ICES Journal of Marine Science, 60: 155–163. 2003
doi:10.1006/jmsc.2002.1319

Estimation and compensation models for the shadowing effect in dense fish aggregations

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Zhao, X., and Ona, E. 2003. Estimation and compensation models for the shadowing effect in dense fish aggregations. – ICES Journal of Marine Science, 60: 155–163.

This paper addresses the problem of acoustic "shadowing" (i.e. first-order scattering) using an heuristic approach. It is shown that the relationship between the shadow coefficient – the proportional reduction of the acoustic energy due to the shadowing effect of fish (Zhao *et al.*, 1993) – and the apparent area backscattering coefficient of the fish is practically linear, and that the linear relationship will hold true even with inhomogeneous fish distributions. Based on this finding a simple linear model for the estimation of the σ_e/σ (extinction cross-section/acoustic cross-section) ratio is developed. The model applies the reference target method of Foote *et al.* (1992), which allows the shadow coefficient to be determined. A model is also developed for compensation of the shadowing effect. This model can also be used to deduce the maximum-detectable fish density when the σ_e/σ ratio is known; and the maximum-detected apparent fish density may, in turn, suggest an upper limit of the σ_e/σ ratio under the specific survey condition. A correction table is provided to serve as an approximate reference and a registration from a typical herring survey is shown as an example.

Keywords: acoustics, compensation, dense fish aggregation, estimation, model, shadowing effect.

Received 11 January 2002; accepted 15 September 2002.

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Introduction

In fish-abundance estimation by acoustics the shadowing effect can seriously alter the linearity of results when dense aggregations of fish are encountered (Røttingen, 1976; Toresen, 1991). Compensation for the excess attenuation of the echo energy due to the shadowing effect is therefore necessary (Foote, 1983; MacLennan, 1990). For this purpose knowledge is needed of the extinction cross-section σ_e for the fish in question and the reference-target method has been widely used to provide it. The target in question can either be a metal sphere having stable or known acoustic properties (Olsen, 1986; Armstrong *et al.*, 1989), or the seabed beneath the fish layer (Foote *et al.*, 1992) or both (MacLennan *et al.*, 1990). The essence of this method is that the amount of excess attenuation due to the shadowing effect of fish is studied by monitoring the returned echo energy of the reference target at various fish densities.

When the extinction cross-section of the fish is known then correction for the shadowing effect is possible. However, most correction algorithms proposed in the literature require knowledge of the actual fish density which is to be determined by acoustic estimation. Thus, the estimated density corrected for the shadowing effect has to be used. The detrimental effect of the errors in such a correction was pointed out by Foote (1990) and Burczynski *et al.* (1990).

In line with the reference-target method, Zhao *et al.* (1993) suggested that the proportional reduction of acoustic energy due to the shadowing effect and termed the "shadow coefficient", might be used as a convenient measure of the effect. Under certain assumptions a linear relationship was derived between the shadow coefficient and the apparent area-backscattering coefficient of the fish. However, when aiming at a correction algorithm, the potential of using this relationship to estimate the σ_e/σ (extinction cross-section/acoustic cross-section) ratio was overlooked. Therefore, it is the aim of this

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work to show how the relationship can be used to estimate the σ_e/σ ratio with greater efficiency and also to compensate for the shadowing effect without knowing the actual fish density.

Throughout this paper a heuristic approach is adopted. It begins with the definition of the shadow coefficient and the derivation of the relationship between the shadow coefficient and fish density follows. Models for the estimation of the σ_e/σ ratio and compensation for the shadowing effect are then developed based on the relationship obtained. Most of the derivations and the resulting models are described in terms of integrator output and acoustic property parameters of the fish relevant to acoustic, fish-abundance surveys. In the discussion section the limitations and advantages of the models are discussed; an example is given to show the application of the correction model and correction curves as well as a correction table are furnished.

Definition of the shadow coefficient

The shadow coefficient, β, is defined as the proportional reduction of the acoustic energy – in terms of integrator output – due to the shadowing effect of fish, or mathematically:

$$\beta=(s_A - s_{\tilde{A}})/s_A, \tag{1}$$

where s_A is the true area-backscattering coefficient of the fish as if there were no acoustic shadowing and $s_{\tilde{A}}$ is the measured, or apparent, area-backscattering coefficient subject to shadowing effect.

The shadow coefficient β is a dimensionless quantity with possible values ranging from 0 to 1, i.e., $\beta\in[0,1]$. It has two bounds:

$\beta=0$ means that the shadowing effect is insignificant and not detectable. The linearity theorem (Foote, 1983) strictly applies at this end.

$\beta=1$ implies that the shadowing effect is so severe that the echo signal from the target in question is indistinguishable from ambient noise and its integration is suppressed.

It is the non-zero β value that is of concern to fisheries scientists using the acoustic method when dealing with densely-schooling fish species. Using the seabed as a reference target, the shadow coefficient due to the intervening fish can be measured as:

$$\hat{\beta}=(s_{A.B_0} - s_{A.B})/s_{A.B_0}, \tag{2}$$

where $\hat{\beta}$ denotes the estimated shadow coefficient, $s_{A.B_0}$ denotes the s_A of the seabed with no intervening fish between transducer and the seabed, and $s_{A.B}$ denotes the s_A of the seabed when there are fish between transducer and the seabed.

Relationship between shadow coefficient and fish density

In the linear domain of fisheries acoustics the following relationship holds:

$$s_A=\rho_A \cdot \sigma, \tag{3}$$

where s_A is the area-backscattering coefficient, m^2 nmi^{-2}, defined as in Knudsen (1990):

$$s_A=4\pi \cdot 1852^2 \cdot \int s_v dz, \tag{4}$$

where s_v is the volume-backscattering coefficient, m^2 m^{-3}; ρ_A is the fish density, individuals nmi^{-2}; and σ is the mean acoustic cross-section per fish individual, m^2, which relates to the target strength of fish as follows (MacLennan and Simmonds, 1992):

$$TS=10\log(\sigma/4\pi). \tag{5}$$

In cases where fish are densely aggregated so that the shadowing effect is significant, the apparent area-backscattering coefficient $s_{\tilde{A}}$ will be an underestimation of the true s_A. Formulae used for the prediction of this effect were given by Foote (1983) in terms of echo energy and by Foote (1990) in terms of s_v, the volume-backscattering coefficient.

When the incident wave penetrates a small depth dz into the fish school it will experience a small amount of excess attenuation because of the shadowing effect. This will be at a rate proportional to the total extinction cross-section encountered within one unit sampling area and may be expressed by a differential equation due to Foote (1990):

$$dI/I= - \rho_v \cdot \sigma_e \cdot dz, \tag{6}$$

where I is the range-compensated, incident sound intensity; ρ_v is the volume fish density, individuals m^{-3}; and σ_e is the extinction cross-section, m^2.

Strictly speaking, Equation (3) and Equation (6) are true only in the sense of the statistical "mean field" (Foote, 1990); consequently, σ_e and σ are the mean values averaged over the scattering field with regard to the shape, structure and orientation of the fish.

To proceed, we assume that the second and higher order scattering is negligible and that the acoustic cross-section and the mean dorsi-ventral extinction cross-section of the fish are statistically constant. We further assume that the fish density is constant within a well-defined layer of thickness h, and that the horizontal dimension of the fish aggregation is larger than the beam-spreading in all depths. Under these assumptions, for an incident wave with initial intensity I(0) at the top of the fish aggregation that travels z metres into the aggregation, the expected sound intensity at z will be:

$$I(z)=I(0)\cdot\exp[-\rho_v\cdot\sigma_e\cdot z]. \quad (7)$$

Because the echo will suffer the same amount of attenuation on its way back to the receiver, the apparent area-backscattering coefficient necessarily becomes:

$$s_{\tilde{A}}=s_A\cdot\int_0^h\exp[-2\cdot\rho_v\cdot\sigma_e\cdot z]\cdot dz/h. \quad (8)$$

Solving the integral and substituting s_A of Equation (3) we have:

$$s_{\tilde{A}}=\rho_A\cdot\sigma\cdot\frac{1-\exp[-2\cdot\rho_v\cdot\sigma_e\cdot h]}{2\cdot\rho_v\cdot\sigma_e\cdot h}. \quad (9)$$

Since $\rho_v\cdot h=\rho_a$, which is the number of fish per m^2, and ρ_A is the number of fish per nmi^2, therefore,

$$\rho_A=1852^2\cdot\rho_v\cdot h. \quad (10)$$

Equation (9) can then be reduced to:

$$s_{\tilde{A}}=\frac{1852^2}{2}\cdot\frac{\sigma}{\sigma_e}\cdot\{1-\exp[-2\cdot\rho_v\cdot\sigma_e\cdot h]\}. \quad (11)$$

For the seabed, according to Equation (7) we have:

$$s_{A,B}=s_{A,B_0}\cdot\exp[-2\cdot\rho_v\cdot\sigma_e\cdot h]. \quad (12)$$

From this and Equation (2), the expected shadow coefficient, as sensed by the seabed, is then:

$$\hat{\beta}=1-\exp[-2\cdot\rho_v\cdot\sigma_e\cdot h]. \quad (13)$$

Substituting Equation (13) into Equation (11) and rearranging, we have:

$$\hat{\beta}=K\cdot\gamma\cdot s_{\tilde{A}}, \quad (14)$$

where $K=2/1852^2$, $\gamma=\sigma_e/\sigma$. On the basis of constant σ and σ_e, Equation (14) means that the shadow coefficient is linearly proportional to the apparent area-backscattering coefficient or the measured fish density.

To reach Equation (14), we have assumed that the fish density is constant. However, as MacLennan *et al.* (1990) pointed out, this assumption is unrealistic. So a natural question to ask is, "What is the relationship between the shadow coefficient and the apparent area-backscattering coefficient when fish density is not constant?"

To address this question we assume that a fish aggregation consists of n layers, not necessarily of equal thickness, and that each layer is characterized by a different but constant fish density. Let $\rho_{a,i}$ and $s_{\tilde{A},i}$ denote the area fish density and its corresponding apparent area-backscattering coefficient for layer i (i=1,2, . . . , n), respectively. We further let $\rho_{a,1\sim i}$ and $s_{\tilde{A},1\sim i}$ respectively, denote the cumulative area fish density and its corresponding apparent area-backscattering coefficient from the first down to the ith layer. As the area density is just the product of the volume density and the layer thickness, according to Equation (11), the following relationship is immediate for n=1:

$$s_{\tilde{A},1\sim 1}=s_{\tilde{A},1}=\frac{1}{K\cdot\gamma}\cdot\{1-\exp[-2\cdot\rho_{a,1}\cdot\sigma_e]\}. \quad (15)$$

We now consider the situation in which n=2. Since the second layer is subject to the shadowing effect from the first as well as its own layer, from Equation (11) and the principle of Equation (12), we have:

$$s_{\tilde{A},2}=\frac{1}{K\cdot\gamma}\cdot\{1-\exp[-2\cdot\rho_{a,2}\cdot\sigma_e]\}\cdot\exp[-2\cdot\rho_{a,1}\cdot\sigma_e]. \quad (16)$$

Combining Equation (15) and Equation (16) and rearranging, leads to:

$$s_{\tilde{A},1}+s_{\tilde{A},2}=\frac{1}{K\cdot\gamma}\cdot\{1-\exp[-2\cdot(\rho_{a,1}+\rho_{a,2})\cdot\sigma_e]\}. \quad (17a)$$

It can be seen that the relationship

$$s_{\tilde{A},1\sim 2}=s_{\tilde{A},1}+s_{\tilde{A},2} \quad (17b)$$

will obviously hold true because $\rho_{a,1\sim 2}=\rho_{a,1}+\rho_{a,2}$. This means that the total shadowing effect is only determined by the mean individual extinction cross-section and the accumulated area fish density. Thus, the actual fish distribution is not very important so long as the fish are sufficiently randomly distributed to maintain incoherent scattering for Equation (3) to hold true.

For completeness, we assume that the above relationship holds true for a j-layered fish aggregation, i.e.,

$$\sum_{i=1}^{j}s_{\tilde{A},i}=\frac{1}{K\cdot\gamma}\cdot\left\{1-\exp\left[-2\cdot\sum_{i=1}^{j}\rho_{a,i}\cdot\sigma_e\right]\right\},\text{ and} \quad (18a)$$

$$s_{\tilde{A},1\sim j}=\sum_{i=1}^{j}s_{\tilde{A},i}. \quad (18b)$$

Appending one more layer to the j-layered aggregation, the apparent area-backscattering coefficient of the (j+1)th layer will be:

$$s_{\tilde{A},j+1}=\frac{1}{K\cdot\gamma}\cdot\{1-\exp[-2\cdot\rho_{a,j+1}]\cdot\sigma_e\}\cdot\exp\left[-2\cdot\sum_{i=1}^{j}\rho_{a,i}\cdot\sigma_e\right]. \quad (19)$$

Combining Equation (18a) and Equation (19) and rearranging, we have:

$$\sum_{i=1}^{j+1} s_{\tilde{A},i} = \frac{1}{K \cdot \gamma} \cdot \left\{ 1 - \exp\left[-2 \cdot \sum_{i=1}^{j+1} \rho_{a,i} \cdot \sigma_e \right] \right\}. \quad (20a)$$

Again, the relationship

$$s_{\tilde{A},1\sim j+1} = \sum_{i=1}^{j+1} s_{\tilde{A},i} \quad (20b)$$

will hold true because $\rho_{a,1\sim j+1} = \sum_{i=1}^{j+1} \rho_{a,i}$. This completes the verification, which ensures that Equation (14) will generally hold true even when the fish density is not constant. Thus, the assumption of constant fish density is no longer necessary.

Given this, Equation (14) tells us that the shadow coefficient is linearly proportional to the apparent area density for most fish aggregations observed during an ordinary acoustic survey where the second and higher-order scattering is negligible, so long as the fish in question are of nearly the same size to maintain a relatively constant extinction cross-section. This is very relevant to the experimental studies of, and corrections for, the shadowing effect.

Model for the estimation of the σ_e/σ ratio

In Equation (14), $s_{\tilde{A}}$ is just the integrator output of a properly calibrated, modern scientific echosounder and $\hat{\beta}$ can be measured through a reference target such as a metal sphere or the seabed. The data collection procedure, established by MacLennan *et al.* (1990), Toresen (1991) and Foote *et al.* (1992), involves pair-wise recording of the area-backscattering coefficients of the reference target and that of the intervening fish (see Foote *et al.*, 1992 for a rigorous account). The recording of the reference target when fish are absent should, of course, be made to enable the estimation of β.

Since γ, the σ_e/σ ratio, should be a small value, the slope of the line described by Equation (14) is usually inconveniently small. This is overcome by rewriting Equation (14) to the following regression model:

$$\beta' = \gamma \cdot s_{\tilde{A}} + \varepsilon \quad (21)$$

where $\beta' = (1852^2/2) \cdot \hat{\beta}$, $s_{\tilde{A}}$ remains the same and ε is a normally distributed error term. It is essentially a simple linear model without an intercept term. This is intuitively reasonable since with no fish to cause it there would be no shadowing effect.

However, in reality, any deviations from those assumptions mentioned earlier and the stochastic nature of the extinction cross-section can easily render the error term in Equation (21) non-zero. Thus it may be desirable to include an intercept term in the model to improve the fit. Either with or without an intercept term this model should be used only if it can describe the data reasonably well. When the data does not fit the model then it should not be used and this will be discussed further.

Model for the correction of the shadowing effect

It is seen from Equation (14) that when the σ_e/σ ratio of the fish, γ, is known the shadow coefficient can be predicted for any measured fish area-backscattering coefficient and so the excess attenuation caused by the shadowing effect can easily be corrected for. The basic correction formula is, from Equation (1):

$$s_A = s_{\tilde{A}}/(1-\beta). \quad (22)$$

Although β is measured in terms of the echo-integral of the reference target, it equally applies to sub-layers of the fish aggregation. Imagine that a small sub-layer (labelled i) inside a fish aggregation gives an apparent area-backscattering coefficient $ds_{\tilde{A},i}$, it can be seen from Equation (22) that its true area-backscattering coefficient $ds_{\tilde{A},i}$ should be:

$$ds_{A,i} = \frac{1}{1 - K \cdot \gamma \cdot s_{\tilde{A},i}} \cdot ds_{\tilde{A},i}, \quad (23)$$

where $s_{\tilde{A},i}$ is the apparent area-backscattering coefficient above the small sub-layer i.

Integrating the right-hand side of Equation (23) over the full range of the apparent area-backscattering coefficient of the fish aggregation, $s_{\tilde{A}}$, we have:

$$s_A = \frac{1}{K \cdot \gamma} \ln\left(\frac{1}{1 - K \cdot \gamma \cdot s_{\tilde{A}}} \right), \quad (24a)$$

where s_A is the area-backscattering coefficient of the fish aggregation corrected for the shadowing effect. This is the correction formula for the shadowing effect for the fish aggregation in the entire water column.

Similarly, the corrected $s_{A,i}$ for a well-defined, large sub-layer, i, can be obtained by limiting the integration range from the start to the end of the layer, resulting in the following:

$$s_{A,i} = \frac{1}{K \cdot \gamma} \cdot \ln\left(\frac{1 - K \cdot \gamma \cdot s_{\tilde{A},1\sim i-1}}{1 - K \cdot \gamma \cdot s_{\tilde{A},1\sim i}} \right) \quad (24b)$$

where $s_{\tilde{A},1\sim i-1}$ denotes the cumulative apparent area-backscattering coefficient of the fish above the ith layer and $s_{\tilde{A},1\sim i}$ denotes the same from the first down to, and including, the ith layer.

Discussion

The estimation model

Within the framework of the reference-target method two distinct models aiming at the estimation of the extinction cross-section of fish exist in the literature. Olsen (1986) employed a "classical" model from Clay and Medwin (1977); using the notation from this paper:

$$\sigma_e = \frac{\alpha_b}{434 \cdot \rho_v}, \quad (25)$$

where α_b is the sound-attenuation coefficient in dB m^{-1}. This model is suited for controlled experiments (e.g., Furusawa *et al.*, 1992) where fish density is known.

For *in situ* applications, Foote *et al.* (1992) proposed a pioneering, practical model in the form:

$$s_{A.B} = a + b \cdot s_{A.F}, \quad (26a)$$

where s_{A_B} and s_{A_F} are the apparent area-backscattering coefficient of the seabed and that of the intervening fish, respectively; and a and b are the two regression coefficients which allow the σ_e/σ ratio to be determined:

$$\sigma_e/\sigma = -1852^2 \cdot b/(2 \cdot a). \quad (26b)$$

A common advantage of Equation (26) and Equation (21) is that only the integrator output, not the true fish density, is needed for the extraction of the σ_e/σ ratio. The derivation of Equation (21) was initially via the same line of reasoning as the former and it was only in the choice of regressand that it diverged. Instead of directly regressing the target echo-integral on the fish echo-integral as in Equation (26a), the shadow coefficient was chosen as the regressand in Equation (21).

It transpires that there are two advantages in using Equation (21). One is the gain in efficiency because the σ_e/σ ratio is just the slope of the line in Equation (21). When using the model outlined by Equation (26), the estimate of the σ_e/σ ratio is determined by the two regression coefficients and each is subject to estimation error. Moreover, the confidence limits of the estimate resulting from Equation (21) can be readily constructed using the standard error of the slope. Thus there is no need to invoke the inverse prediction technique as for Equation (26) (Foote *et al.*, 1992) from which a wider confidence interval is expected.

The other merit of Equation (21) is its potential for generalization. Since the shadow coefficient, once determined, is independent of the reference target used, several data sets can be combined to provide a pooled estimate. This is especially helpful for *in situ* measurements using the seabed as a reference because different geographical areas are likely to be characterized by different seabed types. It therefore avoids the need for prolonged experiments in the same area, thereby reducing vessel time and the associated costs that are often prohibitively expensive. Utilizing this property of the shadow coefficient, data could be collected whenever and wherever suitable during a survey regardless of the seabed difference between areas but given uniformity within each area.

One crucial requirement for the successful use of this model is that the initial area-backscattering coefficient of the reference target needs to be determined with reasonable precision when fish are absent, because calculation of the shadow coefficient relies on this value. Thus, when the initial target value is not available or is in doubt Equation (26) should be used. However, this is not to say that the initial target value is no longer important. On the contrary, it is so important that the adequacy and hence the reliability of these simple models should be checked against this value. Significant deviations from the model when it is included may reveal large measurement errors or, more likely, strong violations of the assumptions imposed on the models. One such example is the day-night difference of the σ_e/σ ratios observed by Foote *et al.* (1992), which renders the assumption of constant σ_e and σ invalid. Splitting the data into day and night groups as done in Foote *et al.* is an effective remedy.

High-order scattering was studied analytically by Stanton (1983) on omni-directional scatterers: the study revealed that second-order scattering might partially offset the excess attenuation of the acoustic energy due to the shadowing effect. This finding was supported by another theoretical study performed by Lytle and Maxwell (1983). On the other hand, Foote (1990) maintained that high-order scattering should be negligible for large and dense aggregations of anisotropic-scattering fish when surveyed by a narrow-beam, high-frequency echosounder. Evidence of high-order scattering phenomena such as a prolonged diffusion tail following below the main fish concentration and even continuing beyond the seabed echo, were found in field observations (see MacLennan and Simmonds, 1992, p. 158, for examples). Whilst these prolonged echoes are observable and may even be deductible the extent to which they overlap with the main fish echo is indeterminate. Nevertheless, so long as the model can describe the data reasonable well an approximate estimate should be attainable and correction for the shadowing effect is then possible.

The correction model

Most correction algorithms proposed in the literature are stepwise or layer-by-layer correction and each layer is corrected for the shadowing effect due to the fish in all the layers above it. These algorithms suffer from a common deficiency viz. in order to correct for the ith layer, the true fish density above the ith layer is needed, meaning that the corrected value in all but the very top layer has to be used. One exception is the empirical work by Toresen (1991). In this the correction factor was calculated based on an exponential empirical relationship between the echo-integrals of the seabed and that of the intervening fish. However, another limitation of the

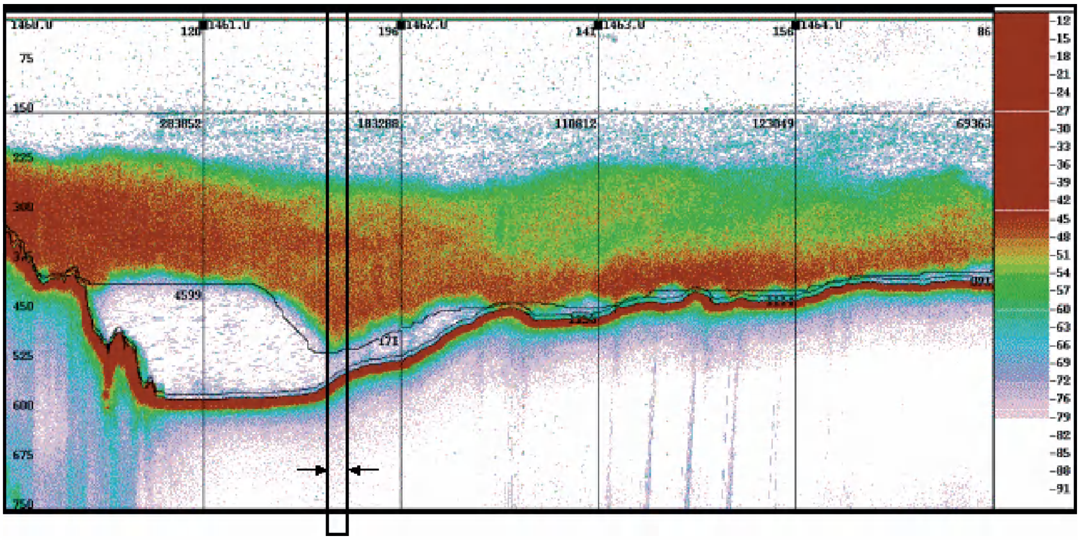

Figure 1. Echogram example from the R/V "G. O. Sars" winter survey for herring, on 17 January 2001 in Ofotfjord, showing 5 nmi of a dense herring layer at 200–550 m depth. The vertical range displayed is 0–750 m depth, as indicated in the left part of the display. On the right hand side are the colour scale (S_v, dB). Integrator lines of the post-processing system are used to isolate the herring layer and the averaged data are stored to the database in 10 m wide depth channels and 0.1 nmi (185.2 m). Correction for the shadowing effect is made on the data at this resolution, and is shown in detail in Table 1 for the 0.1 nmi section indicated by the inserted box, from the distance-log number 1461.6–1461.7 nmi.

Table 1. An example using Equation (24b) of the correction for the shadow effect of measured area-backscattering coefficients on vessel distance-log number 1461.6–1461.7 nmi, from 260–520 m depth. The measured area-backscattering coefficient in each depth layer, $s_{A,i}$ is given in standard units [m^2 nmi^{-2}] and the applied γ (σ_e/σ ratio) was 2.41. This value is now applied during surveys on wintering herring in the Vestfjorden/Ofotfjord system.

Depth (m)	Layer (i)	$s_{A,i}$	$s_{A,1\sim i-1}$	$s_{A,1\sim i}$	Corrected $s_{A,i}$	C_i
260–270	1	1 123	0	1 123	1 124	1.001
270–280	2	2 817	1 123	3 940	2 827	1.004
280–290	3	4 248	3 940	8 188	4 285	1.009
290–300	4	4 594	8 188	12 782	4 663	1.015
300–310	5	6 394	12 782	19 176	6 541	1.023
310–320	6	8 239	19 176	27 415	8 518	1.034
320–330	7	6 963	27 415	34 378	7 279	1.045
330–340	8	14 493	34 378	48 871	15 394	1.062
340–350	9	16 865	48 871	65 736	18 343	1.088
350–360	10	10 979	65 736	76 715	12 200	1.111
360–370	11	9 691	76 715	86 406	10 946	1.129
370–380	12	8 864	86 406	95 270	10 161	1.146
380–390	13	7 971	95 270	103 241	9 263	1.162
390–400	14	11 598	103 241	114 839	13 697	1.181
400–410	15	12 433	114 839	127 272	14 982	1.205
410–420	16	11 598	127 272	138 870	14 266	1.230
420–430	17	13 375	138 870	152 245	16 815	1.257
430–440	18	15 361	152 245	167 606	19 815	1.290
440–450	19	13 269	167 606	180 875	17 572	1.324
450–460	20	15 712	180 875	196 587	21 385	1.361
460–470	21	12 360	196 587	208 947	17 286	1.399
470–480	22	7 754	208 947	216 701	11 063	1.427
480–490	23	4 715	216 701	221 416	6 812	1.445
490–500	24	2 372	221 416	223 788	3 452	1.455
500–510	25	590	223 788	224 378	861	1.460
510–520	26	18	224 378	224 396	26	1.461
Total		224 396			269 578	1.201

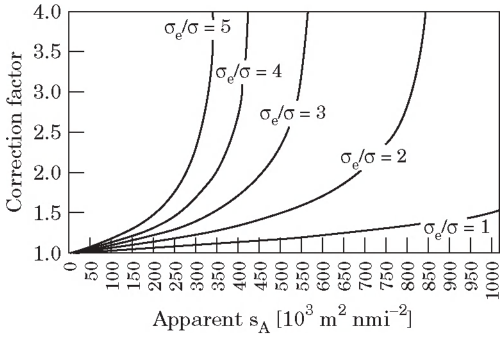

Figure 2. Correction curves for shadowing effect at various σ_e/σ ratios. The correction factor corresponding to 0 apparent area-backscattering coefficient is actually obtained with 1 m^2 nmi^{-2}.

stepwise correction algorithm with regard to the choice of layer thickness in practical applications was revealed in that work. This is because the shadowing effect within each sub-layer of 5- or even 10 m-layer thickness is ignored. This is a reasonable practical choice as used by the author but will result in under-compensation. Further refinement of the layers requires substantial additional work, and is not always possible (Appenzeller and Leggett, 1992). By the use of Equation (24), these problems are elegantly overcome; fish density is not needed for the correction. Corrections can be flexibly made for any selected sub layers as well as for the entire water column, as shown in the example from the dense herring layer in Figure 1 and corresponding Table 1. The measured area-backscattering coefficient for the selected distance is 224 396 [m^2 nmi^{-2}]. Using a γ (σ_e/σ ratio)=2.41 (Foote, 1999), the estimated corrected area-backscattering coefficient is 269 578 [m^2 nmi^{-2}], or a mean correction factor of 1.201 for the entire layer. As seen in Table 1, the correction factor increases throughout the layer, to a maximum of 1.461 in the lower parts of the layer.

It should be mentioned that when the shadowing effect is large, due to the statistical nature of scattering field, the term $1/(1 - K \cdot \gamma \cdot s_{\tilde{A}})$ may be very large and in some circumstances negative for individual sounding-correction operations, rendering its natural logarithm very large or practically non-existent. Therefore Equation (24) is better used with mean $s_{\tilde{A}}$ averaged over a large number of soundings. As pointed out by Foote (1990), if this problem still happens with mean $s_{\tilde{A}}$, it is a warning signal that any attempts to continue the correction process should cease. When the term becomes negative it may suggest that an inappropriate γ (σ_e/σ ratio) value may have been used.

Figure 2 shows a family of correction curves assuming different γ values. The correction factor C is, according to Equation (24a):

Table 2. Correction factor for shadowing effect. $s_{\tilde{A}}$ denotes the apparent area-backscattering coefficient of the fish (in thousand m^2 nmi^{-2}); blank entries denote that the correction factor does not exist, i.e. the corresponding $s_{\tilde{A}}$ values are not observable with the σ_e/σ ratio specified.

$s_{\tilde{A}}$	$\sigma_e/\sigma=1$	$\sigma_e/\sigma=2$	$\sigma_e/\sigma=3$	$\sigma_e/\sigma=4$	$\sigma_e/\sigma=5$
1	1.000	1.001	1.001	1.001	1.001
5	1.001	1.003	1.004	1.006	1.007
10	1.003	1.006	1.009	1.012	1.015
50	1.015	1.030	1.046	1.063	1.081
100	1.030	1.063	1.099	1.139	1.182
150	1.046	1.099	1.160	1.231	1.315
200	1.063	1.139	1.231	1.347	1.500
250	1.081	1.182	1.315	1.500	1.791
300	1.099	1.231	1.418	1.719	2.374
350	1.118	1.285	1.547	2.076	
400	1.139	1.347	1.719	2.897	
450	1.160	1.418	1.966		
500	1.182	1.500	2.374		
550	1.206	1.599			
600	1.231	1.719			
650	1.257	1.872			
700	1.285	2.076			
750	1.315	2.374			
800	1.347	2.897			
850	1.381				
900	1.418				
950	1.457				
1000	1.500				
1500	2.374				

$$C = \frac{1}{K \cdot \gamma \cdot s_{\tilde{A}}} \cdot \ln\left(\frac{1}{1 - K\gamma \cdot s_{\tilde{A}}}\right). \quad (27)$$

It is seen from Figure 2 that if $\gamma = 5$, the correction factor increases rapidly when $s_{\tilde{A}}$ goes beyond 300 000 m^2 nmi^{-2}, which means only a small fraction of the echo energy from the deeper part of the fish aggregation can travel back to the receiver. On the other hand, if a $s_{\tilde{A}}$ of greater than 350 000 m^2 nmi^{-2} is observed, the average γ value is then not likely to be larger than 5. Therefore, when its underlying assumptions are reasonably met the model can also serve as a tool to predict the maximum detectable fish density when the σ_e/σ ratio is known. It may then be applied more usefully to predict an upper bound for the expected σ_e/σ ratio for a given recorded maximum $s_{\tilde{A}}$ value.

Part of the data used to generate Figure 2 is furnished in Table 2. It shows that for most fish densities that may be encountered during an ordinary acoustic survey, the shadowing effect is entirely negligible. This confirms the findings of Furusawa *et al.* (1992). When the fish density is high but the σ_e/σ ratio is not known a conservative but necessary approach is to assume $\gamma = 1$. For isotropic scatterers, this is equivalent to neglecting the absorption term in the extinction cross-section. For directive scatterers, experimental evidence from MacLennan *et al.* (1990) and Foote *et al.* (1992) also showed that γ is generally greater than unity. It can be seen from Table 2 that when $\gamma = 1$ and $s_{\tilde{A}} = 500\,000$ m^2 nmi^{-2}, the correction factor is 1.182 and is no longer negligible.

It should also be noted that in order to maintain the correction as unambiguous, $s_{\tilde{A}}$ should be a monotonically increasing function with increasing fish density. In a field application this means $s_{\tilde{A}}$ should increase with increasing depth into the fish layer, which is automatically fulfilled. However, for encaged fish Røttingen (1976) found that the fish echo-integral increased monotonically only up to a certain limit. When the fish density increased further the echo-integral declined which suggested altered fish behaviour (consequently its σ and σ_e) at extreme high-packing densities (Foote, 1978a, b, 1980). Therefore σ_e/σ ratio measured in the field may not be applicable to fish in restricted environments. When attempting to correct for the fish density in culture net pens (Furusawa *et al.*, 1984; Burczynski *et al.*, 1990), the σ_e/σ ratio should be determined independently.

Acknowledgements

This work was partially supported by the National Key Basic Research Program from the Ministry of Science and Technology, P. R. China (Grant no. G19990437), and by the Research Council of Norway (Grant no. 143249/140). Dr Natalia Gorska at the Institute of Oceanology of Polish Academy of Sciences and two anonymous referees are thanked for their useful comments on the manuscript.

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