 nmi^{-2}], i.e. 24% of the total recorded density.

In both examples, the algorithm for the bottom recognition system worked properly, isolating the fish echo energy from the bottom echo. However, errors may occur when working on a sloping bottom, or on an uneven, rough bottom. Echoes originating from the bottom, detected on the edges of the beam, from stones, outcrops, or grooves, smaller than the horizontal extent of the beam, may not be strong enough to activate the bottom detector. When the wavefront hits solid bottom, these echoes are interpreted as being above bottom and this causes erroneously high echo-integration results from the bottom depth layer.

An example is shown in Figure 12a where two grooves (a and b) and two small outcrops, or hills (c and d), in the bottom contour at about 250 m depth have created four "spikes" which extend through the backstep line in the 10 m expanded bottom channel of the echo-integrator. The area backscattering coefficient for the demersal fish, including the spikes within the expanded channel for the two nautical mile cells shown, are $s_A=99$ and 676 m^2 nmi^{-2}, respectively. The effect of the spikes is removed by the operator during the scrutinizing procedure using a post-processing system like the BEI-500 (the Bergen Echo-Integrator (Knudsen, 1990)).

Table 1. In Figure 10, an example is shown of the deep water registration of cod and haddock, vertically distributed from the bottom to about 100 m above. A combination of pelagic, surface-referenced, and bottom-locked layers were used. The backstep was 0.5 m. This table summarizes data from the echo-integrator related to Figure 10. Corrections made to these data have assumed equal densities of fish in the deadzone and in the bottom 2 m layer

Date	Time	Log	Lat.	Long.	Station	Frequency
05.05.92	1409 h	5812–5813	72N 22	25E 40	73.1	38 kHz
BDL	Backstep	Pulse	Threshold	Z min.	Z max.	10 log Ψ
− 40 dB	0.5 m	1 ms	− 82.3 dB	246	253	− 21 dB

Layers	s_A[m^2 nmi^{-2}] cod+haddock
Pelagic	
10–50	0
50–100	0
100–150	18
150–200	21
200–250	81
250–300	5
Total pelagic+bottom	125
Bottom	
B8–10	8
B6–8	7
B4–6	7
B2–4	15
B0–2	12
Total in bottom layers (uncorrected)	50
Deadzone correction	9
Total in bottom layers (corrected)	59
Total in pelagic+bottom layers (corrected)	134

A new backstep line drawn by the operator is shown in Figure 12b and is used to recompute the area back-scattering coefficient in the bottom channel for fish echoes only. This gives a reduction of the s_A to 23 and 28, respectively. On this particular bottom, without the post-processing capability, a significant increase in the backstep would have been necessary to prevent such spikes from invalidating the measurement of fish in the bottom channel. Post-processing with manual correction of bottom recognition failures is therefore regarded as an essential procedure when conducting acoustic surveys of demersal and semi-demersal fish.

Discussion

Greater accuracy is possible in acoustic surveys conducted in the 1990s than was previously the case. The introduction of echo-sounders having shorter pulses and narrower beams for improved discrimination between targets, and analysis tools such as the BEI-500 have provided a basis for re-examining echo processes near the seabed. What happens in the volume of water ensonified immediately above the seabed can be very important for quantiative assessment, depending on the fish density and distribution.

We have shown that, when measuring fish close to the bottom, the important equipment factors which determine the IDZ, are transducer beamwidth, pulse duration, and backstep. Even more important, though, is the vertical distribution pattern of fish close to the bottom. If the fish are spread vertically close to the bottom, as was the case for the deep water example shown in Figure 10, the accuracy of the IDZ correction is high. This is because the density gradient towards the bottom could be predicted and the total correction is small. If most of the fish are located very near the ADZ, the accuracy of the IDZ correction is low and the total correction is large. Detailed information on the vertical distribution pattern measured on these surveys are therefore valuable data for evaluation of the estimation bias.

The expressions evaluated here have not considered the effect of sloping bottom, nor the effects of roll and tilt of the acoustic beam relative to the seabed. A full evaluation of the IDZ problem should also include monitoring of these variables, or reducing their effects by, for example, the use of stabilized transducers, or the use of adaptively steered sonar beams to ensure normal incidence on the seabed. Significant improvements in the existing bottom recognition systems may also be possible through the use of phase information

Table 2. These data refer to Figure 11 which shows registrations of haddock close to the bottom in shallow water. All echo-integrator channels, except for one, are bottom-locked. The backstep was 0.00 m. Corrections made to data from the echo-integrator have assumed equal densities of fish in the deadzone and in the bottom 1 m layer

Date	Time	Log	Lat.	Long.	Station	Frequency
14.03.94	0421 h	8775–8776	70N 32	30E 50	149.1	38 kHz
BDL	Backstep	Pulse	Threshold	Z min.	Z max.	10 log Ψ
− 40 dB	0.0 m	1 ms	− 80 dB	89.2	93.3	− 21 dB

Layers	s_A(m^2 nmi^{-2}) haddock
Pelagic	
10–500	369
Total pelagic + bottom	369
Bottom	
B50–100	0
B30–50	0
B20–30	0
B10–20	0
B6–10	7
B4–6	6
B2–4	151
B1–2	66
B0–1	139
Total in bottom layers (uncorrected)	369
Deadzone correction	87
Total in bottom layers (corrected)	456
Total in pelagic + bottom layers (corrected)	456

already available from split-beam transducers and echo-sounders.

For surveys of demersal fish abundance, several considerations have to be taken into account. The proximity of a fish to the bottom is important in determining whether proper echo-integration of the fish echo will occur. Optimum setting of instruments and the algorithms used for bottom recognition are also important.

Direct comparisons between acoustic data and bottom trawl data often show inconsistent density estimates. This may be partly due to ADZ effects, but large scale discrepancies may also be expected because of the avoidance behaviour of fish to noisy vessels. In addition, the differences in catch efficiency of the trawl itself (Godø, 1994), and variable net preformance (Engås, 1994) must be considered. With careful collection and scrutinizing of both data sets, reasonably comparable density estimates have been obtained on fish near the seabed (Sigurdsson, 1993; Ona *et al.*, 1991; Aglen, 1995). This indicates that the use of acoustics in the investigation of absolute bottom trawl efficiency will probably increase in importance.

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The authors wish to thank Mrs Valerie Dixon for deriving Equations (2) and (4), the pulse sampling, and single ping ADZ volumes, respectively. Dr Asgeir Aglen and Dr K. G. Foote are thanked for their helpful contribution to the definition and computation of the IDZ. A very useful and comprehensive review from a referee was appreciated.

References

Aglen, A. 1995. Impact of fish distribution and species composition on the relationship between acoustic and swept area estimates of fish density. ICES Journal of Marine Science, 53: 501–505.

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

Buerkle, U. 1977. Detection of trawling noise by Atlantic cod (*Gadus morhua* L.) Marine Behaviour and Physiology, 4: 233–242.

Engås, A., Soldal, A. V., and Øvredal, J. T. 1991. Avoidance reactions of ultrasonic tagged cod during bottom trawling in shallow water. ICES C.M. 1991/B:41, 9pp.

Engås, A. 1994. The effects of trawl performance and fish behaviour on the catching efficiency of demersal sampling trawls. *In* Marine Fish Behaviour in Capture and Abundance Estimation. Ed. by A. Fernö and S. Olsen. Fishing News Books, Blackwell Scientific Books Ltd, London, pp. 45–65.

Godø, O. R. 1990. Factors affecting accuracy and precision in abundance estimates of gadoids from scientific surveys. Dr. Philos. Thesis. Institute of Fisheries and Marine Biology, University of Bergen, Norway, 169 pp.

Godø, O. R. 1994. Factors affecting the reliability of groundfish abundance estimates from bottom trawl surveys. *In* Marine Fish Behaviour in Capture and Abundance Estimation. Ed. by A. Fernö and S. Olsen. Fishing News Books, Blackwell Scientific Books Ltd, London, pp. 166–195

Godø, O. R. and Wespestad V. G. 1993. Monitoring changes of abundance of gadoids with varying availability to trawl and acoustic surveys. ICES Journal of Marine Science, 50: 39–51.

Hylen, A., Nakken, O., and Sunnanå, K. 1986. The use of acoustic and bottom trawl surveys in the assessment of North-East Arctic cod and haddock stocks. *In* A workshop on comparative biology, assessment and management of gadoids from the North Pacific and Atlantic Oceans. Seattle, Washington, June 1985, Ed. by M. Alton, pp 473–498.

ICES. 1995. Underwater Noise of Research Vessels: Review and Recommendations. Cooperative Research Report No. 209. Ed. by R. B. Mitson, International Council for the Exploration of the Sea, 60 pp.

Karp, W. A. and Walters, G. E. 1994. Survey assessment of semi-pelagic gadoids: The example of walleye pollock (*Theragra chalcogramma*) in the Eastern Bering Sea. Marine Fisheries Review, 56: 8–22.

Knudsen, H. P. 1990. The Bergen Echo Integrator: an introduction. Journal du Conseil International pour l'Exploration de la Mer, 47: 167–174.

Mitson, R. B. 1983. Acoustic Detection and Estimation of Fish near the Seabed and Surface. *FAO Fisheries Technical Reports*, 300: 24–37.

Nunnallee, E. P. 1991. An investigation of the avoidance reactions of Pacific whiting (*Merluccius productus*) to demersal and midwater trawl gear. ICES C.M. 1991/B:5.

Olsen, K. 1979. Observed avoidance behaviour in herring in relation to the passage of an echo survey vessel. ICES C.M. 1979/B:18, 8pp.

Olsen, K. 1990. Fish behaviour and fish sampling. Rapports et Procès-verbaux des Réunions du Conseil International pour l'Exploration de la Mer, 189: 147–158.

Olsen, K. Angell, J., Pettersen, F., and Løvik, A. 1983. Observed fish reactions to a surveying vessel with special reference to herring, cod, capelin and polar fish. *In* Symposium on Fisheries Acoustics, Bergen, Norway. Ed. by O. Nakken and S. C. Venema. *FAO Fisheries Reports*, 300: 131–138.

Ona, E. 1988. Observations of cod reaction to trawling noise. ICES Fisheries Acoustic Science and Technology WG, 20–22 April 1988, Ostend, Belgium.

Ona, E. and Toresen, R. 1988a. Avoidance reactions of herring to a survey vessel, studied by scanning sonar. ICES C.M. 1988/H:46, 8pp.

Ona, E. and Toresen, R. 1988b. Reactions of herring to trawling noise. ICES C.M. 1988/B:36, 4pp.

Ona, E. and Godø, O. R. 1990. Fish reaction to trawling noise: the significance for trawl sampling. Rapports et Procès-verbaux des Réunions du Conseil International pour l'Exploration de la Mer, 189: 159–166.

Ona, E., Pennington, M., and Vølstad, J. H. 1991. Using acoustics to improve the precision in bottom trawl indices of abundance. ICES C.M.1991/D:13, 11pp.

Sigurdsson, T. 1993. Application of acoustic information in bottom trawl surveys. Thesis (Cand. Scient.), Department of Fisheries and Marine Biology, University of Bergen, Norway. 135 pp.