

Avoidance behaviour in cod (*Gadus morhua*) to a bottom-trawling vessel

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Abstract

The reaction of fish induced by a trawling vessel was measured using the Bergen Acoustic Buoy. It is a free-floating buoy with a split beam echo sounder system. Individual fish trajectories were obtained by target tracking methods, and average swimming velocities as a function of depth and time before and after passage of the vessel was calculated. A measure for the change in behaviour was applied, showing a significant response during and after propeller passage. The change in horizontal displacement speed is significant at all depths, while the change in vertical displacement velocity is significant at all but one layer of depth. The horizontal reaction seems to occur a bit later than the diving reaction. After the main response, a slightly higher mean horizontal displacement speed was observed for the deepest layers. This indicates a change in the fish state after being exposed to the vessel/gear.

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1. Introduction

When assessing the abundance of cod and haddock in the Barents Sea, the bottom trawl survey and the acoustic measurements produce two independent estimates. In order to combine these estimates, and arrive at an absolute abundance estimate of the stock, the fishing efficiency of the trawl and the reaction of the fish relative to the vessel and gear must be known (Ona and Godø, 1990; Aglen et al., 1999). This paper presents a quantitative methodology for measuring individual response of fish to a trawling vessel, as opposed to changes in density. The method is also capable of quantifying the change in behaviour as the vessel passes.

Fish avoidance of a vessel has been reported both in acoustic surveys (Olsen, 1971; Olsen et al., 1983; Olsen, 1990), and in trawl surveys (Ona, 1988; Ona and Godø, 1990; Nunnallee, 1991). It has been reported that cod react as early as 200 m in front of the vessel propeller (Ona, 1988), and that this reaction occurs between the surface and 200 m depth. Buerkle (1977) reported that Atlantic Cod is able to detect a trawling vessel at a range of at least 2.5 km.

In swept area indices, the effective fishing height of the trawl is taken to be constant between hauls. But as shown by Aglen et al. (1999), this is not always the case. In response to vessel and gear, fish in the pelagic zone may swim towards the bottom. The bottom trawl will thus catch fish that were originally higher in the water column than the height of the trawl opening. Vertical herding might be dependent on the size of the fish and their vertical distribution patterns. Effective fishing heights of 30 m for large fish and 4 m for small fish were used for estimating the amount of fish unavailable to the bottom trawl in Aglen et al. (1999).

This paper shows that by using a free-floating buoy with a split beam echo sounder system, the actual response of single individuals can be measured, not only responses measured as changes in water column S_A values. The method used here also makes it possible to measure the mean displacement of individual fish in both the horizontal and vertical direction, and to compare the two. To our knowledge, this has not been done before, and it is an important step towards estimating the effective fishing volume of the bottom trawl.

2. Materials and method

The experiment was conducted with “R/V G.O. Sars” off the coast of Finnmark (72°N 25°E) from 12 to

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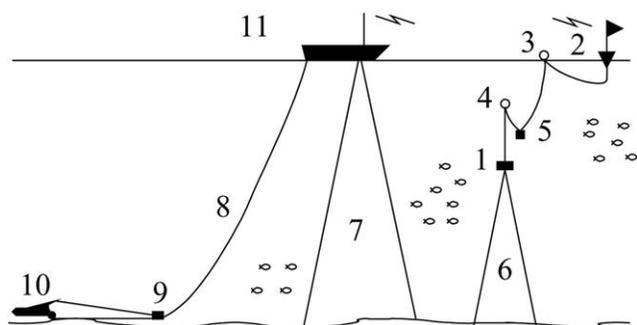


Fig. 1. Overview of the experimental set-up. Note that the figure is schematic and that the scale is not real. Numbers (1) to (6) designate the acoustic buoy. (1) is the transducer with the compass, (2) is the buoy with PC, GPS, Simrad EK60 echo sounder and communication systems. (3 and 4) are the floats and (5) is the weight for stabilising the transducer movement. (6) is the acoustic beam of the EK60 buoy echo sounder. (7) is the beam of the on board mounted echo sounder (operated only at 18 kHz), (8) is the trawl warps, (9) is the trawl doors, (10) is the trawl and (11) is the "R/V G.O. Sars".

21 March 2001. The data were collected using the Bergen Acoustic Buoy (Godø et al., 1999). The buoy is free floating and contains a Simrad EK60 split beam echo sounder, a computer, various communication instruments, GPS and a battery package. Communication to the vessel is maintained through a spread spectrum radio connection with a data transfer rate of 115.2 KB s. This allows for continuous update of echogram, compass data, buoy GPS position and remote control. The transducer is mounted in a stainless steel rig, which is equipped with a compass for continuous recording of transducer direction. The rig is balanced with floaters and weights to stabilise it during operation, and to reduce the

effect of surface waves, cf. Fig. 1. The depth of the transducer can be regulated by the placement of the floaters and counterweights on the cables. The transducer depth varied between 37 and 47 m with a median of 44 m.

The change in fish behaviour was measured by passing the buoy 16 times during bottom trawling (Campelen, 1800). The buoy was passed as close as possible. The distance measured by the GPS between the centreline of the vessel and the buoy GPS varied from 48 to 53 m with a median of 53 m. The buoy drift was monitored by the buoy GPS system and the trawl position was monitored by the Simrad ITI system. This information was used to ensure that the trawl passed within the beam of the buoy. The horizontal distance from the trawl to the buoy, measured by the ITI system and the buoy GPS, varied from 42 to 257 m with a median of 45 m. Two times the buoy was passed with a pelagic trawl. These hauls were used only to identify the species distribution higher up in the water column. Table 1 gives an overview of the catches from the trawl hauls.

2.1. Target tracking

The EK60's single target detection algorithm was used to obtain single targets of fish within the echo beam. As shown by Brede et al. (1990), it is possible to connect the detected single targets to tracks. A target-tracking algorithm similar to the Wintracker algorithm (Ona and Hansen, 1991; Ona, 1994) was used, i.e. a track gate box around the last detection in the track is used to search for the next candidate for the track. The size of this box is given in Table 2. In addition, if the track contains more than five pings, a regression is ap-

Table 1

Bottom trawl catches in weight (kg) by species. Tows conducted during daytime are denoted by D, and tows conducted during night time by N

Date	Time	Day/Night	Catch weight (kg)				Total
			Cod	Haddock	Saithe	Redfish	
14-March-2002	02:50	N	376	14	3	4	398
	07:57 ^a	D	350	22	78	24	475
	14:04	D	468	35	212	12	727
	16:43	N	535	40	10	5	590
	19:06 ^b	N	0	0	0	0	0
	20:50	N	119	8	0	6	132
15-March-2002	22:10	N	58	0	2	3	63
	00:30	N	103	12	14	8	137
	02:24	N	116	22	21	2	162
	19:45	N	150	32	17	4	204
16-March-2002	21:20	N	101	21	20	5	147
	19:03 ^b	N	0	0	0	0	0
	21:10 ^b	N	0	0	0	0	0
17-March-2002	23:36 ^a	N	1050	22	3	2	1077
	10:37 ^b	D	0	0	0	0	0
	18:07	N	247	26	5	4	282
17-March-2002	21:53	N	328	15	59	7	408
	22:12	N	229	23	23	18	293
Total			4494	316	567	112	5489
Proportion			82%	6%	10%	2%	100%

^a Pelagic stations (no buoy measurements).

^b Stations where the trawl net was open.

Table 2
Parameters used in the target detection algorithm and the target-tracking algorithm

Description	Value
<i>EK60 settings</i>	
Min. echo length	0.8
Max. echo length	1.8
Max. phase dev.	8.0
Max. gain comp.	6.0
<i>Target tracking parameters</i>	
Max. ping skip	5 # ping
Max. depth difference	0.5 (m)
Max. XY difference	15 (m)
Min. regression limit	5 # ping
Max. regression limit	10 # ping

plied up to the last 10 pings of the track. This is used to predict the position of the next detection. Then the prediction will be the centre of the track gate instead of the last ping in the track. Five successive missing pings are allowed in the tracking process. When an assignment conflict occurs, the track is terminated. Only tracks of six pings and more are used in the analysis.

The warps produce signals that could easily be mistaken as fish echoes. To avoid any interference with the analysis of fish behaviour, registrations that could be interpreted as warps were manually removed in every passing.

After initial tracking, a constant velocity track,

$$\hat{\mathbf{x}}(t_k) = \mathbf{a} + \mathbf{v}(t_k - t_1)$$

is fitted. Here $\hat{\mathbf{x}}(t_k)$ is the estimated three-dimensional position in the echo beam at time t_k and \mathbf{v} and \mathbf{a} are parameters to be estimated. The fitting is by least squares, i.e. by minimising

$$SS = \sum_k \|\tilde{\mathbf{x}}(t_k) - \hat{\mathbf{x}}(t_k)\|^2$$

where $\tilde{\mathbf{x}}(t_k)$ is the initial track from the tracking process and $\|\cdot\|$ is the Euclidean norm with $\|\mathbf{x}\|^2 = \sum_{i=1}^3 x_i^2$ for $\mathbf{x} = [x_1, x_2, x_3]$. An example is given in Fig. 2.

The estimated velocity, $\hat{\mathbf{v}}$, is called the displacement velocity. This may be different from the swimming velocity if the fish swims in a curved line, or if the current varies in the water column. The mean depth, the mean time and the estimated constant velocity for each track were combined into a dataset containing all tracks from all passings.

2.2. Behavioural indicators

The estimated displacement velocities are binned into groups referred to as running mean (RM) windows, cf. Fig. 3. We let j be the index for the depth bin and i for the time bin. The binning is based on the mean depth and mean time for each track. Inside each RM window the mean horizontal displacement speed, $H_{i,j}$, and the mean vertical displacement velocity, $V_{i,j}$, are calculated with standard error. The vertical components of each $\hat{\mathbf{v}}$ for each track inside the RM window

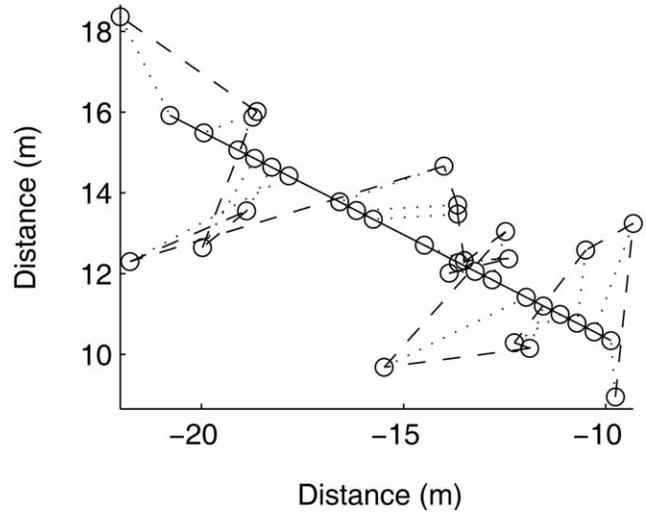


Fig. 2. The dashed line is the measured track, $\tilde{\mathbf{x}}(t_k)$, and the straight line is the mean displacement vector, $\hat{\mathbf{x}}(t_k)$. The distance between each data point, the dotted line, is minimised in a least square sense. The figure shows the projection on the xy -plane.

are used to calculate $V_{i,j}$, and the absolute values of the horizontal components are used to calculate $H_{i,j}$. Positive vertical axis in the coordinate system is pointing from the bottom to the surface, and diving is, therefore, negative. Note that $H_{i,j}$ is not a velocity since it has no direction.

2.3. Statistical analysis

Since the RM windows have identical time steps, $H_{i,j}$ and $V_{i,j}$ at each depth j comprise a time series, $\{y_i\}$. The response in terms of $H_{i,j}$ and $V_{i,j}$ seems to start during vessel passing, rise to a maximum and then fall off again, cf. Fig. 4. A second order polynomial in time could model such an effect, but could not detect any non-symmetric effects, i.e. a steeper incline or decline. Therefore, a third order polynomial was chosen. The polynomial is fitted to parts of the time series, from t_0 to t_1 , where t_0 is the initial time point of the polynomial fitting and t_1 is the end point, cf. Fig. 4. Outside this interval, the fitted curve, \hat{y} , cf. Eq. (1), is set to \bar{y}_0 , where \bar{y}_0 is the mean of the time series where the fish is assumed to be

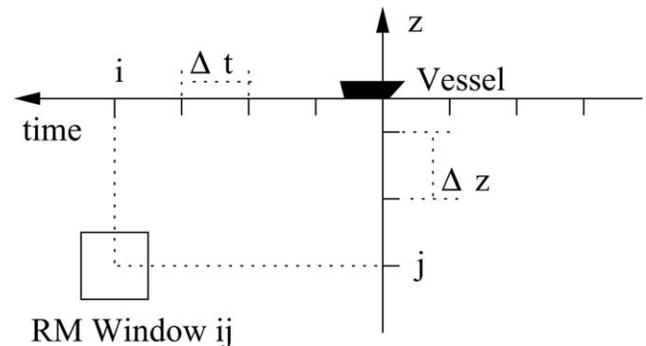


Fig. 3. The behavioural indicators are calculated within each RM window. The size of the RM window is set to $\Delta z = 50$ m and $\Delta t = 60$ s. At 3 knots, 60 s corresponds to 90 m. Note that negative time is before vessel passing.

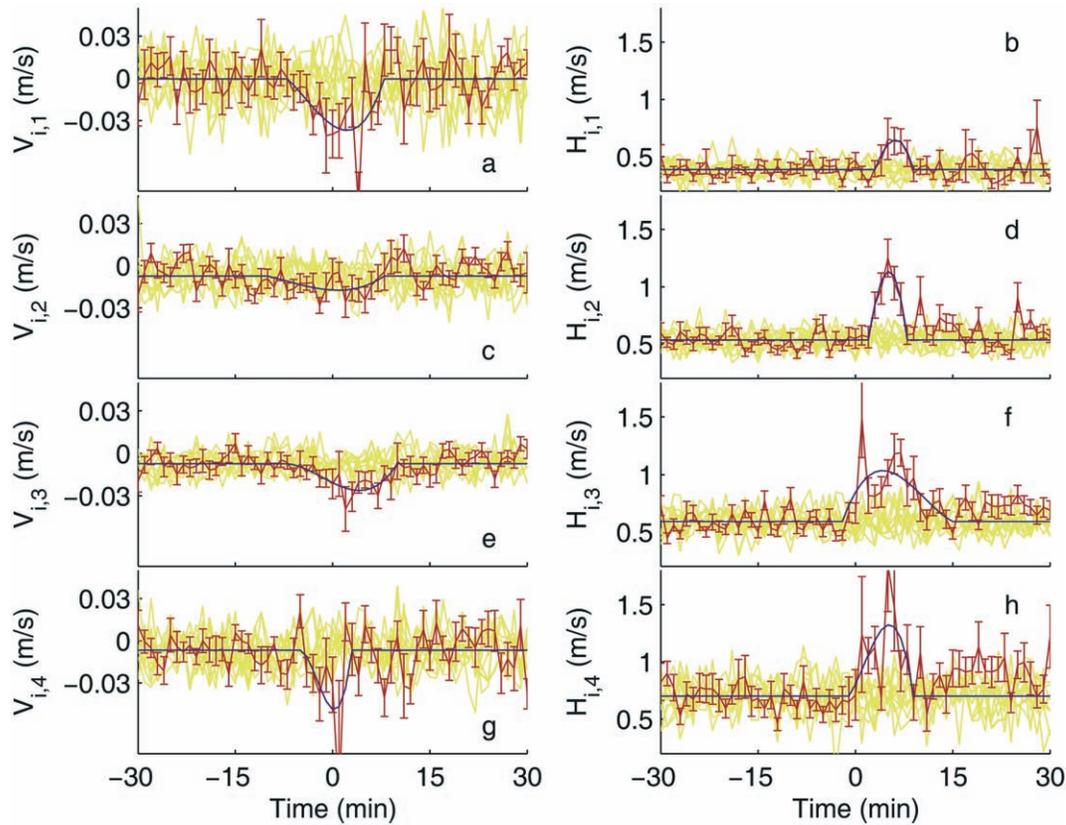


Fig. 4. Yellow curves show 10 realisations of the simulated series under $\{y_i^*\}$, red curves show the time series $\{y_i\}$ plotted with standard error and blue curves show the fitted line, $\{\hat{y}_i\}$, for each time series. The first panel column shows the mean vertical displacement velocity, $H_{i,j}$, and the second panel column show horizontal displacement speed, $V_{i,j}$. Panels (a) and (b) show depths from -75 to -125 m, panels (c) and (d) from -125 to -175 m, panels (e) and (f) from -175 to -225 m and panels (g) and (h) depths from -225 to -275 m. Negative time is before vessel passing, and positive time is after vessel passing (transducer).

undisturbed, i.e. from the start of the series until 5 min before vessel passing, so that

$$\hat{y}(t) = \begin{cases} \sum_{m=0}^3 a_m t^m & t \in [t_0, t_1] \\ \bar{y}_0 & t \notin [t_0, t_1] \end{cases} \quad (1)$$

In addition, the polynomial is forced to have only one maximum, and \hat{y} is forced to be continuous, thus leaving three or four parameters to be estimated. All combinations of t_0 and t_1 , such that $t_0 < t_1$, are tried, and the combination with the lowest square error is chosen. As an indicator for reaction, the maximum or the minimum value for the fitted curve,

$$y_{\text{ext}} = \begin{cases} \min(\hat{y}), & \text{for the time series based on } V_{i,j} \\ \max(\hat{y}), & \text{for the time series based on } H_{i,j} \end{cases}$$

is used. Since we would like to test for a diving reaction, the minimum value is used for series based on $V_{i,j}$.

Under the null hypothesis, H_0 , of no response, we expect that $y_{\text{ext}} = \bar{y}_0$. We assume no dependence of autocorrelation type in the time series under H_0 . The standard error of each behavioural indicator in each RM window gives an estimate of the precision of the behavioural indicator. This information is used to simulate the time series under H_0 . Independent

bootstrap type samples, $\{y_i^*\}$, are drawn according to $y_i^* : N(\bar{y}_0, s_p)$, where p is drawn from $1, \dots, n$. Here n is the length of the undisturbed time series and s_p is the standard error for the p th value of the time series. Standard errors for autocorrelation estimates under H_0 are obtained from the simulated time series. This is compared to autocorrelation estimates for the observed time series. No indication of dependence is found in the undisturbed part of the time series. This supports our assumption of independence in the time series under H_0 .

The time series are simulated 5000 times, and a distribution for y_{ext} under H_0 is obtained for both behavioural indicators for all bins of depth. One-sided confidence intervals, cf. Table 3, are obtained by taking the empirical percentiles from this distribution, with the level of $\alpha=0.05$. If y_{ext} for the original non-simulated data is located outside this confidence interval, it means that a significant velocity change has taken place.

After being exposed to the vessel and gear, the fish may be in another state, i.e. higher alertness. This is investigated by testing the difference in the mean for the behavioural indicators, between the undisturbed situation and the situation after the main response. To simplify, we have used an ordinary t -test even though this is not quite correct in view of the variable standard error from one RM window to another.

Table 3

The results from the analysis where H/V is the behavioural indicator, depth is the depth range for the RM window, t_0 is the start time of the polynomial, t_{ext} is the time where the polynomial has its maximal value, t_1 is the time for the end point of the polynomial, SS is the sum of squares for the fitted line and y_{ext} is the max/min point of the polynomial. Conf. is the confidence interval for y_{ext} under H_0

H/V	Depth (m)	t_0 (s)	t_{ext}	t_1	SS	y_{ext}	Conf. $\alpha = 0.05$	Significant
$V_{i,1}$	[-75 to -125]	-7.0	2.2	8.0	0.0137	-0.0370	[-0.035, 1)	Y
$V_{i,2}$	[-125 to -175]	-10.0	0.8	8.0	0.0046	-0.0174	[-0.029, 1)	N
$V_{i,3}$	[-175 to -225]	-7.0	4.2	10.0	0.0025	-0.0263	[-0.025, 1)	Y
$V_{i,4}$	[-225 to -275]	-3.0	0.3	2.0	0.0162	-0.0671	[-0.034, 1)	Y
$H_{i,1}$	[-75 to -125]	3.0	6.2	9.0	0.4007	0.648	(-1, 0.5530]	Y
$H_{i,2}$	[-125 to -175]	2.0	5.2	8.0	0.6600	1.139	(-1, 0.7251]	Y
$H_{i,3}$	[-175 to -225]	-2.0	4.2	15.0	1.1551	1.035	(-1, 0.8269]	Y
$H_{i,4}$	[-225 to -275]	-1.0	5.3	9.0	2.5361	1.326	(-1, 1.0159]	Y

3. Results

The trawl catches consisted of cod (*Gadus morhua*), haddock (*Melanogrammus aeglefinus*), saithe (*Pollachius virens*) and redfish (*Sebastes*). Cod dominated the catches at all times, cf. Table 1. Throughout the sampling period, the catches varied considerably in weight, especially for cod, but no significant trend over the experimental period was found. The number of trawl stations during daytime was too few to make any conclusion about diel differences.

By trawling at 3 knots the trawl will, at these depths, arrive 8–10 min after the vessel passing. The vessel passing, $t = 0$, is when the vessel mounted transducer passes the buoy.

The time series, $\{y_i\}$, the fitted curves, $\{\hat{y}_i\}$ and a sample of simulated series under $\{y_i^*\}$, are given in Fig. 4. The fish reacts to the gear/vessel both by diving and by horizontal movements. The diving, particularly in the upper channels of depths, seems to start earlier than the horizontal reaction and the horizontal reaction seems to be closer to the warps, cf. Table 3 columns 2–5 and Fig. 4. By comparing columns 7 and 8 of Table 3, it is seen that the change in $H_{i,j}$ for each j is significant in all layers of depth, and the change in $V_{i,j}$ for each j is significant in all but one channel of depth. Moreover, the change in $H_{i,j}$ seems to be more pronounced than in $V_{i,j}$. The number of registrations is lower in the upper depth channels.

The change in $H_{i,j}$ for each j between the undisturbed situation and the situation after the “main response” is significant for some of the depths, cf. Table 4. This is also evident by inspecting Fig. 4 f,h. There seems to be no such effect for the diving velocity.

4. Discussion

The target-tracking algorithm connects the single targets from the EK60’s single target detection algorithm. However, there may be cases where it fails. If fish dive tilted downwards, or swim fast, some echoes may be lost, and the target will not be tracked as one single individual. However, the maximum vertical movement (0.5 m s^{-1} at a ping rate at 1 s) and the maximum horizontal movement (15 m s^{-1} at ping rate at 1 s) is set well above the detected vertical and horizontal movement (i.e. 0.06 and 1.32 m s^{-1}). Missing pings are also allowed in the algorithm, cf. Table 2. If the fish density is too high, the fish will not be resolved into single targets by the EK60’s single target detection algorithm. If the behaviour is different at these densities, this behaviour will not be detected. If the target-tracking algorithm fails to connect two parts of a track, the data will not be independent, i.e. one individual will count as two. The buoy transducer is not fixed, and cyclic movement in the transducer may lead to errors in the tracking process. By fitting a constant velocity line to the tracks, and by avoiding short tracks, this problem will be reduced. If one would like to analyse more detailed fish behaviour, this problem needs to be addressed. Improvements of the tracking algorithm may include a filter to estimate the transducer tilt and roll and methods to take into account the measurement error (work in progress).

The observed change in $H_{i,j}$ seems to occur closer to the warps than the change in $V_{i,j}$, at least in the upper layers of depth, cf. Fig. 4. It seems to be a stronger diving response to the vessel/propeller, and a stronger horizontal movement towards the warps. The warps are believed to produce a low frequency sound with a maximum intensity at $\approx 7 \text{ Hz}$ (unpub-

Table 4

Comparing the horizontal displacement speeds from the undisturbed situation with the swimming speeds after the main response. Significantly higher speeds were found at depths from -175 to -275 using a t -test. Estimation of the sample variance is based on both groups (pooled). No significant difference was found for the vertical velocity

Depth (m)	Method	Var.	DF	t -value	$\text{Pr} > t $	Significant
[75–125]	Pooled	Equal	40	-0.80	0.4278	N
[125–175]	Pooled	Equal	40	-1.73	0.0914	N
[175–225]	Pooled	Equal	40	-3.99	0.0003	Y
[225–275]	Pooled	Equal	40	-5.62	<0.0001	Y

lished data), and the fish may react to low frequency sound (Sand and Karlsen, 1986).

The higher $H_{i,j}$ after the main response indicates that the fish are more alert after being stimulated by the vessel and gear. In future experiments, the time series should be extended to assess when the null situation is restored. Even though measures have been taken to reduce the effect of transducer tilt and roll, transducer movement due to turbulence from the vessel could also explain this effect. It is, therefore, important to improve the method to filter out the transducer tilt/roll effect.

Fish may respond to several stimuli from the vessel/gear (Wardle, 1993). These stimuli could for instance be the noise at different frequencies measured at different depths, visually detectable stimuli, etc. If the fish reacts to the visual stimuli from the warps, the distance to the warp, corrected for light levels, could be correlated with the change in behaviour. The reaction could also be correlated to the different noise levels at different frequencies. This may tell whether the fish reacts to the visual stimuli or noise stimuli, and from which source these stimuli originate.

When more data is obtained, the binning of the displacement velocities for each track could be extended to three spatial dimensions instead of time and depth only, resulting in a three dimensional field for the displacement velocity. The positioning of the track in relation to the vessel could be measured with GPS data from the buoy and the vessel. This velocity field could be used in a model to predict the distribution of fish at any given time, starting from a fixed position in time and space. This could give us some indication of the fishing height of the bottom trawl, and also of the horizontal displacement, from the time the vessel passes to the trawl doors appear. Knowledge of this is important to combine the bottom-trawl- and the acoustic-index into one value, and ultimately to undertake absolute abundance estimation of cod and haddock in the Barents Sea.

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