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BIASING OF FISH ABUNDANCE ESTIMATES DERIVED FROM USE OF THE SECTOR SCANNING SONAR IN THE VERTICAL PLANE

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The imminent use of sector scanning sonars with echo integrators and counters to estimate fish abundance, as in avoidance reaction investigations, has prompted the present theoretical study. Consideration of systematic variations in the acoustic backscattering properties of fish indicates that abundance estimates derived from use of the sonar in the vertical plane will be biased. The two causes of this are the general reduction in mean backscattering cross section with increasingly oblique steering of the sonar from the vertical and the accompanying general change in acoustic sampling volume. Correction of echo integrator-derived abundance estimates in non-, but near-vertical sectors is illustrated for several hypothetical cases. These consider homogeneous and layered saithe aggregations to be ensonified in search and classification modes at 120 kHz.

INTRODUCTION

The usefulness of sector scanning sonars in fisheries research has been appreciated throughout its development [1-5]. A particular application of critical importance to current acoustical methods of assessing fish abundance is the determination of avoidance reactions of fish to the passage of acoustic survey vessels [6]. The unique contribution that the sonar can make to the quantification of such effects has motivated the present study.

Avoidance reactions of fish can be assessed by comparing abundance estimates in different sectors. These can be derived from echo integrators or counters coupled to the individual sector outputs of the beamformer. Systematic differences could be assigned unambiguously to avoidance reactions. The interpretation of the derived acoustic measures is, however, perhaps not so simple as it first appears, especially for use of the sector scanning sonar in the vertical plane. In addition to purely geometric, including beamformer effects, whose influence on the acoustic sampled volume, thence abundance estimates is well known [7-10], there are two reasons for this: The backscattering cross sections of fish of interest at the usual ultrasonic frequencies of application in acoustic surveys are very complicated, but are not completely stochastic, and the acoustic sampling volume depends on the same backscattering cross sections. Acoustic measures of abundance in different sectors are, therefore, biased.

Both biasing effects are treated theoretically in this paper, but in an example meant to simulate the result of observing saithe aggregations in vertical and near-vertical sectors at 120 kHz, only the effect of variations in observed effective backscattering strength is computed. Corresponding variations in the acoustic sampling volume with changing sector are not calculated, as these can be approximated excellently in the present case of a rather directional sonar without reference to the detailed backscattering properties of saithe. This simplification renders specific volume calculations uninteresting, although these are still important in practical cases to gauge the net biasing effect and to derive sector abundance correction weights.

MODEL FOR NOISE-FREE OBSERVATION OF FISH AGGREGATIONS

Interpretation of echo integrator measurements of fish abundance requires knowledge of the mean target strength-to-length relationship for the fish of observation [11]. Development of this relationship from target strength measurements is essentially straightforward [12-15]. Its application is uncomplicated given the usual conditions; for example, the strict applicability of linear acoustics, farfield ensonification of fish, negligibility of background and processor noise, and absence of shadowing effects. The adequacy of target strength measurements on properly prepared fish specimens to represent the corresponding scattering properties of fish in the wild is assumed, at least in so far as observed scattering strengths in the mean are concerned.

The effective observed backscattering strength of a fish in the mean of a large number of observations is, in accordance with the stated and implied assumptions, equivalent to the ensemble average

$$\mathrm{Ave}\ (Gb^2\sigma) = \int Gb^2\sigma\, dF\ , \tag{1}$$

where G denotes the gain factor; b^2, the sonar beam pattern; σ, the backscattering cross section; and F, the cumulative distribution function of fish position, orientation, and other variables, such as time, on which σ may depend. The gain factor depends generally on the fish range r and amplitude absorption coefficient α of the medium in the following manner: $G=r^{-4}\exp(-4\alpha r)$ in the absence of time-varied-gain (TVG) processing of the echo, r^{-2} for "20 log r" TVG, and 1 for "40 log r" TVG. The sonar beam pattern is defined as the product of transmit and receive beam patterns, b_T and b_R, when evaluated in the direction $\hat{k}$ of the fish. The backscattering cross section is generally a sensitive function of the apparent fish orientation.

To facilitate comparison of estimates of effective backscattering strengths for different fish, the single-state effective backscattering strength $Gb^2\sigma$ in Eq. (1) is normalized by $\int Gb^2\, dF$. The resultant ensemble average defines the averaged backscattering cross section $\langle\sigma\rangle$,

$$\langle\sigma\rangle = \int Gb^2\sigma \; dF \Big/ \int Gb^2 \; dF \; . \qquad (2)$$

This expression also avoids the arbitrariness of medium- or processor-limited acoustic sampling volume implicit in F.

For the present computations the constituents of Eq. (2) have the following specific forms:

Gain factor. Application of "40 log r" TVG is assumed; hence, G=1.

Beam patterns. Two modes of operation of the sector scanning sonar are assumed. In the search mode the transmit beam is assumed to be effectively omnidirectional, while the receive beam is assumed to be equivalent to that of a circular piston. For the intended large wavenumber-equivalent sonar radius, these idealized conditions are realistic. Hence, b_T=1 and

$$b_R = [2 \; J_1(ka \; \sin\alpha)/(ka \; \sin\alpha)]^2 \; , \qquad (3)$$

where α is the fish observation aspect relative to the receive beam axis, and $ka \doteq 1.61/\sin\theta_{3dB}$, where θ_{3dB} is the half-beamwidth of the sonar, or the angle between the acoustic axis and -3dB level. In the classification mode the transmit and receive beam patterns are assumed to be equally directive and equivalent to b_R in Eq. (3). In the reported computations the half beamwidth is 2.5 deg, which represents a typical beamwidth of fisheries echo sounders in use at ultrasonic frequencies and a possible beamwidth of sector scanning sonars at similar frequencies.

Backscattering cross section. The dorsal aspect backscattering cross section of saithe at 120 kHz was measured as a function of tilt angle by Nakken and Olsen [16]. The corresponding target strengths of the 48 specimens of that study are reported in Ref. 17. Given the directionality of the sector scanning sonar, the principal orientation of importance is assumed to be that of the apparent tilt angle. In terms of the fish direction $\hat{k}$ and roll-neglecting orientation $\hat{k}'$, this is $\arccos(\hat{k}\cdot\hat{k}') - \pi/2$.

Cumulative distribution function. Avoidance or other observation-provoked reactions among the observed fish are neglected. The position and orientation dependences of F are thus assumed to be independent. Other dependences of F are neglected, which is expected to be a reasonable approximation in many applications to gadoid abundance estimation. In terms of the geometric quantities of Fig. 1, therefore,

$$dF = dF_1(\theta,\varphi) \; dF_2(\theta',\varphi') \; , \qquad (4)$$

where dF_1 and dF_2 are the probability elements describing, respectively, the spatial and orientation distributions of fish. Two different spatial distributions are considered: an effectively homogeneous distribution and a distribution which is homogeneous within a horizontal layer. The θ-dependences of the corresponding probability density functions are the following: sin α for the homogeneous aggregation and $\cos^{-3}\theta$ for the horizontal layer. α is defined through θ and the steering angle θ_s. The orientation distribution is assumed to be characterized by an essentially normally distributed tilt angle variable and uniformily distributed azimuthal variable. Choice of the distribution of tilt angle variable was motivated by Olsen's observations on cod [18]; it has been used previously in a number of computations [11-15, 19]. It is defined precisely by the probability density function

$$f(\theta') = a\ \exp[-(\theta'-\bar{\theta})^2/2\sigma_\theta{}^2]\ \mathrm{rect}[(\theta'-\bar{\theta})/6\sigma_\theta]\ , \qquad (5)$$

where a is the normalization constant, which is approximately 2/5, and $\bar{\theta}$ and σ_θ are the respective mean and standard deviation of non-truncated normal distribution. The values of the two parameters for the present computations are $\bar{\theta}$=0 deg and σ_θ=5 deg.

MODEL FOR NOISY OBSERVATION OF FISH AGGREGATIONS

The effect of background or processor noise on the observation of fish aggregations complicates the previous analysis. In accordance with the considerations advanced in Ref. 20, the effective observed backscattering strength in Eq. (1) becomes

$$\mathrm{Ave}\ (Gb^2\sigma) = \int Gb^2\sigma\ H(Gb^2\sigma - t)\ dF\ , \qquad (6)$$

where t is the echo integrator or counter threshold in units of $Gb^2\sigma$, and H is the Heaviside step function: H(x)=0 for $x\leq 0$ and 1 for $x\geq 0$.

The acoustic sampling volume contained implicitly in F is similarly complicated by the presence of noise. It is

$$V_s = V_o \int H(Gb^2\sigma - t)\ dF\ , \qquad (7)$$

where the sampling or effective observation volume V_s is a function of the total possible ensonification volume V_o, which is defined by range-gating of the processor or physical boundaries of the medium.

In many practical situations the effect of noise can be calculated from simpler considerations. Thus, for example, the acoustic sampling volume can be computed by the conical beam approximation discussed in Refs. 7 and 21. For the equal sector scanning beams of the noise-free model, the sampling volume is constant for the spatially homogeneous distribution and increases as $\cos^{-3}\theta_s$ with increasing steered angle θ_s, which is measured from the vertical, for appropriately narrow transmit or receive beams.

COMPUTATIONS

Variations in the backscattering cross sections of individual fish with changing sector of observation manifest themselves through the averaged backscattering cross section in Eq. (2). This is computed systematically for the measured dorsal aspect target strength functions of 48 saithe at 120 kHz. For a given aggregation geometry, mode of ensonification, and steered angle, the 48 averaged cross sections, after logarithmic conversion, are regressed linearly on fish length ℓ:

$$\langle TS \rangle \equiv 10 \log (\langle \sigma \rangle / 4\pi) = m \log \ell + b \ . \qquad (8)$$

The variable ℓ is expressed in units of centimetres while the target strength variable is expressed in units of decibels such that an ideally reflecting sphere of 2 m radius has a target strength of 0 dB. The various systematic properties of investigation are contained in the regression coefficients m and b, which are estimated from the described data and model conditions.

Estimates of m and b are presented in Table 1 for the case of ensonification of a homogeneous distribution of saithe by a sector scanning sonar used in the search mode. Eight identical equally spaced beams steered from 0 to 35 deg are considered. Associated statistical quantities of estimates of standard errors of coefficients and regression, and correlation coefficient, are also presented. A similar analysis is presented in Table 2 for the case of ensonification of the same kind of aggregation by the sector scanning sonar in the classification mode. Corresponding results for the case of a layered aggregation are not presented in this form because of their close similarity.

Two examples of computed data sets underlying the regression analyses of Tables 1 and 2 are presented in Fig. 2. These represent the result of averaging the measured backscattering cross sections with respect to the described homogeneous distribution of saithe when ensonified at 120 kHz by a sector scanning sonar in both search and classification modes.

The effect of changing the sector of observation may now be estimated by comparing corresponding estimates of averaged backscattering cross sections derived from the regression in Eq. (8). Since the sector scanning sonar is to be used in the vertical plane for the present application, it is convenient to use the vertical sector estimate of backscattering cross section as a reference. If this is denoted $\langle \sigma \rangle_1$, then the underestimate in fish abundance incurred by using this quantity to estimate abundance in the steered sector with true averaged backscattering cross section $\langle \sigma \rangle_2$ is

$$1 - \langle \sigma \rangle_2 / \langle \sigma \rangle_1 \ .$$

The acoustical correction factor to be applied to the abundance estimate obtained from the obliquely steered sector is

$$\langle\sigma\rangle_1/\langle\sigma\rangle_2 ,$$

which does not include compensation for possible volume changes, whether in a noise-free or noisy environment. Computations of abundance underestimates and correction factors are shown in Figs. 3 and 4 for the case of the homogeneous spatial distribution. Corresponding results for the case of the horizontal layer are not significantly different.

DISCUSSION

For the considered case of saithe aggregations observed at 120 kHz substantial underestimates in measures of abundance registered in oblique sectors may be expected. Accompanying changes in the acoustic sampling volume will alter the magnitude of calculated purely acoustical bias, but in general will not precisely cancel it. In fact, for the case of directional observation of an effectively homogeneous distribution of saithe, the abundance bias due to volume change with sector will be small compared to the purely acoustical biases of Fig. 3. The volume will increase with increasingly oblique steering angle θ_s as $\cos^{-3}\theta_s$ for the case of a horizontal distribution. This will only partly offset the systematic acoustical effect of decreasing mean backscattering cross section with increasing θ_s in the present case.

The difference in magnitudes of corresponding underestimates with mode of sonar operation, as shown in Fig. 3, confirms the importance of systematic orientation dependences in backscattering cross sections. The effect of these dependences is exaggerated by the classification mode, which is more isolating than the search mode. The same differences are seen in Fig. 4, which indicates that the size of the sector correction factor is generally larger for observation in the classification mode than in the less directional search mode.

While the present results apply strictly to the case of saithe at 120 kHz, they are generally characteristic of gadoids at ultrasonic frequencies. These further results are being prepared for publication. They suggest, in turn, the reasonable inference that fusiform fish of commercial importance may also be systematically underestimated in oblique sectors of vertically oriented sector scanning sonars.

The import of the present study is clear. The uncritical application of sector scanning sonar to the abundance estimation of fish may incur significant biases. These can be removed, however, by use of the precise beamforming characteristics of the observing sonar and backscattering cross sections of observed fish in the models developed in this paper and illustrated by a numerical example.

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Table 1. Regression analyses of $\langle TS \rangle$ on ℓ for saithe aggregations observed in the search mode at 120 kHz.

θ_s	$\hat{m}$	est[SE($\hat{m}$)]	$\hat{b}$	est[SE($\hat{b}$)]	SE	ρ
0	19.2	0.9	-62.7	1.2	1.7	0.955
5	19.4	0.9	-63.4	1.2	1.6	0.958
10	19.6	0.8	-64.5	1.2	1.6	0.961
15	19.7	0.8	-65.4	1.2	1.6	0.962
20	19.7	0.8	-66.0	1.2	1.6	0.963
25	19.6	0.8	-66.3	1.2	1.6	0.962
30	19.5	0.8	-66.4	1.2	1.6	0.960
35	19.4	0.9	-66.4	1.2	1.7	0.957

Table 2. Regression analyses of $\langle TS \rangle$ on ℓ for saithe aggregations observed in the classification mode at 120 kHz.

θ_s	$\hat{m}$	est[SE($\hat{m}$)]	$\hat{b}$	est[SE($\hat{b}$)]	SE	ρ
0	18.9	0.8	-63.8	1.1	1.5	0.963
5	19.2	0.8	-64.8	1.1	1.4	0.967
10	19.7	0.7	-66.8	1.0	1.4	0.970
15	20.2	0.7	-68.8	1.0	1.4	0.972
20	20.3	0.7	-70.0	1.0	1.4	0.971
25	20.4	0.8	-70.7	1.1	1.4	0.970
30	20.4	0.8	-71.3	1.1	1.4	0.970
35	20.4	0.8	-71.6	1.1	1.4	0.970

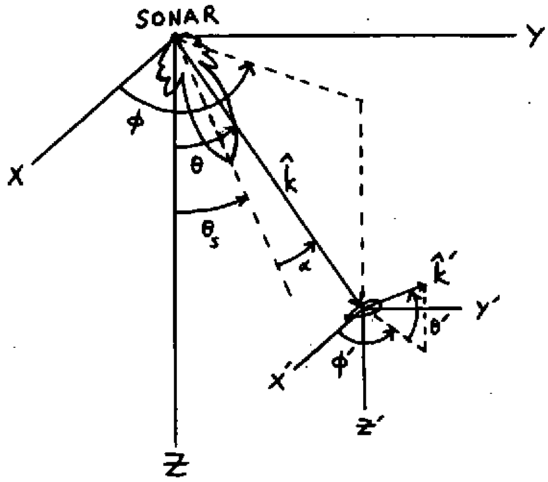

Fig. 1. Geometry of fish observation by a steered sonar beam.

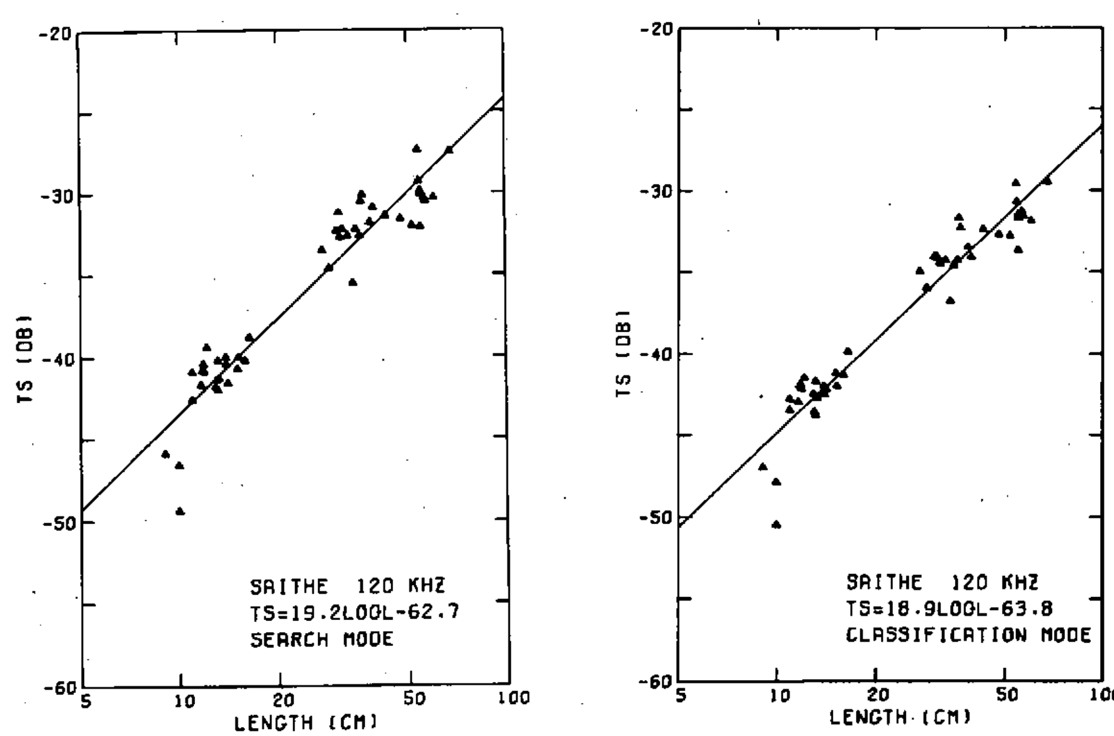

Fig. 2. Scatter diagrams of $\langle TS \rangle$ on ℓ for a homogeneous saithe aggregation observed in the vertical beam of a sector scanning sonar operating at 120 kHz.

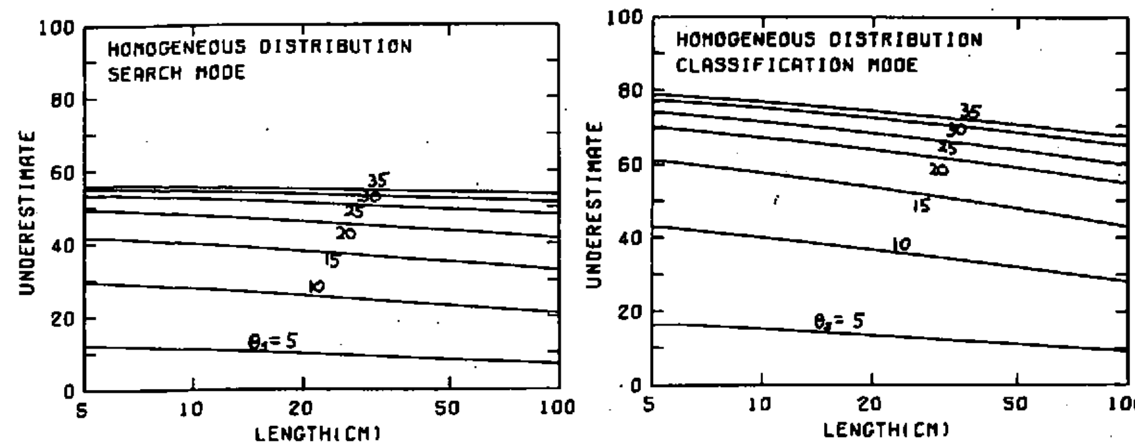

Fig. 3. Percentage underestimates in echo integrator-derived measures of saithe abundance due to oblique steering of a sector scanning sonar oriented in the vertical plane. θ_s is the steering angle in degrees as measured from the vertical.

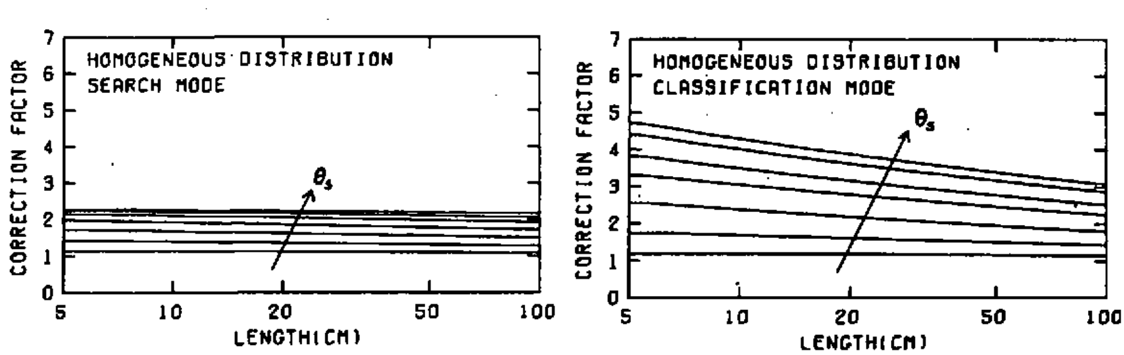

Fig. 4. Acoustical correction factors to echo integrator-derived abundance measures of saithe when observed in obliquely steered sectors of a vertically oriented sector scanning sonar. The steering angle θ_s increases as in Fig. 3.