The effective swept volume of a bottom trawl

Nils Olav Handegard[*†‡]and Dag Tjøstheim[†]

Abstract

The reaction of individual fish towards an approaching trawling vessel has previously been measured using target-tracking methods. In this paper these measured velocities are fitted to a deterministic mean behaviour model and a diffusion-advection model taking the random component into account. The output of the diffusion-advection model is used to estimate the probability of a fish to be caught by the bottom trawl. For typical depths in the Barents Sea, 200 - 350 m, and for immature Cod feeding on capelin, a mean fishing height of about 10 metres is found, and the effect of horizontal herding from the warp is shown. The effect of random fish movement is visualised by the different results from the two models.

[*]Institute of Marine Research, Bergen, Norway

[†]Department of Mathematics, University of Bergen, Norway

[‡]Corresponding author: nilsolav@imr.no (N.O. Handegard); P.O.Box 1870 Nordnes, 5817 Bergen; fax: +47 55 23 68 30

1 Introduction

The standard survey methods for northeast Arctic cod (*Gadus morhua*) and haddock (*Melanogrammus aeglefinus*) in the Barents Sea are based on bottom trawl and acoustic estimates (Jakobsen et al., 1997). These estimates cover different parts of the water column, and it has been argued that a combination of the two could improve survey estimates (Godø and Wespestad, 1993; Godø, 1994; Aglen et al., 1999). However, the vessel-induced behaviour makes this difficult since the bottom trawl will capture fish that were positioned above the trawl headline when the vessel passed and the acoustic estimate was recorded (Okonski, 1969; Ona and Chruickshank, 1986; Ona, 1988; Ona and Godø, 1990; Nunnallee, 1990; Handegard et al., 2003; Handegard and Tjøstheim, 2004). Combining the estimates without taking the overlap into account would thus be incorrect (Godø and Wespestad, 1993). Furthermore, the acoustic estimate itself could be biased by vessel-induced behaviour (Olsen et al., 1983; Fernandes et al., 2000a,b; Vabø et al., 2002; Wilson, 2003; Jørgensen et al., 2004).

The mean reaction pattern for cod relative to a trawling vessel was mapped in Handegard and Tjøstheim (2004). An important motivation has been to understand how fish behaviour affects the survey indices and, if possible, to quantify this effect. Questions that arise are: what are the implications of this measured reaction pattern for the sampling volume of the survey trawl? What is the probability that a fish at a given location will be available for the bottom trawl? Is it enough to know the mean velocity and mean speed of the individual fish to make inferences about this?

2 Materials and methods

We use the results of experiments conducted off the coast of Finnmark in 2001 and 2002, where individual fish behaviour were measured *in situ* vis-à-vis a survey vessel using a free floating buoy (Handegard and Tjøstheim, 2004). A free floating buoy equipped with a split beam echo sounder was used to obtain the data (Handegard et al., 2004a). The vessel passed the buoy and the buoy echo sounder was used to track individual fish from within the echo beam. A special tracking algorithm designed for tracking targets from a floating platform was used (Handegard et al., 2004b). The tracks were positioned relative to the approaching vessel and reaction is analysed in terms of distance to the vessel and gear. The measured behaviour used in this paper is taken from Handegard and Tjøstheim (2004, Figure 11), see Figure 1 for an overview.
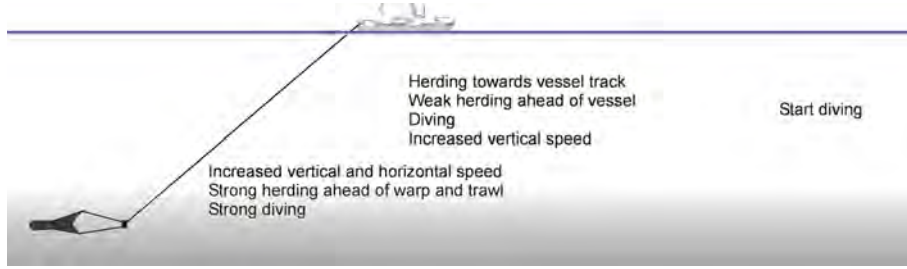
Figure 1: Schematic overview of the reaction reported in Handegard and Tjøstheim (2004).

The fish-capture process of the bottom trawl is a truly four-dimensional process, with three spatial and one temporal dimension. Traditionally, one-dimensional properties like fishing heights and sweeping widths have been used resulting in a rectangular fishing volume. In this paper, the process is treated in a three-dimensional setting: depth (z), athwartship direction (y) and time (t), and the goal is to calculate the probability of a fish to be caught by the trawl. The behaviour along the vessel path (x) is ignored, and this is justified by the fact that the mean fish velocity in the $x-$direction is lower than that of the vessel.

The mean displacement velocities in the y- and the z-directions as a function of time before after vessel passing are taken from Handegard and Tjøstheim (2004, Figure 11). Although the estimated velocities may be biased (Handegard and Tjøstheim, 2004, section 4.1.), we assume here that they reflect true displacement velocities. The estimated velocities, denoted $v_y(t, z)$ and $v_z(t, z)$, are given as functions of depth (z) and time before/after vessel passing (t). Note that a positive v_y means horizontal swimming perpendicular to and away from the vessel path, see definition in Handegard and Tjøstheim (2004, Section 2.3). Vessel-induced behaviour is believed to be weaker farther away from the vessel path. This effect was not investigated in Handegard and Tjøstheim (2004), and here it is assumed that the effect is reduced according to a bell-shaped weighting function $g(y) = \exp\left(-\frac{y^2}{\sigma^2}\right)$, where $\sigma = 300m$. In practical terms it does not have a strong impact, since the model grid is up to $100m$ to each side, and thus the behaviour is not weakened very much by this weighting. At any given time relative to vessel passing, the mean reaction in the yz-plane is

$$\bar{\mathbf{u}}(t, y, z) = g(y) \left[\begin{array}{c} v_y(t, z) \cdot \text{sign}(y) \\ v_z(t, z) \end{array} \right], \qquad (1)$$

where $\text{sign}(y)$ is 1 for $y \geq 0$ and -1 for $y < 0$.

3 Two models

3.1 The mean behaviour model

Assume that the yz-plane is fixed (perpendicular to the vessel path by definition) at a given geographical location, and that the vessel transducer passes this plane at $t = 0min$ and the trawl doors pass at $t = 10min$. The mean velocity component in this plane is now given by Equation 1, and makes it possible to calculate trajectories in the yz-plane indicating the mean fish movement as the vessel approaches.

To calculate these trajectories,

$$\frac{d\begin{bmatrix} y \\ z \end{bmatrix}}{dt} = \bar{\mathbf{u}}(t, y, z), \tag{2}$$

where $\begin{bmatrix} y \\ z \end{bmatrix}$ is the position of the individual in the $yz-$plane, is integrated backwards in time from trawl passage ($t = 10min$), to vessel transducer passing ($t = 0min$) and further to before vessel passing ($t = -10min$). The depth is set to $300m$, the doors spread to $44m$, and the headline height is $5m$; see Figure 2. Individual fish are initialised within the trawl door spread and below the headline height, and their trajectories are found by integration Equation 2 backwards in time. The results, as shown in Figure 2, indicate a "fishing height" of 20 metres as compared to the undisturbed situation $20min$ before vessel passing, and 10 metres as compared to the echosounder registrations. In addition, the trajectories are drawn towards $y = 0$ caused by the horizontal herding by the warps (Handegard and Tjøstheim, 2004).

3.2 The diffusion-advection model

The simple mean velocity model in the previous section does not reflect the actual capture process, since any random movement is ignored. If the measured velocity components of single individuals in the z-direction are given by $u_{z,i}$, then the mean vertical velocity $\bar{u}_z = \frac{1}{N}\sum_i^N u_{z,i}$ within each RM window[1] is a measure of the directional response. Here N is the number of tracks within each RM window. A measure of the random swimming response can be found by:

$$\tilde{u}_z = \frac{1}{n}\sum_{i=1}^n |u_{z,i}| - \frac{1}{n}|\sum_{i=1}^n u_{z,i}|,$$

---

[1]Can be thought of as strata in time and depth; see Handegard et al. (2003) for a definition.
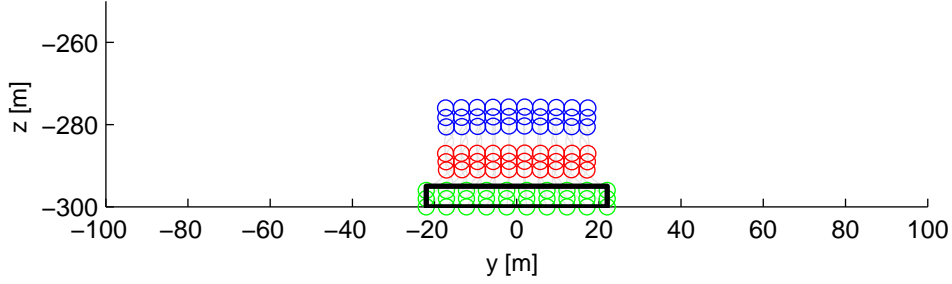
Figure 2: The mean fish movement in the $yz-$plane. The black rectangle defines the availability to the bottom trawl, represented by door spread and headline height. The green circles indicate the initial positions of individual fish at trawl passing ($t = 10min$), the red circles indicate the fish positions at vessel transducer passing ($t = 0min$), and the blue circles indicate the fish positions $20min$ before vessel passing. The grey lines in the background indicate the trajectories in the $yz-$plane.

which is the mean of the absolute value minus the absolute value of the directional response. In addition, $\tilde{u}_y$ is similarly defined.

Assuming a movement made up of a random walk and a directional response, the probability p of a fish being available for the bottom trawl can be described by an advection-diffusion equation model (Okubo, 1980, p.67-69)

$$\frac{\partial p}{\partial t} = -\frac{1}{\partial y}(\bar{u}_y p) - \frac{1}{\partial z}(\bar{u}_z p) + \frac{1}{\partial y}\left(K_y \frac{\partial p}{\partial y}\right) + \frac{1}{\partial z}\left(K_z \frac{\partial p}{\partial z}\right) \qquad (3)$$

where $\begin{bmatrix} \bar{u}_y \\ \bar{u}_z \end{bmatrix} = \bar{\mathbf{u}}$ (from Equation 1), p is the probability density function in the $yz-$plane (the integral of p over the $yz-$plane equals one) and K_y and K_z is the diffusion in the athwartship and vertical directions, respectively, given as

$$K_y = \tilde{u}_y^2 T/2, \text{ and } K_z = \tilde{u}_z^2 T/2. \qquad (4)$$

Here T is a parameter of autocorrelation for the velocity (Okubo, 1980, Equation 5.18). If the fish, for some reason, maintains the same direction (not to be confused with advection) for a long time, or if the changes in direction are small, the values of T will be high. Since no measurements of this are available, two cases with $T = 60s$ and $T = 30s$ are presented. The probability density p at a given time before trawl passage indicates the probability in the $yz-$plane for a fish to end up between the trawl doors and trawl headline. Note that it is the probability relative to a single specific time before trawl passing, not all subsequent times prior to the trawl passing, see the discussion.

The diffusion advection model is solved using a simple upwind differencing scheme; see Appendix A. The model is run in the same coordinate system as the mean position model, i.e. starting at the trawl passing at $t = 10min$ and integrated backwards towards $t = -20min$. The model is initiated by setting the probability to be caught to one in the area available to the bottom trawl, i.e. within the door spread and below the headline of the trawl. The model is integrated from trawl passing ($t = 10min$) backwards to transducer passing ($t = 0min$) and further to $t = -20min$, similar to the mean position approach outlined in the previous section. The results are shown in Figure 3 and Figure 4 for the $T = 60s$ and $T = 30s$ cases, respectively.
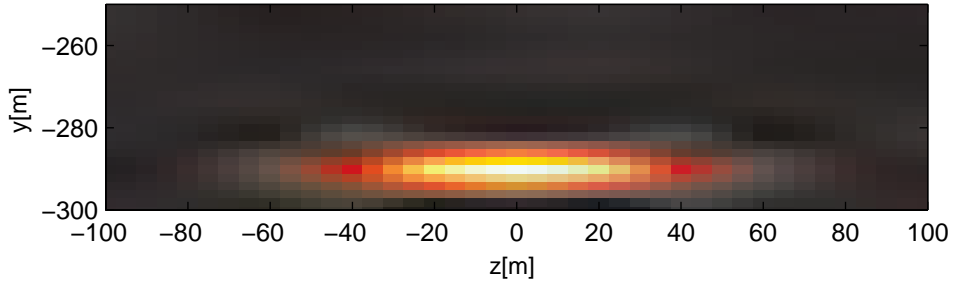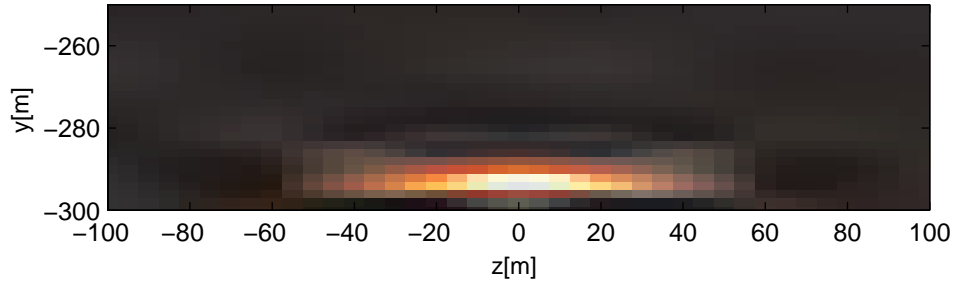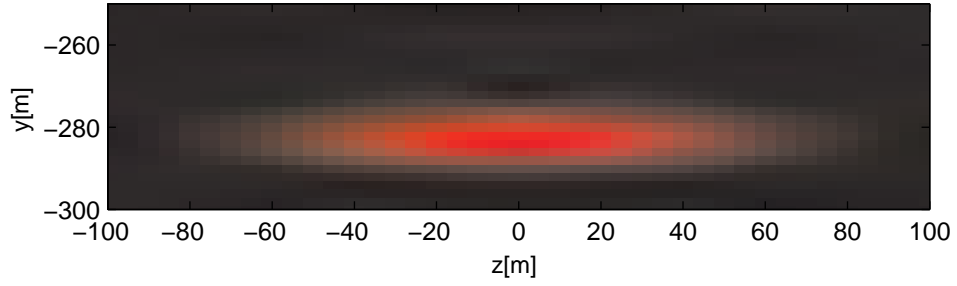

(a) Transducer passing.
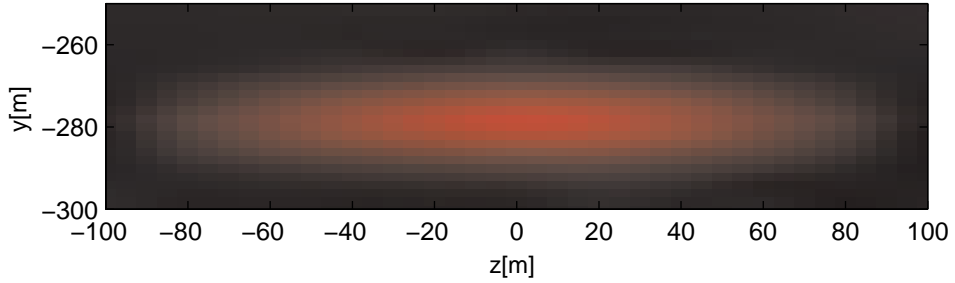
(b) 20min before transducer passing.

Figure 3: Availability to the bottom trawl from the diffusion advection model. The black area indicates $p = 0$. The time constant is set to $T = 60s$.

6

(a) Transducer passing.

(b) 20min before transducer passing.

Figure 4: Availability to the bottom trawl from the diffusion advection model. The black area indicates $p = 0$. The time constant is set to $T = 30s$.

4 Discussion

Using the technique in this paper, the implications of the observed reaction patterns can readily be visualized. The results of the mean field model indicate a fishing height of approximately 10m and a fishing width *less* than the door spread. When random movements are included this picture changes, especially for the horizontal movement. There is a probability of capturing fish well beyond the door spread of the trawl. The diffusion part consists of two components, one of which can be directly established from the mean velocity data, and one, the time lag correlation T, that can possibly be estimated from the information within the tracks. Consequently, measuring the mean velocity of individual fish is not enough to determine the fishing volume.

The availability probability p close to the bottom, and thus close to the trawl, becomes zero. The reason for this is the measured downward swimming component resulting in an upward flux when integrating backwards in time. The probability density is only representative for the availability relative to the time for which the integration is ended, whereas the true catch is a combination of all integration ending times. Combining all these will probably result in non-zero availability close to the bottom.

The proposed model works well to visualize and understand the observed herding process, but still some improvements could be made. The model could be extended to take into account the alongship swimming component and estimates of T could possibly be derived based on the information within each fish track. However, to become a fully operational model to estimate the probabilistic fishing volume, the underlying assumptions that the behavioural data is representative for the whole survey is probably more important than adjustments on the model formulation. As a consequence, the result from this model is successful in the respect of visualising the results of the experiments, but not suitable at this stage to estimate the sampling-volume of the bottom trawl representative for the winter survey.

References

Aglen, A., A. Engås, I. Huse, K. Michalsen, and B. K. Stensholt: 1999, 'How vertical distribution may effect survey results'. *ICES Journal of Marine Science* **56**, 345–360.

Fernandes, P., A. Brierley, E. Simmonds, N. Millard, S. McPhail, F. Armstrong, P. Stevenson, and M. Squires: 2000a, 'Fish do not avoid survey vessels'. *Nature* **404**, 35–36.

Fernandes, P., A. Brierley, E. Simmonds, N. Millard, S. McPhail, F. Armstrong, P. Stevenson, and M. Squires: 2000b, 'Fish do not avoid survey vessels'. *Nature* **407**, 152.

Godø, O. R.: 1994, 'Factors Affecting the Reliability of Groundfish Abundance Estimates from Bottom Trawl Surveys'. In: A. Fernö and S. Olsen (eds.): *Marine Fish Behaviour in Capture and Abundance Estimation.* Oxford, London, pp. 166–199, Fishing News Books.

Godø, O. R. and V. Wespestad: 1993, 'Monitoring changes in abundance of gadoids with varying availability to trawl and acoustic surveys'. *ICES Journal of Marine Science* **50**, 31–51.

Handegard, N. O., O. R. Godø, and A. Totland: 2004a, 'Measuring behaviour of single fish in responce to an approaching vessel using a buoy-mounted split-beam echosounder'. In: N. O. Handegard : *Cod reaction to an approaching bottom trawling vessel investigated using acoustic split-beam tracking.* Paper III. Dr. Scient. thesis, submitted.

Handegard, N. O., V. Hjellvik, and R. Patel: 2004b, 'Tracking individual fish from a moving platform using a split-beam transducer'. In: N. O. Handegard : *Cod reaction to an approaching bottom trawling vessel investigated using acoustic split-beam tracking.* Paper II. Dr. Scient. thesis, submitted.

Handegard, N. O., K. Michalsen, and D. Tjøstheim: 2003, 'Avoidance behaviour in cod (*Gadus morhua*) to a bottom-trawling vessel'. *Aquatic Living Resources* **16**, 265–270.

Handegard, N. O. and D. Tjøstheim: 2004, 'When cod meets a trawling vessel'. In: N. O. Handegard : *Cod reaction to an approaching bottom trawling vessel investigated using acoustic split-beam tracking.* Paper IV. Dr. Scient. thesis, submitted.

Jakobsen, T., K. Korsbrekke, S. Mehl, and O. Nakken: 1997, 'Norwegian combined acoustic and bottom trawl surveys for demersal fish in the Barents sea during winter'. *ICES CM 1997/Y:17.*

Jørgensen, R., N. O. Handegard, H. Gjøsæter, and A. Slotte: 2004, 'Possible vessel avoidance behaviour of capelin in a feeding area and on a spawning ground'. *ICES Journal of Marine Science.* In press.

Nunnallee, E. P.: 1990, 'An alternative to thresholding during echo-integration data collection'. *Rapports et procès-verbaux des réunions (Conseil international pour l'exploration de la mer)* **189**, 92–94.

Okonski, S.: 1969, 'Echo sounding obervations of fish behaviour in the proximity of the trawl'. *FAO fisheries report* **62**(2), 377–388.

Okubo, A.: 1980, *Diffusion and Ecological Problems: Mathematical Models*, Vol. 10 of *Biomathematics*. Springer-Verlag.

Olsen, K., J. Angell, F. Pettersen, and A. Løvik: 1983, 'Observed fish reactions to a surveying vessel with special reference to herring, cod, capelin and polar cod'. *FAO fisheries reports* **300**.

Ona, E.: 1988, 'Trawling noise and fish avoidance, related to near-surface trawl sampling'. In: S. Sundby (ed.): *Year class variations as determined from pre-recruit investigations*. pp. 169–175, Institute of marine research, Bergen.

Ona, E. and O. Chruickshank: 1986, 'Haddock avoidance reaction during trawling'. *ICES CM 1986*.

Ona, E. and O. R. Godø: 1990, 'Fish reaction to trawling noise: the significance for trawl sampling'. *Rapports et procès-verbaux des réunions (Conseil international pour l'exploration de la mer)* **189**, 159–166.

Vabø, R., K. Olsen, and I. Huse: 2002, 'The effect of vessel avoidance of wintering Norwegian spring spawning herring'. *Fisheries Research* **58**, 59–77.

Wilson, C.: 2003, 'Fish Avoidance to a Research Survey Vessel'. Poster at the ICES Fish Behaviour in Exploited Ecosystems symposium. Bergen 27-29 August 2003.

A   Integration scheme

The integration of the diffusion advection model is based on a simple upwind differencing scheme,

$$\frac{s_{(t+1,i,j)} - s_{(t,i,j)}}{\Delta t} = D_{(t,i,j)} + A_{Y(t,i,j)} + A_{Z(t,i,j)},$$

where the indexes i, j and t is indexes in time, athwartship distance and depth respectively,

$$A_{Y(t,i,j)} = \begin{cases} \frac{(s_{(t,i,j)} \cdot \bar{u}_{y(t,i,j)} - s_{(t,i-1,j)} \cdot \bar{u}_{y(t,i-1,j)})}{\Delta y} & \bar{u}_{y(t,i,j)} \geq 0 \\ \frac{s_{(t,i+1,j)} \cdot \bar{u}_{y(t,i+1,j)} - s_{(t,i,j)} \cdot \bar{u}_{y(t,i,j)}}{\Delta y} & \bar{u}_{y(t,i,j)} < 0, \end{cases}$$

and

$$A_{Z(t,i,j)} = \begin{cases} \dfrac{s_{(t,i,j)} \cdot \bar{u}_{z(t,i,j)} - s_{(t,i,j-1)} \cdot \bar{u}_{z(t,i,j-1)}}{dz} & \bar{u}_{z(t,i,j)} \geq 0 \\[2ex] \dfrac{s_{(t,i,j+1)} \bar{u}_{z(t,i,j+1)} - s_{(t,i,j)} \cdot \bar{u}_{z(t,i,j)}}{dz} & \bar{u}_{z(t,i,j)} < 0, \end{cases}$$

are the advection terms, and

$$\begin{aligned} D_{t,i,j} &= \frac{(K_{y(t,i+1,j)} + K_{y(t,i,j)}) \cdot (s_{t,i+1,j} - s_{t,i,j})}{2\Delta y^2} \\ &\quad - \frac{(K_{y(t,i,j)} + K_{y(t,i-1,j)}) \cdot (s_{(t,i,j)} - s_{(t,i-1,j)})}{2\Delta y^2} \\ &\quad + \frac{(K_{z(t,i,j+1)} + K_{z(t,i,j)}) \cdot (s_{(t,i,j+1)} - s_{(t,i,j)})}{2\Delta z^2} \\ &\quad - \frac{(K_{z(t,i,j)} + K_{z(t,i,j-1)}) \cdot (s_{(t,i,j)} - s_{(t,i,j-1)})}{2\Delta z^2} \end{aligned}$$

is the diffusion term.

The upwind integration scheme is used to avoid numerical instability. The scheme adds numerical diffusion to the system, and thus the diffusion will be slightly over-estimated.