

Accounting for scattering directivity and fish behaviour in multibeam-echosounder surveys

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Multibeam echosounders can improve the efficiency and the precision of acoustic-survey estimates by providing greater sampling volumes than single-beam echosounders. For a multibeam echosounder, the target strength of fish can vary with its pitch, roll, and yaw. Here, normalized, acoustic backscatter patterns from fish schools are modelled by beam-incidence angle, $0-180^\circ$, considering the scattering-directivity patterns of each fish. Variation of pitch angle causes a decrease in the mean and an increase in the variance of the backscatter in the vertical beam, but has no effect on the backscatter in the outer beams. Conversely, variation of the yaw causes a decrease in the mean and an increase in the variance of the backscatter in only the outer beams. Because the fish-scattering model predicts different backscatter at dorsal- vs. lateral-incidence angles, backscatter did vary with roll angle. In the hypothetical case of fish avoiding a vessel, the backscatter decreases strongly the outer beams. The results of the model were compared with multibeam measurements of fish schools. In general, the measured mean backscatter vs. beam-incidence angle was nearly uniform. The methods described here provide an approach to accounting for scattering directivity and fish behaviour in multibeam-echosounder surveys.

Keywords: acoustic scattering, directivity, echo integration, fish, fish-scattering model, incidence angle, multibeam echosounder, target strength, volume backscatter.

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Introduction

Fish densities are typically estimated using echosounder measurements of volume-backscattering strength (S_v) of aggregations encountered directly below the survey vessel. The fish density within a sample volume is estimated by the quotient of the total backscattered energy and the energy backscattered from an individual fish. The fish target strength (TS) is dependent on its size, as well as its orientation relative to the incident sound. The accuracy of the method could be improved if the TS is well characterized, and the incidence angles and any reactions of the fish to the survey vessel are characterized *in situ* (Olsen *et al.*, 1983; Misund, 1990; Gerlotto and Fréon, 1992; Gerlotto *et al.*, 2004). The precision of the method could also be improved if the sampling volume could be increased. Researchers have employed “search-light” echosounders to map epipelagic fish schools with large swaths in the near-horizontal plane, extending observations many hundreds of metres from the vessel to reduce measurement uncertainty (Smith, 1970; Hewitt, *et al.*, 1976). To make more quantitative measurements of school dimension, shape, density, biomass, and behaviour, researchers have also experimented with the use of multibeam echosounders orientated horizontally and vertically (Misund *et al.*, 1995; Gerlotto *et al.*, 1999), and are experimenting with calibrated multibeam echosounders (Cochrane *et al.*, 2003; Melvin *et al.*, 2003; Foote *et al.*, 2005). The next step in this evolution is to account for the sound-scattering directivity and the behaviour of fish schools.

The directionality of sound scattering from fish has been characterized by many experiments and modelling studies. Love (1969, 1971) measured the lateral and dorsal TS. Based on measurements of several species of tethered fish, Love (1977) developed a generalized model for estimating the TS of fish with swimbladders at any angle of incidence. Other scattering models represent fish as simple geometric objects with assumed or measured material properties (Stanton, 1988; Clay, 1991, 1992; Reeder and Stanton, 2004). Fish TS is more exactly modelled using a Kirchhoff-ray-mode (KRM) approximation of scattering from a detailed swimbladder shape (Foote, 1985). Clay and Horne (1994) developed a KRM model for the TS of Atlantic cod (*Gadus morhua*). KRM models of TS at any angle of incidence were developed for pilchard (*Sardinops ocellatus*) by Jech and Horne (2002), and for pollock (*Theragra chalcogramma*) and capelin (*Mallotus villosus*) by Towler *et al.* (2003).

Scattering models show that backscattering is a function of the orientation of the fish relative to the acoustic beam and that it varies greatly with the acoustic incidence angle. In the case of a vertically orientated echosounder, it is important to consider the pitch angle of the fish (Clay and Horne, 1994; Horne and Clay, 1998; Jech and Horne, 2002). Yaw is considered inconsequential, and the effects of roll on backscattering can often be ignored because dorsal and lateral TS are often similar. However, in the case of multibeam echosounders, it is important to account for the pitch, yaw, and sometimes even the roll of the fish, relative

to each acoustic beam. These angles of incidence may change if fish react to the survey vessel.

Changes in school shape or location suggest a vertical response or vertical and horizontal responses to vessels by fish (Gerlotto and Fréon, 1992; Soria *et al.*, 1996). A few studies have measured avoidance responses of fish to trawling vessels (Engås *et al.*, 1998; Handegard *et al.*, 2003). Røstad *et al.* (2006) documented the attraction of fish to stationary or drifting vessels, whereby fish avoided underway vessels in a channel and sought shelter beneath a drifting or anchored vessel nearby. Variations in acoustic backscatter have also been observed when trawling vs. transiting (Barange and Hampton, 1994; De Robertis and Wilson, 2006). Misund (1990) and Gerlotto *et al.* (2004) used multibeam sonar to document and evaluate vessel avoidance by fish based on the distribution of schools by distance from vessel, and school length (along-track) to width (across-track) measurements. Gerlotto and Fréon (1992) measured the response of sardine (*Sardinella aurita*) schools to a passing vessel and found increases in school depth for all schools, with a mean depth change of 5 m for the upper limit of a school, and less for its lower limit. The results of Gerlotto and Fréon (1992) suggest that fish schools dive and compress vertically in response to a vessel, supporting the method of avoidance modelled by Olsen *et al.* (1983). Gerlotto *et al.* (2004) observed vertical avoidance, but did not detect horizontal avoidance by anchovy (*Engraulis ringens*) or common sardine (*Strangomera bentincki*). They found a uniform number of sardine and anchovy schools at any distance from the vessel, suggesting no horizontal avoidance. Vertical avoidance was observed for fish only very close to (<10 m) the vessel. Olsen *et al.* (1983) suggested that the avoidance response by fish depends on the sound pressure gradient induced by an approaching vessel, and therefore that different vessels would induce different responses because of vessel-noise characteristics.

In summary, all the models and observations of responses by fish suggest that behaviour associated with avoidance affects fish TS and, therefore, echo-integration results. We have the opportunity to detect fish avoidance of vessels by two effects: altered fish orientations and altered spatial distributions of schools. We assume in the simplest case that the fish swim horizontally before disturbance by a vessel, and that they change orientation in response to the vessel disturbance by swimming away vertically or horizontally, or both, or even swimming towards the vessel path before swimming away (Soria *et al.*, 1996). Fish orientations may return to pre-avoidance orientations (Olsen *et al.*, 1983), but the spatial distribution of fish should be indicative of avoidance (Soria *et al.*, 1996; Gerlotto *et al.*, 2004). If the fish actively dive or swim horizontally away from the vessel during the instance of insonification by a multibeam echosounder, then the volume backscatter (S_v) by beam-incidence angle should also be indicative of the response. The model developed for this study allows us to explore various scenarios by predicting the directivity of backscatter from fish schools observed with a multibeam echosounder.

Concern about the variation in TS with fish orientation, and its potential effect on S_v measured from the multiple beams of a multibeam echosounder, provided the incentive for this study. We investigate the effects of fish orientation on the normalized scattering response from arbitrary numbers of fish measured by any beam. The variation in scattering is estimated for each beam by changing the orientation of fish within a group. Responses of fish to a transiting survey vessel are simulated for hypothetical behavioural scenarios. In addition, measurements of S_v from fish

schools spanning multiple beam-incidence angles in multibeam-echosounder data are compared with the model predictions.

Methods

A simple model of the scattering-directivity pattern (SDP) for a generic fish with a swimbladder was derived from the KRM TS model for walleye pollock (*T. chalcogramma*), and described by Jech and Horne (2002) and Towler *et al.* (2003). Several SDPs in the literature have relatively simple shapes that can be represented by a surface prescribed by simpler geometric objects. This model created surfaces prescribed by ellipses that represented the approximate shapes and the principal variations of two published SDPs with normalized values. The asymmetrical SDP in this model is based on the SDP of a walleye pollock from Towler *et al.* (2003). The symmetrical SDP in this model is meant to represent scattering from fish such as capelin (*M. villosus*), sardine, or anchovy, particularly at lower frequencies. The three-dimensional model object comprised 20 concentric ellipses distributed along and normal to the head–tail axis (x -axis) of a fish (Figure 1). It is a smooth mimic of the original SDP described by Jech and Horne (2002) and Towler *et al.* (2003), suppressing the high-frequency peaks and nulls. The resulting model represents fish TS at any angle of incidence. On the basis of the model, this SDP is asymmetrical along the head–tail axis of the fish, and maximum scattering is on side-incidence, in the plane perpendicular to the head–tail axis, i.e. at $x = 0$.

The model predicts TS at any incidence angle, normalized using the maximum extent of the model surface in side or dorsal aspect. To convert the normalized to realistic values required estimation of maximum TS. For example, if it is known that the maximum side-aspect TS for the fish is -40 dB, then according to this model the maximum dorsal-aspect TS in that same x – z plane is -55.6 dB; maximum head-aspect TS is -75.5 dB, and maximum tail-aspect TS is -100 dB. Maximum side-aspect TS is along the ellipse in the y – z plane where $x = 0$. Maximum dorsal-aspect TS is in a plane where $x < 0$, so the maximum dorsal-aspect TS is encountered when the model fish tilts forward with a pitch equal to approximately -6° , accounting for an upward-tilting swimbladder. Tilted swimbladders are common, and their effect on scattering is evident in the results of Foote (1985) and Clay and Horne (1994), and the models of Jech and Horne (2002) and Towler *et al.* (2003).

To simulate multibeam-echosounder measurements of fish, TS was cast as a function of both the beam-incidence angle (θ_b), and the fish orientation:

$$TS = TS(\theta_b, \theta_p, \theta_R, \theta_Y), \quad (1)$$

where behavioural responses include pitching (θ_p , rotation about the side-to-side axis), rolling (θ_R , rotation about the head–tail axis), and yawing (θ_Y , rotation about the vertical axis) or just one of these modes. Cartesian angles were used to simulate rotations about each of the three coordinate-axes independently. The SDP was first transformed according to specified θ_p , θ_R , and θ_Y , then solved for TS in the direction of every sampled θ_b . This was repeated for an arbitrary number of fish that represent the density of the modelled fish school. A modelled SDP for fish orientated $\theta_Y = 20^\circ$, and $\theta_p = \theta_R = 0^\circ$, was sampled at 15° intervals for $-90^\circ \leq \theta_b \leq 90^\circ$ (Figure 2b). It was assumed that all fish are measured in the centre of each beam, or equivalently that the

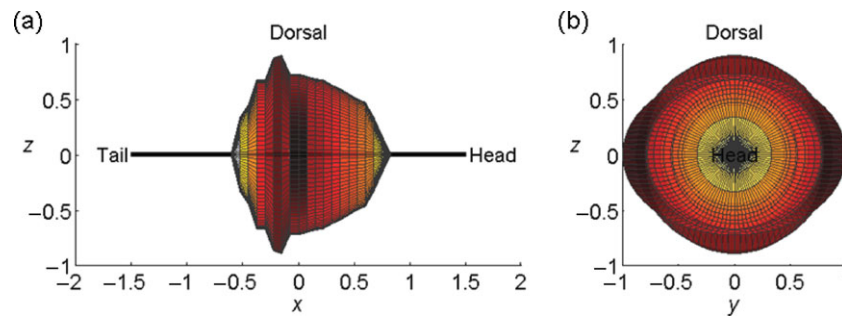


Figure 1. Lateral and head-on views of the generic model of a SDP from a fish with a swimbladder.

acoustic beams had unity gain, and that attenuation and pulse duration had negligible effect or were otherwise taken into account.

The S_v is estimated for each beam of a multibeam echosounder resulting from a group of fish with this SDP, and the orientations listed below:

- (i) fish yaw angles parallel (0°) and normal (90°) to the vessel path;
- (ii) fish pitch, roll, and yaw angles each varied independently, from 0° to 90° for asymmetrical and symmetrical SDPs;
- (iii) highly variable fish pitch, roll, and yaw angles and different school densities; and
- (iv) orientations associated with hypothetical avoidance behaviour characterized by different variations about moderate-to-large pitch and yaw angles.

An arbitrary density of fish was selected for each simulation, with a minimum of 20 fish simulated to produce samples that are approximately normally distributed, and with equal variance per

beam. For each simulated group, the orientation of each fish was randomly generated according to a specified distribution of pitch, roll, and yaw angles about a mean orientation. TS was estimated according to the value of the model SDP closest to the intercepting simulated beam-incidence angle. S_v was estimated as the sum of TS, then normalized (values transformed to range from zero to one). The model results report the mean normalized $S_v \pm 1$ s.d.

Finally, *in situ* data from multibeam echosounders with fish schools were examined and compared with the model results. In one case, avoidance only close to the vessel was modelled and compared with *in situ* multibeam echosounder data from fish schools appearing to exhibit vertical avoidance.

Multibeam echosounder data were collected from a Kongsberg Mesotech Ltd SM2000 90-kHz 90° head (SM20-90) that was vertically orientated and hull-mounted on the NOAA FSV "Oscar Dyson", and a SM2000 200-kHz 180° head (SM20-180) pole-mounted aboard the NOAA FRV "David Starr Jordan". The pole-mounted sonar head was located 3.1 m below the water surface and tilted 30° to the port side, insonifying from the

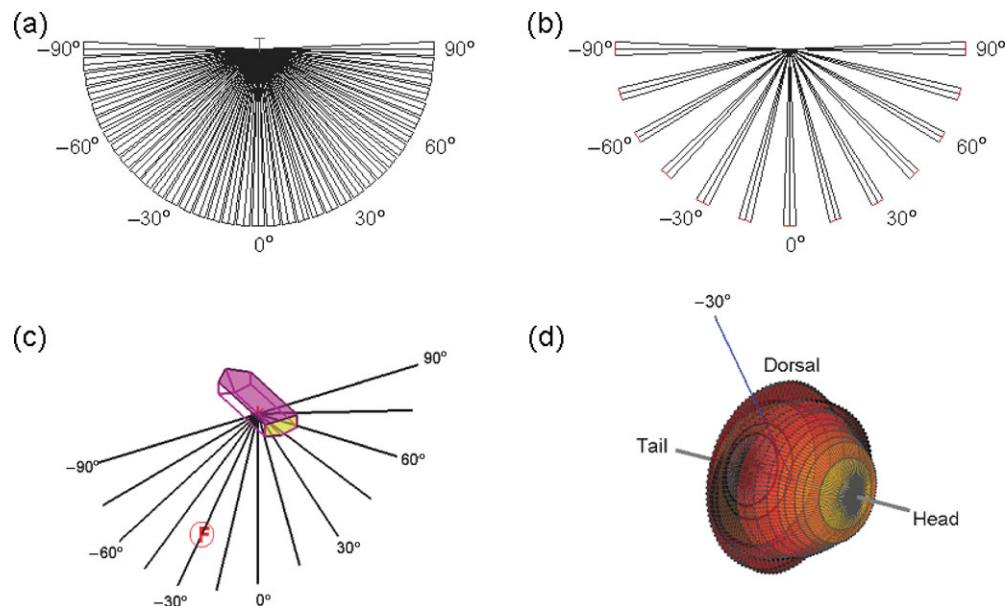


Figure 2. (a) A swath from a multibeam-echosounder with a 180° swath width, with (b) beams sampled every 15° , as in this model, and (c) as projected from a ship with the multibeam hull-mounted and vertically orientated, and with a fish (circled F) located in the -30° beam. The shaded surface (d) represents the modelled fish and the echosounder beam as it intersects the SDP surface if the beam passes through the centre of the fish.

port-side sea surface to $\sim 60^\circ$ to the starboard side of the ship. SM20 processors were used for control and data logging for both systems. The multibeam echosounders were operated continuously during a survey covering the US west coast from San Diego, CA, to Seattle, WA, during April and May 2006. Each multibeam sampled a 200-m range with high power. The SM20-90 used a pulse duration of 385 μs , and the SM20-180 one of 425 μs . Fish schools in the multibeam data were identified visually and delineated manually to extract S_v by beam-incidence-angle data from the school. A simple delineation process was implemented where a bounding line was defined according to visual interpretation of the swath echogram. Best effort was made to draw the bounding line at a fixed distance from the apparent edge of the school. As long as the delineation bounds are drawn consistently, this method is effective for extracting S_v data to examine patterns of S_v across swaths.

Results

The model predicts higher side-aspect TS than dorsal-aspect TS for the plane normal to the x -axis and intersecting the centre of the model fish. Therefore, if all fish are horizontal and aligned in the direction of the ship's track, the normalized S_v is a maximum of 1.0 in the horizontal beams with side-incidence insonification, compared with 0.72 in the vertical beam with dorsal-aspect insonification (Figure 3a). When all fish in the school are orientated across the ship's track (Figure 3b), the echosounder senses the head-aspect in the starboard-most (90°) beam, the dorsal aspect in the vertical beam (0°), and the tail aspect in the port-most (-90°) beam.

An SDP with higher side- than dorsal-incidence TS causes lower values of S_v in the near-vertical beams and a higher S_v in the near-horizontal beams (Figure 4a). In contrast, an SDP that is symmetrical about the head-tail axis, i.e. symmetrical fore-aft, and is also centred at the origin of the fish, S_v does not vary by beam-incidence angle when all fish are aligned parallel to the vessel track (Figure 4b) and changes in roll angle have no effect on S_v . In addition, the S_v is lower from port beams than starboard beams when all fish with asymmetrical SDPs are aligned across the track (and heads are pointed to port) because of the difference between head and tail incidence (Figure 4c). However, the S_v by beam-incidence-angle curve is symmetrical from tail- to dorsal-to head-incidence, when all fish with symmetrical SDPs are aligned across the track (Figure 4d).

The results from modelling S_v by beam-incidence angle for 40 fish in each beam, where the roll (θ_R), pitch (θ_P), and yaw (θ_Y) angles of the group of fish were varied independently while holding the other two orientation angles constant, are shown in Figure 5. The three columns show S_v by beam-incidence angle for fish θ_R , θ_P , and θ_Y equal to 0° , 30° , 60° , and 90° , $\pm 10^\circ$ in each case. The 10° of deviation of θ_R for the 40 fish had little effect on the S_v by beam-incidence angle for any mean θ_R value. Changes in the mean θ_R caused a shift in the location of the maximum and minimum values by beam-incidence angle, such that a 30° θ_R shifted the relative minimum (dorsal incidence) S_v to the -30° beam. At a mean θ_R of 90° , the side of the fish is imaged by the vertical beam, and dorsal and ventral aspects are imaged by the outer beams. The result is high vertical-beam S_v , and low outer-beam S_v when the fish are effectively swimming on their sides.

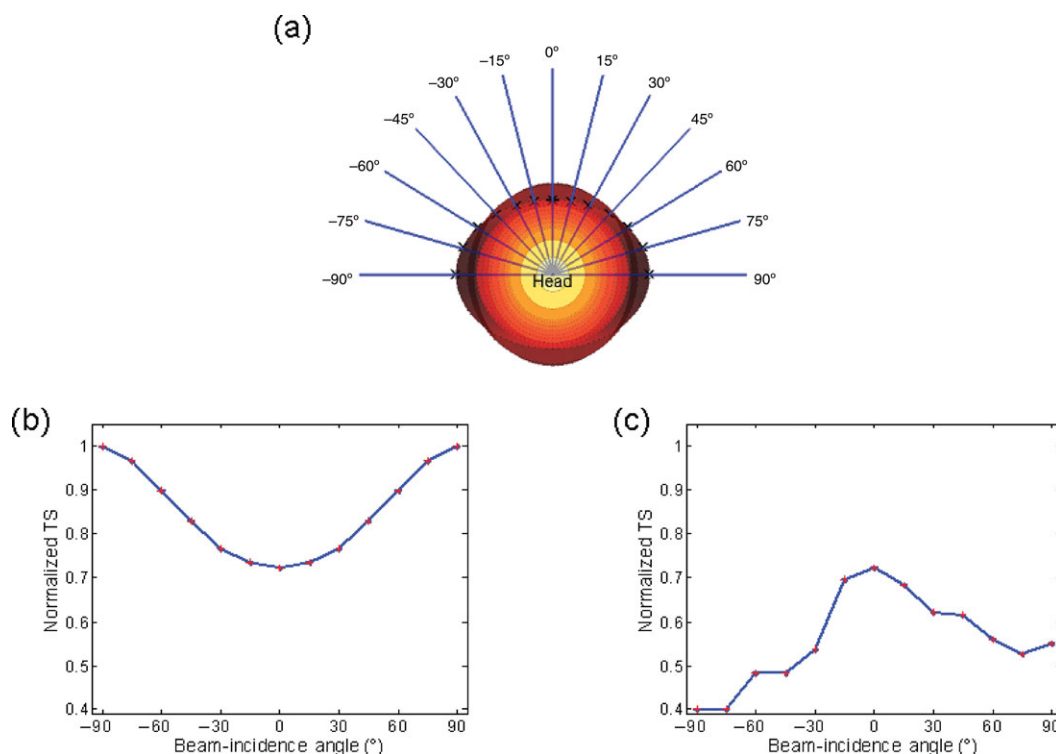


Figure 3. Normalized backscatter for (a) the asymmetrical SDP as modelled from the intersection of each beam of a 180° multibeam and the surface of the SDP, (b) all fish orientated along-track, and therefore the long axis of the fish is normal to the multibeam echosounder beams, and (c) all fish orientated across-track, pointed to the left relative to the vessel track.

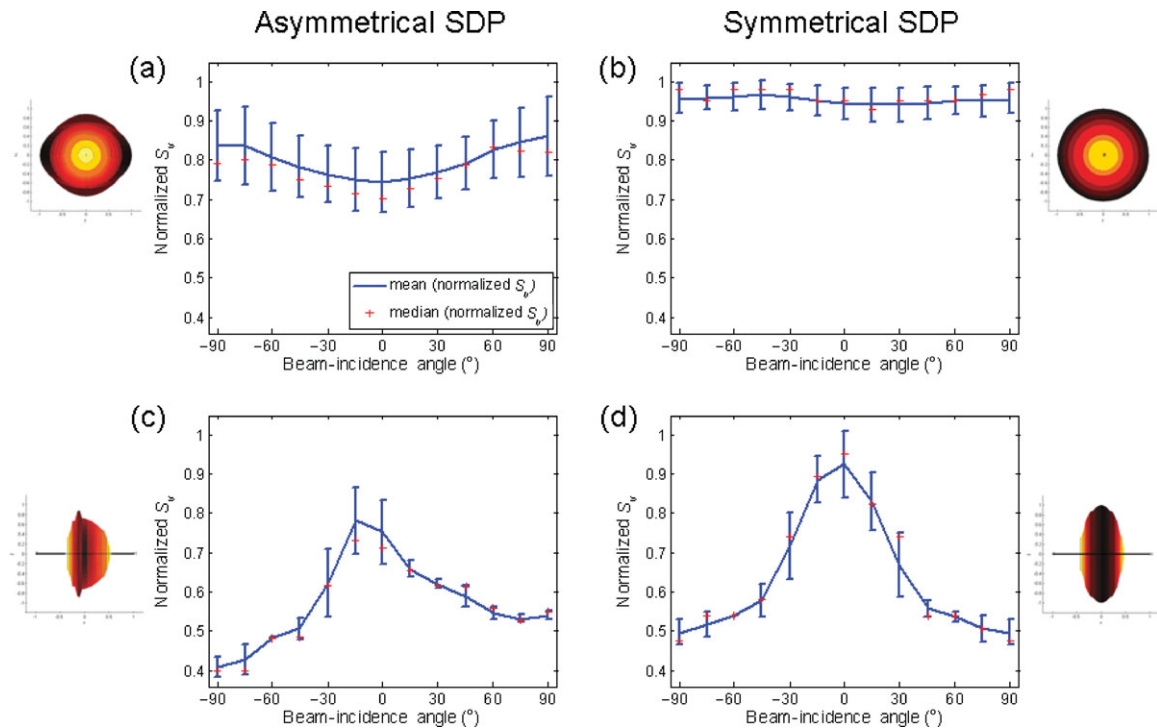


Figure 4. Differences between S_v by beam-incidence angle for symmetrical and asymmetrical SDPs. In total, the figure represents 20 fish with (a) asymmetrical and (b) symmetrical SDPs orientated “along-track” with $\theta_p = \theta_R = \theta_Y = 0^\circ \pm \sim 10^\circ$; and 20 fish with (c) asymmetrical and (d) symmetrical SDPs orientated “across-track” with $\theta_Y = 90^\circ \pm \sim 10^\circ$, and $\theta_p = \theta_R = 0^\circ \pm \sim 10^\circ$.

The highest variation in S_v from deviations in pitch occurred for a mean θ_p of 0° . This is because the peak TS of the SDP used by the model is encountered at a θ_p of approximately -6° . As θ_p is allowed to vary within 10° from 0° , the peak value can be encountered. For mean θ_p angles from 0° to 90° , the shape of the S_v response by beam-incidence angle was consistent: lower

vertical-beam S_v than outer-beam S_v . Change in fish θ_p had no effect on S_v from the outermost beams ($\pm 90^\circ$) (Figure 5). Note, however, that few multibeam echosounders are capable of producing a 180° swath. Hence, unless the echosounder head is tilted, those aspects will not be sensed by typical multibeam echosounders.

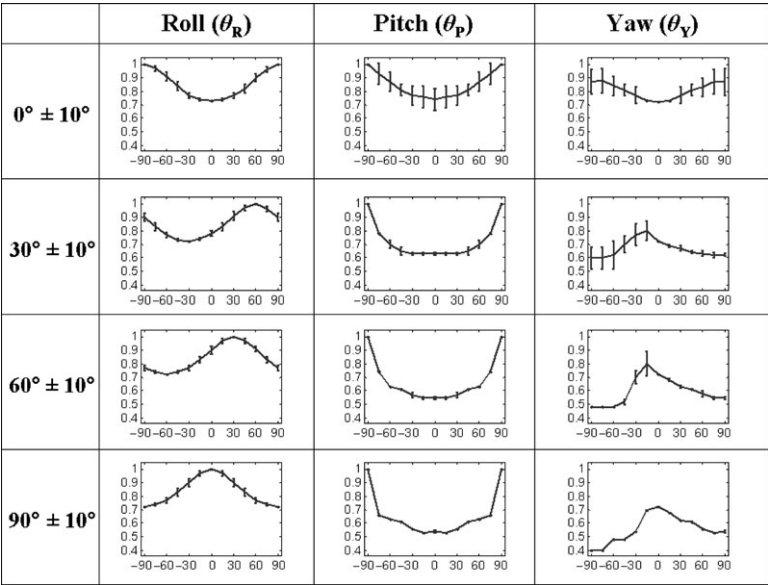


Figure 5. Normalized backscatter from 40 fish at each beam-incidence angle, predicted for scenarios where each orientation angle (θ_p , θ_R , and θ_Y) of the fish was varied from 0° to 90° while holding the other two orientation angles constant, and also allowing for variation ($\pm 10^\circ$) about the mean orientation angle.

Varying θ_Y 10° from a mean of 0° diminished the mean S_v from the outer-beam angles, but had no effect on vertical-beam S_v . For the vertical beam only, variation in fish θ_Y had no effect on S_v . S_v from the vertical beam is constant for any value of θ_Y in only this simple model case. When the mean θ_Y of a fish is zero, the mean S_v from the outer beams is greater than the mean S_v from the vertical beam. However, for a mean θ_Y of just 30° (and higher), the S_v in the outer beams was less than the vertical-beam S_v . For a mean θ_Y of 90° , the S_v response by beam-incidence angle represents a fore-aft profile across the SDP sampled at arbitrary beam-angle intervals (Figure 5), whereas for a mean θ_Y of 0° , the response by beam-incidence angle resembled a side-to-dorsal-to-side aspect profile across the SDP.

The low variance of S_v (equal to or very nearly zero) for most beam-incidence angles at high values of θ_Y is an artefact of the model. The model selects the S_v value for any fish incidence from a discrete set of points representing a SDP, and the shape of the SDP is relatively smooth for those incidence angles.

For a scenario where 100 fish per beam were orientated with near-zero θ_R , θ_P , and θ_Y , but with high variation on each of those angles (s.d. $>45^\circ$ for θ_R , θ_P , and θ_Y), the S_v by beam-incidence-angle response pattern resembled the shape of the response when θ_R , θ_P , and θ_Y and their standard deviations were all equal to zero. In that case, the vertical-beam S_v (dorsal-aspect) was lower than the outer-beam (side-aspect) S_v for non-rotated fish. However, mean values of S_v for all beam-incidence angles were lower than the uniform-alignment case when fish-orientation angles were highly variable.

The model can predict normalized backscatter by beam-incidence angle for a group of fish diving from and exhibiting horizontal avoidance to the vessel, or each reaction separately. Here, a scenario is presented where the fish in a school exhibit strong sideways avoidance, swimming away from the vessel path at θ_Y angles of $45^\circ \pm 10^\circ$ to port and starboard, and are also diving slightly with a θ_P of $-15^\circ \pm 10^\circ$ (Figure 6a). This modelled scenario resulted in high backscatter at the vertical aspect, and steeply decreasing S_v with increasing beam angle until reaching nearly constant minimum S_v for beam-incidence angles $\geq 45^\circ$ (Figure 6a). For comparison, we model a scenario where the fish

in a school exhibit strong vertical avoidance and are insonified by the multibeam while diving with a θ_P angle of $-45^\circ \pm 10^\circ$ (Figure 6b). This resulted in the backscatter at near vertical being reduced by approximately half, but the backscatter from the outer beams ($\pm 90^\circ$) was unaffected (Figure 6b).

The case of moderate sideways avoidance is modelled here by 40 fish per beam having a θ_Y of 30° away from the ship to both sides. When the standard deviation of each of the fish-orientation angles is low ($\pm 5^\circ$), the S_v from beam-incidence angles within 30° of the vertical was greater than the S_v from beam-incidence angles $\geq 45^\circ$ (Figure 7a). However, when the variation of fish orientations is greater, such that the standard deviations of θ_R , θ_P , and θ_Y are equal to 20° , then the same avoidance reaction was not detectable because the S_v by beam-incidence angle was uniform with wide confidence intervals (Figure 7b).

When fish exhibit a diving reaction very close to the vessel, as reported by Gerlotto *et al.* (2004), there should be a decrease in S_v in the beams close to the vertical. This response will only occur during the instance of diving (Figure 8a; solid line). After the fish dive and are repositioned, the S_v by beam-incidence-angle curve is not indicative of avoidance (Figure 8a; dashed line). Model results for the case of vertical avoidance occurring only very close to the vessel, such that the diving fish are only insonified by beams $<15^\circ$ off vertical, show the depressed S_v value in the vertical beam (Figure 8b). For all beam-incidence angles $>15^\circ$, the S_v by beam-incidence-angle curve in this figure is similar to the case of 40 fish (with asymmetrical SDPs) per beam orientated with mean θ_R , θ_P , and θ_Y nearly equal to zero ($\pm 10^\circ$).

In situ backscatter from fish schools imaged by multibeam echosounders deployed during acoustic-trawl surveys were analysed by beam-incidence angle for comparison with model predictions. Data from four pings with fish schools from the SM20-90 and one ping from the SM20-180 are plotted in Figure 9. Swath images are shown to the left and the mean backscatter (S_v), averaged in linear domain, ± 1 s.d., by beam-incidence angle is shown to the right for each of the pings. Figures 9a–9d show data from the SM20-90, and Figure 9e shows data from the SM20-180.

The mean backscatter (S_v) response pattern by beam-incidence angle varied for each fish school examined. S_v by beam-incidence

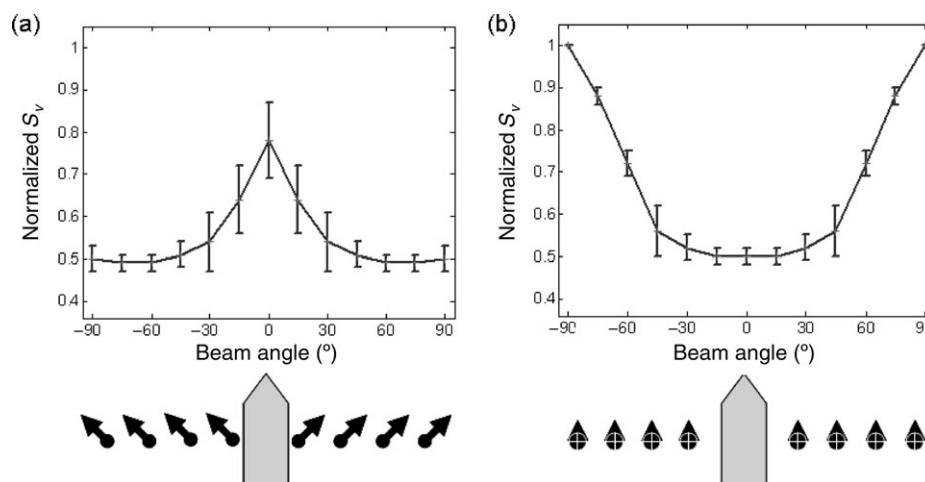


Figure 6. Normalized backscatter predicted for (a) a scenario with 40 fish exhibiting a hypothetical behavioural response of strong sideways avoidance (θ_Y equal to $44.7^\circ \pm 5.8^\circ$ away from the vessel to both sides) and diving (with a θ_P equal to $-15.4^\circ \pm 5.9^\circ$) from the approaching vessel; and (b) a scenario with 40 fish exhibiting a strong vertical response reaction to the vessel, diving at a θ_P of $-45.3^\circ \pm 6.1^\circ$.

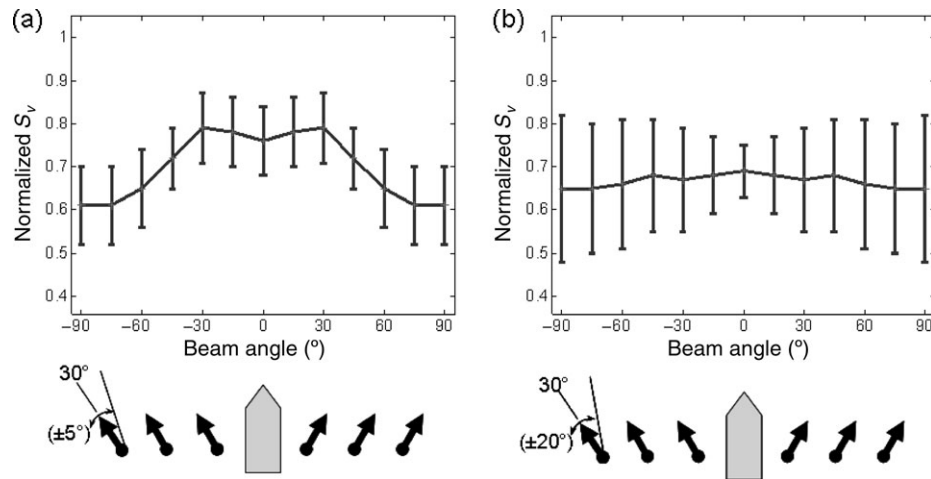


Figure 7. Difference in effect on S_v by beam-incidence angle for the case of moderate horizontal avoidance caused by (a) a small variation in fish-orientation angle (s.d. of θ_p , θ_R , and $\theta_Y \approx \pm 5^\circ$), and (b) a large variation in fish-orientation angle (s.d. of θ_p , θ_R , and $\theta_Y \approx \pm 20^\circ$).

angle for one of the sardine schools (Figure 9b) and for the unidentified school that spanned nearly 100° (Figure 9e) was relatively constant for all beam-incidence angles. Figures 9a and 9c show pings from two sections of a single sardine school, for which the S_v by beam-incidence angle shape was consistent, with lower S_v at the vertical and at beams near -45° , and higher S_v at beam-incidence angles near -20° . Two of the sardine schools spanned $50\text{--}60^\circ$ (Figure 9a–c), and one of the sardine schools spanned only $\sim 20^\circ$ (Figure 9d). The S_v by beam-incidence angle for the smaller sardine school tended to be higher nearer the vertical, and decreased with increasing beam-incidence angle (Figure 9d).

A school of anchovy insonified by a SM20-180, tilted 30° to the port side, appeared to exhibit vertical avoidance related to the spatial distribution of the school from the vessel-based measurement (Figure 10a). In that case, the model result for the diving reaction close to the vessel was consistent with the observed data (Figure 10b). Examination of the echogram within a small range near the echosounder head (Figure 10c) indicated that the part of the school directly beneath the sonar head had low S_v values compared with high S_v values to both sides of the vertical beams (Figure 10b). In addition, the depth of the school varied with the distance from the vessel, from nearly 13 m below the surface near

the vessel and sonar head to within 2 or 3 m, and perhaps even at the surface, at a range of 40–50 m from the vessel (Figure 10d).

Discussion

The results from the model in this study demonstrate the effects and emphasize the importance of fish orientations on acoustic backscatter from multibeam echosounders. Fish orientations clearly influence the mean value and the variance of the backscatter by beam angle. Backscatter from outer beams is highly dependent on yaw angles, whereas changes in yaw do not change backscatter from a vertically orientated, vertical beam. Fish pitch angles (θ_p) are most influential to backscatter from vertical and near-vertical beams, whereas changes in θ_p do not affect backscatter from outer beams. Changes in roll angle (θ_R) can influence backscatter by beam-incidence angle, but are not expected to be significant because fish TS tends to vary least with changes in θ_R for most fish.

The model in this study mimicked a generally smooth, but asymmetrical SDP. The results from a simpler or symmetrical model SDP should be similar for most scenarios, except for the case where only fish yaw angle (θ_Y) varies. For fish with symmetrical SDPs, variation in θ_Y will have symmetrical effects on the backscatter from off-vertical beams.

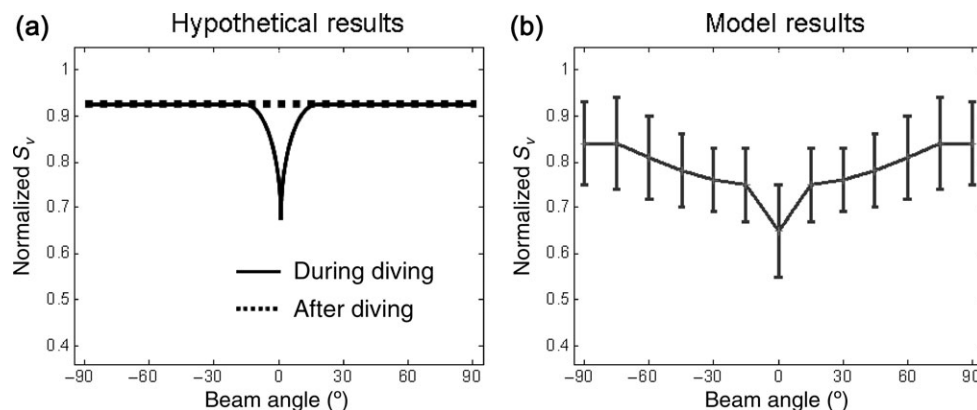


Figure 8. (a) Hypothetical and (b) model results of diving avoidance very close to a vessel.

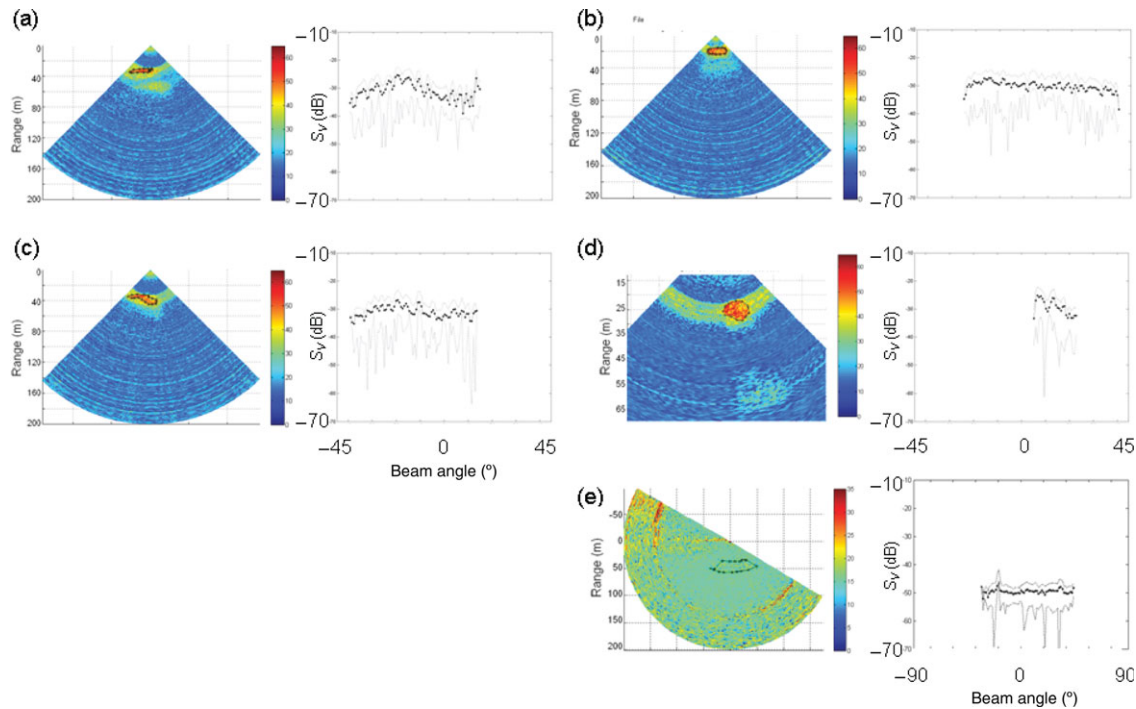


Figure 9. Swath images from a SM2000/SM20 90-kHz 90° (a–d), and 200-kHz 180° (e), and volume backscatter (S_V ; dB) by beam-incidence angle from fish schools; shown are mean $S_V \pm 1$ s.d. Schools in (a)–(d) are believed to be sardine (*Sardinops sagax*) and the organisms in the school in (e) are unidentified.

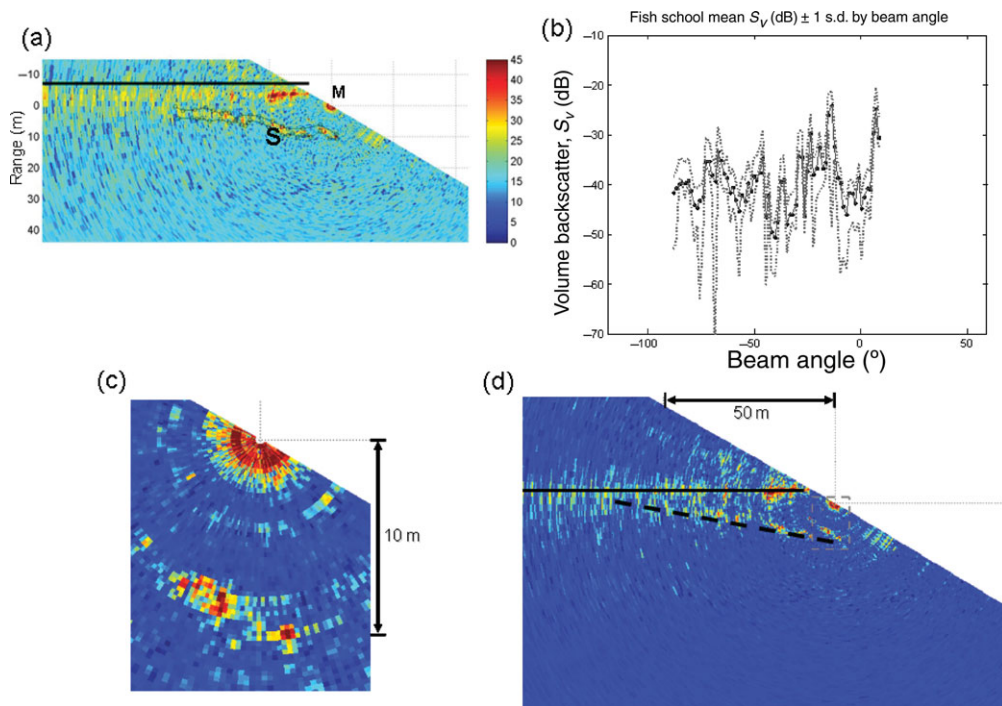


Figure 10. Vertical avoidance observed in *in situ* multibeam-echosounder data. (a) A school of anchovy (S) appearing to exhibit vertical avoidance of the vessel was imaged by the tilted, 180° multibeam echosounder (M); the sea surface is marked by the solid, horizontal line. (b) Measured volume backscatter (S_V ; dB) by beam-incidence angle within the school. (c) Close-up of that part of the school directly beneath the sonar head and the vessel. (d) Variation in the depth of the school (dashed line) with distance from the vessel; the grey dashed-line box indicates the area shown in (c).

This study simulated simple scenarios where fish in schools were orientated with various distributions of θ_R , θ_D , and θ_Y . One scenario was modelled that simulated realistic avoidance of a vessel by fish that included a strong sideways response and a simultaneous diving response. If a particular response is anticipated, the general pattern of backscatter by beam-incidence angle can be predicted to a relative extent by examining the individual effects of various values of θ_R , θ_D , and θ_Y shown in Figure 5. Model formulations can be developed for any hypothetical or real scenario. However, in the real world, it is necessary to know either school density or the distribution of fish orientations to estimate the other quantity with any accuracy. Fortunately, fish density can be estimated using data from vertically orientated, split-beam echosounders, and such information can be used to constrain the problem and facilitate interpretation of multibeam-backscatter data.

If fish avoid an oncoming survey vessel by a predominantly horizontal reaction, swimming away to either side, then that reaction should be evident in the backscatter response by beam-incidence angle measured by a multibeam echosounder. That response pattern would be greater backscatter at vertical and lower backscatter in the outer beams, as shown by the model results from this study. The major complication to interpreting the backscatter by beam-incidence angle, in terms of fish orientation, is the possibility that the density of fish throughout a school is non-homogeneous. If all fish in a school that spans the entire swath respond to the vessel with a similar behaviour, then the backscatter by beam-incidence-angle curve can be indicative of the behaviour. Consider the results of the model for the strong horizontal and vertical avoidance scenarios. Ubiquitous, strong horizontal avoidance should be evident as a backscatter by beam-incidence-angle curve that is high at vertical, and low at off-vertical, whereas strong vertical avoidance will result in a backscatter by beam-incidence-angle curve that is low at vertical and high in the outermost beams for a 180° swath. Yet, backscatter from the diving response would be low for all beams of a

multibeam echosounder with a 90° swath. Hence, the effect of a vertical reaction might not be discernible in data from a multibeam echosounder with a narrow swath. A strong horizontal reaction by all fish in a school should be detectable with most multibeam echosounders, because the backscatter diminishes by nearly half within 45° of either side of vertical in this scenario.

For a 90°-swath multibeam echosounder orientated vertically, it is unlikely that the effect of 30° yaw from horizontal avoidance would be detectable. The beams of the vertical echosounder would be limited to a region where S_v was practically uniform (Figure 11a). However, if the multibeam-echosounder head was tilted, as done by Soria *et al.* (1996, 2003), Gerlotto *et al.* (1999, 2004), and in this study, then any differences in S_v between vertical and horizontal beams attributable to fish orientations should be evident, as shown in Figure 11b.

As the fish disperse at increasing angles, the S_v by beam-incidence angle becomes more uniform, despite the mean orientation of the fish being indicative of a strong behavioural reaction (Figure 7). A symmetrical SDP can produce a uniform S_v by beam-incidence angle when all fish are aligned with the vessel path. Avoidance involving fish diving has an opposite effect from avoidance involving yawing. Diving decreases S_v in near-vertical beams, but the outer-beam S_v is practically unaffected. Yawing, caused by fish swimming away to either side of the vessel, decreases outer-beam S_v , but the near-vertical-beam S_v is practically unaffected. Consistent and coherent reactions to a vessel throughout a school improve the chances that the behavioural response will be detectable in multibeam data.

The model of the SDP used in this study is relatively smooth. At higher frequencies, SPDs typically become more pronounced and dynamic (Jech and Horne, 2002; Towler *et al.*, 2003). In the high-frequency case, a slight change in fish orientation can elicit a large variation in the response. It seems likely that a complex high-frequency SDP of a real fish combined with slight differences in orientation within a group of fish would diminish the general response level, increase response variance, and homogenize

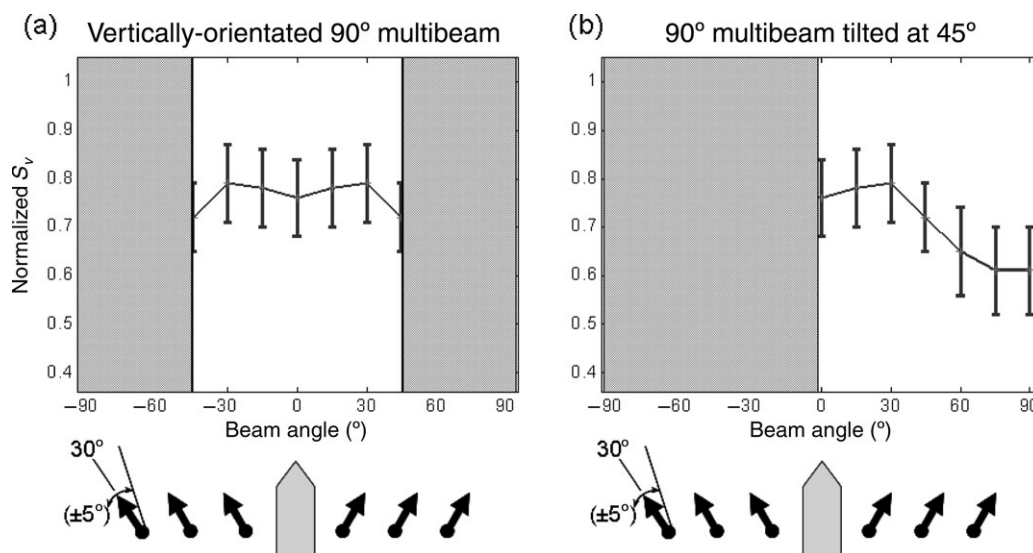


Figure 11. Differences in S_v by beam-incidence angle induced by horizontal avoidance, or other fish behaviour, may be undetectable using a vertically mounted multibeam, but are clear in a 90° swath of a tilted multibeam. (a) S_v is nearly uniform from -45° to 45° beams of a vertically orientated multibeam; (b) detectable differences exist between values of S_v from beams $<30^\circ$ and from beams $>60^\circ$ of the multibeam tilted at a 45° angle.

response across a multibeam swath. The working assumption must be that the low backscatter regions, or local minima, occupy small angular spans relative to the high backscatter peaks in the SDP, and therefore that the low points will be encountered less frequently when fish orientations vary slightly. These local minima in the SDP will contribute to the variance of backscatter, but not significantly affect the mean backscatter for a particular incidence angle.

The orientation of fish in schools is unknown, and a single ping from a narrowband source will not resolve a pattern. Variations in the orientation of fish can overwhelm the signal, such that returns from any beam can represent the TS for a large range of incidence angles, even from a monospecific aggregation. Consequently, unless fish orientation can be measured *in situ*, estimates of the numbers of fish and the fish biomass from backscatter will contain uncertainty that cannot be partitioned into attributes (orientations or sizes). However, if we can measure or estimate the orientation, then multibeam echosounder data will be useful for echo-integration methodologies.

Orientation angle and fish size are key factors affecting TS measurements. If we know the size distribution of the fish, then perhaps we can attribute the residual variation in the TS to fish orientations using a method such as that described by Coombs and Barr (2004), expanded to the case of multibeam-echosounder estimation of TS. Conversely, if fish orientations are somehow known, the measured directivity pattern can provide information about fish size (Jaffe, 2006).

Patterns of S_v by beam-incidence angle observed *in situ* did not seem to represent the hypothetical behavioural response modelled for strong horizontal or vertical avoidance. Previous studies by Olsen *et al.* (1983), Gerlotto and Fréon (1992), and Gerlotto *et al.* (2004) suggest vessel-dependent and limited reactions by fish. Data from multibeam echosounders on two vessels were examined for this study. One vessel is ~52 m long with a draft of 3.8 m, and is relatively noisy, whereas the other is larger (64 m), but designed to meet ICES sound-level emission standards (Mitson, 1995). One case was examined where fish appeared to be exhibiting avoidance of the loud vessel, and the S_v by beam-incidence angle near the vessel was consistent with hypothetical and model results of reduced S_v very close to the disturbance. However, the variation of S_v by beam-incidence angle for this case could be explained by either fish diving or a reduced number of fish in those beams. The SM20-180 was attached to a long pole, extended ~3 m below the surface, and it is conceivable that such a structure moving past would induce a response from the fish. The spatial distribution of the fish showed clear indication of vertical avoidance near the vessel and the pole-mounted echosounder. However, the pattern of S_v by beam-incidence angle could not be interpreted as a result of fish orientations alone; fish density could have been a factor. Alternatively, the avoidance *r* may have occurred before the arrival of the echosounder, possibly because of its radiated noise, so negating a detectable response. The spatial distribution of the fish was, however, the characteristic of an avoidance response.

Interpretations of S_v by beam-incidence angle must also account for the density of fish in the school, because variations in density also influence the mean values of S_v . Hence, if density is not constant across the school, then changes in S_v by beam-incidence angle cannot be attributed solely to differences in fish orientation. The measurement of fish density by single- or split-beam echosounders typically represents a section along the ship's track through a school, and may be biased by

unknown fish orientation. Therefore, even with along-track estimates of density, assumptions of homogeneity would be required for density to be estimated in the orthogonal direction.

The effects of fish orientation on S_v imply that unless we know or somehow measure fish-orientation angles during surveys, then the accuracy of the estimates of abundance and biomass depend on how well real conditions meet model assumptions. The model and survey data of this study suggest that exploring methods of measuring fish orientations *in situ*, by other methods (e.g. broadband acoustic techniques), should be a priority for future work if multibeam sonar is to become a quantitative acoustic tool for estimating fish biomass (Martin Traykovski *et al.*, 1998; Stanton *et al.*, 2003). A method to infer fish orientations using broadband signals, such as that described by Stanton *et al.* (2003), could facilitate the use of multibeam data for echo-integration estimates of fish biomass, but the length of the fish must be known, and the distribution of lengths must be narrow for the method to be accurate. A combination of net or optical sampling of fish lengths combined with a broadband, multibeam sonar (e.g. a Simrad ME70) may provide a satisfactory solution.

Conclusions

It is important to know the distributions of fish orientations in shoals to estimate accurately fish abundance or biomass from multibeam-echosounder data. However, data from multibeam-echosounders containing sardine and anchovy schools suggest that the orientations of fish may be variable enough to induce approximately uniform S_v by beam-incidence angle. If this is the case, a constant offset value is sufficient to compensate the multibeam S_v from any beam-incidence angle for the effect of fish orientations, and the data from multibeam echosounders can be directly used for echo integration.

Our model results suggest that certain behavioural responses to a vessel by fish should be detectable in the S_v by the beam-incidence-angle signature from a multibeam echosounder. Horizontal and vertical avoidance reactions should have distinct S_v by beam-incidence-angle curves that allow such behaviours to be identified using multibeam data. Tilted multibeam echosounders may have an advantage over vertical-mounted multibeam systems for detecting behavioural responses of fish in schools because of the differential effects of fish orientations on the S_v values from vertical and horizontal beams. Even if fish do not exhibit a strong reaction to the vessel, or if they exhibit a reaction only near the vessel (Gerlotto *et al.*, 2004), model results suggest that there will be differences in S_v by beam-incidence angle, depending on the yaw angle of the fish relative to the echosounder. Unfortunately, even in the case of strong avoidance that would otherwise be detectable, if the dispersion is $\pm 20^\circ$ about the mean pitch or yaw angle of the fish, the S_v by beam-incidence angle can be nearly uniform.

Fish reactions to a vessel may include changes in location relative to the vessel, as well as changes in orientation relative to their natural state. To detect such changes in orientation, the fish must be insonified during the reaction. If insonification occurs subsequent to a reactionary change in position relative to the vessel, when, maybe, the fish orientations have returned to normal, then the S_v by beam-incidence angle may not be indicative of the reaction, despite evidence of it in the spatial distribution of the fish. In summary, model and *in situ* data reveal that several scenarios of fish behaviour, and the circumstances of vessel-school encounters, can produce patterns of S_v by beam-incidence angle

that are effectively uniform and practically indistinguishable. However, some behaviours of fish in response to a vessel should be apparent in the pattern, or the coefficient of variation, of S_v by beam angle or a combination of both features.

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