ICES CM 2004/R:26

Studying the relationship between spatial fish distributions and trawl catches

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We propose an approach for studying the relationship between spatial fish distributions and the distribution of numbers in trawl catches. Individual spatial fish distributions are derived from acoustics data collected with a drifting buoy by tracking individual fish. The spatial distribution of these individual fish is then characterised using Generalised Additive Models (GAM). The catch distribution is obtained empirically. A model relating the spatial fish distribution and the catch distribution is then developped. This paper concentrates on the first part of the approach, the identification of the spatial fish distribution from acoustic data, which is illustrated for a demersal example from the Barents sea including mainly cod (*Gadus morhua*) and haddock (*Melanogrammus aeglefinus*).

Keywords: catch; spatial distribution; catchability; acoustic; drift buoy

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Introduction

Studying survey trawl catchability is an important topic in the context of survey based stock assessments. The main components of trawl catchability are fish availability and trawl efficiency (Godø 1998). Fish availability is influenced by factors such as vertical population distributions and diurnal activity patterns (Godø 1994; Godø 1994; Walsh 1991) in addition to habitat preferences. Trawl efficiency is affected by fish reactions leading to escapees or herding (Engås & Godø 1989; Krieger 1992; Ramm & Xiao 1995), but also by population density (Godø et al. 1999).

The relationship between individual spatial distributions and the distribution of numbers per haul obtained from trawl fishing are currently poorly understood. However, it is evident that this relationship in conjunction with behavioural differences observed between individual fish and fish schools when entering a trawl (Godø et al. 1999), are an important part of the variability in trawl catchability. Indeed, Trenkel et al. (submitted) found that the relationship between swept area density estimates and visual (ROV) density estimates was explained by the type of spatial distribution of a species.

The proposed approach consists in comparing spatial individual distributions with the distribution of numbers in the catch through a modelling approach. First, individual spatial distributions are derived from acoustics data collected with a drifting buoy by tracking individual fish and thus determining the distance between individuals and total numbers per unit time or space. This allows to characterise the statistical spatial distribution. Second, the catch distribution is obtained directly. Conditional on knowing the spatial fish distribution, Trenkel and Skaug (submitted) proposed a model for disconvoluting the catch distribution into the underlying spatial fish abundance distribution and a random catchability variable. This paper concentrates on the first step, which is illustrated for a demersal example from the Barents sea including mainly cod (*Gadus morhua*) and haddock (*Melanogramus aeglefinus*).

Material and Methods

The data was collected in 2001 as part of a study aimed at measuring the behavioural reactions of mainly cod and haddock to an approaching trawling vessel (Handegard et al. 2003). The Bergen Acoustic Buoy, a free-floating buoy equipped with a split beam echo sounder system, was deployed at about 1 pm and recovered at 3:30 am the following morning in an area located off the coast of Finnmark (72°N 25°E). During that period, at seven occasions a trawling vessel came past the buoy using a Campelen 1800 bottom trawl. All catch was identified, counted and length measured. The drifting path of the buoy is given in Figure 1; it includes the passing times of the trawling vessel as well as the locations of the observed individuals (see below for criteria used to identify individuals).

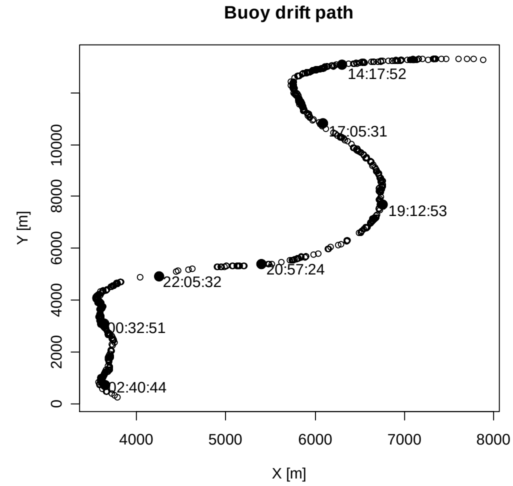

Figure 1. Drifting path of Bergen Acoustic Buoy used for data collection and passing times of trawling vessel. Marked observations (●) correspond to identified individuals (see text).

Information on individual spatial fish distributions and fish movements was derived from the acoustic buoy data in several steps. First, single targets were detected using the Simrad Ek60 built in Single Echo Detection algorithm (SED). Second, application of a tracking algorithm allowed to connect detected single targets in order to identify individual fish (Handegard 2004). The tracking algorithm uses a Kalman filter to predict fish positions and estimates the transducer movement for improved individual tracking. Subsequently, separate linear regression lines are fitted through the connected echoes of each tracked fish (Handegard 2004, paper II). The slope of these regression lines provides an estimate of linear fish speed (see e.g. Figure 2 in Handegard et al. 2003). This estimated speed is denoted "displacement speed" since it may differ from actual swimming speed due to currents in the water column. The geographic position (coordinates relative to some reference position) of the mean observation time of a track is used as the mean track position. Thus for each track or rather detected fish, the available data were: observation time, target strength (TS) value for each single echo within the track, mean vertical position in the water column and mean georgraphic position, mean displacement velocity and track length. Given the narrow width of the area covered by the acoustic beam, the detected fish basically lie on a line. Thus in the further analysis it is assumed that the observation field is one-dimensional.

Various exploratory analyses were carried out to study the properties of the identified tracks, in particular with the aim to determine whether they can be regarded as representing individual fish. For the analysis only tracked targets with target strengths (TS) between –30dB and –10dB were used. For cod this should correspond to fish of length 0.3 to 1 m (Nakken and Olsen 1977). If only some echos of a given track had TS values outside this range, those were removed and the remainder kept. Unless stated otherwise, analyses of tracked targets were carried out by selecting tracks comprised of at least 6 or 15 single echoes (after having removed echos outside the TS selection range). The two different levels of track length were studied in order to evaluate the impact of track length. Ping based Sv values integrated over 19 cm depth intervals were thresholded at -70 and -30 to select for larger species such as cod and haddock.

Individual spatial (horizontal) distributions were characterised using the geographic position of each track and then calculating the horizontal distance to the nearest neighbour along the buoy drift path (next detected track in time). The distribution of these nearest neighbour distances should follow an exponential distribution if individuals were randomly distributed in space and if the identifictication and detection of individual fish by the tracking algorithm did not depend on any environmental conditions such local fish density or bottom depth. Equivalently if individuals were randomly distributed in space, the total detected number of individuals (*Ni*) along subset *i* of the observation line should follow a Poisson distribution. Given that the buoy drifted at rather constant speed, considering numbers per unit distance interval is equivalent to considering numbers per time interval. To explore the relationship between the detected number of fish per unit distance interval (400 m) and covariates that might either be related to local fish densities or/and the detection performance of the tracking algorithm, a generalised additive model (GAM) was fitted. The explanatory variables considered were the geographic coordinates (X and Y) corresponding to east-west and north-south, a continuous time variable and bottom depth. The geographic coordinates represent the effects of any local conditions due to for example heterogenous fish density. Given the course of the buoy (see Figure 1), it was necessary to model separately the geographic effects in the North-South (Y) and East-West (X) directions using an additive model instead of a two-dimensional model. The time variable allows to model diurnal effects that might occur due to fish migrating between the bottom and further up in the water column. Cod has been found to carry out such diurnal migrations (Hjellvik et al. 2001). Bottom depth is considered a proxy for detectability by the tracking algorithm; separation of individual fish tracks becomes harder with depth due to the widening acoustic beam. Note that the time variable and the geographic variables are strongly correlated as any geographic location was only sampled once when the buoy drifted past it at a particular time. Hence the two models were fitted separately:

(1) $\ln(N) = s(X) + s(Y) + s(\text{depth})$
(2) $\ln(N) = s(\text{time}) + s(\text{depth})$

where s(.) indicates a non-linear function (regression splines). The optimal degree of smoothing of the regression splines was estimated by cross-validation (Wood and Augustin 2002). The explanatory power of all covariates was tested using a t-test and the explained deviance was used to compare model fits. For the GAM model, a log-link function and an overdispersed Poisson error distribution were selected. The estimated overdispersion factor is then used to judge whether the underlying distribution was really Poisson. In the case of a true Poisson distribution, the overdispersion factor is 1, if clustering occurs it is larger than 1 and in the case of avoidance it is smaller than 1. In summary, the GAM modelling approach allows to remove systematic covariate effects in order to study the form of the underlying error distribution.

In order to explore whether the acoustic Sa values could be used directly to identify the type of individual spatial fish distribution without tracking targets and indentifying individual fish, the relationship between the number of tracked fish and the acoustic Sa values was studied. A GAM with Sa and continous time as additional covariate was fitted. For this analysis the number of tracks *M* per 400 s observation time was used. The acoustic Sa values were integrated over the same time interval and for the depth range 4 to 40 m off the sea floor. The models was then

(3) ln(M) = s(time) + s(Sa)

As before a log-link function and an overdispersed Poisson error distribution were chosen.

The empirical distribution of numbers per haul for cod and haddock separately and both together were only explored graphically due to the small number of hauls. If fish were distributed randomly in space and catchability was close to 1 or constant, numbers per haul should follow again a Poisson distribution. If enough hauls were avaible, the distribution could be tested formally.

Results

Target identification: track length and swimming velocity

Track length increased with observation time, which also corresponded to a change from day time to night time (Figure 2a) but also with distance off bottom (Figure 2b). Average track length reached a maximum at about 10 m from the sea floor and decreased slightly thereafter. Given that individual displacement speed was rather independent of the distance off bottom (see below), this probably means that targets at distances less than 10 m off bottom were unreliably linked together as individual tracks by the tracking algorithm. Hence individual detection can be expected to have declined at close distances from the sea floor.

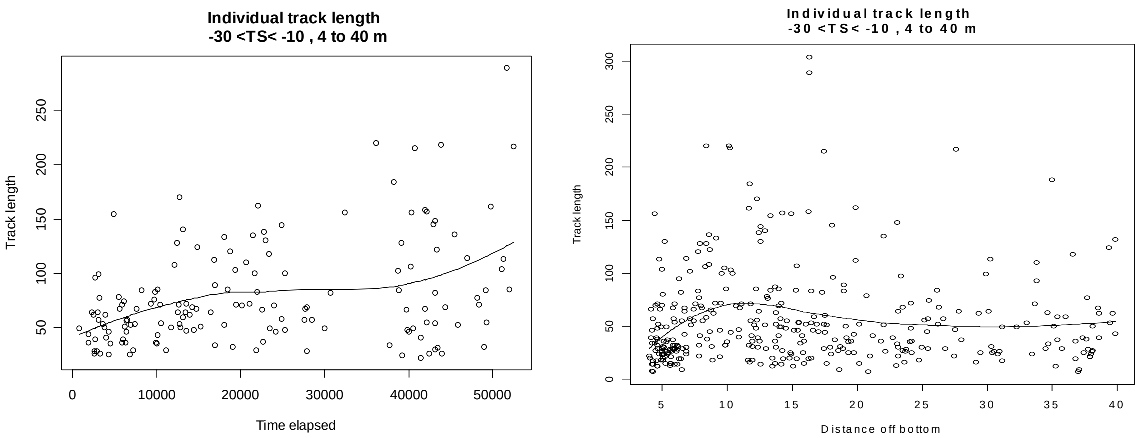

Figure 2. Track length as a function of observation time (a) and distance off bottom (b). Continous lines are loess fits.

As expected, average individual displacement speed decreased slightly with the length of the track from about 1 m/s for short tracks to about 0.5 m/s for tracks consisting of at least 25 observations (Figure 3a). For shorter tracks some high displacement speeds (>2 m/s) occured which seem unplausible. In contrast, individual displacement speed did not change much with distance from the sea floor (Figure 3b). This indicates that some short tracks might be misidentified but that this problem is not related to distance from sea floor.

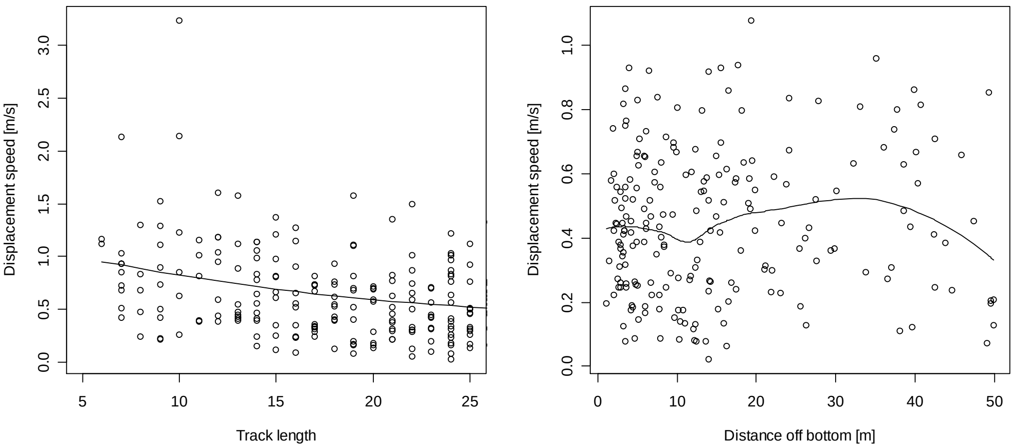

Figure 3. Individual displacement speed (m/s) a) as a function of track length (number of observations of same fish) and b) distance off bottom. Continuous lines represent loess smooth.

Individual displacement speed decreased over time in the bin 1-50 m above the sea floor (Figure 4a); similarly relative displacement direction changed (Figure 4b). At the same time vertical displacement velocity was rather constant (Figure 4c). Most likely these phenomena are of biological nature rather than tracking algorithm problems.

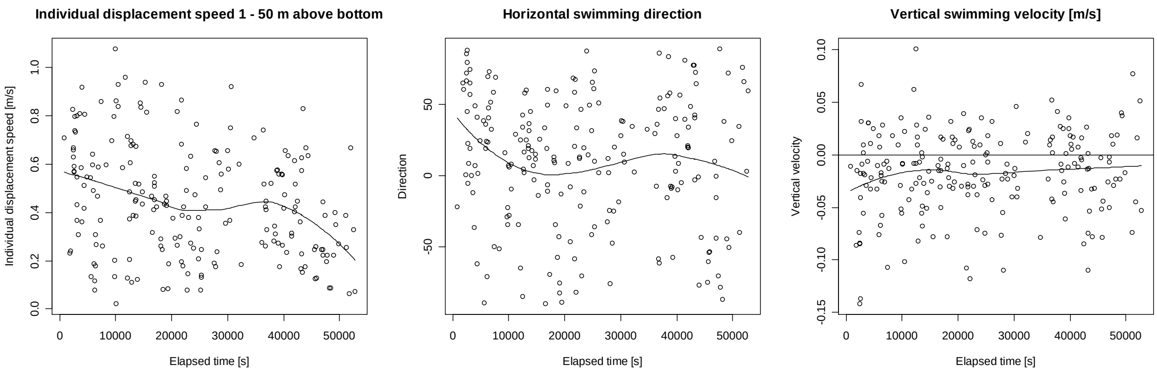

Figure 4. Temporal changes in fish displacement speed for individuals 1-50 m above the sea floor a) average displacement speed; b) average horizontal displacement direction; c) average vertical displacement velocity. Continuous lines are loess fits.

Species identification: target strength and catch composition

The target strength (dB) of tracked individuals decreased slightly over the course of the study (Figure 5). This might be due to a decreasing number of cod being present, as indicated by the composition of bottom trawl catches also shown in figure 5. Alternatively, the tilt angle of individuals might have changed as individuals descended to the bottom at the start of the night or at least reduced their activity. The observation of decreasing average diplacement speeds might be an indication in support of this hypothesis. A negative effect of an increasing body tilt angle on target strength has been observed for cod (McQuinn and Winger 2003). Overall cod and haddock dominated the catch, hence it seems reasonable to assume that this dominance also applies to the tracked individuals, in particular as tracks were only retained if the target strength was at least -30 dB. Most cod were larger than 40 cm, while haddock showed a pick below 20 cm.

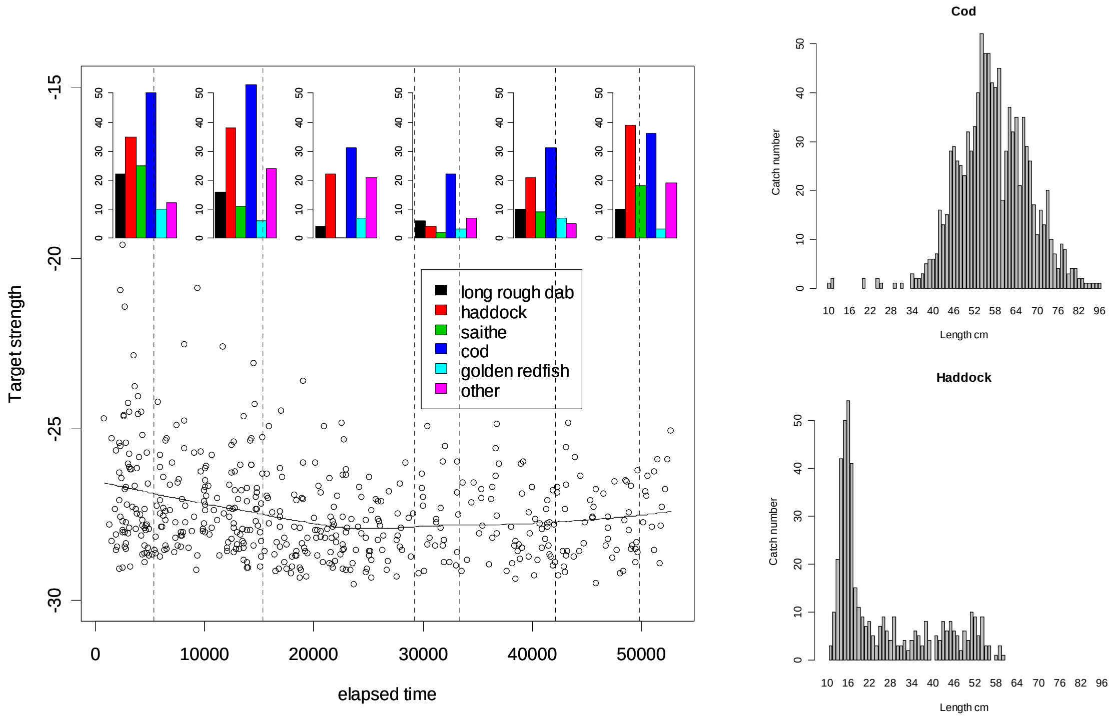

Figure 5. Target strength of tracked fish and catch composition. Vertical lines indicate timing of bottom trawl catches. Continuous line gives loess fit.

Spatial fish distribution

The overall depth distribution of tracks is given in figure 6a&b. The horizontal and vertical fish distributions were then looked at separately. Across the whole study period, the largest number of individuals was detected at about 4-5 m from the sea floor, independent on the track length criteria applied (Figure 6c&d). A majority of individuals were found at distances up to 20 m (only distances up to 50 m were considered).

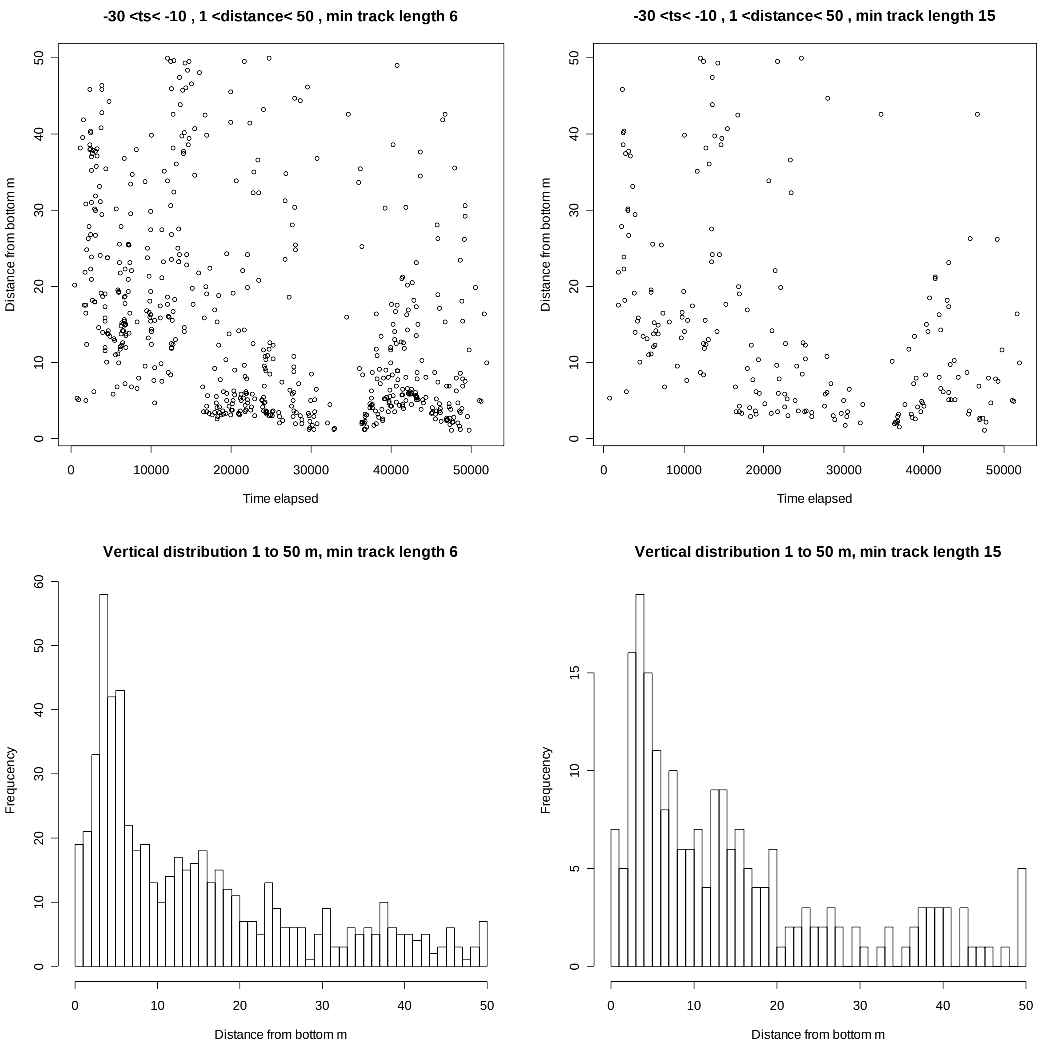

Figure 6. Vertical fish distributions. Track locations and histogram of vertical distance from bottom of tracked individuals. a) & c) individuals with tracks lengths >5, b) & d) individuals with track lengths >14.

Horizontal fish distributions were studied by looking first at the nearest neighbour distance and then considering the number of individuals observed in a given distance interval (corresponding roughly to a standardised observation area). Nearest neighbour distance was defined as the horizontal distance to the nearest neighbour when all fish in the water column 1-50 m are projected onto the sea floor. These nearest neighbour distances were strongly skewed indicating overdispersion, possibly as a result of clustering or other factors (Figure 7).

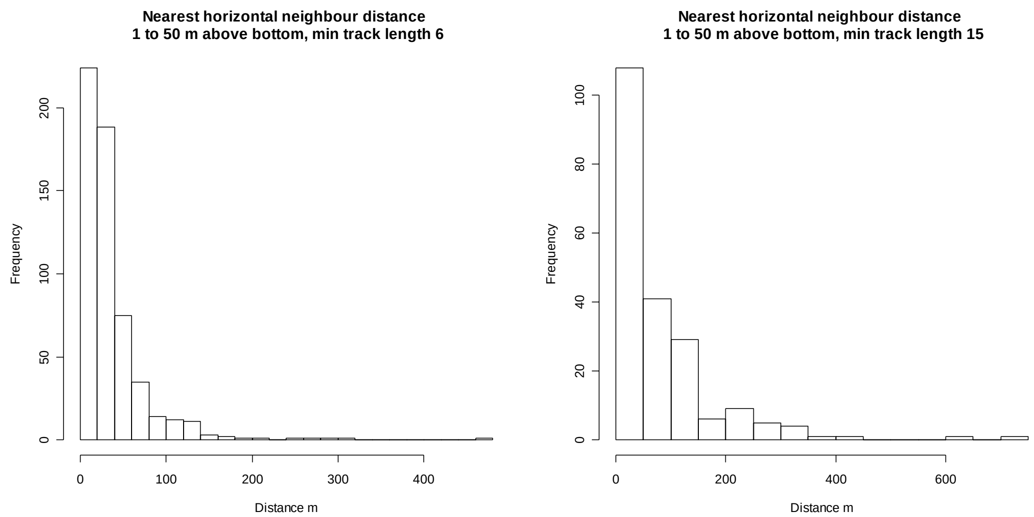

Figure 7. Histogram of horizontal distances to nearest neighbours, independent of vertical position in water column (1-50 m off bottom). a) individuals with tracks lengths >5, b) individuals with track lengths >14.

Generalized additive models were used to study the factors that might explain the observed non-randomness of horizontal distances with the aim to remove systematic effects in order to obtain the true underlying spatial distribution. The number of tracks per 400 m was best explained, i.e. largest explained deviance, by using the spatial coordinates X and Y as explanatory variables (Table 1). Bottom depth was not significant. Results were similar for minimum track lengths of 6 or 15. The time variable provided a nearly as good fit. The time pattern was a decreasing trend with a sharp rise after time 30000, which corresponds to about 9 pm (Figure 8). The estimated overdispersion factor was smallest for models using both spatial coordinates and close to 1 indicating that by taking account of systematic geographic (or temporal) variations, the remaining variability (residuals) indicates randomness of the spatial distribution of tracked fish.

Table 1. Results for GAM models for the number of tracks per 400 m considering all tracks 4-40 m from sea floor. s(.) indicates that the relationship with the explanatory variable is a smooth function (regression spline). Overdispersion factor for Poisson error distribution.

Model	Min track length	Constant	X p-value	Y p-value	time p-value	Deviance explained	Overdispersion factor
s(X)+s(Y)	6	2.02 (0.067)	1.7 10-5	1.2 10-5		62.5%	1.45
	15	1.05 (0.102)	0.00009	0.000014		60.9%	1.06
s(time)	6	2.05 (0.069)			3.28 10-5	56.5%	1.63
	15	1.14 (0.104)			0.001	41.2%	1.32

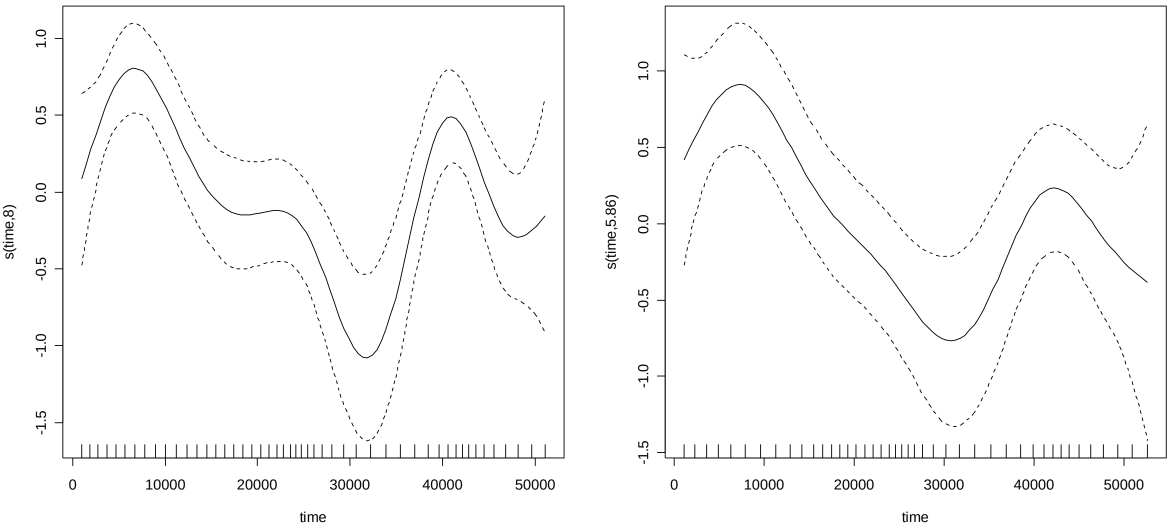

Figure 8. Shape of the nonlinear function time (GAM) of the number of tracks per 400 m for tracks at least 5 (left) and 15 (right) observations long.

The above results were obtained considering all tracks between 4 and 40 m from the sea floor. In order to determine the robustness of the results to the water layer considered, the best fitting model, ln(Y) = s(X) + s(Y), was fitted repeatedly using data from different water layers. The lower depth limit was varied from 1 to 7 m off the sea floor in steps of 1 m. The upper depth limit was varied from 10 to 50 m in steps of 10 m. For example, a model fit indicated as 1-10 means that all tracks situated between 1 and 10 m off the sea floor were included in the analysis. As before the analysis was repeated for tracks with minimum length of 6 and 15 observations. The choice of lower or upper depth limit had little impact on the estimated overdispersion factor when using a minimum track length limit of 6 (Figure 9). The estimated overdispersion factor was around 1.3 in all cases. In contrast, when considering only longer tracks, smaller overdispersion factors indicated that from a distance of about 4-5 m, horizontal distributions seemed to become more random. In this case estimated overdispersion factors were around 1.

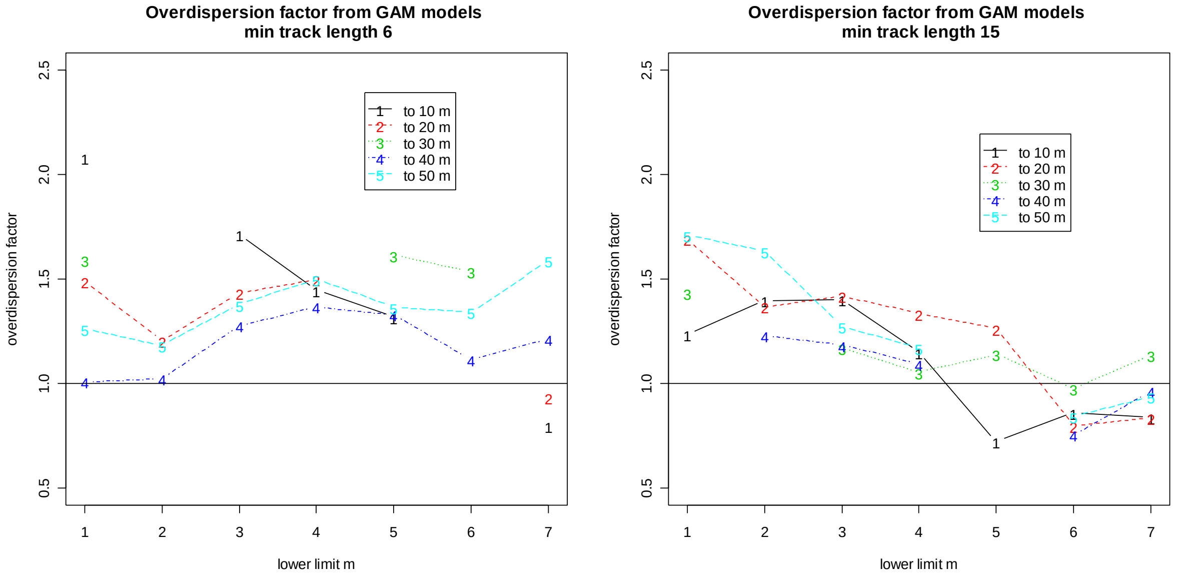

Figure 9. Overdispersion factors of Poisson error distribution (1= random distributon) from GAM models for different water layers: x-axis gives distance from bottom in meters, different data series correspond to upper limit (1=10 m, 2=20 m, 3=30 m, 4=40 m, 5=50 m). GAM model: tracked number per 400 m s(X) + s(Y) where X and Y are geographic coordinates. a) individuals with minimum track lengths 6, b) individuals with minimum track length 15.

Relationship between Sa value and number of tracked individuals

In order to determine whether the Sa values could be used directly to obtain the individual spatial distribution, the Sa values were compared with the identified number of tracks. This time the number of tracks per 400 s was used and the Sa values were integrated in depth and time. Figure 10 shows the relationship between the number of tracks and the Sa values. No clear relationship appears for small Sa values while it is a clear positive relationhip for larger Sa values. The general feature is a large variability of the number of tracks at low Sa values and a clearer relationship at higher Sa values. As before a GAM was fitted with covariates time and Sa values ; only the later variable was significant, independent of the track length criteria (Table 2). The estimated optimal degrees of freedom for the smooth function of Sa values were around 5. This indicates that the number of tracks detected is related to the Sa value but not in a simple linear manner. This was already evident from Figure 10.

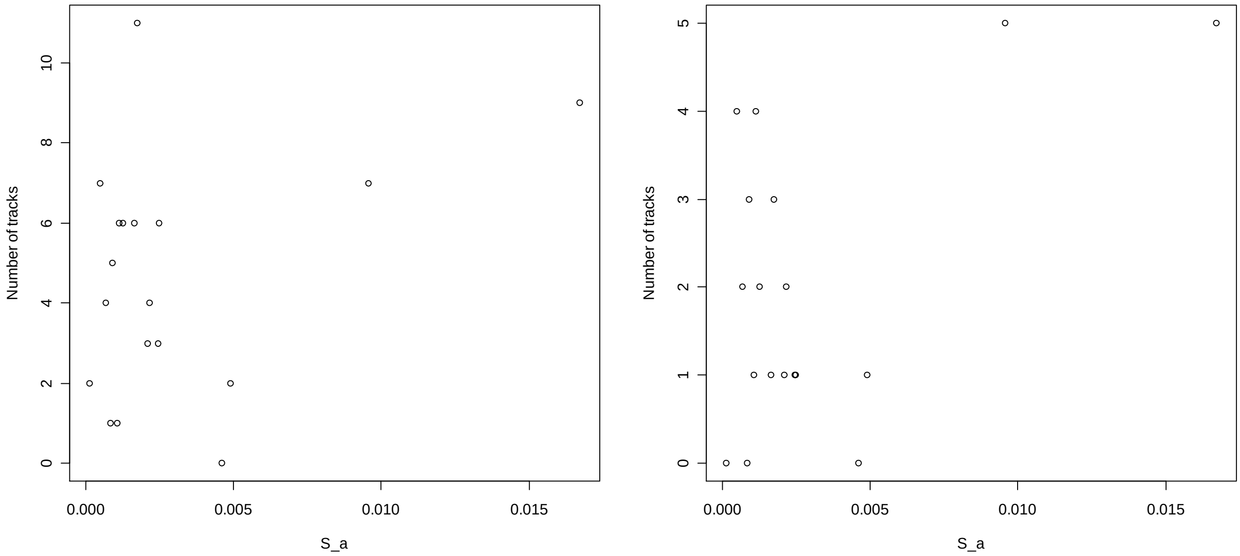

Figure 10. Number of tracks vs depth (4-40m above bottom) and time (400 s intervals) integrated Sa values; a) minimum track length 6, b) minimum track length 15.

Table 2. Results for GAM models for the number of tracks per 400 m considering all tracks 4-40 m from sea floor as a nonlinear function of time and integrated acoustic Sa values. s(.) indicates that the relationship with the explanatory variable is a smooth function (regression spline). Df gives the estimated optimal degrees of freedom for the smooth function. Overdispersion factor for Poisson error distribution.

Min track length	Constant	Time p-value	Time df	Sa p-value	Sa df	Deviance explained	Overdispersion factor
6	1.26	0.9	1	<0.0001	5.4	55.8%	1.17
15	0.25	0.16	1	<0.001	4.6	47.9%	0.68

The correlation coefficient for the number of tracked individuals and integrated Sa values was then calculated (Figure 11). Again different water layers were considered. Correlations were negative when considering the depth ranges included in the range 2-10 m. This means that at higher Sa values the tracker cannot separate individuals reliably. Overall the highest positive correlations independent of the lower depth limit were obtained when the upper depth limit was 50 m or 40 m (for lower limits < 6 m). Thus including a wider depth range seems to compensate to some degree for the detection problems near the sea bed.

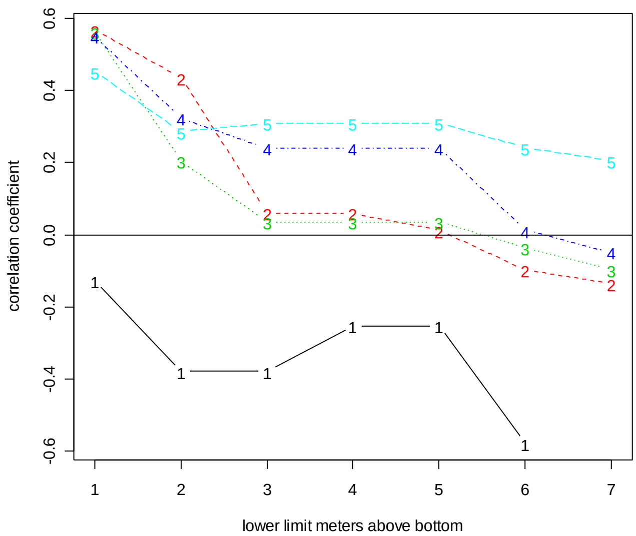

Figure 11. Correlations between numbers tracked per 15 min and Sa values integrated over different water depths. Integrating up to 10 m all correlations are negative indicating that at higher Sa values the tracker cannot separate individuals reliably. Different data series correspond to upper depth limit (1=10 m, 2=20 m, 3=30 m, 4=40 m, 5=50 m).

Discussion

In this paper we derived individual spatial fish distributions from acoustics data. In order to increase the chances of actually identifying individual fish, data collected from a slowly drifting buoy instead of vessel collected acoustics data were used. The data were initially collected for studying the behavioural response of cod to an approaching vessel (Handegard 2004). Consequently the vertical fish distribution might have been disturbed temporarily seven times during the study period. However for this study only the horizontal distribution was of interest for which no obvious disturbance effects appeared (see Figure 4c). Thus we assume that no bias was introduced into the results.

Extensive exploratory analyses were carried out to validate the indentified targets as individual fish and to determine the impact of several technical choices such as minimum track length and depth range, but also target strength. The dependence of the results on the minimum track length and the importance of the lower depth limit seem to point at a detection problem near the bottom. Detection seemd to have been reliable from about 4 m off the sea floor. There are several possible explanations for this. As the acoustic beam becomes wider at greater ranges, hence closer to the bottom, the probability for the presence of single targets increases, but the detection probability decreases. In conjuction with this, population density might be expected to increase closer to the sea floor for some species such as cod. Both problems contribute to reducing individual detectability by the tracking algorithm. In addition, when individual detection is unreliable, a larger number of short tracks is expected to occur. This might explain the finding that track distributions were more random, i.e. a smaller dispersion factor was found, when only longer tracks (> 15 echos) were used in the analysis (see table 1). Furthermore, the excessive displacement speed for some of the short track indicated that a small proportion of the short tracks might be misallocated. However, this problem was small and unrelated to the depth range and should not affect the spatial distribution.

The spatial distribution of individual fish was found to be close to a random spatial distribution (ignoring any vertical components) in the depth range 4 to 40 m off the sea floor if and only if systematic effects due to spatial location or time were accounted for. In contrast bottom depth did not play a role. This seems to indicate that the underlying fish density varied over the study area (or rather study line). As it was not possible to distinguish the tracks of individual species, this change in density could be due to changes in one or several species. We tried to limit the number of candidate species by selecting data from an area where cod and haddock were predominant in the catches and by selecting tracks with strong TS values, however the presence of a mix of species cannot be excluded.

Some initial analyses were carried out to study the relationship between the number of individual fish tracks and acoustic Sa values. The results are not conclusive and more work would be needed. Clarifying this relationship would be of great interest as it would allow to study spatial fish distributions using acoustics data routinely collected from survey vessels proceeding at speeds too high to allow identifying individual fish reliably.

References

Engås, A. and Godø, O. R. 1989. The effect of different sweep lengths on the length composition of bottom-sampling trawl catches. J. Cons. Int. Explor. Mer, **45**: 263-268.

Godø, O. R. Year. Natural fish behaviour and catchability of groundfish. ICES C.M. 1994/G:14.

Godø, O. R. 1998. What can technology offer the future fisheries scientist - possibilities for obtaining better estimates of stock abundance by direct observations. J. Northw. Atl. Fish. Sci., **23**: 105-131.

Godø, O. R., Walsh, S. and Engås, A. 1999. Investigating density-dependent catchability in bottom-trawl surveys. ICES Journal of Marine Science, **56**: 292-298.

Handegard, N.O. 2004. Cod reaction to an approaching bottom trawling vessel investigated using acoustic splitbeam tracking. Dr. Scient. thesis, University of Bergen, submitted.

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

Hjellvik, V., Godø, O. R. and Tjøstheim, D. 2001. Modeling diurnal variation of marine populations. Biometrics, **57**: 189-196.

Krieger, K. J. 1992. Distribution and abundance of rockfish determined from a submersible and by bottom trawling. Fishery Bulletin, **91**: 87-96.

McQuinn, I. H. and Winger, P. D. 2003. Tilt angle and target strength: target tracking of Atlantic cod (*Gadus morhua*) during trawling. ICES Journal of Marine Science, **60**: 575-583.

Nakken, O. and Olsen, K. 1977. Target strength measurements of fish. Rapp. P.-v. Reun. Const. int. Explor. Mer, **170**: 52-69.

Ramm, D. and Xiao, Y. 1995. Herding in groundfish and effective pathwidth of trawls. Fisheries Research, **24**: 243-259.

Trenkel, V. M., Francis, R. I. C. C., Lorance, P., Mahévas, S., Rochet, M.-J. and Tracey, D. submitted. Availability of deep-water fish to trawling and visual observation from an ROV. Marine Ecology Progress Series.

Trenkel, V. M. and Skaug, H. J. submitted. Disentangling the effects of trawl efficiency and population abundance on catch data using random effects models. ICES Journal of Marine Science.

Walsh, S. J. 1991. Diel variation in availability and vulnerability of fish to a survey trawl. J. Appl. Ichthyol., **7**: 147-159.

Wood, S. N. and Augustin, N. H. 2002. GAMs with integrated model seleciton using penalized regression splines and applications to environmental modelling. Ecological Modelling, **157**: 157-177.